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MATHEMATICAL GAMES

Concerning the game of nim and its mathematical analysis

by Martin Gardner

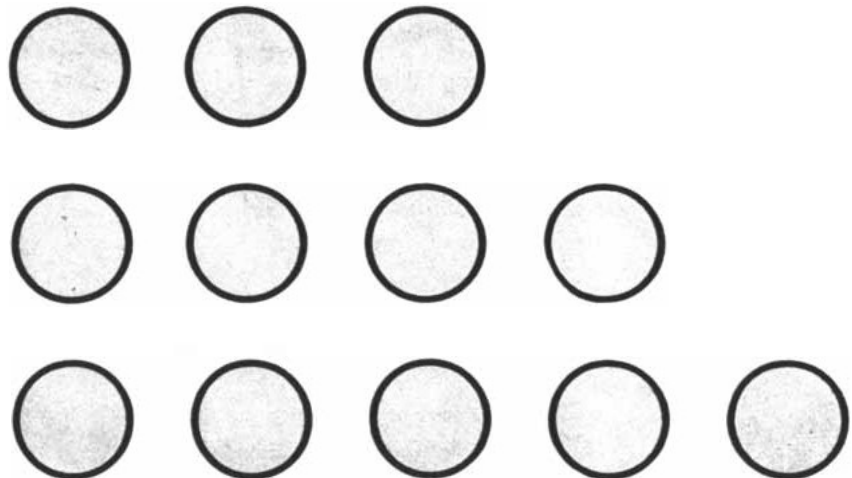
One of the oldest and most engaging of all two-person mathematical games is known today as nim. Possibly Chinese in origin, it is sometimes played by children with bits of paper, and by adults with pennies on the counter of a bar. In the most popular version of the game 12 pennies are arranged in three horizontal rows as shown in the illustration at the bottom of this page.

The rules are simple. The players alternate in removing one or more coins from any one of the three rows. Whoever takes the last penny wins. The game can also be played in reverse: whoever takes the last penny loses. A good gamester soon discovers that in either form of the game he can always win if one of his moves leaves two rows with more than one penny in a row and the same number in each; or if the move leaves one penny in one row, two pennies in a second row and three in a third. The first player has a certain win if on his first move he takes two pennies from the top row and thereafter plays "rationally."

There is nothing startling about the foregoing analysis, but around the turn of the century an astonishing discovery was made about the game. It was found that it could be generalized to any number of rows with any number of counters in each, and that an absurdly simple strategy, using binary numbers, would enable anyone to play a perfect game. A full analysis and proof was first published in 1901 by Charles Leonard Bouton, associate professor of mathematics at Harvard University. It was Bouton, incidentally, who named the game nim, presumably after the archaic English verb meaning to take away or steal.

In Bouton's terminology every combination of counters in the generalized game is either "safe" or "unsafe." If the position left by a player after his move guarantees a win for that player, the position is called safe. Otherwise it is unsafe. Thus in the "3, 4, 5" game previously described the first player leaves a safe position by taking two pennies from the top row. Every unsafe position can be made safe by a proper move. Every safe position is made unsafe by any move. To play rationally, therefore, a player must move so that every unsafe position left to him is changed to a safe position.

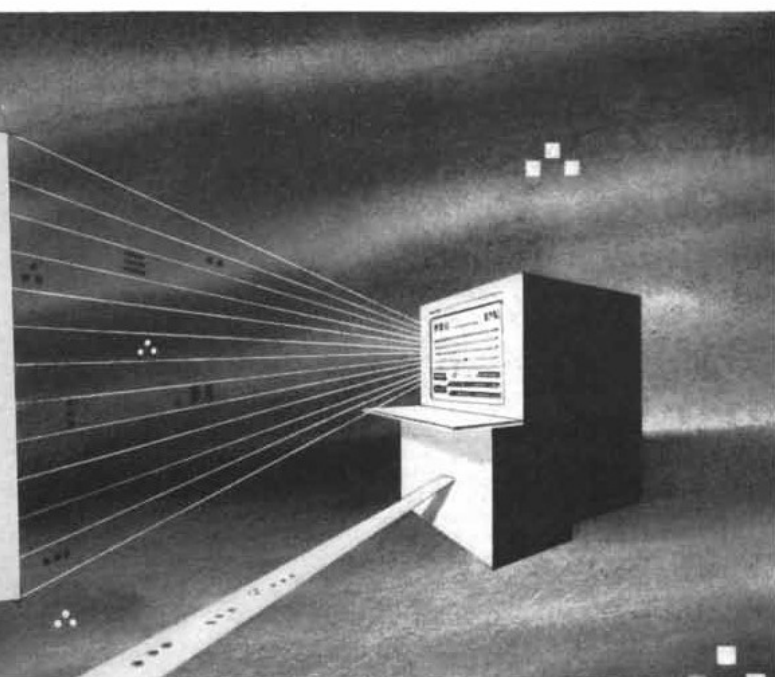
To determine whether a position is



Twelve counters are arranged for a "3, 4, 5" game of nim

Mechanism Discovered in the Brain Which Unlocks Stream of Consciousness Record

By WILLIAM L. LAURENCE
By the method of using...
considering the area of...
the brain...
the new area in the cerebral cortex...



