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# MATHEMATICAL GAMES

*Some diverting mathematical board games,  
and the answers to last month's problems*

by Martin Gardner

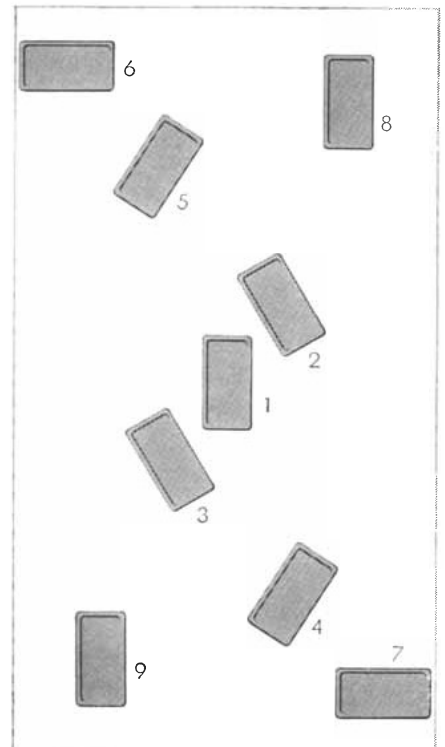
**M**athematical board games such as ticktacktoe, checkers, chess and go are contests between two players that (1) must end after a finite number of moves, (2) have no random elements introduced by devices such as dice and cards, (3) are played in such a way that both players see all the moves. If a game is of this type and each player plays "rationally"—that is, according to his best strategy—then the outcome is predetermined. It will be either a draw or a certain win for the player who makes the first move or the player who makes the second move. This month we shall first consider two simple games for which winning strategies are known, then a popular board game for which a winning strategy has just been discovered and a class of board games not yet analyzed.

Many simple games in which pieces are placed on or removed from a board lend themselves to what is called a symmetry strategy. A classic example is the game in which two players take turns placing a domino anywhere on a rectangular board. Each domino must be put down flat, within the border of the rectangle and without moving a previously placed piece. There are enough dominoes to cover the board completely when the pieces are packed side by side. The player who puts down the last domino wins. The game cannot end in a draw, so if both sides play rationally, who is sure to win? The answer is the player who puts down the first domino. His strategy is to place the first domino exactly at the center of the board [see illustration on this page] and thereafter to match his opponent's plays by playing symmetrically opposite as shown. It is obvious that whenever the second player finds an open spot, there will always be an open spot to pair with it.

The same strategy applies to any type of flat piece that retains the same shape when it is given a rotation of 180 de-

grees. For example, the strategy will work if the pieces are Greek crosses; it will not work if they have the shape, say, of the letter T. Will it work if cigars are used as pieces? Yes, but because of the difference in shape between the ends the first cigar must be balanced upright on its flat end! It is easy to invent new games of this sort, in which pieces of different shapes are alternately placed on variously patterned boards according to prescribed rules. In some cases a symmetry strategy provides a win for the first or second player; in other cases no such strategies are possible.

A different type of symmetry play wins the following game. Any number of coins are arranged in a circle on the table, each coin touching two of its neighbors. Players alternately remove either one coin or two touching coins. The player who takes the last coin wins.



*A domino board game*



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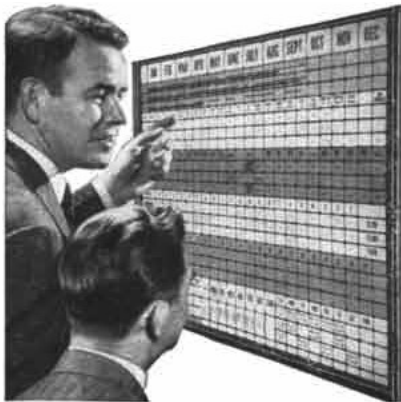
- (1) "C" axis parallel to cylinder axis:  
 $\frac{1}{4}$ " x  $1\frac{1}{2}$ ",  $\frac{1}{4}$ " x 2",  $\frac{1}{4}$ " x  $2\frac{1}{2}$ ", .200" x 2",  $\frac{1}{4}$ " x 3".
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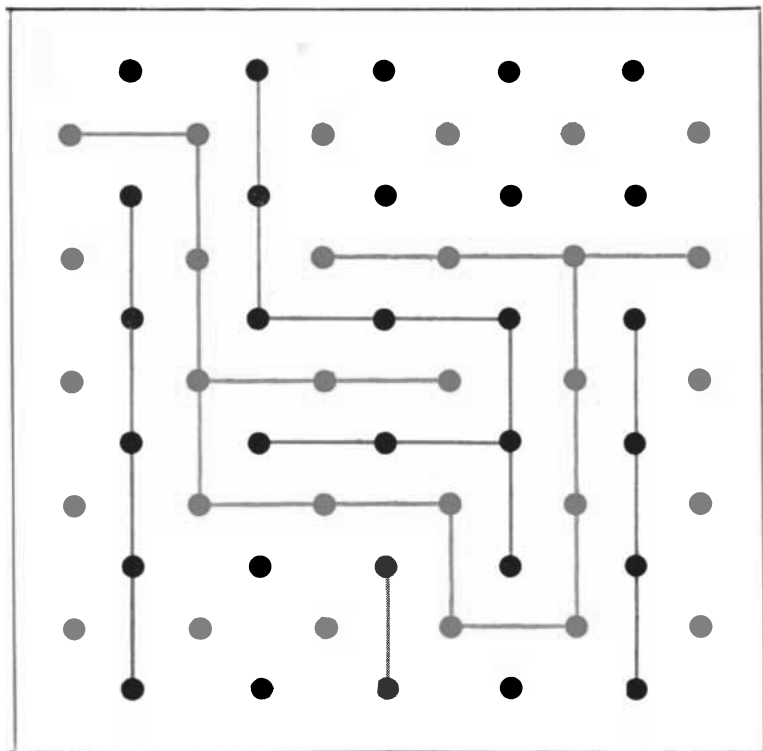
In this case it is the player who makes the second move who can always win. After the player who makes the first move has taken away one or two coins, the remaining coins form a curved chain with two ends. If this chain contains an odd number of coins, the player who makes the second move takes the center coin. If it contains an even number, he takes the two center coins. In both cases he leaves two separate chains of equal length. From this point on, whatever his opponent takes from one chain, he duplicates the move by taking one or two coins from the other chain.

