A NOTE ON THE DESIGN OF AN ELECTRO-MECHANICAL MAZE RUNNER

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In recent years several electro-mechanical devices have been constructed which, in one way or another, "model" simple overt manifestations of organic functions. Among the best known of these are G. Walter's "machina speculartrix" (5) and Ashby's "homeostat" (1). The model described here is designed to run through mazes, and as a result of its "mistakes" on the first run (the trial run) to be able to run through a second time (the performance run) without error. No claims are made that the design of this model will throw any new light on problem-solving by animals. The motives behind its construction were those of interest and curiosity. This line of approach to problems of behaviour is in its earliest infancy, and it is most probable that as the techniques and theory of control and communication advance, the method will prove a valuable way of putting an hypothesis to the best of all possible tests, that is the test of whether or not it will work. Further, by constantly asking the question "will it work," we will be more likely to avoid semantic and metaphysical difficulties.

The attempts of Helmholtz (2), Ewald and Wilkinson (6) and others to model the human cochlea, to provide supporting evidence for one or other of the theories of pitch discrimination, indicate that techniques are still inadequate for such direct methods to contribute much to knowledge; but, on the other hand, the habit of thinking in terms of physical analogies of organic functions is one which has been of definite value in the understanding of auditory functions as well as many other sensory and nervous functions. Indeed, thought, speech and science depend upon man's capacity for comparing and contrasting objects and events and so abstracting the formal relationships between things. The construction of logico-mathematical or mechanical models of organic functions is no more than an attempt to abstract from the complex patterns of animal behaviour a formalised statement of relationships within the process. The more empirical knowledge we have, the less formalised will be the analysis. Care must be taken to ensure that no closer analogy is drawn between the two processes than is warranted by the level at which the formal analysis is carried out. One cannot say that because two processes are similar in one respect or at one level of abstraction they will be so in other respects or at other levels of abstraction, although to do so often leads to the formulation of fruitful hypotheses and experimental programmes. The overt behaviour or task in the present project is the selection and "memorising" of the shortest route through a closed maze, that is a maze which gives no previous information regarding the position of the finish.

In the most general terms, a maze is any continuous N — dimensional pattern of related points, finite or infinite, static or mobile. A solution of a maze in general terms would involve complete "knowledge" of the maze pattern, as there may be any number of starting and finishing points. The particular type of maze which the present model is designed to solve, and the definition of a solution, are as described below. Choice-points, dead-ends and pathways connecting them will be called points of the maze. In the maze there are a finite number of points continuously related in a two-dimensional sequence. Each point (P) presents $(n - 1)$ degrees of freedom to any operator moving through it, where n is the number of points immediately adjoining any point, here called its family, and with each of the adjoining points called a member of the family. Von Neumann and Morgenstern (3) use the term family to denote the degrees of freedom at any point in a "tree" or maze. A point is any region of the maze having a fixed value of "n" and being bounded by two other points with different values of "n." A point where $n = 1$ is a dead-end; where $n = 2$ a maze path, and where $n > 2$ a choice-point. Although the model is only built to solve mazes where $n > 2$, the general theory will cover all values of n. There is one and only one point which is defined as the first in sequence or *start*, and one and only one which is defined as the *finish*.

A point-sequence is defined as the sequence of points encountered in moving from any point in the maze to a dead-end without repeating any one point. The complete point-sequence between the starting point and finishing point is called the *main run* of the maze. The choice-points (where $n > 2$) lying directly on the main run are called the *primary choice-points* of the maze. Those choice-points lying immediately off the main run are called secondary choice-points, and so on.

The maze here considered is one which has no differential features of the choice-points apart from the relative directions of the paths. It is a closed maze; that is there are no clues given as to the location of the finish. An example of such a maze with each choice-point having two degrees of freedom, that is presenting a left and right alternative to the model approaching the choice-point, is given in Fig. 1.

