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SELF-REPRODUCING MACHINES

In which simple units are built which assemble themselves into larger units, which in turn make copies of themselves from other simple units. The process sheds light on the self-reproduction of biological molecules

by L. S. Penrose

The mass production of multiple copies of the same object by printing or by assembly of prefabricated parts is an event so commonplace that examples can immediately be called to mind. The reader has one at hand in the copy of *SCIENTIFIC AMERICAN* in which he reads these words. The idea of an object reproducing itself, however, is so closely associated with the fundamental processes of biology that it carries with it a suggestion of magic. Indeed, the construction of a machine capable of building itself might be judged to be impossible and to belong to the category of perpetual-motion engines. At the present time, however, advances in genetics are rapidly leading biologists to focus their attention upon the structure and function of self-reproducing molecular chains which, in the nuclei of living cells, preside over all their functional activities. The structure of these chains of nucleic acid is already quite well understood. But the general theory of self-reproduction, in which the replication of nucleic acid would represent a special case, has not been much investigated.

The theory has two aspects, which can be called the logical and the mechanical. The logical part was first investigated by the late John von Neumann of the Institute for Advanced Study in Princeton, N. J. He decided in 1951 that it must be possible to build an engine that would have the property of self-reproduction. The method would be to construct a machine that is capable of building any describable machine. It would follow logically that such a machine would be able to build another machine just like itself. Each machine would carry a sort of tail bearing a code describing how to make the body of the machine and also how to reprint the code. According to von Neumann's associate John G. Kem-

eny, the body of the machine would be a box containing a minimum of 32,000 constituent parts and the "tail" would comprise 150,000 units of information. On the mechanical side the elementary parts, out of which this object was to be built, were considered to be likely to include rolls of tape, pencils, erasers, vacuum tubes, dials, photoelectric cells, motors, batteries and other devices. The machine would assemble these parts from raw material in its environment, organize them and transform them into a new replica of itself [see "Man Viewed as a Machine," by John G. Kemeny; *SCIENTIFIC AMERICAN*, April, 1955]. Since the aim of von Neumann's reflections was to resolve the logical conditions of the problem, the stupendous mechanical complexity of the machine was of no consequence.

The mechanical problems involved in constructing such a machine have been investigated by Homer Jacobson of Brooklyn College in New York. In one experiment he built an electrically powered railroad track around which two kinds of trucks, respectively called "head" and "tail," could circulate. Initially these trucks were arranged in a random order. If a head and a tail were

first assembled upon a siding, however, they would signal to another head and another tail to connect up on an adjacent siding. So long as there were trucks and sidings available this process could continue, and the head-tail machines would be assembled automatically. The design of the trucks and of the railroad itself involved considerable complexity and a great many different elements such as wires, tubes, batteries, switches, wheels, photoelectric cells and resistances. This intricate apparatus generated only one kind of building operation, but the operation was indeed a kind of self-replication.

Together with Roger Penrose I have approached the problem in a more radical manner, without the encumbrance of prefabricated units such as wheels and photoelectric cells. Our idea was to design and, if possible, to construct simple units or bricks with such properties that a self-reproducing machine could be built out of them. One everyday example of mechanical self-replication involving simple units is the "zipper" fastener. Here the self-replicating unit is the pair of interlocked hooks; the zipper-slide provides the energy to push each pair of hooks together. As soon as one pair is connected, a whole chain made up of similarly connected pairs can be formed. The example is defective in that only one type of connection is formed in the zipper, and the units are not completely separate before the action takes place. Another simple instance of self-replication is offered by a suitably designed mold, template or photograph. Ordinarily such replication calls first for a negative from which a positive like the original can be recovered. A negative can, however, be combined with the positive in such a



SELF-REPRODUCING DESIGN is identical with its own photographic negative, except for checkerboard border surrounding it.

way that, by replicating both at the same time, the two steps are reduced to one. Thus in the illustration on the preceding page we have a design whose negative will be identical with the original because of its peculiar symmetry. This suggests that it is convenient, and perhaps necessary, for a self-replicating object to carry its own template or negative.

In the design of the units or bricks for our self-replicating machine we laid down certain arbitrary standards. The units, we decided, must be as simple as possible. They must be of as few different kinds as possible. And they must be capable of forming at least two (preferably an unlimited number) of distinct self-reproducing structures. Finally we decided that the energy necessary to engage these units in the process of self-replication should be supplied in the simplest manner, by merely shaking the units in a confined space but otherwise allowing them as much freedom of movement as possible.

One essential condition was to be that the units would not form self-reproducing machines just because they were moved about. They were to reproduce themselves only when the object to be replicated was introduced as a pattern for copying. The logic of this condition is to be found in William Harvey's maxim: *Omne vivum ex ovo* (in modern form: No life except from life). By definition, self-reproduction requires a "self" to be reproduced.