Both this and the preceding strategy are examples of what game theorists sometimes call a pairing strategy: a strategy in which the plays are arranged (not necessarily in symmetrical fashion) in pairs. The optimal strategy consists of playing one member of the pair whenever the opponent plays the other member. A striking example of a pairing strategy is provided by the topological game of Bridg-it, placed on the market last year and now a popular game with children. The reader may remember that Bridg-it was introduced by this department in October, 1958, as "the game of Gale"; it was devised by David Gale, a mathematician at Brown University.

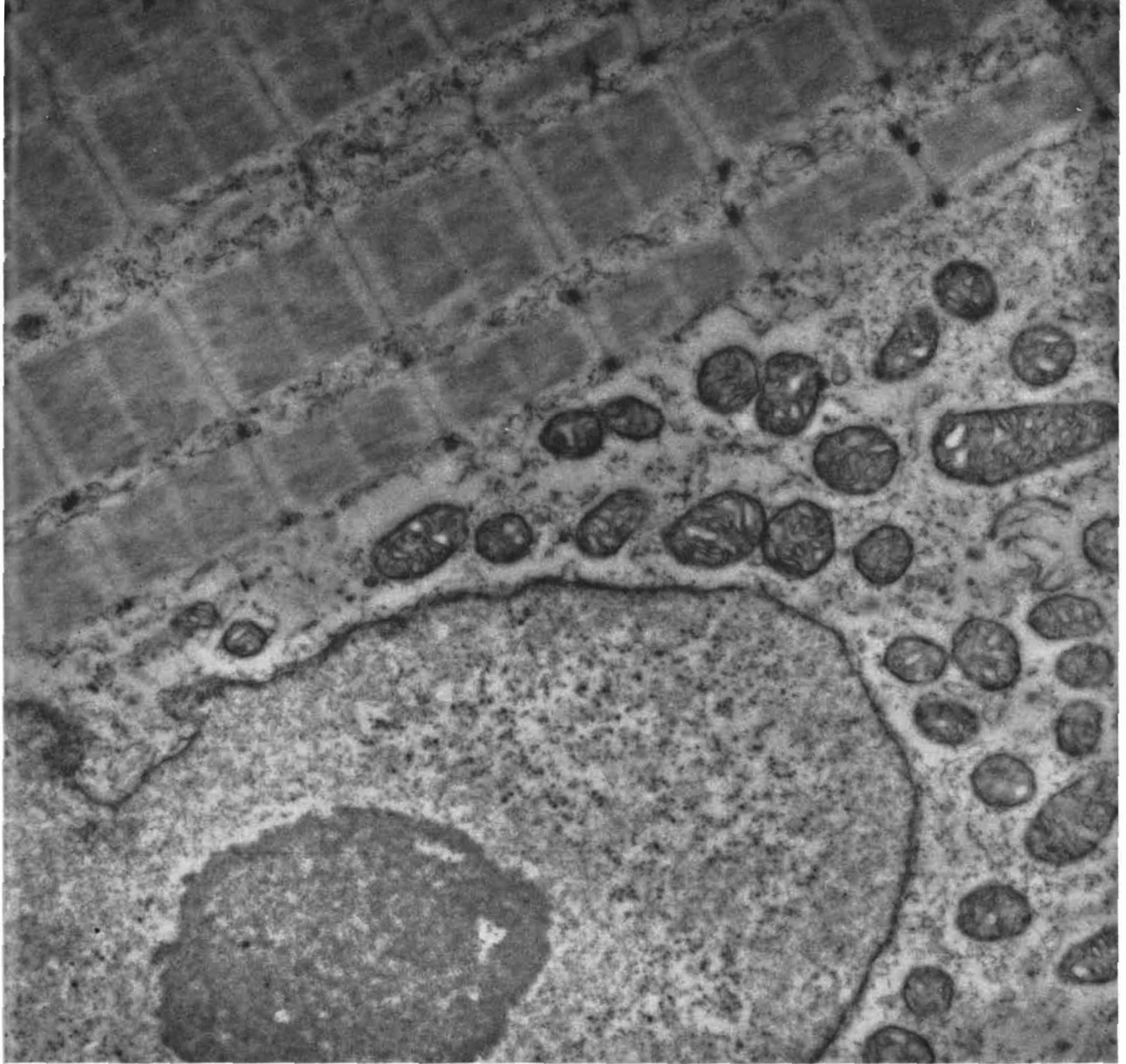
A Bridg-it board is shown in the illustration at the bottom of this page. If it is played on paper, one player uses a black