During the trial run or runs, the model and animals "store," by means of an internal operator or memory, a representation of the primary choice-point sequence and eliminate from the store any representation of secondary, tertiary, etc., choice-points. Animals in fact do not eliminate these dead-end sequences, but at least they do not "work on them" when they have solved the maze. The model reaches the finish of the maze in the trial run by following point sequences and never repeating any point until forced to do so by a dead-end; a rat uses the same method although less perfectly. When a correct sequence of primary choice-points has been stored, the model and animals are able to run straight along the main sequence of the maze to the finish. The selections, however, may be done on a purely random basis until the correct selection is hit upon and then memorised. Such a hit-and-miss method is probably never used by animals, but some more "rational," or at least predictable, method of selection is used. The complexity of animal maze-solving behaviour is due in part to the multitudinous methods of selection which they employ; for example, direction-turning tendency, body momentum, illumination, previous success and failure in that or similar mazes, etc.

Before a formal analysis is given of the operations necessary to solve such mazes, a simplified version of the theory will be given in terms of the introspective reports of an intelligent observer in process of solving a maze of the type shown in Fig. 1.

He will report as he approaches corner 1. "Here's a corner, I can take the left or right alternative, I'll try the right. Here's another corner (corner 2), I'll try the left

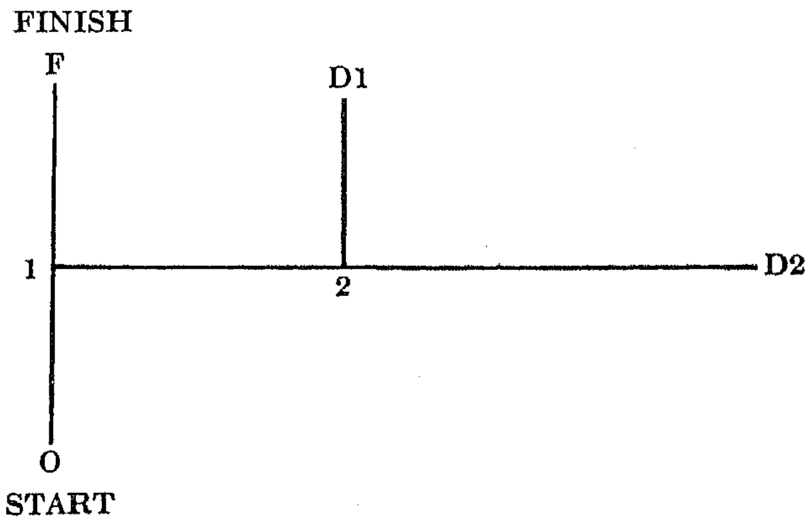


Fig. 1.

alternative this time. Now here's a dead-end (D1). I must have made a mistake at the last corner, so I will turn round and try the other way. I must remember when I come to the second turning in the maze next time to turn right and not left. Here is another dead-end (D2). I must return to the second corner; but I have already tried both possibilities here, therefore I shall return to the first corner. I remember that I turned right here, therefore I will now try the left alternative. That was correct, for here is the finish of the maze. When I enter the maze again I must remember to take the left alternative at the first corner and I can forget all about the second corner." This method is identical in principle with that adopted by the model, and it is, indeed, the only way of solving closed mazes in one trial run, although there is always the possibility that the correct sequence will be hit upon at the first trial. The possibility that this will happen increases as the number of trial runs increases until, if enough trial runs are allowed, a solution is bound to result without the application of any rational method other than remembering the directions taken in the correct run. Animals in general fall half-way between the completely rational "one trial run" solution and the irrational hit-and-miss method, taking more trials than would be necessary in a rational solution, but less than would be expected if they were being completely random in their turning behaviour. The theory set out below is generalised to include mazes with any number of possibilities at any choice corner in the maze, but is restricted to cover the case of rational "one trial run" solutions. It would be possible, however, to cover multi-trial run solutions by the addition of suitable variables and probability functions.

The model makes its selection at any choice-point on the basis of the setting of a switch which corresponds to that point. To simplify construction, the model was built so that it would select the right-hand alternative path at any choice-point in the trial run, that is it runs independently of the switch settings until the performance run. At a dead-end the model turns through two right angles. The following is a statement of the minimal operational requirements in order that any operator shall solve the maze in one run.

