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The first biologically inspired robots

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SUMMARY

Thie first biologically inspired robots, the famous electromechanical tortoises, were designed and built in 1949 by W. Grey Walter. This paper reviews their origins in Walter's theories of the brain and the nature of life, and uses contemporary unpublished notes and photographs to assess their significance then and now.

KEYWORDS: First biological robots; Robot tortoises.

INTRODUCTION

Most articles and books on the history of robotics make only a passing reference to Grey Walter's robot tortoises,[1,2,3] regarding them as quaint period curiosities quite unrelated to our intellectually and technically sophisticated modern creations. This is to some extent understandable, because very little of a satisfactory scientific nature was ever published about the tortoises, and the information that did appear is relatively inaccessible to today's researchers because the technologies employed have been obsolete for a generation. However, in recent years, several previously unknown documents, films, photographs, and even examples of these remarkable machines have been discovered, and it has become clear that their significance must be reassessed. They were in fact the first biologically inspired robots, as well as the first behaviour-based robots;[4] perhaps more importantly, the insights they gave into both robotics and biology are exactly those towards which the new robotics community has been struggling for the last fifteen years. Moreover, they were not simply the expression of the unique and peculiar interests of their creator, but formed part of the ongoing development of a British cybernetics tradition which was consciously attempting to fuse ideas from communications and control with those from biology.

The aim of this paper is to present the evidence for these claims using original materials wherever possible, so that readers may judge the matter for themselves. Some of this archive material has not previously been published; some has appeared in piecemeal form, but is here brought together and published in full for the first time.

GREY WALTER

In any account of the tortoises, it is best to start with a biographical sketch of their inventor. William Grey Walter, universally known as 'Grey', was born in 1910, in Kansas City, where his British father was editor of the Kansas City Star. After attending Westminster School, he studied physiology at Cambridge, and began his research career in neurophysiology with a dissertation on 'Conduction in Nerve and Muscle'. In 1935 he became interested in the new area of electroencephalography, and quickly showed a talent for developing new electronic equipment, which he used to make a series of fundamental technical and clinical discoveries. In 1939 he was appointed Director of Physiology at the newly founded Burden Neurological Institute (BNI) in Bristol; he remained there for the rest of his career. His war work involved him in a variety of activities, including the development of radar, and the use of humans in control loops. After the war he recruited a brilliant group of ex-radar engineers to work with him at the BNI; their technical expertise, combined with Grey Walter's vision and creativity, made a major contribution to the development of electroencephalography over the next twenty years.

The BNI bibliography credits Grey Walter with 174 publications, all but a few dealing with the electrical activity of the brain, and related technical issues. Among other achievements, he identified and named delta rhythms, discovered abnormal EEGs between epileptic seizures, built the first on-line frequency analyser, discovered and named theta rhythms, and discovered the contingent negative variation (expectancy wave). He founded the EEG Society, and co-founded the International Federation of EEG Societies and the EEG Journal. He was at the peak of his powers when he sustained severe head injuries in a motorcycle accident in 1970. Although he recovered physically, and returned to the BNI until his retirement in 1975, his career was effectively over. He died in 1977.

THE TORTOISES

In reference [4], Grey Walter's son, the late Nicolas Walter, recalled discussing his father's work with him in the Spring of 1948, and was certain that no mention was made of any robots or electromechanical models. However, by December 1949, Grey Walter was demonstrating Elmer and Elsie, the first two tortoises, to the press; Figure 1 is a typical photograph from this period, and demonstrates the flair for showmanship of which many of Grey Walter's contemporaries disapproved. An article by the journalist Chapman Pincher, in a December 1949 Daily Express, gives accurate technical details of the robots' construction and behavioural repertoire, along with some interesting background information: Elmer, 'the prototype', is reported to have been built 'more than a year ago'. The robots were built in the 'backroom laboratory' of his house by Grey Walter, 'helped

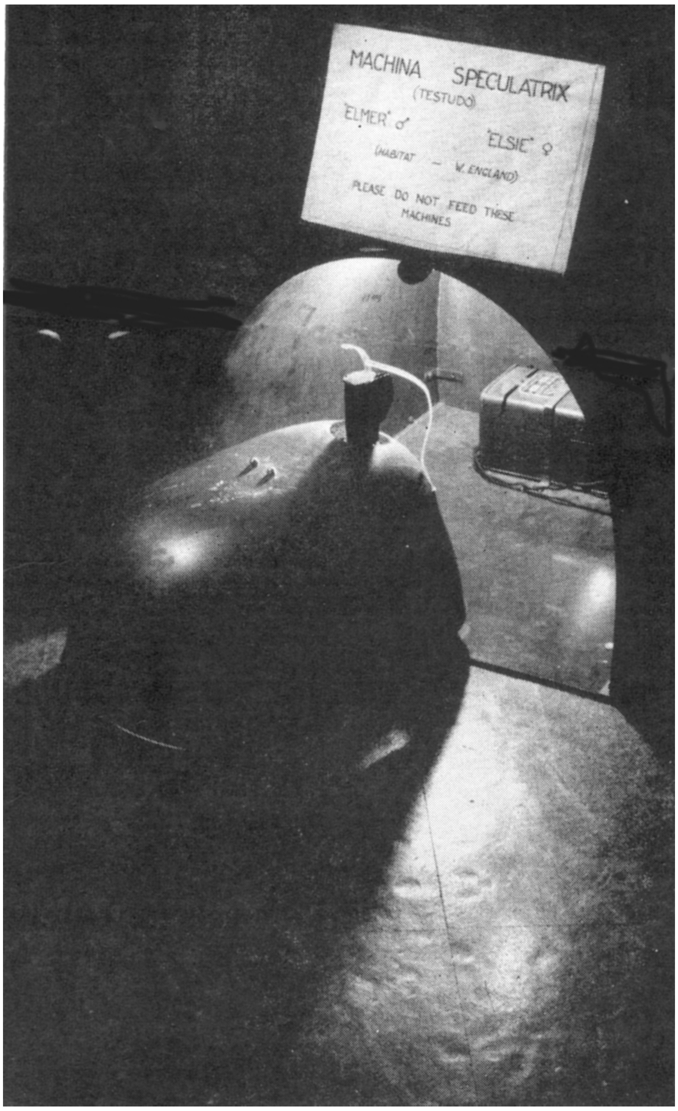

Fig. 1. Dating from 1949, this is probably the earliest surviving image of Elsie, the second tortoise. Through the door of the hutch we can see part of the battery charger. The rather whimsical notice above the hutch reads "Machina speculatrix (Testudo) . . . Habitat – W. England. Please do not feed these machines."

by his wife Vivian'. (Vivian Walter, formerly Vivian Dovey, had been a colleague for many years; she was a co-author with Grey Walter of eight papers on electroencephalography between 1944 and 1957.) Other newspaper accounts were less accurate and more sensational: "Toys which feed themselves, sleep, think, walk, and do tricks like a domestic animal may go into Tommy's Christmas stocking in 1950, said brain specialist Dr. Grey Walter in Bristol last night. For two years he has been experimenting with toys containing an electric brain . . . Dr. Walter said the toys possess the senses of sight, hunger, touch, and memory. They can walk about the room avoiding obstacles, stroll round the garden, climb stairs, and feed themselves by automatically recharging six-volt accumulators from the light in the room. And they can dance a jig, go to sleep when tired, and give an electric shock if disturbed when they are not playful . . . Dr. Walter said: 'There is no other machine like it in the world. This hobby of making toys with brains is proving of great value in the study of the human brain'. The toy has only two cells. The human brain has ten thousand million. 'But', said Dr. Walter, 'most people get along with using as few as possible'.

