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A MODEL FOR NEUROPHYSIOLOGICAL FUNCTIONS

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INTRODUCTION: MODELS IN SCIENCE

SCIENCE does not consider the single object and the single organism; it rather considers classes. The term 'class' is, in a certain sense, a synonym for model. Similarly, if some behaviour is described scientifically, it is the behaviour of a class, and therefore of a model, a physical or a conceptual model. While, so far, the physical model has had rather small an importance in science, this is because, in the first place, physical models of complicated relationships were a technical problem and extremely expensive. Since electronic components allow us to construct bigger complexes with reasonable cost, and since the progress of telecommunication techniques has taught us to handle information as both a quality and a quantity, the idea of models has experienced considerable progress. And it can be predicted that the use of electronic computers for the simulation of models will disclose many new possibilities.

One purpose of the physical model is its visual impression. A mere description frequently gives the reader only a very incomplete idea; the model makes the functional behaviour really vivid. This purpose, however, is a modest one and the specialist can often do without the model. The second purpose of the model is for examining the conception which the model displays. Such examining is valuable under the condition that the complexity of relations is such that one cannot predict every reaction of the model. If such examination reveals differences from the intended function or from the observed natural behaviour, this leads to the third and most important application of the model: the development of the conception itself by means of the model.

The model described in the following paper can claim to include all three applications. It is a model for the conditioned reflex and some functions

* Dr. Angyan has furnished the neurological material and he has co-operated in the development of the model, but he was not present when this paper was written.

connected with it. It must be pointed out, however, that it is not the purpose of this paper to defend the type of behaviour the model displays. This would be no subject for this symposium. What we are trying to show is that such models need not and should not be described as electrical circuits (as is usually done) but as logical structures.

A clear logical description, even if it suppresses some minor details, not only specifies the model but also the conception which the model is intended to display. Furthermore, a clear logical description is the basis for a simulation programme for an electronic computer; with a view to the important advances in algorithmic languages already achieved, we can imagine the time when correspondingly equipped computers automatically translate logical descriptions into programmes so that models of this kind can be exchanged and used like mathematical formulae today.

DESCRIPTION OF FUNCTIONAL STRUCTURES BY BOOLEAN ALGEBRA

The biological model is represented by the block schematic of *Figure 1:* receptors, information processing, effectors. There may be, and frequently

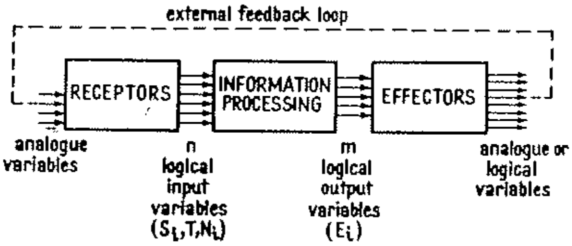


Figure 1. Block diagram of the biological model

are, external feedback loops from the effectors back to the receptors. The block representing the information processing part may include internal feedback loops, of course.

Analogue-to-digital conversion

In this context, the receptors or sensory organs essentially are converters of the information coming from the real world (including the body of the organism) into the information processing system. Since this system operates logically, the receptors must be analogue-to-digital converters.

As a matter of fact, there is not a simple antithesis 'analogue-digital', but there are at least four possible methods:

(*a*) *Continuous analogue methods*—A continuously varying quantity is represented by another continuously varying quantity. *Example:* the ordinary telephone.

(*b*) *Discontinuous analogue methods*—A continuously varying quantity is represented by the variation of a parameter of a discontinuous process. *Examples:* pulse height modulation, pulse position modulation and pulse frequency modulation (the latter is used by the nerve cells).

(*c*) *Counting methods*—A quantity is represented by a sequence of pulses, the number of pulses expressing the instantaneous value or signal. *Examples:* the printing telegraph of HUGHES, pulse count modulation, pulse delta modulation.

(*d*) *Positional methods*—A quantity is represented by a sequence of pulses in which the value is defined not only by the number of pulses but also by their position within a spatial or temporal pattern. *Examples:* the indo-arabic number system, codes of electronic computers, pulse code modulation.

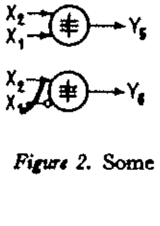
The first two schemes appear in the nervous systems, the other two are of the quantized type and logically defined. The reduction to logical relations is a means for clear description, but constitutes a certain deviation from nature. Nowhere in the organism is an element producing a true conjunction or a true disjunction. Quite similar effects may appear, but they are consequences of the combination of whole arrays of pulses. Anyway, neural networks from the beginning have been considered by logical methods and this is certainly the only reasonable approach.

The effectors in *Figure 1* represent, therefore, a conversion from analogue variables to logical variables corresponding to method (*d*). The input pattern or input 'situation' for the information processing system is a set of 'zeros' or 'ones' of the logical variables S_i, T and N_i.

Logical information processing

Three levels of logical methods must be distinguished: combinatorial logical algebra, sequential logical algebra and the combination of logical functions with arithmetical functions (which are, of course, only special combinations of logical functions—but it pays to symbolize them arithmetically, because they will be better understood in this way).

Combinatorial logical algebra—All variables are either 0 or 1. The functions can be arranged systematically[3] and there are $2^{(2^n)}$ different functions of n variables. All these functions can be expressed by negation ($\bar{X}$), conjunction (&) and disjunction (V). *Figure 2* shows the symbolism for combinatorial logical algebra.