TITLE: MECHANISM DISCOVERED IN THE BRAIN WHICH UNLOCKS STREAM OF CONSCIOUSNESS RECORD
SOURCE: NEW YORK TIMES, NOVEMBER 24, 1957
AUTHOR: WILLIAM L. LAURENCE
AUTO-ABSTRACT: AT THE ANNUAL AUTUMN MEETING OF THE NATIONAL ACADEMY OF SCIENCES, DR. WILDER PENFIELD, DIRECTOR OF THE MONTREAL NEUROLOGICAL INSTITUTE AND ONE OF THE WORLDS LEADING AUTHORITIES ON BRAIN FUNCTION, TOLD A FASCINATED AUDIENCE OF LEADING SCIENTISTS IN ALL FIELDS ABOUT HIS DISCOVERY, BY STIMULATING THE BRAIN OF HUMAN PATIENTS WITH TINY ELECTRICAL CURRENTS, OF A NEW AREA IN THE CEREBRAL CORTEX TO WHICH UNTIL NOW NO FUNCTION HAD BEEN ASSIGNED.
ONE MAY ASSUME THAT AT THE TIME OF THE ORIGINAL EXPERIENCE, ELECTRICAL POTENTIALS PASSED THROUGH THE NERVE CELLS AND NERVE CONNECTIONS OF A RECORDING MECHANISM IN A SPECIFIC PATTERNED SEQUENCE, AND THAT SOME FORM OF PERMANENT FACILITATION PRESERVES THAT SEQUENCE SO THAT THE RECORD CAN BE PLAYED AT A LATER TIME IN A MANNER ANALOGOUS TO THE REPLAYING OF A WIRE OR TAPE RECORDER.

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This research experiment demonstrated the feasibility of automatic abstracting. By extending the current techniques, it may be possible to scan the whole of printed knowledge on a given subject and to make "auto-abstracts" of articles in an incredibly short time. This new exploration may assist in breaking down the barriers imposed by the current mass of printed material between the researcher and the further development of his ideas.



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safe or unsafe, the numbers for each row are written in binary notation. If each column adds up to zero or an even number, then the position is safe. Otherwise it is not.

There is nothing mysterious about the binary notation. It is merely a way of writing numbers by sums of the powers of two. The chart on this page shows the binary equivalents of the numbers 1 through 20. You will note that each column, as you move from right to left, is headed by a successively higher power of two. Thus the binary number 10101 tells us to add 16 to 4 to 1, giving us 21 as its equivalent in the decimal system, based on the powers of 10. To apply the binary analysis to the 3, 4, 5 starting position of nim, we first record the rows in binary notation as follows:

	4	2	1
3	1	1	
4	1	0	0
5	1	0	1
Totals	2	1	2

The middle column adds up to 1, an odd number, telling us that the combination is unsafe. It can therefore be made safe by the first player. He does so, as explained, by taking two pennies from the top row. This changes the top binary number to 1, thereby eliminating the odd number from the column totals. The reader will discover by trying other first moves that this is the only one which makes the position safe.

An easy way to analyze any position, provided there are no more than 31 counters in one row, is to use the fingers of your left hand as a binary computer. Suppose the game begins with rows of 7, 13, 24 and 30 counters. You are the first player. Is the position safe or unsafe? Extend all five fingers of your left hand, palm toward you. The thumb registers units in the 16 column; the index finger, those in the 8 column; the middle finger, the 4 column; the ring finger, the 2 column; the little finger, the 1 column. To feed 7 to your computer, first bend down the finger representing the largest power of 2 that will go into 7. It is 4, so you bend your middle finger. Continue adding powers of two, moving to the right across your hand, until the total is 7. This is of course reached by bending the middle, ring and little fingers. The remaining three numbers—13, 24 and 30—are fed to your computer in exactly the same way except that any bent finger involved in a number is raised instead of lowered.