Some popular magazine articles followed in early 1950, and the BBC filmed a newsreel piece for a television broadcast at around the same time. The transcript of the newsreel commentary reads: "In a modest villa on the outskirts of Bristol lives Dr Grey Walter, a neurologist, who makes robots as a hobby. They are small, and he doesn't dress them up to look like men – he calls them tortoises. And so cunningly have their insides been designed that they respond to the stimuli of light and touch in a completely life-like manner. This model is named Elsie, and she sees out of a photo-electric cell which rotates about her body. When light strikes the cell, driving and steering mechanisms send her hurrying towards it. If she brushes against any objects in her path, contacts are operated which turn the steering away, and so automatically she takes avoiding action. Mrs Walter's pet is Elmer, Elsie's brother, in the darker vest. He works in exactly the same way. Dr Walter says that his electronic toys work exactly as though they have a simple two-cell nervous system, and that, with more cells, they would be able to do many more tricks. Already Elsie has one up on Elmer: when her batteries begin to fail, she automatically runs home to her kennel for charging up, and in consequence can lead a much gayer life."[5] The film itself is a rather more useful source of information. As far as is known, it is the only surviving record of the first two tortoises in action. Careful analysis reveals three interesting facts: the obstacle avoidance/escape response on one of the tortoises did not work; part of the film is run at double speed, presumably to make it more interesting to the viewers; and, in the final sequence where Elsie makes a beeline for her hutch and the charging station, the steering mechanism has almost certainly been disabled to produce a straight path. Although these to some extent devalue the film as a record of the tortoises' performance, they give a useful insight into the unreliability and variability of the machines.

THE SCIENTIFIC RECORD

The first scientific publication dealing with the tortoises is Walter's Scientific American paper of May 1950, entitled 'An Imitation of Life'.[1] It clearly sets out the biological inspiration for the project; Walter even gave the tortoises a mock-biological name, Machina speculatrix 'because they illustrate particularly the exploratory, speculative behaviour that is so characteristic of most animals'[1] (p. 43). Although the paper contains eight roughly-drawn sketches illustrating the tortoises' behaviour, it gives only the briefest textual description of the constructional and electronic details of the robots, and it is not always possible to see exactly how each type of behaviour is generated. A follow-up paper in Scientific American, entitled 'A Machine that Learns',[2] discusses the addition to a tortoise of a hardware learning mechanism (CORA – the conditioned reflex analogue). It includes a time exposure photograph of Elsie, with a candle mounted on her back, finding and entering the hutch; the streak of light left by the candle enables the robot's trajectory to be seen. However, the major published source of information on the tortoises is Walter's book 'The Living Brain', published in 1953.[3] (One possible problem with using the book as a source is indicated in some notes by Nicolas Walter[6] for Grey Walter's entry in the Dictionary of National Biography: 'He also wrote many articles; but he found it difficult to produce more sustained work, and both of his two books were actually written by his father from his notes and conversations'. Grey Walter dedicated the book 'To my father, with whom this book was happily written'. Perhaps Nicolas's revelation explains why much of the language in the book seems more literary than scientific.)

WALTER'S INSPIRATIONS

In 'Totems, Toys, and Tools', Chapter Five of 'The Living Brain', Walter expands and supplements the material in 'An Imitation of Life'. He begins by noting that he could see no practical prospect of building a working model of the brain that had the same number of working components; with 10,000,000,000 units, it would be too large, too expensive, and too power-hungry. "An entirely different approach seemed necessary to make it a practical problem, if we were to learn about life by imitation as well as observation of living things . . . It meant asking whether the elaboration of cerebral functions may possibly derive not so much from the number of its units, as from *the richness of their interconnexion* . . . As a hypothesis, this speculation had the great advantage that its validity could be tested experimentally. An imitation of two or three interconnected elements, including reflexes to demonstrate their behaviour, should be a simple matter for a laboratory that had produced the EEG analyser and the toposcope",[3] (pp. 117–118). In building the tortoises, his intention was therefore, at least in part, to test this hypothesis, and the biological inspiration is clear.

What lay behind this plan was that he had realised that the number of different ways of connecting up a number of elements was very much larger than the number of elements, and that it might be possible to devise a system to exploit that. He began by supposing that each different pattern of interconnection could be made to produce a different system response. He worked out that a system of 1,000 elements could be interconnected in about $10^{300,000}$ different ways – a number of responses sufficient, he thought, for any conceivable individual entity. ". . . Even were many millions of permutations excluded as being lethal or ineffective . . .",[3] (p. 120). But how might different patterns of interconnection give rise to different observable behaviours? He gained some insight into this problem by reasoning as follows: ". . . how many ways of behaviour would be possible for a creature with a brain having only two cells? Behaviour would depend on the activity of one or both of these cells – call them A and B. If (1) neither is active, there would be no action to be observed; if (2) A is active, behaviour of type *a* would be observed; if (3) B is active, behaviour of type *b*; if (4) A and B are both active, but independently, there would be behaviour of both types *a* and *b*, mixed together; if (5) A is "driving" B, type *b* would be observed, but subordinate to A; if (6) B is "driving" A, type *a* would be subordinate to B; if (7) A and B are "driving" each other, behaviour will alternate between type *a* and type *b*. The internal states of such a system in these seven modes may be represented symbolically as:

$$\mathrm{O, A, B, A+B, A \rightarrow B, A \leftarrow B, A \leftrightarrows B}$$

with behaviour types:

$$o, a, b, a+b, b(\mathrm{fA}), a(\mathrm{fB}), ababab \ldots$$

From the above it will be seen that the first four ways of behaviour would be identifiable by simple observation, without interfering with the system, whereas the last three could only be identified by operating on the system – by, as it were, dissecting out the arrows"[3] (pp. 118–119).

There remained the question of what sort of behaviour the model should produce. Here again, Grey Walter took inspiration from biology: "Not in looks, but in action, the model must resemble an animal. Therefore it must have these or some measure of these attributes: exploration, curiosity, free-will in the sense of unpredictability, goal-seeking, self-regulation, avoidance of dilemmas, foresight, memory, learning, forgetting, association of ideas, form recognition, and the elements of social accommodation. Such is life"[3] (pp. 120–121). Of these thirteen attributes, six (from foresight to form recognition) are those derived from the learning machine CORA, and so are not really properties of the two-celled tortoises alone. In practice, Grey Walter did not regard this list as binding or exhaustive, and often added further animal-like attributes as he saw fit.

THE BRITISH CYBERNETICS MOVEMENT

The direct inspiration for the construction of the tortoises, revealed in 'The Living Brain', is at first sight, rather surprising: "The first notion of constructing a free goal-seeking mechanism goes back to a wartime talk with the psychologist, Kenneth Craik . . . When he was engaged on a war job for the Government, he came to get the help of our automatic analyser with some very complicated curves he had obtained, curves relating to the aiming errors of air gunners. Goal-seeking missiles were literally much in the air in those days; so, in our minds, were scanning mechanisms. Long before (my) home study was turned into a workshop, the two ideas, goal-seeking and scanning, had combined as the essential mechanical conception of a working model that would behave like a very simple animal"[3] (p. 125). Today, these ideas seem redolent of cybernetics rather than biology, yet Wiener's 'Cybernetics'[7] was not published until 1948. How had this strand appeared in Walter's thinking at such an early date? The answer, which is only just emerging, is fascinating: there was a strong and independent British interest in cybernetic ideas long before Wiener's landmark book. Walter's own view of Wiener can be seen in a letter to Professor (later Lord) Adrian (12th June 1947): "We had a visit yesterday from a Professor Wiener, from Boston. I met him over there last winter and find his views somewhat difficult to absorb, but he represents quite a large group in the States, including McCulloch and Rosenblueth. These people are thinking on very much the same lines as Kenneth Craik did, but with much less sparkle and humour".[8]

Perhaps the best indication of the early maturity of British cybernetic thinking comes from the archives of the Ratio

