

ON MODELS OF REPRODUCTION

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IN THE last century or so, scientists have succeeded in duplicating most of the characteristic functions of living things, using admittedly non-living models. Such functions as locomotion, energy metabolism, energy storage, perception of external stimuli, and nervous and cerebral activity, have been accomplished with various artifacts. As examples, these functions, respectively, are performed by the automobile, steam engine, storage battery, iconoscope, and digital computer. Only one major function, reproduction (of which growth can be considered a corollary function), has been unrepresented to date by a satisfactory non-living model. This paper describes the construction of a self-reproducing (self-reproduction and reproduction are used interchangeably herein) model of simple order from electromechanical components. It also describes the design of more complete models of reproduction, discusses the nature of the reproductive process as an abstract entity, and the necessary conditions for a system to be self-reproducing. The possible degree of analogy between electromechanical and biochemical self-reproducing systems is explored, and inferences are made about spontaneous origin of reproducing systems on earth, as the existence and complexity of these models suggest.

I. ELECTROMECHANICAL ANALOGS OF REPRODUCTION

Reproduction is so simple a process, in essence, that the lack of a working non-living model to date has been remarkable. Definition of the process is a somewhat moot issue. We will defer the matter of definition to Section II. In this section we will merely describe the models contemplated, designed, and built.

Preliminary Considerations of Possible Models of Reproduction

The obvious essentials in any reproducing system are: (1) an environment, in which random elements, or parts, freely circulate; (2) an adequate supply of parts; (3) a usable source of energy for assembly of these parts; and (4) an accidentally or purposively assembled proto-individual, composed of the available parts, and capable of taking them from the environment, and synthesizing them into a functional copy of its own assembly, using the available energy to do so.

The parts necessary fit into various classifications, of which a minimum would seem to be; (1) an energy transducer, converting the environmental energy into negative entropy within the open system, i.e., a motor using available energy to move and order the parts; (2) a pattern reflecting the order of the individual, which the system can use to arrange its self-assembly, i.e., a plan; and (3) an apparatus for dis-

tinguishing correct from incorrect parts during the assembly, i.e., a sensory system.

In a rough way, we can compare these three necessary functions with effectors (e.g., muscles), inheritance patterns (e.g., chromosomes), and perceptors (e.g., eyes) of living systems.

The first kind of mechanical model of reproduction suggesting itself to the author and to others interested in the problem was a simple mechanical self-assembler, consisting of motor, plan, and senser. Under control of the plan, the motor could move the senser about a junkyard-like environment of parts, pick up the proper part, move it to some nearby assembly area, and perform any necessary assembly operations. It might even be possible to *drop* the parts into place, with proper design. The chief difficulty with designing such a model, however, is in designing a motor which operates on parts at a distance, picks up a copy of itself, and drops it into an accurately positioned spot at some like distance.

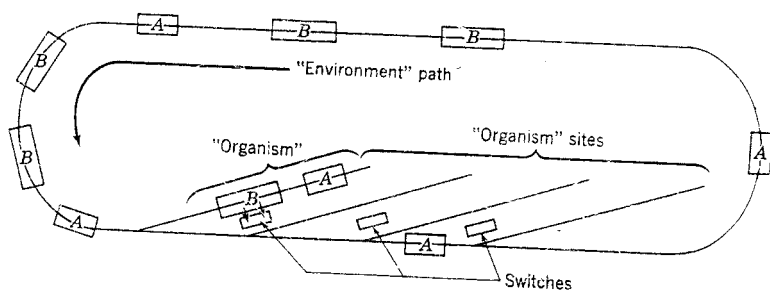


FIG. 1. Over-all layout of RSD I.

A Working Model of Reproduction

This difficulty of designing a motor to move all the parts, however, could be eliminated by allowing the parts to *move under their own power*, i.e., be *locomotive*. Such a system, containing self-mobile parts, can readily be designed to reproduce its own order, as follows:

The parts consist of locomotive cars of various kinds. The environment is a cyclic track bearing these cars in some *perfectly random* sequence; the sequence is determined by some stochastic process like coin-tossing. The "organism" (enclosing a word in quotes in this paper indicates that it is an analog of the corresponding living system or process) is a set of two or more cars, *in a fixed order*, capable of producing more "organisms" from the environment. "Organisms" are assembled on sidings just off the environment track, where they can "watch for" and select parts for new "organisms." "Reproduction" consists of the selection, in proper order, of cars which duplicate the original

"organism." Selection of cars as parts to go onto a particular siding is simply a matter of switching them there. The assembly process is the proper automatic turning on and off of track switches. For this process, model railroad gear is especially adaptable. We have built such a device on an "HO" gauge model railroad track, and call it Reproductive Sequence Device One, or RSD I.

The over-all layout of RSD I is shown in Figure 1. Two kinds of cars are enough, since the "brains" can be put on one kind of car, which we shall call the A, or "head" car, and the "muscles" and "eyes" on the other, or "tail," or B, car. Both A and B cars, of course, have their own locomotive engine to take them where the switches lead them, or simply around the track. The sequence of self-assembly is as follows:

- (1) All of the cars are randomly arranged, running about the track. Nothing of interest is happening.
- (2) By accident, act or will of a Creator, or, most likely, through the operator of the model pushing the buttons for the right switches, an A and then a B car get assembled as the first "organism" on the first siding. This is the stage in the sequence depicted in Figure 1.
- (3) The A car of this "organism" somehow "informs" the B car: "'Watch' for an A car in the environment, approaching the second siding. When it comes, open the switch to the siding." These instructions are obeyed, and the A car rides into the second siding.
- (4) As the A car passes the second switch into the second siding, the "muscles" of the B car of the first "organism" close the switch, since otherwise all the rest of the cars would follow it into the siding. The B car then "informs" the A car that the siding switch has been closed.
- (5) The "brain" on the A car "thinks" long enough to close a relay, and then gives the following changed instruction to the B car: "'Watch' for a B car in the environment, approaching the second siding. When it comes, open the switch to this siding." Again the B car follows the instructions, and now another B car comes into the second siding, just behind the A car which has arrived earlier.
- (6) Again, the B car of the first "organism" closes the switch to the second siding as the second B car passes into the siding. Further entries into the siding are again prevented. This action is communicated to the first A car.
- (7) Again the "brain" on the first A car "ponders," and then instructs its partner B car, "Throw no more switches." And so ends the active "life" of the first "organism," i.e., the first "generation."
- (8) However, a new "organism" is now on the second siding. The "second generation" which it comprises is identical to the first one, except that it is located on a linearly displaced siding. It has, as far as

oncoming trains are concerned, the same properties as the first organism, and proceeds to select another A and B car, in order, to assemble on the third siding. Thus, it continues the pattern of self-propagation.

(9) Any new "organisms" formed continue the propagation in a linear fashion, until the environment runs out of parts, or there are no more sidings available, or a mistake is made somewhere in the operation of a cycle, i.e., a "mutation." Such an effect, like that with living beings, is usually fatal.

Photographs of RSD I, together with details of its circuit and mechanisms, are given in Appendix A.

More Complete Models of Reproduction

Apart from unlikelihood that reproduction from RSD I could get out of hand, or ever replace more familiar mechanisms, certain comments and reservations are in order.

In the first place, RSD I has a *linear* reproductive cycle. One "parent" has one "child," the "child" one "grandchild," etc. This is clearly not the way of nature, nor indeed of any stably persisting reproducing system. In the simplest asexual living forms, a parent produces *two* offspring, disappearing in the process. For any species to survive, the multiplication factor, i.e., the numerical ratio of one generation to the last, must exceed one. Otherwise, losses of life before maturation will not be made up, and the species will vanish. In RSD I, the multiplication factor is *exactly* one. This means that any accident whatsoever (e.g., a misfiring relay) will bring the species to an end. However, it is experimentally possible (and here and later we cover up for some very hard instrumentation problems) to make a multiplying model, RSD II, in which an "organism" assembles two or more new "organisms," which same do likewise. All one needs, in the present kind of model system, is some branching tracks, as in Figure 2, and many parts, plus a more complicated sequence designed to open and close switches in the right order for twice as many new cars per generation. The arrows in Figure 2 show the two "descendants" of each "organism." Four "generations" are visible on the layout. Circuits for the cars of RSD II, along with the sequence directions, are to be found in Appendix B. Similar details on subsequent models to be described in this section, namely RSD III-V, are also to be found there.

A second exception we may take to the parallelism between RSD I and life reproduction lies in the arbitrary environment provided. If one function of food is to provide parts for the build-up of an organism, it may be argued that the switching points represent "mouths" for the ingress of "food." Thus the environment of RSD I may be said to have a set of built-in "mouths," prior to assembly of any "organism." The "organism," according to this viewpoint, merely directs the opening and

closing of these "mouths." On the other hand, the switch points can be considered to be *niches* in the environment, like caves on the edge of the sea, in which action can take place. With this viewpoint, they can be considered merely as a part of the environment requirement for sites.

If one insists on the stricter viewpoint that the switches are really "mouths," another kind of "organism" can be designed. There is no reason why the "organism" could not only put "heads" and "tails" together, but also "mouths." Such a model, which we can call RSD

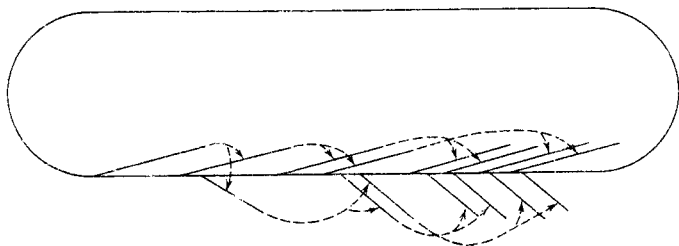


FIG. 2. Over-all layout of RSD II.

III, would carry a siding and switch on each A, or "head" car. It would lay them on the track ahead of it, at the start of its assembly. Once laid into the track, the switch would be controlled by the "organisms" previously present, just as with RSD I. Again, the mechanical difficulties which exist only in practice keep us from having made an RSD III. The layout for RSD III, of course, would be a simple cyclic track.

A third apparent exception stems also from the arbitrariness of the environment. It is noted that the distribution of parts therein is random, but only *one-dimensional*. While biochemical systems are primarily two- and three-dimensional, a one-dimensional model is a perfectly allowable, if simplified, abstract representation of the necessary random parts arrangement.