pencil for drawing a straight line to connect any pair of adjacent black spots, horizontally or vertically but not diagonally. The other player uses a red pencil for similarly joining pairs of red spots. Players take turns drawing lines. No line can cross another. The winner is the first player to form a connected path joining the two opposite sides of the board that are his color. (The commercial Bridg-it board has raised spots and small colored plastic bridges that are placed between spots.) For many years a proof has been known that there is a winning strategy for the player who makes the first move, but not until early this year was an actual strategy discovered.

It was Oliver Gross, a games expert in the mathematics department of the Rand Corporation, who cracked the game. When I learned of his discovery, I wrote immediately for details, expecting to receive a long, involved analysis that might prove too technical for this department. To my astonishment the explanation consisted of nothing more than the diagram reproduced on page 152 and the following two sentences: Make the first play as indicated by the gray line at lower left in the diagram. Thereafter whenever your opponent's play crosses the end of a dotted line, play by crossing the other end of the same line. This ingenious pairing strategy guarantees a



A finished game of Bridg-it. Red has won



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win for the first player, though not necessarily in the fewest moves. Gross describes his strategy as "democratic" in the sense that "it plays stupidly against a stupid opponent, shrewdly against a shrewd one, but wins regardless." This is not the only pairing strategy that Gross discovered, but he picked this one because of its regularity and the ease with which it can be extended to a Bridg-it board of any size.

Note that in the diagram no plays are indicated along the edges of the board. Such plays are allowed by the rules of Bridg-it (in fact, plays of this type are shown on the cover of the box), but there is no point in making such a move, because it can contribute nothing to winning the game. If in the course of playing the winning strategy your opponent throws away a play by making an edge move, you can counter with an edge move of your own. Or, if you prefer, you can play *anywhere* on the board. If at some point later in the game this random move is demanded by the strategy, you simply play somewhere else. Having an extra play on the board is sometimes an asset, never a liability. Of course, now that a winning strategy for the first player is known, Bridg-it ceases to be of interest except to players who have not yet heard the news.

Many board games with relatively

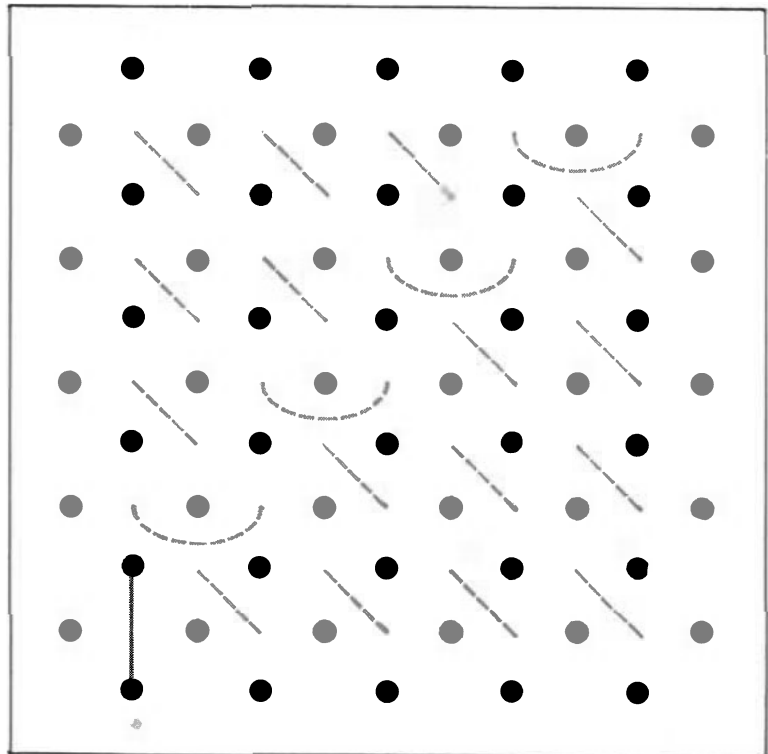
simple rules have defied all attempts at mathematical analysis. An example is provided by the family of games that derives from halma, a game widely played in England late in the 19th century. "The normal English way," wrote George Bernard Shaw in 1898, is "to sit in separate families in separate rooms in separate houses, each person silently occupied with a book, a paper, or a game of halma..." (This quotation is given in *The New Complete Hoyle*, by Albert H. Morehead, Richard L. Frey and Geoffrey Mott-Smith.)

The original halma (the name is a Greek word for "leap") was played on a checkerboard with 16 squares to a side, but the basic mode of play was soon extended to other boards of varying size and shape. The game known today as Chinese checkers is one of the many later varieties of halma. I shall explain here only a simplified version, which can be played on the familiar eight-by-eight checkerboard and which leads to an entertaining solitaire puzzle that is still unsolved.

