

#391

## **Lessons from Perception for Chess-Playing Programs (*and Vice Versa*)**

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### **Introduction**

For nearly twenty years, artificial intelligence and cognitive psychology have maintained a close symbiotic relationship to each other. It has often been remarked that their cooperation stems from no logical necessity. That a human being and a computer are both able to perform a certain task implies nothing for the identity, or even similarity, of their respective performance processes. Each may have capabilities not shared by the other, and may build its performances on those peculiar capabilities rather than upon those they hold in common.

In spite of this logical possibility of total irrelevance of the one field for the other, during the last two decades there has been massive borrowing in both directions. Artificial intelligence programs capable of humanoid performance in particular task domains have provided valuable hypotheses about the processes that humans might use to perform these same tasks, and some of these hypotheses have subsequently been supported by evidence. Bobrow's [2] STUDENT program, for example, which translated story problems into algebraic equations, provided a model, later tested by Paige & Simon [11], for some of the human syntactic processes in performing that task.

Conversely, hypotheses and data about human performance have been important inputs to artificial intelligence efforts. The General Problem Solver, for example, received its early shape from analyses of human thinking-aloud protocols in a problem solving task [8].

The distance between AI and cognitive psychology has not been the same in all task domains. Until quite recently, for instance, AI research on theorem prov-

ing developed in directions quite different from those suggested by the study of human behavior in theorem proving tasks. There is little that is humanoid about resolution theorem proving.

In the domain of chess playing, the distance between AI and cognitive psychology has been neither so close as in the GPS example, nor so distant as in theorem proving. The early chess playing programs, in their reliance on brute force and machine speed, borrowed little from what was known of human chess playing processes [9]. The clear demonstration by their relatively weak levels of performance, that speed was not enough, produced a gradual movement toward incorporating into the programs some of the selective task-dependent heuristics that humans rely heavily upon in their chess playing. However, the strongest chess programs in existence today still rely heavily upon extensive rapid search, usually over thousands or tens of thousands of branches of the game tree [7].

I should like to describe here some efforts on the other side of the line — attempts to explore chess playing mechanisms that can explain human chess performance. These mechanisms may turn out to have important implications for the future of chess playing programs motivated by AI goals. Their own motivation, however, was largely psychological.

### **MATER**

The story begins with an examination of those kinds of chess positions where appropriate search will disclose a checkmating combination against which the opponent has no defense. We have good evidence that strong human players discover these checkmates in over-the-board play after exploring trees of positions having (generally) only a few dozen branches. Simon & Simon [15] hand-simulated a program that achieved this kind of performance, and which discovered checkmates as deep as eight moves (16 plies). This program was further developed and implemented by Baylor & Simon [1] in several versions of the MATER program.

MATER relied, first of all, on being able to detect attack and defense relations among pairs of pieces on the board, and to use this information to guide its search. On the offensive side (in its simplest version), it examined only checking moves — that is, moves attacking the king; but on the defensive side, it examined all legal replies. (This is essential in order to demonstrate that the checkmate cannot be escaped.) MATER's second important heuristic was to employ a search-and-scan strategy — at each stage it explored first that branch on the as-yet-unexplored portion of its game tree which allowed the opponent the fewest replies. The combination of its selectivity in considering attacking moves, and its priority ordering for attention to restricting moves gave it great power with modest amounts of search. In one of its most impressive performances — rediscovering the eight-move mate from a game of Edward Lasker against Thomas — the search tree grew to only 108 positions, and in most positions it was much smaller.

#### PERCEIVER

The claim that selective search could account for many aspects of human performance in chess was challenged by a number of psychologists who thought that perceptual processes, enabling a master player to see "at once" a whole multitude of meaningful relations in a position placed before him, held the key to skilled human chess playing. The Russian investigators, Tichomirov and Poznyanskaya [16], for example, recorded eye movements of a strong player for the first five seconds after he was shown a chess position with instructions to find the best move. During these five seconds, there were about twenty eye fixations, and almost all of these fixations were aimed at "important" squares of the board — those that a skilled player would regard as important for the position. The edges and corners of the board received almost no direct attention. Moreover, the sequence of fixations could not be correlated with any possible tree of moves. Saccadic movements of the eyes from one fixation to the next generally passed along lines of potential action between pairs of pieces. Thus, the eyes might move from one piece to another that attacked or defended it, or was attacked or defended by it.

