COMPUTER RECREATIONS

A Tinkertoy computer that plays tic-tac-toe

by A. K. Dewdney

"I first had that experience [universality of computation] before I went to school. There weren't any [computersl yet, but we had toy construction sets. One was called TinkerToy.... What's strange is that those spools and sticks are enough to make anything."

-MARVIN MINSKY,
in preface to LogoWorks

How many of us remember Tinkertoys, those down-home kits of colored wooden sticks and spools with holes in them? Amid our childhood constructions of towers or cranes, how many of us pondered the outer limits of the Tinkertoy world? Did we conceive of contraptions that reached the ceiling? Perhaps, but we lacked the kits or the time to make it

happen. Such a Tinkertoy fantasy took place several years ago when a student group from the Massachusetts Institute of Technology constructed a computer entirely (well, almost entirely) out of Tinkertoys!

From a distance the Tinkertoy computer resembles a childhood fantasy gone wild or, as one of the group members remarked, a spool-and-stick version of the "space slab" from the movie *2001: A Space Odyssey.* Unlike the alien monolith, the computer plays a mean game of tic-tac-toe. A Tinkertoy framework called the read head clicks and clacks its way down the front of the monolith At some point the clicking mysteriously stops; a "core piece" within the framework spins and then with a satisfying "kathunk"

indirectly kicks an "output duck," a bird-shaped construction. The output duck swings down from i perch so that its beak points at a number- which identifies the computer's next move in a game tic~tac-toe.
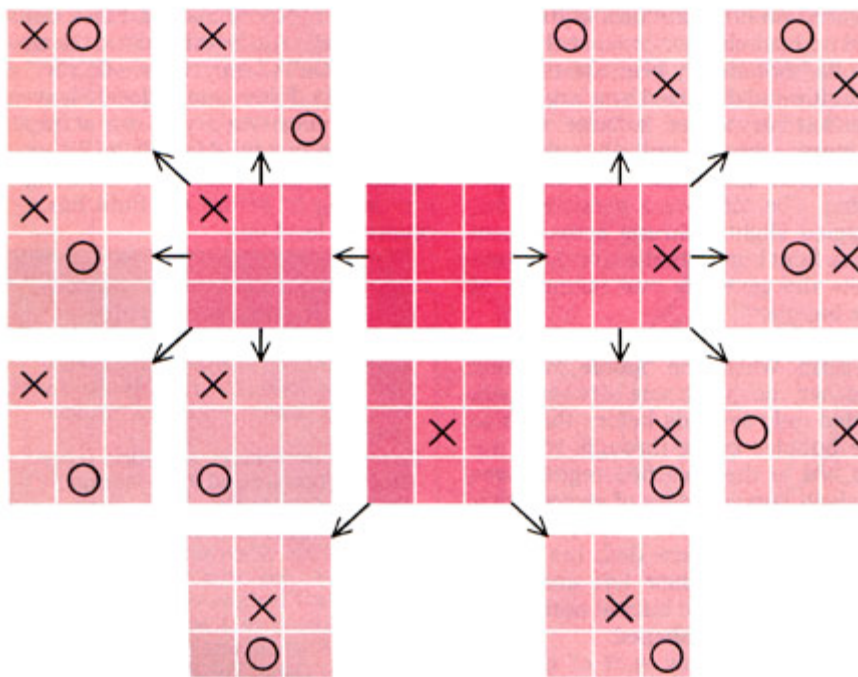
What precisely does the read head scan as it feels its way dow the monolith? Nothing less than rows of Tinkertoy "memory spindles" encoding all the critica combinations of X's and O's that might arise during a game [*see illustration on opposite page*]. Each spindle is a sequence of smooth spools connected axially by sticks and arranged in nine groups of three each, one group for each square of the tic-tac-toe board. The presence or absence o spools from a group indicates tha a corresponding square of the tic tac-toe board is vacant or is occupied by an X or O.

The Tinkertoy computer is not fully autornatic: a human operato must crank the read head up and down and must manage its input After the computer's opponent makes a move, the operator walk to the front of the machine to adjust the core piece inside the read head, registering the contestant's move. The operator then pulls on a string to cock the core piece for its impending whi of recognition. When it discover a memory that matches the curre state of the game, the core piece

The first three levels of the tic-tac-toe game tree

spins, and the computer indicates its move.