It is also noted that certain auxiliary devices (see Appendix A), i.e., spacer system, siding end stops, and motor cutoffs, are present in the environment. These, too, can be considered as mere environment requirements, so as to keep the process feasible, when carried out within the ground rules of the definition discussed in Section II of this paper.

A fourth objection, however, is more fundamental. The reproductive process may be divided into two abstract steps:

- (1) Duplication of an "organism," according to a set of plans in the genetic determiners of its parent(s), and
- (2) Duplication of the plans, as well.

We can show that these functions are separable by considering two devices, which respectively perform (1) and (2). The first is RSD I, and the second is a printing press which prints plans for itself. Now the plans

for RSD I are extremely simple, but they are *pre-built* into each A car, in the form of holes punched in the "chromosomes" described in Appendix A. In principle, then, RSD I is duplicating not a complete self, but a self from parts which include its plans. Conversely, the printing press produces plans, but no new printing presses.

The complete self-reproducing model must do the tasks of both (1) and (2), i.e., put its parts together, and also make a *new* set of plans. This is also possible, but clearly much harder. We have designed, but not built, just such a device, RSD IV.

Such a system must have a plans duplicator of some sort. Since the plan is a "chromosome" with a construction resembling a punched card, the holes allowing contacts to be made through them, the plans

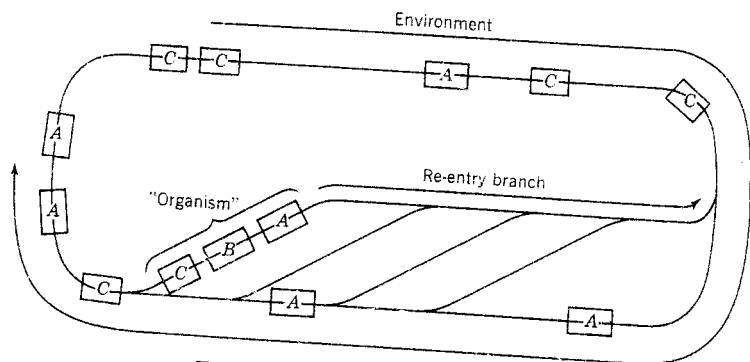


FIG. 3. Over-all layout of RSD IV.

duplicator would naturally be some kind of punch press. It would stamp the holes in a fresh, unpunched, card. Each time the "organism" assembles a new "organism," it must also punch out a new "chromosome" card, which is a duplicate of the past ones. It is essential to this "organism" that it pass *information* to the next generation, either by shipping it a set of completed plans, or else by transmitting proper signals to the new organism, so that it can punch out its own plans.

Figure 3 shows the layout of RSD IV. The functions of duplicating an "organism" for the next "generation" and of making a new set of plans, are carried out simultaneously in RSD IV. The "organism" of RSD IV consists of three parts, labelled A, B, and C. The C and B parts are identical, except that B contains the plans, and C contains only an unpunched card capable of receiving the plans. Many A and C cars are seen in the layout, but only one B car. By gaining plans, a C car can be converted into a B car. If, at the beginning of the "species," a single "organism" lies on the first siding, as in Figure 3, and if the remaining A and C cars are randomly circling about in the environment, the self-and-plans duplication can begin.

Duplication of the "organism" follows the pattern of recognition and switching of the proper cars to the next siding, as described for RSD I. But since there are no more B cars, one needs to be made from a C car, before duplication is completed. In RSD IV, the blank "chromosome" card of the "parent organism" is punched, and then passed from the B car on which it originates to the C car which is being converted into another B car. The new B car is then released into the environment via the re-entry branch shown. It can then be assembled, together with available A and C cars, into the newly formed "organism."

This operation, as described, resembles the production of duplicate germ plasm in a real organism, followed by its passing into the body of

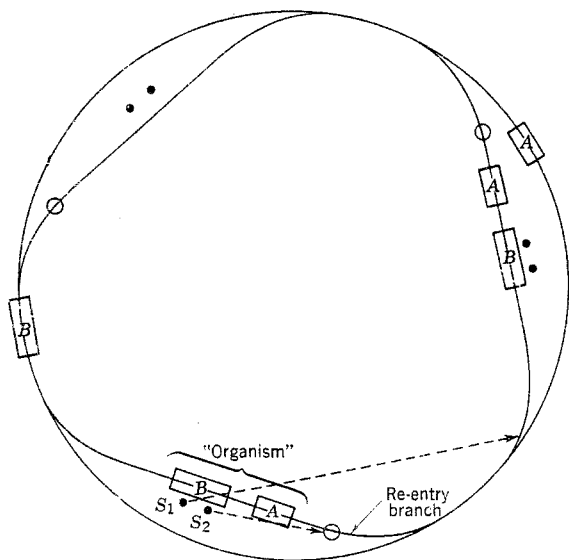


FIG. 4. Over-all layout of RSD V.

the organism of the next generation. It then becomes a constituent part of the new organism, as well as a model for production of more germ plasm. A fifth objection to the completeness of analogy between RSD I and true reproduction consequently might be that almost all real organisms which are differentiated enough to have special germ cells reproduce sexually, a process which none of the RSD sequence is designed to emulate. Since the process of sexual reproduction is known to be of principal importance in expediting evolution, and since all "mutations" in the RSD models thus far observed have been lethal, there seems to be no special advantage to designing any serious model of RSD to duplicate this function of living beings of higher order.

A sixth objection refers to the ultimate fate of the parts of which the organisms in the world of life are made. After death, the parts are almost invariably re-used by other organisms. Animals especially make use of fairly complex pre-built parts from other organisms. This re-use of parts can be built into a fairly simple RSD V. It is only necessary to make provision for the return of the cars forming an "organism" to the environment after its "death," i.e., completion of the cycle of assembly. This is done via the re-entry branches shown in Figure 4, which give its layout. Re-assembly takes place as the "child" takes the parts of the "parent" to assemble a "grandchild," two switching points further along the track. Circuit and sequence details are also discussed in Appendix B.

With some compounding of circuitry, of course, all the functions or any combination thereof could be assembled in a single magnificent model.

II. GENERAL DISCUSSION

The Definition of Reproduction

We have described five obvious models of the reproductive process, without defining the process itself. The definition tacit in the model design is the following: Reproduction is the action of any orderly individual structure in a system which picks out randomly arranged parts from its environment, and reconstructs those and its own parts into additional functionally equivalent structures. The RSD series of models clearly follows this definition of function, and in fact, suggest it. The definition can eliminate processes which are often called reproduction, but which one intuitively feels are not such. For instance, the actions of a printing press or a stamping machine do not fit it, unless they print new printing presses or stamp out stamping machines.

In designing a model of reproduction, it is as important to avoid the Scylla of making a trivially simple system as it is the Charybdis of an impossibly complex one. The number of kinds of parts chosen for RSD is two. This is obviously the smallest number which can be put into an environment *at random*. The number of kinds of parts could be reduced to one, but the definition including randomness would not be obeyed. An interesting trick with RSD I reduces it to the trivial one-component situation. In this process, the A cars are put into position, one in each siding, and set so that their "chromosomes" are in the second position, i.e., so that their instructions allow only a B car to come in to the siding. If one B car is let into the first siding, the subsequent sidings fill up one by one with B cars. While this illustrates a nice automatic sequence device, it no longer illustrates reproduction.

This process is reminiscent of crystallization, which is also often

adduced as an example of reproduction. That there is an increase in order in crystallization is undoubted. There is, however, no clear individuality to the crystallization process, expressible as an *ancestry* of some sort. Even a two-component crystallizing system, such as sodium chloride, cannot be so justified. In such a crystal, nowhere can it be said that any particular sodium or chloride ion came from any other particular ion or group.

Another chemical parallel often cited as an analogy of reproduction is autocatalysis. Similarly, autocatalysis differs from reproduction because of the individuality of the latter process. The origin of life, often explained as the emergence of a process of crystallization or autocatalysis, demands more than this, in order to explain the origin of the individuality expressed in the parent-offspring relationship present in all known life. Some kinds of crystallization and autocatalysis were undoubted precursors of life; yet alone they cannot fulfil the demands of our definition of reproduction.

The definition is incomplete to the extent that it does not specify the permissible nature of the environment. This is apparently arbitrary. Two abstract models of reproduction have been mentioned by von Neumann [1,2], who was the first to give meaning to the possibility of such automata. In these, the first environment mentioned is the inside of a Turing tape-punching machine, an obviously unlikely one; the second environment is a strange group of contiguous rectangular cells in which energy transformations in one cell can affect the finite number of states in the neighboring cell. Both of these environments are extremely arbitrary, and likewise that of the RSD models. The only thing which makes the RSD models an advance over von Neumann's systems is the fact that they are planned in detail and, in at least one case, work.

What makes such arbitrary environments uncomfortable to accept is their unnatural, i.e., artifactual, quality. Biologists are looking for a system which does not require the hand of man to set up the environment, i.e., a model for the spontaneous emergence of self-reproducing species. Life assuredly did not originate on a model railway track! Yet these must be accepted as models, no matter what their environment. Perhaps they can be rated as to an elegance factor which increases as the environment is made simpler, with less built-in instrumentation, and simpler parts.

We now venture to suggest that this self-ordering process can be built into an electronic system. While such will lack the spectator appeal of moving parts and toy trains, the ordering of flip-flop circuits, magnetic domains, or even relays can be made just as relevant to our definition as any models so far mentioned. Should a group of subcircuits be arranged such that the ordering of one in a certain way causes it to order

the others in the same way, we will have an electronic model of reproduction.