The game begins with the checkers in the standard starting position for a checker game. Moves are the same as in checkers, with these exceptions:

1. No jumped pieces are removed.

2. A checker may jump men of either color.



Oliver Gross's pairing strategy for winning at Bridg-it

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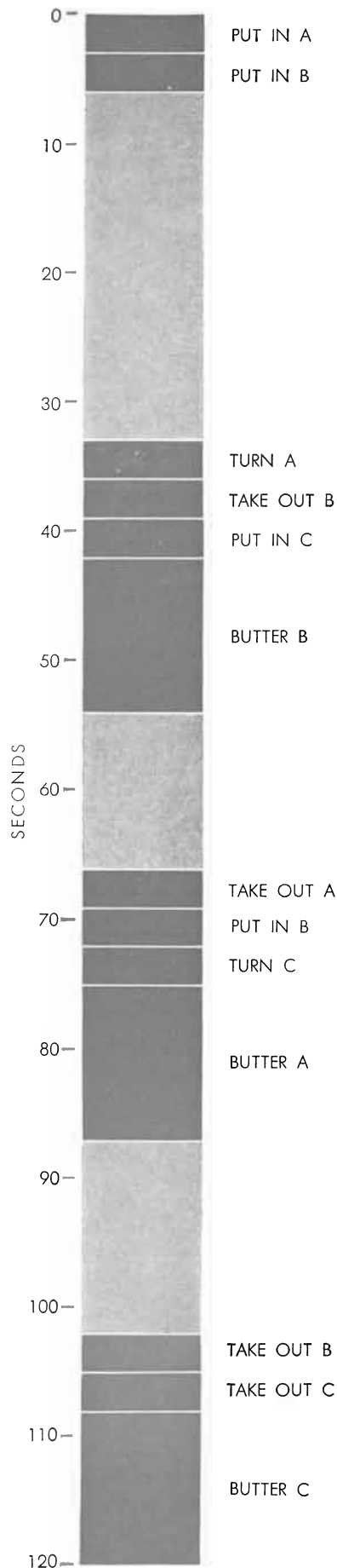
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Solution to the toaster puzzle

3. Backward moves and jumps are permitted.

A chain of unbroken jumps may be made over men of both colors, but one is not allowed to combine jumps with a nonjump move. The object of the game for each player is to occupy his opponent's starting position. The first to do so is the winner. A player also wins if the game reaches a situation in which his opponent is unable to move.

Some notion of how difficult it is to analyze games of the halma type can be had by working on the following puzzle, first called to my attention by Octave Levenspiel. Arrange 12 checkers in the usual starting positions on the black squares of the first three rows of checkerboard. The rest of the board is empty. In how few halma plays can you transport these men to the three rows on the opposite side of the board? A "play" is defined as either a diagonal checker move, forward or back, to a neighboring black square; or a jump over one or more men. An unbroken jump may include forward and backward leaps and is counted as a single play. As in halma, it is not compulsory to jump when jumps are available, and a series of unbroken jumps may be terminated wherever desired even though more jumps are possible.

Although this problem is familiar to many puzzlists throughout the world, it has not to my knowledge ever received a final answer. May I call on readers of this department for help? If the reader will send me the shortest solution he can obtain, I shall discuss in the October issue the best solutions received. It will not be possible to acknowledge these letters, but I shall appreciate getting them, and it will be instructive to see how short a record can be achieved. The problem is quite easy to solve in 30 moves, so there is no point in writing unless you do better than that. For convenience in recording a solution, number the black squares, left to right and top to bottom, from 1 to 32.

Here are the solutions to the short problems given last month:

### 1.

The dime and penny puzzle can be solved in four moves as follows. Coins are numbered from left to right.

1. Move 3,4 to the right of 5 but separated from 5 by a gap equal to the width of two coins.

2. Move 1,2 to the right of 3,4, with coins 4 and 1 touching.

3. Move 4,1 to the gap between 5 and 3.

4. Move 5,4 to the gap between 3 and 2.

### 2.

Three slices of bread—A, B, C,—can be toasted and buttered on the old-fashioned toaster in two minutes. The illustration on this page shows the way to do it.

### 3.

The illustration at the top of page 156 shows how the 6-by-10 rectangle, formed with the 12 pentominoes, can be cut into two parts and the parts refitted to make the 7-by-9 rectangle with three interior holes. The illustration at the bottom of page 156 shows the only two possible patterns for the 6-by-10 rectangle in which all 12 pieces touch the border. The first of these patterns is also remarkable in that it can be divided (like the rectangle in the preceding pentomino problem) into two congruent halves.

### 4.

A man goes up a mountain one day, down it another day. Is there a spot along the path that he occupies at the same time of day on both trips? This problem was called to my attention by psychologist Ray Hyman of the General Electric Company, who in turn found it in a monograph entitled "On Problem-Solving," by the German Gestalt psychologist Karl Duncker. Duncker writes of being unable to solve it and of observing with satisfaction that others to whom he put the problem had the same difficulty. There are several ways to go about it, he continues, "but probably none is... more drastically evident than the following. Let ascent and descent be divided between *two* persons on the same day. They must *meet*. Ergo.... With this, from an unclear dim condition not easily surveyable, the situation has suddenly been brought into full daylight."

