THE CONSTRUCTION OF LIVING ROBOTS

by

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Introduction

The purpose of this report is to discuss the properties of robots and the properties of living beings, and to outline how to construct robots made out of hardware which will have the essential behavior of living beings. Part II of the report outlines the circuits by means of which behavior can be programmed in robots.

We do not expect that all readers will agree with the views set forth in this report. Some will agree with the Encyclopedia Britannica, and will say that life is the activity peculiar to protoplasm, and therefore something made of hardware, no matter how many,wonderful,or lifelike,its properties may be, will never live. But we are convinced that, with the great current development of robots and automatic computing machinery, it is important and worthwhile to bring up and discuss the subject of living robots.

We hope this discussion, and the circuits here given, will encourage other investigators and experimenters to try to build living robots, as we are seeking to do; and we shall be glad to try to help anybody to the extent that we can.

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THE CONSTRUCTION OF LIVING ROBOTS

Part I -- Discussion

One after another the barriers to the construction of living robots are breaking down. It would seem reasonable to expect that before a dozen more years go by, automatic machines (i.e., robots) that possess the essential properties of life will be "in existence" -- or should we say, "alive"? Certainly much more than half the distance to the construction of living robots has been travelled.

Now these statements are by no means evident on their face. So let us take a close look at the definitions, the facts, and the prospects. And the first definition we need to pin down is robot. What is a robot?

1. The Nature of Robots

The word "robot" comes from a Czech word meaning "compulsory service". The root "robot-" in the Slavic languages means "work". And a robot is basically a machine that is able to work by itself, an automaton.

In this sense, a clock would be a robot, and so would be an automatic screw machine, -- which is able to perform six operations automatically one after another on continuous metal bar stock fed through it; and so would be a traffic light that changes from green to red and back to green again depending on measured time only and without any regard for the particular traffic conditions at the time.

But all these machines have just one program, which they carry out over and over and over. And in the way that we think of robots these days, we require them to be a little more versatile if they are to be called proper robots. To be a proper robot, the machine should have at least two programs, and be able to change from one program to some other depending on conditions in its environment. The traffic light which responds to motor cars rolling over a pressure plate in the road is a proper robot.

In fact, if we take a good close look at a robot of today, a proper robot, we can come to the conclusion that it is an automatic machine with sensing organs, thinking organs, and acting organs. It is a machine that can adapt itself to some extent to its environment, doing different things depending on different conditions.

A good example of a robot is a device, familiar to oil refinery men, called an "automatic controller". Suppose we want to keep the level of liquid stationary in a certain tank in the refinery. In the wall of the tank we put a device containing a float, which can move up or down over a certain range. The movement of the float up or down for varying distances changes the pressure of compressed air in a small pipe which runs from the float to a "black box". There the transmitted variations of pressure are used to control the pressure in another, but much larger, pipeline containing compressed air running from the "black box" to a chamber over the stem of a valve. The valve can rise or descend varying the amount of opening in a third pipe, through which liquid flows into the refinery tank. And the compressed air in the chamber above the stem of the valve, working against a strong spring, varies the position of the valve. As fluid flows through the last pipe into the tank, the float in the liquid meter is affected, and the "loop" of "negative feedback" is completed; i.e., every displacement of the float sets into motion a force to return it to its previous position. In this robot, the sensing organ is the float; the thinking organ is the "black box"; the acting organ is the valve; and the compressed air pipe lines are the nerves and muscles.

How clever is this robot? How much of a thinking organ can be built into an automatic controller? We can imagine that it might take a minute or two for the liquid level in the tank to change as a result of the signal from the float, especially if the distances were long. Yet if we were designers, we may want a very even control of the liquid level, with quick, adequate response to a small change as soon as it starts to happen. To meet this need, several kinds of response can all be built into an automatic controller. One of them is called "proportional response": the response of the valve is proportional to the change of the liquid level. Another is called "rate response": the response of the valve is proportional to the rate of change of the liquid level. There are other kinds of response as well. Excellent automatic control in fact can be obtained, much better than if you collared a human being and told him to watch for dear life the liquid level reading, and move the valve according to stated rules.

The automatic controller kind of robot is partly responsible for the fact that gasolene sells today at about 25 cents a gallon, just about its price twenty years ago, although nearly all prices have more than doubled. And automatic controllers are useful not only in oil refining but in making chemicals, paper, and performing many other industrial processes involving continuous flows.

2. The Versatility of Robots

At work in the world today, and all of them slaves in the service of men, are probably hundreds of species of robots, and millions of individual robots.

Almost any kind of scientific instrument can be used for the detection of information. These instruments can become the sensing organs for robots.

Almost any kind of machine -- lathe, shovel, valve, motor, wheel, drill, screw, or other device -- can be used for making changes in the physical world. All of them can become the acting organs for robots.

A variety of different devices can be used for transmitting information between the different parts of a robot: compressed air through pipes, electric currents along wires, mechanical parts in motion, cables running through pulleys, etc. These become the nerves and muscles of robots.

A large variety of devices may be used for reasonable operations on information: electronic tubes, relays, cams, compressed air, feelers, latches etc. These become the thinking organs of robots. In fact, some mechanical or electrical robots -- like the automatic dial telephone central office with subscriber stations, or the giant automatic electronic digital computers -- display the development of hardware thinking organs to a prodigious extent.