Analogies to Biological Systems and Functions

The real value of models of this sort is that they call attention to the abstract *functions* inherent in the processes they represent. A model, together with the living reality, both have some irreducible minimum of functions. We have already called attention to the absolute necessity of (a) a source of parts, including a motor, plans, and some kind of sensory system, (b) a source of energy, and (c) an information-handling, or sequencing system. These, in the abstract, can be considered as the minimum functions of any self-reproducing system. We consider analogs to each, as follows:

(a) *Parts*. The parts of living things comprise the nutrients: water, minerals, essential amino and fatty acids, and vitamins for animals, and water, carbon dioxide, and minerals for plants. These rather simple parts are formed into replica organisms. Comparing with the RSD models, we can see that living beings are complex assemblies of simple parts, while the models are simple assemblies of complex parts. In this sense, the models are not true to life. One wonders how few parts a simple living being could use, and still function and reproduce. This is, of course, a function of what one calls a part. If one starts with parts readily available in the environment, the models show a need for only two or three, while living beings need millions up. Any actual, i.e., non-artificial, environment is rather unlikely to contain appreciable numbers of parts as complicated as the A and B cars described. The likelihood of emergence of such parts depends on their complexity, and upon how often *their* component parts are found in the environment, and on the free energy of the arrangement. What we have done is to bypass this colossal unlikelihood by *pre-building* the parts. In nature, the complexity equals of A or B cars would not appear in years. This leaves the question of whether the first living beings were assemblies of a few complex parts, or of many simple ones, quite unanswered. Any attempt to make inferences on this point will give a very tenuous answer.

(b) *Energy*. The sources of useful energy in living beings are remarkably uniform. The utilization of energy from solar radiation and intermediary metabolism, of short-period energy from high-energy ester bonds, and of stored energy of reduced polymers, is employed in living systems to perform chemical syntheses, fiber contractions, active transport, and membrane formations. This energy utilization shows no apparent relationship to the electromechanical transducers of our models.

(c) *Sequence system*. Every living being uses the same sequence method to reproduce, at some stage in its life cycle, i.e., mitosis. Uni-

cellular organisms double material and then divide, mitosis being the entire cycle. In the cycle, half the parts come from the parent, and half are taken in from the environment. With multicellular organisms, mitosis increases the number of cells, and combines with differentiation to give rise to the organism's characteristic form. Here most of the progeny parts come from the environment, with only a small to infinitesimal fraction traceable to the parent. With the RSD series, *all* the parts of the "organism" come from the environment, except in the case of RSD IV, which uses one of its three parts from its "parent." Thus, the sequence of RSD and mitosis are in no way directly comparable, except that both have strongly defined sequences.

In mitosis, the actual duplication goes on at a microscopically rather inaccessible time. The spectacular portion of this sequence is the breaking up of the doubled material, especially of clumps of nucleic acid and associated material to which most of the plans of higher order organisms have been traced. Just as the order of the holes in the "chromosomes" of RSD models direct their assembly, so do the orders of the nucleotide components of the nucleic acids in chromosomes of living organisms direct their development.

But the chromosomes do not necessarily contain their self-duplicating apparatus. The mitotic apparatus, which does the actual separating of the doubled set of plans, must also be duplicated. Different organisms contain utterly different chromosomes, but they all seem to contain the same kind of duplicating apparatus, with minor variations. This extra-chromosomal apparatus is the probable biological analog of the *whole* RSD model "organism." The chromosomes are probably merely the "punched cards." They are very complicated for living organisms, which are complex assemblies, but a very trivial part of the design of machines like RSD I-V, which are simple assemblies.

The comparison of the actual sequence patterns of biochemical systems with those of electromechanical ones should be a very fertile field, though presently unexplored. Connections between functioning components in RSD are established by electrical wires; in life by diffusing ions and proteins. Mechanical connections exist as such in both kinds of system. The biochemical analog of a relay, which is essentially an all-or-none amplifier, is an autocatalytic enzyme system. Negative feedback in biochemical systems is commonly established by competitive or inhibitory catalytic systems. The analog of the contact or contact pair in RSD is probably found in the biological threshold phenomenon, such as that of a nerve resting potential breakdown. The answers to the biochemical assembly problems must be sought in such systems as these, which bear the proper analogy to the self-reproducing systems mentioned.

While analogy is dangerous, it is also stimulating. If such considera-

tions as these show us where to look, or how to talk about the phenomena of life, the contemplating and building of models has been worth while.

The Informational Capacity of RSD, and the Origin of Life

By far the most interesting of the dynamic processes in reproduction is the transfer of information, from plans to action. As one of the prime unanswered questions of biology, this transfer of the plans from the chromosome, or punched card, into the assembly of the organism, constitutes the true understanding of the life cycle. In electromechanical models, the transfer takes place by the influence of the holes in the punched cards on the operation of the working parts of the apparatus. Obviously, chromosomes have some analogous information storage effect. In so far as the chromosomes describe the organism, they must be as *complex* as the organism.

The proper way to describe the complexity of anything is given by information theory. Expressed in terms of "bits," or binary choices, the complexity of the "chromosomes" of RSD models is easy to compute, and small, while the complexity of a real chromosome is also possible to estimate (to the extent that its structure is established), and quite large. Each time that a binary choice is made for a punched card (to punch or not to punch), one bit of information is demanded. In the "chromosome" of RSD I, there are six possible sites for punching. Of these, two are actually punched. However, the existence of six punchable holes demands that the "chromosome" furnish six bits of information to the model, for its perusal and instruction.

One can see, however, that the model must be *attuned* to the information provided by the card. This is made possible only by its careful and complex construction. A similar kind of function is present in real chromosomes. Instead of punches, particular nucleotides appear, chosen from four (usually) possible ones. Such a quaternary choice is equivalent to two binary choices, i.e., two bits of information per nucleotide. The Crick-Watson model of DNA puts restrictions on the nucleic acids present, allowing only about half as much freedom of choice as on a perfectly random chain, and consequently, the amount of potential information, in bits, is only roughly equal to the number of nucleotides. This amount naturally varies with the actual organism [3]. In a bacterial virus, with a molecular weight of about 1.2×10^8 , there are about 4×10^5 nucleotides (although a virus is probably not a complete organism). In a unicellular animal, if one assumes all the DNA present is in chromosome-like material, there are about 5×10^6 nucleotides; in a mammalian cell, about 10^{10} .

It is interesting to calculate the complexity of the *entire* RSD models. The information involved in assembling them is quite small, only six

bits for RSD I, and similarly only nine ternary digits, or about 14 bits, for RSD IV. But the cars themselves are quite complex. The over-all complexity of the models is mainly that of the cars, in distinction to the over-all complexity of organisms which is largely, if not overwhelmingly, that of the chromosomes. This over-all complexity of RSD I might give some clue as to the order of magnitude of possible minimum complexity of an organic self-reproducing system.

This calculation of complexity has been performed by straightforward application of the principles of information theory to the mechanism considered [4]. Consideration of the connections between the components of RSD I, for both mechanical and electrical linkages, allows the complication of array to be calculated. In informational units, it amounts to 116 bits. This figure must be taken as a minimum, as it does not include the information required in "concentrating" the parts from the environment. Nevertheless, it indicates that some kind of a self-reproducing device is possible, given a free supply of components, with no more complexity, i.e., information, than this. This small amount of information is dwarfed by the huge detailing of structural complexity in living beings, as potentially available from the numbers of nucleotides in the "plans" of living cells. But this quantity may be representative of the minimum information of the mitotic process, a sort of *sine qua non* for a being to reproduce.

A similar calculation has been made for RSD IV, the quantity of organizational information being computed as approximately 570 bits. Even though plans duplication is at present a universal characteristic of life, it is not necessary to assume that the earliest forms of life duplicated their own plans. For, with plans so simple as those of a few-part organism, they may have used plans present in the environment, just as RSD I uses plans found on one of its parts. Barricelli has presented [5, 6] the engaging hypothesis that present life originated as a symbiosis between the mitotic system, corresponding to RSD I, and the virus-like nucleic acid plans system. The former provided the minimum self-reproducing system, with complexity of the order of a few hundred bits, perhaps, and the latter, on being incorporated into the system, provided the necessary flexibility and mutability which has given rise to evolution of higher forms. At present, the idea is pure fancy, but its implications should be explored.

It has been assumed that similar informational requirements might characterize self-reproducing mechanisms of electromechanical type, and of biochemical nature. This leads to a natural comparison of these figures for RSD I and IV with those which might be expected for spontaneously arising life forms. Estimates [7, 8] have been made of the permissible complexity of the latter, and suggest that the first forms could not have had more than 100-200 bits of complexity. Any being much

more complicated than this, e.g., one equalling RSD IV in complexity, would be unlikely to have formed on the globe over the billion years available for spontaneous genesis. Thus, considerations of models, information theory, and thermodynamics all seem to agree that the probable complexity of the first living being was rather small.

It is reasonable that further research into the origin of life can be developed from an informational standpoint, along the following lines: (1) Estimates of the probable concentration of useful parts will be made; (2) Development of suitable analogs to the relays, sensors, program storage, and similar devices will be discovered in the realm of biochemical mechanism; and (3) Specific models, using these biochemical mechanisms, will be developed for self-reproducing systems. The appropriate calculation of the free energy of this class of models will then throw light on the probable spontaneity of development of such systems, and whether any *a priori* hypothesis as to the origin of life need be made.

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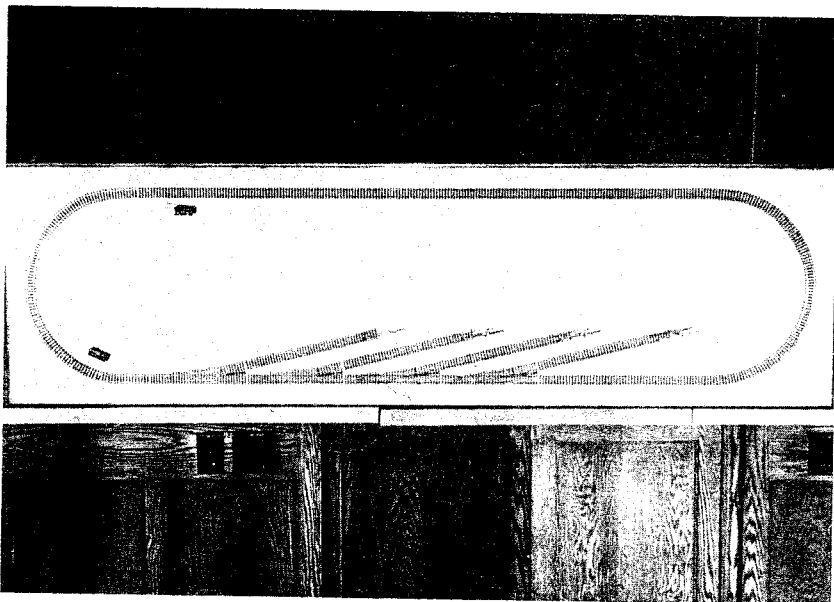
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APPENDIX A

The Design and Construction of RSD I

Photographs of RSD I, as actually constructed, are shown in Plates I-VII. Plates I-III show the entire model, while Plates IV-VII show details and interactions of individual cars. Plate I shows the over-all layout, without any cars present. The environment track and four sidings with their end stops are visible, as well as the



Photos by Videika and Wacks

PLATE I. Over-all layout of RSD I, top view.