Regardless of how many rows there are in the game, if you finish this pro-

	16	8	4	2	1
1					1
2				1	0
3				1	1
4			1	0	0
5			1	0	1
6			1	1	0
7			1	1	1
8		1	0	0	0
9		1	0	0	1
10		1	0	1	0
11		1	0	1	1
12		1	1	0	0
13		1	1	0	1
14		1	1	1	0
15		1	1	1	1
16	1	0	0	0	0
17	1	0	0	0	1
18	1	0	0	1	0
19	1	0	0	1	1
20	1	0	1	0	0

Table of binary numbers to analyze nim

cedure with all your fingers raised, then the position is safe. This means that your move is sure to make it unsafe, and that you are certain to lose against any player who knows as much about nim as you do. In this example, however, you finish with first and second fingers bent, telling you that the position is unsafe, and that you can win if you make a proper move. Because there are many more unsafe combinations than safe ones, the odds greatly favor the first player when the starting position is determined at random.

Now that you know that 7, 13, 24, 30 is unsafe, how do you find a move that will make it safe? This is difficult to do on your fingers, so it is best to write



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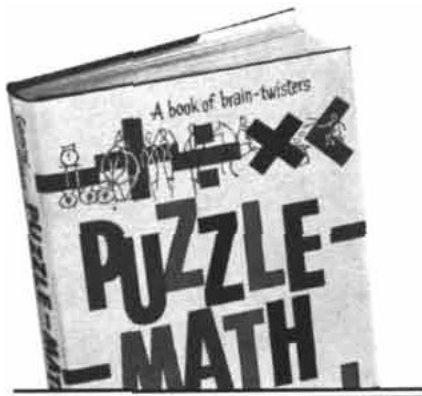
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down the four binary numbers as follows:

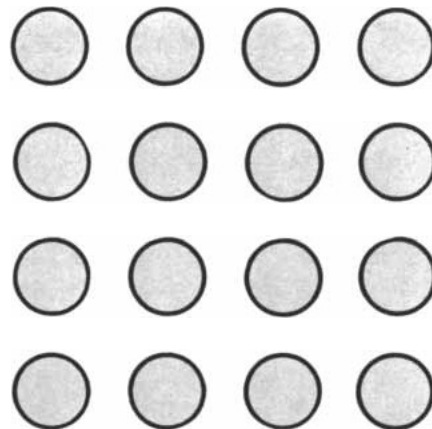
	16	8	4	2	1
7				1	1
13			1	1	0
24	1	1	0	0	0
30	1	1	1	1	0
Totals	2	3	3	2	2

Note the column farthest to the left that adds up to an odd number. Any row with a unit in this column can be altered to make the position safe. Suppose you wish to remove a counter or counters from the second row. Change the first unit to 0, then adjust the remaining figures on the right so that no column will add up to an odd number. The only way to do this is to change the second binary number to 1. In other words, you remove all counters except one from the second row. The other two winning moves would be to take four from the third row or 12 from the last row.

It is helpful to remember that you can always win if you leave two rows with the same number of counters in each. From then on, simply move each time to keep the rows equal. This rule, as well as the preceding binary analysis, is for the normal game in which you win by taking the last counter. Happily only a trivial alteration is required to adapt this strategy to the reverse game. When the reverse game reaches a point (as it must) at which only one row has more than one counter, you must take either all or all but one counter from that row so as to leave an odd number of one-unit rows. Thus if the board shows 1, 1, 1, 3, you take all of the last row. If it shows 1, 1, 1, 1, 8, you take seven from the last row. This modification of strategy occurs only on your final move, when it is easy to see how to win.

Since digital computers operate on the binary system, it is not difficult to program such a computer to play a perfect game of nim, or to build a special machine for this purpose. Edward U. Condon, the former director of the National Bureau of Standards who is now at Washington University of St. Louis, was a co-inventor of the first such machine. Patented in 1940 as the Nimatron, it was built by the Westinghouse Electric Corporation and exhibited in the Westinghouse building at the New York World's Fair. It played 100,000 games and won 90,000. Most of its defeats were administered by attendants demonstrating to skeptical spectators that the machine could be beaten.

In 1941 a vastly improved nim-playing machine was designed by Raymond



A variation of nim called Tac Tix

M. Redheffer, now assistant professor of mathematics at the University of California at Los Angeles. Redheffer's machine has the same capacity as Condon's (four rows with as many as seven counters in each), but where Nimatron weighed a ton and required costly relays, Redheffer's machine weighs five pounds and uses only four rotary switches. More recently a nim-playing robot called Nimrod was exhibited at the Festival of Britain in 1951 and later at the Berlin Trade Fair. According to one newspaper account, the machine was so popular in Berlin that visitors "entirely ignored a bar at the far end of the room where free drinks were available, and it was necessary to call out special police to control the crowds. The machine became even more popular after it had defeated the economics minister, Dr. Erhard, in three games."

