Deciphering the Enigma of Human Creativity: Can A Digital Computer Think?

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***Abstract*—It is possible to understand how scientific geniuses made discoveries, if we treat the paths leading to a discovery as a process of pattern recognition and we further recognize that there are two different modes of reasoning that can be used to generate solutions but are used by highly creative and less creative individuals with different proportions: visual thinking and verbal thinking. The power of visual thinking lies in its inherent parallel processing and random access. These features can explain why geniuses often had no clue as to how the solution had been arrived at. Intuition, which is intimately related to parallel processing and visual thinking, is so difficult to articulate since articulation is a sequential process, and a suitable parallel-to-serial conversion must be sought for in advance. However, the pitfalls of visual thinking include liability to additional errors and a lack of objectivity. However, potential solutions discovered by visual thinking must be strictly verified by logical reasoning, which is sequential and inherently verbal in nature. When the latter is done properly, it is highly objective and less error-prone, and can eliminate most errors incurred at the stage of solution generation. There is no straight answer to the question whether a digital computer can think, because there is a gray scale of thinking and understanding. Taking Herbert Simon's programs as examples, we found that some of these programs did indeed surpass the intellectual performance of a special class of human being: the so-called high achievers who are strong in taking standardized tests but weak in formulating ideas to solve problems that have not been taught previously or covered in the textbook. But human geniuses seemed so far to be able to stay one step ahead of these programs, because Simon's programs were constructed by pooling together thinking strategies of many past creators, so as to generate heuristics. As for the creative performance of future computers, it is better to suspend our judgment. Science and technology history taught us a lesson: never say never, except perhaps just this once.**

***Index Terms*—Creativity, intuition, computer-based creative problem solving.**

I. INTRODUCTION

THE thought process of geniuses or individuals with superior mental abilities has captured the fascination of philosophers and scientists since the inception of these professions. The mystery of human creativity is embroidered in the common report that the creator himself or herself had no clue as to how the solution was arrived at, even after the fact. Legend had it that Carl Friedrich Gauss, in referring to a long-standing problem which he had just solved, said, "Like a sudden flash of lightning, the riddle happened to be solved. I myself cannot say what was the conducting thread which connected what I previously knew with what made my success possible" [1]. In a monumental treatise with the title *The Logic of Scientific Discovery*, Karl Popper essentially negated the message conveyed by his title by proclaiming that there is essentially no logic that leads to a scientific discovery (p. 31 of [2]). With the advent of digital computers that had been programmed to make discovery, philosophers pondered whether a digital computer actually thinks [3], [4]. Since these programs followed a certain logic conceived in the mind of their programmer, the perennial question whether there is logic of discovery has revived.

For almost a century, psychologists have strived to decipher the enigma of geniuses' creativity with modest success. Early models of thought processes were based on introspective reports of geniuses in science and mathematics. One of the earliest such reports was presented by mathematician Henri Poincaré in 1908 [5]. Mathematician Hadamard [6] also compiled a collection of introspective reports by fellow mathematicians or scientists, including Albert Einstein.

With the advent of behaviorism, psychologists began to behavioral evidence that could only be objectively demonstrated. Tangible conclusions were reached after extensive behavioral experiments often with the aid of statistical methodology to sort out meaningful factors from interfering circumstances. A genius' introspection was therefore deemed too subjective and lacked objective behavioral evidence. Introspection and intuitive feeling of practicing scientists and mathematics has thus been banished to the back alley of "folk psychology." In hindsight, this attitude was somewhat strange, because it was tantamount to the attitude of studying politics and business administration by honoring only the opinions of academic scholars while ignoring the testimonials of practicing politicians and business leaders.

Both Poincaré and several eminent physicists after him, such as Albert Einstein, Richard Feynman and Stephen Hawking, have given introspective testimonials of their predominant use of visual thinking — as opposed to verbal thinking — in solving problems and making scientific discoveries and mathematical inventions. Visual thinking and verbal thinking thus correspond to the domains of function of the right and the

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left cerebral hemisphere, respectively, in accordance with early theory of cerebral lateralization. However, as a result of progress made in lateralization research, this line of thinking fell out of favor of psychologists because earlier theories were oversimplified and because no detectable differences regarding the preferential uses of the two cerebral hemispheres could be demonstrated between geniuses and ordinary but competent individuals [7], [8]. Mental imagery, which exists in imagination — as opposed to visual imagery which one actually sees — was dismissed by some psychologists as an epiphenomenon and serves no real physiological function [9]. In hindsight, this mainstream thought represented a missed opportunity (see discussion in [10]).

Presently, there are two schools of thought among practicing psychologists: the elitist and the non-elitist views regarding geniuses' thought process. The elitists claimed that geniuses use a qualitatively different process in creative thinking, whereas non-elitists believed that geniuses' thought process is not fundamentally different from that of ordinary but bright individuals. Hayes [11] and Weisberg [12], [13] claimed that geniuses simply know more, work harder, and more strongly motivated than ordinary people. Yet, knowledgeable, hard-working and strongly motivated scientists far outnumber scientific geniuses that made break-through type discoveries — what Thomas Kuhn [14] regarded as paradigm shifts. Bailin [15] asserted a non-elitist view but claimed that the thinking process of geniuses is excellent thinking without stipulating what constitutes excellent thinking. The non-verbalizable factors that contribute to a scientist's discovery are often referred to collectively as intuition, inspiration, and insight. The predicament in describing these terms is epitomized by a remark made by Sternberg and Davidson [16]: "[W]hat we need most in the study of insight are some new insights!"

We studied the problem by a multi-disciplinary approach that includes past "insight" gained in cognitive science, artificial intelligence, and biocomputing. Contrary to the advice of mainstream psychologists, we paid attention to introspective reports of creative scientists and mathematicians. We further used basic linguistic tools to clarify our verbal thought. We find Simonton's chance-configuration theory [17] a convenient point of departure in our discussions. In particular, we treated creative problem solving as a process of pattern recognition. We also resurrected the abandoned dichotomy of cerebral lateralization and analyzed the process of pattern recognition in terms of parallel and sequential processing. Cohen [18] was the first to report an association of the right and the left hemispheric functions with parallel and sequential processing, respectively. But the idea has never gained popularity among psychologists presumably because of poor reproducibility of the proposed experiments. We conclude that geniuses use essentially the same repertoire of thinking tactics as ordinary folk, but geniuses simply push the process to the limit. We will also discuss a perennial and controversial question: can a digital computer think? (Full versions of this paper are available elsewhere [19], [20].)

II. EXHAUSTIVE SEARCH, RANDOM SEARCH, AND HEURISTIC SEARCH

In problem solving, the "space" that contains all theoretically possible solutions is commonly known as the *search space*. For a well-defined problem with a finite number of possible solutions, it is possible to examine each and every solution exhaustively, or even systematically so as to make sure that no tiles remain unturned. When the search space is sufficiently large, it may not be possible to examine each and every possible solution in real time. One of the few options left is random searching, which essentially depends on luck for the success.

In operations research and human problem solving, approaching a problem by trial and error and by examining every possible way is simply not realistic. This is because the number of possibilities rapidly increases beyond bound as the complexity of the problem increases (a situation known as combinatorial explosion). A typical example is provided by the enormous number of possible moves, countermoves, countermoves against countermoves, etc., in a chess game when a player tries to outsmart the opponent and searches for a strategic move by planning ahead at a search depth of several levels (or, rather, plies — half moves). Even IBM supercomputer Deep Blue, which defeated world chess champion Garry Kasparov in 1997, could not afford to explore the search space exhaustively [21]. Therefore, selective searching based on explicitly prescribed rules of thumb (called heuristics) often allows a problem to be solved in a reasonable length of time, whereas an undirected or trial-and-error search would require an enormous amount of time, and often could not be completed in a human lifetime. The approach is known as heuristic searching in cognitive science and operations research [22], [23].

For some types of novel problems, the search space may be poorly defined and/or it may be difficult to come up with explicit heuristics. In the latter case, the creators often attributed the "vague" rules to intuition or inspiration. Heuristics can be articulated whereas intuition is often vague and difficult to articulate. How intuition differs from explicit heuristics will be made clear in this article.

III. MODELS OF CREATIVE PROBLEM SOLVING

A. *Wallas' Four Phase Model*

Wallas [24] was among the first to suggest a paradigm for the creative process. Apparently modeling after Poincaré's account, Wallas proposed that the creative process consists of four phases: preparation, incubation, illumination and verification. When a human problem solver is confronted with a problem, the first step is task analysis or preparation. Task analysis usually involves identification of the crucial steps and feasible angles of attack. Task analysis often involves transformations of an original problem into another, which looks less formidable, or into another problem for which a "cookbook-recipe" solution already exists. This is done with reference to one's previously acquired knowledge and with the hope of matching the present problem with a previously known answer. The preparation phase is then followed by a period of incubation. The problem is often set aside for a while before it is taken up again. The period in which the idea begins to "crystallize" is the illumination phase. The final phase of verification consolidates the solution of the problem.