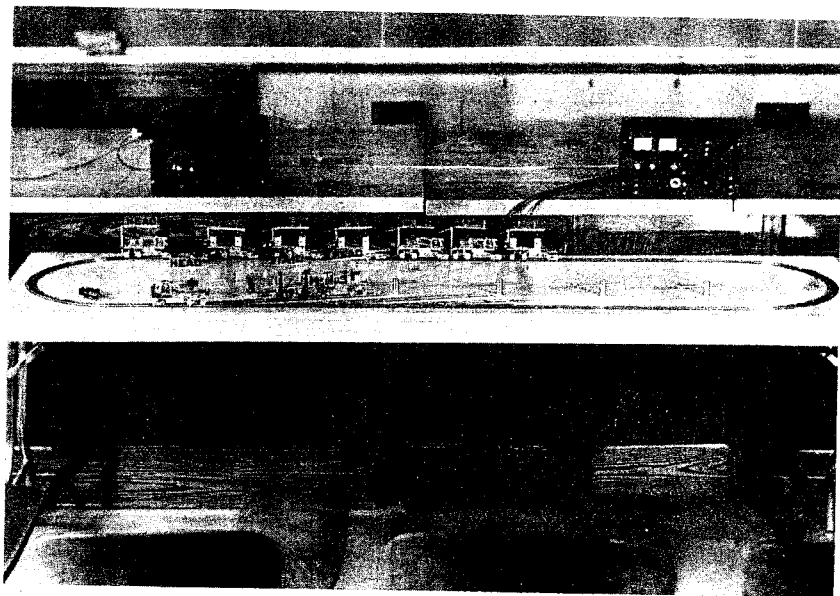


PLATE II. RSD I at beginning of cycle. First "organism" assembled.

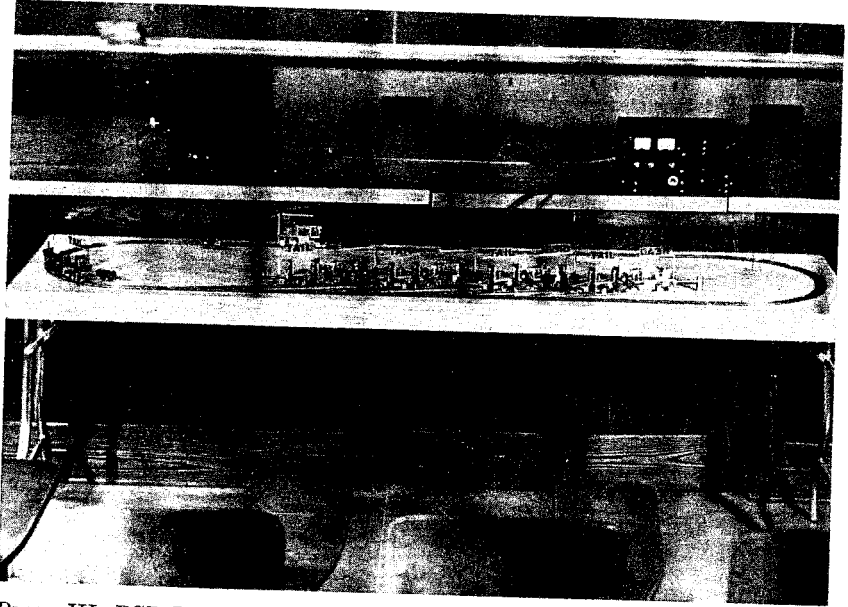


PLATE III. RSD I at end of cycle. All four "organisms" assembled; no room for remaining parts.

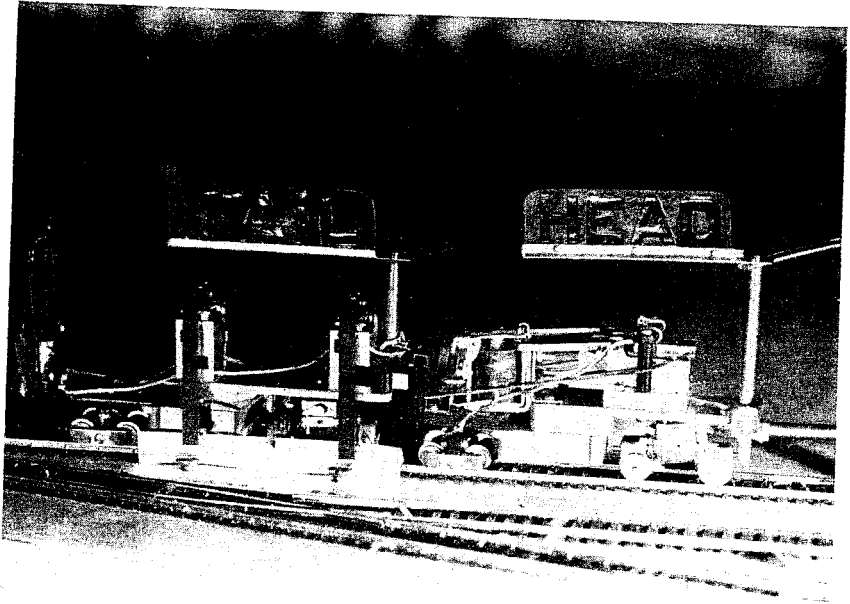


PLATE IV. Single assembled "organism."

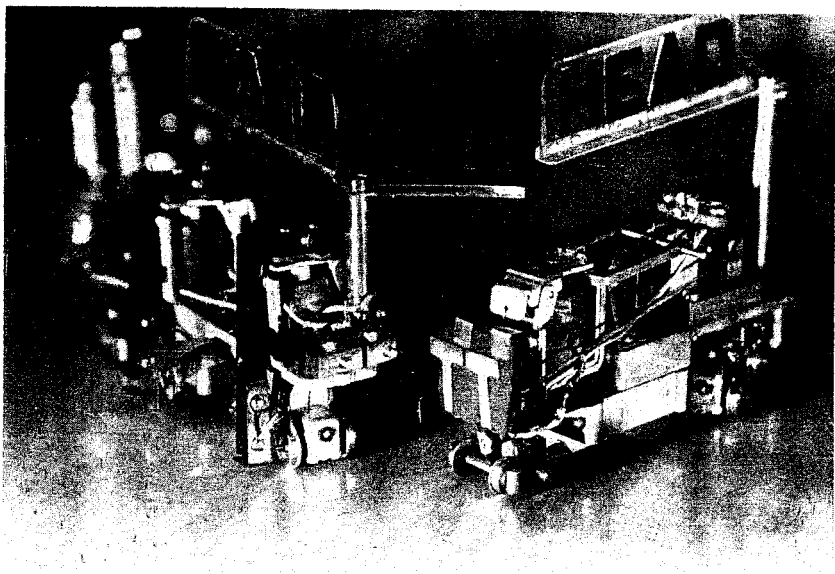


PLATE V. B and A cars, with bumper contact detail.

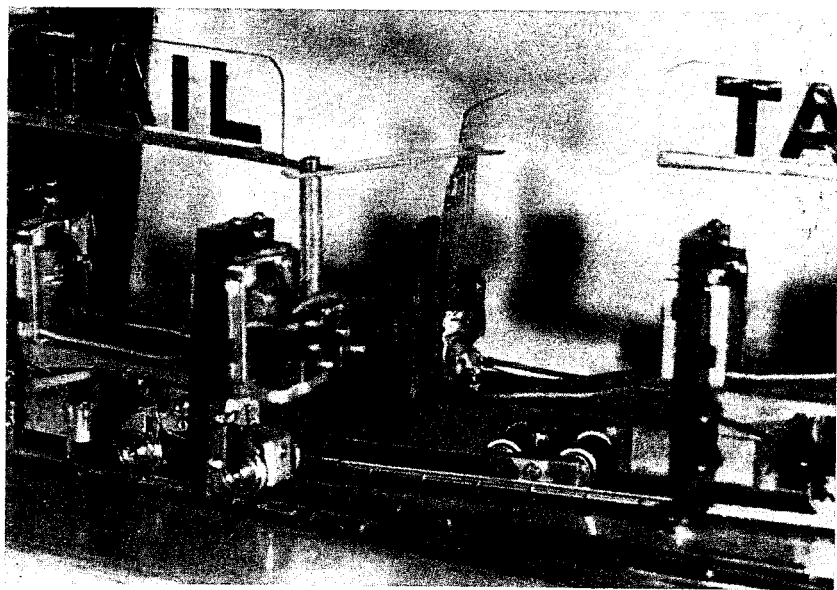


PLATE VI. Approach of B car to "organism" detected by B "eye" on B car of assembled "organism."

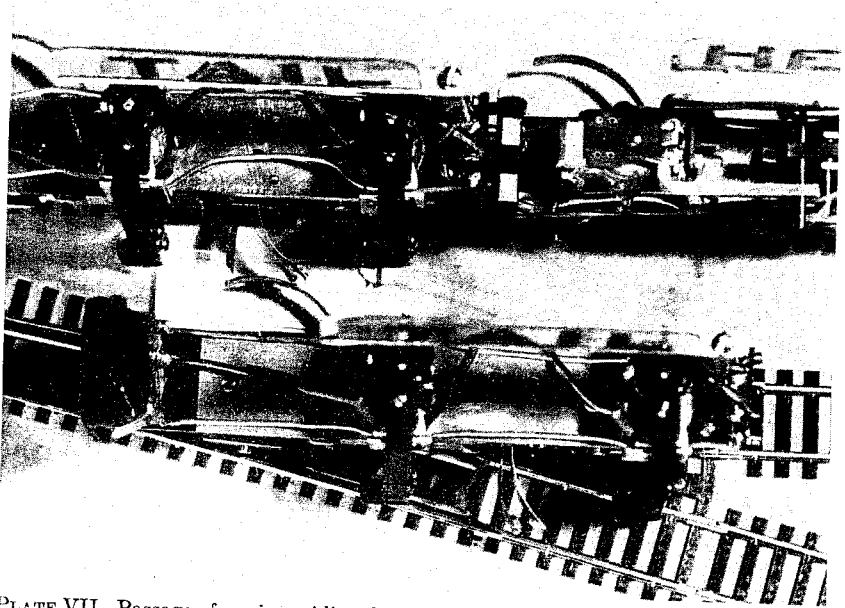


PLATE VII. Passage of car into siding detected by A or B "eye" on B car of assembled "organism."

three pairs of buttons controlling the switches to the last three sidings, and the two microswitches controlling the spacer system described later.