X_2 X_1	0 0	0 1	1 0	1 1
Y_1	0	0	0	1
Y_2	0	0	1	0
Y_3	0	1	1	1
Y_4	1	1	1	0
Y_5	0	1	1	0
Y_6	1	0	0	1

Figure 2. Some symbols for combinatorial functions

Sequential logical algebra—In the model, time is very important; there are delays and there are storing elements. In the sequential logical algebra, time is strictly quantized; what is happening, happens in a set of equidistant moments $\xi = -1, 0, 1, 2, 3, \ldots$ (*Figure 3*). The sequential variables are

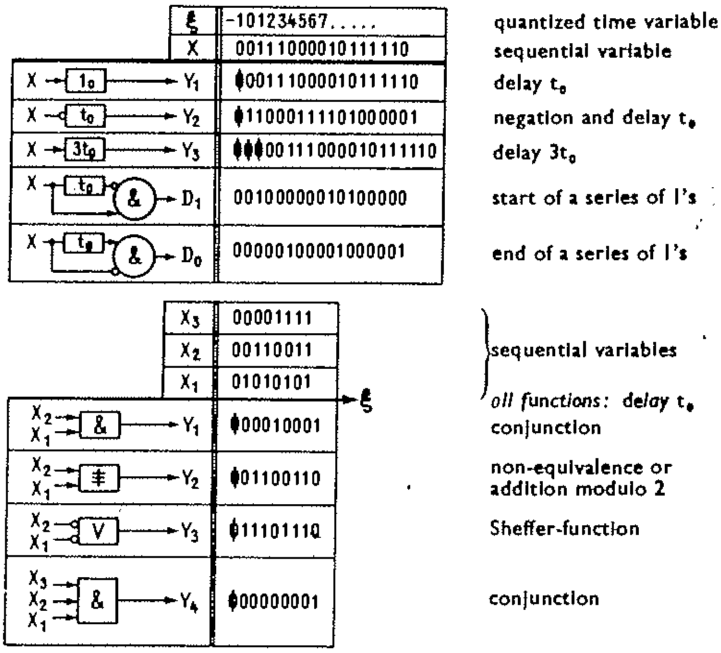


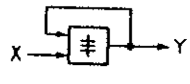
Figure 3. Some symbols for sequential functions

series of values either 0 or 1 for each moment ξ. There are different possibilities for sequential functions. The corresponding functions of the combinatorial algebra produce the results at the very moment when the input signals occur. We denote them by circles around the logical symbol. Furthermore, the result may be produced with a delay of the unit distance t_0 or of a multiple of it (*Figure 3*). The simplest form is the unit delay element t_0; it can be negated or it can have a delay of βt_0.

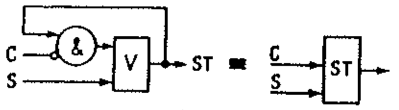
It is possible to use a kind of 'differentiating' function D_1, which emits only the first of a series of ones; a dual form is the function D_0 which emits a one when the first of a series of zeros occurs at the input.

Functions which produce their results with a delay are denoted by squares around the logical symbols. Unless otherwise stated, the delay is t_0 (*Figure 3*).

Delayed functions with a feedback loop can store information. *Figure 4* shows three basic types: the antivalence function with feedback loop changes its state (the output can be considered as a state of this function) any time the input $X = 1$ occurs; the second function has one storing or setting input S and one clearing input C; the third function has two feedback loops and stores for a certain period of time βt_0. These three functions are logical forms of the flip-flop circuit with one input, with two inputs, and the mono-stable form).

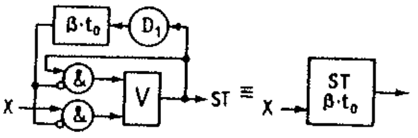


Whenever $X_\xi = 1$, $Y_{\xi+1}$ changes; when $X_\xi = 0$, $Y_{\xi+1}$ remains at the value of Y_ξ



State	ST	0	0	0	0	1	1	1	1
Clear	C	0	0	1	1	0	0	1	1
Store	S	0	1	0	1	0	1	0	1
State	$ST_{\xi+1}$	0	1	0	1	1	1	0	1

The storing pulse S sets the store, i.e. it makes $ST_{\xi+1} = 1$; the clearing pulse C clears the store, i.e. it makes $ST_{\xi+1} = 0$; if S and C coincide, the store is set (there are other possibilities in this case which define other flip-flops)



				β				
X	0	0	1	0	0	1	0	0,....0
ST		0	0	1	1	1	1	1.....1

$X = 1$ is stored during the time $\beta.t_0$; another pulse $X = 1$ during this time has no influence. Instead of $\beta.t_0$, we will write also the time, for instance 5 sec or 3 min

Figure 4. Some sequential functions with feedback. (*a*) Flip-flop with one input; (*b*) flip-flop with two inputs; (*c*) monostable flip-flop

Many more such functions are feasible and may be used. We have defined here only the functions which are made use of in the models described.

Arithmetical elements—Phenomena which depend on repetitions of events can be represented in the model by counting systems. Such systems are, like those in a computer, logically defined and could be reproduced by their sequential function. It is, however, easier to think of them arithmetically. We have used two kinds of counting systems (*Figure 5*), one without and one with negative values of the sum or contents.

