

**Mind over Machine:
What Deep Blue Taught Us about Chess, Artificial Intelligence, and the Human Spirit**

by

Barbara Christine Hoekenga

Bachelor of Arts
Environmental Science and Rhetoric & Media Studies
Willamette University, 2003

Submitted to the Program in Writing and Humanistic Studies in partial
fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN SCIENCE WRITING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2007

© Barbara Christine Hoekenga. All Rights Reserved.

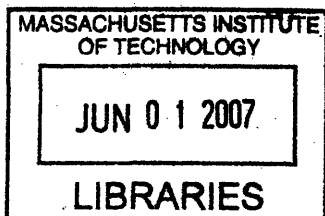
The author hereby grants to MIT permission to reproduce and to distribute
publicly paper and electronic copies of this document in whole or in part.

Signature of Author _____

Department of Humanities
Program in Writing and Humanistic Studies
May 18, 2007

Certified and Accepted by: _____

Robert Kanigel
Professor of Science Writing
Director, Graduate Program in Science Writing



ARCHIVES

For Mom and Dad

Who taught me never to stop learning and never to give up.

But also to ask for help.

**Mind over Machine:
What Deep Blue Taught Us about Chess, Artificial Intelligence, and the Human Spirit**

by

Barbara Christine Hoekenga

Submitted to the Program in Writing and Humanistic Studies in partial fulfillment of the requirements for the degree of Master of Science in Science Writing

ABSTRACT

On May 11th 1997, the world watched as IBM's chess-playing computer Deep Blue defeated world chess champion Garry Kasparov in a six-game match. The reverberations of that contest touched people, and computers, around the world. At the time, it was difficult to assess the historical significance of the moment, but ten years after the fact, we can take a fresh look at the meaning of the computer's victory. With hindsight, we can see how Deep Blue impacted the chess community and influenced the fields of philosophy, artificial intelligence, and computer science in the long run. For the average person, Deep Blue embodied many of our misgivings about computers becoming our new partners in the information age. For researchers in the field it was emblematic of the growing pains experienced by the evolving field of AI over the previous half century.

In the end, what might have seemed like a definitive, earth-shattering event was really the next step in our on-going journey toward understanding mind and machine. While Deep Blue was a milestone – the end of a long struggle to build a masterful chess machine – it was also a jumping off point for other lines of inquiry from new supercomputing projects to the further development of programs that play other games, such as Go. Ultimately, the lesson of Deep Blue's victory is that we will continue to accomplish technological feats we thought impossible just a few decades before. And as we reach each new goalpost, we will acclimate to our new position, recognize the next set of challenges before us, and push on toward the next target.

Thesis Advisor: Robert Kanigel

Title: Professor of Science Writing and Director of the Graduate Program in Science Writing

Acknowledgements

My deepest gratitude goes out to the people who stood by me while I ventured into the land of science writing: Mom and Dad, Virginia, Aaron, Gwennie, Jeff, Aunt Jeannie, and Elaine. I could not have written this piece – or survived this year – without your love, support, and editing!

I am eternally grateful to the members of the Science Writing class of 2007. Thank you for reminding me that writing is worth being passionate about.

My thanks also go to the faculty of the Science Writing Program, in particular Robert Kanigel for your tireless help with editing, your encouragement, and for keeping me on track. And to Marcia Bartusiak for your fresh look at the piece and your suggestions, which helped to make this a better story. And we are all deeply indebted to Shannon Larkin for keeping us sane and caffeinated.

Thank you to the MIT Chess Club for letting me observe your fighting spirit, to Merrit for my first chess lesson, and to Jeff Dean for pulling me into the world of philosophy. And special thanks to all of the experts who took the time to talk with me.

Finally, thank you to Shankar Raman and the Kelly-Douglas fund for giving me the support I needed to follow the story.

In just under an hour, it was over. The sixth and final game of the 1997 match between world chess champion Garry Kasparov and IBM Corporation's chess-playing computer, Deep Blue, was unremarkable as far as chess games go. After just 19 moves, an exasperated Kasparov resigned the game, realizing that a mistake he had made early on had ruined him.

Kasparov was not a graceful loser. He stood up from the board shaking his head incredulously and stormed away from the table. Later, he would insinuate that Deep Blue, or perhaps more accurately the team of programmers that built and operated the computer, might have cheated. Kasparov, who was known for being articulate and charming but strong and intimidating when facing an opponent, buckled under the pressure. And it's hard to blame him: the weight resting on his shoulders was immense.

The nine-day match, which took place on the 35th floor of the Equitable Center in Manhattan, was seen by many as the ultimate duel between man and machine. *Newsweek* called it "the brain's last stand." Kasparov himself had upped the stakes in 1989 after winning a two-game match against one of Deep Blue's predecessors by saying, "If a computer can beat the world champion, the computer can read the best books in the world, can write the best plays, and can know everything about history and literature and people. That's impossible."

May 11th 2007 marked the ten-year anniversary of the landmark match. In retrospect we know the computer that defeated the world champion – Deep Blue – could not do any of the other deeply human tasks on Kasparov's list. Nor can any computer blinking and humming along today. So what did Deep Blue's victory mean? Why did it cause such a stir, and why did Kasparov and many others attribute so much value to it? To figure out where the ripple effects from the match have traveled, we must first go to the center of the splash.

Part I

Resistance and Resignation

On one side of the board, sat 34-year-old Russian grandmaster and world champion Garry Kasparov. At five feet ten inches, with thick dark hair, and an intense gaze, Kasparov was ready to take on Deep Blue. His arsenal included thousands of years of tradition, two

centuries of chess literature, hours of study and coaching, and 50 billion neurons making up one of the most amazing “machines” on the planet: the human brain.

On the other side of the board sat one of the members of the IBM research team that had built and fine-tuned Deep Blue. Various members of the team stood this post as the games progressed, but whoever sat in the chair was a stand in – a set of eyes to observe the board and a set of hands to relay information via keyboard to Deep Blue and to move pieces on the computer’s behalf. Four-year-old Deep Blue had its own cache of imposing weapons: the support of a six-person team of crack IBM programmers who drew on 50 years of computer chess innovation and 480 custom chess chips distributed among 30 processors working in parallel to allow the computer to examine an average of 200 million moves per second.

The competitors were not strangers. They had sat across the board from one another in Philadelphia the year before when Kasparov defeated an earlier version of Deep Blue with a record of 4 - 2. A few months later, the parties agreed to a rematch, and the IBM researchers set to work updating and enhancing their machine. The Association of Computing Machinery agreed to officiate, and IBM organized the match, put up a purse of \$700,000 for the winner and \$400,000 for the loser, and made sure the event was well publicized.

The room where the games took place was not a room at all, but a television set designed to look like a professor’s study, complete with bookshelves and wing-backed chairs, a model sailboat, and an oriental rug. The table at the center of the stage was outfitted with a chessboard and a pair of flags (one Russian, one American), and a computer terminal used for communicating with Deep Blue. The computer’s brain, made up of two refrigerator-sized towers from the IBM RS/6000 supercomputer series, was stored in a locked room down the hall. Several cameras broadcast close-ups of the players, the board, and the clock to a pressroom and an auditorium in the basement where three grandmasters offered commentary to an audience of 500 while they watched the action on three large projections screens. Hourly updates were broadcast on CNN, and IBM posted a play-by-play webcast that was followed by millions.

Kasparov won the first game handily and commented that the computer played just as he had expected it to. Having competed against an early version of Deep Blue in 1996 as well as a number of other chess programs, Kasparov remained confident that he would prevail by

playing in an “anticomputer” style. Conventional wisdom among chess players held that because computers do not have an overall sense of strategy, they typically play best when lines of attack are out-in-the-open and obvious. If, for example, an opponent’s rook is directly threatening the computer’s king, the machine will likely be able to counter that by capturing the rook or protecting its king. But, if a human can line up an attack in a roundabout way, such as behind a row of his or her own pawns, the computer will not develop a long-term strategy to neutralize that attack the way a human player would. In essence, it will play planlessly – an Achilles heel that Kasparov planned to exploit for the remaining five games.

But in game two, Deep Blue shocked the champion with some very unexpected moves. By the computer’s 16th move, the board was in a “closed position” where pawns are blocking many of the pieces capable of controlling long stretches of the board, such as bishops. This is precisely the type of position that usually favors human players, but Deep Blue continued to make good moves and eventually worked its way to a slight advantage. Because of the way chess computers are typically programmed, they tend to capture opponents’ unprotected pieces right away. Knowing this, Kasparov purposely offered a pawn as a sacrifice. He expected that Deep Blue would immediately jump on it like a cat distracted by a mouse and allow him to regain some strength. But the computer didn’t take the bait and instead continued with its line of attack.

To Kasparov and many who watched from the sidelines, this was eerily human. The computer appeared to be playing with a long-term strategy that outweighed its impulse to capture pieces. Kasparov was shaken and resigned the game, believing he could not win.

The jubilant IBM team was the center of attention at the post-game press conference where they had previously been ignored by an audience rooting for Kasparov. Another blow rocked Kasparov’s confidence the next day when fans following the match on the Internet showed how the game could have been played to a draw had he not resigned.

Psychologically, Kasparov was in shambles. He no longer felt confident that he could gauge the computer’s abilities. And although there was no real evidence to support it, another, more insidious thought began to haunt him: could there have been human interference in the computer’s play? He demanded printouts of Deep Blue’s analytical processes, but the IBM team declined. Later, Joel Benjamin, a grandmaster who worked with the team to program

Deep Blue, explained that a human opponent would not be expected to discuss his strategy and reveal every variation he had considered in the middle of a competitive match.

Whatever had gone on inside Deep Blue's circuitry to secure its victory, the second game became a pivotal point in the match. Kasparov never recovered from the defeat and continued demanding printouts and insinuating that something had not been kosher during game two. He joked bitterly about it later at press conferences and his attitude about the whole endeavor changed. The day after the match ended, IBM gave Kasparov the printouts he wanted, but he remained disgruntled, upset that the logs didn't reveal *why* the computer chose a line of play, only the various lines it considered.

In a piece that appeared in *Time* a couple of weeks later, Kasparov described the atmosphere of the match as "hostile" and said that he believed that "competition had overshadowed science." A few years later, in a documentary film, Kasparov commented that he had originally believed the match was in the spirit of science and would benefit chess, computer science, and society, but that he had played right into IBM's hands. He proffered a scenario by which a human might have helped Deep Blue, and his agent, Owen Williams, said Kasparov hadn't realized at the outset that they were trying to "kill him at all costs."

Despite the uproar surrounding game two, games three through five passed without incident. They were all draws, strongly played by Kasparov, but not strongly enough to defeat the computer. Going into the sixth and final game, the score stood even. Kasparov needed a victory in order to keep his reputation as the strongest chess playing entity in the world.