### 5.

A. If OODDF is the square root of WONDERFUL, what number does it represent? O cannot be greater than 2 because this would give a square of 10 digits. It cannot be 1 because there is no way that a number, beginning with 11, can have a square in which the second digit is 1. Therefore O must be 2.

F, the last digit in the square root, cannot be 1, 5 or 6 because in each case this would make the *same* digit the final

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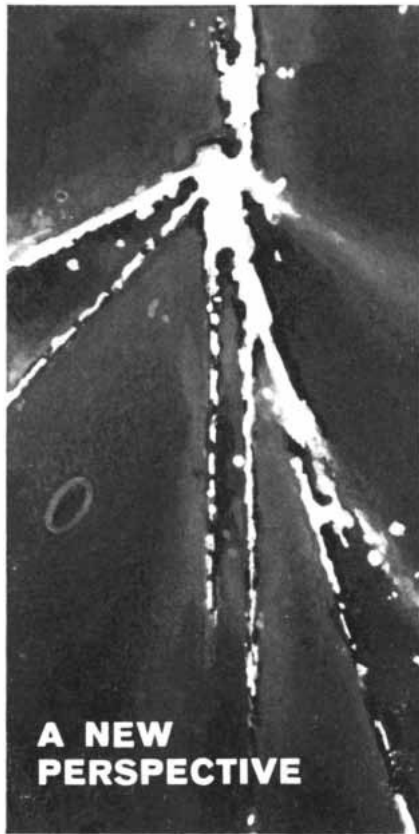
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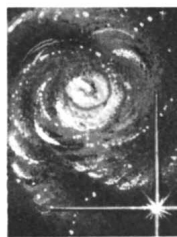


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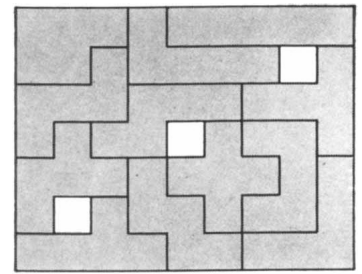
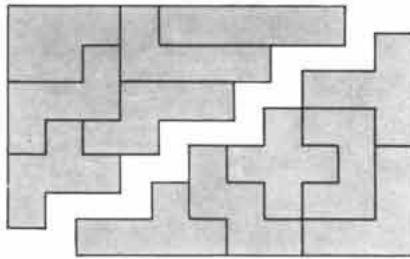
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*A 6-by-10 rectangle made up of pentominoes is refitted into a 7-by-9 one with three holes*

digit of WONDERFUL. With this in mind, we find that there are 30 different possible combinations of digits for OODDF: 22334, 22337 and so on.

We can eliminate more than half of these by using a dodge based on the concept of the digital root. The sum of the nine digits of WONDERFUL (we were told zero was excluded) is 45, and this in turn sums to 9, the digital root of the original number. The square root of WONDERFUL must have a digital root that, when squared, gives a number with a digital root of 9. The only digital roots meeting this requirement are 3, 6 and 9; therefore OODDF must have a digital root of 3, 6 or 9. This eliminates all but 11 possibilities, of which only 22887 has a square (523814769) that fits the code word WONDERFUL.

B. The timesaving insight in this problem is the realization that if the nine digits are placed on a 3-by-3 matrix to form a rookwise connected chain from 1 to 9, the odd digits must occupy the central and four corner cells. This is easily seen by coloring the nine cells like a checkerboard, the center cell black. Since there is one more black cell than white, the path must begin and end on black cells, and all even digits will fall on white cells.

There are 24 different ways in which the four even digits can be arranged on the white cells. Eight of these, in which 2 is opposite 4, can be eliminated immediately because they do not permit a complete path of digits in serial order. The remaining 16 patterns can be quick-

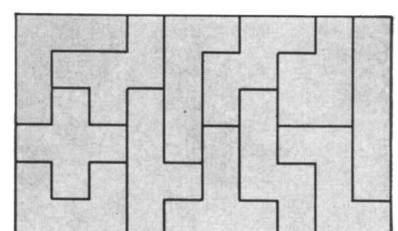
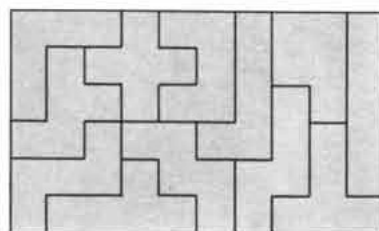
ly checked, keeping in mind that the sum of the two upper digits on the left must be less than 10 and the sum of the two upper digits on the right must be more than 10. The second assertion holds because the two upper digits in the middle are even and odd, yet their sum is an even digit. This could happen only if 1 is carried over from the sum of the right column. The only way to form the path so that the bottom row of the square is the sum of the first and second rows is shown on page 158.

6.