Operational Requirements of a Generalised Maze Solver

There are variables (switches round the circumference of a wheel in the model), each known as S with an appropriate suffix (*a*, *b*, *c*, etc.), depending on the position of the switch in a fixed linear series of switches collectively known as the wheel.

Each S is limited in the number of values which it can have by the family size of the choice-point in the maze to which it corresponds. Let α denote the number of switch values thus defined.

The actual value of a switch at any time is denoted by β where $\beta < \alpha$. β corresponds to the particular member of the choice-point family which is being operated upon by the model at any one time.

The wheel is related to a ratchet setter, such that each S approaches or withdraws from the setter in an order determined by the position of S in the wheel.

The S immediately to one side of the setter at any one time is in position i, and the S on the opposite side of the setter is in position ii with respect to the setter.

S*a* is always placed in position i when the model enters the maze; this ensures that there is correspondence between the switch settings and the primary point sequence of the maze in the performance run.

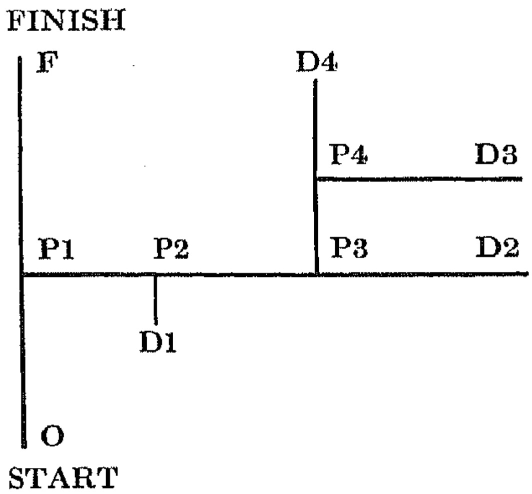
The model selects one of the alternative paths at a choice-point except the one along which it approached the choice-point (in fact, it always selects the right-hand alternative in the trial run, but this is immaterial for the general theory). The path selected corresponds to the setting of the appropriate S, which has the value $\beta = 1$, and any subsequent re-selections at that point correspond to $\beta = 2$, $\beta = 3$, etc., in that order. The model by this means only runs along point sequences and never repeats a point sequence in any one run, that is it does not repeat a mistake (a dead-end). The operations upon the switches during a trial run of a maze may be stated as follows, it being remembered that points in the maze are denoted in general by Pn, where n is the number of points adjoining any particular Pn.

1. For any Pn, where $n > 2$, an S in position i with any value of α and β becomes an S in position ii with $\alpha = n$ and $\beta = 1$ (except under condition 3), until the model reaches a dead-end, when condition 2 becomes operative as a result of the recording motor being set to run in reverse.

2. For any Pn, where $n = 1$ (a dead-end), an S in position ii, with any value of α and β, becomes an S in position i with α unchanged and β increasing in value by 1. When this has occurred, the recording motor is de-reversed and the model operates according to condition 1 again at the next choice-point, provided that condition 3 is fulfilled, and excepting under condition 4.

3. Where a switch has just had its β value increased by 1 as in condition 2 and the recording motor has just been de-reversed, the following operation is carried out at the next choice-point. For any Pn, where $n > 2$, any S in position i with any value of α and β becomes an S in position ii with the value of α and β unchanged.

4. If all the degrees of freedom $(n-1)$ at the particular corner approached have been tried, that is, when the β value of the corresponding switch equals $(\alpha - 1)$ or α, then the model continues to operate according to condition 2 until a switch with a β value of less than $(\alpha - 1)$ has been operated on by the setter.



The setter is represented by the arrow; 'D' corresponds to a dead-end.

Recording operations at choice-points.

Switches	0	P1	P2	D1	P2	P3	D2	P3	P4	D3	P4	D4	P4	P3	P2	P1	F
Sa	R ⩽	R	R	R	R	R	R	R	R	R	R	R	R	R	L ⩽	L	L
Sb	R	R ⩽	R	L ⩽	L	L	L	L	L	L	L	L	L	L ⩽	L	R ⩽	R ⩽
Sc	R	R	R ⩽	R	R ⩽	R	L ⩽	L	L	L	L	L	L ⩽	L	L	L	L
Sd	R	R	R	R	R	R ⩽	R	R ⩽	R	L ⩽	L	L ⩽	L	L	L	L	L
Se	R	R	R	R	R	R	R	R	R ⩽	R	R ⩽	R	R	R	R	R	R
Sf	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R

Table 1.