The best way to understand how the machine works in detail is to recount the story of its creation at the hands of the M.I.T. students: Erlyne Gee, Edward Hardebeck, Daniel Hillis, Margaret Minsky and brothers Barry and Brian Silverman. Most of the group has long since graduated and entered various computer professions. Perhaps the best-known team member is Hillis. He was the moving force behind Thinking Machines, Inc., which produces the well-known parallel supercomputer called the Connection Machine. (Perhaps Tinkertoys have something to teach us.)

In 1975, when Hillis and Brian Silverman were in their sophomore year, they participated in a class project to build something digital from Tinkertoys. The students sat down to play. One made an inverter—a logic device that converts a binary 1 signal to a 0 signal and conversely. Another made an OR gate; if either of the device's two input signals happened to be a 1, then the output would also be a 1. It quickly became clear to the students that Tinkertoys were "computation universal," the theoretical term for a set of components from which a fully program

mable computer can be constructed. Theoretical possibility was one thing, the practical demands of money and time another.

The demands were met in a rather roundabout manner through Hillis's interest in robots. From time to time he had mused openly about building a robot. Word of his idea somehow reached the ear of Harry Loucks, then director of the Mid-America Center in Hot Springs, Ark. Would the students like to construct a robot as a display in the center's museum? The students agreed in principle, but the project seemed too complicated. Just then the old Tinkertoy dream resurfaced. Would the center like a computer made out of Tinkertoys instead?

Hillis and company set out to assemble the first Tinkertoy computer in a laboratory at M.I.T. The first model, unlike its successor, was a bulky cube with sides about one meter long. It was impressively complicated. Packed with logic devices made entirely of wooden sticks and spools, the machine signaled its moves by waving nine flags from the top of the framework. The prototype Tinkertoy computer had to be taken apart for the trip to Hot Springs, and once it was reassembled on site, the machine never quite worked properly again. On the other hand, it did make an intriguing exhibit. (It is currently on display at the Computer Museum in Boston.)

In 1979 Loucks contacted the group again. Could they make a new Tinkertoy computer, one that worked? By this time Silverman was in Ottawa and Hillis in Boston, each pursuing a new career. Over the telephone Hillis and Silverman worked out an improved design. It was to be reliable, and that meant simple. They decided to lay out all the possible tic-tac-toe boards in a row and devise some kind of reading mechanism that would move from row to row until it found a pattern matching the current board. The very act of recognition could trigger a preset response.

While Hillis contemplated ways to represent tic-tac-toe boards with digital Tinkertoy components, Silverman analyzed the game. To appreciate the
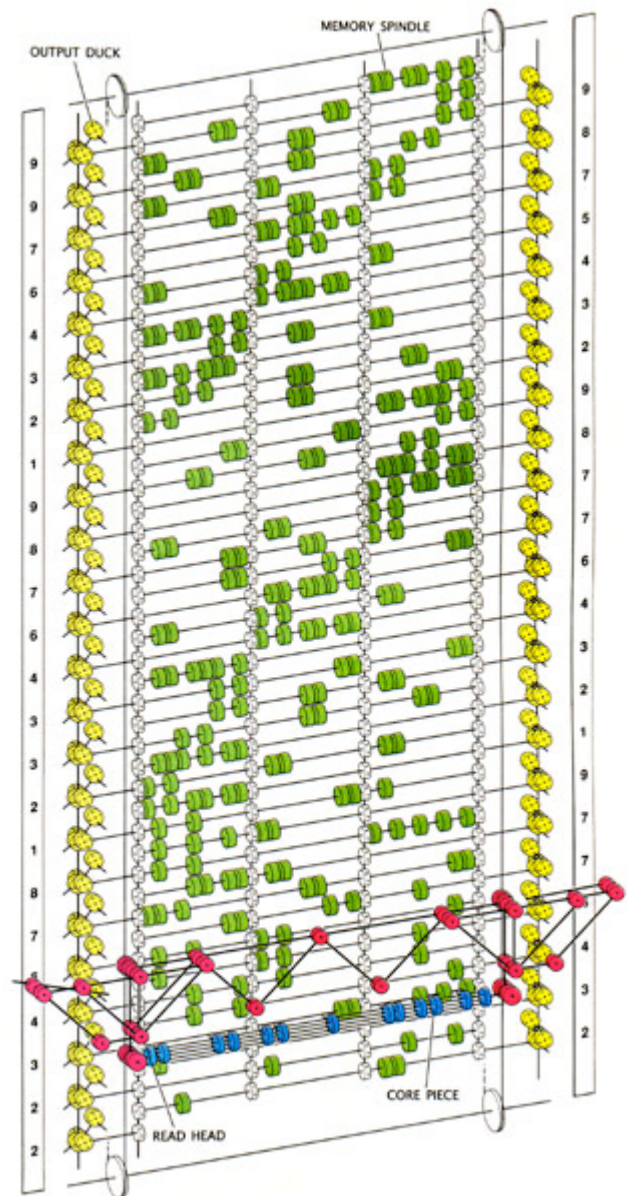
The Tinkertoy computer: ready for a game of tic-tac-toe