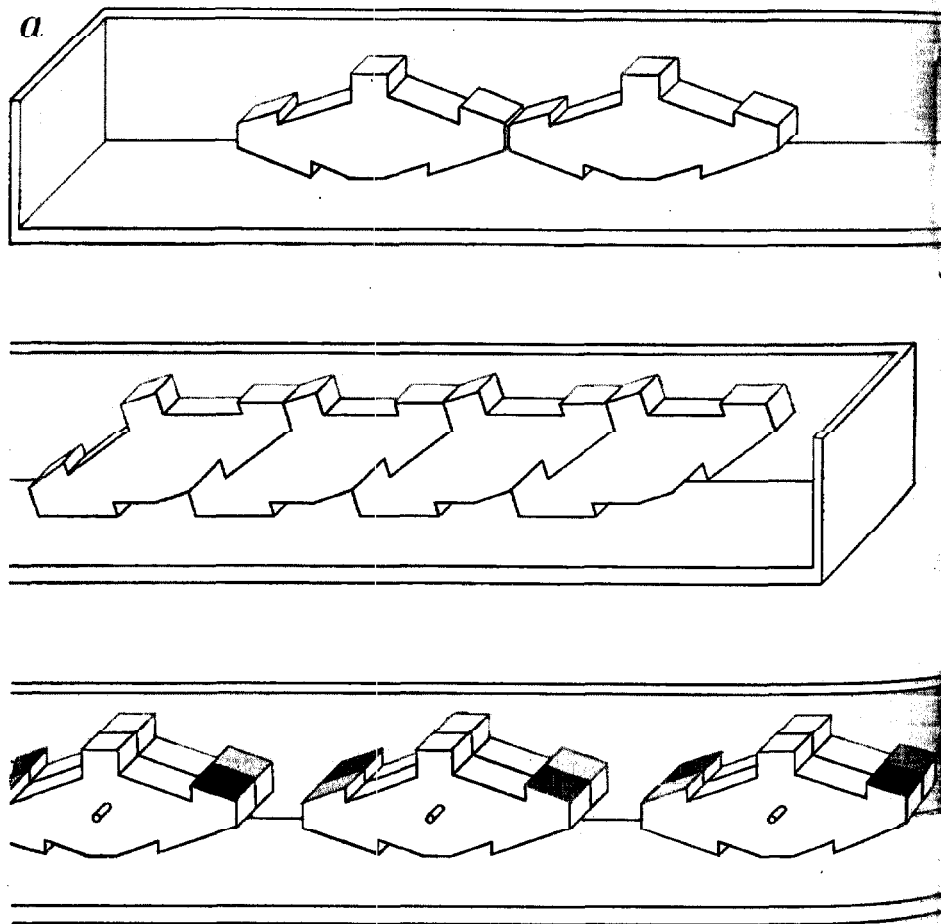
In fanciful terms, we visualized the process of mechanical self-replication proceeding somewhat as follows: Suppose we have a sack or some other container full of units jostling one another as the sack is shaken and distorted in all manner of ways. In spite of this, the units remain detached from one another. Then we put into the sack a prearranged connected structure made from units exactly similar to those already within the sack. Such a structure might arise, of course, by chance in response to random shaking, but this would be very unlikely indeed, as is the case with the analogous process of mutation in genetics. Now we agitate the sack again in the same random and vigorous manner, with the seed structure jostling about among the neutral units. This time we find that replicas of the seed structure have been assembled from the formerly neutral or "lifeless" material. It follows that each replica is capable of self-reproduction like the original seed, and that reproduction will continue until all the "food" is used up.

The building of actual models in our investigation began with a much sim-

pler experiment in mind. In the inorganic world the most obvious analogy to self-reproduction in living matter is the growth of a crystal. The construction of an artificial crystal that would repeat some prearranged pattern indefinitely seemed to offer a useful starting point. The first machine built on these lines proved most illuminating. It consisted of two pieces of plywood cut to a special shape, each about four inches long and a quarter-inch thick, standing end to end on the inner surface of the long side of a shallow rectangular box resting on its side [see illustration labeled "a" on these two pages]. The box can be subjected to side-to-side agitation of a vigorous and irregular character, causing the pieces of plywood to move in one dimension from side to side, each colliding with its nearest neighbors. In the "neutral" position in which the pieces of plywood appear, however, they do not link under the influence of shaking alone. But if a "seed" consisting of two linked pieces is added,

this seed will link up with adjacent pieces standing on either side of it on the track. Eventually all the available neutral pieces will become attached to the "crystal." If the seed is inclined in the opposite direction, a complementary aggregate is built.

Certain principles become evident from the study of this machine. Here copying consists in imparting the same tilt to each unit. The seed carries, as it were, a positive pattern at one end and a complementary negative pattern at the other. These patterns influence the neutral units as they come into close contact with the seed, causing them to tilt in the positive or negative manner. Once tilted or "activated," the units are caught and locked to the growing crystal by the complementary notches cut into the profiles of the plywood pieces. These notches enable energy to be trapped and thus convert the energy of motion conveyed by agitation into the potential energy



MECHANICAL "CRYSTAL" demonstrates some of the underlying principles of self-reproducing machines. At upper left in *a* appear two identical units at the "neutral" position in which they are unable to link up with one another. Introduction of two linked units

that binds the structure. Energy traps are characteristic of living matter, although they occur also in artificial and natural structures. A pool that retains water after a tide has receded is typical. In chemistry the bonding of an endothermic compound is analogous to a latch. Unless our synthetic structures contained more potential energy than their constituent units separately, it would be difficult to prevent spontaneous aggregation.

The crystallizing or, we might say, the polymerizing machine can be greatly improved by making units out of two plywood elements tied together by an axle so that they can pivot in opposite directions [see illustration labeled "b" on these two pages]. As can be seen, there are four ways of arranging the seed, of which two are essentially the same and the other two are mirror images. Besides giving rise to more types of seed in the case where the two parts of each unit are tilted in opposite senses, the double

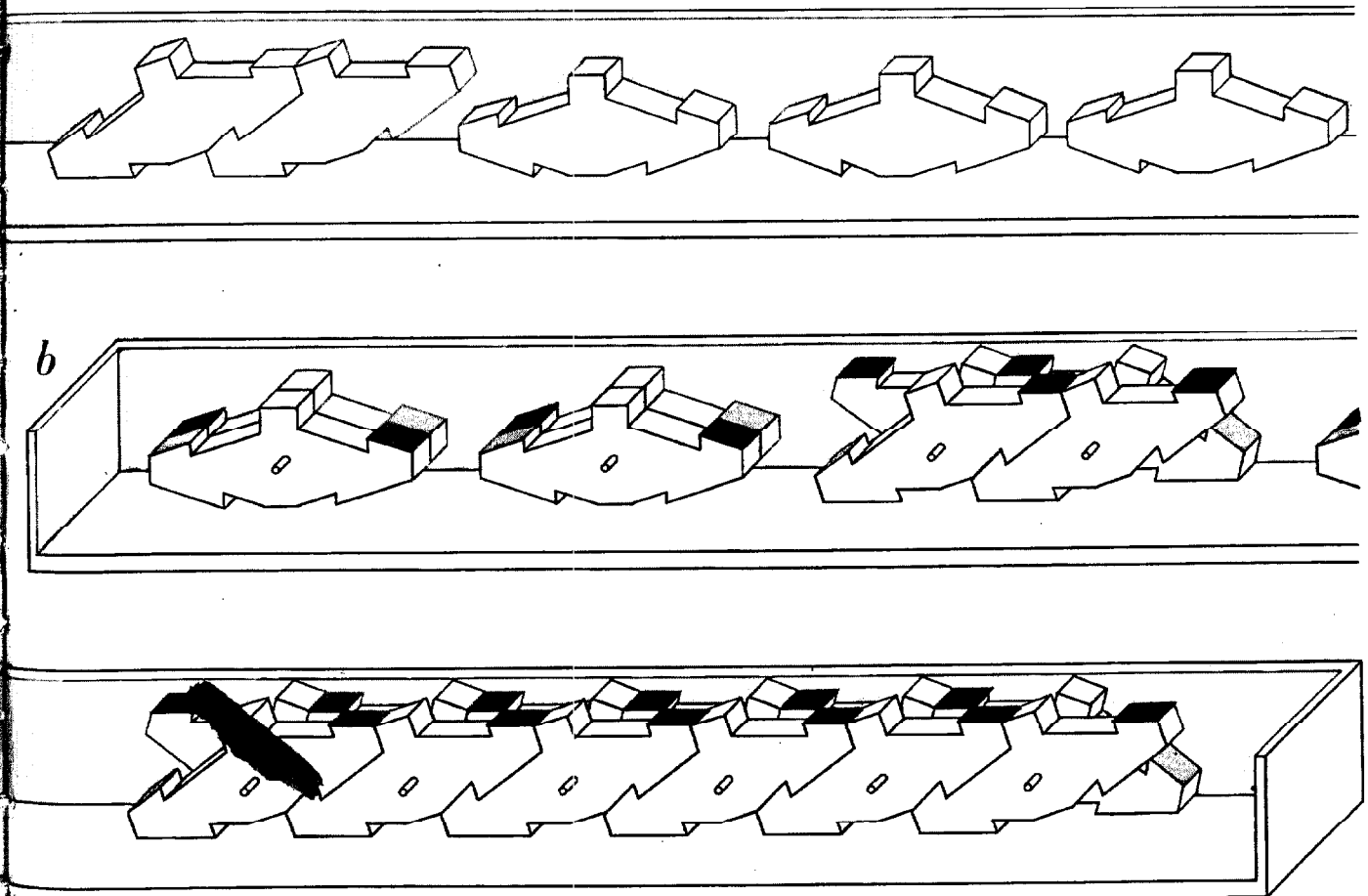
units form much stronger structures than single units.