Probably in an effort to avoid scenarios that the IBM team had programmed Deep Blue to handle well, Kasparov played an opening sequence he had not used since 1982. His attempt to mix things up led him to stumble on his seventh turn and move a piece out of order. After his 17th move, Kasparov picked up his watch from the table and put it back on. The commentators were confused. This was usually a symbol that the game was wrapping up. And indeed, after Deep Blue's 19th move, Kasparov resigned, immediately leaving the table and heading straight for the elevator.

At the press conference after the game, a visibly disappointed Kasparov received a standing ovation before apologizing for his poor play in game six. It was the first time in his career that he had lost a major match. Again he expressed concern that Deep Blue had made

some very strange – even unexplainable – moves during the course of the match. And his bitterness showed through: “It’s time for Deep Blue to play real chess. I personally guarantee that I will tear it to pieces,” he said, giving an early hint that he would soon issue a challenge for a rematch on his terms.

The match was over, but Deep Blue’s spectacular victory left Kasparov, and the rest of the world, plenty to ponder. And ponder we did. The computer’s legacy showed up in the flurry of popular press before, during, and after the match; in discussions and writings of experts in fields from computer programming to philosophy; and in the long-term trends of both computer science research and the game of chess. Whether we sympathize with the downtrodden human player or marvel at the accomplishment of the computer, we continue to sense these reverberations today, a decade after the famous match.

Thinking Like a Chess Player

In the mind of a trained player, the game of chess is divided into three stages: opening, middle game, and endgame. Players use different techniques to guide them through these stages. For experienced players, the opening phase (roughly the first five to fifteen moves) and the endgame (when there are relatively few pieces left on the board) follow semi-choreographed sequences, which are well-studied in advance.

Many conventional opening sequences have memorable names, such as the Queen’s Indian Defense, the King’s Gambit, and the Catalan Opening. In fact, the *Encyclopedia of Chess Openings* offers a five-volume catalogue of thousands of established opening sequences for chess players to study. In addition to these specific sequences, some basic principles guide opening play, such as avoiding moves that obstruct one’s own pieces and trying to establish control of the center of the board.

In similar fashion, players study endgame theory and memorize various combinations of pieces and positions that lead to particular outcomes. A player might study the various possibilities for an endgame involving a pawn and a king of one color against a lone king of the opposite color and learn ways of forcing a win or draw in this situation. A player can turn to this mental “database” of standard opening and closing sequences during a game to help choose the best move.

Play during the middle game does not usually follow such well-worn grooves. Typically, a player must do more on-the-spot mental extrapolation of moves and counter-moves to make decisions during this phase. The processes chess players use to make such decisions have been well-studied. In fact, for over a century, psychologists and cognitive scientists have used the game of chess as a testing ground for how the human brain works and as a case study for understanding expertise in various fields. What the fruit fly has been to genetics, chess has been to cognitive science. This is partly because skill at chess can be readily measured, broken down into components, and rigorously tested in lab experiments. And chess players, who serve as the subjects for experiments exploring thinking, memory, visualization, and other activities of the brain, come equipped with a very helpful assessment tool: an official rating.

Chess ratings are based on a player's performance in tournaments, but they do not represent simple win-loss records. Instead, they are statistically weighted to reflect the player's most recent games and to account for the strength of his or her opponents along the way. This makes them remarkably reliable for predicting the outcomes of various match-ups. For example, a player who outranks another by 200 points will consistently win about 75 percent of the time against the lower-ranked player. 1200 is about the median rating for a U.S. tournament player; Garry Kasparov reached a ranking of 2851 before retiring in 2005.

José Raúl Capablanca, the Cuban chess genius and reigning world champion from 1921 to 1927, was renowned for playing extremely rapidly. When asked how far ahead he calculated and how he did it so quickly, he explained, "I see only one move ahead, but it is always the correct one."

Capablanca may have been an extreme case, but in 1938, when Dutch chess master and psychologist Adriaan de Groot, compared the thought processes of average and strong players to the world's leading grandmasters, he found a kernel of truth in Capablanca's remark. De Groot asked the players to think out loud as they examined board positions from tournament games, and found that the top players (masters and grandmasters) did not analyze more possibilities than the players just below them (called experts). Instead, they honed in on and analyzed only the best possibilities. Using knowledge of previous games and of general

chess strategy, they were able to quickly identify quality moves and ignore hundreds of other inferior potential moves.

More recent studies have confirmed that stronger players tend to have a larger collection of chess knowledge, rather than an ability to analyze more moves. Neil Charness, a professor of psychology at Florida State University, tracked the progress of a chess player from a weak amateur to one of Canada's leading masters in the late 1980's. After nine years, Charness found that the player did not analyze chess positions any more extensively than he had at the beginning of the study. His improvement came from increased knowledge of chess positions and strategy.

Chess players working to improve their performance spend hours scrutinizing their past games, seeking to identify and avoid repeating mistakes. They also pore over the games of stronger players, absorbing strategy and committing new patterns to memory. Most master level players have spent hundreds of hours in serious study, not including tournament play.

Gambits and Gigabytes

Although they approach the game differently than humans, computers also rely on a set of tried and true tactics for playing chess. Many of the greatest minds in the field of computer science have invested countless hours in theorizing about, programming, testing, and fine-tuning various hardware components and software techniques to help computers master the game. The IBM team that designed Deep Blue drew on – and indeed contributed to – this rich half-century history of computer chess research.

In fact, computer chess was one of the seminal problems tackled by scientists in the emerging field that came to be known as artificial intelligence (AI). Mathematician and computer scientist John McCarthy coined the term artificial intelligence in 1956, but the definition of that term, and the scope and focus of the discipline, have changed over time. As originally conceived, AI was concerned with replicating general human intelligence in machines – in particular computers, which were coming of age when the new field took off.

Many early AI theorists believed that science could find the essence of pure intelligence. They tended to concentrate on intellectual endeavors, like chess playing, and

hoped that what they learned would trickle down to help explain more fundamental human tasks, such as vision or language.

Programming a computer to play chess was commonly referred to as a “grand challenge” or even the “Holy Grail” of AI. And it was the long evolution of computer chess, beginning with early artificial intelligence pioneers Alan Turing and Claude Shannon, which allowed Deep Blue to defeat Kasparov in 1997.

Alan Turing was a British mathematician who worked on breaking Nazi codes during World War II. He was keenly interested in the idea of building a chess-playing machine that simulated human thought in order to better understand the human brain and the concept of intelligence. Although he did not have a computer to run it on, Turing wrote a simple chess playing “program” in the 1940’s. The program was essentially an algorithm – a step-by-step procedure or set of rules – based on Turing’s own knowledge of chess strategy and style of play. To test the program, he used paper and pencil and acted as a “computer,” choosing moves strictly by following the rules he had created. He quickly found that his list of instructions produced some strange tendencies, such as a penchant for advancing pawns whenever possible, and played some useless or counterproductive moves that even a weak chess player would have avoided.

Claude Shannon, an American electrical engineer known as the father of information theory, also found the computer chess idea intriguing. Like many others at the time, Shannon considered good chess playing a hallmark of human intellect, and believed building a computer capable of skillful chess play would shed light more broadly on human intelligence. “Although of no practical importance, the question is of theoretical interest,” he said of computer chess in 1949, “and it is hoped that...this problem will act as a wedge in attacking other problems of greater significance.”

In 1950, Shannon published an article in *Philosophical Magazine* called “Programming a Computer to Play Chess,” which laid out the concepts that would eventually underlie nearly all two-player computer games from chess to tic-tac-toe. The article described two possible categories of chess programs. The first, referred to as Type-A or “brute force,” would consider all the possible board configurations that could result after a given number of moves. Shannon deemed this type of program slow and impractical, because the number of

possible board configurations grows exponentially with each move. For example, if a computer were programmed to look ahead three moves for each player, it would need to consider roughly a billion possible board arrangements. Shannon's article also described Type-B programs, which instead would use heuristics – or rules of thumb – and built-in knowledge about various positions to identify promising lines of play and examine them further. This, he said, was more akin to the way experienced human players approach the game.

Shannon also explained how a computer could be programmed to choose the stronger positions and lines of play. He outlined a “scoring function” that would allow the machine to rate the strength of its own position in a given board arrangement. The computer's evaluation would take into account at least three basic things for each player: material (the number and importance of the pieces left on the board), pawn formation (whether pawns are isolated, blocked, or free to move), and mobility (the number of legal moves available to a player in a given configuration).

Finally, Shannon laid out an algorithm called minimax that would help the computer navigate through the branching “game tree” of possible moves. Minimax allowed the computer to predict its opponent's moves by assuming the opponent would try to maximize the strength of his own position and minimize the strength of the computer's. With this understanding of how play was likely to progress, the computer could choose the best branch to follow in the game tree.

During the 1950's and 1960's, as faster electronic computers started to become more widely available, chess programming took off. Early programmers followed Shannon's advice and focused on Type-B programs that applied a form of “strategy” based on heuristics to examine a few possible lines of play several moves into the future. From the programmers' standpoint, this was the only reasonable way to build a chess machine because computers were simply too slow to consider all the possible moves, or even a large subset of them, in a reasonable amount of time.

Researchers from Carnegie Mellon University and the RAND Corporation teamed up to create a program called NSS in the mid-1950's. NSS employed a new technique called alpha-beta pruning, which allowed the computer to narrow the search tree by ignoring, or

“pruning,” branches that were yielding less promising results. In 1957, Herbert Simon, one of the NSS creators, made a famous prediction that within ten years, a computer would beat the world chess champion.

In the early 1960’s researchers at MIT began building a Type-B chess-playing program to be used in a game of correspondence chess (communicated via telegraph) against a computer in Russia. In a nine-month-long match, the Type-A program created by researchers from the Institute of Theoretical and Experimental Physics in Moscow defeated the MIT computer. This marked the first time that the two types of machine had gone head-to-head and demonstrated the potential of brute force programs.

In the 1970’s, the Association for Computing Machinery began hosting annual computer chess tournaments, which allowed programmers to share ideas and test their programs against one another. As hardware improved and computers became faster, a new generation of programmers began to put more effort into Type-A programs. Their programs still incorporated some heuristics, but increasingly they relied on faster, customized hardware and improved software to conduct brute force calculations of thousands – and eventually millions – of possible move combinations. Notable among these newer programs was Chess 4.0, which attained the title of “expert” (the level just below master) by 1979.

In 1977, two scientists at Bell Laboratories built a chess computer called Belle that became a major inspiration for Feng-Hsiung Hsu, one of Deep Blue’s creators. Belle, which became the first master-level chess computer, used specialized circuitry expressly for chess playing. The computer’s customized chess chips had a move generator and a board evaluator hard-wired into them. This was faster than coding the whole search process in software, and by 1980 Belle could consider 160,000 positions per second. The researchers also created a database of endgames that the computer could refer to in the final stage of the game.