complexities involved even in this childhood pastime, readers might consult the game tree shown on the opposite page. In the middle of the tree sits the initial board, a three-by-three grid empty of X's and O's. From this initial board nine new ones can arise, depending on which of the nine squares X plays. The figure shows just three possibilities; the remaining six are rotated versions. Each of the three

boards at the second level gives rise to other cases. For example, the board in which X plays the center square and then another square results in two different boards. The other two boards at the second level each generate five new boards at the third level.

I pruned many branches from the tic-tac-toe tree by appealing to a symmetry argument: the excluded boards are merely rotations or reflections of the included ones. Symmetry seems simple to humans, but a computer must be programmed or wired to recognize it. In a world of Tinkertoy engineering, symmetry operations would require elaborate structures.

Silverman was dealing with a tree, therefore, that was many times larger than the fragment shown in the illustration. But perseverance paid off, especially when Silverman employed a computer program that analyzed the game of tic-tac-toe and discovered that a great many boards could be collapsed into one by a forced move. Suppose, for example, that two squares in a row contain O's and the third is blank. The

their spool-and-stick odyssey: 30 boxes of Tinkertoys, each containing 250 pieces. Some team members put together the supporting framework that would hold all 48 memory spindles. To explain precisely how the spindles were made, I must digress for a moment and describe the conventions employed by the team to encode tic-tac-toe positions.

First, the squares of a tic-tac-toe board were numbered as follows:

1 2 3
4 5 6
7 8 9

Then a memory spindle was divided conceptually into nine consecutive lengths in which information about the status of each tic-tac-toe square was stored from left to right.

Each length was further subdivided into three equal sections, one for each possible item one might find in a square: an X, an O or a blank. Each possibility was encoded by the

along the axis of the core piece in any of three possible positions: one for X, one for O and one for blank. The core piece could therefore store any possible tic-tac-toe board by virtue of the positions of its nine fingers as moved by the operator for each play by human or machine. In the illustration below fingers in the consecutive position 2,1, 2, 3,1, 2, 2, 2, 2 would represent the board shown.

If the current situation of play is stored in the core piece, does the Tinkertoy computer require any other memory? Could spool-and-stick logic devices be strung together to cogitate on the position and ultimately to signal a move? Well, yesbut such a Tinkertoy computer would be complicated and immense. The memory spindles eliminated the need for most of the computer's cogitation. All the Tinkertoy computer had to do was to look up the current board in the memory spindles. The only purpose of the search, naturally, was to decide what move to make.

A glance at the illustration on the preceding page makes it clear that each memory spindle was

contents of the remaining two rows are irrelevant since an opponent must fill the third square with an X or lose the game.

Silverman was delighted when he tallied up the final total of relevant boards: only 48. For each of them he noted the appropriate move by the machine. The surprisingly short list of possible board positions heartened Hillis. The group converged on Hot Springs, Silverman says, "with the list of 48 patterns and only a vague idea of how to interpret them mechanically."

(Readers who have a fanatical bentor are stranded in airline terminalsmay enjoy working out the game tree on a few sheets of paper. How long does it take, after all, to draw 48 tic-tac-toe patterns? Four symbols should help sort things out X O, blank and a dash for "don't care.")

Once settled in Hot Springs, the team assembled the raw material for

lack of a spool. For example, if an X happened to occupy a certain square, the memory spindle would have no spool in the first position, one spool in the second and one spool in the third. Similarly, a spool missing in the second position denoted an unplayed square, and one missing in the third position symbolized an O. Finally, if all three spools were missing, it meant that what occupied the square was irrelevant.

One can hardly mention the subject of memory spindles without bringing up the core piece, a thing of digital beauty. Here the Latin *digitus* came into its own, the construction resembling a kind of rotating claw with nine fingers. The core piece and a sample memory spindle are shown in the illustration below.

The core piece consisted of nine equal sections. Each had its own finger, a short stick protruding from the rim of a sliding spool. Within each section the finger couid be moved

accompanied by a number writter on a paper strip hanging next to it output duck. These numbers were the machine's responses. As the read head clicks down the rows o spindles, the core piece wants to turn but cannot as long as at least one memory-spindle spool blocks one of the core piece's nine finger Only when the read head falls adjacent to the spindle that match the current board do all nine finge miss. Then the core piece whirls.