To interpret the results of Tichomirov and Poznyanskaya, we need a few facts about the nature of vision. The eye has a central area, or fovea, about  $1^\circ$  in radius, of very high resolution, surrounded by a much wider peripheral area (about  $7^\circ$ ) in which familiar objects can usually be recognized, but no detailed information about them can be acquired. Since the angle between successive fixations is usually several degrees, the information that directs the saccadic movements must be acquired peripherally.

Simon & Barenfeld [12] set out to demonstrate that a serial processor could simulate the observed eye movement phenomena without requiring the assumption that large amounts of information can be acquired instantaneously and in parallel over the whole visual field. Their simulation program, PERCEIVER, used a stripped-down version of MATER (removing the executive routine that guided its search for mating combinations) to detect attack and defense relations between pairs of pieces. These relations, once detected, drove the eye movements.

More specifically, PERCEIVER assumed the eye to be fixated, initially, on some prominent piece in the position. The attack and defense relations between that piece and other pieces would be detected (presumably by a combination of foveal and peripheral vision), and the eye would then move to a new fixation at one of the squares so related to the point of previous fixation. Successive saccadic movements would carry the eyes around the board, but would tend to move them most often to those parts of the board where the network of chess relations among pieces was densest. Hence, PERCEIVER had many fixations on the "important" squares, and seldom strayed out to the corners of the board. In fact, its fixations and their sequence were indistinguishable from the human eye movements.

PERCEIVER showed that the basic perceptual processes required for the initial reconnaissance of a chess position were just like those that had already been incorporated in MATER for the search of the tree of moves. The amount of visual information to be acquired during the initial "perceptual" phase was not more than could be accounted for by this kind of scanning process. There was no evidence that the Gestalt of the position was seized "instantaneously".

### Reconstructing Chess Positions

Another chess perception phenomenon, first discovered in 1925 in Moscow [5], studied in detail by de Groot [4] in Amsterdam in the 1930's, and replicated again in our laboratory within the past couple of years, raised a different set of questions about how the mechanisms incorporated in MATER and PERCEIVER could account for the perceptual abilities of skilled chess players. This phenomenon was the remarkable ability of chess masters and grandmasters to reproduce a position from an actual game (not previously known to them) after they had seen it for only five or ten seconds.

In brief, the empirical findings are these: take a position (typically, with about 25 pieces on the board) from a game between strong players. Allow a master to examine it for five seconds. He will then be able, with about 80% accuracy, to replace the pieces correctly on the board. Let a weak player examine the same position for five seconds, and then try to reconstruct it. He will be able to place only six or seven pieces correctly on the board: about 25%.

But an equally surprising result is obtained if we now perform the same experiment with a board on which the pieces have been placed at random. Now the performance of the master falls to the level of the amateur, while the latter does slightly less well than before. That is to say, both master and amateur will now recall the positions of only about one quarter of the pieces, and the master will do no better than the weak player.

The first part of the experiment might seem to suggest that the chess master has unusual powers of visual imagery — a hypothesis about chess players that has been widely believed. But the second part of the experiment shows that these visual powers evaporate when the situations are different from those encountered in actual chess play. Evidently, the chess master's superior perceptive powers rest on special chess knowledge, and not on any unusual properties of his visual or imaging system.

This experiment seems at first to conflict with what we know about short-term memory [10]. There is a large body of evidence to show that one can hold only about a half dozen "chunks" of information in short-term memory. The information — up to about that amount — can be kept there indefinitely, but transferring it to long-term memory (to free up the short-term memory for other information) requires about five or more seconds for each chunk.

The term "chunk" in this theory is not quite as vague as might appear. A "chunk" is any unit of information that is already familiar to the subject, and which he can therefore recognize as an old friend. Thus, for a native speaker of a language, any common word is (at most) a single chunk, and even common idiomatic phrases (*e.g.* "make or break") may be chunks. Hence it is often possible to estimate in advance the number of chunks contained in a given stimulus — a string of words or numbers, say.

The findings in the chess perception experiments could be reconciled with the hypothesis of limited short-term memory if the chess master could recognize a chess position as a configuration of a half-dozen chunks of three or four pieces each, while the amateur recognized each piece as a separate chunk. The master's chunks would be configurations familiar to him from having seen the same arrangements of pieces in many previous positions.