Condition 3 ensures that any switch which has just had its β value modified shall retain this modification until it requires modifying anew.

These four conditions or operations are sufficient to ensure a solution of the maze. The value of β for each S determines which of all the possible alternatives must be selected in the performance run of the maze, and in theory in the trial run also, although the model is built so as to always select the right-hand alternative at a choice-point in the trial run. In theory all that is necessary is that the steering at any choice-point is controlled by the setting of the appropriate switch after the switch has been operated on at that particular corner.

As an example of how these conditions work out in practice, a simple T maze is taken. For the sake of simplicity, the model is made to take the right-hand alternative in the trial run and the solution lies to the left. The settings of the switches will be denoted by R and L, corresponding to right and left turns respectively, that is β = R or L.

The model enters the maze at the base of the T and runs to the choice-point when, according to condition 1, the recording wheel turns to carry switch *a* from position i to position ii, and in so doing the ratchet setter throws it into the R position, that is $\beta = 1$. (The α values of all the switches in the model are equal and fixed, as the model only solves mazes where there are left-right alternatives at each choice-point in the maze.) The model then turns right and moves to the dead-end. Here the recording wheel is set to run in reverse according to condition 2. Switch *a* is now carried from position ii back to position i, and in passing the setter is thrown into the L position (its β value increases by one). Condition 3 states that when this happens the wheel is again set to run normally, that is to operate according to condition 1. The model turns round at the dead-end, runs to the choice-point, and again takes the right-hand alternative. Before it steers, however, the switch *a* is again moved from position i to position ii, but its setting remains unchanged according to condition 4. It now runs to the finish of the maze, and if switch *a*, which now has an L setting, is put into position i, the model will turn left at the choice-point when again placed in the maze, thus solving it.

A more complicated example of the model's operation is set out in tabular form in Table I. Theoretically each switch should have three setting positions ($\alpha = 3$) for such a maze; but as it is built to take the right-hand alternative in the trial run, it is only necessary to have two setting positions for each switch. This completes the essential theory of a maze-solving device working according to a method of systematised trial and error. The rest of this note is devoted to an outline of the input system and the way in which the operations are controlled in temporal sequence.

The Input System.—The input is from three *feelers*, one frontal feeler operating an input relay when pressed, and two lateral feelers operating relays when not pressed in by the side of the maze path, that is when the model reaches any type of turning other than a dead-end. Let the feelers be denoted by the letters A, B and C; B being the frontal feeler, A and C the left and right feelers respectively. Let the relay operating positions of the feelers be represented by 1 and their off positions by 0. Table II gives the input combinations for all possible types of turning in a maze, assuming that the model is running up the page.

Timing Control.—Finally, mention must be made of the timing-control features of the machine. When receiving any input, the machine stops; but before stopping it must run on long enough for all the relevant feelers for that particular corner to come into action. The completed input-setting of the feelers is then "fed into" the steering and recording units by the rotation of a timing can which previously stopped the main-drive motor of the machine. The feeler input must immediately be disengaged from the steering and recording circuits by the cam and the model kept in the same place while turning, and then the drive motor started and kept going by the cam long enough for

TABLE II

INPUT				CONSEQUENCES		
	FEELERS			STEERING OPERATIONS		RECORDING OPERATIONS
TYPE OF CORNER	A	B	C	TRIAL RUN	PERFORMANCE RUN WHEN TURNING LEFT	
STRAIGHT RUN	0	0	0	NONE	NONE	NONE
┤	1	0	0	NONE	LEFT TURN	RECORDING OPERATION
DEAD END	0	1	0	LEFT TURN TWICE	NOT MET WITH	RECORDING OPERATION IN REVERSE
┐	1	1	0	LEFT TURN	LEFT TURN	NONE
├	0	0	1	RIGHT TURN	NONE	RECORDING OPERATION
┼	1	0	1	NOT NORMALLY PRESENT		
┌	0	1	1	RIGHT TURN	RIGHT TURN	NONE
┬	1	1	1	RIGHT TURN	NONE	RECORDING OPERATION

the machine to reach the next channel of the maze. The timing cam will then have completed its rotation, and any further input from the feelers will start it once more to repeat the cycle of operations at the next turning in the maze.