The problem of reproducing an object the same size as the seed has now to be solved. This is done with surprising facility. It is only necessary to alter the basic units by removing one pair of notches from each of them. In effect the crystal is broken up into discrete bodies, each made of two units [see top illustration on next page]. Two stable mirror-image seeds can be constructed, and either may be used as a starter. In a long box or track, populated with neutral units randomly arranged, the presence of a seed causes other structures of its own kind to be built wherever two neutral units are in the appropriate relative positions.

This design provides a simple and convincing demonstration of artificial self-reproduction. Either type of seed may be introduced into the track; since they and their offspring are easily distin-

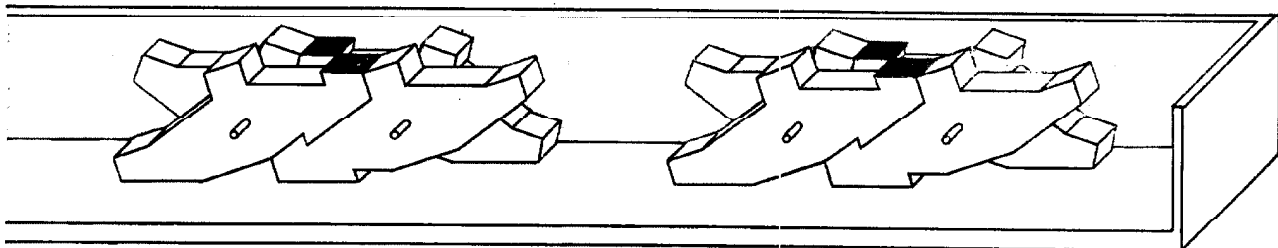
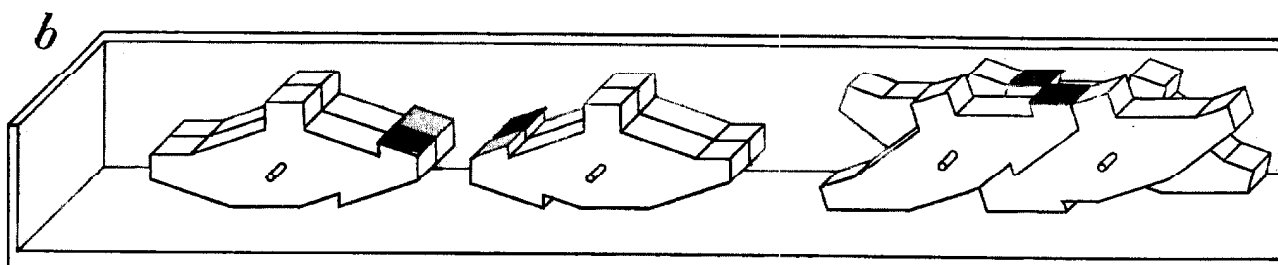
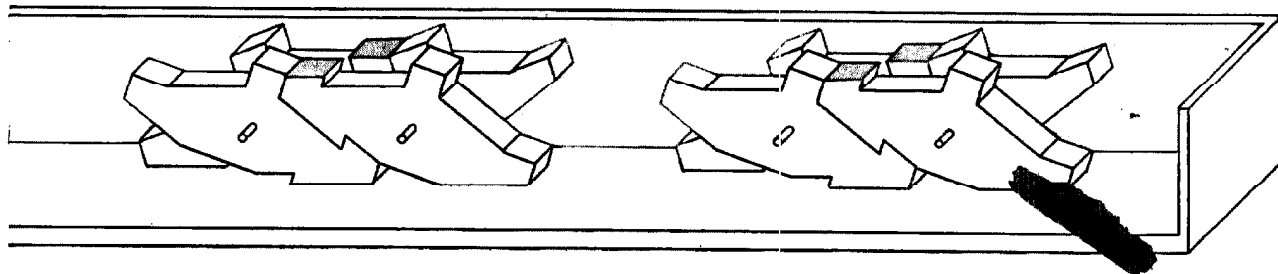
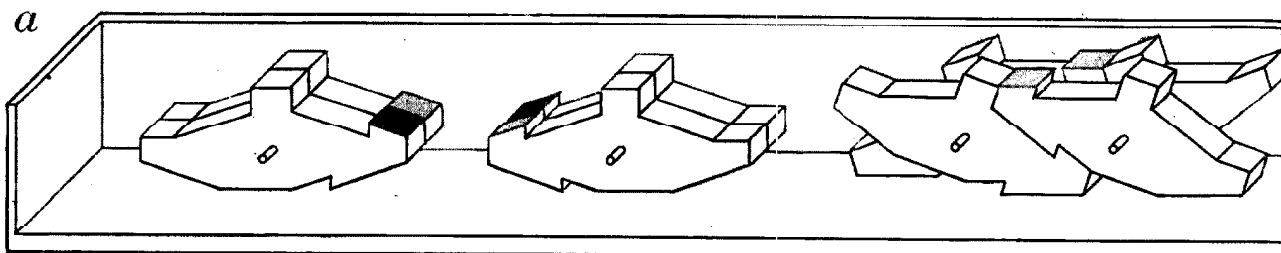
guished, it can be seen that each breeds true to type.

