THE DESIGN OF EVOLUTION

by

STEPHEN NATHANIEL FLANDERS

SUBMITTED IN

PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE

DEGREE OF BACHELOR OF ARCHITECTURE

at the

MASSACHUSETTS INSTITUTE OF

TECHNOLOGY

June, 1971

Department of Architecture, May 14, 1971

Certified by

Accepted by

Chairman, Departmental Committee on

Graduate Students

DESIGNING EVOLUTION
Stephen N. Flanders
Submitted to the Department of Architecture on May 14, 1971 in partial fulfillment of the requirements for the degree of Bachelor of Architecture.

The complexity of problems facing mankind is increasing beyond our ability to deal with them unaided. We seek to comprehend meaningful complexity and to diminish inimicable complexity. An artificial intelligence can aid us only if it can understand us. To do so, it must possess ways of sensing and effecting the same world we do, as we seek to understand all that is about us and within us.

Artificial intelligence is itself probably too complex a problem to design in its entirety. If so, we require some process that will design itself into the desired artifact. The design of such an evolutionary process should require a less-than-total understanding of the entire problem. Even less-than-intelligent evolution embodied in problem environments would enable them to reconfigure themselves on the spur of the moment to limited changes in user context.

This thesis seeks to explore evolution as a medium of self-design. The study of evolution presents the problems of feedback of form, self-organization and self-reproduction. The work of this thesis is to develop cellular automata as a medium for experimentation.

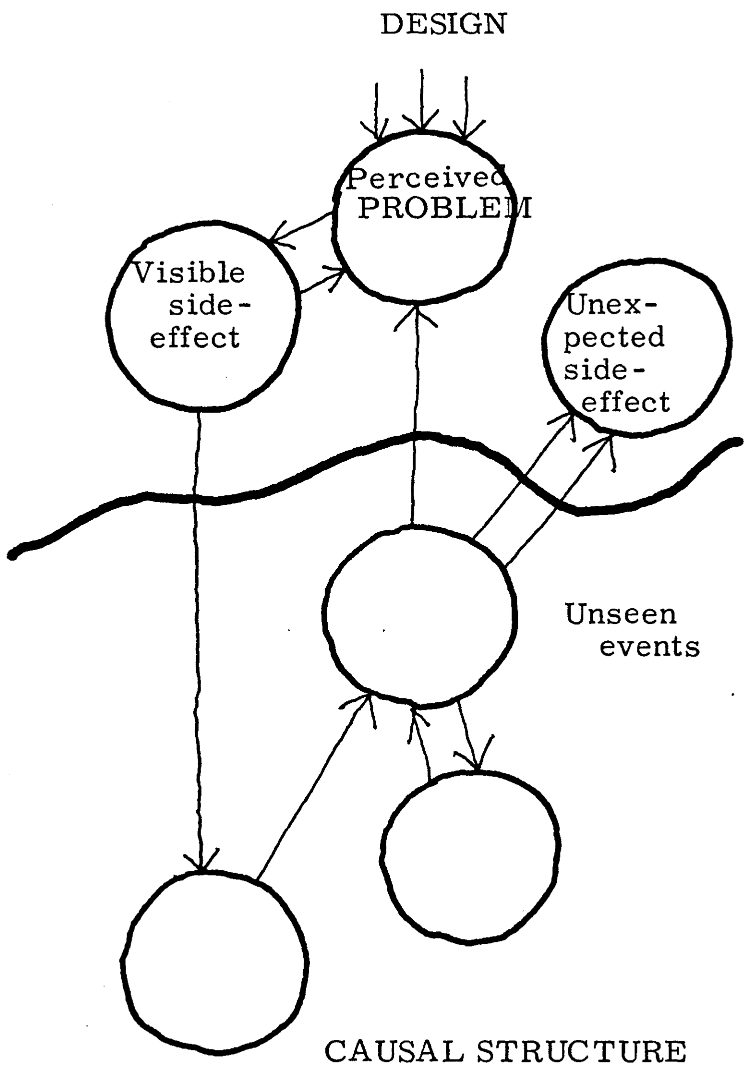
Thesis Supervisor: Nicholas P. Negroponte
Title: Assistant Professor of Architecture

TABLE OF CONTENTS

INTRODUCTION

The growth of civilization worries me. It seems to create ever more complex problems as it attempts to solve others. Working to house the millions more people of tomorrow ignores and perpetuates the cause of their arrival. Yet even if a city is a place where people compete in furious disarray for limited space and services, it is also a place where the most organized human interactions can flourish. J. W. Forrester demonstrates[1] that the prospects for a world that does not grow in population or in its depletion rate of sources of energy and material and yet continues to improve to the satisfaction of all its inhabitants are slim. Yet if such a world is possible, it requires an understanding of how to respond to our environment more than it requires a response with our present ability to understand.

The process of design takes place in a world of interwoven causal connections. Beneath the surface there are mechanisms causing the events we perceive. When we manipulate one set of phenomena, we set off a chain of events that extends beyond our direct influence, but often returns to affect conversely our intended region of



manipulation. Such a mistake is a result of misunderstanding causal structure. Given some knowledge of a structure, we still require information about the quanta that participate in it. A designer cannot hope to have complete knowledge of either structure or quanta, consequently *he cannot hope to know how to solve completely a problem as he perceives it or to perceive a problem he creates as he solves another*.

Clearly this is a very deterministic view of how all things wo rk. Neverthe-less, it does not preclude or contradict aiding the process of design. In one sense everything is deterministic. At any given time only one set of events is possible and that consists of those events that actually happen at that time. Every event that takes place emits information about its occurence in the form of energy. Depending on how and when it is received, the information determines an event in one set of ways only, be the event a collision between gas molecules or a turn of affairs in international diplomacy. No event takes place under the influence of what will occur in the future because energy does not arrive from such events before they occur. On the other hand some events are very difficult to predict based on past information. This depends largely on <u>how we are receiving information, how much is going on and whether we are altering events by our presence</u>. At one level of perception the behavior of air in a balloon is very simple: its pressure changes uniformly with pressure and volume. At a vantage-point where we can discern many gas molecules individually, all is in chaos; Brownian motion is famous for its randomness. But in observing a single collision between two gas molecules, the events become more comprehensible. Randomness as unpredictability in one frame of reference becomes uniformity or total predict-ability in another, yet both are determined by information about past events. In terms of this description, design is deciding how to affect wisely that which affects oneself and others; design is (self-) control.

The difference in meaning between deterministic and probabilistic becomes useful in describing our ability (or the ability of any other entity) for predicting future events based on information about past events. The need for prediction arises out of the need to have a response at each point in time. Design forms the response to such a prediction. The prediction represents an implicit model of the structure and behavior of the environment it takes place in. The designer bases his model of an environment on information he receives from it. That information can only be less than and different from the environment emitting it. Therefore the model can never be complete. In order to make the model as useful as possible, the designer must solicit information about the environment by testing it with responses which work in his current model. Only by discriminating between model and test results can he reformulate his model. Somehow, he can now choose a response which will probably represent an improved model.

Unaided, human beings are suited for modeling only a narrow range of their environment. We receive information and understand structure of causal events in a limited way. Although we organize our individual environments in a way comprehensible to each of us, we contribute to an over-all organization beyond the comprehension of any one of us. Only through association with an intelligent entity with powers of information gathering and understanding both greater than and different from ours, can we be aided in modeling the complexity that organizes our lives.

To many the proposition of living in consort with a machine seems shallow and demeaning at best. How can a machine understand and benefit us? How can it understand how we feel in terms meaningful to us? The answer lies in the rhetorical question, how can anybody do all these things? No-one can, completely. One must settle for a model of other people as well as of ourselves. The hardware necessary to construct a model consists of some black box (we call it intelligence) which organizes the model, based on information it solicits by controlling extensions of the body (effectors) in experiments that result in information about the environment which is detected by energy receivers (sensors) and transmitted back to the black box for comparison with the current model. The quality of the model in man or machine depends on its black box and its sensors and effectors.

One response we make to our environment is art. Art is our model of human experience. Art is not a model of the reality that human experience is itself a model of. Because art, both already made and in the making, is itself a portion of human experience, this description of art applies recursively to itself. A sufficiently intelligent machine to meet our requirements would not only model machine experience as a form of art, but would also model human experience.

The M.I.T. Architecture Machine is an effort in the direction of a responsive environment. Along the way there are many sub-goals that contribute to the process of design. These have centered on developing an ability for the machine to enhance the designer's and user's understanding of the environment they deal with and their relationships to it. To do this, the machine must solicit information both from the environment under discussion and the people who use it and design it. The machine can then represent the problem in a manner that its human proteges would find difficult to construct, but find easy to understand.

Much work on the Architecture Machine has gone into interfacing it with the real world. Eyes have been constructed; an arm is under construction; a mechanism called Seek builds and alters an environment for gerbils and a sketch recognition program accepts a sketch and translates through Seek into a physical configuration of blocks. The sensors and effectors are receiving a lot of attention, but our black box is not, beyond there being an expressed desire for routines that write themselves and heuristics that continually modify themselves.

Artificial intelligence is an awesome problem, so awesome that approaching it as an all-encompassing design problem may well be more difficult than any problem we might first apply the intelligence to. The most sensible approach may be to design something that somehow organizes itself into intelligence, in short, which evolves. Finding an elementary component capable of evolution is difficult by itself.

Using the real world as a continuous

and complete environment for evolution has obvious advantages over attempting to stash away a data point inside a computer memory to represent every possible piece of energy that might influence evolution. On the other hand, if one can construct a probabilistic model maker for generating responses to an environment, one should be able to make a deterministic model to represent the environment where needed only. If one can not conveniently interface with the real world, an internal environment generator might be a substitute for, but not a simulation of, reality. Of course, one would have to be able to monitor internal events from the outside.

Studying evolution as an approach to artificial intelligence will not assure that any given evolutionary mechanism will achieve our goal in a reasonable amount of time, but it will impute at each stage of progress how to improve the elementary entity one uses to precipitate the process in each experiment.