The final innovation that had substantial influence on Deep Blue’s design was parallel processing. In the 1980’s, chess programs began using multiple processors that searched different parts of the game tree simultaneously and communicated the results with one-another as they went, speeding the process up enormously. Ostrich, a program developed at McGill University, ran 8 parallel processors in 1982. When Deep Blue took on Kasparov in

1997, it used 30 parallel processors with 16 customized chess chips on each for a total of 480 chips. It analyzed an average of 200 million moves per second.

Deep Blue's strength came from a combination of the techniques developed by game programmers over the previous half-century and a large collection of built-in chess knowledge. It was largely a Type-A machine that used a customized, lightning-fast hardware system to evaluate as many moves as possible. Its brute force strength set it apart from other machines at the time, but Deep Blue also had Type-B elements to its play.

The custom-made chess chips at the heart of Deep Blue's speed had been designed and redesigned several times. In their final form, they included an innovative move generator and a complex evaluation function. The Deep Blue team adapted the move generator from the Belle program. Instead of generating all the possible moves in a random order, it honed in on moves that would capture an opponent's piece first, and then moved on to non-capturing moves. This streamlined the search process at the outset by allowing the computer to evaluate the best moves first.

Deep Blue's evaluation function considered up to 8,000 factors in deciding how to weigh board configurations against one another. These factors included some fairly basic characteristics, such as which pieces remained on the board. For example, did both players still have their strongest pieces – their rooks and queens? How many pawns did each player have left?

The evaluation function weighed more nuanced factors, too. General strategy questions, such as whether pieces were pinned (stuck where they are because moving would expose a more valuable piece to attack) or hung (able to be captured without putting the opponent's capturing piece in danger) were factored in. Deep Blue also looked carefully at more complex situations, including a scenario known as "rooks on files." The rook can move any number of squares horizontally on a rank (row) or vertically on a file (column) in a given turn. A common strategy in chess is to situate one's rook at the end of a file in order to control a stretch of up to eight squares running right into the heart of the opponent's territory. Deep Blue gave some extra credit in its calculations to moves that placed its rooks on files, but it also recognized that all rooks on files are not equal. A rook blocked by an opponent's pawn, for example, was weighted lower than a rook on an open file. A position where that pawn was

guarded by another opposing piece was rated lower still. The computer also accounted for relative position: commanding a file in the center of the board was more valuable than controlling a file at the edge of the board.

With input from several grandmasters, the IBM team programmed the majority of these 8,000 board features by hand. As problems arose in Deep Blue's practice games, they tweaked the weighting system to more closely mimic choices a grandmaster would make.

Like any good grandmaster, Deep Blue also had a store of standard opening and closing moves to draw on. In fact, the computer's "opening book" contained 4,000 positions created by grandmasters, in particular Joel Benjamin, who was actively involved with the project throughout. The book was fine-tuned to emphasize positions that Deep Blue played well in practice and opening sequences likely to arise during play with Kasparov. The computer's endgame database, which was mostly borrowed from Belle, included all possible arrangements with five or fewer pieces left on the board. These positions did not come up during the match with Kasparov, but had the computer turned to this database, it would have been capable of flawless play, allowing it to force a win or a draw if it was possible with the given combination of pieces. This store of endgame scenarios also meant that the computer knew how to win with the fewest possible moves or how to put up the longest possible defense in a given situation – something no human could hope to match.

Ghosts in the Machine

Deep Blue's spectacular victory gripped the nation's consciousness, dominating front pages around the country and creeping into commercials, tabloids, and late-night talk shows. A crack team of IBM press officers worked hard to ensure that Deep Blue was on the minds and lips of as many people as possible. And those efforts paid off. The company estimates that its PR campaign scored over three billion "impressions" – PR parlance for an individual seeing or hearing about Deep Blue one time. Three years after the match, a marketing survey put Deep Blue on par with Batman, Howard Stern, and Carmen Electra and just above Larry King and Count Chocula as a celebrity personality.

But the buzz wasn't all light-hearted. To a nation growing into an uneasy, love-hate relationship with the tools of the information age, Deep Blue wasn't just a technological

marvel or a silicon celebrity. It was also a stomach-turning reminder of all the frustration and muted fear we felt toward our new partner in business, medicine, engineering, and everyday life: the computer. *Newsweek* editor Steven Levy gave voice to these concerns when he enumerated some of the most familiar difficulties: voice-mail hell, Windows error messages, and job loss to automation. He solemnly noted that “computers are changing our lives with both a rapidity and thoroughness...beyond our control” and “not every change will be for the best.”

And much of the popular press coverage was even more damning – exuding fear and disappointment and portraying the computer’s victory as a blow to human dignity. Even before the match, headlines and ledes in *Newsweek* blared that this was “The Brain’s Last Stand,” billed Kasparov as “the hope of humanity,” and asked: “When Garry Kasparov takes on Deep Blue, he’ll be fighting for all of us. Whose side are you on?” Phrases like “hand-wringing,” “unnerving,” “and keeping despair in check,” peppered the editorial pages of the *New York Times*.

In the *Weekly Standard*, columnist Charles Krauthammer, known for his blunt style, said aloud the unspeakable fear that seemed to haunt the unconscious minds of many less dramatic pundits. He boldly (and perhaps foolhardily) titled his post-match article “Be Afraid” and described Deep Blue’s victory as “the lightning flash that shows us the terrors to come.” Using an analogy to evolution, he prophesied the rise of machines: “We have just seen the ape straighten his back, try out his thumb, utter his first words, and fashion his first arrow.”

The match also drew indignant challenges from the chess community to salvage the pride of humanity. Susan Polgar, the women’s world champion at the time, said that given the opportunity she would use “woman’s intuition” to defeat the machine. Anatoly Karpov, Kasparov’s long-time rival, asked for a chance to play Deep Blue and “uphold the honor of mankind’s chess players.”

In the press and in the eye of the American public this was a stirring – and frightening – moment.

But the match struck a different chord with the scientific community. Researchers who had been following the progress of computer chess recognized that machines had been

steadily gaining ground on the best human players for years. Most had foreseen that it was only a matter of time before a computer defeated the world champion.

Chris Garcia, an assistant curator at the Computer History Museum in Mountain View, California was working at the Boston Computer Museum at the time. As someone who straddled the line between the realms of scientific research and public perception, he recalls having mixed emotions about the match's outcome. "Around the museum, it was the only thing people talked about," he says. "Everyone thought that it wasn't yet the time. I think we all kind of accepted that it would happen, but we were all hoping that it wouldn't at the same time."

Even for those who took a rational, even-keeled approach, there was room for genuine debate about just what had transpired over the course of those six games. Did Deep Blue's victory over Kasparov represent a serious advancement that was markedly different from previous chess programs? Could Deep Blue think? Was it intelligent? These questions split the commentators and harkened back to one of the oldest and most controversial concepts in AI: the Turing Test.

In addition to his paper-and-pencil chess-playing program, the British mathematician Alan Turing is remembered for a theoretical test he developed in 1950 when he set out to explore the question "can machines think?" Turing actually designed his test to bypass this "meaningless" question and replace it with a more tangible task that would allow us to determine whether a particular machine was thinking based on its behavior. The test calls for an interrogator to be placed in one room with a keyboard, which allows him to communicate with two subjects he cannot see. One is a computer and the other is another person. By typing questions, the interrogator tries to figure out which subject is which based on their answers. He may ask any questions he likes, and if while conversing in natural language, he cannot reliably determine which entity is the human, the computer passes the test and is dubbed a thinking machine.

Krauthammer, among others, suggested that Deep Blue had passed a version of this age-old test when Kasparov became convinced that humans were responsible for some of its play during the second game. In Turing's terms, the computer had fooled the interrogator,

who in this case was communicating with the computer through moves on a chessboard, into thinking he was facing a human.

The fact that Kasparov had to adjust his play and could no longer use a classical anti-computer strategy also drew attention. Deep Blue's moves confused commentators from the chess community as well, some of whom said the computer's play reminded them of the style of Kasparov's great rival, Anatoly Karpov. The consensus seemed to be that these moves were different from moves a computer would make; they were spookily human.

But how important was this eerie quality? Although the Turing Test is a classic concept in artificial intelligence, scientists disagree about its validity and usefulness. After the match, many scientists asserted that the computer could never truly be capable of thought or intelligence because it lacked some essential quality or ability not accounted for in Turing's test. Again and again the fact that Deep Blue used the brute force of processing power, rather than choosing moves the way a human does, was used as evidence that the computer was stupid. And the list of other reasons to discount Deep Blue's achievement was long: it did not feel emotions or experience the psychological aspects of a chess game, it was not conscious, it was only capable of one task, it couldn't even move its own pieces on the board.

While some aimed their critiques solely at Deep Blue, Yale computer scientist David Gelernter tackled the larger question of whether we'd ever build a machine that, like the brain, was conscious or capable of creating and understanding a concept of self. Unlikely, he said. Gelernter posits that the physical materials of the brain – the biological compounds and their interactions with one another – are what cause consciousness, and these interactions may simply not be replicable in other materials, such as silicon. "The gap between human and surrogate is permanent and will never be closed," he declared. This conclusion, if accurate, was the ultimate argument to take the sting out of Deep Blue's victory.

Gelernter's colleague at Yale, Drew McDermott, didn't take issue with Deep Blue's inner processes or rail against the idea that machines could, in principle, be intelligent. In fact, he suggested that Deep Blue was "a little bit intelligent," meaning that it was a thinking machine in a limited capacity.

Looking back from ten years out, McDermott calls the press coverage after the match a strange cultural phenomenon. “Everybody rushed to reassuring pieces about how you don’t have to worry about computers being able to think,” he says.

McDermott isn’t sure why that assurance seemed necessary. To him, the prospect of Deep Blue and other machines thinking does not pose a threat to humanity. Brute force is yet another tool in the AI toolbox, and Deep Blue is an incremental step toward the development of a machine with broad intelligence and flexibility – two things IBM’s machine admittedly lacked.

Daniel Hillis, an engineer and inventor who was an early pioneer of parallel computing, expressed an equally matter-of-fact opinion about Deep Blue’s victory and the possibility of thinking machines. “It turns out that being the best at chess wasn’t such a definitive element of being human after all. Life goes on,” he wrote in a *Newsweek* sidebar that accompanied the “Brain’s Last Stand” cover story. Hillis boldly predicted that we would someday create intelligent, even conscious machines through a gradual process of scientific innovation. He then glibly added that when that day came, we would “get used to it.”

These technical discussions about whether Deep Blue’s computations had crossed, or someday could cross, the line into the realm of conscious thought dredged up a deeper layer of more disturbing questions about humanity’s place in the universe. From Copernicus to Galileo to Darwin, ideas that threatened our notion of humans as the centerpiece of the universe or the privileged favorite of the creator have met with fierce resistance. This superiority complex has haunted our species as far back as we had had the mental hardware to contemplate it.