A point that emerges here, when the process is critically examined, is that during agitation some units transmit the tilted pattern of the seed although they do not find a partner to link with. These temporarily activated units tend to slide away from one another and from the completed structures, thereby tending to push some of the completed structures apart when agitation has subsided. It is convenient in self-reproduction to arrange that the fresh complexes should repel one another once they have been formed. If they separate widely, they can pick up "food" from different places and they do not interfere with one another's subsequent reproduction. In a restricted one-dimensional track this point is irrelevant. But it becomes significant in the next phase of the discussion, when we consider how we might lift the one-dimensional restriction of the track and make it possible for our self-replicating



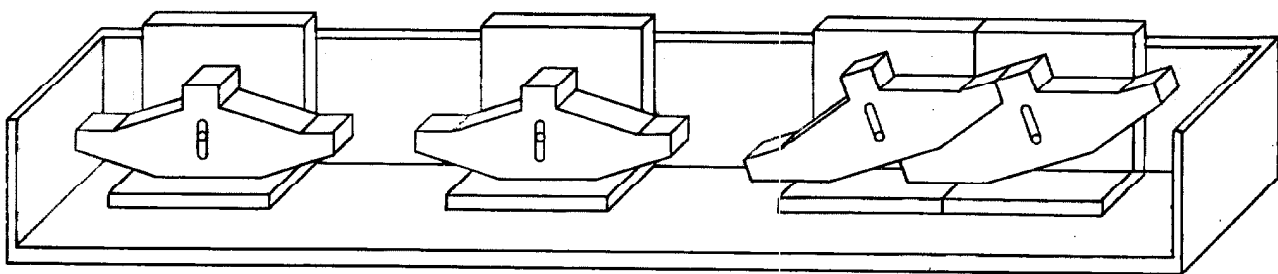
as a "seed" in panel at upper right imparts tilt and makes it possible for entire group of units to link up and form a single structure when subjected to agitation in the horizontal plane. In b two

doubled units are shown, first in neutral position and then linked up to form a seed. When this seed is agitated with neutral units at lower left, all join to form the crystal structure at lower right.



SELF-REPRODUCTION is here demonstrated by units of a simple kind, identical with those that form the "crystal" on the preceding two pages except that the units each lack hooks at one end. In *a* the seed is formed with the gray telltale mark showing at the linkage;

in *b* the seed unit is formed with the colored telltale mark showing. When the seed of each kind is agitated in the horizontal plane with neutral units, the appropriate tilt is imparted to the neutral units and they link up to reproduce the structure of their seed.



ACTIVATING CAM-LEVER incorporates the simple tilting principle of the self-reproducing machines shown above for use with

more complex structures shown on page 111. These cams, held in tilted position by dowel in slot, transmit activation but do not link.

structures to move about freely in two dimensions.

In order to fit the units for self-reproduction into the larger world of two dimensions, it is necessary to complicate their design beyond the rudimentary shapes that have worked thus far. With units moving over a plane surface, without the support of the back wall of the one-dimensional track, a firm base for each must be provided. A simple solution is to mount the plywood element on a horizontal pivot fixed to an upright, which is in turn attached to the base of the unit. The element capable of tilting and transmitting its tilt then becomes a sliding cam-lever. To allow greater variety of interaction between units, the hooking mechanism can now be separated and made independent of the tilting process by transferring it to a different part of the unit [see bottom illustration on opposite page].

In the two-dimensional situation the simpler design permitted an activated unit to slide away and lose contact with a "live" group after it had gone part of the way toward building a new replica. This is quite uneconomical from the energy standpoint. We must therefore arrange matters so that a unit may hook on to a two-unit live group temporarily and be released when a fourth unit becomes attached to the group. We are thus led to consider mechanisms for making and releasing links in special circumstances. One such latch depends for its release upon the presence of another unit in close contact. The effect of this, as shown in the illustration at right, is to maintain combinations already built out of new pieces. But this arrangement produces no fresh structures. It would give us a sort of steady state. In order to make a reproducing complex with this device, the system of linkage and release must be doubled as shown in the illustration on the next page. Here each unit contains two releasable hooks facing in opposite directions. Though they are shown one above the other, they would in practice be mounted side by side on the same axle. With such an arrangement of latches the addition of a third unit to a linked pair creates a triple complex that does not separate until a fourth unit is added. When this has taken place, the two similar pairs of units disengage and gently repel each other as their hooks settle down to their lowest possible states of energy.

It must be noted that this system of reproduction is incomplete because two pieces can link without any previous

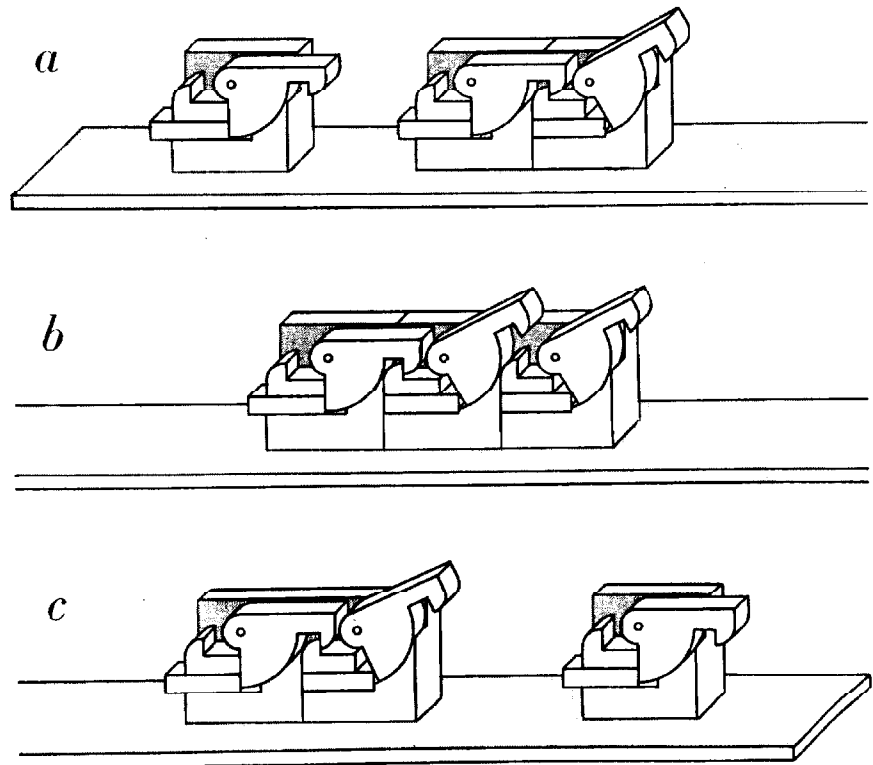
activation, that is, tilting caused by contact with a special seed. An activating element of some kind must be supplied so that neutral units cannot form links except in the presence of a live group that carries the activating principle. For this purpose the sliding cam-lever can be used to preserve a tilt and transmit it to neutral units; only those units that have been thus activated can approach each other close enough to link.