Each of the operations of steering, recording and timing described involves discreet operations which are carried out by separate 12-volt D.C. motors with gear chains and devices (holding contacts), whereby, once set in motion, auxiliary circuits are completed which maintain the motors in action until the cycle of operations is complete.

A circuit diagram is given in Fig. 2.

Summary.—Some observations regarding the analysis of organic functions were given. One cannot extend mathematical or mechanical analogies beyond the level at which they are made; but the method provides the best way in which hypotheses can be stated and tested.

A general theory covering the minimal requirements for solving a defined type of maze in one trial was stated.

A model operating according to a simplified form of the theory was described. The

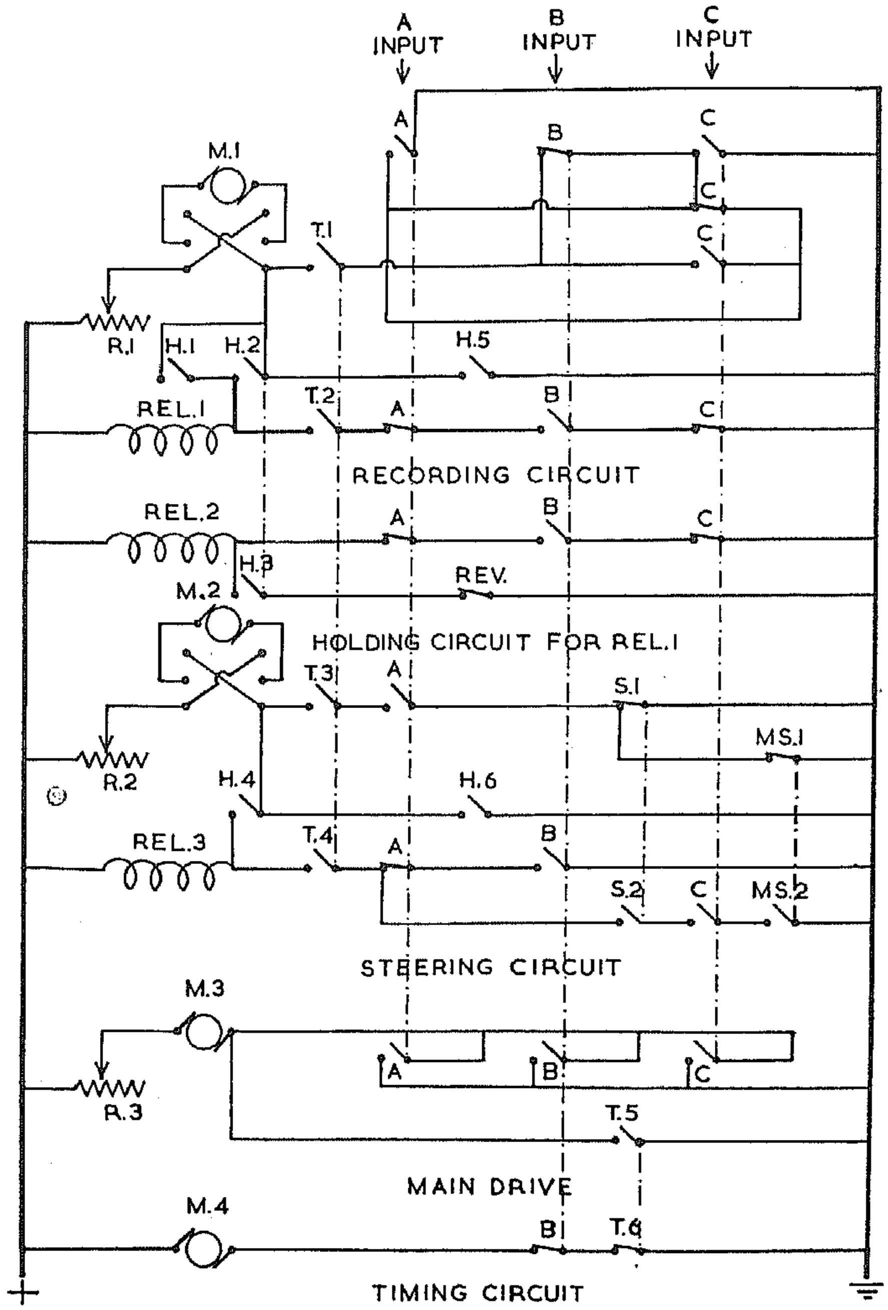


FIG.2 CIRCUIT FOR MAZE RUNNING MODEL

KEY TO FIG. 2

Relay 1 — Reverses M_1 and closes H_1.
Relay 2 — Operates H_2 and H_3.
Relay 3 — Reverses M_2 and closes H_4.
M_1 — Motor controlling recording operations.
M_2 — Motor controlling steering operations.
M_3 — Motor controlling timing cam.
M_4 — Motor controlling main drive.
T_1, T_2, T_3, T_4. Gauged contacts closed by timing cam and governing the input from the feelers.
T_5 — Contact controlling the running of M_3 and closed by it.
T_6 — Contact operated by M_3 and controlling M_4.
H_1, H_2, H_3, H_4, H_5, H_6. Holding contacts maintaining the respective motors in action during any one cycle of operations.
MS_1, MS_2 — Manually operated switches for disconnecting the switch settings from the steering motor in the trial run.
S_1, S_2 — Contacts operated by the switch settings, modifying the steering operations.
REV. — Contact de-reversing the recording motor, M_1.
R_1, R_2, R_3. 50 Ω resistances for "balancing" the motors.
A switches are operated by the input from feeler A.
B switches are operated by the input from feeler B.
C switches are operated by the input from feeler C.

direction in which the model must turn at any choice-point in the maze is represented by the setting of a switch. For each dead-end encountered, an appropriate switch setting is corrected so that the model avoids all dead-ends in subsequent runs of the maze.

APPENDIX