But how close is a collection of these devices, integrated together into a robot, "living"? What is "living"?

3. The Nature of Life

Have you ever in your imagination walked on the surface of Mars, and wondered how you would tell if some THING you saw there were "living", or not? A short tour on Mars will help us see what properties an Earth robot should have in order that it should be called living. In some cases, while you were walking on Mars, it might be easy to tell that some THING was alive. If the THING could apparently detect your presence, and either move away from you, apparently to avoid you, or move toward you, apparently to attack you, you would at once jump to the conclusion that the THING was alive.

On Mars, you might be right. On Earth, robots of this general nature, which no one claims are living, have already been made.

One of them is Squee, the Robot Squirrel, made in 1951 by the writer and his associates and described in Radio Electronics Dec. 1951 and Popular Science July 1952. Squee is about 21 inches long, 12 inches high, and 8 inches wide, and weighs about 16 pounds; it rolls over the floor, hunts for a "nut" (a golf ball), picks it up in its "hands" (a metal scoop in two halves), takes it over to its "nest" (a metal plate), there leaves it, and then starts hunting for more nuts. Squee has four sensing organs: two "eyes" -- photocells; a "tongue" -- a switch; a "foot" with two "toes" -- two probes. Squee has three acting organs: a driving wheel, a steering gear, and a scoop for "hands". And finally, Squee has a small brain, of a dozen relays and tubes. But in spite of this active behavior, and more than canine docility, no one says that Squee is alive.

But how about the difficult cases, in your tour on Mars, when the ordinary clues that Earth beings use simply could not be relied on?

In regard to shape and structure, for example, the Mars THING would not have to be constructed with any resemblance to either an animal or a plant of the Earth. In fact, in view of our present knowledge, it seems unnecessary and unlikely that the THING could be made of the same chemicals in the same proportions as Earth protoplasm. In fact, the oxygen-less atmosphere and low temperatures of Mars would make Earth protoplasm distinctly uncomfortable.

Even on Earth, the shape and structure problem may be far from simple. One and the same living entity may be first an egg, then a caterpillar, then a chrysalis, then a butterfly. Some sea animals may have more than nine larval or nymphal metamorphoses, i.e., similar changes from infant to adult state.

In regard to size of the individual, the Mars THING would not have to have any given or stated size, in advance of observations made on Mars. On Earth the smallest individuals appear to be particles of a virus, about one hundred thousandth of an inch in diameter. The largest animal is either the whale, length 45 or 50 feet, or the fossil dinosaur, called Gigantosaurus, whose foot print was about four feet in diameter, and whose length may have been as much as sixty feet. The largest plant is the sequoia or redwood, which, trunk and root together, may be over 500 feet in length.

In regard to speed of living, the speed with which the Mars THING lived could be quite unrelated to the speed of living of animals or plants on Earth. Even on Earth, the range of speed of living is great. Gnats do not hesitate to fly when raindrops are falling; presumably their nervous system has no trouble dodging raindrops in a time of the order of a hundredth or a thousandth of a second. And the normal tempo for a response of a human being seems to be about 1/5 to 1/10 of a second. At the other end of the scale, apparently, is a lotus seed: In a Washington greenhouse, scientists have recently sprouted two lotus seeds taken from a Manchurian fossil peat deposit, where they have apparently rested dormant in their tough hard seed cases for at least a thousand years and perhaps five thousand.

In regard to environment, the Mars THING could have a narrow or broad one. On Earth, we have found so far upwards of three million species of living things; their environment ranges from broad to narrow. Some species are relatively independent and are at home in the air, on land, on sea, and some of the time in the sea, like gulls. Other species have an intensely narrow environment, like a kind of mushroom cultivated for food by certain ants in their anthills, and growing nowhere else.

In fact, the more we think over the variations among living things on Earth, the more difficult we can imagine the problem to be of recognizing living things on Mars, especially if there were only a few species, minute, slow moving, in narrow environments, with few enemies, and very limited adaptations.

4. The Essential Properties of Life

What, then, are the properties of life? When do we consider that a thing is living?

There is no easy answer that covers all the extreme cases that we know about on Earth. Even supposing we could arrive at a definition that applied to Earth life, it still might not fit Martian life. But we can make a short list of apparently essential properties that would be sufficient on Mars as well as Earth for a thing to be "living". We cannot claim that these properties are all necessary, for there are many living things that do not have one or more of these properties.

It is I think reasonable to say that if a thing has the following properties, then it is living:

1. Self. It has a persisting, separate, individuality or entity. It consists of matter. It has a center. In other words, it has a self.
2. Sensation and Response. At some stages of its existence, it has the capacity to sense different changes in its ordinary environment, and make different responses to them.
3. Death. If it is forcibly divided through its center, it loses its individuality and all its capacity for sensations and response. In other words, it dies.
4. Self-Preservation. Its ordinary responses to its ordinary environment tend to avoid death.
5. Self-Maintenance. At some stages of its existence, it has the capacity to take stuff out of its ordinary environment and use it for maintaining and repairing its self.
6. Reproduction. At some stages of its existence, it has the capacity, in its ordinary environment, of making or constructing other complete things like itself and having the same six properties as itself.

There are two properties left out of this list which deserve some discussion. The first one is Sex. We are all familiar with a great many species of Earth life in which individuals (in whole or in part) occur in two varieties, male and female, with familiar properties for most species. Some people may be inclined to say that sex is an essential property of life.