Club, a ‘cybernetic dining club’ founded by the neurologist John Bates in 1949, and dissolved in 1958. Membership was by invitation only, and Bates’ idea (set out in a letter to Grey Walter dated 7/7/1949) was that the club should consist of “about fifteen people who had Wiener’s ideas before Wiener’s book appeared”.[9] In fact they found twenty such people, including Ross Ashby, Horace Barlow, Donald MacKay, Grey Walter, Alan Turing, Jack Good, and ‘Pete’ Uttley. Their attitude is nicely summed up by Bates in the draft of a paper on cybernetics intended for the British Medical Journal: “Those who have been influenced by these ideas so far, would not acknowledge any particular indebtedness to Wiener, for although he was the first to collect them together under one cover, they had been common knowledge to many workers in biology who had contacts with various types of engineering during the war.”[10]

THE DESIGN OF THE TORTOISES

There are no records of any intermediate stages in the design of the tortoises. The two models shown in 1949 were in their final form, and the six subsequent examples manufactured in early 1951 differed only in detail. (The first two tortoises appear to have been dismantled in 1951.) The best published account of the electronic design of the control system appears in Appendix B of ‘The Living Brain’, along with a circuit diagram described as ‘only one of many possible arrangements’[3] (pp. 287–292). The accompanying description of the mechanical design, which contains no diagrams, appears to be not so much an account of what Walter had built, but more of a guide for anyone who wanted to build his own tortoise. The net effect is that it would be practically impossible for anyone relying on these sources alone to understand exactly how the tortoise produces each piece of ‘animal-like’ behaviour; this represents a severe potential difficulty in the scientific evaluation of the machines. Fortunately, the discovery of a number of manuscripts, photographs, and diagrams in the archives of the BNI has meant that today we are in a much better position to judge Walter’s achievement than his contemporaries ever were. An additional factor is that two tortoises from the 1951 batch have survived, and both have recently been put on public display. (One is in the Science Museum, London, and the other is in the MIT Museum, Boston, on loan from the Smithsonian Institute, Washington.) In 1996, the London tortoise was used as a model for the construction of two working replicas at the University of the West of England, Bristol; some of the findings of this project are described in reference [4].

In order to understand how the tortoises worked, it is probably best to start with the mechanical design. Figure 2 is a labelled view of Elsie with her shell removed. On the left, a single structure extends vertically from the photoelectric cell down to the driving wheel; this structure is capable of being rotated in one direction only about its vertical axis by the steering motor acting via the steering gear. The driving wheel also rotates in one direction only when driven by the driving motor. The two rear wheels, seen on the right, are not driven. The photoelectric cell is fitted with a shroud which blocks the entry of light from all directions except the front of the cell; the shroud and cell are aligned with the driving wheel so that the direction in which light is sensed is always the direction toward which the driving wheel is moving. When the shell is fitted, it is hung on the rubber touch contact mount. If the tortoise is on the level, and the shell is not touching anything, the contact is

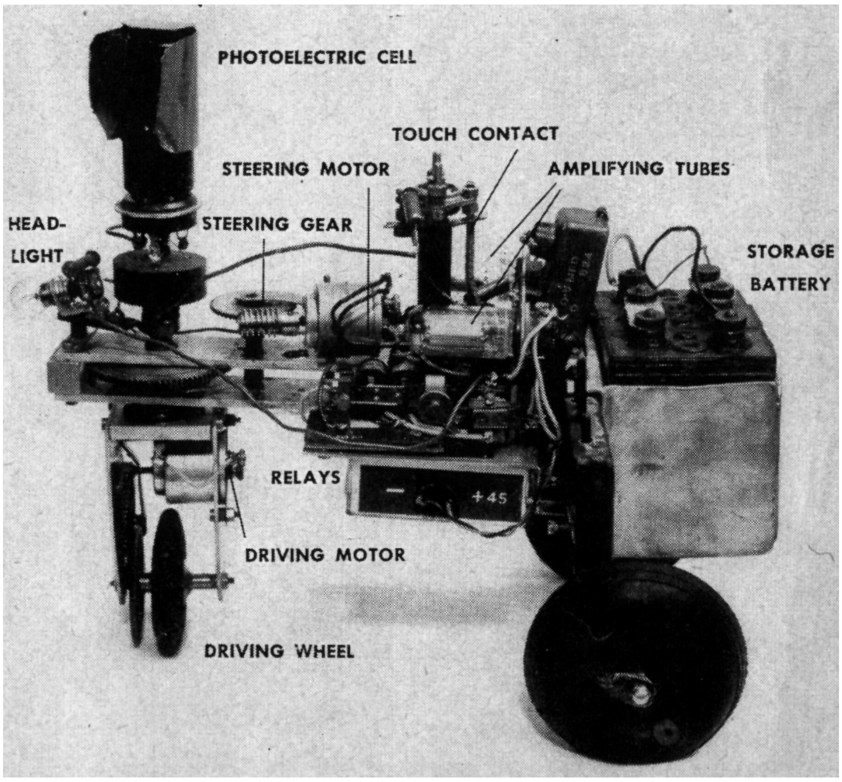

Fig. 2. A labelled illustration from the files of the Burden Neurological Institute, showing a tortoise (Elsie) with its shell removed.

open circuit, but if the shell is deflected by gravity (when the tortoise is on a slope) or touch, the contact is closed. The headlamp is a torch bulb connected in series with the steering motor, so that it is lit only when the motor is turned on; a hole in the shell allows the headlamp to be seen from the front when the shell is on.

The circuit diagram shown in 'The Living Brain' is unfortunately not very easy to understand; Figure 3 shows a rather clearer version from the BNI archives which describes the circuit used in the 1951 batch.

The photoelectric cell (PEC) is on the extreme left; just above it is the switch contact. The two miniature thermionic valves, or vacuum tubes, are represented by the two circular symbols in the upper half of the diagram. Current flows through the valves from the upper flat electrodes (the anodes, or plates) to the lower looped electrodes (the cathodes). The dotted lines within the symbols represent the control electrodes, which control the current flow; the upper control electrode is known as the screen, and the lower as the grid. Above each valve is a relay coil (marked RL1 and RL2); when sufficient current passes through a relay coil, it changes over the contacts on the corresponding relay (marked RL1 and RL2 below each valve). When the relays are 'off' (i.e. when the coil current is low) each relay is connected to the steering or turning motor; when they are 'on', they are connected to the driving motor. RL1 can deliver only about half the current of RL2, as it is connected to the power line via the headlamp and a resistor, whereas RL2 is connected directly.

THE OPERATION OF THE TORTOISES

How do the mechanical construction and the circuit interact with environmental conditions to produce behaviour? Until recently, the only available sources (Walter, 1950, 1953) gave little more than summary descriptions of the behaviours, with very shallow technical content. However, a remarkable document[11] found in the BNI archives enables us to both understand how the tortoises worked, and appreciate how Grey Walter himself viewed their operation. The typed document is headed 'Machina Speculatrix – Notes on Operation'; it can be dated to around 1960. The front page, which is marked 'Please return to GW' in Grey Walter's hand, is clearly intended to be read by someone who has just received a tortoise and wishes to set it up for a demonstration; the main text, which is probably unfinished, since it ends rather suddenly and without any conclusion, is a clear and insightful technical explanation of how the tortoise produces lifelike behaviour. The whole text, from which a long excerpt is published in reference [4], is here presented for the first time complete and unabridged. It is best read in conjunction with the circuit diagram (Figure 3).

"Machina Speculatrix
("Robot tortoise")

"When we were little . . . we went to school in the sea. The master was an old Turtle – we used to call him Tortoise".
"Why did you call him tortoise if he wasn't one?" Alice asked.
"We called him tortoise because he taught us" said the Mock Turtle angrily: "really you are very dull!"
(*Alice's Adventures in Wonderland*, Lewis Carroll).