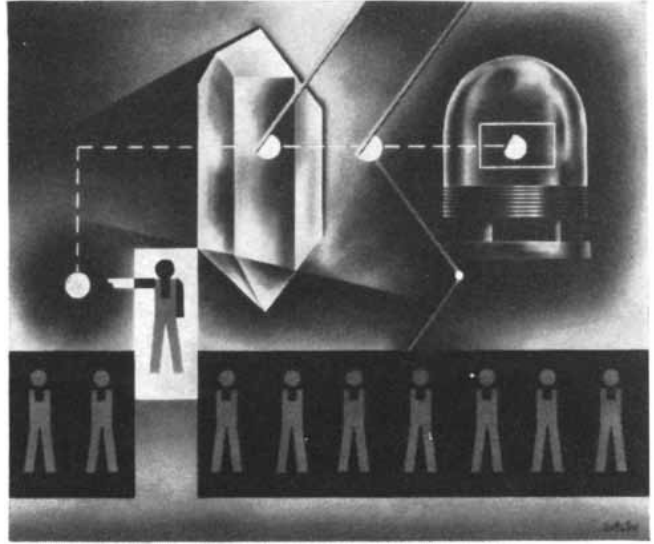
Several interesting variations of nim have been fully analyzed. To my mind the most exciting variation, and one that has not yet been analyzed, was invented about 10 years ago by Piet Hein of Copenhagen. Hein is the inventor of Hex, a topological game discussed in this department for July, 1957.

In Hein's version, called Tac Tix in English-speaking countries and Bulo in Denmark, the counters are arranged in square formation as shown at the top of this page. Players alternately take counters, but they may be removed from any horizontal or vertical row. They must always be adjoining counters with no gaps between them. For example, if the first player took the two middle counters in the top row, his opponent could not take the remaining counters in one move.

Tac Tix must be played in reverse form (the player who takes the last counter loses) because of a simple strategy which renders the normal game