B. *Simonton's Chance-Configuration Theory*

Simonton's theory of chance-configuration theory [17] claimed its parentage in Campbell's blind variation and selective retention model [25]–[27]. The latter in turn followed the analogy of evolution and learning [28], [29]. Simonton's theory stipulates three stages of problem solving: blind variation, selection and retention. At a metaphoric level, Simonton's model of creative problem solving is analogous to evolutionary learning: the evolutionary triad of (random) variation, natural selection, and perpetuation (reproduction).

The cognitive process in Simonton's model is divided into three phases: "blind" variation, selection, and retention, which correspond to searching for a potential solution, recognizing it, and implementing the solution. Superficially, the notion of "blind" variation implies "random" searching. However, according to Wuketits [26], it means, instead, "not guided by anticipation," although Campbell himself had difficulty making it unambiguous. In my opinion, the notion implies searching for a solution can neither be conducted by following a pre-determined route nor by means of trail and error alone (with luck). This point will be made clear later.

In reference to the phase of "blind" variation, Simonton specifically considered the process of solving a difficult problem, perhaps a problem with no previously known answers. Most people probably would not launch a truly blind or truly exhaustive search, but would rather engage in the search for an appropriate solution from the known and learned repertoire. Only when one becomes convinced that the existing approaches are exhausted does one begin the search for an unknown and unprecedented solution. Only a fraction of people is actually willing to invest the required time and effort to follow through a difficult problem.

In the phase of selection, the problem solver chooses, upon first screening of the search space, a short list of candidate solutions that are deemed more likely to be an appropriate solution. The ability to recognize the appropriate or probable solutions during the search process is just as important as the ability to define an appropriate search space. Failure to find a solution can be due to either the exclusion of the solution from the search space or the inability to recognize the solution when included.

In the phase of retention, the solution that has been selected or recognized must be preserved and retained by some thought process. Often, more than one probable solution is found to match the problem, but not all of them are appropriate or right. Verification is thus required to complete the creative process. In the subsequent discussions, no distinction will be made between the terms "retention phase" and "verification phase."

IV. A PATTERN EMERGING FROM COMPARISON OF VARIOUS MODELS OF CREATIVE PROBLEM SOLVING

The main approach in this article is to treat creative problem solving as a process of pattern recognition. To the best of my knowledge, Herbert Simon was among the first to point out that creative problem solving involves recognition (p. 117 of [23]). If a given problem is regarded as a pattern, then the available candidate solutions in the search space can be regarded as templates, and finding the probable solutions and/or the correct solution within the search space is tantamount to recognizing suitable template, i.e., pattern recognition. Searching for suitable candidate solutions begins with the search phase and ends with the match phase, thus resulting in the acquisition of a small number of solution templates that reasonably match the problem pattern. However, these candidate solutions must be subjected to further scrutiny in the verification phase, before either some of them are retained as the final solution(s) or none of them actually works and the search continues.

In real life problem solving, the first two phases of Simonton's model often take place alternatingly in high speed, and are difficult to separate. If the two phases are combined into a single phase of search-and-match, it becomes relatively apparent that Simonton's model is equivalent to several other models reported in the literature. Perceiving the equivalence of terminology may clarify our thinking regarding how we actually think. It is obvious that the search-and-match phase and the verification-retention phase correspond, respectively, to the solution-generating and solution-verifying processes, stipulated by Newell, Shaw and Simon [30]. The two phases also correspond to: a) Poincaré's intuitive and logical approaches (pp. 210-212 of [5]; Sec. 2.1 of [31]), b) Kris' inspirational and elaborative phases [32] (see also [33]), c) Bastick's visual-ability and verbal-ability modes (pp. 192-193 of [31]), and d) Boden's parallel-intuitive and sequential-deliberative thinking (p. 205 of [34]).

Taking the formal correspondence seriously, the above comparison implies that elaborate logical reasoning, which can be verbalized, is often invoked during the solution-verifying phase. By the same token, the above models also imply that intuition and inspiration are often responsible for effective searching and keen identification of novel solutions to a difficult problem during the solution-generating phase. In fact, Poincaré said it explicitly: "It is by logic that we prove, but by intuition that we discover" (p. 274 of [35], p. 2 of [31] and p. 233 of [10]). It is also readily identifiable that intuition or inspiration corresponds to Freud's primary-process thinking. Primary-process thinking was often characterized as irrational, or non-rational, as opposed to secondary-process thinking, which was considered logical and rational. Batick's reference to visual and verbal modes of thinking implies that intuition and inspiration is often associated with visual thinking and is consistent with the afore-mentioned testimonials of several eminent creators.

The various sets of terminology mentioned above are not completely synonymous. But the comparison and identification allows for the meaning to shift from being explicitly descriptive of the phases or stages, such as the search-and-match phase and solution-generating phase, to being descriptive of the underlying mechanisms, (such as visual vs. verbal, or parallel vs. sequential). Freud's terminology was conspicuously non-descript. But it helps explain why primary-process thinking was often regarded as irrational and non-rational. Actually, there is nothing irrational about primary-process thinking, because, just like intuition, it is difficult to articulate or verbalize. But silence in offering a logical, verbal explanation is not equivalent to an admission of irrationality. By arranging the corresponding terms in a judicious order, in essentially a word-replacing game, the range of diverse terms helps connect the underlying mechanisms to cognitive science (e.g., visual vs. verbal), on the one hand, and to computer science (e.g., parallel vs. sequential), on the other hand. Visual pattern recognition (and other sensory pattern recognition) involves recognition of the pattern as a whole — what Gestalt psychologists have always been preaching. The idea sits well with the common knowledge that it often takes an enormous software overhead to accomplish pattern recognition in a sequential digital computer. It also explains why intuition is difficult to verbalize, since verbalization is a sequential process and verbalization of an intuitive feeling is tantamount to a parallel-to-serial conversion.

Here, it is important to realize that it is not the conversion process that is time-consuming. Rather, it is finding an appropriate way of verbalization that is sufficient to capture the essence of a parallel process that is time-consuming or skill-dependent. Verbalization of a parallel process is tantamount to matching a pattern with an unknown nametag with another pattern with an already-known nametag. This is illustrated by a first-hand account of a survivor of the September 11, 2001, terrorist attacks of the Twin Towers of New York City's World Trade Center.

This survivor described his ordeal of an hour-long journey on the way down via a staircase of one of the attacked buildings (C. Sheih, personal communication):

> There was no smoke at all in the stairwell, but there was a strange peculiar smell, which I later remembered it smelling like how it does when one boards an aircraft. I later found out that this was jetfuel.

His immediate awareness of the peculiar smell apparently stemmed from recognition of the smell pattern (olfactory pattern recognition). The verbal awareness of the presence of jet fuel was not immediate, since his mind was not primed towards a heretofore-unprecedented attack by means of an airliner turned a manned missile. The peculiar smell pattern was remembered nevertheless, despite a temporary lack of verbal meaning. Verbalization came in two stages. First, it became associated with a location where previous experience with the same smell pattern took place. Then, more specifically, the smell pattern became associated with a particular substance, once his mind was prompted by detailed news of the terrorist attacks.

V. ROSEN'S GENERALIZATION OF A BASIC LINGUISTIC PRINCIPLE

Further manipulations in the above word-replacing game are suggested by Rosen's generalization of basic linguistic principles. Rosen [36] classified natural processes including biological ones. Those processes that can be described by a sequential process such as a mathematical theory are called syntactic processes, whereas those processes that cannot be so described are called semantic processes. This usage of linguistic terminology includes the linguistic process as a special case. Equivalently, Rosen's syntactic process can be expressed in terms of a computer algorithm, i.e., algorithmizable, whereas his semantic processes cannot adequately be expressed as a computer algorithm, i.e., non-algorithmizable. In view of Rosen's generalization, even the humorous remark made by Sternberg and Davidson [16] becomes meaning. Essentially, Sternberg and Davidson' remark attempts to define the term "insight" by a simple example: "[W]hat we need most in the study of insight are some new insights!" Linguistically, this sentence has zero syntactic content, since it merely enunciates a tautology. Yet, it is a meaningful sentence, which proclaims a conclusion that many, if not all, readers would agree to. Therefore, the entire meaning of this sentence is contained in its semantic content. In other words, the notion of "insight" can only be "articulated" semantically though not syntactically. This "new insight," together with Rosen's generalization, allows us to conclude that insight is a semantic, non-algorithmizable process. In brief, insight is a parallel process, so is intuition.