After this paper was completed an article by T. Ross (4) was found which describes a maze-solving machine.

This machine, which was built at the University of Washington, involves the use of a "memory wheel" with a series of two-way switches corresponding in their setting to left and right turns in the maze. It is, however, only designed to solve mazes with first-order choice-points, all of which must be of the T pattern. The author of the article in claiming that all learning of closed mazes must involve an essentially similar mechanism to that of the model, substantiates what has been claimed here. The similarity between our two memory wheels and their mode of functioning is quite remarkable.

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A NOTE ON THE RELIABILITY OF SOME MENTAL TESTS

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THIS note on the reliability of certain tests reports our own observations, which we hope may be of some interest to teachers or others who may be thinking of using such tests. The population and tests are those used by Peel and Graham in the investigation reported in numbers 2 and 3 of this *Research Review*. The children were tested twice, for the first time in 1949 and for the second time in 1951, approximately eighteen months later. The population in 1949 consisted of 221 children (118 boys and 103 girls), and in 1951 of 192 of the same children (103 boys and 89 girls), the loss being due to sickness, leaving the district and the like. There was no reason to suppose that the loss was selective. All the children were between 8·6 and 9·6 years of age at the time when the first tests were given.

The table below gives the odd-even split-half coefficients corrected for length by the Spearman-Brown formula for five group tests for both 1949 and 1951, and the test-retest correlations for these group tests and for four performance tests (with decimal points omitted). Correlations are based on raw scores, not on I.Q.s. One of the group tests, the Essential, is a verbal test; two group tests, Otis Alpha A and Sleight Non-Verbal, are mainly pictorial, and the other two group tests, the first Peel Group Test of practical ability and Peel's (unpublished) V.S.10, are two rather similar pattern tests. The performance tests consist of the three sub-tests of the Alexander Performance Scale,