The first "artificial animal" was built about 12 years ago to test some theories about how simple machines could develop complex behaviour if their parts were allowed to interact more freely than usual. This first hardware pet was called "Machina speculatrix" because it is not a passive machine like a typewriter or an electronic computer that waits for a human being to operate it – M. Speculatrix *speculates*, it explores its environment actively, persistently, systematically as most animals do. This is its first and basic *Behaviour Pattern (E)* and appears when it is switched on by the lever at the back on the right being pushed *forward*. (When unpacked the batteries must be inserted and the link

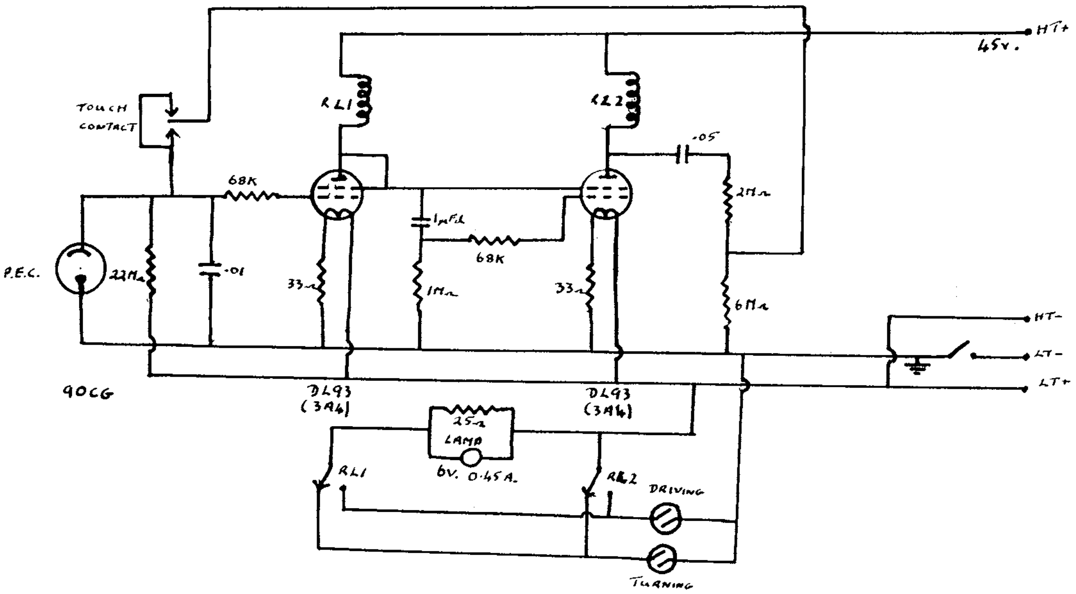

Fig. 3. The original circuit diagram for the 1951 batch of tortoises, preserved in the Burden Neurological Institute archives. It is particularly useful because it gives device types and component values.

which is left un-connected for transport to avoid accidental starting must be attached). When it is switched on three circuits are closed:

(Note: the circuit diagram shows both relays in the open position. However, when the circuit is powered up in the absence of light, RL1 closes – OEH)

(i) The driving motor is on at half speed, the headlamp being in series with it. This propels the model slowly in the direction of the driving wheel. But this is itself rotated by –

(ii) The steering scanning motor (which) is on at full speed. This turns the driving wheel continuously so that the direction of motion is continually changing. The same spindle supports the photoelectric cell or "eye" so this rotates too; it is always "looking" in the direction in which the model is moving. This is called *scanning*. The combination of linear motion (driving) with circular rotation (steering-scanning) gives the model a *cycloidal* trajectory, rather like a point on the wheel of a moving vehicle. This cycloidal exploration continues indefinitely in the dark or when there is no light on the horizon bright enough to affect the "eye". (The mask on the eye provides both blinkers that give it a direction of gaze and a visor that stops it seeing ordinary room lights above it). But when a light is "seen" the behaviour changes because switching on also –

(iii) Provides current for the filaments of the two miniature vacuum tubes. These amplify the response of the photoelectric cell to light so that, when a moderate light is seen, the relay in the plate circuit of the second tube closes. This introduces behaviour pattern P, the positive phototropic or light-seeking response.

Pattern P involves immediate closing of relay 2. This disconnects the steering-scanning motor so that the driving wheel is fixed at whatever angle it was when the light was seen, and the scanning of the horizon by the eye also stops of course. At the same time the "make" contact on the relay short circuits the headlamp which was in series with the drive so that the driving motor is turned up to full speed. The model stops looking slowly round and hurries toward the light. However, unless the light was seen when the eye happened to be facing straight ahead, the angle at which the steering came to rest at the moment of sighting will deflect the model gradually *away* from the light. When the deflection is so great that the activation level of the photocell falls below threshold, the Relay 2 opens again, the scanner starts up, the drive is reduced to half speed and the model is re-positioned, this time so that the light is more directly ahead. This process of *progressive orientation* is an important part of the behaviour mechanism. It is cumulative – every time the model steers itself slightly off-beam, the momentary operation of the steering-scanning mechanism brings it back more nearly on course and it ends up with a heading on-beam. The process often looks clumsy, because the eye seems to veer away from the light and then the scanner has to make nearly a whole rotation to bring it back, but inevitably with each such operation the model gets itself into a better position to bear down directly on its goal. The aiming-error is steadily reduced as the goal is approached. As the model gets near to a bright light – a 40 watt lamp or a hand flashlamp – it "sees" the light as brighter and brighter – the brilliance of a light is inversely proportional to the square of the distance from it. For example, if the brilliance of a light was just great enough to operate the Relay 2 four feet away, the apparent brilliance will be four times greater (from the model's viewpoint) when it gets two feet up to the light. When it gets close enough the behaviour will change again to:

Behaviour pattern N, that is *negative phototropism*; the model will *avoid* a *bright* light. This is because the two vacuum-tubes are in series or "cascade". The action of a moderate light on the photo-cell is so weak that it does not affect Relay 1 in the plate circuit of Tube 1, only the Relay 2 after amplification by *both* tubes. But a bright light produces enough change in the photocell to *open* Relay 1 after only one stage of amplification and this relay starts the steering scanning motor going again at half speed through the headlamp. The drive motor is still full on because, of course, Relay 2 is still firmly closed. The result is that when the model gets "too close" to a light it veers smoothly away from it and avoids the fate of a moth in a candle. M. Speculatrix is moderate and restrained – it seeks an *optimum* light, not a maximum.

There is a minor feature of the light-seeking manoeuvre which is hard to notice but is quite important both to the success of the model's speculation and to its resemblance to living creatures. The coupling between the two vacuum-tube amplifiers is "semi-direct". There is a capacitor from the plate of Tube 1 to the control grid of Tube 2, in the conventional fashion. This provides for high amplification of *transient* signals; the glimpse of a light will have the maximum effect on Tube 2 and therefore upon Relay 2. Thus, a distant light will just stop the scanner and put on full drive for a moment so that the model will start toward the light, but the effect will die away and the scanner will start up again. Next time round the model will be a little nearer the light and the hold period will be a little longer and so on. But there is another connection between Tube 1 and Tube 2, directly from the first plate to the second screen. This keeps the screen of Tube 2 at the correct positive voltage (the plate voltage of Tube 1) and at the same time provides for amplification of larger signals without decay in time. So as the model gets nearer to a light, the closing of Relay 2 lasts longer and longer and finally it stays closed as long as the eye is on the light. In mathematical terms small signals are *differentiated*, large ones are *integrated*. In physiological jargon the model adapts to faint stimuli but maintains its response to intense ones.