By playing the above word-replacing game, various pieces of the jigsaw puzzle known as the enigma of creativity suddenly fall into the right slots in a single snap. All the above-mentioned models essentially conclude that the search-and-match (solution-generating) phase invokes non-algorithmizable process variously known as intuition, insight, inspiration, and primary-process thinking — essentially a Gestaltic process of (visual) pattern recognition. Logical reasoning is used only during the verification of the generated solutions.

VI. TWO MODES OF THINKING

It has long been known that there are two modes of thinking: visual thinking and verbal thinking [35], [37], [38] (see also p. 191 of [31]). Discussions presented in the previous section indicate that various models of creative problem solving all points to the distinction between the solution-generating phase and the solution-verifying phase, which invoke visual and verbal thinking, respectively. Still something is missing, because the models and our interpretation do not offer an explanation as to why some people are more creative and are bestowed by muse with the gift of intuition whereas others never have had the privilege. Choosing the right parents does not seem to be a practical answer.

This missing link was inadvertently provided by one of most devastating frustrations as a veteran teacher in a medical school: an apparently bright individual who knew the test materials failed to answer a previously exposed test question simply because the question was rephrased in a different form superficially. Apparently, this individual failed to recognize what he had already known as the relevant answer. An attempt to understand the situation led to a serendipitous finding that students who managed to make high marks did so by learning physiology as a set of rules to be applied at examination time, much like a novice cook learns to cook by following step-by-step instructions listed in a cookbook. I first referred to the process as rule-based learning as opposed to picture-based learning. The terms, rule-based reasoning and picture-based learning, which I coined at that time, turn out to be nothing new but verbal and visual thinking, respectively. One thing peculiar did not fail to attract my attention though. The student used verbal thinking in the solution-generating phase instead of the solution-verifying phase. I, for one, and most, if not all, my predecessors had not realized that verbal thinking can be invoked in the solution-generating phase — a conclusion far too obvious to be noticed.

Of course, an algorithmic process can be utilized to generate a solution, because that is exactly what an expert system does. Furthermore, if a subject is learned and memorized as a set of rules, a problem can be solved by matching certain descriptive features of the problem with the descriptive content of relevant rules and the search space is simply the repertoire of previously learned and memorized rules. Indeed, that was how the majority of our high achievers achieved their high marks.

VII. ADVANTAGES AND DISADVANTAGES OF PICTURE-BASED REASONING

Picture-based reasoning and rule-based reasoning are two sides of the same coin. Advantages of one are disadvantages of the others. In addition, the strengths of one mode of reasoning are also its weakness. Picture-based reasoning is error-prone because the recognition is often based on similarity instead of identity. Rule-based reasoning is more accurate and reliable than picture-based reasoning if the rule is correct and if the rule is followed properly. For example, a street address, if correct, is more reliable in locating a destination than a mere hunch or impression about landmarks of the neighborhood surrounding the destination. However, if the street address is incorrect, one can get forever lost whereas an imprecise hunch may still lead to the correct destination. In other words, recognition in picture-based and rule-based reasoning is based on analog and digital information, respectively. This difference is reflected in a remark aptly made by someone: to err is human, but to completely foul things up requires a digital computer. As we shall see, exclusively rule-based reasoning is no less error-prone than exclusively picture-based reasoning. Thus, it takes a combination of rule-based and picture-based reasoning to minimize errors.

The identification of a proper rule to be used in problem solving relies heavily on the matching of keywords or key phrases, which are often nametags of rules or terse descriptions of their key features. A practitioner of exclusively rule-based reasoning thus runs the risk of becoming a “prisoner of words”: one can recognize a rule only when the name or the (written or verbal) description matches the features being sought. The criterion of matching is too strict. This pitfall was recognized by Francis Bacon, who pointed out that “the ill and unfit choice of words wonderfully obstructs the understanding” (p. 49 of [39]).

In contrast, loose matches are made considerably more readily in pictures than in words. Picture-based reasoning allows for pattern recognition on the basis of analogies — analogical reasoning [40]–[43] — because an analogy is often based on perceived patterns or visual imagery. As compared to rule-based reasoning, picture-based reasoning is more likely to include false matches. In other words, rule-based reasoning is powerful in excluding false positive matches but tends to exclude false negative matches, whereas picture-based reasoning is more likely to include false negative matches as well as false positive matches. This is one of the reasons why creative individuals tend to make more mistakes than non-creative ones. But practitioners of exclusively rule-based reasoning tend to be so dogmatic as to miss crucial opportunities. This is because practitioners of exclusively rule-based reasoning are less likely to recognize an appropriate solution than practitioners of combined rule- and picture-based reasoning, when they stumble on one. They may impose excessive restriction on the search space when a heuristic search is called for. The use of strict criteria imposed by words may inadvertently “prune off” useful search paths in the search tree. Bastick stated that the visual-ability mode (picture-based reasoning) is superior to the verbal-ability mode (rule-based reasoning) in intuitive processing because it is oriented more to the whole problem than to particular parts (p. 192 of [31]). The visual mode of internal representation of global knowledge allows for simultaneous processing of the whole physiognomy, free from the physical restrictions that reality places on the objects they represent

On the other hand, practitioners of exclusively rule-based reasoning sometimes make false matches due to misleading keywords. Although such a false match can, in principle, be detected during the verification phase, the task is not always feasible for practitioners of exclusively rule-based reasoning to perform, for reasons to be presented next.

Since the verification phase requires the use of strict rules and rigorous logical arguments, practitioners of exclusively rule-based reasoning are expected to excel in verification. However, in reality, practitioners of exclusively rule-based reasoning are often poor logicians for the following reason (personal observation; see also [44]). Being compressed information, a rule often contains scanty descriptions or reminders of its domain (range) of validity or applicability. By retaining the pictures that are associated with the generation of a rule (or the derivation of a mathematical theorem), practitioners of combined rule- and picture-based reasoning are more likely to be reminded of the conditions under which the particular rule was created or derived. In contrast, practitioners of exclusively rule-based reasoning are more likely to misuse an irrelevant rule, or abuse a relevant rule beyond its domain of validity, during the verification phase. This shortcoming was hinted at by Poincaré in answering a question he raised (p. 383 of [5]): "[H]ow is error possible in mathematics?" Here, it is important to point out that the above discussion does not imply that only practitioners of exclusively rule-based reasoning make mathematical mistakes. Mathematical mistakes were sometimes so subtle that even highly creative mathematicians occasionally applied an established theorem beyond the domain of its validity (e.g., see Chapter 7 of [45]).

In summary, practitioners of exclusively rule-based reasoning suffer in all three phases of the creative process stipulated in Simonton's model: a) the search space is too restricted, b) the criteria for matching candidate solutions to a given problem is too strict, and c) the use of logic in the verification phase lacks rigor. Thus, lost opportunities may be caused by an excessively small search space, by the inability to recognize a subtle match, or by failure to detect an erroneous solution. Exclusive use of rule-based reasoning in the search-and-match phase may be tightly associated with dogmatism or the lack of divergent thinking; this is a speculative assertion that can be experimentally tested. On the other hand, the lack of objectivity in picture-based reasoning is an obvious drawback. The handicap can be alleviated or eliminated by careful verification. It is the verification phase that imparts objectivity to the overall creative process.

VIII. REDEEMING VALUES OF RULE-BASED REASONING

If picture-based reasoning is the predominant mode of some, if not all, geniuses, why is rule-based reasoning adopted by some of the high-achievers in our medical school? Apparently, there are some advantages. According to the above-mentioned student who inspired me to unravel his mode of thinking in taking examinations, rule-based reasoning is simply faster in handling standardized tests. Subsequently, several students admitted to me that, in the interest of time, they often just matched the keywords with almost total disregard of the content of the examination questions. Clearly, the main advantage of using rule-based reasoning in the search-and-match phase is speed and objectivity. Rules, in general, and mathematical theorems, in particular, are highly compressed and condensed information. Thus, one can quickly apply the rule or theorem to match the problem without spending time on rediscovering the rule or re-deriving the theorem, and on recreating the "picture" from which the rule was originally derived. Since strict rules must be adhered to, the outcome of rule-based reasoning is independent of the individuals that perform it, i.e., it is highly objective. I suspect that striving for objectivity might have been instrumental in the development of logic and laws in the Western culture.

In addition to speed, the conciseness of rules or concepts in representing knowledge offers yet another advantage. Loading a rule instead of the detailed knowledge that it represents allows more information to be loaded concurrently in working memory. However, this advantage is dubious, in view of the comprehensives of pictures in representing knowledge. Perhaps an optimal balance by means of a judicious combination of loading both pictures and rules in working memory may resolve this dilemma.

Being synonymous with verbal reasoning, rule-based reasoning stands ready to be communicated to others. In contrast, it is difficult to articulate the rationale of picture-based reasoning in unambiguous terms. Therefore, it is difficult to convince others by means of picture-based reasoning alone. The lack of a "verbal backup" for an argument renders picture-based reasoning highly subjective, thus stigmatizing its practice.