Having watched the progress of electrical engineering from tubes to integrated circuits and from crystalline semiconductors to amorphous semi-conductors, I am tempted to make a science fiction speculation about the technology that might accomplish evolution of environments as well as intelligence. A self-designing, self-building and self-tending set of components, whose total complexity exceeds our or its own total understanding, may chemically resemble the components of life. They may evolve from initial specifications only as complicated as the human sperm and egg relative to their fully developed state. We might not live in machines after all, but in organisms.

In proceeding with this paper, I will:

1) Contrast the power of designing evolutionary artifacts with the drawbacks of what I call "total design" that we now pursue;

2) Demonstrate the role of feedback in evolutionary design by analogy to one of the few responsive feedback control systems used in built environments; (To do this, I will clarify the principles of positive and negative feedback).

3) Model several evolutionary phenomena as embodying feedback of form -- feedback in a multiplicity of changing dimensions;

4) Demonstrate, in a survey of the interest in evolving environments and components of evolution, the roles of self-organization and self-reproduction;

5) Describe the possibilities of using cellular automata as a medium for experimentation of the properties mentioned above;

6) Finally, discuss my work on the M.I.T.

Architecture Machine providing a vehicle for further investigation of evolution.

1.0 THE DESIGN OF EVOLUTION

1.1 Total Design versus Evolution

God created the universe in six days. In this bootstrap operation He made order out of chaos. Where "the earth was without form, and void" (Gen. 1, 2), He made a firmament in the midst of the waters. He caused the sun, moon and stars to move in an orderly fashion in the heavens. He created plants and animals which interact with their surroundings in a complex, but orderly manner. Finally, out of the dust He made his most complex creation, man. This is one story.

Other lore maintains that a process of "natural selection" enabled certain creatures and plants to endure the vagaries of a changing environment by the "survival of the fittest" of successive generations. This process led from a relatively primeval state to the complex degree of organization we are aware of today.

However it happened, regard the Creation as a design event. The process described in the Bible required complete knowledge of the future if the grand design was to be adequate to meet the challenge of its own existence. Evolution, however, describes a process that responds solely to events in the (usually immediate) past.

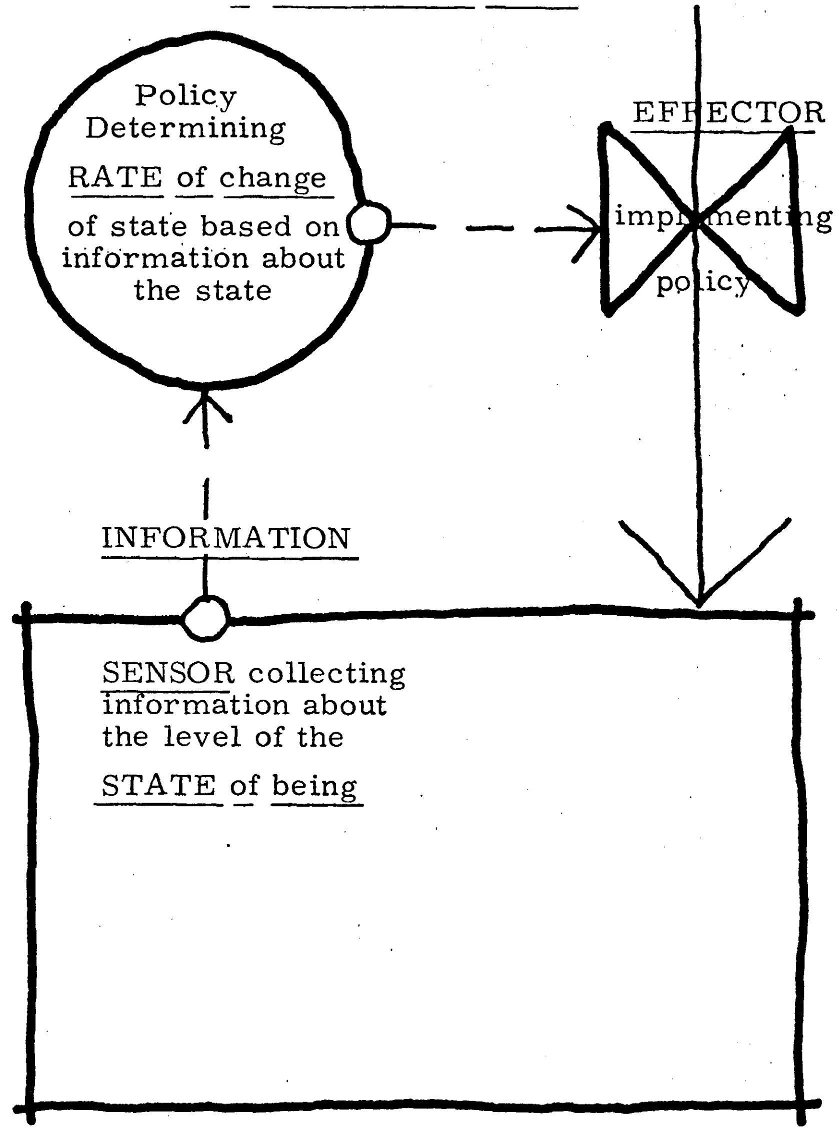
No matter what happens to alter a state of affairs, there is a mechanism capable of restoring an equilibrium to the now changed circumstances. The human design process resembles the Biblical creation in that it draws on a great deal of information (as complete as possible) to result in a fully developed artifact, not a developing one. In compensation for our lack of omniscience, we make the artifact somewhat open-ended and call it a design for "flexibility," "growth" and the "future." _Very little is known about how to create the self-designing process of evolution._

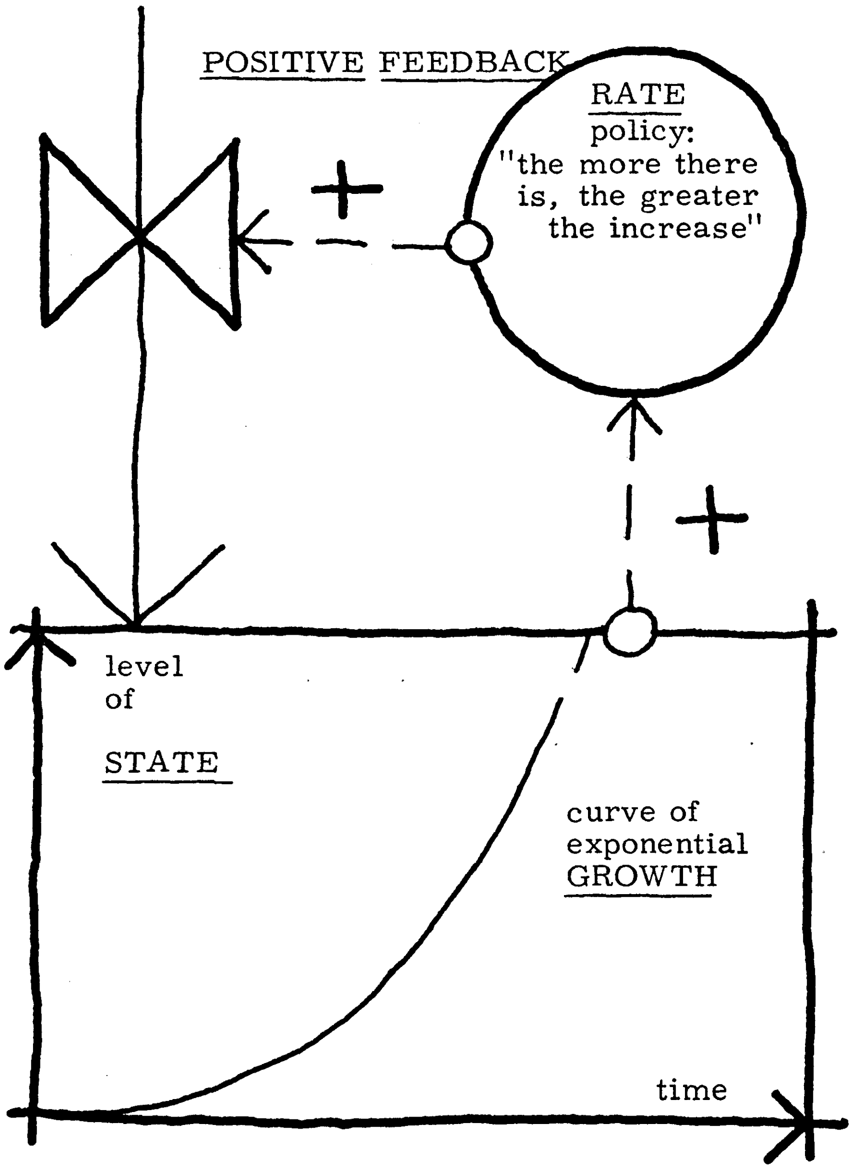
Thermostatic control of temperature provides the closest analogy in our everyday experience to self-designing environment. We take this regulating system for granted. But consider the total design alternative. Probably one would define a schedule for heat or cooling output based on average seasonal and diurnal changes of outside temperature. Lacking prior knowledge of exactly what goes on at any given moment, like someone leaving the outside door open in order to bring in the groceries, the designer must rely on very general likelihoods which result in a building that attains the desired temperature only by coincidence.