Plate II is a perspective view of the entire apparatus. The cars, marked "head" and "tail," have been randomly arranged, by coin toss, as HTHHTTTHHT, and the first two cars let into the first siding. The directions for this assembly of the first "organism" came from the operator of the model, who manipulates two buttons on the main control box, to the right. These buttons open and close the first siding switch, called, for obvious metaphorical reasons, the "God switch." The power supply is seen as the left-hand black box.

Plate III shows the end of the "species," with all four sidings containing non-functioning "organisms." Further reproduction is impossible because of lack of more sidings, although an extra A ("head") and B ("tail") car are still available in the environment.

The apparatus as a whole runs on 10-12 volts of D.C. supplied by the power supply to the electrified rails. It can be seen to be mounted on a braced maple-veneered panel of over-all dimension 215 × 60 cm, fitted with a set of tubular steel folding legs.

Plate IV shows the details on a single A-B car pair *in situ*, i.e., a single "organism." The cars are seen to consist of a main casting, at the front of which is mounted a standard HO gauge motor, and in the rear a pair of insulated wheels on a machined bakelite block. Mounted on the cars are visible relays, contacts, and arms, and a fairly complex assembly with an escapement mechanism on the A car. The cars are seen to be held in place by a siding end stop, and to make electrical contact with one another at four bumper contacts, with the driving force of the B car naturally tending to maintain this contact by pushing it against the stopped A car. The assembly of the A and B cars, and the four contacts, are seen more easily in Plate V.

Plate VI shows the approach of a B car to the rear of an "organism" assembled on a siding, and Plate VII shows the interaction between a (B) car entering a siding, and the B car of the already assembled "organism" of the previous siding.

The two relays on the B cars, particularly visible in Plate IV, carry electricity to the switches controlling the next siding. In a manner reminiscent of Prometheus,

the extension arm, mounted on the moving top of the relay, is fitted with a contact at its end which is electrified by connection with the rails. Closing the relay causes this arm to lower the contact near the base of the track. Under the arm can be seen the buttons which carry this electricity to the switch. Closing of the back relay causes electricity to open the switch to the next siding, while closing of the front relay closes the switch to the siding.

These relays must be activated by current which is properly directed. This direction involves a "knowledge" of which kind of car is passing by the "organism" on the way to the next siding. This means that the cars must naturally "look" different to something on the B car, on which are mounted not only the relay "muscles," but the contact "eyes." The "eyes" are a pair of differently placed contacts, one sensitive to

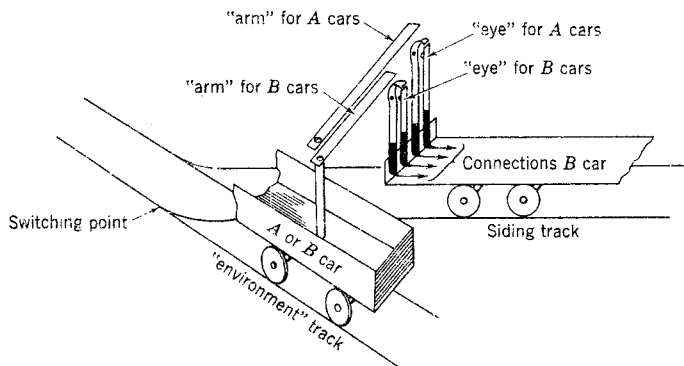


FIG. 5. Contact "eyes" of B cars, and "arms" of A and B cars.

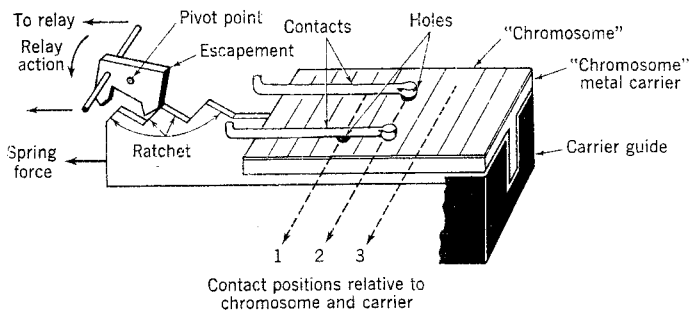


FIG. 6. Details of "chromosome"-advancing mechanism.

passage of A cars, and one to B cars. This sensitivity is achieved by providing the A and B cars with identifying arms which reach out to the siding, and close the appropriate contact on the "organism" A car, thus identifying themselves as A or B cars. This can be seen in Plate VI, and most clearly in Figure 5. On the A car, the arm is a quarter inch higher than on the B car, and consequently misses the lower pair of contacts; the arm on the B car misses the higher pair of contacts because it is a half inch shorter than that on the A car, and doesn't reach it. Thus a passing A car will close the contact pair which is higher and further away from it. Provided the "organism" circuit is set to do so, the closing of the contact pair will send current through the back relay on the B car, and cause the switch to the next siding to open. A similar action may occur when a B car passes, if the circuit is so set, by closing of

the shorter and nearer contact pair. The contact pairs are referred to as A "eyes" and B "eyes," respectively.

The arms on the cars are also seen to carry the "head" and "tail" signs. These are simply for information of the spectators.

A similar kind of sensing must take place to control the *closing* of the switch to the next siding. This must occur *after* the car has passed the switching point. This function could have been made automatic, but was not. A third contact pair, not so discriminating, called the A-or-B "eye," is mounted on the right side of the B car. It is most readily visible on Plate VII, as a pair of curved metallic strips projecting from the middle of the side of the car. This "eye" responds to a short flange extending from the side of the car. This "eye" responds to a short flange extending from the left side of either A or B cars, as is also visible in Plate VII. With passage of either kind of car just beyond the switch, this contact pair is closed. Closing of the pair is always circuited to send current to the front relay on the B car, and consequently to close the switch to the next siding.

The question of setting up a sequence of directions for the choices to be made by the "eyes" remains. They must first be set to be sensitive only to an oncoming A car; after the A car passes into the siding, they must become sensitive to a B car; and after the B car has passed into the siding, they must be set so that no sensitivity remains at all. This sequence is handled by the escapement mechanism on the A car, the plan, or "brains." Details of this mechanism are schematically depicted in Figure 6. It consists of a relay, an escapement, a punched-card type "chromosome" bearing the coded instructions, a set of two contacts, and a spring-loaded "chromosome" carrier set in a grooved guide block. When the relay is activated, it moves the escapement up and down, allowing the "chromosome" carrier to advance one (6 mm) notch along its guide. Since the "chromosome" is an insulator, separating the contacts from the conducting carrier and guide, its motion allows for alternate electrical contact between the two contacts and the guide. At the beginning of the life cycle, one contact (the lower one in Figure 6; the one marked Cr₁ in Figure 7) makes contact with the guide through the first hole in the "chromosome." This contact is connected to the A "eye" contact pair on the B car, through one of the bumper contacts connecting the two cars. In this condition, it grounds one side of the A "eye" contact pair, thereby sensitizing it, and the "organism" to the passage of A cars on the environment track. When the A car enters the siding, however, it also activates the relay controlling the "chromosome," causing it to advance a notch with its carrier. It is now in the position depicted in Figure 6, with the contacts at the second position. Now the other contact (the upper one in Figure 6, and the one marked Cr₂ in Figure 7) is connected to the guide through the second hole in the "chromosome." The first contact, of course, becomes insulated from the guide. The other, or B "eye" contact pair on the B car now becomes sensitive to passage of B cars, and one side of it is grounded. A B car is shunted into the siding, and once again the "chromosome" and carrier are advanced a notch, by action of their relay. The contacts are now in the position marked 3, on Figure 6, and are both insulated from ground by the unpunched "chromosome" portion in this position. Further switching of cars on to the siding is thus prevented, as both contact "eyes" on the B car are insulated. As a complete "organism" has formed on the siding, there is no need for the first "organism" to do any more switching.

An interesting possibility arises when one considers the possible results of changing the holes punched in the "chromosome." With very slight alteration, any set of three instructions whatever can be given the "organism," from the "chromosome." We have made one "chromosome" such that it gives the reverse directions to the switches, i.e., assembles an organism backwards on the siding. Such a "mutation," of course, is perfectly inviable, so far as effecting any reproduction is concerned. The car fitted with these backwards instructions can be regarded as having a mutant "gene," expressed in the "phenotype" of the next "generation." This A car has actually been so mis-outfitted. It can be seen on the group in Plate III as the "head" in the fourth siding. The sign "head" is reversed on this car, so as to indicate its reversed "brain."

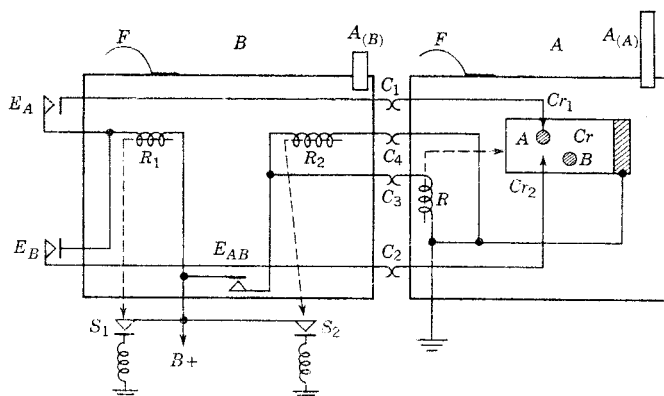


FIG. 7. Circuit of cars of RSD I.