This hypothesis has been explored by Chase & Simon [3] in a series of experiments in which they videotaped players reconstructing positions and timed the intervals between successive placements of pieces. Long intervals (over two seconds) were assumed to represent chunk boundaries; short intervals (less than two seconds) were assumed to be within-chunk intervals. The data gave support to several aspects of the hypothesis: the chunks so defined were in fact clusters of pieces of kinds that occur with high frequencies in games. Several kinds of evidence reinforced the plausibility of the two-second criterion for chunk boundaries.

The master's chunks were, in fact, larger than those of the weaker players — perhaps fifty per cent larger, on average. To that extent the short-term memory hypothesis was supported. However, contrary to the hypothesis, Chase & Simon found that the master held more chunks in memory (also by a margin of about fifty per cent) than did weaker players. Hence the master appeared to have a somewhat larger short-term memory capacity, measured in chunks, than did the others. This discrepancy between theory and data remains unexplained at present, and constitutes one of the important targets of our continuing research on this subject.

## MAPP

If we take, for the moment, an optimistic position, and assume that further investigation will reconcile the chunking hypothesis with the observed data, we still have to discover what kind of organization of processes would produce these phenomena. In the interest of parsimony, we don't want to invent explanations *ad hoc* for this purpose, but wish to limit ourselves to processes that are already known to exist from other psychological experiments.

38

The MAPP program was written by Simon & Gilmartin [14] to simulate the phenomena of the position-reconstruction experiment with the help of well substantiated mechanisms. MAPP can be regarded as the offspring of a marriage between the PERCEIVER program, used to simulate the eye movements, and EPAM, a venerable simulation program first devised by Feigenbaum to explain the main results from a whole range of standard rote-learning experiments [6].

Since the 19th century, psychologists have been studying the processes for memorizing syllables, either in the form of paired associates (stimulus = BYX, response = GOV) or in the form of series (CEV, DAR, CUJ, *et cetera*). Meaningfulness and familiarity of items have been shown to have major facilitative effects on learning (as much as a three-to-one increase in learning rate for meaningfulness); similarity of items, a deterrent effect. In a list, the items at the ends are generally learned with fewer errors than the middle items (serial position curve). For materials of a given kind, amount of learning is roughly proportional to total time. These are illustrative of some of the main findings from rote-learning experiments.

The EPAM program gives correct predictions — and in many cases quantitatively correct predictions — of the effects of these and other learning variables [13]. It is a reasonably well verified first approximation to a theory of rote learning. The MAPP program combines the main EPAM mechanisms with the mechanisms embodied in PERCEIVER in an endeavor to explain the chess position-recognition data. Since not all of the detail of the two parent programs is relevant to these data, MAPP incorporates somewhat stripped-down versions of EPAM and PERCEIVER.

MAPP has two main components: (1) a learning program and (2) a performance program. The learning program is exposed to many configurations of chess pieces (two to seven pieces each) of kinds that occur frequently in chess games. It grows, through this exposure, a large discrimination net that allows it to recognize these configurations when it encounters them again, and which stores the information needed to reconstruct each of them. The net-growing processes are essentially the processes of EPAM, and the configurations that become recognizable through this learning are the chunks to be held in short-term memory.

The performance program of MAPP scans a chess position that is presented to it, looking for salient pieces. It fixates on each salient piece, and uses the previously grown EPAM net to recognize the largest possible configuration of pieces around it. If it succeeds in recognizing a configuration, it stores in short-term memory the address in the EPAM net where the information about the configuration can be found. Up to six (or whatever number is specified by the parameter) such chunks can be stored simultaneously in short-term memory.

After short-term memory has been filled — or all salient pieces have been scanned, whichever occurs first — information about the board is removed, and MAPP is instructed to reconstruct the position. It takes the chunk addresses stored in short-term memory, recovers from the EPAM net the configurations corresponding to each of these chunks, and reconstructs the position (or as much of it as it has stored in memory) on the board.

How successful is MAPP in accounting for the superior ability of chess masters to reconstruct positions? The largest EPAM net that MAPP has grown thus far contains 1,144 configurations, of two to seven pieces each, selected more or less unsystematically from diagrams in standard chess works. We cannot be sure that these are the configurations that occur most frequently in chess games, but they certainly include a large fraction of the configurations of high frequency. Using this EPAM net, MAPP was able to replace 55% of the pieces in nine positions. In experiments with the same nine positions, a master replaced 81% of the pieces, while a Class A player replaced 49%.