1.2 Growth and Control

The thermostat's advantages are manifest; furthermore, it provides the opportunity to extract the principles governing its usefulness. It is part of a system that includes an information receiver (sensor) and a responding mechanism (effector), both dealing with the same medium, temperature. The sensor guides a policy determining what the effector does. When the results of the effector's response reach the sensor, they complete a feedback loop. The feedback loop governs the change (rate) of temperature in the environment (state of being). A feedback

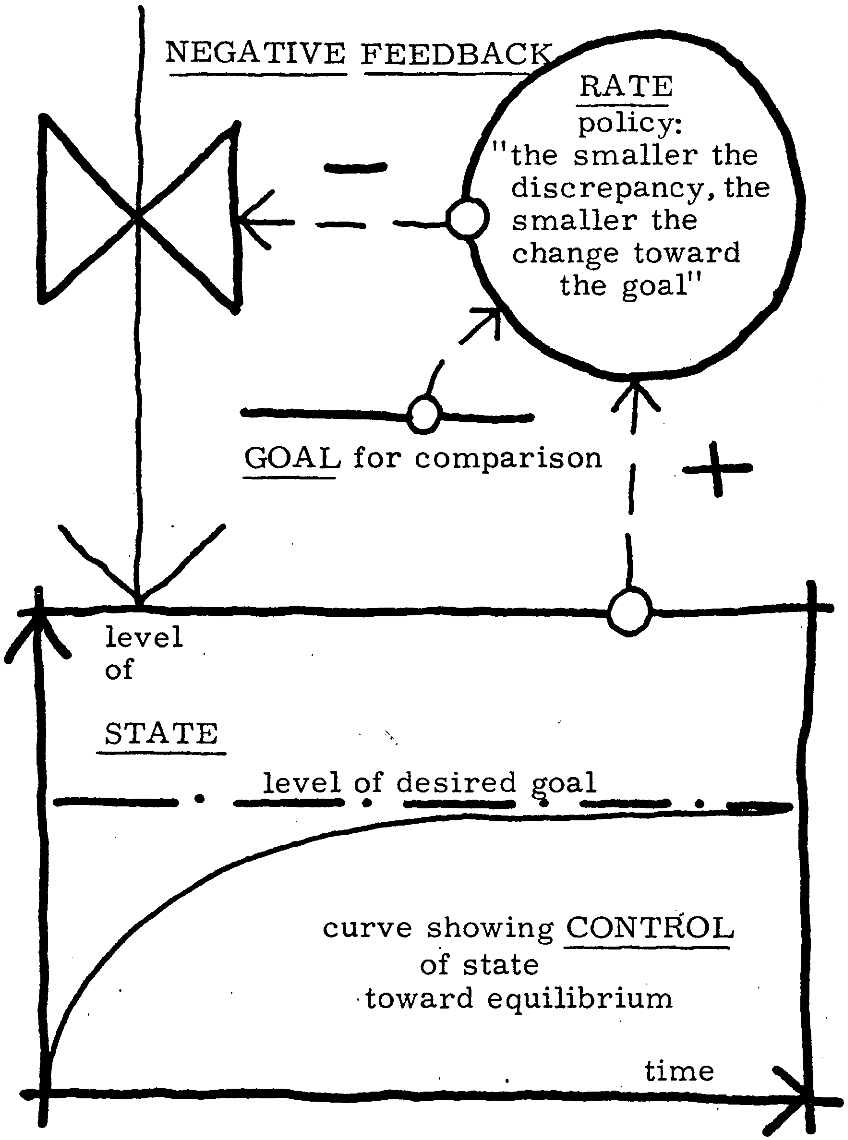
A FEEDBACK LOOP





loop would not exist if the sensor monitored the temperature in the Boston Edison smokestacks or the water level of the Charles River, since the effector would not alter the sensed state of being.

Consider some feedback policies the effector might pursue. One possibility is to change temperature by the following rule: "the more there is (state of being), the greater the increase (rate of change)." Such a policy, governing what one calls a positive feedback system, would have exponentially increasing growth of both rate and state. Another possibility is to set a goal and strive for it. In



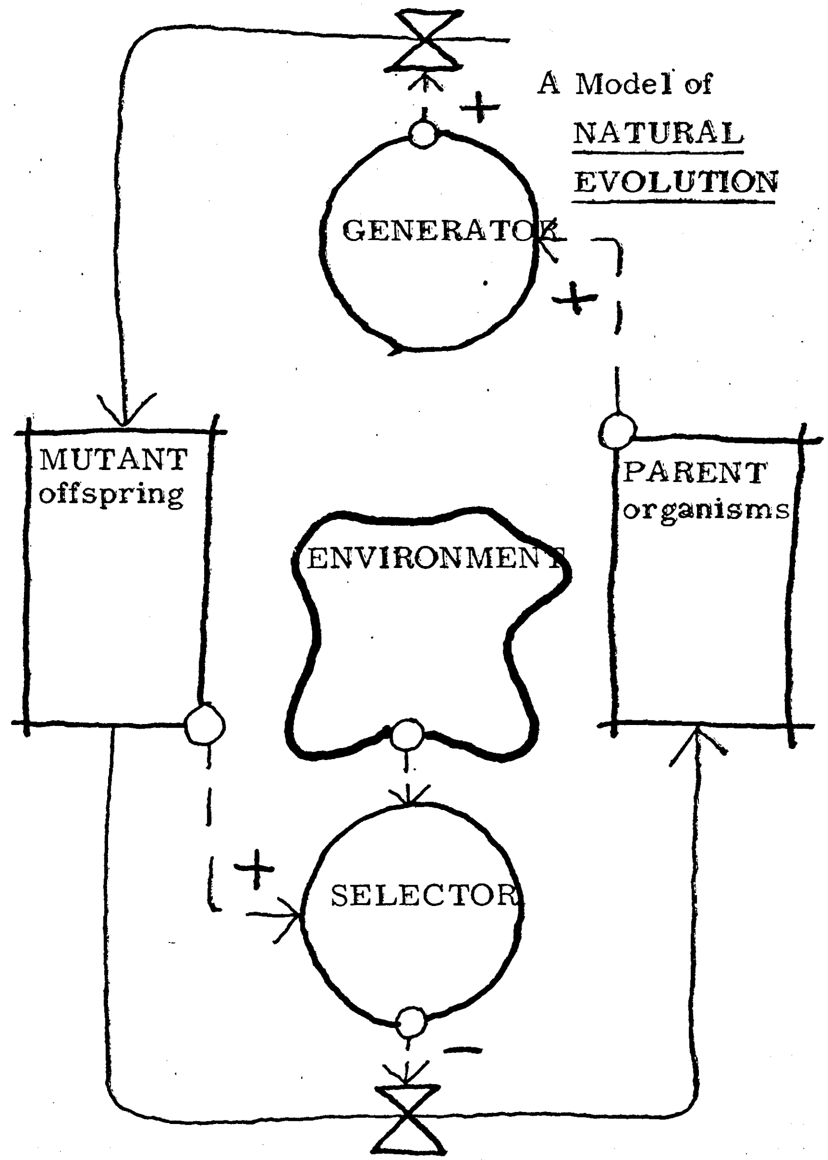
this case the policy would follow the rule: "the greater the discrepancy between goal and state, the greater the rate of change in the direction of the goal." This policy is called negative feedback and characteristically approaches its goal ever more slowly. Every control system, notably the thermostat, is an attempt to emulate this behavior.

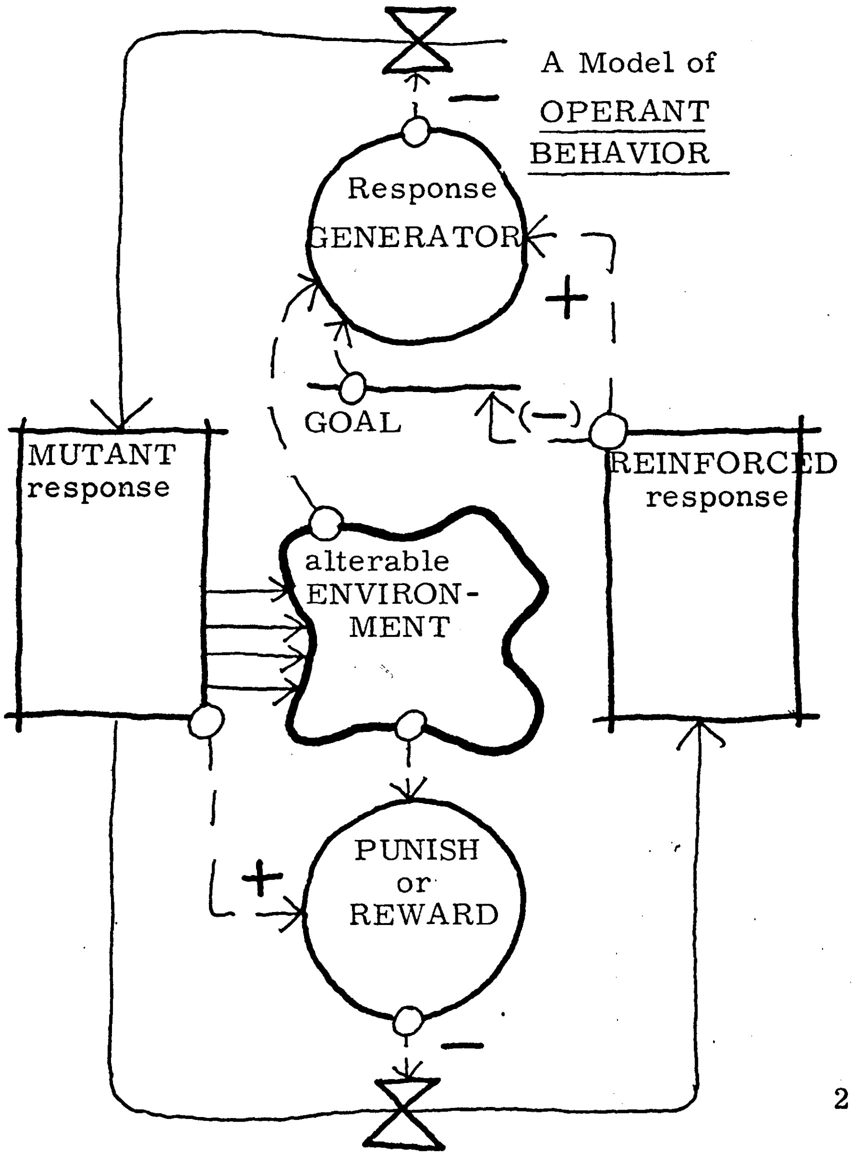
The control system determining temperature in a house is larger than a set of rooms, a furnace and a thermostat. It includes a person who adjusts the thermostat (determines its goal) at a setting comfortable for what he is doing. His comparison of the surrounding temperature with his own goals (a function of the amount of his activity, clothing, weariness, etc.) determines how he adjusts the thermostat.