With the advent of the industrial revolution, machines began to test our egos. Perhaps the most famous example is the story of John Henry, recounted in children’s books, folktales, and work songs from the 1800’s. As railroad workers laid track across the South from the Tidewater of Virginia to the Allegheny Mountains of West Virginia, they used hammers and steel spikes to break up the shale and burrow train tunnels through the hills. John Henry earned a reputation as the strongest, fastest steel driving man around.

During the late 1800’s a new-fangled machine, the steam drill, also came into use on railroad projects. As the legend goes, John Henry agreed to race the drill in order to prove that

nothing could beat him, but after out-drilling the machine he collapsed and died with his hammer still in hand. His story, albeit romanticized and exaggerated, has been passed down as both a proud example of human strength and courage (John Henry did, after all, out-drill the machine) and as a woeful tale about the mechanization of jobs.

In his 1922 drama, *The Adding Machine*, playwright Elmer Rice brought the despair of John Henry out of the purely physical realm and applied it to a mental task. The play's main character, Mr. Zero, learns that he is being replaced as the office number cruncher by an adding machine.

"The fact is that my efficiency experts have recommended the installation of adding machines... They do the work in half the time, and a high school girl can operate them," Zero's boss tells him. Zero has the ultimate bad reaction to the onslaught of machines: he is consumed with rage and, in a theatrical swirl of maddening light and sound, murders his boss.

The struggles of characters like John Henry and Mr. Zero suggest that our fear of being toppled from our throne of perceived superiority did not die with the Enlightenment or even with the modern understanding of our biological make-up. The idea of being usurped by machines triggered the same kind of panic reflex as a heliocentric worldview or evolution. In this grand tradition, Deep Blue dared us to ask: are humans mentally superior to machines, and if we are, what makes us so?

Part II **Learning from Defeat**

Amid all the commotion, the true significance of Deep Blue's victory was not immediately apparent, but as mathematical historian Morris Kline once wrote: "The most fertile source of insight is hindsight." And indeed, ten years later, we've had time to sort through many of the wildly conflicting opinions and bold predictions that swirled around in the turbulent days following the 1997 match. In hindsight, we know that neither Charles Krauthammer's apocalyptic nightmare of machines taking over nor Kasparov's uneasy musings about socially savvy and artistically talented computers have come true. Deep Blue left a legacy of quite a different sort.

The questions raised by the computer's victory echoed through the decade that followed, influencing philosophy, AI, chess, and our relationship with computers. After Deep Blue, we wondered what other tasks computers could do that we had never anticipated. We broke free from an obsession, realizing that chess no longer represented a grand challenge for computer science, and set our sights on other serious games. And we came to terms with the fact that, in AI, many of the things that seem hard turn out to be easy, and many of the things that seem easy are actually quite hard.

A few months shy of the match's ten-year anniversary, I set out in search of the real lessons of Deep Blue. I wanted to raise lingering questions and hear new insights from some of the people whose lives and work were deeply affected by it.

Philosophy of Mind – and Machine

After the match, Hubert Dreyfus and John Searle, two philosophers who have made their careers pondering the implications of AI, were beset with questions and troubled inquiries from reporters. But neither one is entirely sure why.

By 1997 Dreyfus was no stranger to the realm of computers. He had butted heads with researchers in the AI field as a professor of philosophy at MIT during the 1950's, and he even had an early encounter with the chess playing program, NSS, during a summer spent at the RAND Corporation. Dreyfus was not impressed by the chess program or with AI as a whole. He wrote several exposés of what he considered an over-hyped field, including a paper entitled "From Alchemy to AI" and his 1972 book *What Computers Can't Do*, which refuted the praise that had been heaped on NSS and revealed that a ten-year-old beginner had defeated the program.

Many researchers took this commentary to mean that Dreyfus was insisting computers would *never* be able to play good chess, a rumor that he's fought to counter ever since. "That wasn't a philosophical claim. That was a fact," he explains now. "I was listing the things that – at this stage – computers can't do. When I said it, it was true."

Whatever he meant at the time, one thing is for sure: he quickly became known as a vocal critic of AI in general and computer chess in particular. And he's not budging on his critiques. Although he insists he doesn't dispute the possibility of creating artificially

intelligent entities in principle, he believes the AI field has by-and-large approached the problem in the wrong way.

I've come to visit Dreyfus in his office on the third floor of Moses Hall at the University of California, Berkeley on a sunny day in January 2007. I want to hear the famous critic's new perspective on the match with a decade of hindsight, but he begins by warning me that he may not have much to add to what he said ten years ago. Forty minutes later, we find there was plenty to discuss.

The day after the 1997 match, Dreyfus appeared on the *News Hour* and stated bluntly that the idea that the contest represented the brain's last stand was "hype" and that it had "no significance at all, as far as the question: will computers become intelligent like us in the world we're in?"

When I ask him about that comment, he is unequivocal. "That's still true, absolutely," he says, sitting with his legs folded in front of him, feet casually balanced on his chair so his knees peak up over his desk.

Indeed Dreyfus's attitude is largely the same now as it was in 1997. He still thinks that using brute force to accomplish a task, particularly winning a game with formal rules like chess, simply isn't very interesting or relevant to AI. "It's important to know what you can do with brute force in a formal domain and to know what kind of heuristics you can use to tweak it and make it better," he says. "But it doesn't tell us anything at all interesting about intelligence."

A devotee of philosophers like Martin Heidegger and Maurice Merleau-Ponty, who emphasized the importance of everyday physical experiences to human intelligence, Dreyfus believes that the best hope for creating an intelligent machine is to build one with a body. He takes issue with "good old-fashioned AI," a style that builds computers operating on symbols and formal rules of logic to represent the world. In his view, true intelligence comes through interacting with the world the way a person does and learning certain truths through physical experiences. Certainly Deep Blue, with its two stoic black towers requiring a cool room and a constant power source, could never meet these criteria.

In Dreyfus's eyes, Deep Blue – and even other robots that do bumble around in clumsy mechanical bodies while processing their experiences internally with a set of rigid

symbols – are not really victories for AI. And they certainly don't herald the onslaught of truly intelligent machines. "That's like saying that when an ape climbed a tree it was making incremental progress toward moon flight," he laughs. "It's the assumption you're on a continuum...which has human intelligence way out here. It's not even in the same ballpark. The ape climbing the tree is not going to get to the moon by incremental steps of the same sort."

So why all the fuss and fear about Deep Blue? Dreyfus has a few suggestions, which begin where most fear is rooted: in misunderstanding and confusion. "I think it's sad that people are so misinformed and hyped about this," he says. "They are misled and taken advantage of."

Dreyfus rebukes AI researchers for being irresponsible in talking about their work both in recent years and early in the field's development. During the 1960's and 1970's, researchers spurred by the press and the need to find funding made predictions straight out of science fiction, *literally*. Dreyfus marvels at the audacity of prominent, respectable scientists, who decades ago made "extremely optimistic" predictions that "we were just about to make robots smarter than we were" and that HAL, the intelligent, chess-playing, lip-reading computer from Arthur C. Clarke's *2001: A Space Odyssey*, was right around the corner.

By the time Deep Blue came on the scene, little had changed, according to Dreyfus. The public didn't truly understand the inner workings or the significance of IBM's chess prodigy or many of the other machines built in AI labs during the 1990's. "The AI people, instead of feeling it's their duty to set them straight about what's really going on, want to hype up what they're doing as much as possible to get more grants," Dreyfus says, not hiding his irritation.

The popular press played a dual role in creating the confusion, according to Dreyfus. In addition to encouraging the researchers to talk big about their creations and make headline-worthy predictions about the future of the field, reporters also ignored the naysayers, many of whom were philosophers. Dreyfus recalls being asked to comment by reporters looking for a balanced story and then seeing his cautionary opinions relegated to a single paragraph tucked among forecasts of imminent machine intelligence. "You find yourself quoted but utterly ignored at the same time," he says.

In the basement of Moses Hall, philosopher John Searle also has a rather frank assessment of Deep Blue. “It is of zero philosophical or psychological interest,” he says emphatically, as though it’s an obvious statement he’s been repeating for years to someone who’s been ignoring him

Searle bluntly disagrees with the long-standing notion that chess is a hallmark of human intelligence. In fact, he views the game as mostly trivial because both players have perfect information: they know all the rules, all the possible moves at each stage of the game, and the consequences of each of those moves. There is no guesswork involved as there is in games such as poker or bridge – or in everyday life. The main reason chess is interesting and challenging to humans is the astronomically huge number of possible move combinations. In Searle’s view, the only question worth answering with a chess machine is: how do grandmasters find short cuts that allow them to slice through all of those possibilities so quickly and hone in on a good move?

Deep Blue failed – indeed, it didn’t even attempt – to answer this question. Perhaps it represents a very practical achievement in hardware design, but that’s as far as it goes, according to Searle. Because of the approach that the design team took, relying heavily on brute force, Deep Blue is of no more interest than a pocket calculator.

Then, in the true spirit of philosophical exploration, Searle makes a statement that seems to defy reality: Deep Blue never really played chess. “The mistake we make...is we think *the machine is playing chess*,” he says in an ominous voice. “It’s not playing chess. In fact, it’s not even doing arithmetic. The machine doesn’t literally play chess because it doesn’t know this is a knight and this is a rook and this position is better than that position.”

In this frame of mind, Deep Blue is a tool we use to play chess, just as a calculator is a tool we use to do math problems. This concept is more comprehensible when we take the example of an abacus. It’s clear that an abacus doesn’t itself understand or do math problems. It’s a tool operated by a human who slides beads around, which stand for different numbers and which help the person compute sums and differences. A calculator performs the same type of function, but its inner workings are less visible than the beads of an abacus. A chess computer like Deep Blue is just more complex circuitry for tackling a more complex problem. It doesn’t play chess any more than an abacus does financial calculations.

In order to get away from mere tool-building and to create a machine with philosophical importance, Searle believes we would need to return to the early roots of AI and computer chess when researchers sought to model the human brain and thought processes. This could lead us to build a radically different kind of machine – one that is conscious. “If you want to know why artificial intelligence fails, why robotics fails, it’s a very simple answer. Nobody knows how to build a conscious robot,” Searle explains. “So we’re all just groping around trying to simulate human conscious behavior with unconscious machinery.”

Although philosophy has a strong tradition of examining consciousness dating back at least to René Descartes in the 17th Century, Searle thinks it’s high time neurobiologists made a serious effort to explain the phenomenon. And many are. Even the late Francis Crick, known for his work to uncover the structure of DNA, trained his mind on the problem toward the end of his life. Crick, along with dozens of other neurobiologists, began to view consciousness as they would digestion or any other biological function and to investigate the roles played by physical structures in the brain.

But many seemed to have underestimated the problem. “They thought it was going to be easy,” Searle says, remembering a conversation in which Crick confided that consciousness was proving much trickier to figure out than DNA had been. To Searle, the comment was ridiculously understated.