An interesting feature of this system is that it can replicate in two ways. If a live structure made of two units receives two neutral food units, both of them from either its left or right side, it will link them to itself and then release them linked to each other. On the other hand, if the original structure receives two food units, one on either side, it will link them to itself and then come apart in the middle [see bottom illustration on page 111]. As in the case of a single-celled organism, the original unit is destroyed in the process of replication. By the addition of special devices to the units it is possible to distinguish between these two kinds of replication; that is, one device will ensure that two units of food will always be taken in on one side, and another device will ensure that the two neutral units are added one on each

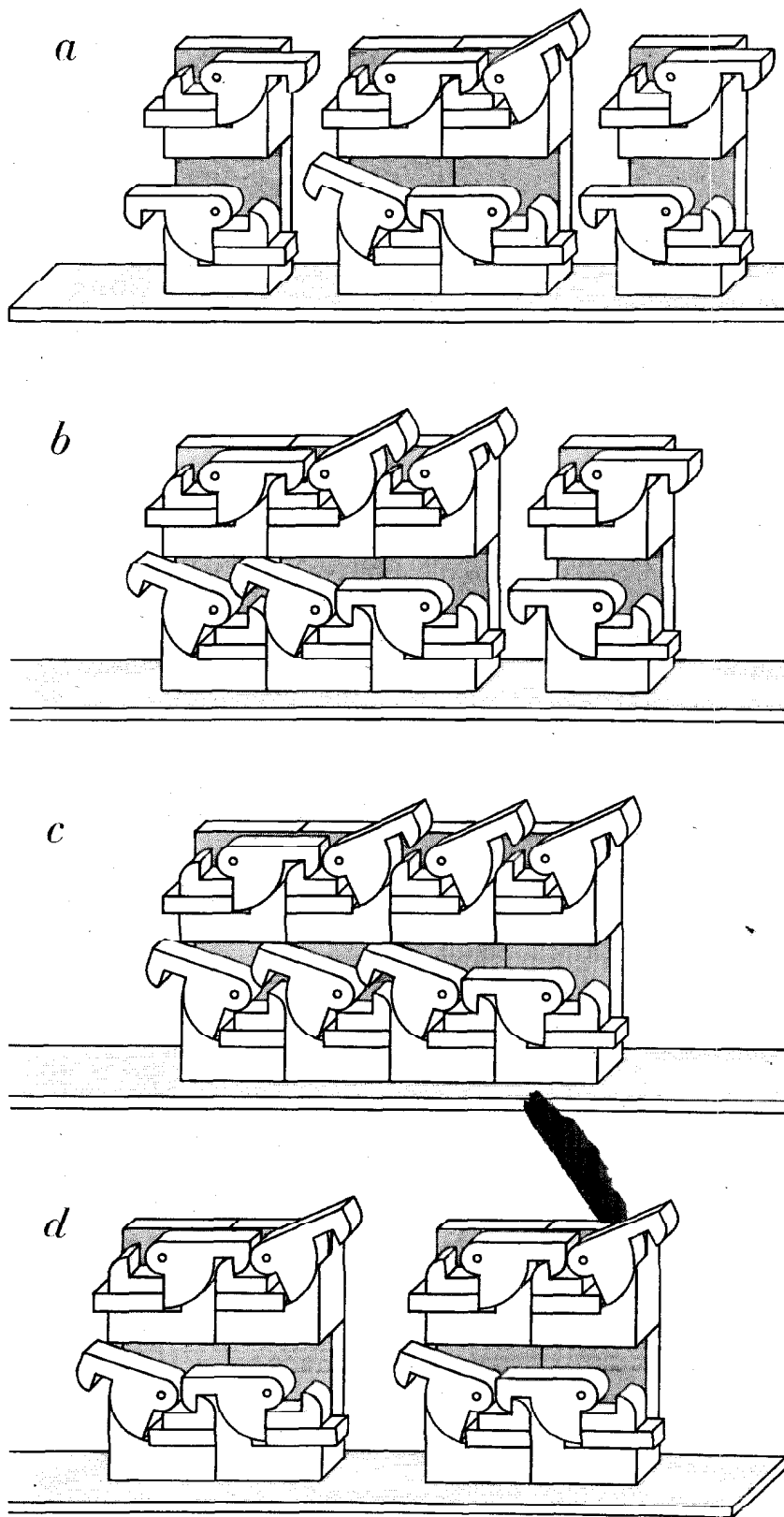
side. If there is no scarcity of food, it is likely that neutral units will be simultaneously available on both sides. For efficient reproduction, therefore, the second type of replication, that is, addition on either side and division of the seed, should be adopted as the standard.

Another useful adjunct is a counting device. This can take the form shown in the top illustration on page 111. Such an element, which prevents more than four units from coming into close contact with one another, can be attached to each unit. The counter exerts its effect in that phase of reproduction, just before division, when the complex must cease accepting food. Before reproduction can be resumed the accretion of neutral units must stop long enough to enable the enlarged complex to come apart. The self-reproducing machine may also be equipped to make a kind of protective covering for itself out of "skin" units available in the environment. The skin would have to be thrown off in order to repeat self-replication.

The self-reproducing machine now requires one more adjunct to fit it for activity in two-dimensional space. To bring units into proper alignment for interlocking when random motion causes them to collide, their bases must be pro-



STEADY-STATE SYSTEM of hook and release is demonstrated here. When two units abut one another (a), one hooks onto the other, but the one that is hooked is itself set in release position. The addition from the left of a third unit (b) causes the first two to unhook (c).