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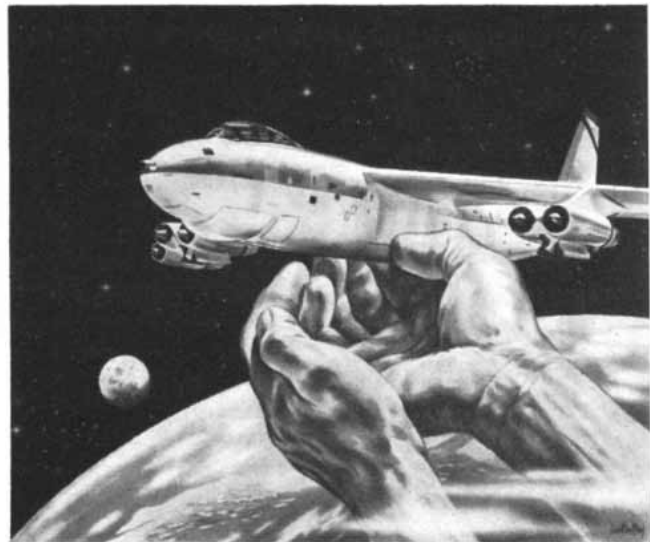
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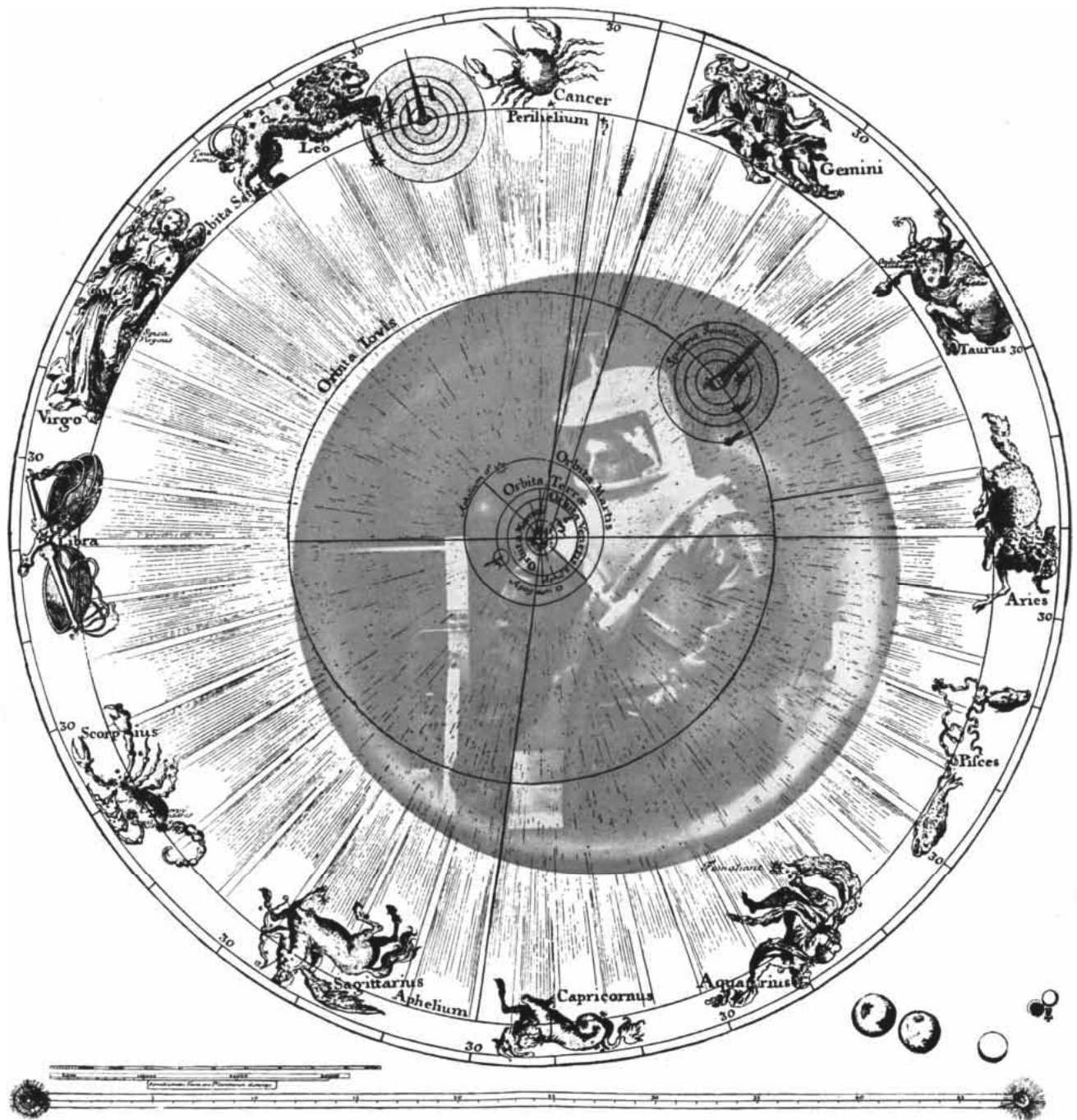
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trivial. On squares with an odd number of counters on each side the first player wins by taking the center counter and then playing symmetrically opposite his opponent. On squares with an even number of counters on each side the second player wins by playing symmetrically from the outset. No comparable strategy is known for playing the reverse game, although it is not difficult to show that on a 3×3 board the first player can win by taking the center counter or a corner counter, or all of a central row or column.

The clever principle behind Tac Tix, that of intersecting sets of counters, has been applied by Hein to many other two- and three-dimensional configurations. The game can be played, for example, on triangular and hexagonal boards, or by placing the counters on the vertices and intersections of a pentagram or hexagram. Intersections of closed curves may also be used; here all counters lying on the same curve are regarded as being in the same "row." The square form, however, combines the simplest configuration with maximum strategic complexity. It is difficult enough to analyze even in the elementary 4×4 form, and of course as the squares increase in size the game's complexity rapidly accelerates. Perhaps some industrious reader can answer the tantalizing question: Who has a win on the 4×4 reverse game, the first or second player?

Among analyzed variations of nim one proposed in 1910 by the American mathematician Eliakim H. Moore is of special interest. The rules are the same as they are for regular nim except that players are permitted to take from any number of rows not exceeding a designated number k . Surprisingly the same binary analysis holds, provided a safe position is defined as one in which every column of the binary numbers totals a number evenly divisible by k plus 1.

Many readers have improved upon the answers, given in this department for December, to the problems published here in November. It develops that not only six but also seven cigarettes can be so placed that each touches all the others; that there are a large number of equally simple solutions to the match problem; and that there are procedures by which the efficient electrician can label any number of wires (except two) in one round trip between top floor and basement. In the drawing for the sphere problem, the six-inch hole was incorrectly labeled, but the text should make the solution clear.

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