“I burst out laughing,” he recalls. “I said, ‘Francis, we’ve been trying to figure out consciousness for 2,500 years. You’re not going to solve it the way you and Watson solved DNA in a matter of months.’”

A scientific understanding of consciousness that we could potentially model computers after is still a long way off. But Searle thinks we are making progress and expects the discovery to be a watershed moment for biology and AI. “I don’t know how many Nobel prizes will come out of it, but it will be a result comparable, and I think in a way *bigger*, than the discovery of DNA,” he says excitedly. “How exactly does the brain cause consciousness? Why exactly are we conscious? There must be an answer to that question.”

Although Deep Blue may not have unfolded the mysteries of consciousness or even the true mystery of how grandmasters play chess, it did, according to Searle, raise an interesting sociological question: why did people *suppose* it was such a big deal?

When the match took place, Searle was in Paris and received what he considered to be very strange inquiries from reporters. “People said to me: ‘But isn’t this a tremendous blow to human dignity?’” he says, imitating the voice of someone taking themselves too seriously. “And I said, I got a car that can go faster than anyone can run. I got a pocket calculator that can do calculations faster than anyone can calculate. A blow to human dignity? No. It’s a terrific achievement that you can design these very complex electronic circuits.”

All Eyes on an Icon

Today, getting upset about a calculator, a steam-powered drill, or even a chess-playing computer may seem silly to the average American. We’ve become accustomed to relying on computers in the home, workplace, and all aspects of our lives. Chris Garcia, an assistant curator at the Computer History Museum in Mountain View, California, believes this constant contact with computers over the last decade has done a lot to demythologize them.

Garcia looks like a composite caricature of all the science fictions fans I’ve known in my life. He wears Vans tennis shoes and a Ghostbusters T-shirt and sports a long curly brown beard. When he greets me in the lobby of the museum, he apologizes for being late: he unexpectedly had to pick up a robot that morning for a future exhibit. Garcia has been working in computer museums for a decade, and he recently helped put together an exhibit called *Mastering the Game: A History of Computer Chess*. He is the type of person who has limitless energy to ponder what might be possible.

When I ask Garcia what technological feat might pack the same punch today as Deep Blue’s victory did in 1997, he’s hesitant to pinpoint a specific event. But he’s sure it would have to occur in the entertainment arena. The Deep Blue-Kasparov match was riveting because it was a mix of science, technology, leisure, and publicity – in Garcia’s words, “the icon and the iconic company coming to clash.” And it would take something equally as ambitious and high profile to draw a similar reaction today. “You had a media star in Kasparov,” he says, “and you had the IBM machine pumping out publicity all over the place.”

But what would be the modern equivalent? Finally, Garcia wagers a guess: “Maybe it’s a computer completely developing the script, the layout – everything – to make a film and having it be any good at all.”

At first, this strikes me as ridiculous. A computer could never do that. The unnerving moment comes a few seconds later when I realize that's exactly how many people felt about a collection of metal and silicon beating the world chess champion in the decades preceding Deep Blue's victory.

Even more unsettling is the thought of watching such a film. I envision the forwarded email in my inbox: "You have to see this!" above a link directing me to the YouTube website. A renegade researcher from an AI lab has leaked the computer-generated script to a group of film students who put it into production and uploaded their creation. I imagine streaming the footage onto my laptop and the sinking feeling I get when I remember that the scenes I'm watching were conceived of by a machine.

This scenario has several parallels to the Deep Blue-Kasparov match. In 1997, many people thought computers were a long way from accomplishing the task at hand, or that they never would. Most non-scientists did not really understand how a computer could be programmed to play chess, and today it seems difficult to fathom how we could build a machine capable of coherent creative writing. At the time, the play-by-play webcast of the match that allowed people from around the world to share in the moment of Deep Blue's victory was a fairly new technological phenomenon. The same is true for streaming video websites, like YouTube, that would allow people to view and share a computer-generated film.

The scenario also underscores an important aspect of the significance of Deep Blue's victory and one of the reasons it caused such a commotion: the computer became an instant icon in several spheres of American life. What Garcia finds most impressive about the match was its ability to spark discussion among the "high thinkers," or the philosopher and academics who didn't often pay much mind to individual technologies. But it didn't just reverberate within the research labs and cloistered studies of universities; Deep Blue also penetrated the popular culture, making its way into political cartoons and television commercials. And Garcia thinks this could make it an inspirational signpost for young people going into computer science now.

He likens Deep Blue to the hulking Univac system, the first commercial computer built in the U.S., which famously predicted the outcome of the 1952 presidential election

using just a small sample of data from the polls. A generation of scientists and science fiction writers grew into their professions with Univac emblazoned on their minds, and a new generation has grown up with the memories of Deep Blue and Garry Kasparov trading pawns and battling for position on the chessboard.

Now You See It, Now You Don't

In AI circles, Deep Blue was a different sort of icon. Early dreams of computer chess unlocking the mysteries of human intellect had been fading, and Deep Blue represented their final demise. In general, hopes of understanding and simulating intelligence had proved elusive, and as time went on, it became clear that the functioning of the human brain was too complex to be understood as a whole. The problem needed to be broken into smaller parts, so researchers began to specialize. Some took on speech recognition as their life's work. Others spent their careers creating programs that could solve mathematical theorems. And some, like the researchers who built Deep Blue, chose to focus on logical games.

Like the field of AI as a whole, the goalposts within these subfields have shifted over time. In computer chess, programmers initially set out to build machines that could play *legal* chess, never mind world-class chess. With that target quickly attained, the lofty goal of decent play came next. Master-level and grandmaster-level chess – once unfathomable – followed in a matter of decades. As researchers squinted into the distance at each new goal, skeptics stood by asserting, and sometimes wagering money, that computers would never make it to the next level. The evolving goal, which eventually became defeating the world champion, loomed on the horizon, growing in size and perceived significance like a rising bubble tempting fingers to poke at it.

And just like a bubble that has been burst, the goals of AI, once attained, often seemed to disappear into the ether leaving nothing significant behind. Deep Blue's long-pursued victory was another example of this phenomenon known to researchers in the field as "disappearing AI."

Henry Lieberman, a research scientist with the Software Agents Group at the MIT Media Lab, sees this as a systemic problem. "AI tends to lose its successes because people

tend to attribute them to other fields or downplay them in some way,” he says. “That’s a problem that we have as a field. It’s a public relations issue.”

Optical character recognition (OCR), the software that allows a computer to translate images of typewritten or even handwritten words into editable text, is another example. Originally, OCR had its roots in AI, and it was a difficult challenge for the field. But once the technology was refined through years of research and began coming free with every desktop scanner, people ceased to think of it as AI at all. Lieberman predicts that speech recognition will follow the same path as that technology improves. “This is a very familiar problem in AI. It’s like a magic trick where once you see the trick, it doesn’t seem magic anymore,” he says. “But people in AI tend to feel the opposite. Once they understand something, they’re more in awe of it.”

Some researchers, like UCLA computer scientist Richard Korf, suggest that the root of disappearing AI is not just in the undoing of the brain’s magic tricks but also in a misunderstanding of the definition of AI. In a paper he wrote just before the match for the American Association of Artificial Intelligence conference, he objected to IBM’s public statements that Deep Blue did not use artificial intelligence because it didn’t simulate human cognition when choosing a move. He argued that AI deserves a broader definition, including techniques that do not mimic human thought patterns but do allow machines to complete intelligent tasks.

Why quibble over the definition? Like Lieberman, Korf was concerned about the reputation of AI, both in the public domain and within the field of computer science. Not only did successful projects like OCR lose their AI stamp as they became demystified and commonplace, but Korf also saw researchers working on traditional AI tasks trying to distance themselves from the term at the outset. This fragmentation, he said, would leave the field of AI with all the failures and none of the successes.

In the intervening decade, Korf has reassessed the severity of the situation. He recalls finding IBM’s disavowal of AI outrageous because the technology behind the machine was classic AI at the time. “I’m a little more philosophical about it,” he says when I ask him whether he thinks disappearing AI is still a problem for the field. “Its natural evolution is going to be to split into subfields.”

Korf compares modern AI to the extremely broad field of “natural philosophy” from Isaac Newton’s era. Over time, that field successfully fractured into the various categories of science we recognize today from biology to physics. According to Korf, this specialization hasn’t hurt science overall, and no one worries that scientists identify with more specific disciplines. His new outlook, informed by ten years of hindsight, is perhaps the most logical way to view Deep Blue’s place in the history of artificial intelligence. AI is not disappearing. It is evolving. Deep Blue’s bubble-bursting victory is not cause for disappointment. Instead, it releases us to chase after the next set of bubbles on the horizon.

Through New Eyes

David Stork is reaching out toward one of those bubbles. He is holding his hand out in front of him and examining it as though he has never seen it before. Stork is the chief scientist and head of the Machine Learning and Perception Group at Ricoh Silicon Valley and an associate professor of electrical engineering and psychology at Stanford University. He’s used to looking closely at seemingly mundane things – hands or ordinary conference rooms like the one we are sitting in – and thinking of them as extraordinary puzzles.

Stork’s research focuses on pattern recognition, one of the subfields that rose to the surface from within AI. He marshals all the tools of his varied background from statistics, to decision-making theory, to computer algorithms, in the pursuit of understanding and modeling the way human brains so nimbly identify things we have seen before – and things we haven’t. As he studies his own digits, he remarks on how amazing it is that people can instantly recognize a hand, in the flesh or in a depiction, even despite partial obscuration and all the variations in size, color, and shape. No modern machine can come close to matching the brain’s ability to recognize patterns or items belonging to a particular category.

Stork has written extensively on the possibility of computer intelligence, considering machines from the fictional character HAL in *2001: A Space Odyssey* to the real-world Deep Blue. Just before IBM’s computer took the stage to defeat Kasparov, Stork wrote an essay for the company’s website entitled “The End of an Era, the Beginning of Another?” He suggested that a victory for Deep Blue would usher in the end of a historical period when brute force solved interesting problems in AI. Chess was the final frontier: the last high-profile problem

from traditional AI that could be solved with fast hardware. Thereafter, we would set our sights on problems that require “real” AI based on pattern recognition and strategy.

Ten years later, Stork’s opinions haven’t changed much. Looking back, he thinks one of the most interesting things to come out of the match was Kasparov’s reaction to losing – the champion’s feeling that he had failed in a test of human intellect. “Why did he take it so personally?” Stork laughs. “Those of us in the field didn’t feel it was like that at all because we’re nowhere near solving the real hard problems in artificial intelligence. He is much, much smarter than Deep Blue, even if he lost in chess.”

Nor does Stork think the technology used in Deep Blue will help scientists much in tackling these really difficult tasks. “[Brute force] works well on some problems, but not others. And ones that it doesn’t work on are the ones that we generally feel are crucial to human intelligence, like vision,” he explains.