Conversion of logical results in the effectors

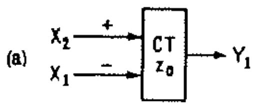
The results are received in the form of sequential variables E_i; this does not mean that the behaviour of the model is restricted to yes-no effects: any transformation into analogue signals and movements is possible.

In our logical schemes we have not reduced the number of logical variables to the minimum m (when 2^m is the number of possible output situations); we rather have provided for one logical output variable E_i for each situation, i.e. a one-out-of-2^m code. It is more convenient to read the schematic in this form; there would not be any problem with such reduction (*Figure 6*).

External feedback loops

The activity of the effectors produces variations in the input variables. Consequently, any such model shows feedback behaviour, even if no such behaviour has been planned deliberately. In natural organisms such external feedback loops are of great importance; frequently, they are applied in the receptors themselves for quicker movement and for better adaptation.

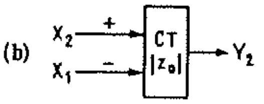
(a)



X_2	0	1	1	1	0	1	1	0	0	1	1	0	0	0
X_1	0	0	0	1	1	0	0	1	1	1	0	1	1	0
z	0	1	2	2	1	2	0	0	0	0	1	0	0	0
Y_1	0	0	0	0	0	0	1	0	0	0	0	0	0	0

Each Input $X_2 = 1$ adds 1 to the contents[z]; each Input $X_1 = 1$ subtracts 1 from the contents[z], but does not subtract, if the contents are zero. If contents z become z_0, the contents are cleared and $Y_1 = 1$ at the next moment (single pulse)

(b)



X_2	0	1	1	1	0	1	1	0	0	1	1	0	0	0
X_1	0	0	0	1	1	0	0	1	1	1	0	1	1	0
z	0	1	2	2	1	2	0	1	2	2	0	1	2	2
Y_2	0	0	0	0	0	0	1	0	0	0	1	0	0	0

Each Input $X_2 = 1$ adds 1 to the contents z; each Input $X_1 = 1$ subtracts 1 from the contents z. If the contents become z_0 and if the contents become $-z_0$, the contents are cleared and Y = 1 at the next moment (single pulse)

Figure 5. Some combined logical and arithmetical sequential functions (z_0 chosen as 3 in both examples). (*a*) Counter for positive value z_0; (*b*) counter for absolute value z_0

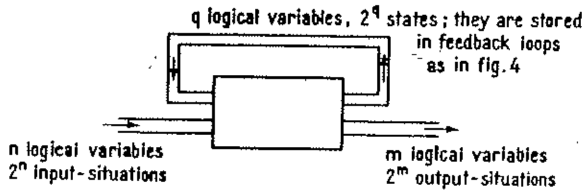


Figure 6. The information processing part as a generalized logical function

MODELS FOR THE CONDITIONED REFLEX

Almost simultaneously, about 1950, three biological models appeared which then formed the nucleus of practical cybernetics: the Homeostat of W. R. ASHBY[3], the Maze Runner of C. E. SHANNON[4] and the Conditioned Reflex Model of W. G. WALTER[5]. In our institute in Vienna, we have built a copy[6] of the Homeostat and have developed a maze runner[7] with some new properties; it should be very interesting to analyse both models in the way mentioned, but here we prefer to investigate four models for the conditioned reflex.

Model No. 1. Unconditioned reflex behaviour: W. G. Walter's Machina Speculatrix[5]

Reduced to its logical properties, this model (*Figure 7*) is rather simple. There are three input variables: *T* is a touch contact indicating an obstacle; S_1 is signalling a weak light source and S_2 a strong one. The four output situations are: E_4—the model moves backwards, then turns right and moves forwards, which helps the model to master obstacles and to get out of corners; E_3—scanning at half speed; E_2—scanning at full speed and driving at half speed, the pilot light being alight; E_1—no scanning, but driving at full speed.

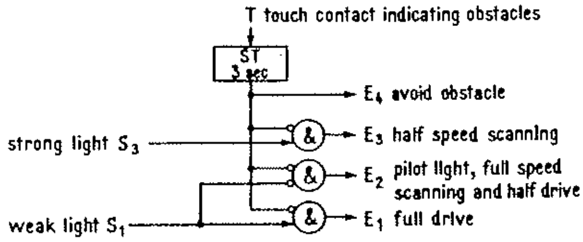


Figure 7. Model No. 1. Unconditioned reflex behaviour. W. G. Walter: Machina Speculatrix

Model No. 2. Conditioned reflex analogue (CORA):
W. G. Walter's Machina Docilis[5,8]

Here (*Figure 8*) another input variable is introduced: the unspecific stimulus N, indicating a certain kind of sound. If S_1 & N happens 20 times, the behaviour is changed for 5 min, i.e. the conditioned reflex is established.

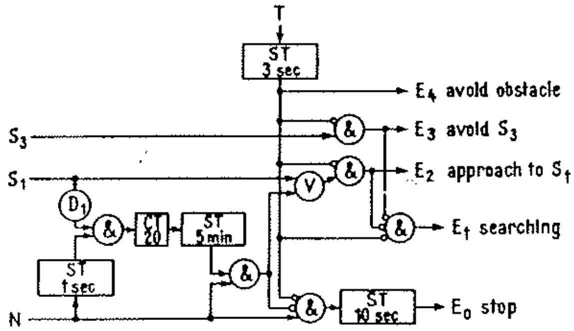


Figure 8. Model No. 2. Conditioned reflex analogue (CORA). W. G. Walter: Machina Docilis

Model No. 3. Temporal extinction of conditioned reflex.
A. J. Angyan's Machina Reproducatrix:

This model (*Figure 9*) has two more inputs, N_1 and N_2, being two tones of different pitch, and N_3, similar to S_3 indicating acoustic signals in excess of a certain threshold in amplitude. Initially, N_1 and N_2 have equal influence and effect. When the conditioned reflex has been established, it can be suspended by another logical system which, after 18 repetitions of N_1 or N_2, prevents the input N_2 from taking any further effect. This means discrimination between N_1 and N_2. The shock N_3 inhibits the conditioned reflex for 35 sec and thus clears the discrimination.