IX. SERENDIPITY, POINCARÉ'S INCUBATION AND UNCONSCIOUS WORK

One of the mysteries surrounding creativity is the phenomenon of incubation, reported by Poincaré. Some mainstream psychologists such as Hayes dismissed the importance of incubation [11]. Yet, many of us who are lesser talents than Poincaré had the experience of benefiting from incubation. What really turned mainstream psychologists off was Poincaré's subscription to the concept of the unconscious preached by Sigmund Freud's psychoanalytic school. Poincaré thought that there were two selves. While his conscious self was relaxing at an excursion, his unconscious self continued to work and seemed to be superior to his conscious self in achieving a novel discovery.

In the above interpretation of intuition, picture-based reasoning offers a better strategy of heuristic searching. Clearly, picture-based reasoning is not the sole factor in making novel discoveries. But the principle of heuristic searching remains valid, and the judicious choice of an appropriate search space remains crucial. Why is a hard problem hard? There are at least two possibilities. First, there is no solution, but few problems can be proved a priori to have no solutions. Therefore, the second possibility is more like: the choice of a search subspace inadvertently excludes some relevant subspace. For example, the exclusion of geniuses' introspective reports merely because these geniuses had no training in psychology and because introspection is too subjective to be reliable prematurely excluded a relevant part of the search space.

Poincaré's incubation can be understood in terms of modern theory of selective attention and in terms of the choice of appropriate search space. Poincaré's sustained concentration on his work for a period of four or five days might have led him to focus on an unfruitful part of the search space. His trip to a preplanned excursion led to a defocused attention and allowed him to shift his attention to a previously neglected portion of the search space. This interpretation is supported by both arousal and affect research. The detail will not be pursued here (see [19], [20]).

However, defocused attention alone is probably not sufficient for incubation to work. It was probably necessary for Poincaré to maintain his interest to his problem in the back burner. That is, he must keep his problem at the "edge" of his attention, so that when plausible solutions began to surface, he was ready to recognize. This is probably one of the many crucial character traits of creative individuals. Andrew Wiles, who proved Fermat's last theorem that eluded many of his predecessors, said "I was so obsessed by this problem that for eight years I was thinking about it all of the time — when I woke up in the morning to when I went to sleep at night" (cited in p. 60 of [46]). Here, the keyword in Wiles' remark is "obsession."

The same factor may go with the occurrence of serendipity: scientists sometimes make important discoveries by accidents or mistakes [47], [48]. It was not just sheer luck. Louis Pasteur claimed, "In the fields of observation chance favors only the prepared mind" [49]. Root-Bernstein [50] thought that it is not sufficient simply to be in the right place at the right time: a scientist must be expecting something for serendipity to occur. But how to expect an unexpected event is an intriguing problem. As Boden pointed out, parallel processing of the mind is a key factor for serendipity; it is not mere random chance alone but rather "chance with judgment" (p. 220 of [34]). Boden also presented an extensive discussion about the unpredictability of serendipity. Her interpretation can be made clear, if the word "judgment" is replaced by "recognition": serendipity is pattern recognition at an unguarded moment. Here, at work is the ability to make a subtle match between a pattern and templates under an unplanned, unexpected circumstance. On the contrary, Hayes [11] thought what Pasteur means by "the prepared mind" was someone who is sufficiently knowledgeable to recognize the chance of a discovery (see also pp. 59-60 of [46]). However, examples abound that discoveries of the serendipity type often eluded many others that were just as knowledgeable as the "lucky" ones. In my opinion, a prepared mind is one that stretches one's attention to the problem beyond the formal session of working hours so that when the right solution popped up in an unexpected moment and in an unexpected "form" or circumstance, the stimulus automatically elicit a process of recognition. Thus, serendipity, just like the effect of incubation, requires a stretch of diffuse attention to the problem. It is not something one can work towards by acquiring an inordinate amount of knowledge or merely expecting the unexpected to happen.

One of the many mysterious exhibitions of intuition-related discoveries is the suddenness of its occurrence and an apparent discontinuity of the thought process — the so-called "aha" phenomenon (or simply "eureka" experience). It is difficult to explain the discontinuity if the search process is following a certain logic in a sequential manner. But it is relative easy to understand intuition as a parallel process; the suddenness of recognition has something to do with random access inherent in a parallel process. Unless the approach is a purely random trial and error, it is difficult to expect such a discontinuity in a pre-planned algorithmic process.

X. OTHER FACTORS BEYOND VISUAL THINKING

Einstein once said: "Most people say that it is the intellect which makes a great scientist. They are wrong: it is the character" [51]. What Einstein referred to as "character" is part of what is known as personality. The exclusive use of rule-based reasoning is a mind habit, which is part of the personality. Psychologists have established that divergent thinking — though it does not guarantee creativity — is a character trait of high creativity. Divergent thinking reflects the mind's exploration in the search space and is part of the mind habit. The opposite character trait is dogmatism, which can be interpreted as self-imposed constraint on the mind's exploration.

One of the character traits being emphasized in both learning and creativity is motivation. Many educational psychologists believe that there is a positive correlation between motivation and learning. Yet I witnessed, almost on a weekly basis, that an intense desire to achieve high marks had seriously impaired a student's ability to learn — really to learn, not just memorizing the course content.

By the same token, the university administration, in order to enhance research productivity of its faculty, often resorted to monetary rewards as a motivational factor. Such a strategy is of course fully in tune with the capitalist tenet that competition breeds excellence and productivity. But it is a highly questionable practice from the perspective of creativity research.

Eisenberger et al. [52] investigated how the explicitness of promised reward affects creativity in a group of preadolescent schoolchildren. These investigators concluded that promised reward increases creativity, if there is currently, or was previously, an explicit positive relationship between creativity and reward. I have no specific reason to doubt the validity of such an investigation under the stated conditions. Such a conclusion is, however, extremely misleading if one tries to extrapolate it to other age groups, because preadolescent school children are considerably more innocent than other age groups.

Motivation in adults is a complex issue: it usually involves a combination of multiple factors. Although this complexity is widely known among the general public, some administrators in institutions of higher education seem unaware of it and continue to draft policies under the assumption that people are motivated by a single factor. Thus, premedical students know how to impress the admissions committee by claiming that they choose the medical profession solely because they wish to answer a calling to help patients. Likewise, many universities use monetary rewards (euphemism: merit raises) to promote productivity and excellence in research and/or teaching; these administrators must have assumed that most academic professionals have a major ulterior motive — monetary gain — in their pursuit of excellence.

As Deci and Ryan pointed out, the practice of using extrinsic rewards to ensure desirable behavioral outcomes gratifies caretakers' needs that may or may not be related to the designated missions (see p. 129 of [53]). Thus, at least in certain cultures, parents use extrinsic rewards to suppress children's noisy exploratory activities as well as bothersome and unending curious questions simply because the parents need a quiet moment. School health-care officers prescribed Ritalin (methyl phenidate) primarily to silence disruptive students, despite their claim that the purpose was to enhance the students' capacity to learn. The school officials' often astonishing lack of concern about the dubious effectiveness and harmful medical side effects of the Ritalin treatment betrayed their true and ulterior motive (p. 117 of [54]). Likewise, university administrators use extrinsic rewards to encourage the investigators to seek government funding simply because they need to enhance the institutional revenue. Investigators are often discouraged to seek funding from private agencies that do not pay indirect cost return (institutional overhead), or are even penalized for doing so — part of the direct cost (funds for research) is to be deducted in order to recover the lost institutional revenue.

Regarding the dubious uses of extrinsic rewards, Deci and coworkers [55] and others have shown that extrinsic rewards can undermine intrinsic motivation. On the other hand, Eisenberger and Cameron's group [56]–[58] claimed otherwise. A controversy erupted between the two camps in 1999 (see, for example, [59]–[61]). The practice of using extrinsic rewards to enhance creativity and educational excellence is not compatible with our understanding of the creative process. Reward- or approval-oriented motivation has been associated with diminished cognitive flexibility, reduced depth in processing of new information, impaired integration of new information with preexisting knowledge, and diminished creativity in general [62]. This observation was corroborated by experiments performed by Viesti [63]: monetary rewards interfere with insightful problem solving (see also p. 185 of [31]). Similar conclusions were reached in experiments regarding artistic creativity and writing creativity [64], [65].

Like other human endeavors, pursuits of excellence are motivated by multiple factors: pleasure, curiosity, desire of independent mastery, self-fulfillment/self-actualization (including proof of self-worthiness), peer recognition, fame, vanity, fortune and power, which form a continuous spectrum, with intrinsic motivation at one end, and vanity and extrinsic rewards at the other end [53], [66], [67]. An average normal person is probably motivated by a combination of all of these factors in different proportions; there is an individual difference of where the peak of the spectrum is located (personality factor).