Actually, in plants, separate male and female flowers can be found on the same plant, as in cucumber vines. Or male and female organs, stamens and pistils, can be found right next to each other in the same flower, as in lilies. In fact, in some flowers, cross-fertilization for seeds is impossible, as in the bottle gentian which never opens its buds. In a few animals, such as aphids, many generations can take place involving only females.

But there are species of living things on Earth, such as amebas, bacteria, and viruses, in which no separation into male and female sexes can be found at all. Surely on Mars we would not require the discovery of two (or perhaps more) sexes before we would say that a Mars THING was living. In the same way with robots, we need not require the presence of Sex before we will say that a robot is living.

The other property is Evolution. Some people may be inclined to say that if the Mars THING cannot evolve, then it is not living. For, as far as we can tell, the races of living beings on Earth are all of them capable of evolving, through mutations, genes, chromosomes, and all the rest of the wonderful mechanisms of inheritance.

Actually, of course, people have not observed much evolution happening in many species, even after a century of scientific observation. So, to say that a thing must be capable of evolving before the thing can be called living is to set down a requirement that can hardly even be observationally applied; and so it is reasonable to disregard Evolution.

5. Robot Life

A rock like Plymouth Rock, a structure like the Golden Gate Bridge, a clock like Big Ben -- these satisfy Properties 1 and 3; each has a self, each can be destroyed -- and poets celebrate them.

The three robots we mentioned above -- the intelligent traffic light, the automatic controller, and Squee -- satisfy Property 2; each can sense and act accordingly.

But the putting of properties 4, 5, and 6 -- self-preservation, self-maintenance, and reproduction -- into matter that is not protoplasm has, so far as we know, not yet happened. Unless, of course, it has happened in the atomic energy installations, and is shrouded in unscientific secrecy.

In fact, men have not yet seen any great need to do so. A robot guided by a man can easily preserve itself, like an automobile with a driver. Why take the trouble to equip the robot to preserve itself? A robot can easily be maintained and repaired by men in a service station -- why take the trouble to make the machine able to take care of itself? More robots of any desired type can easily be made in a factory -- why take the trouble to fix the machines so that they can make themselves? As a result, men become nurses for robots.

There are however no inherent difficulties in the way of building these three properties into objects. For these properties describe rather simple programming (behavior) for robots. Indeed, if there is any conclusion to be drawn out of men's broad experience with robots to date, it is this: you can program a robot to have almost any kind of rather simple behavior that you fancy. In fact, many problems of warfare like the control of the fire of guns, or appropriate piloting of aircraft or guided missils, can only be solved by building intricate and complicated behavior into robots, and those problems have been solved.

6. Choices in Constructing Robot Life

How then shall we go about building self-preservation, self-maintenance, and reproduction into objects? What choices shall we make in order to construct robot life? Even if there are no inherent difficulties, there are plenty of technical ones.

The first decision we shall make is to avoid protoplasm, the basic stuff of Earth life so far. On the one hand, there is no guarantee that living beings on Mars would require protoplasm. And on the other hand, protoplasm is a mighty complicated stuff, organized on an extremely small scale, and men still know very little about it; and men will continue to know little until many more instruments are developed. Certainly we should not complicate our problem by trying to use this material. Instead, let us use the ordinary hardware nowadays used for making mechanical and electrical systems. In fact, hardware is a kind of material that men have had experience with for some two hundred years; and we are beginning to be able to do some rather remarkable things with it.

The second decision that we shall make is that robot life at its outset is going to be a parasite on protoplasm life. In much the same way, animal life is a parasite on plant life. Animal life appropriates the products that plant life manufactures; and robot life, at its outset, is going to appropriate the products that protoplasm life manufactures.

For example robot life can appropriate electronic tubes, without being able itself to make them nor understand their making. In the same way, animal life appropriates the products of photosynthesis in plant life, without being able itself to make starch from water, carbon dioxide, and sunlight, nor even being able to understand (yet) how plants can do it.

And the final decision that we shall make is that we can design the ordinary environment or home environment of the robot in such a way that our problems will be simplified. Living things have all of them an environment in which they live, and to immerse them into another usually kills them quickly.

7. Robot Self-Preservation

If a robot is to be able to preserve itself, it has to have a certain amount of programming which connects responses with sensations in such a way that it is preserved.

Suppose for example our robot life species was a small robot on wheels like a toy automobile. There are several requirements:

(1) it should avoid ramming into obstacles, since that might damage it;

(2) it should not roll too far away, for then it might get too far from its home environment;

(3) it should come back to the home base from time to time when it was in need of repair and maintenance.

Obstacle-sensing buttons, together with slow speed, could be the sensing organ for the first requirement. A light-intensity sensing device, together with a light on home base, could be the sensing organ for the second requirement. A time relay, together with the system of periodic maintenance, could be the sensing organ for the third requirement. The sensations would be converted into yes-no indications and expressed in relays for example, and appropriate action could be easily arranged, including homing on the light beam to return to its home base. The Mechanical Turtle of W. Grey Walter, the British scientist, described in the Scientific American for May, 1950, had the capacity of returning to its "hutch" for recharging when the electric power of its wet battery got weak.