If the way to the goal is clear the model will approach and circle around any adequate light, will leave bright lights in search of more moderate ones and explore the whole room in this way. But life is full of obstacles, even for humble hardware, and if the model bumps into something, its behaviour will change again. Its skin is slung on a rubber bush which allows it to pivot freely; the skin movements are restricted only by a stick-and-ring limit switch in its belly. Beyond a certain range of movement in any direction this switch connects the grid of Tube 1 to the plate of Tube 2 through a capacitor, and this produces another change in behaviour to

Pattern O, Obstacle avoidance. Normally the two vacuum tubes act as amplifiers with the joint and individual effects described for Patterns P and N. But when, by displacement of the skin the output plate of Tube 2 is connected back to the input grid of Tube 1 the whole system is transformed from an amplifier to an oscillator, since any signal that appears on grid 1 is amplified by Tube 1 and by Tube 2, the much bigger signal is fed back to the grid of Tube 1 and so on. This sort of amplifier is called a "multivibrator" – because it generates a multitude of vibrations. As arranged in M. Speculatrix, the oscillators (sic) recur about once a second, and their effect is to open and close Relays 1 and 2 alternately as long as the skin is displaced. This makes the model butt, turn and recoil continuously until it is clear of the obstacle. It may edge steadily along until it comes to an edge it can get round, it may shove the obstacle to one side if it is movable, or if it gets into a tight corner it may end by swivelling right round and trying another approach. In any case it is very pertinacious and it is also quite discerning, because as long as it is in trouble it will not respond to a light, however intense and attractive. It cannot, because as long as the skin is displacing the limit switch, the amplifiers are completely preoccupied with sending signals back and forth to one another and are quite blind to outside information – an oscillator does not act as an amplifier. When the model has cleared an obstacle and the skin swings back to its normal position, the input-output circuit is opened and after one more oscillation the amplifiers resume their function of transforming light signals into movements of the relays and the whole model.

A similar effect is produced by more subtle obstacles – a steep gradient that tips the skin to the limit or rough ground that makes it wobble will bring in the obstacle-avoiding oscillation.

If there are a number of light low obstacles that can be moved easily over the floor and over which the model can see an attractive light, it will find its way between them, and in doing so will butt them aside. As it finds its way toward the light and then veers away from it and wanders about, it will gradually clear the obstacles away and sometimes seems to arrange them neatly against the wall. This tidy behaviour looks very sensible but is an example of how apparently refined attitudes can develop from the interaction of elementary *reflex functions*. This is particularly evident when one reflex pattern is *prepotent* over another; in M. Speculatrix, Pattern O is prepotent over Pattern P and Pattern N (because of the nature of the two tubes acting as a multivibrator). But, because of this, Pattern O assists the completion of Pattern P (by avoiding or clearing away obstacles that impede approach to the goal). The model as a whole is more likely to attain its goal even though the goal seeking mechanisms (photocell tubes and relays) are apparently thrown out of gear by the appearance of the O pattern.

Behaviour mechanisms of type P and N are sometimes described as exhibiting "*negative feedback*" because the system tends to reach an *equilibrium* or balance point in the light field, and does this by progressive reduction of the "error", that is the distance from the light. Simpler examples of negative feedback used to establish *stability* are the ballcock in a water cistern that keeps the water level constant and the thermostat that regulates a refrigerator or heating system or air-conditioner to maintain a constant temperature. On the other hand the internal oscillation in M. Speculatrix when its skin is moved is an example of "positive feedback" – the signals get bigger and bigger because they are fed back from plate 2 to grid 1. A negative feedback system tends of itself to run into a goal or target, to maintain stability; a positive feedback system tends to run away to some limit set by the available power or energy. An explosion, whether chemical or nuclear is a dramatic example of positive feedback. But in M. Speculatrix, the positive feedback O mode can assist completion of a negative feedback P manoeuvre because it introduces a random but persistent hunting for clearance when the path to the target is cluttered. In real animals, too, positive feedbacks and oscillations are often found as parts of systems that as a whole tend to reach equilibrium. The pulsating bell of a jellyfish, the steadily beating heart, breathing, the strange complex electric rhythms of the brain must all, as oscillations, depend on some mechanism with positive feedback, however subtle and inconspicuous.

There is an intriguing feature of the behaviour of M. Speculatrix when it is faced with two exactly symmetrical and equal lights. One might expect that since it is only a piece of machinery and cannot exert free choice, it would inevitably fall between two stools, crawl half way between the lights or jitter at its starting point. But the eye of the machine is not stationary – it is moved systematically to scan the horizon. This process of scanning separates the two equally attractive lights on a *time-scale*. One is sighted *before* the other and this first effect, however slight and transient, immediately destroys the perfect symmetry. This does not imply that the model will inevitably drift toward whichever light is seen first – its behaviour will depend on other factors such as the precise angle and bearing of the scanner in relation to the whole model. But it will go first toward one light and then, if this becomes too bright with proximity, it will move off toward the other. Although the whole system is quite simple and deterministic mechanically, it seems to be able to choose between two or more equal attractions. Whatever connection there may be between choice of this sort and decisions made by human beings, this effect shows that the mere fact of being capable of choice does not depend on any mysterious power, only an ability to change a point of view.

Some people who have watched this little model have called it a "fertile turtle" because it produces so many arguments and discussions about how animals work. One thing it cannot produce is another turtle – nor can it learn from experience though another similar model can. But it does behave rather surprisingly when it sees its own headlamp in a mirror – or the headlamp of another of its kind."[11]

Although the manuscript breaks off here, the missing text would probably have followed the explanation in 'An Imitation of Life':[1]

> "When the models were first made, a small light was connected to the steering motor to act as an indicator showing when the motor was turned off and on. It was soon found that this light endowed the machines with a new mode of behaviour. When the photocell sees the indicator light in a mirror or reflected from a white surface, the model flickers and jigs at its reflection in a manner so specific that were it an animal, a biologist would be justified in attributing to it a capacity for self-recognition. The reason for the flicker is that the vision of the light results in the indicator light being switched off, and darkness in turn switches it on again, so an oscillation of the light is set up.
>
> Two creatures of this type meeting face to face are affected in a similar but again distinctive manner. Each, attracted by the light the other carries, extinguishes its own source of attraction, so the two systems become involved in a mutual oscillation, leading finally to a stately retreat"[1] (p. 45).

THE EVIDENCE OF TORTOISE BEHAVIOUR

All that we seem to require now is confirmation that the behaviour described in this manuscript and in the published sources was actually produced by the tortoises. Again, the BNI archives have provided the crucial evidence, in the form of a set of time exposure photographs in which tortoises carrying candles trace out their trajectories in various environmental arrangements. (It must have been necessary to shield each tortoise's photocell from the light of the candle it was carrying; one of the photographs shows what looks like a metal screen mounted just behind the photocell.) The photographs were taken at Grey Walter's house, probably in late 1949 or early 1950. They may well have served as the basis for some of the drawings of trajectories in 'An Imitation of Life'. The BNI archives also yielded a typed manuscript entitled 'Accomplishments of an Artefact',[12] consisting mainly of descriptions of what seem to be several of the photographs, and of others that have unfortunately been lost. The manuscript seems to have been written to accompany some sort of display or exhibition of work at the BNI; it mentions 'The Living Brain', so it dates from 1953 or later. It is impossible to be sure that Grey Walter was the author of the manuscript, but some of the phrasing is similar to his other work, and it must at the very least have been approved by him.

Figure 4 is typical of the photographs. Although it is far too dark to see many details of the robots or the room, the traces of the candle flames are clear. At the beginning of the exposure, Elsie (with the smooth one-piece shell) is at the top left, and Elmer (with the segmented shell) is at the top right. After a rather messy interaction with Elmer, Elsie crosses his track. Immediately afterwards, we can see Elsie executing Behaviour Pattern E: the faint cycloidal trace (about five cycles) is made by the headlamp, and the heavy zig-zag by the candle. Elsie then switches into Behaviour Pattern P for about a body length – presumably as a result of catching a glimpse of the hutch light – and then reverts to E for a couple of cycles. She then makes a long straight excursion towards the hutch (P again) followed by another five cycles of what may be E, or a mixture of E and N. Elmer's behaviour is less clear because his headlamp is too dim to be seen, but the candle trace implies a similar alternation of E with P.

Fig. 4. A time lapse photograph of Elmer and Elsie, taken at Grey Walter's house in 1949 or 1950, and showing the tortoises interacting with one another. The candles mounted on the backs of the robots trace out their trajectories; the fainter traces are made by the headlamps. Elmer, with the darker segmented shell, starts from the top right, and Elsie from the top left. The hutch is at the bottom of the picture.