Although involving an advance, this model was not regarded as a correct solution and a further step, including the combination of two conditioned reflexes, was made by the authors.

Model No. 4. Combination of two conditioned reflexes:
A. J. Angyan's Machina Combinatrix[10]

There are still only 6 input variables: S_3, S_1, T, N_3, N_2 and N_1, but the model (*Figure 10*) has two basic states: an active one W and a sleep state $\overline{W}$. The

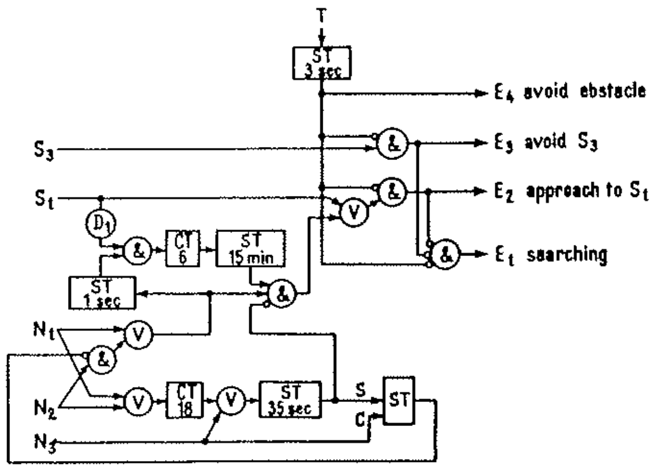


Figure 9. Model No. 3. Model with temporal extinction of the conditioned reflex. A. J. Angyan: Machina Reproducatrix

model can even assume a total of 40 states, defined by the state variables W, Q_1, Q_2, Q_I (conditioned reflexes Q_L & $\overline{Q}_1$ = negative reflex 1; Q_L & Q_1 = positive reflex 1; Q_L & $\overline{Q}_2$ = negative reflex 2; Q_L & Q_2 = positive reflex 2; Q_N (shock reaction) and Q_I (inhibition). The detailed description of this model is given in the following section.

MODEL FOR COMBINATION OF CONDITIONED REFLEXES

The model is intended to demonstrate an advanced hypothesis of the conditioned reflex and some related simple neurogical functions.

A first attempt to modify Walter's model was made in 1955 by Angyan and Banyasz in Hungary; this led to two technical embodiments of model 3. In experiments, concurrently carried through on animals and on model 3, and the results recorded and standardized, a conception was developed which became the basis for model 4. During the design of the model, in Vienna, this conception has repeatedly been modified and cleared up logically by the authors.

The model aims to reproduce in an approximate way the states of 'sleep' and 'wakefulness', and an intermediate state of 'inhibition' in which, generally, only the conditioned responses but not the unconditioned ones should be blocked. 'Activation' by shock stimulation should induce a shift from wakefulness to sleep and vice versa.

Some related biological terms

Specific or unconditioned stimuli S are followed immediately by given reactions corresponding to two *dominant states*, the *active* or approach state W and the *passive* or avoidance state $\overline{W}$. The related processes are referred to as *unconditioned reflexes* (e.g. E_6).

Neutral stimuli N, generally exerting no effect, can be correlated with specific ones. By combining a certain number of 'rise' or 'decay' pulses* of

* 'Rise' and 'decay' pulses indicate the beginning and end of a D.C. block, by differentiation (followed by change of sign in the case of the 'decay' pulse). In the logical model these are the first and last pulses of a block of ones—Editor.