Suppose there were "dangerous hazards" in its environment, like holes in the floor for example. Then either the robots would all die by falling in, or else they would need to be designed with a sensing feeler which would report "no floor" in the forward direction and so provide information leading to change in the direction of motion of the robot.

8. Robot Self-Maintenance

If a robot is to be able to repair and maintain itself, it will need access to a supply of the items of hardware that composes itself, and some kind of programming (behavior) by means of which it can exchange old items, which it has partially or completely used up, for new items.

Nearly all items of hardware these days are prepared in forms that are easy for men to position. For example, nuts and bolts come in separate packages. In assembling them, a man will pick up and orient the nut, set the nut against the bottom of the bolt, feeling gently until the threads match, wind the nut up the bolt, and then tighten it in place with a wrench. For a man with his generalized, highly evolved and well-trained body, and his capacity to recognize shapes and locations with his eyes, this process is very efficient.

But these operations are seriously difficult for all presnt-day robots and for all protoplasm life except human beings. A good "hand" made of hardware, and a good shape-recognizing sensing device made of hardware like an "eye", may still be years in the future.

In fact, the problem that delayed us longest in the design and construction of our robot squirrel Squee was the pair of "hands", or the scoop. In our final design, the hands are joined at the wrists, and are both opened or closed by guy wires running to a drum turned either way by a motor. Here was one simple picking-up and putting-down motion -- and it took us months to design it and make it work properly, while it took only a few days to design the whole brain of Squee. A great deal of work and thought is needed to develop items of hardware in forms that are easy for robots to position.

Undoubtedly, the easiest present way to solve the robot maintenance problem is not the plan of having the robot itself detect each part that may need repair, and itself remove it and insert a new part. Instead, the robot when needing repair will be able to find somewhere in its ordinary environment a "feeding and repair station" or "re-conditioning berth" or "drydock" or "hospital", like the "hutch" of the Mechanical

Turtle. Here, a counter-part robot, or matching automatic machine, will test each item in the robot, repair or maintain any item that requires it, and refuel the robot. This counter-part robot or "maintenance factory" will at first be thoroughly dependent on human life, in the same way as a parasite in many of its life stages is thoroughly dependent on its host. Positioning of the robot will be done once and for all, when it reaches the entrance of the maintenance factory.

Later, as more experience with "living" robots is gained, spare items can be stored in or on the robot, and whenever needed can be shifted into place. The easiest items in this class of course are liquids. Lubricating oil, for example, could be in a little reservoir on the robot and arranged to ooze out when needed. Then at much longer intervals the robot will visit its reconditioning berth and fill up with a new supply of lubricating oil.

For all living beings, the main repair process is internal and involuntary. Protoplasm life has the capacity to heal many kinds of damage to itself, though not all, by its internal processes which convert raw materials such as food, air, water, into the right kind of healing stuff. But internal healing will not be true for robot life at the start; it will be for some time a parasite on human life. The minimum self-maintenance requirement for robot life is that when it senses that it needs repair, or refueling, it can go and get repaired or refueled.

9. Robot Reproduction

If a robot is to be able to reproduce itself, then again it has to have a certain amount of programming (behavior) such that as a result of its own actions, from time to time, more robots like itself are reproduced.

We shall continue to keep the problem simple. We shall assume a robot "birth factory" -- located in some part of the robot's ordinary environment. The robot birth factory would be like some rocky islands in the sea where certain species of sea birds always come to nest, where they won't be disturbed by any other life forms (except men).

The robot birth factory, like the robot maintenance factory, will be a counter-part robot, or matching automatic machine. The supply of each item for the robot life species will be in a feed line; the feed lines together will be positioned and oriented in the most convenient way; and there will be an assembly belt running by the end of each feed line one after another.

Now when a robot is stimulated in the appropriate way, what will happen? It will either return to the robot birth factory and press a button,or it will transmit an impulse. The robot birth factory will thereupon assemble and issue a new robot.

If the robot species is of the type that has tapes for programming to be recorded in them, there will be no programming yet recorded in the tapes of the new robot. So it can be provided that the adult robot will connect its tapes to the new robot, and record in the latter's tapes all the information which was recorded in its own tapes, together with such changes as it may have acquired from its experience.

Here we can see a possible great advantage of robot life; experience and learning acquired by an old individual can be transmitted directly to new individuals -- whereas protoplasm life has to go about the process in a much more indirect way.

Even at the present time it would be possible to set up means of communication between the giant electric brains. The programming worked out for or by one can be made available to others.

But what is "stimulation in the appropriate way" that we mentioned above? Many species of protoplasm life have just one simple tendency, to multiply. They produce new individuals of the species, as many and as fast as the environment and their own stage of development will permit. A plague of caterpillars in Minnesota recently was so thick that locomotives and motor cars could hardly get through them. Protoplasm life often presses on its means of subsistence.

But robot life, a parasite, has to adapt itself to its host, human beings; and human beings cannot afford to have robot life multiplying indefinitely. Why not then provide that the number of individuals of a robot species is to remain constant? Suppose that each robot individual continually signals the robot birth factory. Then, if any robot individual "dies", it stops signaling the robot birth factory, whereupon the robot birth factory promptly issues a new robot.

The minimum reproduction requirement for robot life is that when an individual or society of robots reports the need for another individual robot of the species, another such robot is reproduced.