1.3 Evolution as Feedback of Form

Evolution is not a thermostat. As a controller of an environment, a thermostat deals only with the dimension of temperature. An evolutionary controller must be able to alter the shape as well as the size of its response to an environmental situation. It might be adaptable enough only to provide lighting, shapes and textures for enjoyable living. Or it might be intelligent enough to take care of and educate a child.

Evolution is a feedback process in two parts: one is reproduction, a generator of mutant versions of previous generations; the other is environment, a selector of fit entities that provides the basis for a new generation. Consonance of mutants with the environment provides teleology insofar as the mutants do not alter significantly in their favor the environment that is the basis for selection. With a teleological environment the generator of mutants must pursue a policy of positive feedback of form; "the greater the differences in form among parent entities, the greater the increase of differences among offspring." The environment then provides negative feedback of form; "the greater the dis-





parity between the qualities of the environment and those of the mutants, the greater the rate of rejection."

If a generator stubbornly pursues a goal disparate from the environment without being able to alter it, there is no tendency for mutants to move toward either goal; the surviving mutants will be scattered in quality between the requirements of the two goals. The generator may change its goal as a result of its inability to change the environment. If the mutants can converge in quality with that of the environment or the environment with that of the mutants, then an equilibrium occurs. If the environment does not represent a constant goal because the mutants are capable of changing it in their favor and the generating process pursues no converging goal, the total system will grow exponentially in mutation of succeeding generations.

The coelacanth lives unchanged for millions of years in one of the most constant of environments, the bottom of the sea. Other fish, accepting the coelacanth as a part of their environment, as it must accept them, find sustenance in other niches of the same world. The cooling of the earth's crust and its motion in relation to the sun drive the change of the surface environment; the evolution of species follows suit. One creature, man, as a mutant is able to alter significantly the environment which affects him. The power of adaptation depends on the speed and variety of mutation. Single-cell creatures can reproduce rapidly, but their range of mutations per generation is small. Where such creatures specialize within the organization of a sexually reproducing animal, like a dinosaur, their rate of regeneration as a whole is much slower, but the combinations of possible genetic instructions are greatly increased. The ability of a given body to evolve its own responses to its environment offers a crude description of intelligent behavior.

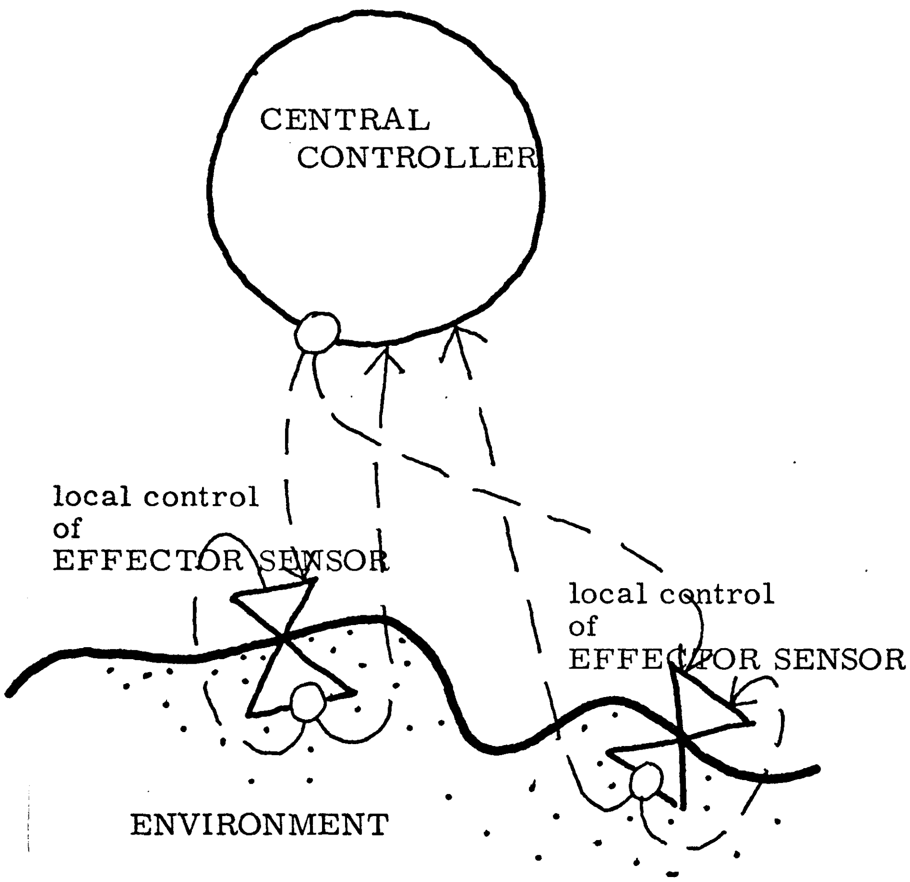
Any feedback response to an environment is an implicit prediction about the state of the environment, since the response is in the future relative to the sensing that prompted it. If the sensors and effectors involved deal with only one stimulus dimension (like temperature), then there is no basis for improving the prediction beyond fielding responses to stimuli as rapidly as the time lag in feedback permits. The ability to sense time improves the prediction of sequential patterns of stimuli, such as the cyclical numbers in Fogel's experiments described below. The greater the number of stimulus dimensions an organism can respond to in correlation to one another, the greater its power of prediction (adaptation). The ability to respond to correlated stimuli requires abstraction, classifying stimuli so as to detach them from the specific objects that possess them, and a means of recalling events from before the most recent impulse of feedback information. Armed with these additional observations, let us refine our understanding of intelligence as an evolutionary phenomenon.

One can model intelligence at many

levels. Following is a very elementary description: operant behavior is the ability to acquire new responses to stimuli without any prior propensity to shape them. In the course of natural evolution a mass of one-celled creatures has no greater propensity to organize into a rhinoceros than into an elm tree. A person has no more propensity to evolve the responses of his body to play the piano than to speak Japanese. Ability for these things to occur depends on the mechanisms involved; propensity depends on the environment they operate in. Operant behavior is evolutionary. This is in contrast to reflexive behavior, such as breathing or eye-blinking, which is a hard-wired response that can come under the control of stimuli other than the original, as happened to Pavlov's dogs when a bell-tone controlled their salivation in place of the stimulus of food.

Unlike natural evolution, operant behavior relies on a direct information link between the environment and the response generator. The information provides a reinforcing stimulus to the response that caused the environment to emit it and when compared with a goal, it provides a discriminating stimulus determining the generator's response. This system represents feedback at the highest level. In addition, there are many feedback loops controlling

HIERARCHY OF CONTROL



the effector-like movements of sensors seeking information from their environment, and the local sensing that controls the effectors' response as directed from the brain. Local control of sensors and effectors provides the information necessary for central control, but the speed of the convergence of responses to an environmental context hinge on the ability of the response generator to form mutants of previously successful responses to a similar context.

1.4 The Response Generator, an Iceberg

"Response generator" is a term that hides a formidable problem. The information that determines the shape of a mutant response cannot be as complete as the response itself without being identical with it. Surely the sperm and the egg do not contain information equilavent to every portion of a human being such that,for every atom in the complete entity, there is a corresponding atom in the information representing the entity. Each cell in a human being is about as complex as the original two. The development of a human being from two cells embodies positive feedback of form; the information transmitted from the parent entities to the generator is a set of instructions on how to make another more complicated set of instructions on how to make the next set, etc. One speculates that a sparse amount of information initiates a self-organizing process with complex results. In an absurd analogy one could select two books from a library shelf, choose a number between the Library of Congress numbers of the books selected, and insert it into a book generator; the book received, would be not just a random distribution of paper and ink, but an original work with real ideas in it, be they of high or low quality.

The purpose of such a generator would be to propagate widely varied responses when the mismatch between mutant and environment is great, and not so varied responses as the disparity diminishes. As such, it embodies a probabilistic model of an environment. If one can construct such a generator of form for mutant responses, one can use a similar method to simulate an environment within a machine without real-world contact. It would require a set of data as sparse as that which generates mutants. A deterministic generating process would simulate environment where only sensors and effectors were in operation. The French used a ruse similar in principle for deceiving the Germans in the movie, "The Train." The Germans loaded a train with art work stolen from the Louvre to take to Germany in case Paris was to be burned. The French partisans diverted the train away from Germany. Each station along the way had the name changed to correspond to the appropriate one along the route intended by the Germans. This obviated the need to simulate all of France and Germany to save the paintings.

The advantage of using the real world as an environment for the simulation of evolution is that it provides a continuous multiformity of energy to be sensed and altered. Wherever a response occurs in whatever form, the real world offers something to parry it. No matter what the inclination or wavelength of a sensor, the real world is emitting energy ready for reception. Internal representation of an environment might be useful only if it were more convenient than interfacing with the real world; it would be foolish to simulate the real world instead of some convenient imaginary one. For the machine it would be a logically constrained dream. The problem with machine dreams as with human ones is to witness the internal events.