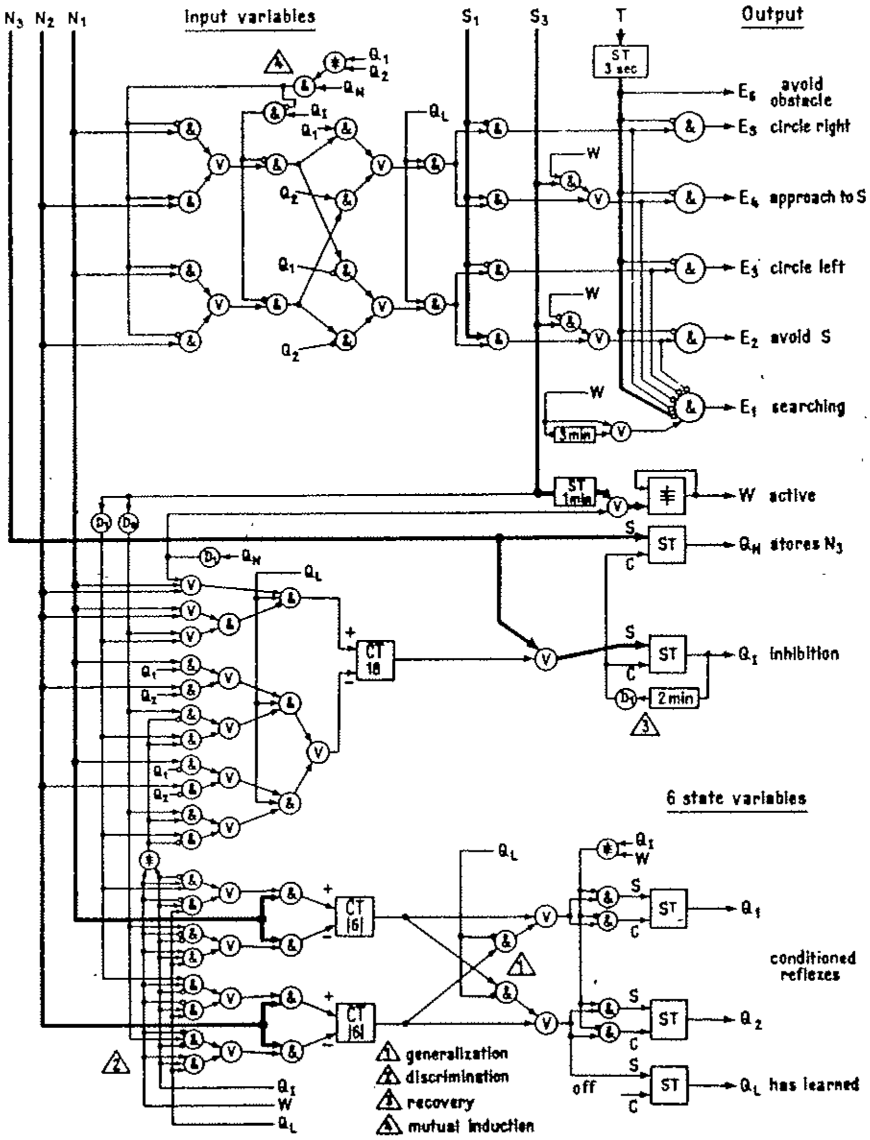


Figure 10. Model No. 4. Model with combination of conditioned reflexes. A. J. Angyan: Machina Combinatrix

specific stimuli S with preceding neutral stimuli within the protraction time of the latter, *conditioned reflexes* CR can be established. Thus neutral stimuli N become *conditional stimuli*, that is they now will trigger essentially similar reactions to the above-mentioned (combined) specific stimulation. The first conditioned reflex ever established is *generalized* to all neutral stimuli of equal classes.

Internal inhibition Q_I is effected by repeated application of conditional stimuli N which are not reinforced by unconditioned stimuli S, and is non-specifically applied to all conditional stimuli N of the same class (N_1 and N_2).

External inhibition Q_N of conditioned reflexes occurs with strong, disturbing, external stimuli N_3. At the same time the dominant state will be changed too.

Discrimination ($Q_2 \not\equiv Q_1$) may be obtained in two ways. *Passive discrimination* will be effected by carrying extinction beyond a certain level within the inhibition time.

Active discrimination can be obtained by establishing contrary conditioned reflexes through antagonistic training.

'Spontaneous' recovery or desinhibition of conditioned reflexes CR depends on the lapse of a certain period of time, after which the original state will be restored.

Simultaneous application of conflicting conditioned stimuli results in passive reactions, whereas a strong stimulus N_3 may induce the reversal of conditioned reflexes (mutual induction).

Functional properties of the model

Figure 10 gives a complete schematic of the functional properties of the model. Some comments may be useful.

Input variables—The six input variables are shown on the top of *Figure 10*, and their influence is indicated by heavy lines. The hierarchical order can easily be detected.

The states—The model can assume 40 different states; there are 6 state variables determined by the conditions in the stores ST and $\not\equiv$. These 6 logical variables have $2^6 = 64$ states; but in this case, the variable Q_L is combined with Q_2 and Q_1 only in its non-negated form, but never in its negated form $\overline{Q}_L$. If the state variables are arranged as in *Table I*, and if their 0, 1-values are considered as binary numbers, each state can be denoted by this number, which is given in *Table I* also as a decimal number. The state numbers 9 through 31 do not occur for the reason mentioned, and this yields 40 instead of 64 states.

In *Figure 10* the influence of the state variables is indicated by arrows, which simplifies the diagram.

The output variables—From E_6 through E_0 these have a hierarchical order. The dominant input variable is T: avoiding obstacles, E_6 is the most important activity and T blocks all other outputs. E_6 is an alternating backward-turning and forward-turning movement by which obstacles are mastered.

E_5 and E_3 are the responses to the conditioned stimuli. Such a response consists in either motor running so that the model makes a circular motion, thereby scanning its environment for light sources.

E_4 and E_2 are the responses to a strong light source; actually, the model makes a serpentine motion, to approach the light source or to retire from it, the model facing the light source in either case.

E_1 is an alternating motor-driving condition for random scanning.

If none of the above outputs is active, the model stops (E_0).

Biological terms as logical functions—Starting from given input and output variables, the biological terms had to be properly defined and then transformed into the corresponding logical functions.

Most of the terms are defined by logical variables as given in the preceding sections. Only a few terms need further explanation.

There are four conditioned reflexes, logically defined by:

$+CR\,2 = Q_L \& Q_2$ positive tropism to weak light upon N_2

$-CR\,2 = Q_L \& \overline{Q}_2$ negative tropism to weak light upon N_2

$+CR\,1 = Q_L \& Q_1$ positive tropism to weak light upon N_1

$-CR\,1 = Q_L \& \overline{Q}_1$ negative tropism to weak light upon N_1

The positive and negative conditioned reflexes of the same index are mutually exclusive.