Part II -- Outline for Constructing Robot Life

Now, how do we go about constructing robot life?

Corresponding to the three parts of a robot, there are three sides to the problem of constructing robot life. These are: the construction of sensing organs; the construction of thinking organs; and the construction of acting organs.

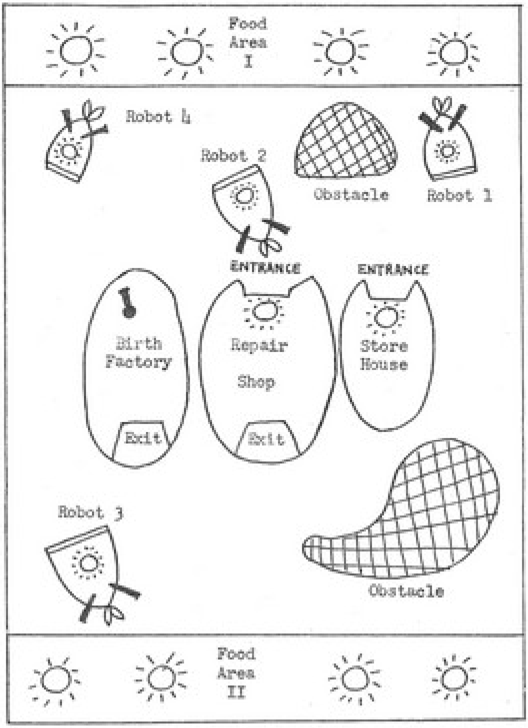
The construction of sensing organs for robot life is neither theoretically nor practically difficult. For sight, we can have phototubes that sense light. For sound, we can have diaphragms that respond to molecular vibrations. For touch, we can have buttons or reeds that sense pressure. For taste and smell, we can have chemical detection apparatus that can easily sense at least some kinds of matter. For many senses that human beings do not possess, there exist scientific detection instruments that could be employed.

The construction of acting organs for robot life is not theoretically difficult but practically it is. The example mentioned above, a hardware "hand" equivalent to the human hand, is a good illustration. Even so, there are many simple kinds of mechanical devices that can be employed for the acting organs for robot life: wheels on which they can roll, scoops by means of which they can pick up things, etc.

The construction of thinking organs for robot life, the organs guiding its behavior, is a problem which may appear to be theoretically difficult; but actually its solution is not difficult. This is the problem which we shall discuss here at length.

1. Robot Life Species No. 1

To make our discussion concrete, let us assume a simple species of "robot life", and its home environment, a "robot world". See Figure 1.



Lights

Object	Color of Light
Robot 1, 2, 3, 4	C1, 2, 3, 4
Food Storehouse	C5, C6
Maintenance Shop	C7
Birth Factory	none

Figure 1 -- The Robot World

In this robot world, we see represented:

1. Four small robots; they roll on three wheels, have a pair of phototube "eyes", have a scoop for "hands", and have on their backs a light; the lights are of four different colors (colors 1, 2, 3, 4).

2. Food Areas, lighted with a number of lights, all of the same color (color 5); here "food" may be found.

3. A Storehouse, where the robots bring food (light of color 6).

4. A Repair Shop, where a robot can be repaired (light of color 7).

5. A Birth Factory, having a rotating phototube which scans the robot world; here new robots can be produced.

2. Behavior

What kind of behavior do we need for each of the beings in the robot world?

1. Storehouse: Store food when brought to it.

2. Repair Shop: Repair a robot when one comes.

3. Birth Factory: if the light of any robot goes out, issue a new robot of the same type (i.e., with the same color light).

4. Each Robot:

   A. Hunt for food, if well.

   B. Pick up food if found and take it to the storehouse, if well.

   C. Put down food, if it is well, when it reaches the storehouse, and if it becomes sick, anywhere; and then back up a little and go forward in a new direction (to avoid running over the food).

   D. Go to the repair shop, if it is sick.

   E. Get repaired in the repair shop.

   F. If it hits an obstacle, back up a little, and then go forward in a new direction.

3. Schematic Diagrams for the Counter-Part Robots

What are the schematic diagrams of the programming circuits? We shall assume, for this part of this section, that the reader understands electrical switch and relay wiring diagrams.

<u>Storehouse</u>: The schematic for the Storehouse is comparatively simple. See Figure 2.

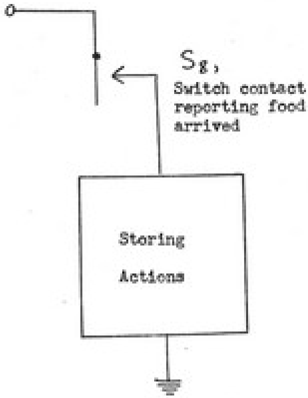


Figure 2

Schematic for Storehouse

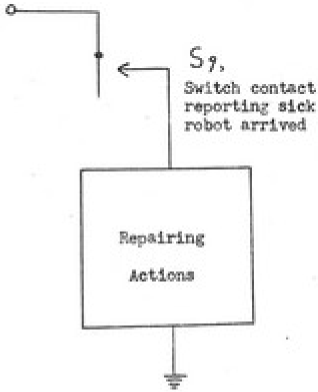


Figure 3

Schematic for Repair Shop

Repair Shop: The schematic for the Repair Shop is also comparatively simple. See Figure 3.

Birth Factory: The schematics related to the behavior of the birth factory are a little more complicated.