Motivation stemming from either end of the spectrum often exerts opposite effects on creativity [62]. Conformity is anathema to creativity [62], [68], [69]. Conformists tend to respond positively to extrinsic rewards whereas creative performance tends to require strong task involvement, which may lead to paths that run afoul with the establishment. Crutchfield [68] described conformist motivation as ego-involved. Conformists care immensely about how they are perceived by peers and the establishment. Thus, their primary goal is to protect or enhance their self-image and/or to avoid being rejected or ostracized by peers and the establishment. They often stop exploration when they encounter an "ego-threatening" novel problem; a strong desire to succeed instantly (so as to protect or enhance their self-image) inadvertently restricts the search space (personal observation). The mental habit eloquently summed up by the phrase "fear of failure" may be one of the reasons why highly educated people often exhibit an apparent lack of common sense. They may not actually lack common sense but rather they elect not to exercise it for fear of letting their common sense run afoul with expert knowledge, thus losing their hard-earned image as an intellectual or failing a critical examination. This may just be my speculation, but is supported by an anecdotal observation: a student who failed to comprehend a principle in physiology could answer a similar problem which is based on the same principle but was framed in an area outside of his expertise. The student claimed that he had to use his intuition because there is "no book to lean upon." But I suspect that another reason was that the problem did not threaten his ego (see below). Of course, a genuine lack of common sense may still be possible in view of the prevailing occurrences of fragmentation of knowledge and specialization of expertise.

Bastick pointed out that, although mild emotional involvement has an integrating effect on perception, extreme emotional involvement — e.g., due to an *ego threat* — could produce the disorganization of emotional blocking, giving inaccurate perceptions. This trend is described by Yerkes-Dodson law, which shows the peak performance in the medium range of emotional involvement and declining performances towards both extremes [70]. Another way in which conformist pressures may inhibit creativity is by reducing the willingness to follow through with a new idea or course of action, for fear of disapproval by peers or being ostracized by the establishment [62].

Thus, vanity can be an inhibitory factor for solving a difficult problem that threatens the problem solver's ego: it inhibits exploration and discourages risk-taking by invoking a fear of failure. In contrast, the lure of a challenging problem and a strong desire to achieve self-fulfillment (task involvement) enhance creativity and help overcome the roadblocks to the goal. Presumably, the same considerations also apply to fine art and music. Mozart said, in a frequently cited letter [71], [72]: "For I really do not study or aim at any originality." I believe that Mozart was telling the truth since modesty was not one of his strengths.

So far we have restricted our discussion, regarding the influence of personality and motivation, to the search-and-match phase of creative problem solving. Personality also affects the outcome of problem solving at the verification phase. It is well known that conformists, by definition or by default, are usually insensitive to errors committed by the authority for fear of antagonizing the authority. It is also well known that individuals with a strong ego are usually insensitive to their own errors because admitting errors is ego-threatening. In both cases, the insensitivity to inconsistencies may not be the consequence of a conscious and voluntary decision; self-deception (denial) is a convenient psychological defense mechanism. In contrast, high sensitivity to inconsistencies is the hallmark of highly creative people. Often, creative people are equally critical to themselves and to others, presumably because of their own keen awareness of the possibility of self-deception and perhaps also because of their unwillingness to fool others even if the error is unlikely to be exposed — a manifestation of strong task involvement. The peril of self-deception is always lurking in "the unconscious," thus waiting to rear its ugly head when suspended judgment should have been called for instead. When an individual's tolerance of ambiguity is exceeded, it is always expedient to summon self-deception to the rescue so as to persuade oneself to accept those conclusions that ought to have been rejected in hindsight. I suspect that no one, including publicly certified geniuses, can confidently claim to be immune to self-deception.

In view of the multiplicity and complexity of motivation, it is inappropriate to mix different kinds of motivations under the same broad category, thus introducing sample heterogeneity. Take motivation by vanity as an example. An individual's aspiration for a legacy in posterity (posthumous vanity) is certainly very different from an individual's desire to please the peers (conformist vanity). The former strengthens task involvement, but the latter demands instant gratification. Thus, behavioral experiments, with a mixed sample containing opposing types, can yield data with striking disparity: some experiments show no effect if the opposing types are evenly distributed, and others show either positive or negative effects if one type outnumbers the opposite type. In this regard, I suspect that Weisberg's excessive emphasis on the role of strong motivation in creative problem solving might also be due to a failure to distinguish various types of motivation from one another (see Chapter 8 of [12]).

In summary, the lack of appreciation of the gray-scale nature of factors involved in the creative process has contributed to sample heterogeneity in the creativity literature, thus rendering the reported data difficult to interpret, or even misleading. Sample heterogeneity is also a serious problem in meta-analyses, customarily done in combining a large group of similar data. However, the judgment regarding "similarity" is highly subjective and inappropriate grouping is not uncommon. As Lepper et al. [59] properly warned, a meta-analysis of the diverse literature of motivation must be performed with great caution.

Thus, it appears that flawed theories of human behaviors often led to experimental designs that produce data in support of the locally logical but globally absurd hypothesis (see comments of Lepper et al. [59] about theory-driven hypotheses). The outcome is: the hypothesis becomes a self-fulfilling prophecy, except that the prophecy may not be about gospels but rather about fallacies sometimes. Paradoxically, having a decent theory in advance is a prerequisite of designing a meaningful behavioral experiment or meta-analysis. No wonder conclusions drawn from this type of investigation is notoriously model- or theory-dependent.

XI. SIMULATION OF GESTALT PHENOMENON

Simon and his coworkers designed a series of computer programs with intent to simulate intuition and "aha" phenomenon. The pioneering contributions to computer-based creative problem solving by Simon and coworkers were compiled in several books [73]–[75]. The discussion can be further brought into focus by also referring to the critique of Michael Wertheimer [76] and Simon's rebuttal [77]. Michael Wertheimer's analysis was based on the Gestaltist view of creativity outlined in Max Wertheimer's book *Productive Thinking* [78]. Max Wertheimer distinguished two types of thinking: ("blind" or senseless) reproductive thinking and (truly insightful) productive thinking. Reproductive thinking manipulates mental structures, but does not generate new mental structures, whereas productive thinking does both. While Michael Wertheimer acknowledged the accomplishment of AI computer programs such as General Program Solver (GPS) [30], [79], he thought that such programs perform only reproductive thinking. Specifically, he thought that crucial Gestalt elements, such as understanding (grasping both what is crucial in any given problem and why it is crucial), insight, and the associated "aha" experience, are lacking in these programs. Furthermore, the construction of problem-representations was done by the programmer, rather than by the computer program itself. Wertheimer dismissed a computer's learning as learning by rote ("mechanical" learning) rather than learning by understanding. Simon disagreed and claimed that all these had been accomplished by digital computers.

Simon found that the definition of intuition was either missing or vague in the Gestalt literature. He could only seek helps from dictionaries: Webster's unabridged dictionary defined intuition as "the act of coming to direct knowledge or certainty without reasoning or inferring." Simon thought that intuition could be interpreted as essentially "recognition." He set as criteria for testing the presence of intuition the following attributes: the suddenness of apprehension or cognition, understanding. However, the detailed process is unreportable. As an illustration, Simon cited a program named EPAM (Elementary Perceiver and Memorizer) [80], [81], which is a model of the processes that occur during the performance of verbal learning and related tasks. When a stimulus is presented to EPAM, the program applies a sequence of tests to it, using the outcomes of the tests to sort it down a discrimination net until it is distinguished from alternative stimuli. A threshold is set in the discrimination net for recognition. EPAM can learn by experience and improve its discrimination net. Patterns need not be identical in order to be recognized as the same by EPAM; EPAM tests only some portion of the features of a pattern. EPAM can deal with similarity as well as identity of patterns. EPAM can indicate its recognition but no information is stored in short-term (working) memory about the specific tests in its recognition net that led to the recognition. Therefore, the recognition process is not reportable. Simon thought "the process named 'intuition' by Gestalt psychologists is none other than our familiar friend 'recognition'." Although this statement is a meaningful one to which we can agree, it merely replaces an illusive term with another. As we shall see, face recognition is a holistic process, which Simon's programs simulated but did not duplicate; it was close but not quite as close as Simon had claimed. However, it is obvious that what Simon's programs did was not just "mechanical" learning. These programs are not strictly rule-based systems like expert systems constructed at the early AI stage. It began to deal with the gray-scale nature of matching much like picture-based reasoning.