Generalization: In the 'unlearned' states $(\overline{Q_L})$, the first activation of an adder ADD |6| operates both store Q_1 and store Q_2. Simultaneously, store Q_L is also set and Q_L inhibits ($\Delta 1$) the generalization function.

Discrimination: Active discrimination is effected by a number of antagonistic combinations ($\Delta 2$) N_2 and N_1 with $W \& S_3 \& D_0$ and $\overline{W} \& S_3 \& D_1$. Thereafter $Q_1 \not\equiv Q_2$.

Passive discrimination (also $\Delta 2$) can be established if $Q_I \& (Q_1 \equiv Q_2)$. The single application of N_1 (or N_2) will lead to reversed adding on adder ADD |6| and thereupon $Q_1 \not\equiv Q_2$ will be stored too.

Recovery: The feedback loop ($\Delta 3$) at the store of Q_I clears both store Q_I and store Q_N after 2 minutes.

Mutual induction: If $Q_2 \not\equiv Q_1$ and a shock is stored in store Q_N ($\Delta 4$), the effects of N_2 and N_1 are interchanged.

Action patterns—The sequence of input activations and changes in states, followed by output activations, forms an action pattern which accurately describes the behaviour of the model. *Table I* gives an illustration, *Figure 11* shows the flow-diagram of the states. Initially, when the model is switched on it is in state 0. Items 1–6 illustrate the unconditioned reflexes. The establishing of conditioned reflexes (conditioning), which may also be called 'learning', needs some repetitions of the combination of strong light S_3 with one of the neutral stimuli N_2 or N_1. According to the state variable W (W or $\overline{W}$) the positive or negative conditioned reflexes CR 1 and CR 2 are generated; items 9 and 10 show that both N_2 and N_1 produce the conditioned reaction: the model has 'generalized' the input variable.

The repeated application of N_2 or N_1 without S_3 'habituates' the model, and it becomes 'internally inhibited' (items 11 and 12). During the inhibition, N_2 produces passive discrimination (item 13). After 2 min, the inhibition disappears and the conditioned reflexes will be re-established, in order to allow discrimination between N_2 and N_1 to take place.

A shock turns the model into the antagonistic dominant state (item 17).

Items 18 and 19 illustrate 'mutual induction', i.e. the reversal of reactions on N_1 and N_2, whereas in item 20 'spontaneous' recovery of state No. 17 is shown.

Switching off the model clears all stores to 0.

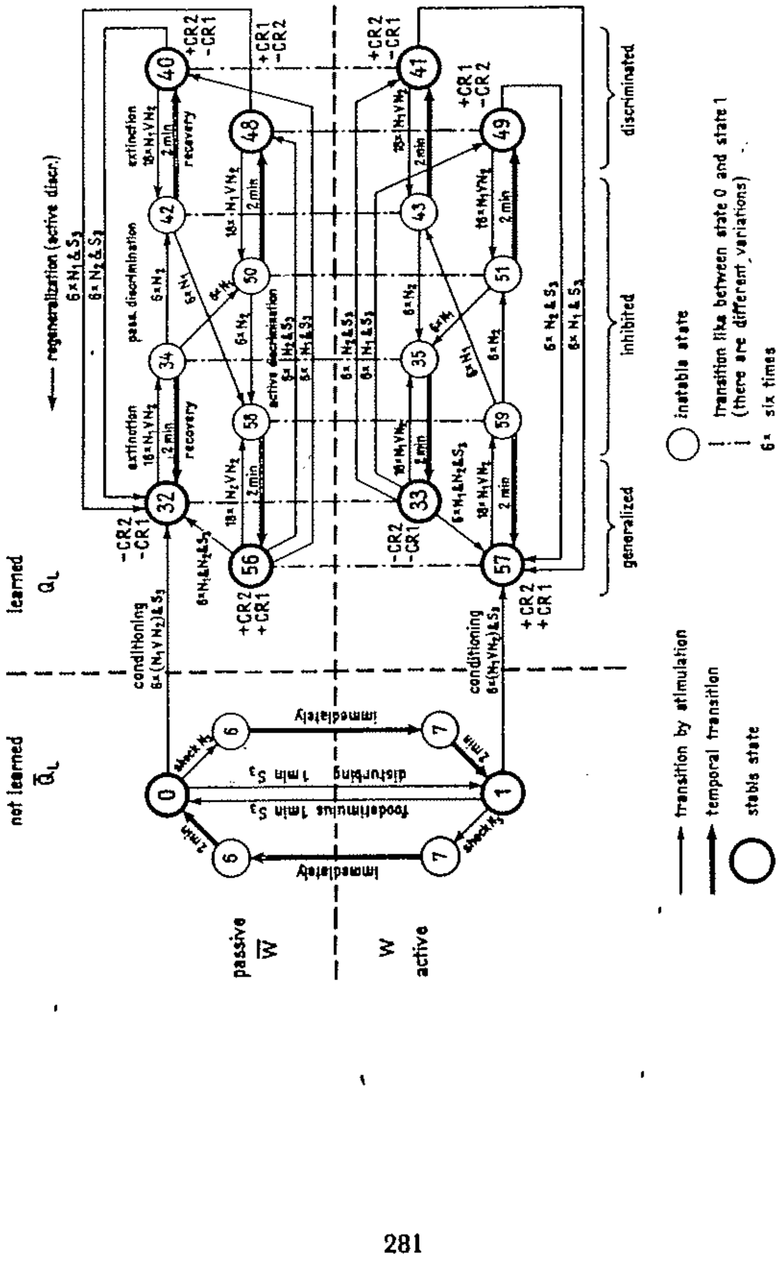


Figure 11. State diagram of model No. 4. This is a simplified version, the transitions between the passive and the active states are only indicated