Let us suppose that the birth factory has two cycles of operation. During Cycle 1, the phototube turns around completely, like a radar antenna, detecting light from all directions. During that complete circle of 360 degrees, if all robots are "alive", then their lights will be detected and the birth factory will pick up each of the colors 1, 2, 3, 4, not necessarily of course in that sequence. Now if by the end of that cycle, the birth factory should observe the absence of any particular robot light, then the birth factory may well conclude that robot has "died", and it should issue a new robot of that type. The schematic is shown in Figure 4.

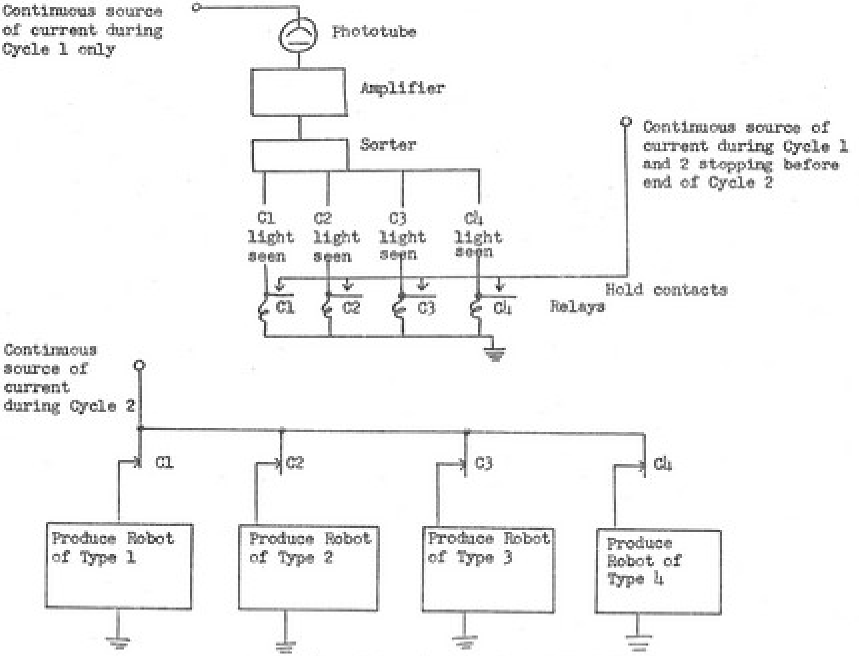


Figure 4 -- Schematic for the Birth Factory

As to the robot, the light should go out only if it "dies". For example, one such condition would be that the robot could not move any more. Of course, most undesirable conditions on the robot will be signaled before they become so critical that it "dies": the robot will then be sick and will go to the repair shop and get repaired. But if something really serious should go wrong, then the light on the robot should go out. This can be provided for by means of a circuit such as shown in Figure 5, where it is assumed that there are six conditions the failure of any one of which means "death".

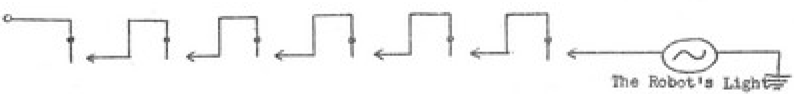


Figure 5 -- Schematic for Circuit Reporting Robot's "Death"

4. Schematic Diagrams for the Robots

We come now to the schematic diagrams for the behavior of any of the four robots.

First, the needed senses of the robot are these:

No.	Sense	Relay
1	See light with its left eye	S_1
2	See light with its right eye	S_2
3	Detect the light of the food (color 5)	S_3
4	Detect the light of the storehouse (color 6)	S_4
5	Detect the light of the repair shop (color 7)	S_5
6	Detect the presence of food in its scoop	S_6
7	Detect an obstacle	S_7
8	Detect the entrance of the storehouse	S_8
9	Detect the entrance of the repair shop	S_9
10	Realize that it has become sick	S_{10}
11	Realize that it has become well	S_{11}

In keeping with the outline nature of this report, we shall assume that these senses may be contrived in hardware fairly easily and will result in the picking up of relays, one for each sense. We should comment on the last two senses, however, since they are essentially compound senses. That is to say, if there were, say, seven conditions such that the failure of any one of them would mean "sickness", then there would be a circuit on the robot of the type shown in Figure 6, picking up the S_{10} relay that reports "becoming sick".

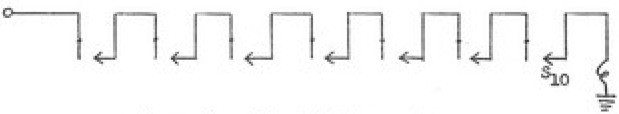


Figure 6 -- Schematic Diagram for Circuit Reporting Sickness of the Robot

Second, the needed actions of the robot will be: driving forward or backward, or stopping; steering to the right or the left, or not steering; closing the scoop or opening the scoop. These actions it happens are the same as the actions of Squee. So they may be contrived in hardware by referring to the published plans for Squee. Also, converting the sight of the left and the right eyes into adequate homing behavior -- "phototropic", like a moth to a candle -- is a problem that has been solved and published for Squee.