1.5 Relevant Research and Interest

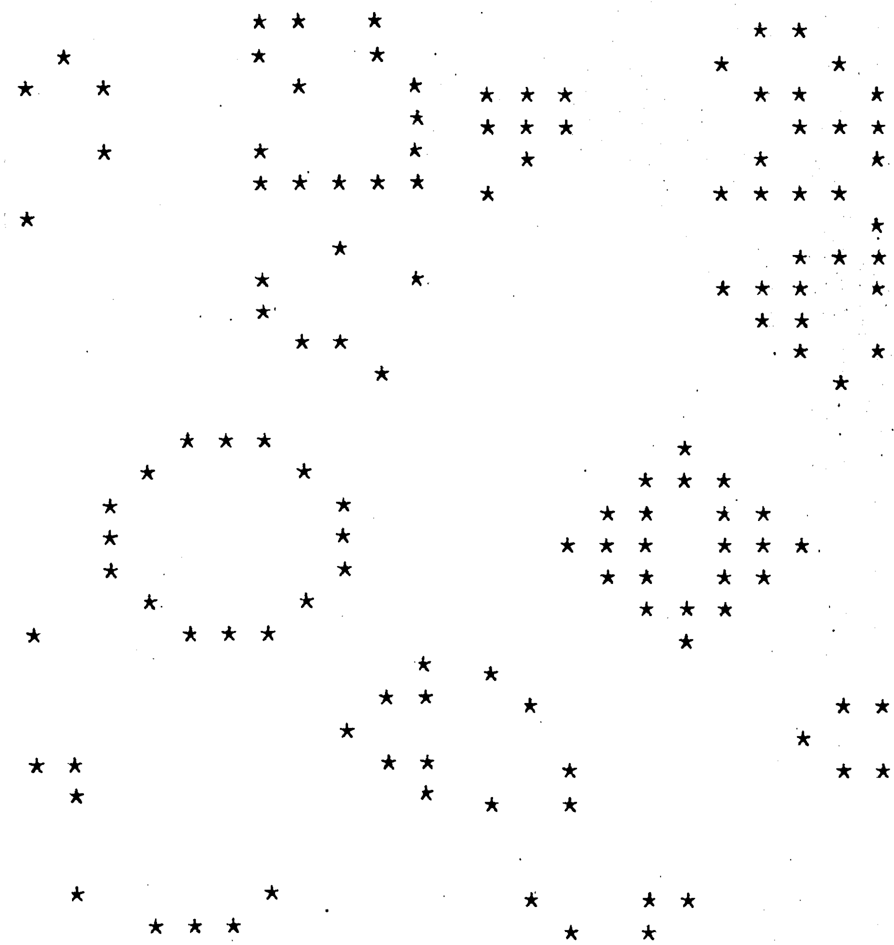
The understanding and especially the simulation of evolution are steps less than, but probably necessary to, understanding and creating artificial intelligence. This is evident from the progress in nature of organizing intelligence, not because intelligence must evolve from less organized phenomena, but because it is a special and particularly complex manifestation of evolutionary processes.

Warren Brody expects evolutionary environments to be intelligent in order to be sufficiently discriminating, rapid in response, and able to learn when confronted with the changing contexts of their users. "Human Enhancement through Evolutionary Technology" argues that we are enslaved by the necessity to adapt to the viscissitudes of "stupid" unresponsive machines and (by extension) environments. "Our entire machine environment needs to be given a self-organizing capability that is similar to the self-organizing capability of men, so that both kinds of systems can evolve and survive over the long run."[2]

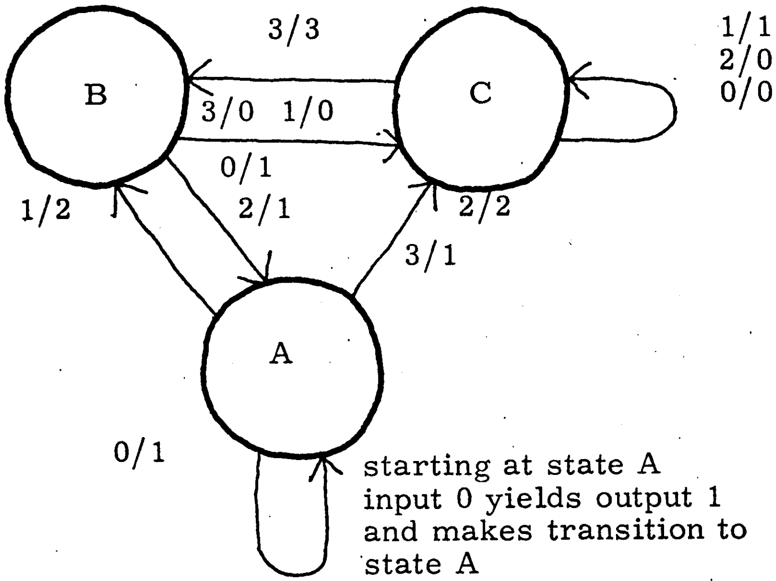
"Human Enhancement: Beyond the Machine Age" is a survey of efforts in pursuit of the aims espoused in Brody's above-mentioned article. Of importance to this paper are the concepts of self-organizing control systems and artificial intelligence through evolutionary programming. The self-organizing controller was developed by Gilstrap, Barron, et al. to relieve pilots of the burden of controlling air-craft with unstable handling properties due to the delay between a pilot's response and the aircraft's reaction. "There is (1) a goal circuit (performance assessment logic), which is a means for evaluating current performance; (2) a conditioning logic for computing and effecting suitable changes of the controller parameters and/or output signals; and (3) a memory for storing information concerning past parameter states. The memory exhibits an 'exponential forgetting', important in control applications because experiences in the remote past usually have less pertinence to present actions than do relatively recent experiences."[3]

The importance of a self-organizing controller is that it uses a certain amount of randomness in its responses to search out a suitable response to its environment at each point in time. Its responses are along a finite set of stimulus dimensions, defined in terms of pitch, roll and yaw. The controller's goals are to cause the unstable aircraft's motion to conform to its model of the pilot's intentions. These are communicated through his controls in response to the plane's motion. This system is not truly evolutionary because it generates vectors only for those fixed dimensions, rather than qualitatively changing its behavior when the rules of its environment change.

In his paper, "Environments of Self-Organizing Systems," Heinz von Foerster demonstrates that a closed, bounded self-organizing system cannot exist because it would be in contravention to the Second Law of Thermodynamics. Instead, it must exist in close contact with an environment from which it can draw energy and order. Hence the earth, which is becoming increasingly more organized, relies on the sun for the energy necessary to evolution, and the rules of interaction among the elements represent the source of order. "Cheap, undirected" energy enables rule-following entities to increase the orderliness of their association by encouraging random contact with other entities. In terms of the Bible, these conditions create order from chaos; in terms of the engineer, they create a signal out of noise.



SELF-ORGANIZATION



A FINITE-STATE AUTOMATION AND ITS PREDICTIONS[4]

State	B	A	C	C	C	C	B	C	C	B	A	B
Input	2	2	1	0	1	3	3	0	3	0	1	2
Output		1	2	1	0	1	3	0	0	3	1	2
Error Cost		1	1	1	1	1	0	0	1	1	0	

Fogel, Owens and Walsh's Artificial Intelligence through Simulated Evolution demonstrates the approximate state of explicit interest in artificial evolution. Fogel uses finite-state automata to provide responses to an environment of cyclical number series. A finite-state automation exists in only one of a number of states at a given time. Each responds to any one of a finite number of inputs by emitting an output and changing its state (perhaps back to the same one) in a way that differentiates it from any other possible state. In this way a finite-state automaton determines a sequence of outputs depending on the inputs it receives. In order to successfully respond to the environment Fogel has defined, it must correctly predict each subsequent signal emitted by the environment. In terms of the operation of the machine, each input signal from the environment should cause the machine in its particular state to emit the signal identical to the one that the environment will emit next. Input signals that elicit the incorrect response from the machine are noise until a machine is chosen that can correctly predict that response.

Fogel's automata are sensitive to two stimulus dimensions: integers and cyclicality. He does not discuss time, but his machines demonstrate what is necessary to respond to it. Time is the abstraction of any sequence of events apart from the specific events themselves. In order to respond to time a machine must change states thereby distinguishing the events of one time from those of another.

Because there are really only two fixed dimensions of response these experiments do not demonstrate evolution. Mutant variations of parent machines are evaluated in comparison with their forerunners and improved versions are selected on the basis of their performance. However Fogel points out that "as long as evolutionary programming is restricted to the use of finite-state machines as the representation for the evolving organism, it is possible to encounter plants or environments that can never be completely expressed within the logic of a single organism. For example, the binary sequence 101100111000... and the characteristic function of the prime numbers are sequences that cannot be perfectly described by a single finite-state machine."[5] The process for generating mutant machines itself does not improve.

The noise in the generating process permits it to organize favorable mutant response predictions about the environment. Since the regeneration of an entity is itself a response to the environment, the process of regeneration should mutate itself in order for the responses to improve.

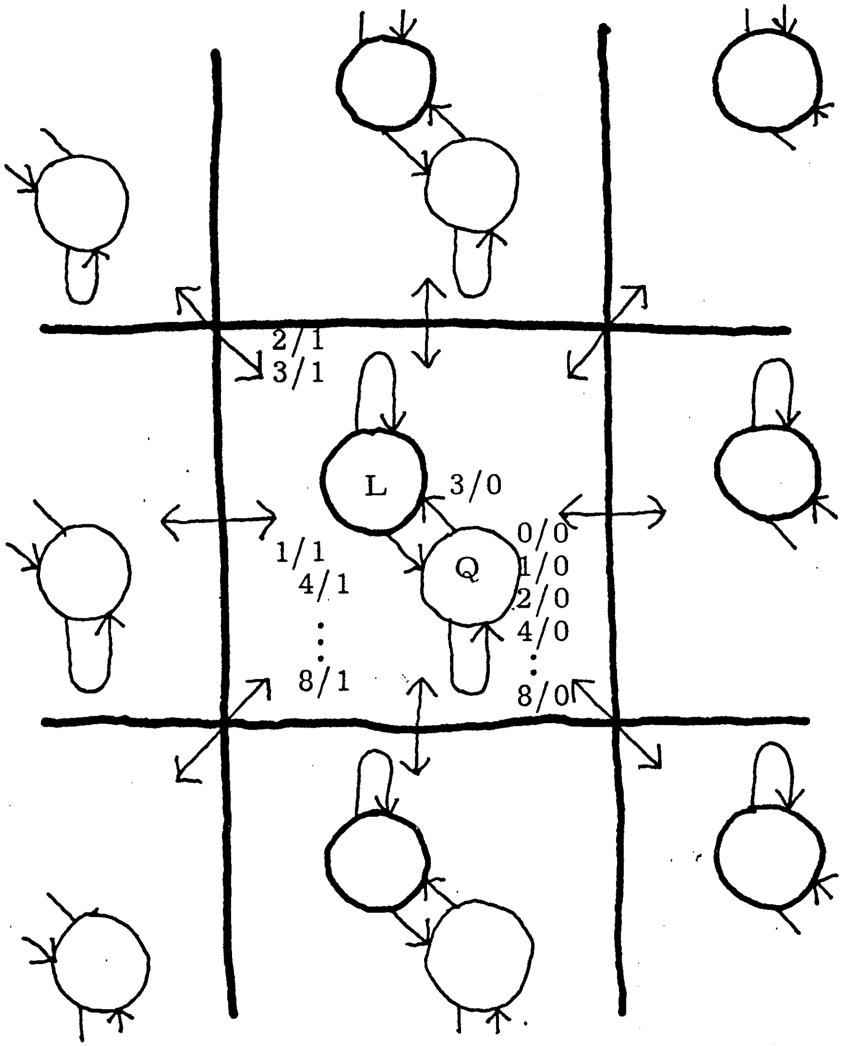
Self-reproduction requires much more than the original response-machine. There must be some kind of machine sufficient to construct the things we require. In order for the constructor to make the original machine, there must be a set of instructions for it. Upon following the instructions, there exists a copy of the response-machine without the means for reproduction. The constructor must execute a set of instructions on how to construct itself, how to construct a controller to decide the order of construction and activate newly created machines that might otherwise interfere with the ongoing process, and how to construct instructions for the controller as well. Now it can construct everything except that it has not reconstructed all the instructions on how to repeat the process. With a machine to be reproduced, a constructor, a controller and a set of instructions on how to reconstruct everything including themselves, self-reproduction can take place.