Immanuel Kant calculated the exact time of his arrival home as follows. He had wound his clock before leaving, so a glance at its face told him the amount of time that had elapsed during his absence. From this he subtracted the length of time spent with Schmidt (having checked Schmidt's hallway clock when he arrived and again when he left). This gave him the total time spent in walking. Since he returned along the same route, at the same speed, he halved the total walking time to obtain the length of time it took him to walk home. This added to the time of his departure from Schmidt's house gave him the time of his arrival home.

7.

The young lady is older than 20, younger than 30. Her most likely age is 29, the next most likely is 28 and so on



*All the pentominoes in these 6-by-10 rectangles touch the border of the rectangle*

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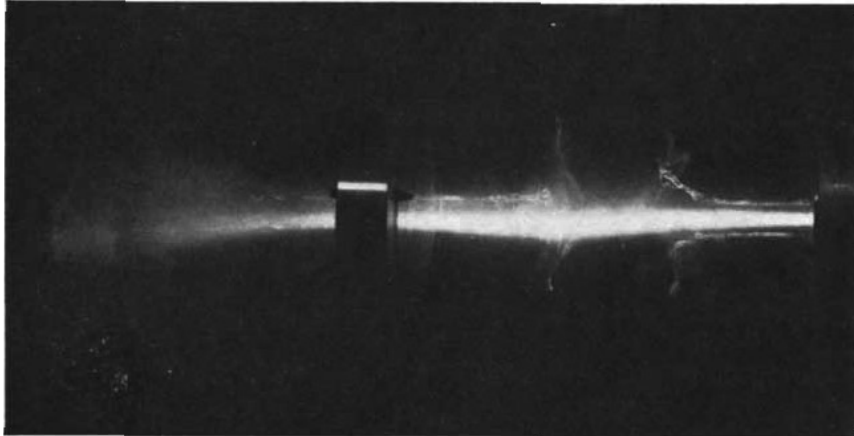
an important  
word  
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**SPERRY RAND RESEARCH CENTER**

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# PHYSICISTS

for advanced studies of high-performance electrical propulsion systems...



Great interest has been aroused by our unusual oscillating-electron ion engine which produces a high-velocity, electrically-neutral plasma beam. Since this electrically-neutral stream eliminates the space-charge effect, there is no theoretical limit to the thrust capability of the device. ● Past successes and current progress with this device, (and in other areas of plasma research) now require a material expansion in this entire effort. As a result, a number of very attractive Senior Positions are being created for electrical propulsion specialists — particularly physicists with advanced degrees and experience. ● These positions should have particular appeal to those interested in studies of high-energy plasma sources, diagnostic techniques and other basic investigations that will lead to practical space propulsion devices. Included are both theoretical and experimental investigations of factors that determine plasma potentials, ionization and power efficiencies. ● This program is of the long-range sustained type with both corporate and government sponsorship. Superior facilities and assistance are available for numerical computation and experimental work. Publication of papers is encouraged as is close contact with related university research. ● Salary levels, benefits and the semi-academic approach will appeal to experienced men with demonstrated abilities.

*You are invited to contact Mr. W. H. Walsh, Personnel Department*

## RESEARCH LABORATORIES UNITED AIRCRAFT CORPORATION

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All qualified applicants will receive consideration for employment without regard to race, creed, color or national origin.

+	1	2	9
	4	3	8
	5	6	7

*Solution to the chain-of-digits problem*

down to 21, the least likely. If the mathematician wishes to guess her age in as few yes or no questions as possible, his best first question is "Are you 29?" If she says no, he adopts the usual strategy of binary division on the remaining eight ages, obtaining the answer in three more questions.

Seth Zimmerman of Dartmouth College gives the general solution in his article "An Optimal Search Procedure," in *The American Mathematical Monthly* for October, 1959. Only the procedure, not the proof, will be given here.

The first step is to list the possible elements (in this case nine different ages) from left to right in increasing order of probability. (If two or more elements have the same probability they are placed side by side in any order.)

21, 22, 23, 24, 25, 26, 27, 28, 29

The elements are grouped by pairs, beginning at the left:

(21, 22) (23, 24) (25, 26) (27, 28)  
(29)

These parenthetically enclosed sets are now treated as five single elements and once more grouped into pairs, beginning at the left:

[ (21, 22) (23, 24) ]  
[ (25, 26) (27, 28) ]  
[ (29) ]

The three bracketed sets are handled the same way, making two final elements:

[ [ (21, 22) (23, 24) ]  
[ (25, 26) (27, 28) ] ]  
[ [ (29) ] ]

The best strategy for minimizing the number of questions is to take these di-



## How Nickel gets music out of solid rock

Deep in the Caverns of Luray in Virginia is one of the world's musical marvels—the famed “Stalacpipe” organ—a unique instrument that gets rare tonal beauty from age-old stalactites.

To get music out of solid rock, the stalactites have threaded metal rods bolted through them—close to small, wire-wound magnets. When an electronically-controlled hammer strikes a stalactite, the combination of rod and magnet becomes a tone generator whose impulses pass out through an amplifier.

**Imagine the dampness of the Caverns . . .** the rust-producing environment . . . and what could soon happen to these musical rods bolted through the rock. Here is where a metal has to really prove itself.