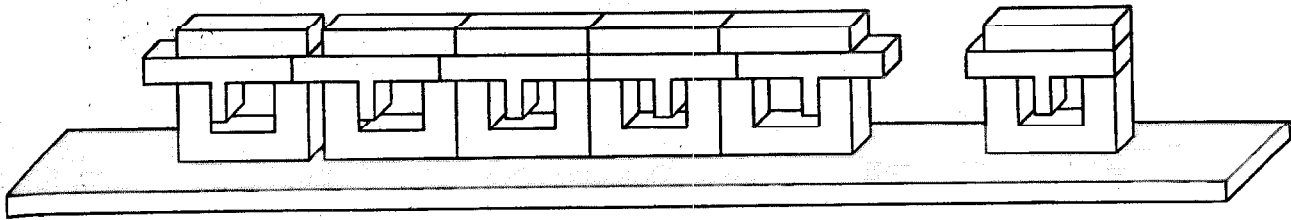
DOUBLE-HOOK UNITS, in contrast to steady-state system, possess capacity for self-reproduction. Cycle begins with linked group and two neutral units (a). Addition of neutral unit at left (b) causes one of two hooks in linked group to release. Addition of fourth unit (c) causes second hook in linked group to release. Linked group parts (d) in two replicas.

vided with interdigitating guides. The guides can also serve passively as hooks [see top illustration on page 112]. Some of the guides ensure correct apposition of hooks or activating levers and others cause the firm attachment of rows of pieces. With this additional device our units are endowed with a sufficient number of mechanical principles to enable self-reproducing machines of any desired degree of complexity to be built from them. Yet the units are of fairly simple construction and are either all of one kind or of a few different kinds.

The replication scheme of one such machine, made out of a set of units of two kinds, is shown in the bottom illustration on page 112. To ensure that replication proceeds regularly and that attempts at interconnection do not end in a tangle of hooks and guides, an ordering mechanism is included; an asterisk in the diagram indicates positions where the ordering mechanism permits new units to be added. The units each have two levers of the kind which can be activated positively or negatively, that is, tilted up or down; thus four types of activated units or rows of units are possible. The chain of units acting as a seed may be built in any predetermined number of rows and each row can be set with any one of four types of activation. When a fresh unit is added on either side of the double chain, no additional units of the same kind can attach themselves in that row. A different type of unit now forms a nonreplicating protective "skin" chain in response to the activating pattern of the complex. When all the open positions are filled with appropriate units, the self-replicating machine splits in two, sheds its skin, and the process may begin again.

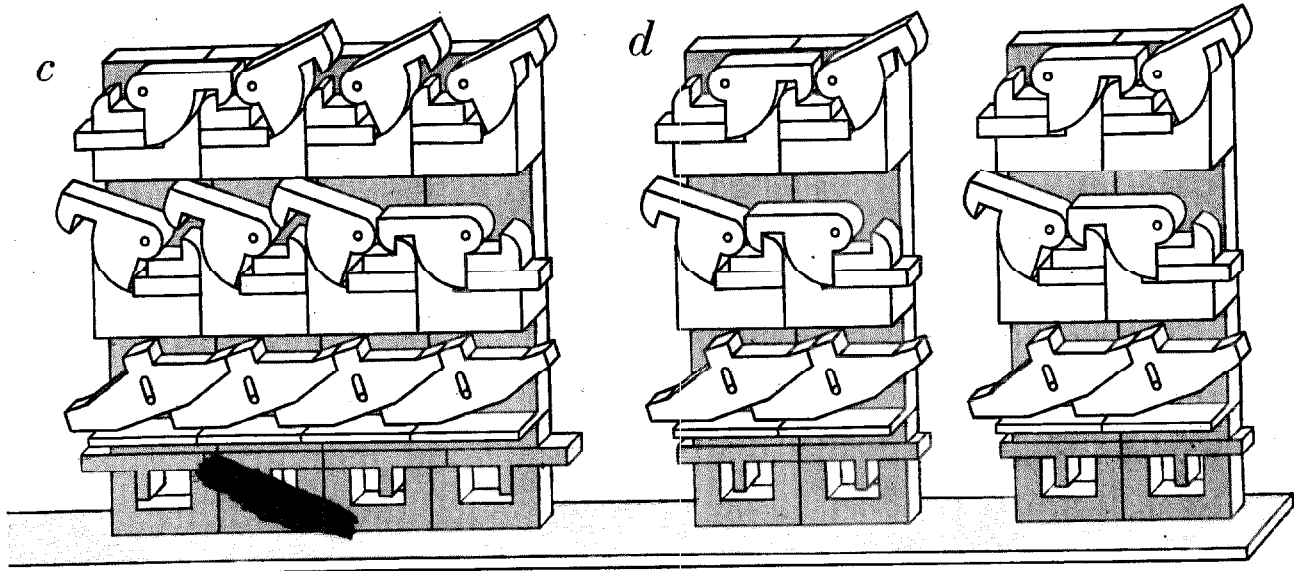
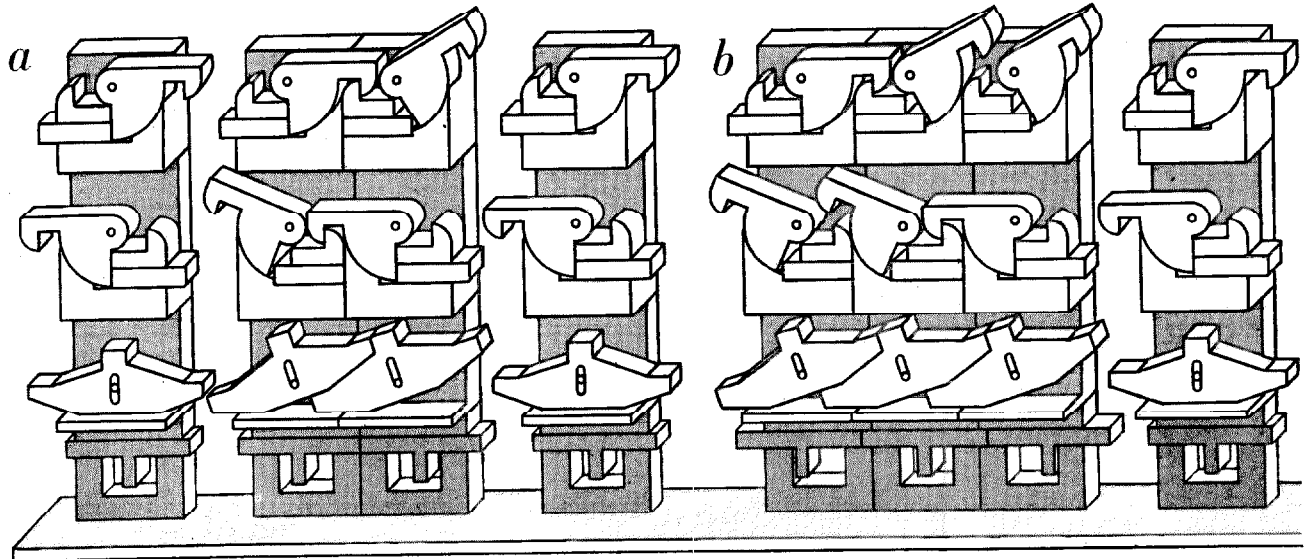
The design of units suitable for forming the protective chains presented peculiar difficulties; in overcoming these I came upon a new method of controlling and sequencing the latching and unlatching which provides an elegant solution of the von Neumann problem. A single string of determinate length, made up of units of a slightly different design, can replicate itself in the manner shown in the illustration on page 114. The addition of each new unit to the daughter chain has the effect of releasing the one behind it from the original chain. The final unit to join the new chain does not attach itself to the old chain at all, although it releases the new one from the old.