Once equipped with the necessary instructions and mechanisms to implement them, the problem is how to keep the information necessary for self-reproduction small relative to the complexity of the eventual organism. Positive feedback of form must implement successively more complex stages of growth. If the germinating information is small relative to the eventual entity, one must still be able to effect a small change in the simple beginning stages without causing a major change in the final complex stages, if one is to have a reasonable range of variation in mutability.

1.6 Cellular Automata, a Medium

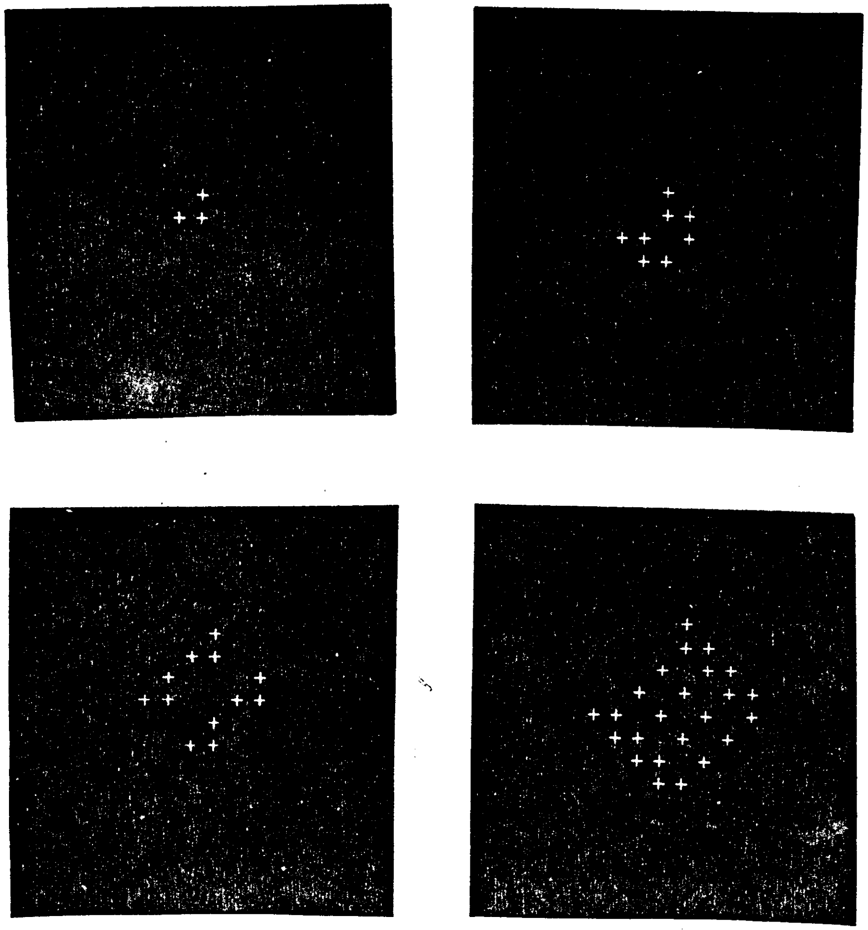
The medium of cellular automata provides an avenue for probing positive feedback of form, self-reproduction and possibly evolution. Cellular automata are similar to the finite-state machines used by Fogel, except that there are many of them arranged in a grid of consistent geometry and each represents a part of its neighbors' environments. Each cell changes state and emits a signal depending on the pattern of signals it receives from its neighbors. Most interest is focused on very simple automata with a small number of states and a small number of rules for changing states.

Edward Moore in "Machine Models of Self-Reproduction" gives a more complete description. Consider "a universe which is a two-dimensional Euclidean space subdivided into square cells of equal size, like squares of graph paper . . . [Call] such a space a tesselation . . . Located in each of the cells of this tesselation there is to be one copy of a finite-state machine. Each cell-machine is to be deterministic and synchronous; that is, at each integer-valued time T g.t. O, the state of each cell-machine is to depend only on its own state at time T-1 and on the states



A TESSELATION of 2-State Automata

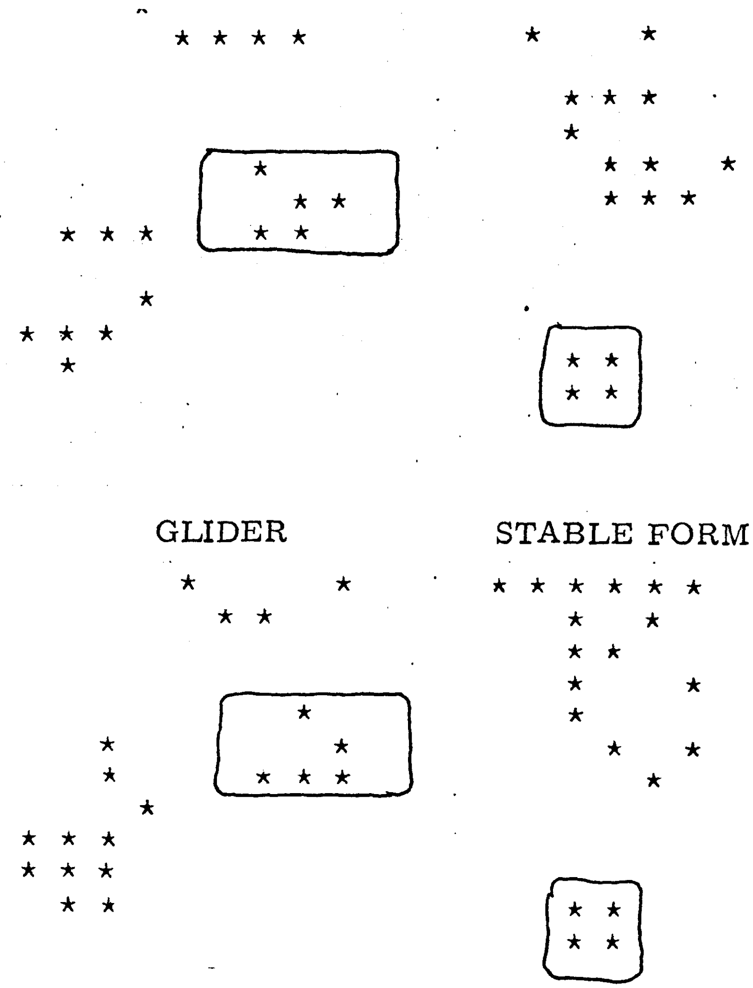
of its neighboring cell-machines at time T-1. All of the cell-machines are to be exactly alike as to their list of states and the rule determining their transitions, but different cell-machines are permitted to be in different states. The list of the possible states of the cell-machines must include a special state called the quiescent state, and all except a finite number of cell-machines will be in the quiescent state. The quiescent state is to have the property that if any cell-machine and all of its neighbors are in the quiescent state at time T-1, then the cell-machine will be in the quiescent state at time T''.[6]



FREDKIN'S SELF-REPRODUCING TROMINO

It is easy to make rules capable of trivial self-reproduction. Moore points out that a rule stating, "there are only two states, X and O, and having the transition function f such that each cell will be in state X at time T if at least one of its neighbors was in state X at time T-1, then the configuration consisting of one cell in state X will be a self-reproducing configuration."[7] Fredkin's tromino[8] in orthogonal four-neighbor cellular space is a slightly less trivial example of trivial self-reproduction.

In the October 1970 issue of <u>Scientific American</u> there appears a tesselation devised by John Conway, called Life. His rules are of particular interest because they involve only two-state automata and a simple set of rules governing the change and survival of states, but at the same time are sufficiently tenuous to make a configuration that continuously increases the active population of the tesselation, not obvious even after initial experimentation. Patterns that do not decay are rare, although there do exist patterns that are stable, some that oscillate and some that move across the space (so-called gliders and rocket ships). More interesting was the discovery of a glider gun



which did indeed increase the population by creating a new glider every fifteenth time period. Each glider moves out of the way for the next one. Furthermore, a certain fortuitous collision of gliders causes the formation of a glider gun.

This is not sufficient to demonstrate self-reproduction in Conway's space. If one considers the gun to be the object of reproduction, then the parent guns have to be positioned and phased in such a way as to line up the trajectories of their gliders on the appropriate collision courses. This process requires thirteen guns to generate the thirteen necessary gliders to create, not thirteen, but only one gun that is being bombarded by the original sources of gliders. Reproducing gliders also falls into a trap if it requires the same immobile guns.