By a mechanism that would do Rube Goldberg proud, a stick protruding from the end of the co piece engages another stick connected to the output duck. The spinning core piece thus kicks the duck off its perch to peck at a number writ large on the paper strip.

Computer purists will ask whethe the Tinkertoy contraption really deserves the title "computer." It is not, to
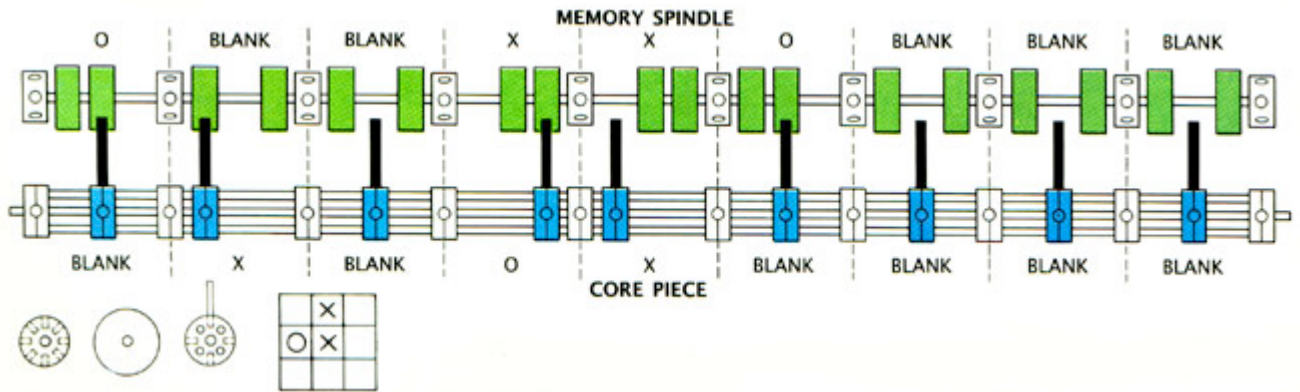
A memory spindle, which encodes the X's and O's of a tic-tac-toe board, prevents the core piece from turning.

be sure, programmable in the usual sense: one cannot sit at a keyboard and type in a program for it to follow. On the other hand, one could certainly change the memory spindles, albeit with some difficulty, and thus reprogram the computer for other games. Imagine a Tinkertoy device that plays *go-moku narabe* (a game played on an 11-by-11 board in which one player tries to place five black stones in a row while preventing an opponent from creating a row of five white stones). A Tinkertoy computer programmed for *go-moku narabe*, however, would probably tower into the stratosphere.

The real lesson the Tinkertoy computer can teach us resides in a rather amazing feature of
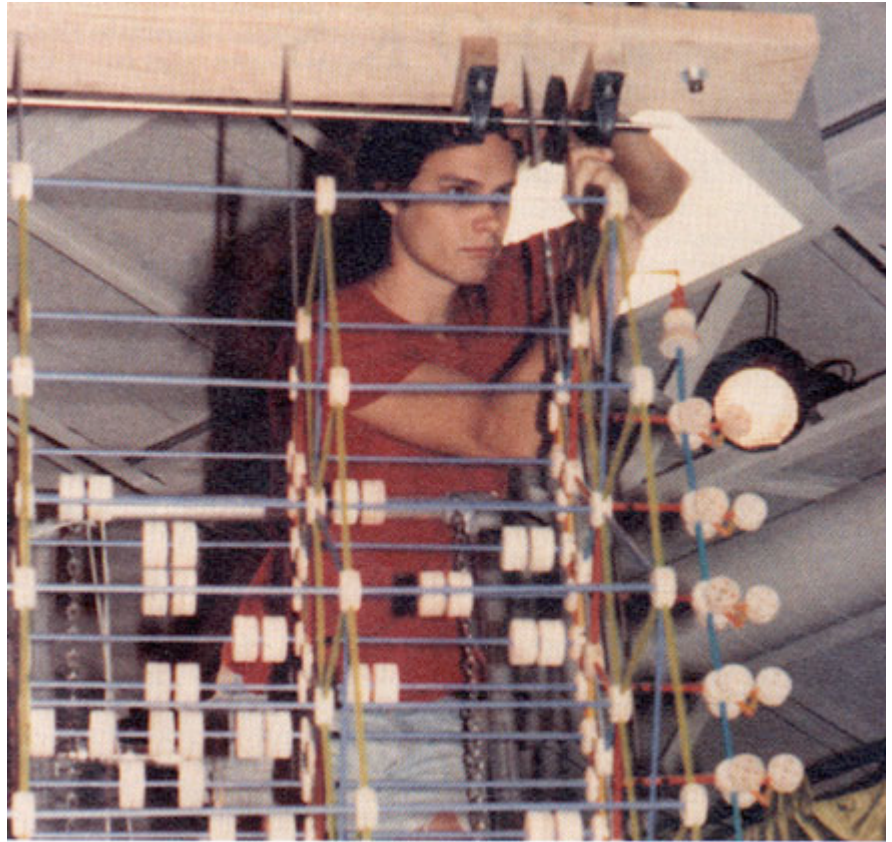
Edward Hardebeck helps to assemble the Tinkertoy computer