Figure 7 shows the complete circuit of all the relays, contacts, "chromosome" assembly, and siding switches, for the cars of RSD I. We identify the elements of the diagram as follows: On the A car are:

(1) The "chromosome" and guide, Cr, with the holes marked A and B. The guide is seen to be grounded.

(2) The contacts Cr₁ and Cr₂, which conduct the instructions from the "chromosome" toward the B car.

(3) The "chromosome" relay, R, whose mechanical connection to Cr is shown by the dotted line terminating in an arrow. Its effect on the circuit is alternately to ground Cr₁, Cr₂, and then neither.

(4) A set of four bumper contacts C₁-C₄, connecting A with B.

(5) The "arm" A(A) and flange F.

On the B car are:

(1) The pair of siding relays R₁ and R₂. When energized, R₁ causes the siding open switch S₁ to be given electrical energy, and the siding switch to open. Energizing of R₂ gives energy to the siding close switch S₂, closing the siding switch.

(2) The pair of contact "eyes" E_A, sensitive to the arm A(A); the pair E_B, sensitive to the arm A(B); both on passing cars in the environment.

(3) The contact pair E_{AB}, or the A-or-B "eye," sensitive to flange F on either car, as it passes into the next siding.

(4) A corresponding set of four bumper contacts, C₁-C₄.

(5) The "arm" A(B) and flange F.

In addition, both cars bear motors which furnish locomotion, and are also the source of electrical connection with the track power. The motor of the A car is shut off on reaching the end of the siding, by insulating the B⁺ supply on the track. The motor of the B car, however, keeps running, and supplies the pressure which gives the bumper contacts a reliable connection between cars.

We describe the sequence of events leading to assembly as follows:

(1) An "organism" is assembled on the first siding by manipulation of the "God switch" controls on the main control box by the operator.

(2) Contact at bumper contacts C₁ grounds one side of E_A via Cr₁.

(3) Passage of an A car on environment track closes E_A, due to "arm" A(A).

(4) Siding open relay R₁ is thereby energized, and causes S₁ to open siding switch.

(5) A car enters second siding.

(6) Action of flange F on entering A car closes "eye" E_{AB}, as A car passes second siding switch.

(7) Closing of E_{AB} energizes siding close relay R₂, which closes siding switch via S₂.

- (8) Simultaneously with (7), closing of E_{AB} energizes "chromosome" relay R via C_3 . Cr is thus advanced to second position.
- (9) One side of B "eye" E_B is consequently grounded via C_2 and Cr_2 .
- (10) Passage of a B car on environment track closes E_B , due to "arm" A(B).
- (11) Siding open relay R_1 is thereby energized, and causes S_1 to open siding switch.
- (12) B car enters second siding.
- (13) Action of flange F on entering B car closes "eye" E_{AB} , as B car passes second siding switch.
- (14) Closing of E_{AB} energizes siding close relay R_2 , which closes siding switch via S_2 .
- (15) Simultaneously with (14), closing of E_{AB} energizes "chromosome" relay R via C_3 . Cr is thus advanced to third position.
- (16) "Eyes" E_A and E_B , together with Cr_1 and Cr_2 , are insulated from ground by Cr in third position, and consequently no further action takes place with "organism" on the first siding.
- (17) Organism on second siding repeats steps (2-16) with third siding as site; process continues until sidings are filled, or parts are used up, or mistake is made.
- Occasional bumping of A and B cars on the environment track has no particular effect, simply because no action can be taken by any car unless it is on a siding, nor can its "chromosome" position be altered, except when it has allowed another car to pass into the next siding.

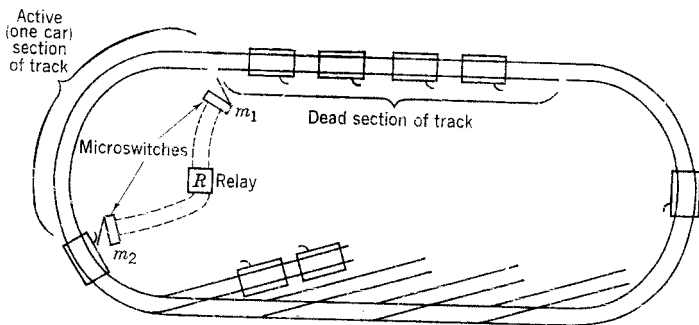


FIG. 8. Layout of spacer system.

One precaution proved absolutely essential, however. This was a spacer system for the cars. If allowed to run together on the environment track, two cars would often be in direct contact with one another. When the first of these cars was switched into a siding, owing to the finite length of the switching assembly, the second would necessarily follow into the siding before it could be closed. This naturally would usually end the cycle. Consequently, a system was devised to see that two cars would not run this close together as the first approached a switching point. The layout of this system is depicted in Figure 8, and some components thereof can be seen in Plates I-III. As erected, it took the form of a long section of track which was made electrically "dead" as soon as a car left it, and entered the "active area" just ahead of it. Only on reaching the end of the "active area," just prior to the area of switches, would this car re-energize the "dead" section. The next car, coming out of the "dead" section, would then in turn deaden the section for the cars following it. The net effect of the spacer system was to cause a one-by-one spewing forth of trains from the front of the section. The front of the section was located immediately prior to the curved "active area" preceding the switching points. Thus, by the time one car reached a switching point, the next car would be coming, but never close behind it, as the speeds of the cars were relatively uniform. The arrangement served not only to prevent mishaps in the assembly process, but also to keep cars from jostling one another on the curved sections, and from the derailing with which HO gauge enthusiasts are so familiar.

Operation of the spacer system is visible in Plate II, in which six cars are being held up at the "dead" section of track, one car is in the "active area," and one about to enter the second siding. Two cars have entered the first siding. Separation of the cars at the curved parts of the track, and at the switch points, is quite clear, as the piling up occurs along the straight "dead" section.

APPENDIX B

Design of RSD II-V

We now present details of the design of circuits and sequences of the more complete models of reproduction referred to as RSD II to V, in the text of this paper. None of these have been built. As is apparent from their designs, construction of such models is of varying degrees of practicability. All are, in principle, workable.

The first model to be described in this Appendix is RSD II, a self-reproducing multiplying model. The layout of RSD II is given above in Figure 2. As can be seen, each "organism" has two "offspring." The arrows indicate which "offspring" belong to the "organism" on a particular siding. Fifteen "organisms," belonging to four "generations," can be accommodated on the track layout depicted.

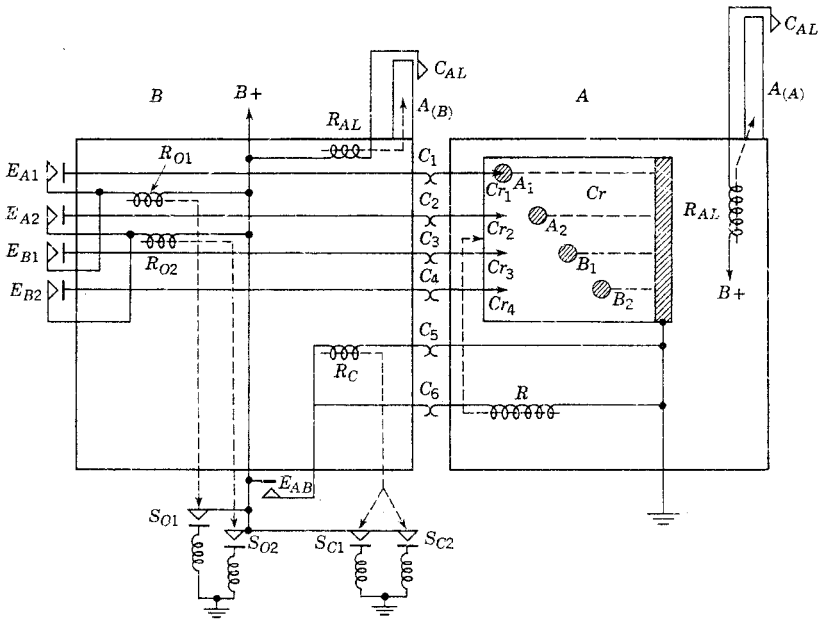


FIG. 9. Circuit of cars of RSD II.

The circuit of the cars of RSD II is shown in Figure 9. It differs from that of RSD I in the following ways:

(1) Cr bears four punched holes, labelled A_1 , B_1 , A_2 , and B_2 , indicating A car in the first siding, B car in the first siding, A car in the second siding, and B car in the second siding, respectively. The circuit as designed will fill the "offspring" sidings in the order A_1 , A_2 , B_1 , B_2 , although, of course, other orders are perfectly possible. First and second siding here refer to the two "offspring" sidings as indicated by the arrows from the "parent" siding.

(2) There are corresponding extra chromosome contacts Cr_3 and Cr_4 , and spring contacts C_5 and C_6 .

(3) There are twice as many "eye" circuits on the B car. In practise, there need only be two "eyes," but these must be double-pole single-throw contacts. There are also two siding open relays, R_{O1} and R_{O2} , one for each of the "offspring" sidings. Only one siding close relay, R_C , is necessary; it closes both "offspring" sidings at once.

Except for this multiplicity of equipment, the circuits are seen to be identical with those of RSD I. The reader can easily follow the sequence of assembly, leading to filling of both "offspring" sidings.

When several "organisms" are reproducing at a time, there can be interference between them. An "arm" from an A car, say, might open *two* sidings, as it passed A "eyes" on two different reproducing "organisms." Cure for this interference involves either setting up a sequence allowing only one "organism" to reproduce at a time, or more conveniently, as follows: All cars are given an arm-lowering device, which is sensitized when the arm touches any sensitive, i.e., grounded "eye." It is indicated in Figure 9 by the relay R_{AL} . Contact C_{AL} , on touching any grounded "eye," causes this relay to lower the "arm" $A(A)$ or $A(B)$ which it controls.