Thus, given familiarity with 1,144 common configurations of pieces, MAPP performs twice as well as a beginner, a little better than a Class A player, and not nearly so well as a master. We can now ask how much the EPAM net would have to be expanded to bring the performance of MAPP up to master level. Since the net already contains the configurations that occur most frequently, each new configuration we add will be somewhat more rare than those already in the net — hence will make a less than proportional contribution to performance. We cannot estimate what that contribution will be without making some assumption about the frequency distribution of patterns. It is probably not unreasonable to assume that this distribution is much like the frequency distribution of words in natural language. The latter distribution is highly skewed, and is closely approximated by the so-called harmonic, or Zipf, distribution. In the harmonic distribution, when words are arranged by the frequency of their occurrence, the  $k$ th most frequent word occurs about  $1/k$  times as often as the most frequent word:  $f_k = (1/k) f_1$ . (Interestingly enough, when authors are ranked by the numbers of their publications, or cities by their populations, the distributions also conform approximately to the harmonic law.)

If we assume that the frequency distribution of patterns of chess pieces is also a harmonic distribution, then we can estimate the size of the EPAM net required to match the master performance. Taking the continuous approximation to  $f_1/i$ , the cumulative distribution is the log function:  $F_i = k \log_e i$ . From the MAPP simulation data,  $.55 = k \log_e 1144$ . Solving this equation, we find  $k = .078$ . Using this value of  $k$ , we now calculate the size of the net for a performance level of .81 by  $\log_e N = .81/.078$ , whence  $N = 32,000$ .

How reasonable is it to assume that a chess master is familiar with 32,000 configurations of chess pieces? First, there are a number of other indirect ways for estimating the size of the net, all of which yield estimates of the same order of magnitude. Further, the estimate computed above is of about the same size as the natural language vocabulary of a college-educated adult. Such a person might be expected to have a recognition vocabulary in his native language of 25,000 to 100,000 words. When we consider that no one becomes a chess master without some years of intensive application to the game (grandmaster status is never achieved in less than a decade), the estimate becomes quite plausible; for, a chess master has spent about as many hours staring at chess positions as other educated adults have spent staring at the printed page.

There are other tests of MAPP besides the relation between its vocabulary of chess patterns and quantitative performance as on the recognition task. We can compare the nature of the chunks it recognizes with those recognized by human players in the same positions. The agreement is generally good. Hence, MAPP must be taken seriously as an explanation of the phenomena, and it would be desirable, as soon as possible, to test it with an EPAM net grown to 25,000 or 50,000 configurations. Since the smallest net grown for the experiment occupied about 100,000 words of PDP-10 memory, and since the time required to grow the net was more than an hour, the experiment will probably not be attempted until memories become somewhat larger, faster, and cheaper.

### Prospects

To understand the implications of the research on chess perception for the design of chess-playing programs, one other phenomenon should be discussed. It is well known that when strong chess players engage in rapid-transit games, taking only a few seconds for each move, their play is weaker, but only moderately weaker, than when they take a longer time for their moves. Masters and grandmasters can play dozens (or even hundreds) of simultaneous games against strong amateurs, and win almost all of them.

Drawing upon what has been learned about chess perception, we can provide a plausible, though as yet untested, explanation for such feats. Consider a production system programmed to play chess. The condition part of each production is a configuration of pieces on the board — just such a configuration as is stored in the EPAM net. The action part of the production is a move that is to be considered whenever that configuration occurs. The productions are arranged in priority order, with the most important at the head of the list. Thus, an attack on a queen will be noticed before an isolated pawn. The program then takes the first action whose condition is satisfied.

Such a program will undoubtedly not play good chess. It will certainly play rapid chess. What would have to be added to it to permit it to play plausible chess must be determined by experiment. Notice that for a "fair" test, a very large number of productions — tens of thousands — would have to be provided. But the real point at issue is not whether a program that is "nothing but" such a production system can be a strong chess player. Rather, the point at issue is whether any program that does not incorporate a range of chess knowledge like that imbedded in the production system can play good chess.

The experiments I have described bring us face-to-face again with one of the central issues of artificial intelligence: to what extent can intelligence be made general and independent of knowledge about particular subject-matter fields? To the extent that artificial intelligence is to be modelled on human intelligence, these experiments suggest that general mechanisms, however powerful and indispensable, are no complete substitute for the ability to recognize a very large number of quite specific features imbedded in complex situations: if the skilled man is an intelligent man, he is also a learned man.

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