It is difficult to determine how simple an elementary machine can be to participate in self-reproduction. Von Neumann demonstrates[9] a 29-state transition function capable of reproduction of its own 200,000 cells. Edgar Codd requires a much smaller 8-state tesselation.[10] Distinguishing trivial from non-trivial self-reproduction in the absence of a satisfactory definition of either, further complicates the problem. Certainly simulation of evolution using self-reproduction will qualify as non-trivial, and not merely complex. The elementary machine need not be evolutionary in itself. It must have sufficiently complex rules to permit an increase in overall order in association with others like itself. Witness physics as a basis for chemistry, chemistry as a basis for biology, biology as a basis for physiology, physiology as a basis for psychology, psychology as a basis for sociology, and sociology as a basis for political science. All these studies are looking at hierarchies of order, whose boundaries in the universe are neither distinct nor finite-dimensional, but represent an increase in self-organization from a relatively constant set of principles to a set of evolutionary phenomena.

If they do not yet demonstrate self-reproduction, Conway's rules for Life do permit positive feedback of formation. The r-pentomino is a configuration of five live counters which after more than a thousand time-increments stabilizes at a formation of several blinkers, gliders and other stable forms. There are many other less impressive examples.

Although a mathematical environment can

test cellular configurations for stability, growth, or even self-reproduction, it cannot generate such forms. No one has yet discovered a heuristic for generating interesting formations. Nature has a large advantage. There is a sufficiently complex set of elementary rules to permit self-organization and plenty of "cheap, undirected energy" permitting many concurrent events to stumble across evolutionary configurations after billions of years.

Finding a self-reproducing formation and especially an evolutionary one requires patience. If one starts out with the right rules for evolution (without yet knowing it), one has only to permit random events to take place long enough before one has an evolving system. That probably takes a long time, but not so long as the now-famous monkeys with their typewriters who will probably randomly type the works of Shakespeare making many mistakes with commas, when other things are correct, and vice versa, before they type a correct version. When the evolutionary state approaches "Shakespeareness," it will work on that quality in the presence of an environment encouraging it until its "Shakespeareness" becomes quite good. After waiting a long time in vain, one might never know that the rules were not sufficient for evolution.

1.7 Recapitulation or Capitulation?

Evolution is self-organizing; it draws on an environment for energy and order.

Evolution must be self-reproducing, otherwise the process of improvement will not improve itself.

Evolution includes:

Responses embodying a model of an environment that determines which responses a selection process will permit to participate in the generation of new mutant responses.

It is easier to create an evolutionary process with evolving components than with non-evolving components.

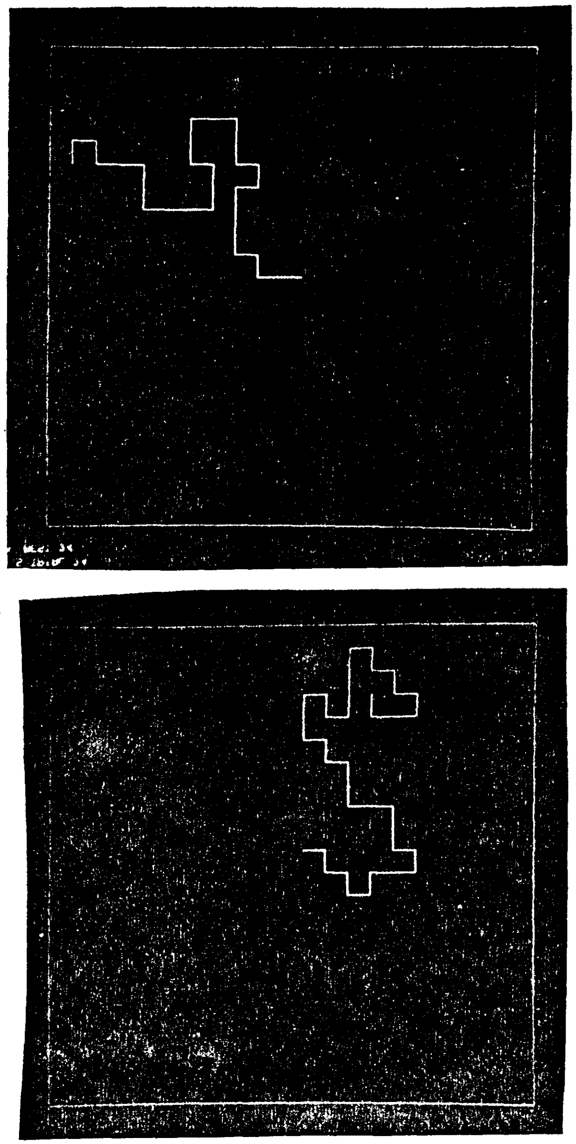
2.0 THE EXPERIMENTAL MEDIUMS

2.1 A Probability Walk

My work started with an experiment to explore how well a hierarchy of probabilities could improve a mechanism's ability to predict. A simulated machine wandered in a bounded region. Capable of turning only 90° right or left, or going forward, its task was to avoid the boundaries. At a hierarchy level of one, having no memory, it would accumulate a probability for going in each of the three possible directions. Unable to sense its environment, its longevity of movement would determine the value of its current set of probabilities; these would change in the direction indicated by subsequent, more successful trials.

An obvious secret to longevity in this environment is to make nothing but right turns. The machine had no initial propensity to do this and had only a small likelihood of discovering this strategy from the many other possible combination of responses. Although the machine's ability to perform could improve, its ability to improve could not.

Beyond the first level of hierarchy was the possiblity of controlling each of the movements to follow each of the other movements. Beyond the second level



one could control (for example) the likelihood for right to follow left where left had just followed forward movement. The hierarchical structure burgeons as it handles all the possible combinations of responses specifically. That experiment was a straw man, and was not worth pursuing as a route toward evolution.

LEFT: PROBABILITY WALKS

2.2 The Construction of a Tesselation

The February 1971 issue of Scientific American describing discoveries about Conway's game of Life suggested that cellular automata would be an interesting medium for exploring the problems of evolution, not by representing a population of creatures as Conway's metaphorical name suggests, but as a self-organizing system. My task became one of building a tesselation that would accept cellular automata, varying in numbers of states and rules of behavior.

I started using the Interdata Fortran programming language with I/O (input/output) software developed to enable Fortran to communicate with ARDS storage tubes and Sylvania tablet. My initial set of rules operated with a neighborhood of the four orthogonally located cells determining quiescence and activation. Quiescence remained in effect for a cell unless it acquired exactly three neighbors; activation continued as long as there were two or three neighbors.

Because Fortran placed severe limitations on the size of the tesselation, I soon started to write a similar program in assembly language, the learning of which was crucial to this thesis. Assembly language permits detailed control of events and economy of usage since it is the closest thing to the "machine" instructions that govern the behavior of the computer. Its inconvenience stems from the same fact; it compels one to pay great attention to minute detail which a higher-order language, like fortran, takes care of automatically. The effort was worthwhile, since it changed the limits of the tesselation size in the Interdata Model 3 from 10 x 10 in Fortran to 55 x 55 in assembly language, an increase by a factor of more than 30. The speed of operation for the respective languages increased from about 3 elements per second to about 600 elements per second. Several different rule structures were tried including Conway's with an eight cell neighborhood and several rules that represented "bugs" in the program.

From one's transition function, one hopes to see self-organization through positive feedback of form, where a small population germinates a more complicated one. Necessary to self-reproduction is a configuration that moves out of the way of other similar figures during the process. Evolution requires both positive feedback and self-reproduction with the possiblity for mutation.

Inspection of interesting configurations already discovered by others revealed that there is no apparent heuristic that would be likely to generate interesting forms. Although symmetry was a common phenomenon, the most interesting formations usually had at least one asymmetric property. The glider gun was not even a contiguous pattern. Failing a heuristic, the choice was to generate random initial conditions and watch their progress in self-organization. Although not as desirable as trying out many "almost good" configurations, it is a lot more satisfactory than generating random static solutions. If one seeks to find a stable form that is resilient to a hostile environment, it is interesting to bombard the tesselation with stray live counters occasionally; this might provide mutations that have more interesting behavior than the stable forms they mutate.

The problem remains to find a self-reproducing entity that is mutatable enough to provide a large number of alternative configurations at any stage in a self-improving process. Von Neumann's universal constructor with a neighborhood of four orthogonal elements and 29 states would be capable of self-reproduction, but it would still require mutation. After mutation it might not be able to reconstruct itself.

Von Neumann's demonstration does not address itself to the positive feedback of form from a simple to a complex entity.

The appendices contain portions of sample output representing an initial state of "primordial ooze" that organizes itself into stable formations. The assembly language program is also included with comments on how to modify the number of states, transition functions, etc. The end of the usefulness of this medium for studying evolution will provide the conclusion for this thesis.

BIBLIOGRAPHY and REFERENCES

	Arbib, M. A.	Self-Reproducing Automata- Some Implications for Theoretical Biology	Stanford University Stanford, California	1969 July
	Brody, W. M.	Soft Architecture	Landscape, 17, No. 8-12	1967 Autumn
3	Brody, W. M., and Lindgren, N.	Human Enhancement: Beyond the Machine Age	Institute of Electrical and Electronics Engineers Spectrum, 5, No. 2, 79-93	1968 February
2		Human Enhancement Through Evolutionary Technology	Institute of Electrical and Electronics Engineers Spectrum, 4, No. 9, 87-97	1967 September

	Burks, A. W.	Von Neumann's Self-Reproducing Automata	Essays on Cellular Automaat, A. W. Burks (editor). Chicago: University of Illinois Press	1970
10	Codd, E. F.	Cellular Automata	New York: Academic Press	1968
4, 5,	Fogel, L. J., A. J. Owens, and M. J. Walsh	Artificial Intelligence Through Simulated Evolution	New York: Wiley	1966
1	Forrester, J. W.	Urban Dynamics	Cambridge, Mass.: M.I.T. Press	1969

	Forrester, J. W.	World Dynamics	Cambridge, Mass.: Wright-Allen Press	Forthcoming 1971
8	Fredkin, E.	See reference in Gardner	Scientific American	
	Gardner, Martin	Mathematical Games	Scientific American 224, No. 2, 112-117	1971 February
	Hendrix, C. E.	Operant-Conditionable Machines	Santa Monica Cal.: Telluron	1970 March
6, 7	Moore, E. F.	Machine Models of Self-Reproduction	Essays on Cellular Automata, A. W. Burks (editor). Chicago: University of Illinois Press	1970