Simon also made an attempt to explain how computer programs, such as GPS and EPAM, could exhibit the "aha" phenomenon. However, Simon's explanation was rather tenuous and failed to convince this author. Essentially, Simon's programs simulated parallel processing by what I have referred to as pseudo-parallel processing. Just like the commonly known technique of multi-tasking (in software) or multiplexing (in hardware), rapid deployment of sequential processing often gives the illusion of parallel processing. However, the process lacks random access inherently available to parallel processing. Therefore, Simon's programs cannot exhibit true "aha" phenomenon. A more detailed discussion can be found in [19], [20].

Let us examine how EPAM works. Superficially, EPAM is a rule-based program. What sets it apart from those rule-based programs known as expert systems is the comprehensiveness of the heuristics and the relative "freedom" granted by the programmer. By increasing the number of criteria for matching the features and by allowing similarity instead of just identity, EPAM introduces a gray scale of matching, and converts a digital pattern recognition process into a quasi-analog pattern recognition process. EPAM searches for a trillion (10^{12}) possibilities on an average run, and is able to quickly reach a step of recognition in about two-tenths of a second through the uses of heuristics. The last test prior to recognition is simply the last straw that broke the proverbial camel's back, and is not the sole or main criterion that makes recognition possible. Naturally, the computer program does not keep track of all the intermediate steps of testing — there are too many of them — and, therefore, EPAM cannot report exactly how it reaches the conclusion. The computer simply does not remember. However, this is not what intuition is all about, in view of our discussion presented above. Intuition is inherently difficult to articulate not because the details are forgotten but rather because the details are not even known to begin with: one simply has no clue, from the very outset, about the rationale behind an inspired critical decision.

Although Simon was perhaps the first to recognize that problem solving is an act of recognizing the solution, he made no distinction between rule-based and picture-based reasoning. Simon certainly appreciated the difference between sequential processing and parallel processing. But he insisted that a parallel process can be simulated by a sequential process, and he deliberately attempted to blur the distinction between the two processes. He thus missed the opportunity to link intuition to parallel processing and the absence of intuition to sequential processing. Rather than claiming a "home-run," he could have been better off taking the partial credit: just acknowledging the distinction and conceding that pseudo-parallel processing merely meets part of the demand of true parallel processing. His simulation programs did not quite exhibit intuition but still did exceptionally well in solving novel problems. We thus have to agree with Michael Wertheimer that Simon's interpretation of intuition constituted a misunderstanding and distortion of the Gestaltist notion of insight. But this misstep did not detract from Simon's groundbreaking contributions to computer-based creative problem solving. Simon's success was rooted in the attempt to emulate human's thought process. Whether one agrees with Michael Wertheimer or with Simon is tantamount to the opinion whether the bottle is half-empty or half-full.

XII. CAN A DIGITAL COMPUTER THINK?

Simon's programs and Wertheimer's critique are also relevant to the question whether digital computers can think and understand. Simon followed a test suggested by Michael Wertheimer: "one test of whether learning [with understanding] has really happened is to check whether what has been learned will generalize to a related task — if all that has transpired is sheer memorizing or mechanical associating, the learner will be unable to recognize the similarity between a task that has already been mastered and a new one which, while it may be superficially quite different, requires the same insight to solve it that also worked in the earlier task. The transfer of learning is a central issue for the Gestalt theorist" (p. 23 of [76]).

Simon pointed out that it is no great difficulty in constructing computer programs, which can do just that. In fact, some programs can even learn to solve problems by examining worked-out examples and to construct a set of new instructions (rules) adequate for solving a wide range of algebra equations.

It is sometimes said that a problem is understood when it can be formulated or represented appropriately. The program UNDERSTAND [82] accepts simple problems stated in plain English and constructs representations of the problems that are suitable as inputs to a general problem-solving program like GPS. Several computer programs exist that have simple capabilities to use analogies to form new representations. Again, it is helpful to distinguish between two types of understanding: one based on rule-based reasoning and another based on picture-based reasoning. In human performances, knowledge acquired by picture-based learning can be "transferred" to more remotely related situations than knowledge acquired by rule-based learning.

Can a digital computer make scientific discoveries? Since a digital computer is good at making logical, rule-based reasoning, this question is equivalent to: does scientific discovery have logic? As mentioned earlier, Popper [2] did not think that there is one, but Simon's answer was affirmative [83]. Newell et al. [30] constructed and analyzed several such programs, including one named “Logic Theorist” that managed to “discover” a shorter and more elegant version of proof of a theorem in Chapter 2 of Whitehead and Russell’s *Principia Mathematica* than that originally published by Whitehead and Russell. It is of interest to examine how these programs made discoveries. For simplicity, let us examine an earlier program named BACON that could examine actual data and re-discover several known physical laws (Part II of [84]; pp. 102-115 of [75]). A sample of heuristics used in earlier versions of BACON, as summarized by Boden, gives us a glimpse into the strategy (p. 195 of [34]):

- IF the values of a term are constant, THEN infer that the term always has that value.
- IF the values of two numerical terms give a straight line when plotted on a graph, THEN infer that they are always related in a linear way (with the same slope and intercept as on the graph).
- IF the values of two numerical terms increase together, THEN consider their ratio.
- IF the values of one term increase as those of another decrease, THEN consider their product.

If the ratio or product of two variables, x and y, is not constant, additional heuristics instruct the computer to compute more complex ratios or products, such as x^m/y^n or x^my^n (where m and n are integers), and check whether any of them is constant. Furthermore, BACON does not have to try every pairs of integers. Rather, it considers whether a ratio, if not constant, increases or decreases monotonically, thus cutting the number of pairs of integers to be tested in half (i.e., heuristic searching). In this way, BACON can discover a modest subset of numerical models, which are simple algebraic combinations of two variables. For example, BACON re-discovered Boyle’s gas law and Kepler’s Third Law of planetary motion.

There is a major difference between BACON and an ordinary rule-based expert system. In programming BACON, the programmer only provided some basic heuristics, but did not micromanage BACON’s step-by-step chores of problem solving. These heuristics allow the program to go for the most obvious and simplest numerical models. There exist several later versions of BACON, in which improvements were made to allow it to use existing heuristics to act upon each other. Thus, a heuristic for creating discriminant rules might act upon a generalization heuristic to create a more powerful domain-specific generalization heuristic. Essentially, the program can learn to learn. By adding a radically different strategy or approach to the repertoire of heuristics, BACON’s power of problem solving could be vastly enhanced. For example, by adding a symmetry heuristic, BACON re-discovered Snell’s law of refraction. However, not all laws are quantitative. Programs, such as GLAUBER, STAHL and DALTON, can discover qualitative laws (Part III of [84]).

Are any of the above-mentioned problem-solving programs creative? It depends. If a dichotomy with only two classes of creativity — being creative or being non-creative — is posited, then most, perhaps all, existing programs are not. However, the thinking process of Simon’s programs is not fundamentally different from what a student does when he or she learns a neat trick, which was invented and once utilized by a past master. Once the student becomes familiar with the trick, he or she can then apply the trick to similar situations without having to re-learn the same trick (in disguise) all over again. In contrast, some modern biomedical students, who had been trained to perform exclusively rule-based reasoning, could not make such a transfer of problem-solving tactics to similar situations and must relearn the whole trick all over again, thus appearing to be thinking at a lower level than Simon’s programs. To say Simon’s program cannot think but a highly educated human being always can think appears to be hypocritical and reflects our anthropomorphic bias.

So far the examples demonstrated computer programs that could re-discover what had been discovered in science. This kind of creativity is what Boden [34] referred to as P-creative, or psychologically creative. Although the computer programs had no access to existing scientific literature, the programmer had. In programming BACON, investigators used insights gained in past discoveries of known physical laws to construct the basic heuristics, thus inadvertently tipping off the computer regarding the secret. A program that could discover something that had never been discovered by any human being, living or dead, is said to be H-creative, or historically creative. In the latter case, no hindsight of the law-to-be-discovered can be incorporated into the heuristics. Such programs indeed exist. Boden cited an algorithm known as ID_3, which discovered a chess-playing strategy for winning an endgame that was not known to any human experts (p. 189 of [34]). Interested readers are referred to Boden’s reviews [34], [85]. Thus, Boden warned: “It’s a mistake to think that sequential computer programs cannot possibly teach us anything about psychology [of creativity]” (p. 93 of [34]). It is perhaps also a mistake to think that creativity is a unique feature of conscious human beings. In view of the astonishing performance of these advanced problem-solving programs, humans’ superiority in intellectual performance can no longer be assured.

XIII. LIMITATION OF SIMON’S PROGRAMS

Regarding the dispute between Popper and Simon, the above-mentioned examples appear to favor Simon’s view since rule-based reasoning is equivalent to logical reasoning. However, it is still premature to declare that *all* scientific discoveries have logic. In making scientific discoveries, humans do not *always* think logically. The designation “pseudo-parallel processing” implies that digital computers still do not think like humans. However, to register our dissent to Simon’s claim effectively, we must find a way to verbalize our disagreements.