Brief technical description

While the logical description is based on dynamic techniques (time is strictly quantized and the variables and functions are sequences of values 0 or 1 for each moment), the model has been designed using a static technique: relay

Table I. Example of action pattern

(The arrow means temporal sequence, e.g. $E_2 \rightarrow E_3$ means E_3 after E_2)

No.	Comment	Input	State							Output
			No.	Q_L	Q_1	Q_3	Q_N	Q_I	W	E_i
0	ON	—	0	0	0	0	0	0	0	E_0
1	Strong light	S_3	0	0	0	0	0	0	0	E_3
2	After 3 min	—	0	0	0	0	0	0	0	E_1
3	After 1 min strong light	S_3	1	0	0	0	0	0	1	
4	Two pitches of sound or weak light	N_2, N_1, S_1	1	0	0	0	0	0	1	E_1
5	Obstacle	T	1	0	0	0	0	0	1	E_2
6	Strong light	S_3	1	0	0	0	0	0	1	E_3
7	Tone and strong light	$S_3 \& N_1$	1	0	0	0	0	0	1	E_3
8	Learning 6 times	$S_3 \& N_1$	57	1	1	1	0	0	1	
9	Pos. cond. reflex on N_1	$N_1 \& S_1$	57	1	1	1	0	0	1	$E_1 \rightarrow E_3$
10	Pos. cond. reflex on N_2	$N_2 \& S_1$	57	1	1	1	0	0	1	$E_2 \rightarrow E_3$
11	Extinction 18 times	N_2 v N_1	59	1	1	1	0	1	1	E_2
12	Internal inhibition	N_2 v N_1	59	1	1	1	0	1	1	E_1
13	Passive discrimination 6 times	N_2	51	1	1	0	0	1	1	E_1
14	Recovery, after 2 min	—	49	1	1	0	0	0	1	E_1
15	Pos. cond. reflex on N_1	$N_1 \rightarrow S_1$	49	1	1	0	0	0	1	$E_5 \rightarrow E_3$
16	Neg. cond. reflex on N_2	$N_2 \rightarrow S_1$	49	1	1	0	0	0	1	$E_2 \rightarrow E_3$
17	Strong sound	N_3	54	1	1	0	1	1	0	E_0
18	Mutual induction	$N_1 \rightarrow S_1$	54	1	1	0	1	1	0	$E_2 \rightarrow E_3$
19	Mutual induction	$N_2 \rightarrow S_1$	54	1	1	0	1	1	0	$E_2 \rightarrow E_3$
20	After 2 min	—	48	1	1	0	0	0	0	E_0
21	Conflict	$N_2 \& N_1 \& S_1$	48	1	1	0	0	0	0	$E_2 \rightarrow E_3$
22	1 min strong light	S_3	49	1	1	0	0	0	1	
23	Active discrimination 6 times	$S_3 \& N_2$	57	1	1	1	0	0	1	
24	Strong sound	N_3	62	1	1	1	1	1	0	E_0
25	External inhibition	N_3 v N_1	62	1	1	1	1	1	0	E_0
26	Recovery after 2 min	—	56	1	1	1	0	0	0	E_6
27	Searching after (further) 1 min	—	56	1	1	1	0	0	0	E_1
28	OFF	—	0	0	0	0	0	0	0	E_3

contacts and potentials are maintained for the time between activation and disactivation (time quantization is not strictly necessary and series of ones are replaced by blocks of direct current.

The receptors—A microphone controls two selective feedback amplifiers for N_2 and N_1 and one biased amplifier for N_3. The decision between 0 and 1 depends on thresholds circuits in the amplifiers.

A phototransistor with a cylindric lens controls a multistage D.C. amplifier which discriminates strong (S_3) and weak (S_1) light and which includes the differentiating circuits D_0 and D_1.

Instead of Walter's moving shell this model has a relay circuit for checking the motor current. When an obstacle is encountered, the motor current increases and the relay operates, i.e. $T = 1$.

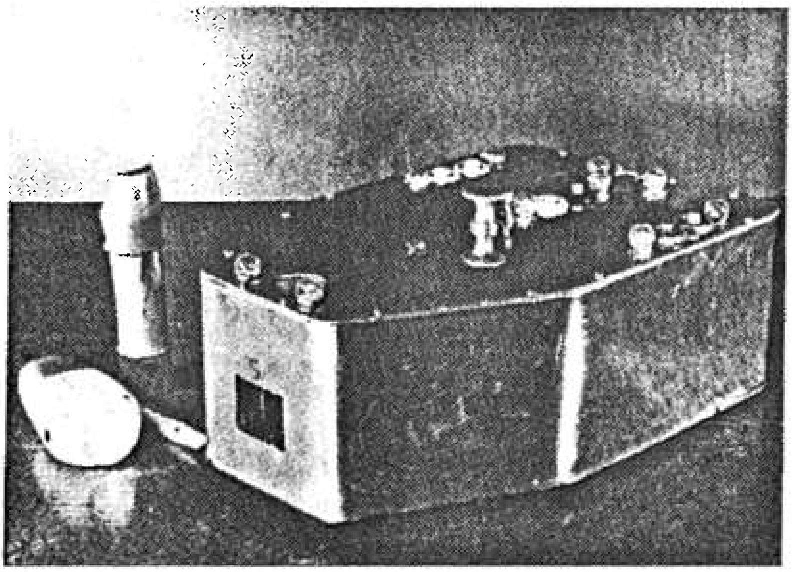


Figure 12. Photograph of model No. 5 with cover. (Model No. 5 is a second version of model No. 4 with small alterations)