'The Accomplishments of an Artefact' contains what may be a rather misleading description of this photograph:

> '*Social Organisation*. The formation of a co-operative and a competitive society. When the two creatures are released at the same time in the dark, each is attracted by the other's headlight but each in being attracted extinguishes the source of attraction to the other. The result is a stately circulating movement of minuet-like character; whenever the creatures touch they become obstacles and withdraw but are attracted again in rhythmic fashion. While this evolution was in progress the light in the feeding hutch was turned on; the common goal disrupted the co-operative organisation and transformed it into a ruthless competition, in which both creatures jostled for entrance to the source of nourishment.'[12]

Our grounds for suspicion come from the description in the same document of the behaviour of Elsie in what is almost certainly Figure 5:

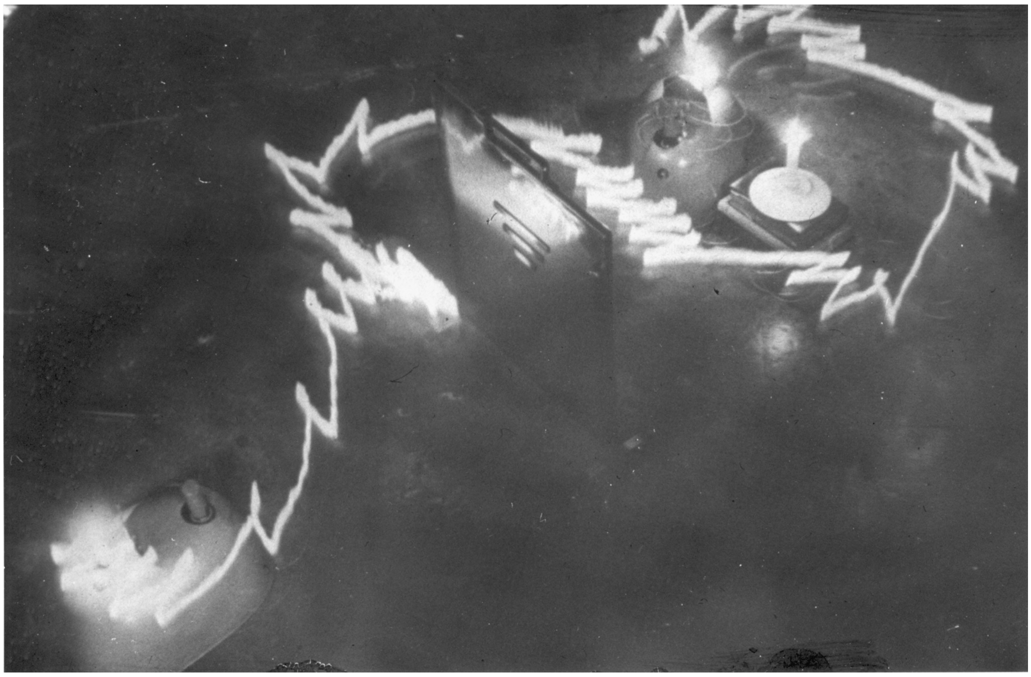

Fig. 5. Elsie demonstrates 'Pertinacity'. Initially distracted by the reflection of its own candle in the polished fire-screen, the robot eventually finds its way to the candle behind the screen.

> "*Pertinacity.*
> Catching sight of a faraway candle the creature loses itself behind an opaque and polished fire-screen, behind which it sidles. On the way it catches sight of the reflection of its candle in the fire-screen and spends some time chasing its tail, but later catches another glimpse of the distant candle and homes into an orbit round its original goal."[12]

This confirms that the candles used to produce the trajectory traces are bright enough to trigger Behaviour Pattern P, and so it is probable that the interaction between the two tortoises in Figure 4 is mediated at least in part by the candles, rather than by the headlamps alone.

Figure 6 shows Elsie in front of a mirror. This may be the photograph described in 'Accomplishments of an Artefact' as follows:

> "*Recognition of self*
> A pilot light is included in the scanning circuit in such a way that the headlamp is extinguished whenever another source of light is encountered. If, however, this other source happens to be a reflection of the headlamp itself in a mirror, the light is extinguished as soon as it is perceived and being no longer perceived, the light is again illuminated, and so forth. This situation sets up a feedback circuit of which the environment is a part, and in consequence the creature performs a characteristic dance which, since it appears *always and only* in this situation, may be regarded formally as being diagnostic of self-recognition. This suggests the hypothesis that recognition of self may depend upon perception of one's effect upon the environment."[12]

There are two problems with this photograph. The first is that by far the brightest light visible to the camera, and presumably to the photocell, is the candle on the tortoise's back and its reflection in the mirror. Unlike the headlamp, the candle is independent of the tortoise's current behaviour pattern. The second is that the drawing of the 'mirror dance' in 'An Imitation of Life' is nothing like this regular alternation between approach and avoidance, but is an altogether more irregular and complex trajectory. There may well have been a mirror dance that could have been argued to be a form of self-recognition, but unfortunately this photograph cannot be said to be a record of it. It looks more like the alternation of Behaviour Pattern P (approach to the reflected light) with Behaviour Pattern O (obstacle avoidance on contact with the mirror).

In 'The Living Brain', Grey Walter characterises discernment as follows: "Distinction between effective and ineffective behaviour. When the machine is moving towards an attractive light and meets an obstacle, or finds the way too steep, the induction of internal oscillation does not merely provide a means of escape – it also eliminates the attractiveness of the light, which has no interest for the machine until after the obstacle has been dealt with. There is a brief 'memory' of the obstacle, so that the search for lights, and the attraction to them when found, is not resumed for a second or so after a material conflict"[3] (pp. 127–128).

Figure 7 appears to correspond to the description of 'Discernment' in 'Accomplishments of an Artefact':

> "Presented with a remote goal (seen at the top of the slide) the creature encounters a solid obstacle which it cannot move, and although it can still see the candle, it devotes itself to circumventing the obstacle (of which it retains a short memory) before it circles round in an orbit and reaches the objective."[12]

It is clearly not possible to deduce all of this from the trace of this trajectory. Dealing with the obstacle involves four or five forward and backward movements of the candle; it is impossible to be sure that the forward movements did not

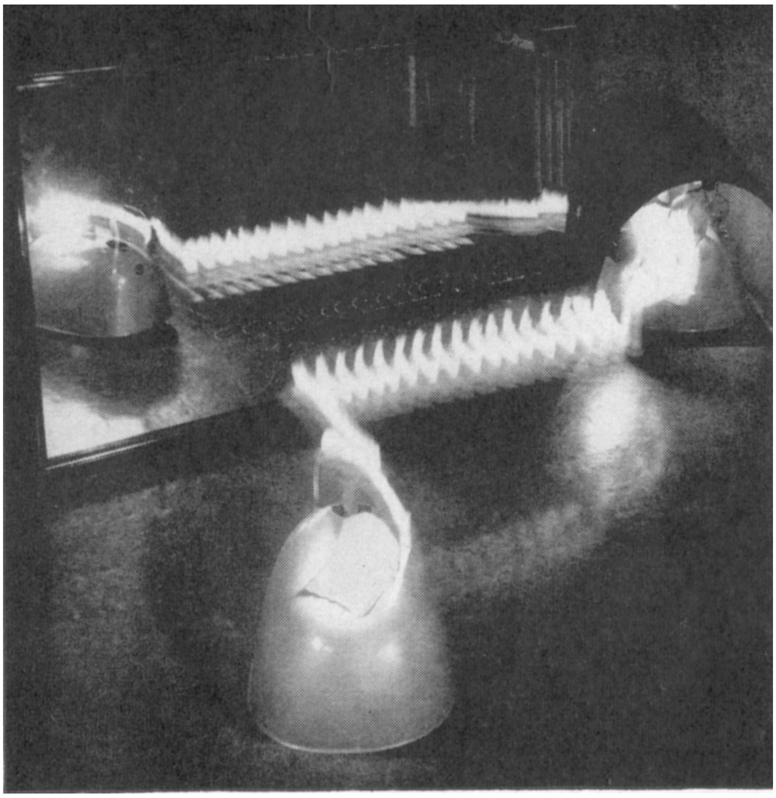

Fig. 6. Elsie performs in front of a mirror; however, the tortoise's movements are very different from the descriptions and drawings of the 'mirror dance' in published sources.

contain any episodes of Behaviour Pattern P. Similarly, the trajectory contains no unequivocal evidence for the claimed memory of the obstacle. However, it is at least consistent with the description.