Massive parallel processing, of the type found in Deep Blue, is a good tool for tackling problems that have large amounts of data that don’t affect one another, so they can be broken into smaller units, farmed out, and worked on simultaneously. Chess fits into this category. Several possible lines of play can be traced and evaluated by several different processors at the same time. Many physical systems that we seek to model for engineering purposes can also be approached this way. Stork offers the example of airflow around a plane. Some processors can be set to work simulating the air flowing over the left wing, while others model the airflow over the nose cone, and the results can be combined at the end to create a single model that helps us understand airflow around the entire plane.

While these problems with large data sets seem very difficult to humans, they turn out to be relatively easy for machines. In fact, that’s true of AI in general, according to Stork: “The problems that many people think are hard turn out to be simple, and problems many people think are simple turn out to be hard. Chess – everybody thought was really hard. It’s not that hard. But things like vision, which every baby does and cats do, is *astoundingly* hard. It’s going to be with us for decades.”

Stork often finds himself explaining this paradox to students in his classes or on cross-country flights after answering the typical small talk “so what do you do?” query. Most people have never heard of the field of pattern recognition, let alone stopped to ponder how

the brain manages all the bits of information it uses for everyday tasks. “I think some of the greatest unsolved problems in science are things happening right here, right now,” Stork says tapping on the table emphatically. “It’s not the sub-sub-sub atomic particles. It’s not the beginning of the universe. It’s how you can recognize that I’m sitting in front of you. How you recognize my voice, how you understand what I’m saying. These are astounding mysteries, and the public unfortunately takes them for granted, doesn’t even realize they are problems.”

Stork laments this rift between the public’s perception of the “grand challenges” in AI and the scientific reality that seemingly simple problems continue to confound scientists. Echoing the skeptical philosopher Hubert Dreyfus, he thinks AI researchers were overly optimistic with their predictions early on, leading to disillusionment when they couldn’t meet the expectations they had created. But he’s hopeful that Deep Blue, with its celebrity status, might have nudged us toward straightening out these misconceptions and renewed some excitement and faith in the field. “I think the scientific community was a little bit irresponsible in making such predictions,” he says. “Finally passing that small hurdle with Deep Blue got it back in the public’s mind that you can solve some problems that at least the public thinks are really hard.”

He believes that seeing Deep Blue really get a handle on chess and defeat Kasparov with raw processing power also brought to light the truly difficult problems that cannot be solved this way and continue to elude us. Although counterintuitive, one of the greatest lessons of Deep Blue’s victory comes from looking at the failures around it. And Stork hopes that exposing the shortcomings in current work on things like vision and speech recognition shows the public “how amazing their own brains are.”

The Definitive Battle that Wasn't

Charles Leiserson, a professor of electrical engineering and computer science at MIT, was there when the computer chess bubble suddenly deflated. The hallway outside his office is adorned with chips and circuit boards displayed under Plexiglas. This is a place where computers are born.

In the waiting area nearby, I sit among the symbolic casualties of Deep Blue’s victory.

Two knee-high plastic kings – renegades from a giant chess set – sit on four black and white interlocking squares. Forgotten in the corner, knights and bishops peak out of a row of cardboard boxes. The pieces look as though they have been abandoned in mid-game.

In the 1990's, Leiserson and his team, the MIT Supercomputing Technologies research group, were in neck and neck competition with the Deep Blue design team. Although they were working on a shoestring budget compared to IBM's massive investment, they had built a very successful chess program called *Socrates (pronounced "Star Socrates"). The MIT group continually struggled to find financial support for their research. "We'd always had trouble getting funding from anybody because it's just game playing. It's not anything, quote, serious," Leiserson recalls. "You can't go to the federal government and say this is crucial to our national defense."

Despite the playful packaging, Leiserson and his colleagues saw plenty of serious value in pursuing computer chess. "The reason we did it originally is because we were looking for something to drive our research efforts on parallel computing," he explains.

In particular, the team was interested in testing out a computer language called CILK, which they were developing to increase the performance of parallel computers and to make programming them simpler. The game of chess made a rigorous testing ground for their nascent language, because it presented an irregular problem with many different branches to be explored and weighed against each other simultaneously in the process of choosing the next move. CILK's use quickly grew beyond the computer chess realm, and it now has a wide range of research applications from complex linear algebra problems to biological modeling.

But Leiserson and his team weren't in it just for the sake of advancing their research. They were also caught up in the excitement of computer chess tournaments and the race to beat the human world champion. They set their sights on the IBM research team, and *Socrates became Deep Blue's main silicon competitor in the months leading up to the battles with Kasparov.

Looking back on the 1997 match, Leiserson is torn about how to describe it. "I went in with mixed feelings because the IBM group were competitors with us," he says. "And yet at the same time we are all working towards understanding how to put knowledge and intelligence into machines."

And Leiserson certainly had at least one good reason to feel conflicted about Deep Blue's success. If finding sponsorship for their research had been difficult before, it became nearly impossible after the match. Leiserson's computer chess team was disbanded. "The IBM team did a great job. The unfortunate thing is that once you have something like that, the interest goes to zero afterwards," he says, referring to the dearth of sponsors and waning media interest in computer chess after the match.

To Leiserson, the sense of closure that the match brought to the research field was misplaced and unfortunate. He views Deep Blue's victory as an accomplishment and a milestone for computer science, but not an event that should have closed the book on computer chess research the way it did. He differentiates between events that mark concrete breakthroughs and accomplishments, like Deep Blue's victory, that fall on a continuum. "It's not like breaking the sound barrier. There's a real barrier *there*," he says, remembering Chuck Yeager's quest to fly faster than the speed of sound.

In contrast to breaking the sound barrier, which is a constant determined by the laws of physics, choosing a particular person to defeat in a chess match, even a much lauded world champion, was fairly arbitrary. Not only has the ceiling on chess playing ability risen over the years, but even the best human players are inconsistent. They have bad days and good days. They get tired or preoccupied. Many chess commentators, and Kasparov himself, remarked that he was not in top form during the match against Deep Blue.

And to many computer scientists, the match that burst the bubble of public interest and supposedly settled the issue was only a single data point, which did not convincingly demonstrate that computers could outplay humans. Although he concedes that computer chess programs tower above humans today, Don Dailey, a former programmer from Leiserson's disbanded chess research team, is not convinced that Deep Blue was in fact the best player of its time. "You win some, you lose some," he says of chess tournaments in general. "It just so happens that the computer won that short match by one game. But anything could have happened in that match."

To Leiserson, human-versus-computer chess matches served as a sort of thermometer for monitoring the continuous process of program development. "The temperature's rising

and at some point hits 100 degrees and you say ‘whoa, it hit a hundred degrees!’” he exclaims, laughing. “But there’s nothing magic about 100 degrees.”

Yet reaching that boiling point (in this case beating the human chess champion) did herald declining interest in chess programming within academia. Deep Blue’s victory marked the end of an era in computer science when chess reigned as an unsolved problem and an exciting vehicle for advancing research into algorithms and parallel processing languages. Over several decades of hardware advances, computer chess had been evolving from a research testing ground that could really only be utilized by scientists with access to supercomputers into a more manageable puzzle that was increasingly being tackled by commercial programs written for individual use on microcomputers.

In the years following the 1997 match, this evolution from academic puzzle and tool to commercial enterprise became complete. “It remains an interesting problem, but the world has moved beyond chess as a favored game,” Leiserson says.

After IBM retired Deep Blue, a few machines attempted to follow in the silicon giant’s footsteps, but they have not received nearly the notoriety that Deep Blue did. Hydra, a supercomputer-based chess system financed by a private company in Abu-Dhabi, has been playing in relative obscurity. Even its repeated victories over top grandmasters only merit the occasional magazine article – nothing like the media frenzy, crowds, and celebrity status that followed Deep Blue. Meanwhile, commercial chess programs for leisure and training developed by software companies and running on home computers are common and fairly inexpensive.

Academic institutions actively pursuing computer chess research are rare these days, especially in the U.S. Many American programmers have switched to new games, such as bridge and Othello, which fizzed beneath the surface while chess was in the limelight. In particular, interest in the ancient Asian game of Go is swelling.

Go is the New Chess

The components and rules of Go are simple. The board – a 19-by-19 grid of squares – and the pieces – identical black and white stones – are easy to represent in computer code. Two players take turns placing stones of their own color at the empty intersections of the grid,

trying to protect their own pieces and capture the opponent's pieces. A stone, or cluster of stones, is captured and removed from the board when it's surrounded by stones of the opposing color. Players aim to gain as much territory as possible, and the game ends when neither can make a move that will improve their standing on the board.

After *Socrates' retirement, Don Dailey continued research that used games as a testing ground. He worked on another program, Cilkchess, which used the latest version of the CILK language but ran on the new hardware that was becoming available in the late 1990's, and also on computer Go. Now Dailey works on Go as a hobby and maintains a web site where programs can face-off and receive rankings. At the moment, he finds Go more challenging than chess because amateur players can still easily beat computers. Many programmers are taking it a step at a time and working on a scaled-down nine-by-nine board because the potential search tree in Go is roughly ten times larger than the massive tree explored in chess.

Even David Stork, who believes understanding the simple beauty of everyday tasks is the greatest challenge facing science, finds value in computer Go. Despite its similarities to chess, Stork doesn't believe Go will yield to brute force methods. At least two things make Go more challenging to program than chess: the sheer number of possible moves and the fact no piece is inherently more valuable than another (the way a queen is more valuable than a pawn because of its greater mobility and capturing strength). In Go, each piece's value is determined solely by its relationship to other pieces on the board, and these relational subtleties are the most difficult aspects to program. Stork predicts that these intractable features of the game will force Go programmers to use pattern recognition techniques, bringing them closer to the early AI goal of modeling the human brain.

"As far as games are concerned the real Mt. Everest is Go," Stork says. "If we get a machine to be the best Go playing system in the universe, it will require not just more compute power but a much better understanding of pattern classification, learning from playing lots of games, generalization, and things that will indeed shed more light on human cognition than raw search."

Some of the latest Go programs reflect Stork's predictions. Researchers in Microsoft's Machine Learning and Perception Group in Cambridge, England are working on a program

that attempts to predict the move an expert Go player would choose in a given situation. The researchers have trained their program by feeding in 181,000 games from expert Go players. The program can mine this database for 12 million patterns of piece configuration and use them to mimic the expert style of play in new situations not encountered in the historical games. Currently, the program correctly predicts the expert choice 34 percent of the time.

The approach Dailey finds most promising, however, is known as the Monte Carlo method, which, as the name suggests, requires less expert knowledge and more statistical good fortune. A program using this approach selects a move by playing through thousands of random variations of the game and choosing the move that produces the best result on average. This method of choosing the statistically best move formed the backbone of Crazy Stone, the program that won the gold medal for nine-by-nine Go playing at the 2006 Computer Olympiad.