To do so, we need to examine why Simon’s problem-solving programs succeeded. Obviously, the key to the success was not telling the computer what to think but rather how to think; by providing a set of heuristics the programmer told the computer how to think. These programs performed so well because the embedded heuristics had been constructed by pooling together the tactics of thinking of many past creative scientists even though these scientists might not know exactly how they came up with these tactics. Regardless of their performance, these computers are not as creative as the scientists from whom the computer (or rather, the programmer) drew their inspiration.

Boyle was creative to discover the law that bears his name. Nowadays every competent scientist knows how to examine the relationship of two experimental variables by first checking whether they bear any relation of direct or inverse proportionality, as well as any logarithmic or exponential relations. In fact, all well-trained scientists learn these neat "tricks" devised by past masters. In other words, the computer masqueraded as a creative thinker by being a very good copycat. It is not surprising that these computers might outperform human beings because of their speed, memory capacity, stamina and patience, and because they had uniformly mastered the pooled tactics of many past masters. However, the underlying heuristics of discovery are not *a priori* programmable but rather *a posteri* programmable: programmable only with the aid of hindsight. That is, someone — either past creative scientists or the programmer — must have discovered the heuristics ahead of time. Of course, the computer can discover new heuristics by recombination of old ones. However, creative human beings can devise new heuristics that are not obvious recombination of old ones. Since the programmer has no way of knowing what new and radically "revolutionary" heuristics are to appear in the future, these heuristics are not a priori programmable. This point shall be made clear by means of a simple example. Two additional examples can be found in Sec. 4.26 of [20].

The first example is the discovery of recursive rules underlying an infinite sequence of alphabetic symbols cited in Simon's 1973 article [83]. Simon demonstrated that the recursive pattern could be discovered efficiently (heuristically) by programming the computer to examine the relations of "same" and "next" between symbols that are not too far separated (p. 476 of [83]). Simon's point is well taken. Now consider a few more examples of which the rules of construction are easy to conceive but considerably harder to discover. The rules are the presence or absence of a certain feature of the symbols. For notational convenience, the sequences are made finite by first listing those with the designated feature and then those without the feature. They certainly can be presented as infinite sequences, by repeating each finite sequence infinite times, without compromising the arguments to follow:

- (A, E, F, H, I, K, L, M, N, T, V, W, X, Y, Z) vs. (B, C, D, G, J, O, P, Q, R, S, U)
- (A, B, D, O, P, Q, R) vs. (C, E, F, G, H, I, J, K, L, M, N, S, T, U, W, X, Y, Z)
- (A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, R, S, T, U, W, Y, Z) vs. (Q, V, X)

The selection rule in the first sequence is whether the letters are constructed exclusively with straight-line segments or with both line segments and curves. In the second sequence, the letters are grouped according to whether there is one or more (topologically simply connected) enclosed area or not. In the third sequence, the grouping is based on a single criterion: presence or absence in the Polish alphabet set (the Polish set of alphabets does not include "Q", "V" and "X"). Undoubtedly, stranger and more obscure selection rules can be easily conceived to construct additional examples with increasing degrees of difficulty. The above three rules cannot be readily discovered by examining the relations of "same" and "next" between symbols alone, certainly not by considering their relative "alphabetized" positions on the alphabet list. However obscure a selection rule may be, the rule, once known, can be included in the heuristics and the computer can be instructed to examine additional features of the sequence such as shapes, topology, etc., thus expanding its search capability.

However, there are virtually infinite kinds of selection rules that can be conceived. Before a class of obscure rules are suspected and preconceived by the programmer, a specific search tactic designed to discover this particular class cannot be included in the repertoire, i.e., not *a priori* programmable.

In any case, creativity of the programmers still decides how creative a digital computer can be. The subtle difference enunciated here is intimately related to the issue of origination of free will [20]. Thus, it can be concluded that some, but not all, discoveries have logic.

What made Popper reach the opposite conclusion can only be speculated here. Perhaps Popper, like Koestler and many other highly creative individuals, considered only high creativity to the exclusion of the possibility that certain types of discoveries can be made by means of a more methodical approach suggested by past creators' insights, or simply by means of rule-based reasoning plus hard work. That is not to say Simon was not in the same league with Popper and Koestler. Simon came very close to elucidating the problem by suggesting that creative problem solving is a matter of recognition. Had he not been single-mindedly determined to prove that intuition could be simulated by sequential processes, he would have recognized the subtle difference between parallel processing and pseudo-parallel processing.

There is no reason to assume that existing programs have exhausted all tactics of human creativity. There is also no good reason to claim that these programs cannot be further improved. Therefore, the above verdict regarding the dispute of Popper and Simon remains tentative. Strong AI detractors' objections were similar to what transpired in the controversy of primate language capability [86]: the arguments were often based on *what the apes* [or *computers*] *had not yet done*. A skillful programmer simply takes hints from strong AI detractors' objections, and then devises clever algorithms to implement what the computers have not yet done. As investigators continue to discover new strategies for the construction of heuristics and programmers continue to delegate more tasks to the discretion of the computer, there may still be room for major improvements in the future. One should not overlook the precedents that gains made in computers' processor speed and memory capacity often made it possible to absorb the large software overhead needed for performing lengthy, sophisticated sequential (or, rather, pseudo-parallel) processing, thus making previously impossible task feasible. If science and technology history ever teaches us anything, it is the advice "never say never" — except perhaps just this once now and never again.

XIV. GENERAL DISCUSSIONS AND CONCLUSIONS

Reflective cognition is unique to animals with consciousness. Its survival value lies mainly in its empowerment of a conscious animal with a capability of making predictions. A prehistoric hunter who had a better capability of predicting the flight path of a lance, which he threw against an animal, either a prey or a predator, would have a better chance of survival. From a modern human's point of view, a better understanding of the basic mechanism of reflective cognition will enable policy makers to design a better educational policy and will enable engineers to design a better computer. A thorough demystification of the cognitive process practiced by human geniuses is thus an important first step. Advances made in cognitive science and in artificial intelligence make the opportunity ripe for such an endeavor.

Most, if not all, models of creative problem solving had its lineage in Henri Poincaré's introspective account. However, Poincaré did not speak the language (jargon) familiar to experts. His view was either ridiculed or dismissed as the vague account of a non-expert witness. In the present article, Simonton's chance-configuration theory is singled out for extensive analysis because of its similarity to the triad of evolution. The theory is recast as pattern recognition in the framework of parallel and sequential processing. A contemporary interpretation of Freud's concept of the unconscious in terms of selective attention allows Poincaré's introspective account to be understood in terms of Simonton's theory. The improved re-interpretation suggests that the creative process practiced by geniuses is not fundamentally different from everyday ingenuity practiced by common folk. A demystified theory of creativity suggests where improvements are possible by training, and may guide educational policies in a concrete way.

With the benefit of hindsight, we can now enumerate the important insights that helped demystify the creative process:

- The common *pattern*, exhibited by all creative processes or discoveries, is a process of "pattern recognition."

- There are two ways — via holistic pictures or algorithmic rules — of matching a candidate solution (template) to the problem (pattern).

- Picture-based reasoning is a parallel, analog, semantic, and non-verbalizable process, whereas rule-based reasoning is a sequential, digital, syntactic, and verbalizable process.

Once we realized that, in addition to picture-based reasoning, rule-based reasoning could also be invoked during the search-and-match phase of creative problem solving, the linkage of intuition as well as related concepts, such as insight and primary-process thinking, to picture-based reasoning became apparent. An individual's preference of either mode of reasoning critically affects the outcome of thinking. Without the distinction of this preference, it would be difficult to explain why some people ever have an "aha" experience in their discovery process whereas others never have. Picture-based reasoning is conducive to the occurrence of a snapping action that gives the feeling of "Eureka!" On the one hand, Simon refused to acknowledge the subtle distinction between pseudo-parallel processing and true parallel processing. On the other hand, Simon's success was rooted in his approach of using pseudo-parallel processing to closely emulate parallel processes in human's thought: a triumph of the cognitive approach in computer-based problem solving.

In view of the elucidated meaning of intuition and primary-process thinking presented in this article, it is evident that Kris' theory is essentially correct, with only a minor modification needed. Kris associated Wallas' preparation and verification phases with secondary-process thinking, and associated the incubation and illumination phases — i.e., the search-and-match phase — with primary-process thinking. The difference lies in the search-and-match phase: primary-process thinking is the only option in Kris' formulation, whereas primary-process and secondary-process thinking are two available options in our current rendition of Simonton's model. Kris' omission is understandable because the rampant epidemic of exclusively rule-based reasoning, which I had the misfortune or privilege to witness, was a relatively recent occurrence [44]. Had I not had this personal experience, I would never have suspected that rule-based reasoning could be a preferred option during the search-and-match phase.