Figure 8 is probably the photograph described in 'Accomplishments of an Artefact' as *Search for an Optimum*. "Attracted at first by a distant bright light, the creature reaches the zone of brilliant illumination where it is repelled by the excessive brilliance of the light and circles round it at a respectful distance, exhibiting a search for optima rather than maxima – the idea of moderation of the classical philosophers."[12]

The implication here is that the tortoise approaches the light using Behaviour Pattern P, but when the light becomes too intense, it is repelled by Behaviour Pattern N. The problem is that, although P is easily recognised by its long straight or curving runs, it is impossible to tell whether a run of P is terminated by E or N. E will occur quite frequently, when the motion due to P causes the photocell to lose its alignment with the light; N will occur only if the light becomes too bright while still in alignment – but the immediate effect of N will be to rotate the photocell, which will soon cause the light to become misaligned and lead immediately to E. It is therefore impossible to conclude from the photographic evidence that N is definitely involved in this particular trajectory; it could easily have been produced by P and E acting alone, and would then merely constitute a failure to achieve a maximum, rather than a success in achieving an optimum.

It is interesting to note that, in Figures 5 and 7, the tortoises appear to circle round a candle, which should be too dim to excite N. However, a close examination suggests that they may have approached close enough to have touched the candle support, raising the possibility that their apparent circling may be mediated by P, E, and O, rather than P, E, and N, or P and E alone.

For Grey Walter, one of the major achievements of the tortoise was the demonstration of 'free will, in the sense of unpredictability'. Figure 9 shows the experimental setup he used to demonstrate this – two light sources, with the tortoise started equidistantly from them. In 'Accomplishments of an Artefact', the commentary on what is probably Figure 9 runs as follows:

> "*Free-will*
> The solution of the dilemma of Buridan's ass. The photoelectric cell which functions as the creature's eye scans the horizon continuously until a light signal is picked up; the scanning stops, and the creature is directed towards the goal. This mechanism converts a spatial situation into a temporal one and in this process the dilemma of two symmetrical attractions is automatically solved, so that by the scholastic definition the creature appears endowed with "free-will". It approaches and investigates first one goal and then abandons this to investigate the other one, circling between the two until some other stimulus appears or it perishes for want of nourishment."[12]

This photograph, while apparently demonstrating the tortoise's abilities, is rather puzzling. The tortoise is released at the top, equidistant between the two candles, and heads for the candle on the left with some clear instances of P

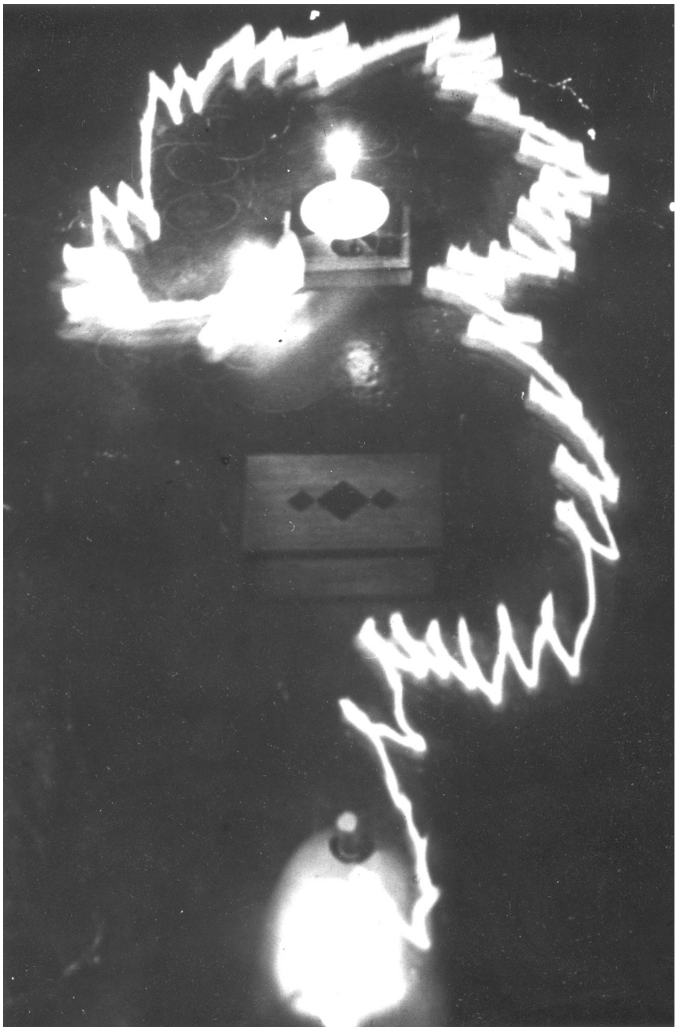

Fig. 7. Elsie demonstrates ‘Discernment’ by ceasing to respond to the attraction of the candle while dealing with an obstacle.

Fig. 8. Elsie demonstrates the ‘Search for an Optimum’ by approaching the lamp, and then circling round it at a distance.

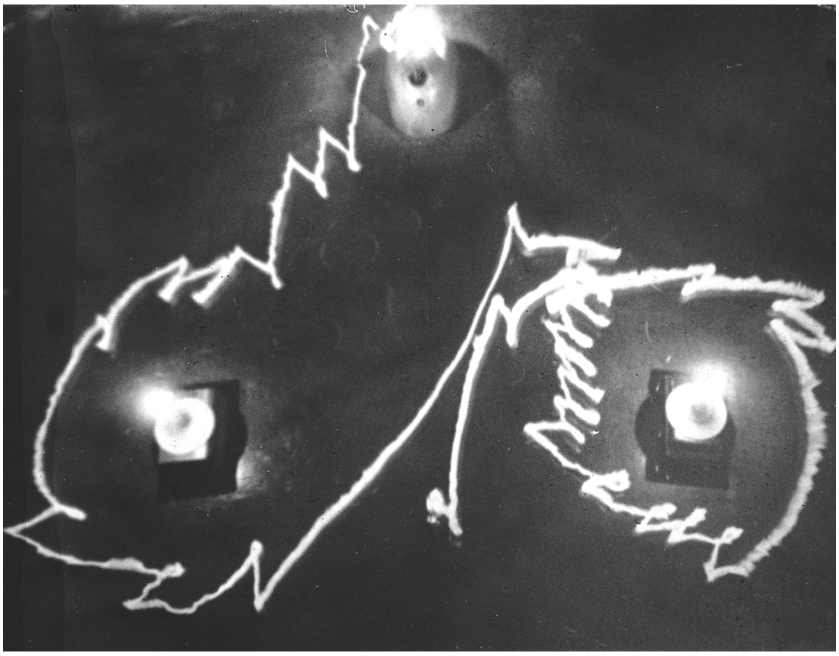

Fig. 9. Elsie demonstrates ‘Free-will’ by solving ‘the dilemma of Buridan’s ass’. Started at a position equidistant from the two equal lights, the tortoise moves first to one, and then to the other, rather than remaining poised at some equilibrium position.