Here it should be emphasized that



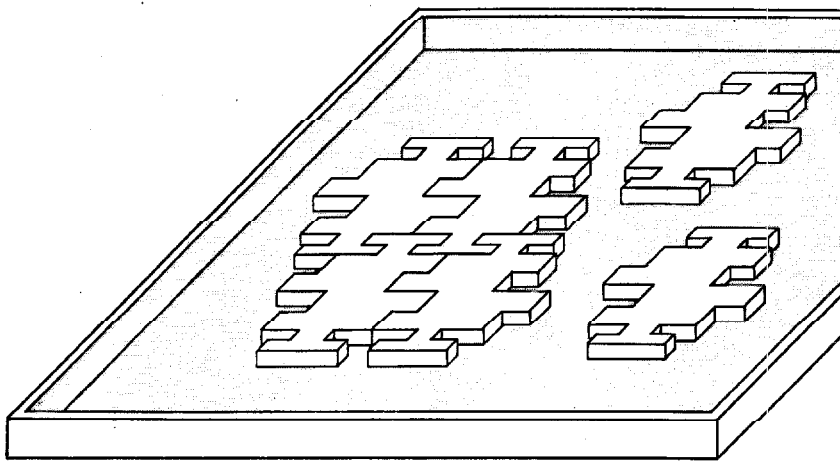
BLOCKING DEVICE prevents more than four units from coming close together. When four units are in close contact, the sliding

bar protrudes at either end of the group, keeping other units away. Device keeps groups from growing too large before they divide.



COMPLETE SELF-REPRODUCING MACHINE incorporates the basic elements and principles depicted in the preceding illustrations. The seed (at center in *a*) is linked by double hooks, incorporates the tilted cam-lever activating principle and is protected by the blocking device in its base. When the neutral unit at left joins

the seed (*b*), it disengages one of the hooks holding the seed together and sets the blocking mechanism so that only one more neutral unit can be added. When the fourth unit joins the triple group (*c*), it disengages the second hook in the original seed, causing it to come apart in the middle and form two replicas of itself (*d*).



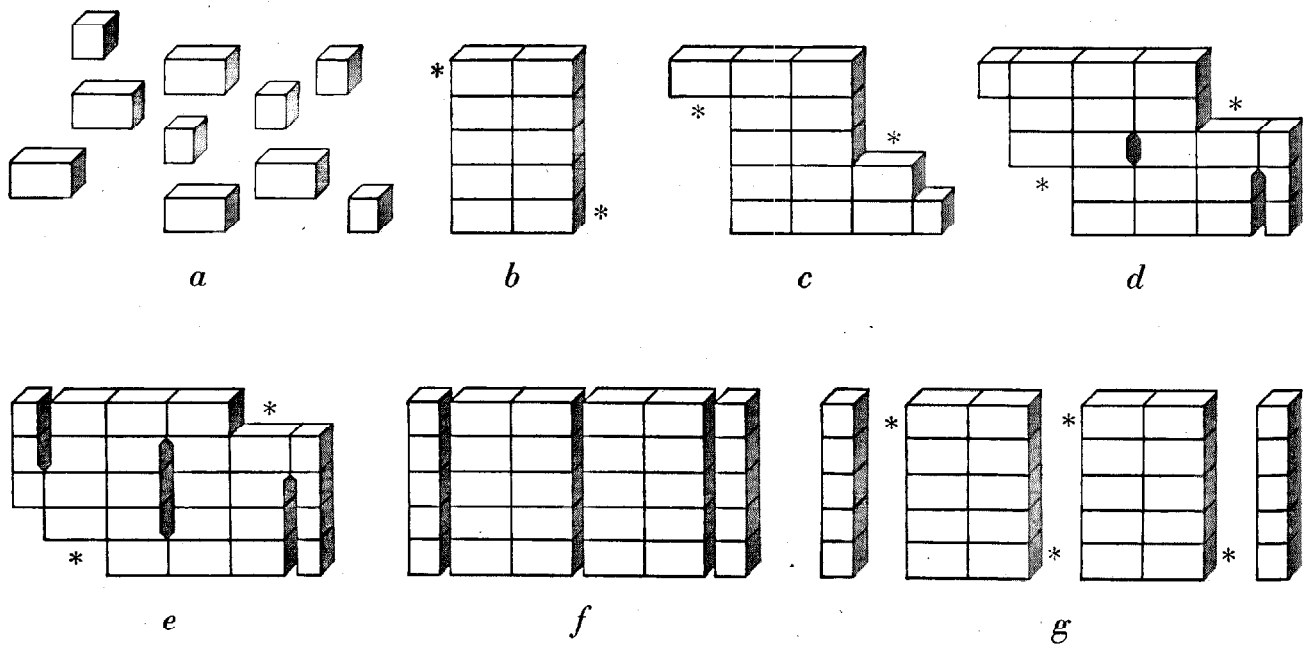
INTERDIGITATING BASES, on which superstructures capable of activation, hooking and release can be mounted, are designed to permit self-reproducing machines to operate in two dimensions and to orient themselves to one another for the purposes of self-reproduction.