digital computation: at the very root of a computation lies merely an essential flow of information. The computer hardware itself can take on many forms and designs. One could build perfectly accurate computers not only of Tinkertoys but also of bamboo poles, ropes and pulleys [see "Computer Recreations," SCIENTIFIC AMERICAN, April, 1988], plastic tubes and watereven, strange to think, electrical components. The lastnamed are preferred, of course, because of their speed. It would be shortsighted indeed to sneer at a computer made of Tinkertoys merely because it is not electronic. After all, even electrons and wires may not be the best materials for quick computer processing. Photons and fibers are gaining on them fast.

Actually, Tinkertoys are well suited to digital computing. For example, the memory spindles use a binary principle: the presence or absence of spools denotes the status of a particular square on a tic-tac-toe board. The core piece exhibits digital logic: it can turn only if all its fingers miss corresponding spools on a memory spindle. Such an operation is called "and." One can trace the logic for the core piece in the illustration on the opposite page: if the first spool is absent from the first section of the memory spindle and the second spool is absent from the second section and the third spool is absent

motive power to the awesome machine for its next move. Finally, the very joints of sticks and spools were made firm by glue and escutcheon pinspieces of hardware that commonly hold commemorative plaques in place. The team inserted the pins in holes drilled through the rim of the spool down to the original, central hole and through its sticka task they had to repeat more than 1,000 times. (When Hillis walked into a hardware store to obtain several thousand escutcheon pins, the manager looked bewildered. "We have," Hillis said with a straight face, "a lot of escutcheons.")

The Tinkertoy tic-tac-toe computer suffered the fate of most museum exhibits. It was taken apart and crated. It sits in storage at the Mid-America Center, waiting to reemerge, perhaps, into the limelight. It may yet click its way to victory after victory, a monument to the Tinkertoy dreams of childhood.

Well into my sixth year of "Computer Recreations," I am as painfully aware as ever that there are many things the department cannot do. It cannot, for example, teach readers how to program, nor can it mention the hundreds of fascinating programs and the many computer stories and ideas that readers

send in, given the limitations of space and time. It took six years to discover remedy to these and other needs: a newsletter. Its name is Algorithm: Th Personal Programming Newsletter, an the first issue is now available.

The newsletter will appear bimonthly It seeks to pack a lot of information between its covers. In particular it wil have two columns for people who lik to program. One will be for beginners and the other for more experienced practitioners. A "bulletin board" at th back of the newsletter will make som of the world's underground programs public for the first time. Letters, stateof-the-art-icles and speculative pieces will aim to lead the mind into unexplored territory. I shall be delighted to send a free sample of the first issue to anyone who writes to me in care of Scientific American.

FURTHER READING

CHARLES BABBAGE: ON THE PRINCIPLES AND DEVELOPMEN OF THE CALCULATOR AND OTHER SEMINAL WRITINGS. Charles Babbage et al. Edited by Phil Morrison and Emily Morrison. Dover Publications, 1961.

OPTICAL COMPUTING. Special issue edited by Sing H. Lee and Ravindra A. Athale in *Optical Engineering*, Vol. 28, No. 4; April, 1989.

from the third section *and* so on-only if all nine conditions are met will the core piece turn. The beauty of the Tinkertoy computer is not just its clever mechanics but its subtle logic.

Tinkertoy purists will be happy to know that the M.I.T. students stuck to the original wooden sticks and spools with only a few exceptions. An occasional aluminum rod runs through the framework to strengthen it. Two wire cables, an axle and a crank transmit

http://www.rci.rutgers.edu/~cfs/472_html/Intro/IntroToc.html