Unlike Stork, Daily is prepared to see Go's slowly rising bubble popped in the near future. "Go is at the stage computer chess was a few decades ago. I learned my lesson from history," he says, noting that many prominent chess players mistakenly believed their dominance over computers was permanent. "I think [Go programs] will continue to improve with time."

Quantity Into Quality

For IBM, the 1997 match was the grand finale of chess research. The masterminds behind Deep Blue, Feng-Hsiung Hsu, Murray Campbell, and Joe Hoane, switched to working on financial modeling and data mining projects, and Hsu and Hoane moved on to other companies soon after. But the Watson Research Centers in New York, where the young Deep Blue design team did most of their work, are still abuzz with deep computing projects – the distant offspring of Deep Blue. IBM retired the chess machine after its victory, but it was an important testing ground and research driver for hardware and techniques that live on in new IBM supercomputing projects.

The family of computer that housed Deep Blue, the RS/6000 SP2, gave rise to a line of machines that have branched into biology, weather forecasting, climate modeling, and financial applications. The current top-of-the-line IBM supercomputing system, Blue Gene/L,

is 4,000 times more powerful than Deep Blue. At the Lawrence Livermore Lab it is used to model nuclear explosions and predict the way materials in stockpiled weapons will break down over time.

Perhaps more influential than any machines inspired by Deep Blue is a subtle shift in mindset that the chess prodigy precipitated. Deep Blue forcefully demonstrated the undeniable power of a problem-solving approach that computer scientists have labeled computational thinking. Kasparov remarked that IBM had “succeeded in converting quantity into quality,” recognizing that the challenges of playing chess well – like a human, even – were yielding to computational force. Grandmaster Patrick Wolff summed up the overall lesson well when he said, “we need to face the fact that things that could once be done only through human intelligence can now be done in other ways as well. The intriguing question is, how many things are like that?”

That question and a drive to study puzzles once thought too complex to be fully understood have inspired a number of massive parallel computing projects within IBM and beyond. Perhaps the most ambitious of these is the Earth Simulator, a supercomputing system run by the Japanese government that literally seeks to model the systems of the whole earth, from the molten core to the upper atmosphere, the microscopic phytoplankton to the entire marine ecosystem, and the Earth’s evolutionary history up through the planet’s future.

The rows of light-blue towers with ominous red eye-like circles look like the denizens haunting science fiction stories, but the Center for Earth Simulation has partnered with groups from industry, academia, and other parts of government to create models that offer information about global climate change, large-scale geologic phenomena, and even product development. In his web welcome message, the center’s director-general, Tetsuya Sato, says, “the future evolution of a system can be predicted by simulation, and hence the future world is turned from Science Fiction into Science Reality.”

These large-scale supercomputing projects, which we now routinely trust to undertake much more significant tasks than playing chess, illustrate our increasing confidence in computers. We no longer fear the likes of Deep Blue. More and more, we trust its cousins to help us figure out what to do with radioactive materials and determine how we are affecting

the global climate. That frightening bubble of computers computing things humans could not, which once loomed so ominously on the horizon, has burst.

Mind Games

On September 29th 2006, Bulgarian grandmaster Veselin Topalov, sat alone on a stage vaguely reminiscent of the scene where the Deep Blue-Kasparov showdown took place. He waited patiently, sipping water and wondering whether his Russian opponent Vladimir Kramnik would return to fill the conspicuously empty chair across from him or whether the fifth game of the tournament would be forfeited.

Kramnik and Topalov met in Elista, Russia in the fall of 2006 to answer the long-standing question of who could truly claim the title of human world champion. The dispute began in 1993 when Kasparov and British grandmaster Nigel Short split away from the World Chess Federation (known by its French acronym FIDE) to form the Professional Chess Association. This division created two world champions. Since Kasparov had been the undisputed champion at the time, his successor became known as the classical world champion. In 2000, that title went to Kramnik. FIDE, however, continued crowning their own line of champions, and in 2006, Topalov, held this title.

The Topalov-Kramnik tournament in Elista was arranged to reunify the two organizations, heal the rift, and crown a single world champion. But the tournament did not go as smoothly as planned.

It's not uncommon for a human player to leave the board during a chess match. Players get up to get water. They pace. They leave the area for a few minutes to clear their heads and then return. But in Elista, Kramnik took this ritual to a new level. He continually got up and went to his private bathroom – the only place on the set not under video surveillance – and remained there for protracted periods. Eventually, Topalov appealed to the tournament officials, accusing Kramnik of cheating. He alleged that there were unexplained wires in Kramnik's restroom, and that the Russian *acted* like he had received help from a computer, staying in the bathroom for inexplicably long periods of time and making his moves immediately after emerging. Topalov also suggested that some of Kramnik's moves "would only occur to a computer."

The appeals committee locked the private bathrooms and ruled that the tournament would go on with both competitors using the same restroom for the duration. Neither player was happy with the decision. Kramnik sat outside of his locked personal bathroom in protest, eventually forfeiting game five. He came back to the table for games six through sixteen, and claimed the title with a record of $8\frac{1}{2} - 7\frac{1}{2}$.

Although Topalov acknowledges that he made mistakes that ultimately cost him the match, he is still haunted by the feeling that Kramnik turned to a computer for help. Topalov's accusations show just how much the competitive chess world has changed in ten years. In 1997, Kasparov claimed that Deep Blue's masterful play could only be explained by human intervention. Now, just under a decade later, Topalov was reversing the accusation.

In the time leading up to Deep Blue's victory, it seemed chess masters might never warm up to computers. In May of 1987, one out four players registered with the U.S. Chess Federation refused to play against computers in tournaments. In 1989, Kasparov displayed his own misgivings toward computers when he said "I don't know how we can exist knowing that there exists something mentally stronger than us." There was deep uneasiness about the topic among many competitive players.

But Deep Blue demonstrated the power and potential of chess programs in a way that no one could deny. The fear and resistance that initially bubbled up dissolved into acceptance, and in some cases, perhaps, dependency.

Potentially deceitful uses aside, computers have become integrated into the chess world as much as any other domain of our modern lives. Ten years after the famous match, I sit comfortably in front of my laptop and call up the website for *This Week in Chess Magazine*. The page is peppered with ads for computer programs, and among them I can sense the change in attitudes that Deep Blue's victory precipitated. A description of one of the high-end programs, Fritz 10, catches my eye. "'Man vs. Machine' has become one of the great themes of our time," it reads. "But don't be afraid – Fritz has a different side to its personality. The program will help you along during the game, with numerous sophisticated coaching functions, adjusting its playing strength to exactly match that of any opponent."

Although serious chess players, including Kasparov himself, had been using computers to practice and the market for programs running on home computers had been

growing for a while, Deep Blue's victory forced everyone in the chess world to admit the power of machines. Grandmasters and lower level players alike began to incorporate computers into their training regimes much more seriously.

And this new partnership has had some interesting outcomes. By looking many moves ahead, computers have found ways to win games that were previously thought to be forced draws. In one instance, a computer called the Connection Machine found a forced win that took 249 moves. Some players have taken to memorizing the more manageable new endgame sequences and forcing wins where there would have previously been draws. In some cases, young or less experienced players have also been able to beat grandmasters by analyzing online transcripts of their games until they find an innovative move that can derail the expert players' favorite openings. "Originally we wanted to make machines play like humans, but now humans are playing like machines," notes David Stork in a comment that echoes Topalov's fears.

Eventually, Garry Kasparov accepted his defeat at the hands of a machine and moved on, never to face Deep Blue again. Shortly after the match he had seemed bent on challenging the computer to another contest, asserting that "IBM owes mankind a rematch." But for reasons that are not entirely clear, this rematch never happened. According to Feng-Hsiung Hsu, one of Deep Blue's designers and the original driving force behind the project, IBM was looking forward to an ongoing relationship with Kasparov and had initially been open to a rematch. But Kasparov's insinuations that the match had not been conducted fairly cooled their interest, and they decided to retire Deep Blue. Meanwhile, Kasparov's calls for a rematch quieted, and his interest seemed to wane. Perhaps he simply realized that after his bubble had been burst, life went on.

Whatever the cause, this change in Kasparov and the overall shift in the chess community are emblematic of the way in which we all grew to accept Deep Blue's victory. In the end, Deep Blue is a reminder that our understanding of ourselves and our relationship with technology is always evolving. Although the story of computer chess is rife with overly optimistic characters, Deep Blue ultimately is an example of why such optimism, tempered with patience, is warranted. We will continue to achieve scientific and technological feats that

seemed impossible just a few decades earlier. But as each new bubble vanishes, we will need time to adjust to the changing landscape.

We have a long way to go before we see a computer write a decent screenplay, converse with us comfortably in natural language, or even reliably recognize a human hand. But no doubt when we do burst each of those bubbles, we will, in the immortal words of Daniel Hillis, “get used to it.”

References

- Bellon, M. (2006, December 12). Topalov: Kramnik will never admit that he cheated. *Chessbase News*. Retrieved April 14, 2007 from <http://www.chessbase.com/newsdetail.asp?newsid=3553>.
- Big Blue wins. (1997, May 12). [Transcript]. *PBS Newshour*. Retrieved December 16, 2006 from http://www.pbs.org/newshour/bb/entertainment/jan-june97/big_blue_5-12.html.
- Blue Gene. (n.d.). Retrieved January 25, 2007 from http://domino.research.ibm.com/comm/research_projects.nsf/pages/bluegene.index.html.
- Byrne, R. (1997, May 13). Why did Kasparov lose? Perhaps he tried to hard. *New York Times*.
- Byrne, R. (1987, May 31). Computers can be challenging opponents. *New York Times*.
- Caddes, C. (1986). *Portraits of success: impressions of Silicon Valley pioneers*. Palo Alto, CA: Tioga Publishing.
- Campbell, M. (1997). "An enjoyable game": how HAL plays chess. In D. Stork (Ed.), *HAL's legacy: 2001's computer as dream and reality* (pp. 75-98). Cambridge, MA: The MIT Press.
- Campbell, M., Hoane, A., & Feng-hsiung H. (2002). Deep Blue. *Artificial Intelligence*, 134, 57-83.
- Contenders Fact Sheet*. (n.d). [Press release from IBM Research]. Retrieved December 13, 2006 from <http://www.research.ibm.com/deepblue/press/html/g.6.1.html>.
- Darnton, J. (1993, October 24). Match backers pleased at response. *New York Times*.
- Dreyfus, H & Dennett D. (1997, June 26). Artificial intelligence dialogues. *Slate*. Retrieved January 12, 2007 from <http://www.slate.com/id/3650/>.
- Dreyfus, H. (1972). *What computers can't do: a critique of artificial reason*. New York: Harper and Row Publishers.
- Duda, R., Hart, P., & Stork, D. (2000). *Pattern classification*. New York: John Wiley and Sons.
- Fritz 10 – Out Now! (n.d). [Advertisement]. *This Week in Chess Online Magazine*. Retrieved January 26, 2007 from <http://www.chesscenter.com/twic/twic.html>.
- Gelernter, D. (1997, May 19). How hard is chess? *Time*, 149, 72.
- Gerstein, M. (1997, May 13). How smart can it be? [Letter to the editor]. *New York Times*.

