Please return
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Machina Speculatrix.

Notes on Operation.

When unpacked the batteries should be connected by completing the link left off to avoid accidental connection in transit. They should then be slid under the contactors of matching color and the terminals screwed down. They will run the model for about three hours, and must then be recharged at about ½ ampere for 24 hours. They should be kept topped up with distilled water.

The model will run best on a bare floor; it is seriously impeded by a carpet with a soft pile which gets into the driving mechanism. Fluff, hair and other debris that gets into the gears should be cleaned out with a small brush.

The hood on the photo-cell "eye" is designed to avoid response to ordinary room lights above eye level. An ordinary flashlamp can be used to attract the model by shining it onto the photocell as it rotates. Daylight from a window or standard lamp is also effective. If too bright the model will be repelled, and in any case its movement toward a light is interrupted as described in detail in the accompanying text. Suitable obstacles to evoke its avoidance behavior are books, waste baskets, its own transit case and so forth. Half a dozen such obstacles in the centre of a dark room and two people with flashlamps at either end make quite a provocative set up. The race is not to the swift when the voice of the turtle is heard in the land.

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

1. 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 -

2. The steering scanning motor 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 photo-electric 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 behavior changes because switching on also -

3. Provides current for the filaments of the two miniature vacuum tubes. These amplify the response of the photo-electric cell to light so that, when a moderate light is seen the relay in the plate circuit of the second tube closes. This introduces behavior 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 photo-cell 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 behavior 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 behavior will change again to:

Behavior 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 on 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 behavior 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 behavior 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 recur about once a second and their effedt 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 behavior looks very sensible but it 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 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 appearance of the O pattern.

Behavior 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 ball-cock 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 in to 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 feedbacks however subtle and inconspicuous.

There is an intriguing feature of the behavior 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 behavior 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 own kind.