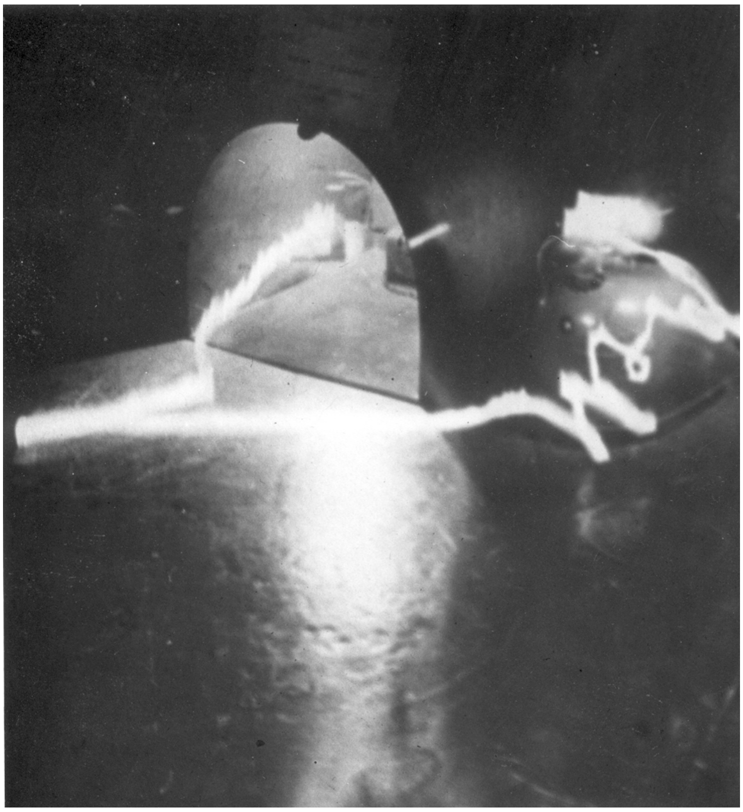

Fig. 10. Starting at the right-hand side of the hutch, Elsie successfully enters it, attracted by the light.

interspersed with E. (The cycloidal movement of the headlamp during the episodes of E is clearly visible under magnification.) However, the long, slightly curving run of P which achieves the transition to the candle on the right is mysterious, because for the last half of the run there does not seem to be a source of light in the right position to produce P.

In the early days, Grey Walter gave much weight to an attribute he called 'internal stability'. (In fact, the names Elmer and Elsie were derived from *EL*ectro*ME*chanical *R*obots, *L*ight-*S*ensitive with *I*nternal and *E*xternal stability.)[1] (p. 43). One quirk of the tortoises' circuitry was that, as the batteries became exhausted, the gain of the amplifiers decreased. This meant that a lamp strong enough to elicit Behaviour Pattern N (negative phototropism) with a freshly charged battery would be unable to do so when the battery had run down, and so the tortoise would run right up to the lamp using Behaviour Patterns P and E. Walter installed an automatic recharging system inside the tortoises' hutch, along with a 20-watt lamp. (Part of the charging system can be seen at the back of the hutch in Figure 1 and Figure 10; the light from the lamp is also visible.) Initially, a tortoise would be repelled by the lamp, and so would not enter the hutch; however, once the battery reached a low enough state of charge, the tortoise would approach the lamp and enter the hutch, where the charging system would disable any further movement until the battery was fully charged. When the tortoise was automatically released from the charger, it would once again be repelled by the lamp, and would leave the hutch.

Although the scheme is obviously satisfactory in principle, there are no records showing that this cycle of events was ever executed with complete success. Perhaps significantly, Grey Walter remarks in reference [3]: 'This arrangement is very far from perfect; there is no doubt that, if left to themselves, a majority of the creatures would perish by the wayside, their supplies of energy exhausted in the search for significant illumination or in conflict with immovable obstacles or insatiable fellow creatures'[5] (p. 130). It is perhaps also worth noting that, when the original hutch was set on fire by the lamp, the replacement hutch included a lamp, but no new charging system was ever fitted.

Whatever doubt may exist concerning the success of the implementation of internal stability, there is no doubt that the tortoises could make their way into the hutch under the influence of the lamp; Figure 10 and Figure 11 show the trajectories of two such movements. In 'Accomplishments of an Artefact', these two photographs are described as follows:

> "*Simple goal-seeking*.
> Started in the dark the creature finds its way into a beam of light and homes on the beam into its feeding hutch."[12]

Apart from the reference to the feeding hutch, the idea of internal stability seems to have melted away.

EVALUATION

There is no doubt that the tortoises were the first biologically inspired robots. Their inventor was a physiologist, and he built them to test a hypothesis about the nervous system. He described their behaviour both in biological terms, and also in cybernetic terms; however, his approach to cybernetics was essentially that of a biologist seeking

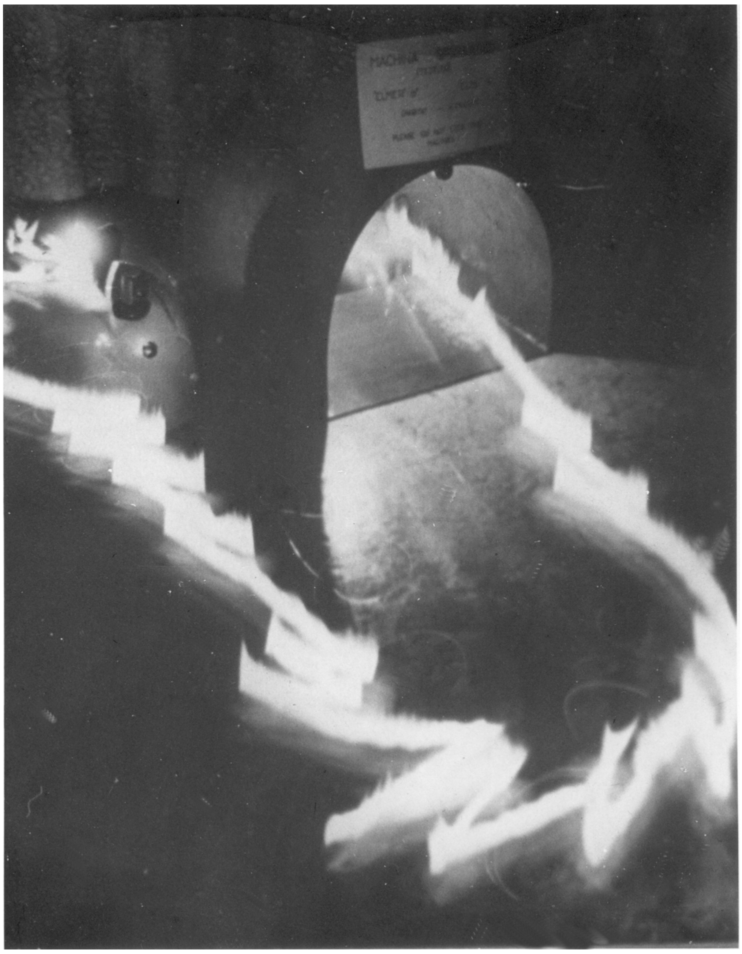

Fig. 11. Elsie enters the hutch again, this time from a starting point on the left. Note the difference between this trajectory and that of Figure 10; this is due to the asymmetry of the system produced by the unidirectional rotation of the photocell.

analytical and descriptive tools from engineering. The evidence that survives is sufficient to enable us to understand in considerable detail exactly how the tortoises worked, and much of it serves as proof that they performed in line with Walter's descriptions. And while many today would regard some of his concerns as being ill-founded, and some of his comments as being over-interpretations, he was undoubtedly the first person to build a robotic system that challenged the observer to produce behavioural descriptions without using naturalistic and biological terms.

However, the real significance of the tortoises goes well beyond their biological inspiration. As was pointed out in reference [4], they were the first examples of behaviour-based design, and of the occurrence and use of emergence in robotics. But they are very much more than mere historical curiosities, because in spite of being over fifty years old, they are still in many ways in the vanguard of modern robotics, and deserve both recognition and study on that basis.

ACKNOWLEDGMENTS

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