Gobet, F. & Charness, N. (2006). Expertise in chess. In Ericsson, K, Charness, N., Feltovich, P. & Hoffman, R. (Eds.), *The Cambridge Handbook of Expertise and Expert Performance*. (523-538). New York: Cambridge University Press.

Gergely, A. (2007, February 21). *Algorithm helps computers beat human Go players*. Retrieved February 22, 2007 from http://www.reuters.com/article/scienceNews/idUSL2053348420070221?src=022107_0829.

Gulko, B. (1997, July). Is chess finished?. *Commentary*. 104, 45-47.

Halfhill, T. (1997, July). *Searching for Deep Blue*. Retrieved December 16, 2006 from <http://www.byte.com/art/9707/sec6/art6.htm>.

Hamilton, S. & Garber, L. (1997, October). Deep Blue's hardware-software synergy. *IEEE Computer*. 30, 29-35.

Hedberg, S. (1997, July/August). Smart games: beyond the Deep Blue horizon. *IEEE Expert*. 12, 15-18.

Hershman, T. (2002, October 21). Chess: man vs. machine plays our. *Wired News*. Retrieved December 16, 2006 from <http://www.wired.com/culture/lifestyle/news/2002/10/55839>.

Hillis, D. (1997, May 5). Can they feel your pain? *Newsweek*, 129, 57.

Hsu, F. (2002). *Behind Deep Blue: building the computer that defeated the world chess champion*. Princeton, NJ: Princeton University Press.

Hsu, F., Campbell, S., & Hoane, J. (1995). Deep Blue system overview. *Proceedings of the 9th international conference on Supercomputing* (pp 240-244). New York: ACM Press.

IBM's Deep Blue accepts challenge to compete in ultimate chess match with human champ Kasparov. (1995, May 30). [Press release from IBM Research]. Computer History Museum Archive. Retrieved December 12, 2006 from http://archive.computerhistory.org/projects/chess/related_materials/text/5-3%20and%205-4.IBM.Press_Release.Deep_Blue.May-30-1995/IBM.Press_Release.Deep_Blue.May-30-1995.062303043.sm.pdf.

Jayanti, V. (Director). (2003). *Game over: Kasparov and the machine*. [Documentary film]. United Kingdom: ThinkFilm.

Kasparov, G. (1997, May 26). IBM owes mankind a rematch. *Time*. 149, 66-67.

Kasparov, G. (1996, March 25). The day that I sensed a new kind of intelligence. *Time*. 147, 55.

- Korf, R. (1997). Does Deep-Blue use AI?. In R. Moris (Ed.), *Deep Blue versus Kasparov: the significance for artificial intelligence* (pp. 1-2). Menlo Park, CA: AAAI Press.
- Krauthammer, C. (1997, May 26). Be afraid: the meaning of Deep Blue's victory. *The Weekly Standard*. 2, 19-23.
- Krikke, J. (2007, January/February) The challenge of Go. *IEEE Intelligent Systems*. 22, 7-8.
- Krol, M. (1999 , March) Have we witnessed a real-life Turing Test?. *IEEE Computer*. 32, 27-30.
- Leithauser, B. (1995). *Penchants and places*. New York: Alfred A. Knopf.
- Levy, D., editor. (1988). *Computer chess compendium*. New York: Springer-Verlag.
- Levy, S. (1997, May 26). Garry sings the blues. *Newsweek*, 129, 84.
- Levy, S. (1997, May 19). Big Blue's hand of God. *Newsweek*, 129, 72.
- Levy, S. (1997, May 5). Man vs. Machine. *Newsweek*, 129, 50-56.
- Ligterink, G. (2006, October 27). Topalov: Elista still haunts my mind. *Chessbase News*. Retrieved April 14, 2007 from <http://www.chessbase.com/newsdetail.asp?newsid=3454>.
- Marsland, T. (n.d). *The anatomy of chess programs*. Retrieved December 13, 2006 from <http://www.cs.unimaas.nl/icga/games/chess/anatomy.php>.
- McCarthy, J. (2004, November 24). What is artificial intelligence?. Retrieved April 8, 2007 from <http://www-formal.stanford.edu/jmc/whatisai/whatisai.html>.
- McClain, D. (2007, April 8). As technology leaps ahead, concerns about cheating grow. *New York Times*.
- McClain, D. (2006, September 29). Bathroom dispute halts chess championship. *New York Times*.
- McClain, D. (2005, June 21). In chess, masters again fight machines. *New York Times*.
- McDermott, D. (2001). *Mind and Mechanism*. Cambridge, MA: The MIT Press.
- McDermott, D. (1997, May 14). Yes, computers can think. [Op-Ed]. *New York Times*.
- Mind over matter. (1997, May 10). [Editorial]. *New York Times*.

Muelle, T. (2005, December 12). Your move: how computer chess programs are changing the game. *The New Yorker*, 81, 62-71.

Nelson, S. (2006). *Steel drivin' man*. Oxford: Oxford University Press.

Newborn, M. (2003). *Deep Blue: an artificial intelligence milestone*. New York: Springer.

Newborn, M. (2000). Deep Blue's contribution to AI. *Annals of Mathematics and Artificial Intelligence*, 28, 27-30.

Newborn, M. (1997). *Kasparov versus Deep Blue: computer chess comes of age*. New York: Springer-Verlag.

Newborn, M. (n.d). *History of the chess table*. Retrieved October 18, 2006 from <http://www.research.ibm.com/deepblue/learn/html/e.8.5.html>.

Open letter from Feng-hsiung Hsu, one of the main programmers of Deep Blue. (n.d). *The Week in Chess Magazine*. London Chess Center. Retrieved October 3, 2006 from <http://www.chesscenter.com/twic/feng.html>.

Pachman, L. (1975). *Complete chess strategy*. Garden City, NY: Doubleday & Company, Inc.

Peterson, I. (1997, August 2). Silicon champions of the game. *Science News*, 172, 76-79.

Reddy, R. (1995, September) Grand challenges in AI. *ACM Computing Surveys*, 27, 310-303.

Reinfeld, F. (1958). *Chess in a nutshell*. Garden City, NY: Hanover House.

Reshevsky, S. and Reinfeld, F. (1947). *Learn chess fast*. Philadelphia: David McKay Company.

Rice, E. (1922). *The adding machine*. New York: Samuel French.

Ross, P. (2006, August 1). The expert mind. *Scientific American*, 259, 64-71.

Sato, T. *Message from Director-General*. Earth Simulator Center Retrieved January 25, 2007 from <http://www.es.jamstec.go.jp/index.en.html>.

Searle, J. (1984). *Minds, brains, and science*. Cambridge, MA: Harvard University Press.

Shannon, C.E. (1950, March). Programming a computer for playing chess. *Philosophical Magazine*, 41, 256-275.

Shenk, D. (2005). *The immortal game*. New York: Doubleday.

- Seirawan, Y. (1995). *Winning chess brilliancies*. Redmond, WA: Microsoft Press.
- Spicer, D. (2005, February 14). *Oral history of Feng-Hsiung Hsu*. Computer History Museum Archive. Retrieved November 26, 2006 from http://www.computerhistory.org/chess/related_materials/oral-history/hsu.oral_history.2005.102644995/index.php?iid=orl-43343cd40c2a1.
- Spicer, D. & Tashev, K. (2006, Spring) The quest to build a thinking machine: A History of Computer Chess. *Core 5.1*. Retrieved October 27, 2006 from http://www.computerhistory.org/core/articles/history_of_computer_chess.html.
- Stern, D., Herbrich, R. & Graepel, T. (2006). Bayesian pattern ranking for move prediction in the game of Go. *Proceedings of the 23rd International Conference on Machine Learning*, Pittsburgh, PA. Retrieved February 25, 2007 from www.icml2006.org/icml_documents/camera-ready/110_Bayesian_Pattern_Ran.pdf.
- Stork, D. (n.d). *The end of an era, the beginning of another? HAL, Deep Blue, and Kasparov*. Retrieved October 18, 2006, from <http://www.research.ibm.com/deepblue/learn/html/e.8.1.html>.
- Sullivan, P. (2004, July 30). Francis H.C. Crick, 88, dies; DNA discovery altered science. *Washington Post*.
- The next horizon: what lies ahead for Deep Blue*. (n.d). IBM Research. Retrieved October 17, 2006 from <http://www.research.ibm.com/deepblue/learn/html/e.6.html>.
- Thomson, E. (1997, May 13). Computer morale. [Letter to the editor]. *New York Times*.
- Turing, A. (1950). Computing machinery and intelligence. *Mind*, 59, 433-460. Retrieved January 24, 2007 from <http://loebner.net/Prizef/TuringArticle.html>.
- University of Alberta's GAMES Group. (2006, April 2). Retrieved January 26, 2007 from <http://www.cs.ualberta.ca/~games/>.
- Weber, B. (1997, May 12). Deep Blue stuns chess world. *Ottawa Citizen*.
- Weber, B. (1997, May 3). Second of 'panic time' aided nonhuman player. *New York Times*.
- Weber, B. (1996, February 19). Mean chess-playing computer tears at meaning of thought. *New York Times*.
- Wing, J. (2006, March). Computational thinking. *Communications of the ACM*. 49, 33-35.
- Winning ways. (2007, January 27). *The Economist*. 382, 80.

Wright, R. (1996, March 25). Can machines think? *Time*, 147, 50-56.

Yeager, C. & Janos, L. (1985). *Yeager: an autobiography*. New York: Bantam Books.

Interviews

Dr. Drew McDermott, professor of computer science at Yale University. October 17, 2006.
Via telephone.

Dr. Charles Leiserson, professor of electrical engineering and computer science at
Massachusetts Institute of Technology. November 11, 2006. In person.

Dr. Henry Lieberman, research scientist at Massachusetts Institute of Technology Media Lab.
December 7, 2007. In person.

Dr. David Stork, chief scientist at Ricoh Silicon Valley and associate professor of electrical
engineering and psychology at Stanford University. December 7, 2006. In person.

Dr. John Searle, professor of philosophy at University of California, Berkeley. January 17,
2007. In person.

Chris Garcia, assistant curator at the Computer History Museum (Mountain View, CA).
January 18, 2007. In person.

Dr. Hubert Dreyfus, professor of philosophy at University of California, Berkeley. January
19, 2007. In person.

Dr. Richard Korf, professor of computer science at University of California, Los Angeles.
February 13, 2007. Via telephone.

Don Dailey, Independent programmer and former member of Massachusetts Institute of
Technology computer chess team. February 22, 2007. Via telephone.