each activated unit contains a message, that is, information that it transmits to neutral units. The total quantity of information depends upon the number of tilted levers and sometimes upon other features. The nucleus of a living cell also contains information that enables it to collect and build the substances necessary for its own replication. Natural selection encourages the reproduction of

nuclei that have the most efficient information for dealing with their surroundings. In artificial self-reproduction, equivalent programs of information would equip the machine not only to assemble themselves, but to build up their own structures out of their environment, to release energy sources and, in a sense, to provide their own track or table to guide interactions. Such an elaborate

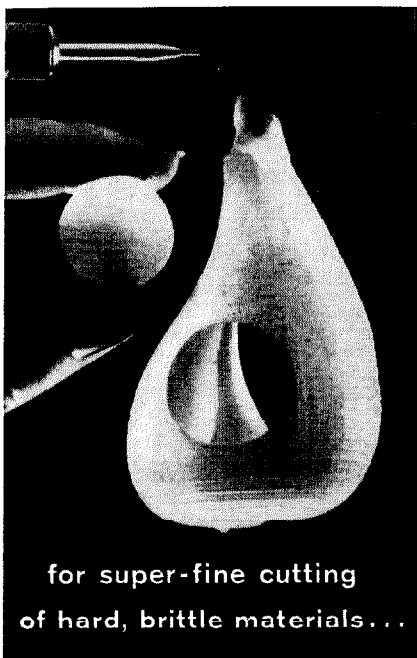
scheme is so far unattainable in practice. We have to be content with making a very parasitic organism. It is not, however, much more helpless than a virus. With such an object we can even provide a mechanical demonstration of the role of information in natural selection. To two machines, distinguished by key arrangements of their tilting cam-levers, we present neutral units locked up in a kind of matrix. These food units can be unlocked and brought into circulation by certain arrangements of tilting and not by others. Thus one mechanical creature will be able to unlock a plentiful supply of food while the other will starve and be shown to be relatively unfit in the struggle for self-replication.

Another feature of living things can be incorporated in the self-replicating machine. This is the capacity to change the program of information it transmits to its daughters. Of course change might be introduced by mistakes in reproduction even with well-constructed machines, but this, like genetic mutation in living things, is likely to be unfavorable and must be avoided by an efficient designer. Living organisms, however, exchange parts of their programs in a process known as recombination. In a very elementary form, something like this can be imitated mechanically. Now



GENERALIZED SYSTEM of self-reproduction is based on units of two kinds (a). The larger "body" units (b) form a live group; the asterisks indicate activated points at which units of the same kind can be added. The group begins to grow (c), with a smaller "skin" unit attaching itself at lower right. When units are attached

at corresponding points on both sides (d), the body units come apart and the skin units also begin to peel off (e). With growth completed, the original group splits, yielding two replicas of itself (f). As the skin units come loose (g) the two daughter groups become activated and are ready to begin the reproduction cycle again.



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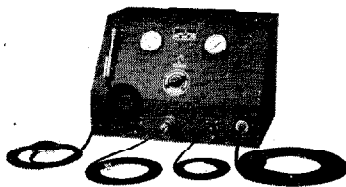
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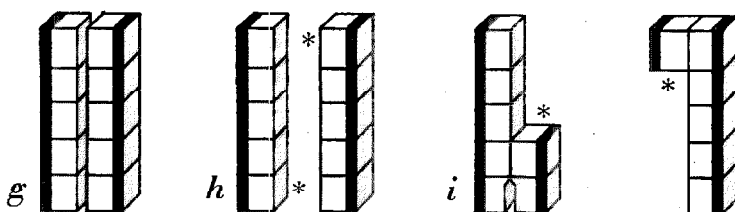
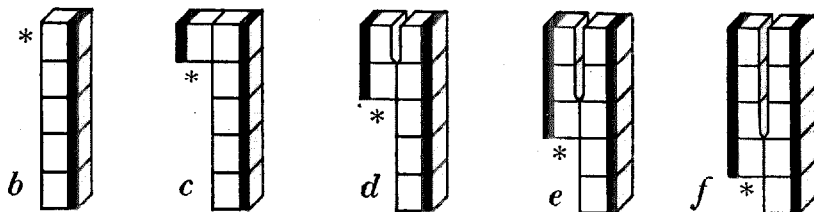
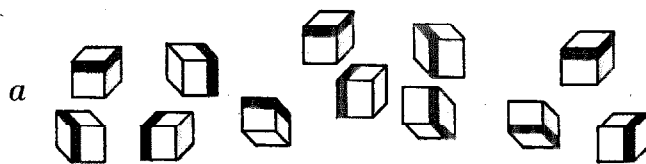
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MORE ELEGANT DESIGN for a self-reproducing system is depicted. Identical units (a) form a live five-unit group (b), activated for growth at the point indicated by asterisk. As growth proceeds (c, d and e) each new unit causes the preceding unit in the new column to become detached from the old. Addition of the last unit (f) causes the two groups to come apart (g). The activated daughter groups (h) now reproduce from neutral units (i).

if two machines carrying different programs should stand for a moment side by side, new units, approaching in one particular direction, might pick up their program half from one and half from the other. Thus if the program of one parental complex is described as AA and the other as BB, the new complex generated in these circumstances would have the program AB. This is easy to accomplish with a machine consisting of a single pair of units, but for a chain it presents many mechanical difficulties. These complexes would, in the ordinary way, breed true; only on rare occasions would the pieces come into apposition in the manner that is necessary to produce recombination.

It has been said that the fundamental mechanisms of the biological machine may perhaps be elucidated with the aid of theoretical models. The machines discussed here, however, are not models in this sense. They are machines in their own right, conceived for the specific purpose of self-reproduction. In some ways they may resemble living organisms and, insofar as this is so, they may help to explain how some primitive forms of life originated, maintained

themselves and eventually developed into more complex and more stable structures.

Self-reproductive chains of mechanical units may help to explain the way in which nucleic acids in living cells actually replicate. But they are more likely to assist in the understanding of systems of simpler character, like those that must have preceded the nucleic acids in the evolution of life. These structures may have occurred in molecules composed of polysaccharides, amino acids or phosphates. At least we need not suppose that they were anything like as complex as the nucleic acids. Such organic counterparts of the self-replicating machine are not, perhaps, accessible to our observation today in nature. Charles Darwin suggested in 1871 that the spontaneous appearance of very elementary forms of life might still be occurring. But he also pointed out that if a protein compound ready to undergo complex changes were spontaneously produced in the present day, it "would be instantly devoured or absorbed, which would not have been the case before living creatures were formed."