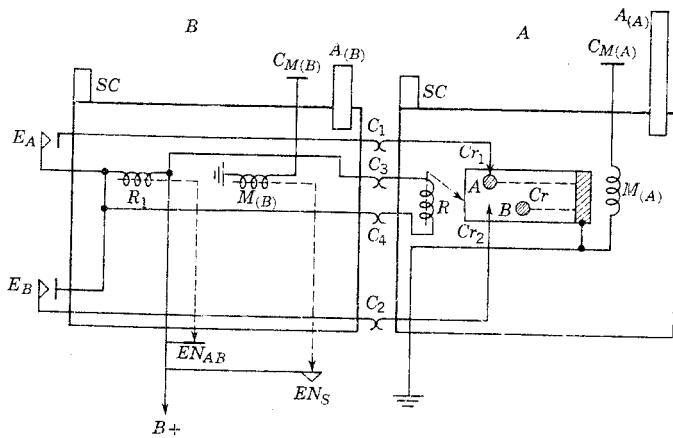


FIG. 10. Circuit of cars of RSD III.

The next model taken up is RSD III, a system requiring no built-in switches on its track, as it lays its own sidings and switches. In addition, it must make provision for the switching on to this siding track to be controlled, directly or indirectly, by previous "organisms." RSD III has the same layout as RSD I, except for the absence of sidings. The circuit of the cars is given by Figure 10. It differs from RSD I in the following respects:

(1) A new mechanism is on each car, labelled $M(A)$ and $M(B)$, respectively. Mechanism $M(A)$, when activated via $C_M(A)$ effects, in order: (a) stopping of the A car, (b) laying down of switch and siding ahead of the A car, and (c) proceeding of the A car into the siding. Mechanism $M(B)$, when activated via $C_M(B)$, effects only the opening of the siding switch in the newly laid siding just ahead of it, via current sent to the energizer EN_S .

(2) Each car bears contact labelled $C_M(A)$ and $C_M(B)$, via which $M(A)$ or $M(B)$ are energized, as the appropriate car passes an "organism" on a siding. The relay R_1 on car A, corresponding to the siding open relay R_1 of RSD I, causes such energizing on the passing cars, via the energizer EN_{AB} which it controls. R_1 must be set to remain closed, once energized, long enough for the passing car to move from the point when its "arm" closed the "eye" on the B car, to the point where its contact C_M touches the energizer EN_{AB} on the B car.

(3) Each bar bears a siding switch-closing arm, labelled SC, which automatically closes the siding switch as it goes past.

(4) Siding close relay R_2 , flanges F, and "eye" E_{AB} of RSD I are absent from RSD III.

The sequence of operation is wholly analogous to RSD I, as follows:

(1) The operator energizes M(A) on an A car, via $C_M(A)$. The A car stops, lays its siding and switch, and goes in. SC closes the switch as it comes in.

(2) He then energizes M(B) on an approaching B car, via $C_M(B)$. The B car then furnishes current to EN_B , which opens the switch just laid on the track, and lets the B car into the siding. SC then closes the siding switch. This completes the "act of creation." One side of "eye" E_A is grounded via C_1 and Cr_1 .

(3) Passage of an A car on the environment track closes E_A , as its "arm" A strikes it.

(4) Relay R_1 on the B car is energized. It then effects energizing of M(A) on the passing A car, via EN_{AB} , which remains electrically active for a short while after energizing of R_1 .

(5) M(A) on the passing A car causes it to stop, lay its (second) siding and switch, and go in.

(6) and (7) SC closes the second siding switch as the new A car enters the second siding.

(8) Simultaneously with step (4), relay R is energized, via C_3 and C_4 , and causes Cr to move to the second position.

(9) One side of "eye" E_B is now grounded, via C_2 and Cr_2 .

(10) Passage of a B car on the environment track closes E_B , as its "arm" A(B) strikes it.

(11) Relay R_1 on the B car is energized. It then effects energizing of M(B) on the passing B car, via EN_{AB} .

(12) M(B) causes the passing B car to open the second siding switch with EN_B , which it controls.

(13) The B car goes into the second siding.

(14) SC closes the switch to the second siding.

(15) Simultaneously with step (11), relay R on the A car is energized, via C_3 and C_4 , and causes Cr to move to the third ("dead") position.

(16) Contacts E_A and E_B are both thus isolated from ground, and no further action takes place on the first siding.

(17) The "organism" on the second siding repeats steps (2-16), etc.

It is clear that formidable mechanical difficulties attend construction of RSD III. The most difficult part of RSD I to make is M(A), which sequentially stops the car, lays down a rather large siding and switch, and starts the train into the laid siding. Perhaps the switch itself would be the most difficult part to construct. It would have to fit over an already placed track, to have a provision for being closed by the SC arms on either train, and also to have a provision so that an approaching B car with an energized contact EN_B sticking out of it could cause it to be opened again. While the reader may recognize such a device as in principle constructible, we do not recommend that he try to make one without very substantial machining and engineering facilities at his disposal. The cost and effort of producing such a delicate, topheavy, and probably intricate mechanism will not be justified by mere reduction of a principle of a self-siding-laying model to practise. None of the other RSD group described embody the track-laying circuits of RSD III.

We now describe RSD IV, the self-and-plans-duplicating model. In RSD IV, as described above, the "organism" transforms a blank card into a "chromosome" with proper punched holes, and passes it to a car missing the "chromosome." A duplicating punch apparatus is necessary, as well as a "chromosome"-advancing and passing device. The over-all layout of RSD IV is shown in Fig. 3, along with a general discussion of its functions. The circuit of the cars is shown in Figure 11, and the stages in the "chromosome" advancing and punching sequence in Figure 12. The complement of equipment shown on the individual cars is labelled as follows: The A car bears:

(1) A blank "chromosome" card Cr. Cr is visible in Figure 11 as the lower left-hand area on the A car, surrounded by dashed lines; it is also visible in Figure 12a on the left side of the A car box.

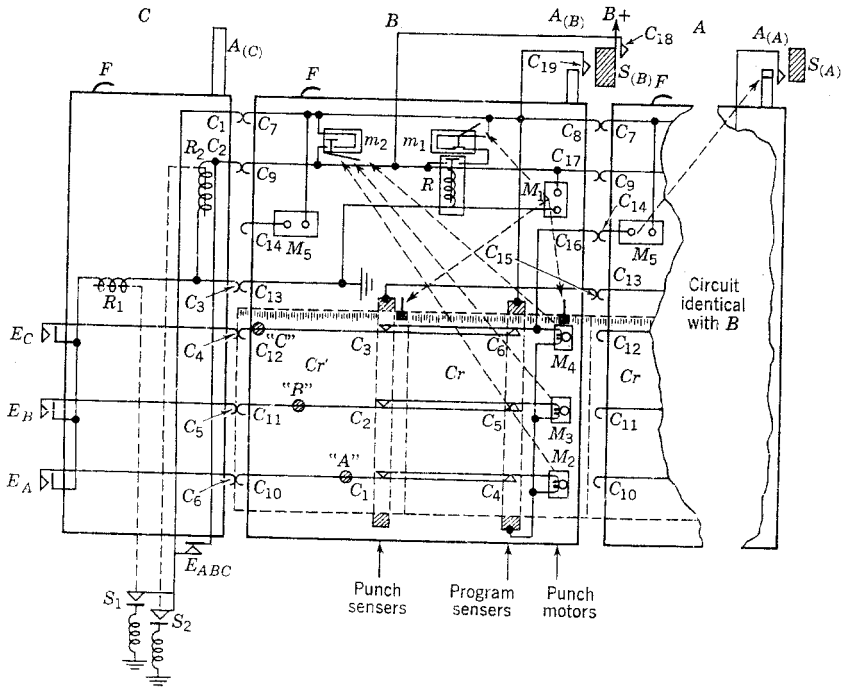


FIG. 11. Circuit of cars of RSD IV.

(2) A "chromosome"-advancing and passing motor M_1 . In Figure 11, M_1 is visible only as a box with connections on the B car. Its important action in shifting the "chromosome" cars toward the right is indicated by the two arrows leading downward toward the boxes marking the cards Cr and Cr' on the B car. The arrows are seen to lead to two blackened outlines of two small spur gears, which are the moving agents for the cards. The cards, also seen as large rectangular boxes with dashed-line outlines, have a sprocketed edge. The rotating spur gears move the cards along the edge of the cards. The cards are consequently to be imagined as moving toward the right in a horizontal direction, when so acted upon by motor M_1 .

(3) Three "chromosome" punch motors, M_2 , M_3 , and M_4 . These are also shown as small boxes with connections above the card on the B car. When activated, they punch a hole at the spot indicated by their position.

(3) An "arm"-changing motor M_5 . This motor is necessary to change the length of "arm" $A(A)$, when the A car is turned into a B car.

(4) A relay R connected in self-holding circuit, and activating motor M_1 .

(5) An interruptor microswitch m_1 , normally closed, activating R .

(6) A circuit closing microswitch m_2 , normally open, activating R .

(7) A set of three punch sensing contacts, C_1 , C_5 , and C_3 .

(8) A set of three program sensing contacts, C_4 , C_5 , and C_6 .

(9) A set of bumper contacts, C_7 - C_{17} .

(10) Two contacts, C_{18} and C_{19} , for bringing in a B^+ supply.

(11) Flange F and arm $A(A)$.

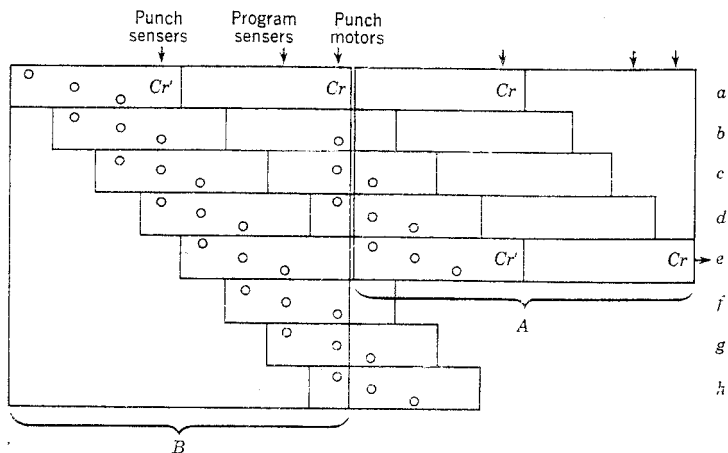


FIG. 12. "Chromosome" advance sequence and production in RSD IV.

The B car is like the A car, but with the following differences:

- (1) It bears a punched "chromosome" card Cr', as well as the blank one, Cr.
- (2) Arm A(B) is in a different position from A(A).