The process of pattern recognition invoked in the word-replacing game regarding various models of creativity was not a process of logical deduction, and might appear not very scientific. Indeed, it was a process of induction based on a small number of examples, but the practice allowed the collective insight of many past investigators, regarding creativity, to be pooled together so as to generate new insight.

The saving grace of this approach is subsequent verification. For that matter, one has almost a century worth of observations and experimental reports to rest upon. In addition, new occurrences that are being played out in our daily life — for me, it was students' performance — continue to bear witness to the explanatory power of the present rendition of Simonton's theory. As for its predictive power, it is just the beginning. But the early returns of my personal practice appeared encouraging. The most dramatic case exhibited a positive result in less than five minutes when a student was instructed to close her eyes and refresh the lecture content, in pictures, which she still remembered after nine months. Others were less dramatic and some were simply skeptical and unwilling to try.

Again, with the benefit of hindsight, it is apparent that creative problem solving frowns at extremism. To maximize the likelihood of creative problem solving, several conflicting requirements must be met:

- to use picture-based reasoning so as to maximize the probability of finding novel solutions, but to use rule-based reasoning so as to increase the speed of thinking,
- to focus on problem solving so as to enhance the retrievability of key techniques and knowledge, but to defocus on problem solving so as to avoid getting trapped in an unfruitful search path,
- to subdue one's attention during a problem-solving session so as to optimize one's affect, but to extend one's attention beyond a formal problem-solving session so as to reap the benefit of serendipity,
- to perform heuristic searching so as to select a manageable search space, but to avoid premature shrinking of the search space,
- to "zoom in" and pay attention to details, but to "zoom out" and pay attention to big pictures,
- to be highly explorative so as to expand the search space, but to have sufficient task involvement so as not to spread oneself too thin.
- to be sufficiently confident to assert an unpopular view, but not to be so excessively confident as to overlook clues provided by critics or opponents,
- to be sufficiently disciplined to perform rigorous logical deductions and to play by the rules forged by social consensus, but to be sufficiently undisciplined to defy authority whenever necessary — a "mood swing" between the traditionalist and iconoclast dispositions, in the words of Simonton (see below).
- to be able to flexibly and dynamically switch between two opposing modes of action, as listed above.

Getzels spoke of the "paradox in creative thought": creative thinking entails child-like playfulness, fantasy and the non-rationality of primary-process thinking as well as conscious effort, rationality, reality orientation and logic [87]. Csikszentmihalyi mentioned the conflicting requirements of openness and critical judgment. Simonton emphasized the well-adjusted trade-off between the traditionalist and iconoclast dispositions (p. 5 of [17]). However, there is no compelling reason that the conflicting requirements must be fulfilled simultaneously. A creative mind is not a static mind; it is dynamic and flexible. Therefore, there is no real paradox — just our temporary confusion — and there is hardly any trade-off or compromise — just well timed mood swing between extreme randomness and extreme determinacy in the thought process. For example, one can be extremely speculative and subjective at the stage of formulating a hypothesis, but later becomes extremely logical, methodical and objective at the stage of verification. In contrast, individuals with low creativity often fall short of both extremes and practice a static compromise (trade-off) between the two extremes, instead. Such dynamic flexibility, or the lack of it, reflects an individual's mind habit, which is part of character or personality. It is common knowledge that personality can change with the passage of time. Perhaps it can also be changed by environmental influences and external interventions. If so, an individual's creativity is not entirely innate, because it can be improved, but it can also be ruined by schooling — the so-called dumbing down effect.

Ironically, advances in machine intelligence with the accompanying automation have helped exacerbate information explosion. Widely used standardized testing further encourages students to use deductive reasoning at the expense of inductive reasoning, to discourage explorations and to encourage learning within the confines of narrative thoughts presented by the teacher, to ruin the good habit of verification, and to foster a passive work ethic. Essentially, knowledge is dispensed in a highly efficient but ineffective top-down fashion. In attempts to cope with information explosion and fierce competition that were not significant at the time when standardized testing [88] was installed more than half a century ago, students are often forced to practice exclusively rule-based reasoning instead of combined rule- and picture-based reasoning, thus forsaking a major advantage of cerebral lateralization. The deductive ability of students suffers in spite of the penchant for exclusively rule-based reasoning. The only accomplishment appears to be the mass-production of — if John Holland [40] is paraphrased — highly optimized mediocre examination-taking biomachines. The resulting degradation of performance exacerbates the situation and makes an individual even less capable of coping with information explosion. Excessively heightened affect (anxiety) caused by poor performances further diminishes the effectiveness of learning. Essentially, modern biomedical students seem to be so hopelessly trapped in the morass of the stimulus-response (SR) learning scheme of behaviorism that they become overwhelmed by the vicious cycle of information overload.

Apparently, the thinking of behaviorism is so deeply entrenched in the educational community and society at large that the evaluation methods that were originally designed for the purpose of enforcing behaviorism remain largely intact. A surprising number of educators continue to believe that learning can only be achieved by repeated drills, and continue to think that every bit of useful information must be taught and memorized, as if the students were robots or expert systems of the old-generation, constructed during the early phase of AI research. In order to achieve high grades while being flooded and overwhelmed with information, students often find clever ways — they are not robots after all — to defeat the purpose of education, i.e., to perform spectacularly in standardized testing without actually mastering the skill of utilizing the acquired knowledge.

In recent decades, it has become fashionable to advocate computer-assisted education and Internet-based distance education. The advantages of computer-aided learning are generally recognized: the ease of making multi-media presentations (with animation, in particular), the ease to update the content, and the widespread availability that transcends the limitation of distances, to name a few. However, some other advantages are rather dubious. For example, the widely acclaimed "links" actually present more problems than solutions. First, the links are pre-determined and limited by the imagination of the designers; there is no provision for creating novel links without first becoming a network "hacker." Second, the limit of screen size of a computer monitor often requires segmentation (serialization) of information with a pre-determined sequence of links. Thus, the current technology of computer-aided education lacks the feasibility of parallel processing and random access made possible by browsing a book. Although these limitations are not impossible to overcome in the future, the present difficulty actually hampers the practice of picture-based reasoning in spite of the plethora of graphic information that floods the computer screen.

Understanding the cognitive process is also needed in implementing health-care reform. In the interest of cost cutting, U.S. health-care providers have implemented a procedure of dispensing health care that is rooted in exclusively rule-based reasoning. The powerful executives of the health-care industry apparently believe that medical diagnoses can be made exclusively by rule-based reasoning. Regrettably, some biomedical investigators proposed evidence-based medicine (EBM) [89], and claimed it to be a major paradigm shift in medical practice. The advocates of EBM vowed to de-emphasize intuition and experience in medical practice, and to replace it with a uniform practice of computerized medical management on the basis of 30 year-worth of the clinical literature.

I do not object to the use of EBM as a supplementary and complementary approach by physicians who still can call the ultimate shot. However, in view of the failing educational system, this may just be my wishful thinking. Besides, EBM is currently a nascent basic research topic; the technology is not yet ripe for harvest and ready for clinical applications. The exclusive and premature use of EBM without effective human supervisors spells trouble. It is well known that handling of digital information that does not make intuitive sense is prone to errors. It is probably the reason why there was an increase of the incidence of "friendly fire" accidents in the battle fields, as a consequence of the advent of high-tech weaponry: it is difficult to recognize that one is actually aiming at friends instead of foes, or even at oneself, by just looking at the numerical coordinate information that controls the launching of a cruise missile. Besides, a cruise missile only takes orders from its controller. It harbors neither affection for friends nor hatred towards foes, and is essentially selfless.

It is not clear how EBM advocates manage to minimize errors and make error corrections, especially if physicians staffed at the front line are forced to overwork without adequate rest. The likelihood of blunders committed by an exhausted medical staff is significantly increased by the advent of managed care systems, of which the executives are well known for their so-called bean-counter mentality. I suspect that the incidence of "friendly poisoning or injury," and even "friendly killing" of patients will rise sharply with the premature advent of EBM. I suspect that institutionalizing exclusively rule-based reasoning in medical training and practice will seriously undermine the quality of health care and exacerbate the already-skyrocketing health-care cost, contrary to the declared intent of the proponents.

Rumor had it that *New York Times Magazine* hailed EBM as one of the most influential ideas of the year 2001. EBM advocates believed that physicians have the moral imperative to practice EBM, and began to act with a religious fervor and forcibly demand a conversion. Based on our understanding of the creative process, EBM advocates threatened to undo what humans have gained in cerebral lateralization through evolution. If EBM ever makes its way prematurely into the mainstream medical practice, it will probably earn the reputation of the most devastating calamity that befalls human health in the 21st century.

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