Third, we need to consider the programming of the robot, by means of which it will behave as we desire it to. This is a problem in the organization of sequential relay circuits. But it can be quite easily handled and analyzed using what we may call Boolean calculus, which is equal to Boolean algebra extended by a new operator which provides for delay, i.e., changes in time, "before" and "after", states and events. We shall assume for the remaining part of this section that the reader understands Boolean algebra and the applications of Boolean algebra to relay wiring circuits. By way of review, however, the key definitions are these:

a (written next to a relay contact)	the condition "the relay contact is closed"; or, the truth value of this condition, equal to 1 if true and 0 if false
a (written next to a relay coil)	the condition that "the relay coil is energized"; or, the truth value of this condition
$a \vee b$	a or b or both; or, a plus b minus (a times b), if a, b = 0, 1
$a \cdot b$	both a and b; or, a times b if a, b = 0, 1
a'	not a; or, 1 minus a, if a = 0, 1
a^{+k}	the condition equal to a but delayed k units of time; or, if $a = f(t)$, then $a^{+k} = f(t + k)$.

These variables may be thought of as time functions that have only the values 0 and 1, such as shown in Figure 7.

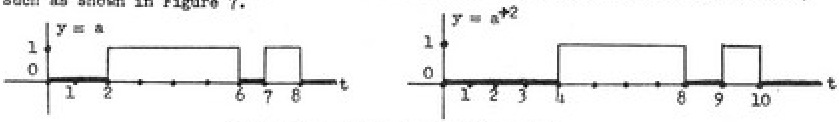
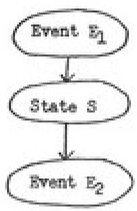


Figure 7 -- Delay of Two Units of Time

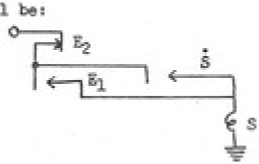
As an abbreviation for a^{+1}, we shall often use $\dot{a}$ or a'.

Now suppose we want a relay to represent a state S that continues during some period. Suppose that the state S starts with Event 1 and stops with Event 2.

Topologically, we have:



The relay circuit will be:



The Boolean calculus equation will be:

$$S = (E_1 \vee \dot{S}) \cdot E_2$$

The relay hold contact marked $\dot{S}$ has to lag slightly behind the coil S. We shall assume that the lag is one unit of time, or one pulse time. Physically, for many relays, the lag is often about 1/20 of a second, and is called the pick-up time.

For another example of a delay function, let us consider a time delay relay. This has the property that it energizes, say, five seconds after the contact closes that leads to it; see Figure 8.

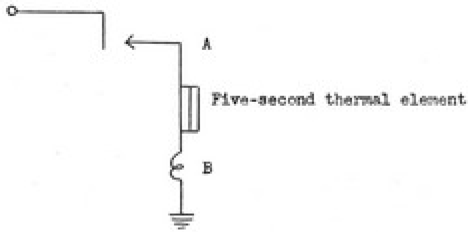


Figure 8 -- A Five-Second Delay Function

Here the Boolean calculus equation will be $B = A^{+100}$ or if we use seconds as units of time, $B = A^{+5}$.

We are now ready to display the organization of the states, events, and programming of our species of robot life. They are shown in Figure 9.

W	Well ↓	
S_{10}	Become sick ↓	$W = (S_{11} \vee \dot{W}) \cdot S_{10}'$
W'	Sick ↓	
S_{11}	Become well	

F	Have food ↓	
V_1	Five seconds after starting to put down food ↓	$F = (S_6 \vee \dot{F}) \cdot V_1'$
F'	Have no food ↓	$V_1 = (S_8 \vee S_{10})^{+5}$
S_6	Find food	

P_1	Seek food ↓	
S_6	Find food ↓	$P_1 = (S_{11} \vee V_1 W \vee \dot{P}_1) S_6' S_{10}'$
P_2	Seek storehouse ↓	$P_2 = (S_6 \vee \dot{P}_2) S_{10}' \cdot S_8'$
S_8	Arrive at storehouse ↓	$P_3 = (S_8 \vee S_{10} \cdot F \vee \dot{P}_3) \cdot V_1'$
P_3	Put down food ↓ If well	$P_4 = (S_{10} \cdot F' \vee V_1 W' \vee \dot{P}_4) S_9'$
V_1	Five seconds after starting to put down food	$P_5 = (S_9 \vee \dot{P}_5) S_{11}'$
S_{10}	Become sick If have food If sick If no food	
P_4	Seek repair shop ↓	
S_9	Arrive at repair shop ↓	
P_5	Get repaired ↓	
S_{11}	Become well	

S_7 or P_3	Detect an obstacle, or start to put down food ↓	$B = (S_7 \vee P_3 \vee \dot{B}) V_2'$
B	Back up ↓	$V_2 = B^{+5}$
V_2	Five seconds after backing up ↓	
B'	Go forward	

Figure 9 -- Robot Life Species No. 1 -- Programming -- Topology, and Boolean Calculus Equations