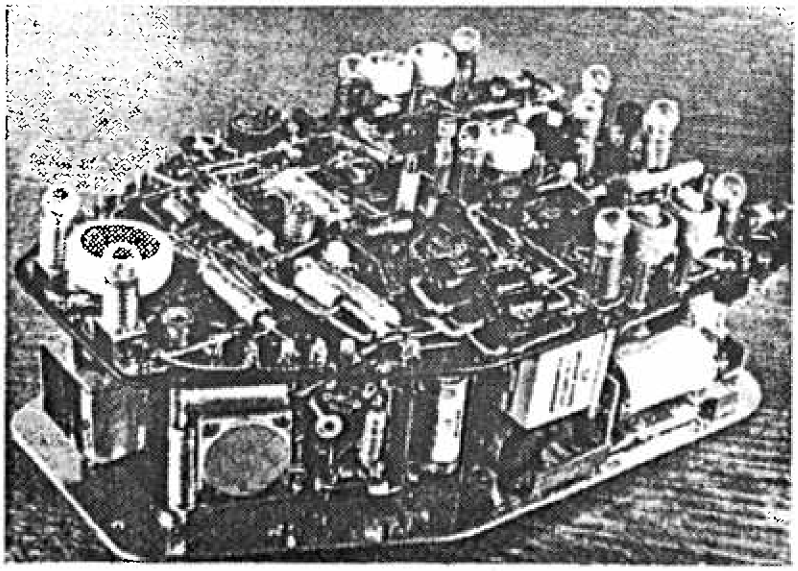


Figure 13. Photograph of model No. 5 without cover

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Information processing circuits—The logical functions make use of relay contacts and diode circuits. Delays are produced by thermistors or by RC networks; storing is by self-locking relays.

The counters are networks of contacts and capacitors controlling bi-stable relays with neon lamps.

The effectors—These actually consist of two motors controlled in a way that produces the desired movements E_6 through E_0. A special effect is the goal-seeking mechanism which is controlled by the single phototransistor: every time a beam of light reaches the phototransistor there will be a slightly delayed change-over from one motor to the other resulting in a serpentine movement.

Technical data: differences between models 4 and 5—There is no basic difference between the two models 4 and 5. Both are compact automata running on two wheels (each wheel driven by a separate motor) and one ball-type castor. A 6 volt Ni-Cd-battery powers the entire equipment of two motors, 19 relays, 14 transistors and 8 pilot lamps. A D.C.-converter supplies 270 volt for the counting units. 6 push-buttons also permit manual establishment of various states.

Model 5 used the experience gained in constructing model 4 and has somewhat smaller dimensions (10 in. by 7 in. by 4 in.) and lower weight (about 5 lb.).

PROGRAMMING OF BIOLOGICAL MODELS

Figure 10 makes it clear that both technical design and logical examination of such intricate models is an involved job. In particular, development and functional improvements on the model can be made only by engineering experts who, in addition, understand the biological language.

A much better, more straight-forward, more flexible and less expensive answer to the problem of biological models would be programming on a computer. This, however, is subject to two pre-requisites. First, biologists must be able to express the functional structures to be simulated by a model in terms of logical algebra; secondly, an algorithmic language for logical algebra and the associated formula translator must be developed. In 1960, the Viennese team working with the computer MAILÜFTERL began investigations on the processing of logical data by this computer; consideration is at present given to the development of a suitable algorithmic language. Efforts are being devoted to programming the structure of *Figure 10.*

The authors wish to give acknowledgement to the Rockland State Hospital for financing model No. 4 and to Siemens & Halske, Wernerwerk München, for supplying most of the relays. They are indebted to the MAILÜFTERL team for helpful discussion as to logical programming and to H. Resele for help in translation work.

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DISCUSSION

J. E. MEOOITT: If into any electronic computer performing a programme one inserts a probe, one will in general discover a complex waveform, probably consisting of apparently random pulses. However this waveform will not enable the observer to discover very much, either about the computer, or about the programme, except that there is a fair degree of complexity.

If one simulates a model of a nervous system on a computer and if one then looks at a waveform inside it, this seems analogous to looking at a waveform in the actual animal nervous system of which this is a model; so it seems to me that one should not be surprised at apparently random waveforms. Statistical models purporting to explain these waveforms seems to me to have no relevance.

H. ZEMANEK in reply: The point is, in our case and in similar cases, not the explanation of waveforms but the checking of the logical structure underlying the model. If this structure is correct, the response of the model to any stimulus must be the same as the response of the modelled system. If the answer is not correct, the model needs further consideration and development. Whereas the structure of the modelled system may be fully or almost fully unknown, the structure of the model or the modelling programme *is* known, and the wrong or weak feature can be detected. By such a process the structure of the model is corrected and, within the limits of the considered features, the same as that of the modelled system.