The C car bears:

- (1) Relays R_1 and R_2 to open and close siding entry switches via S_1 and S_2 , respectively.
- (2) Contact "eyes" E_A , E_B , and E_C , respectively, to distinguish passage of A, B, and C cars on the environment track.
- (3) Contact "eye" E_{ABC} to sense passage of any car through the entry switch on the next siding.
- (4) Spring bumper contacts C_1 - C_5 .
- (5) Identifying "arm" A(C) and flange F.

The sidings bear two stops S(A) and S(B), which make contact with arms A(A) and A(B), respectively. The cars are held together, and against these two stops, by the pressure of the moving locomotive motors. The B^+ supply comes into the circuits of the B car from the stop S(B), through contact with contacts C_{18} or C_{19} . Thus no circuits can be completed in the "organism" until the cars are assembled in their sidings, and the life cycle cannot start without a temporary supply of B^+ coming into relay R via C_{18} . It cannot continue without a constant B^+ from C_{19} . Accidental contacts of the cars on the environment track will have no effects.

The detailed picture of the punch, advance, and pass cycle of the "chromosome" cards is found in Figure 12. As can be seen by following the stages a-h in Figure 12, the blank card Cr on B is punched out in the image of the punched one, Cr'. It is then passed on to car A, as the blank card on A also advances. When eight advances have been made, A has the exact complement of cards and punches which B had at the beginning of the cycle. The vertical arrows in Figure 12, as well as Figure 11, indicate the position of the contacts and motors which operate on the cards, or are affected by the cards, at various times of the cycle.

The detailed sequence of the life cycle is as follows:

- (1) Cars A, B, and C, are assembled in order on the first siding.
- (2) Arrival of B in the siding causes a temporary current, via C_{18} , to the primary of relay R; it is shortly followed by a permanent current via C_{19} , as C_{18} passes stop S(B) and C_{19} reaches it. The following are the results, which are always duplicated whenever relay R is activated:

The self-holding (positive feedback) character of R causes it to remain closed until current to its primary is interrupted by microswitch m_1 ;

Current is supplied to motor M_1 , via the leads connecting it in parallel with relay R;

M_1 proceeds to advance both cards Cr and Cr' on B;

M_1 continues running until it has advanced Cr and Cr' by $\frac{1}{8}$ of the distance between the centers of A and B cars, and then opens the normally closed interruptor microswitch m_1 ;

Relay R opens, and M_1 stops;

Relay R on the A car is activated simultaneously with relay on the B car by current through contacts C_7 on the B car and C_9 on the A car;

Motor M_1 is started on the A car, and goes through the same cycle as M_1 on the B car, advancing Cr on the A car the same distance as the other Cr and Cr'.

At this point, the "chromosome" cards have advanced to the positions indicated in Figure 12b, but no holes have been punched in Cr.

(3) Contact C_1 is closed when the first hole ("A") reaches the position of punch sensor contact C_1 . This activates motor M_2 , the B⁺ coming from C_{16} , and the ground connection being made through the hole "A" and C_1 , via C_{15} on B and C_{13} on A. Motor M_2 punches the first hole in Cr. The situation is now portrayed in Figure 12b.

(4) Operation of M_2 includes closing of microswitch m_2 , which sends a surge of current through the primary of R, and causes another cycle of advancing "chromosomes," as described in step (2).

(5) C_2 is closed when Cr' reaches the position where hole "B" is at the punch sensor contact line. This activates motor M_3 , and the second hole in Cr is punched, as in step (3). The situation now is as portrayed in Figure 12c.

(6) As in step (4), all "chromosomes" are advanced another step, following the punching of the second hole.

(7) When the third hole "C" reaches the punch sensor line, contact C_3 is closed. As in steps (3) and (5), punch motor M_4 is activated by C_3 . After punching of the third hole, the situation looks like Figure 12d.

(8) As in steps (4) and (6), all chromosomes are advanced another step. Activation of motor M_4 , however, has also the result of activating motor M_5 on the A car, as their ground returns are in parallel, through C_3 and C_{15} on the B car, and C_{13} on the A car. After enough delay to allow for advancing of the chromosomes on both cards, M_5 changes the length of identification "arm" A(A) into that characteristic of A(B). Stop S(A) is no longer capable of detaining car A, which is now identical with the original of car B (Fig. 12e), and the new-"born" B car sails away into the environment through the re-entry branch. Breakage of the ground return through C_{15} of B and C_{13} of A deactivates the punch sensor contacts, and prevents further action of the punch motors.

(9) In this position (Fig. 12e, with the new B car sent away), program sensor contact C_4 is closed, and the B⁺ is made available, through C_{16} of B and C_6 of C, to one side of "eye" E_A , which is sensitive to "arms" on A cars passing by in the environment.

(10) As an A car passes E_A , and B⁺ energizes relay R_1 on A, which has a ground return through C_3 of C and C_{13} of B, R_1 opens the entry switch to the next site, using S_1 , and an A car passes into it, to be stopped by stop S(A).

(11) As the A car passes through the entry switch, "eye" E_{ABC} on the first "organism" is closed by flange F. E_{ABC} is permanently supplied on one side with B⁺ from car B through C_1 , and C_7 of B. On closing, it activates relay R_2 , which closes the entry switch to the next site, using S_2 . It also activates, through contacts C_2 on C and C_9 on B, relay R on the B car, which causes Cr' on B to advance, leaving a situation as portrayed in Figure 12f.

(12) In this position, program sensor contact C_5 is closed, and as in step 9, "eye" E_B on C is given a B⁺ supply on one side.

(13) As in step (10), when the B car (there is only one, and it was just "created" in this cycle) passes, the entry switch to the next site is opened by the closing of E_B , and it passes into this site, to be stopped by stop S(B). The next "organism's" "life cycle" actually begins here, as car C is not essential except for the program aspects thereof.

(14) As in step (11), passage of the B car into the next site through the entry switch, E_{ABC} and R_2 close the entry switch with S_2 , and also the "chromosome" on B is caused to advance to the position shown in Figure 12g.

(15) As in step (12), program senser contact C_6 is closed, sensitizing contact "eye" E_C .

(16) As in step (13), a C car, as it passes E_C , is shunted onto the next site, to complete the next "organism" (which has already begun to duplicate its plans). It is now necessary to deactivate the entry switch to this siding permanently, as the next advance in the "chromosome" of the first "organism" will leave all three contacts C_4 , C_5 , and C_6 closed. While Car C might be fitted with a counter which allowed relay R_1 only three actions before "expiring," a simpler method is the following: Place a normally closed microswitch in series with the entry switch to the siding, in such a position that it only is opened by the "arm" A(C) of a C car. As soon as a C car comes into the siding, it opens the microswitch, and allows no more activities of R_1 from the "organism" of the previous siding to open the entry switch again. Thus, no more trains can be shunted onto a full siding.

(17) Gerontologically, passage of the C car into the next siding closed E_{ABC} , and R_2 closes the entry switch with S_2 . The "chromosome" on B advances to the position of Figure 12h, and flutters off the spent "organism." Closing of the program contacts has no further effect, owing to the precautions described in step (16). Occasionally a car goes by the "eyes" E_A , E_B , or E_C , causing the relay R to push an unavailing button.

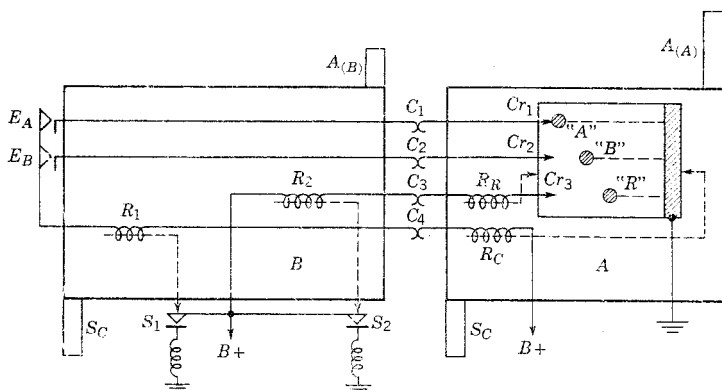


FIG. 13. Circuit of cars of RSD V.

Construction of RSD IV should be exceedingly difficult and expensive, in view of its large complexity. Special large-gauge trains would doubtless be necessary as there is a great deal of equipment carried on each car. Its design importance, of course, is in establishing the possibility of building a non-living analog of the complete process of reproduction.

Finally, we describe a model which should be as practical to build as RSD I. RSD V is a device whose "organisms" "decay" after "death," and whose parts are used to reproduce new organisms. The practicability of building this model stems from the small number of cars needed, since the old "generation" is cannibalized. The layout is shown in Figure 4. No more than four cars are necessary, although more can be used. As soon as an "organism" of two cars has made a second one, it breaks up itself, and its parts go into the environment via the re-entry branch.

Figure 13 shows the circuit of the cars in RSD V. The following differences from RSD I can be noted:

(1) The "chromosome" bears a third hole, "R," and contact Cr_3 , whose instructions say, "Break up, and re-enter the environment."

(2) A "chromosome" reset relay R_R is connected to Cr_3 . When energized, it *resets* Cr to its original position, so it can go into the environment ready to function again. A cyclic "chromosome" might again obviate the need for resetting, and for R_R , altogether.

(3) The relay R_2 is connected to Cr_3 via the contacts C_3 . When energized, it opens the stop on the end of the siding via S_2 , and lets both cars back into the environment via the re-entry branches.

(4) The closing of the siding switches is done automatically by the siding close arm SC on each car, as it enters the siding. This is necessary, as the job of R_2 , which closed the siding switches in RSD I, is now pre-empted by its duty as an opener of the siding end stop.

(5) The "chromosome" is advanced by R_C , the "chromosome" relay, each time the correct car closes the proper "eye" E_A or E_B , since R_C is in series with the siding open relay R_1 .

The sequence is fairly clear from the circuit, and from analogies with the RSD I sequence, taking into account the differences noted above. If only four cars are used for the whole system, the broken-up pair will come out in the same order as they went in, and the other "organism" will have no ordering to do. Therefore, it is not really a model of reproduction unless at least one additional car is present to give some randomization of the parts in the environment.