**Nickel means trouble-free performance.** To prevent excessive rust and resulting expansion that could easily crack or snap off the stalactites, a special electrical steel—a steel with Nickel in it—was chosen. This high

nickel alloy steel—47-50% Nickel—stands up to the eternal dampness of this underground concert hall . . . and provides the exact combination of magnetic properties needed for low power requirements and full high fidelity.

**Don't overlook Nickel** even if you're not thinking of building an underground organ anytime soon. Alone or with other elements Nickel improves hundreds of alloys . . . makes possible almost any combination of properties for fabricating or service demands.

**Whatever your metal problem**—high or low temperatures, corrosion, stress, or an unusual combination of factors—consider the advantages of Nickel. For more information, just write us.

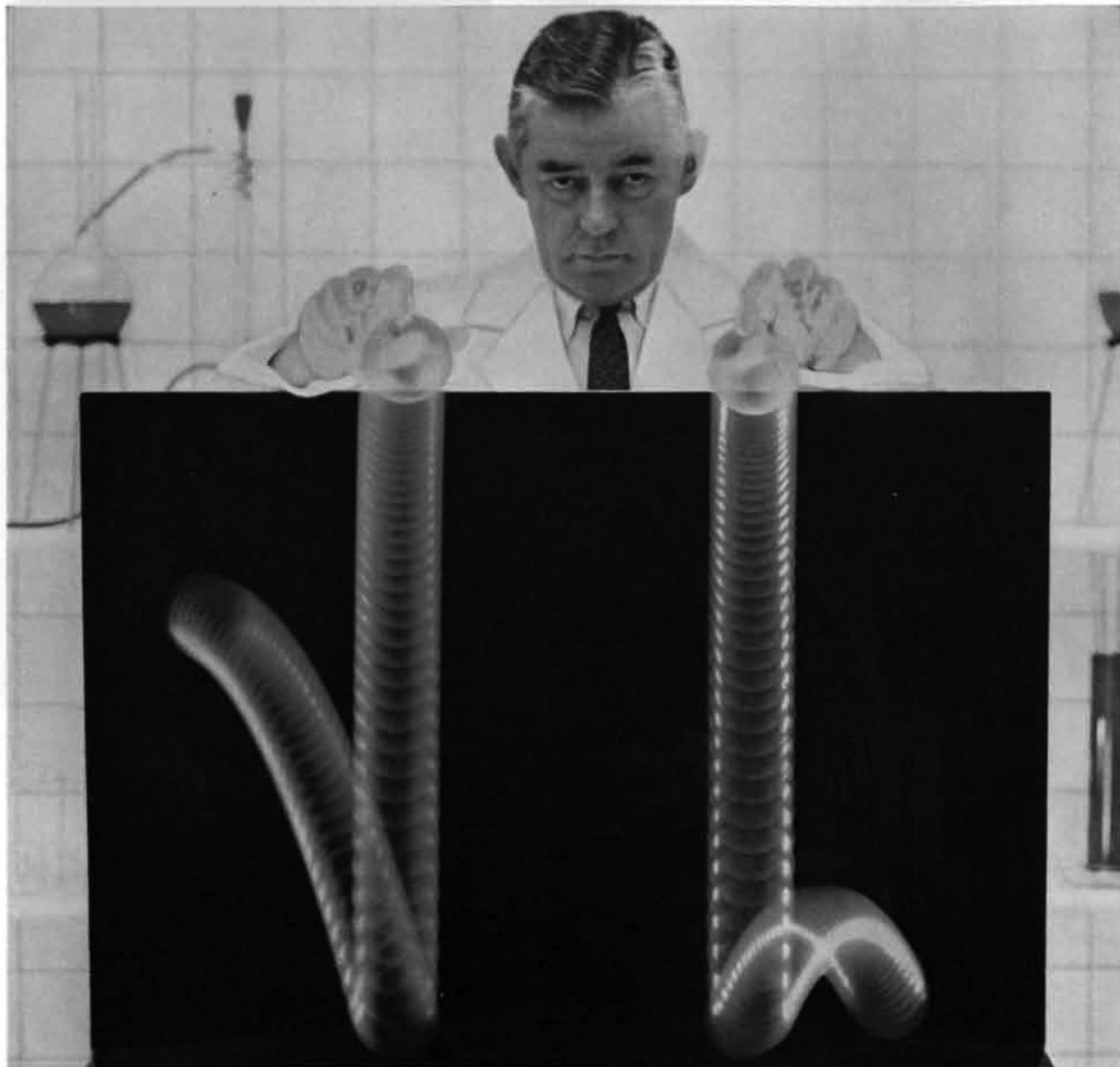
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**Big tone from little Nickel alloy rods.** Pen shows the size of Allegheny Ludlum Steel Corporation's AL-4750 nickel alloy special steel rods bolted through ancient stalactites. The rods vibrate with the rock after being struck by rubber-tipped hammers.

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NICKEL MAKES ALLOYS PERFORM BETTER LONGER

## *What's News in Rubber...*



## **Tires of Enjay Butyl smooth the bounce out of bumps!**

Unlike ordinary rubber (red ball), which makes a tire that bounces high when it hits bumps, Enjay Butyl (blue ball) absorbs shock with very little bounce—for a smoother, quieter ride.