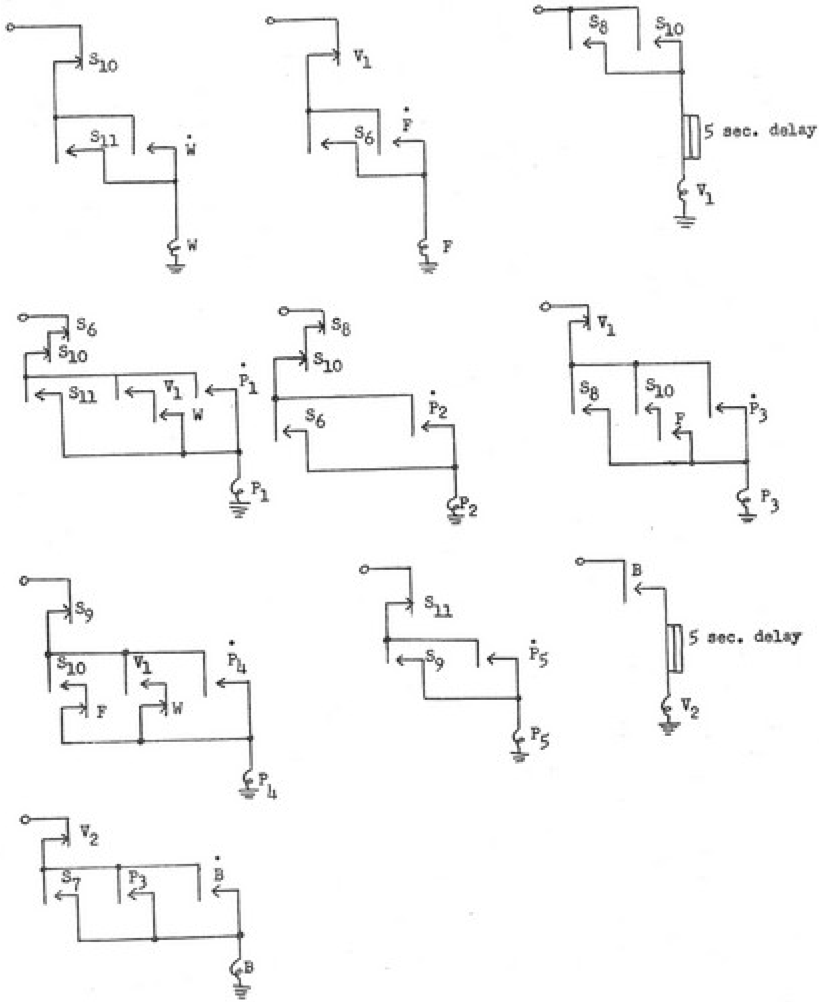


Figure 10 -- Robot Life Species No. 1 -- Programming Circuits

Now that we have the programs, it is quite easy to finish the schematic circuits. See Figure 11.

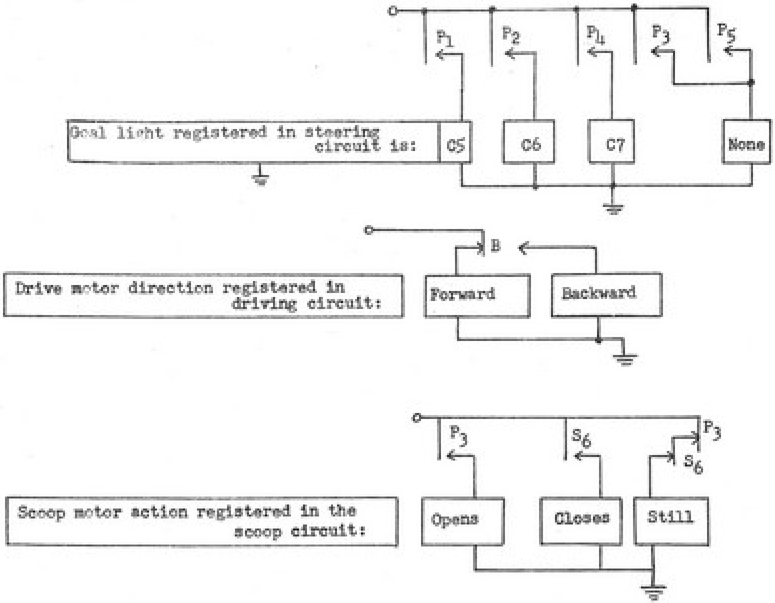


Figure 11 -- Robot Life Species No. 1 -- Programming Correlated with Action

Part III -- Practical Conclusions

Now is all this theoretical? what use is it? Who in the world wants living robots anyhow?

Well, we do. In our small organization we are engaged in a small-scale program of constructing brains and robots. We have finished Simon, a miniature mechanical brain, and Squee, the robot squirrel; and we are at work on other robots. We have in mind the construction of still other robots -- kinds that will handle ideas, or live, or be companionable. Why do all this? It is exciting to push back the frontier; it is fun to fire people's imagination; and it seems to be good business.

But entirely apart from the interests of our own small organization, there is no doubt that robots which are able to preserve themselves, repair themselves, and reproduce themselves, will as slaves or colleagues of men, open up unheard-of, unimagined ways for human beings to pursue their goals.

For example, think of exploring the bottom of the ocean, or the interior of volcanoes, or the surface of the moon, or the surface of Mars, with a swarm of such robots. Think of dealing with plagues of caterpillars or locusts by hordes of small flying robots about two inches long, equipped to slaughter such insects. They would be much more economical and versatile than robots that could not preserve or repair or reproduce themselves. In fact, it is not beyond possibility that such robots already exist in present-day atomic energy or guided missile installations, hidden in unscientific secrecy. In fact, in a number of environments hostile or impossible for human beings or protoplasm life, living robots will in the future become useful, practical, and essential.