In addition to unique dynamic performance, this copolymer of isobutylene and isoprene has many other

useful properties: low permeability to gases, excellent resistance to ozone, weathering, heat, chemicals, tear and abrasion; and outstanding electrical characteristics.

Enjay now offers a family of Butyl rubbers, including new Butyl Latex and Butyl HT, which is halogenated

for high heat resistance and faster cures.

In rubber, plastics, chemicals and petroleum additives, Enjay is continually bringing you advanced new products. For full details, write to Enjay, 15 West 51st Street, New York 19, New York.

EXCITING NEW PRODUCTS THROUGH PETRO-CHEMISTRY

**ENJAY CHEMICAL COMPANY**

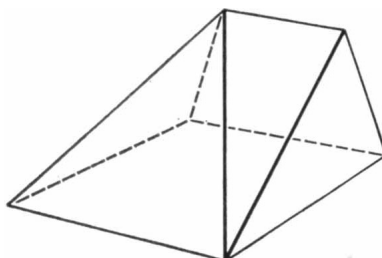
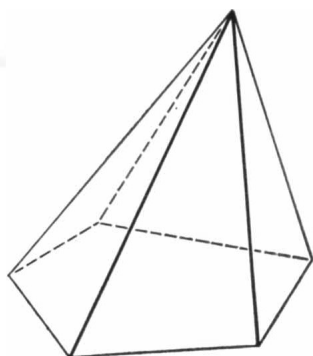
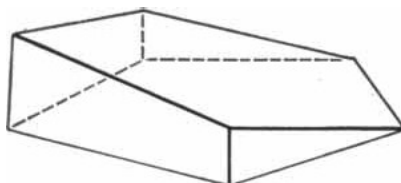
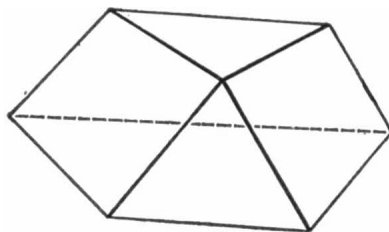
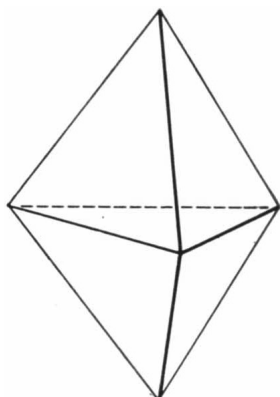
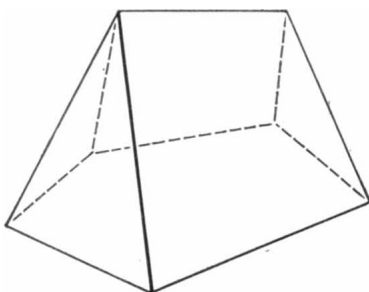
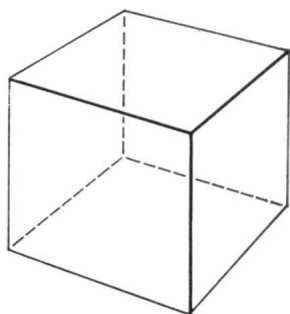
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visions in reverse order. The first question, therefore, is whether or not the girl is 29. If not, three more guesses are required. In the case of nine elements, it does not matter how the eight are divided for the last three questions provided that they are halved at each division, because the optimal strategy provides no way of pinpointing the correct age in less than three more questions.

8.

In the chess problem white can avoid checkmating black only by moving his rook four squares to the west. This checks the black king, but black is now



The seven varieties of hexahedron

free to capture the checking bishop with his rook.

9.

The seven fundamentally different varieties of hexahedron (six-sided polyhedron) are shown in the illustration on this page. I know of no simple way to prove that seven is the maximum number. For those who are interested, there are 34 varieties of seven-sided polyhedron and 257 varieties of eight-sided polyhedron. Beyond this, the problem of determining the number of varieties of an  $n$ -sided solid becomes enormously difficult.

## What's News at Enjay



### Dynamic Growth at Enjay keeps pace with chemical progress

**GROWTH:** Production of chemicals from oil is growing at a rate 3 times faster than the chemical industry as a whole. Enjay has been among the leaders contributing to this fast-paced petrochemical average!

**SALES:** Last year Enjay sales were higher than ever before — up more than 12% over 1959. This outstanding performance places Enjay among the top ten chemical companies in the country.

**NEW PRODUCTS:** Two new rubbers, Enjay Butyl HT 10-66 (chlorobutyl) and Butyl Latex, have just been announced. BUTON resins, another result of Enjay research, are being used for paints, can coatings and electronic components.

**NEW CAPACITY:** The first of 3 new Butyl expansion projects, needed to supply this growing market, was put in operation in 1960. When all are completed, Enjay Butyl facilities will be increased by 33%.

**CONTINUING EXPANSION:** Enjay planned expansion program in aromatic hydrocarbons, for example, will reach 79 million gal/yr of benzene by 1962; 55 million gal/yr of toluene; and 105 million lbs/yr of paraxylene.

If you use rubber, resins, plastics, chemicals or petroleum additives, Enjay offers you dependable supply and a growing number of new and improved products — backed up by outstanding technical service. Let us prove it.

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