Negroponte, N.	The Architecture Machine	Cambridge, Mass.: M.I.T. Press	1970
Pask, G.	A Discussion of Artificial Intelligence and Self-Organization	Advances in Computers, 5, 110-218	1964
	The Conception of a Shape and the Evolution of a Design	Conference on Design Methods, J. C. Jones and D. G. Thornley (editors). Oxford: Pergamon Press 153-168	1963
Von Foerster, H.	On Self-Organizing Systems and Their Environments	Self-Organizing Systems, New York: Pergamon Press	1959

9	Von Neumann, J.	Theory of Self-Reproducing Automata	Urbana, Ill.: University of Illinois Press	1966

APPENDICES

```
                                               OPT    PASS3,PRINT,PUNCH,STOP,...
0000R C890     LOAD     LHI    9,X'13'
      0013
0004R 0B77              SHR    7,7
0006R 0B11              SHR    1,1
0008R C820              LHI    2,1
      0001
000CR 4830              LH     3,UP
      022AR
0010R 0B44     OOP1     SHR    4,4
0012R C850              LHI    5,1
      0001
0016R 4860              LH     6,UP
      022AR
001AR C880     OOP2     LHI    8,0
      0000
001ER D287              STB    8,COUNT(7)
      0E22R
0022R D287              STB    8,FIELD(7)
      0238R
0026R 9B98              RDR    9,8
0028R 4480              NH     8,ONE                 MASK OUT EVEN NUMBER
      0236R
002CR D287              STB    8,FIELD(7)
      0238R
0030R CA70              AHI    7,1
      0001
0034R C140              BXLE   4,OOP2
      001AR
0038R C110              BXLE   1,OOP1
      0010R
003CR 41A0              BAL    10,OUTP
      0044R
0040R 4300              B      TESTS                   OUTPUT
      0100R
0044R 0B77     OUTP     SHR    7,7
0046R C890              LHI    9,X'82'
      0082
004AR 0B11              SHR    1,1
004CR C820              LHI    2,1
      0001
0050R 4830              LH     3,UP
      022AR
0054R 0B44     POOL1    SHR    4,4
0056R C850              LHI    5,1
      0001
005AR 4860              LH     6,UP
      022AR
005ER D3C7     POOL2    LB     12,FIELD(7)
      0238R
0062R 08CC              LHR    12,12
0064R 4330              BZ     BLAND
      0076R
0068R 9D98              SSR    9,8
006AR 4290              BTC    9,*-2
      0068R
006ER DA90              WD     9,EX
      022ER
```

```
                  0072R 4300              B       CONT
      008AR
0076R 4100     BLAND    BAL    0,BLANK
      007ER
007AR 4300              B      CONT
      008AR
007ER 9D98     BLANK    SSR    9,8
0080R 4290              BTC    9,*-2
      007ER
0084R DA90              WD     9,BL
      0230R
0088R 0300              BR     0
008AR CA70     CONT     AHI    7,1
      0001
008ER 4100              BAL    0,BLANK
      007ER
0092R C140              BXLE   4,POOL2
      005ER
0096R 4100              BAL    0,LFCR
      00AAR
009AR C110              BXLE   1,POOL1
      0054R
009ER 9D98              SSR    9,8
00A0R 4290              BTC    9,*-2
      009ER
00A4R DA90              WD     9,FF
      0234R
00A8R 030A              BR     10
00AAR 9D98     LFCR     SSR    9,8
00ACR 4290              BTC    9,*-2
      00AAR
00B0R DA90              WD     9,CR
      0233R
00B4R 9D98              SSR    9,8           COUNTING
00B6R 4290              BTC    9,*-2         SUBROUTINE
      00B4R
00BAR DA90              WD     9,LF
      0232R
00BER 0300              BR     0
00C0R 0B11     TALLY    SHR    1,1
00C2R C820              LHI    2,1
      0001
00C6R 0833              LHR    3,3
00C8R 0A7E     LOOP1    AHR    7,14
00CAR 0B44              SHR    4,4
00CCR C850              LHI    5,1
      0001
00D0R 0866              LHR    6,6
00D2R D387     LOOP2    LB     3,FIELD(7)
      0238R
00D6R 0888              LHR    8,8
00D8R 4330              BZ     SAME1
      00F0R
00DCR CA00              AHI    0,1
      0001
00E0R 0897              LHR    9,7
00E2R 0A9F              AHR    9,15
00E4R D389              LB     8,COUNT(9)
```

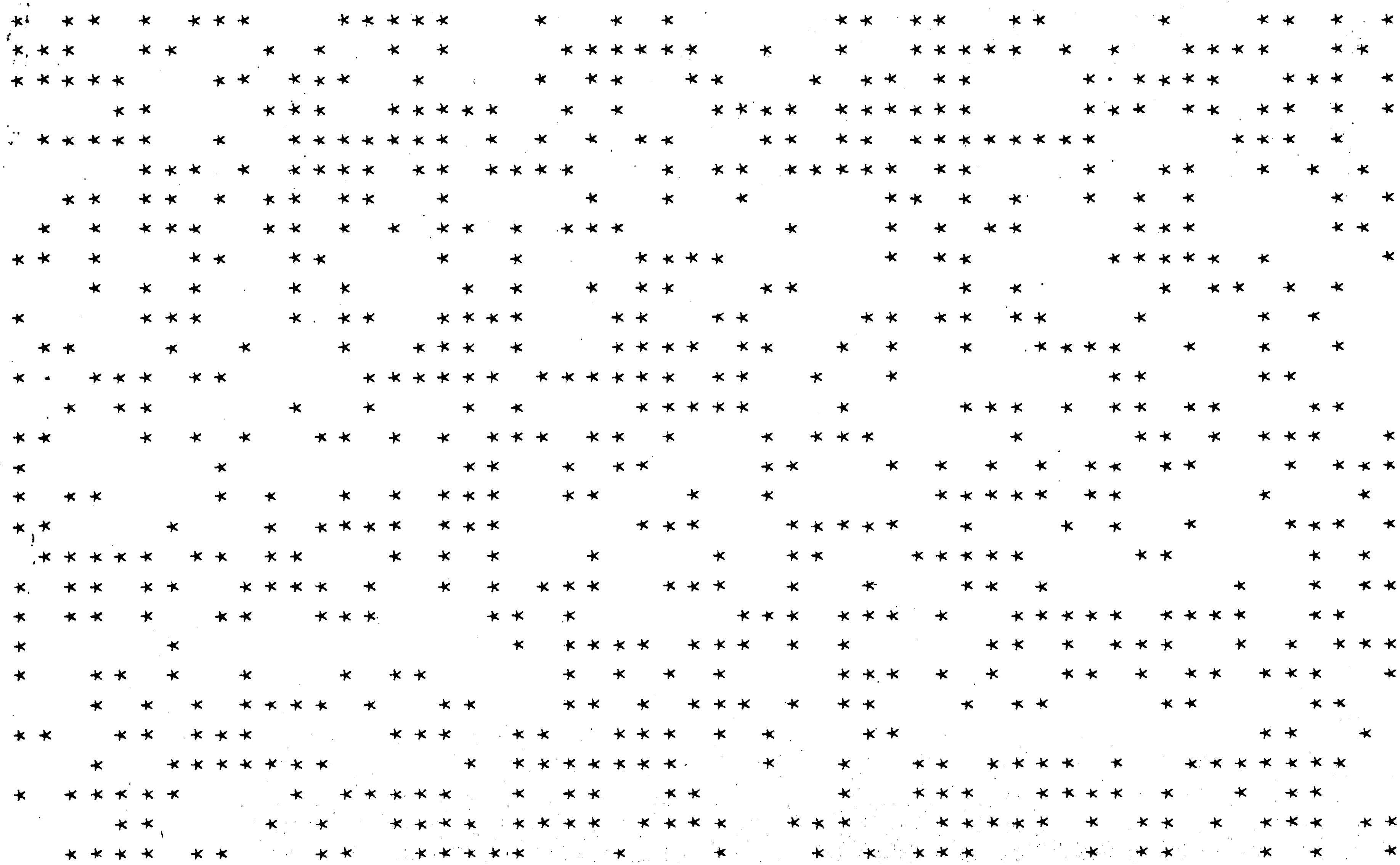
```
                              0E22R
00E8R CA80                    AHI    8,1
      0001
00ECR D289                    STB    8,COUNT(9)
      0E22R
00F0R CA70       SAME1        AHI    7,1
      0001
00F4R C140                    BXLE   4,LOOP2
      00D2R
00F8R 0A7D                    AHR    7,13
00FAR C110                    BXLE   1,LOOP1
      00C8R
00FER 030A                    BR     10
0100R 0B00       TESTS        SHR    0,0
0102R C870       RIGHT        LHI    7,0
      0000
0106R 4830                    LH     3,UP
      022AR
010AR CAE0                    AHI    14,1
      0001
010ER 4860                    LH     6,UPM
      022CR
0112R 0BDD                    SHR    13,13
0114R 0BFF                    SHR    15,15
0116R C7F0                    XHI    15,X'FFFF'
      FFFF
011AR 41A0                    BAL    10,TALLY
      00C0R
011ER C8D0       LEFT         LHI    13,1
      0001
0122R 0BEE                    SHR    14,14
0124R 0B77                    SHR    7,7
0126R C8F0                    LHI    15,1
      0001
012AR 41A0                    BAL    10,TALLY
      00C0R
012ER 4830       BELOW        LH     3,UPM
      022CR
0132R 4860                    LH     6,UP
      022AR
0136R 4870                    LH     7,UP1
      0228R
013AR 0BDD                    SHR    13,13
013CR 48F0                    LH     15,UP1
      0228R
0140R CBF0                    SHI    15,1
      0001
0144R C7F0                    XHI    15,X'FFFF'
      FFFF
0148R 41A0                    BAL    10,TALLY
      00C0R
014CR 0B77       ABOVE        SHR    7,7
014ER C8E0                    LHI    14,0
      0000
0152R 48F0                    LH     15,UP1
      0228R
0156R 41A0                    BAL    10,TALLY
      00C0R
```

TESTS NEIGHBORHOOD (8 ADJACENT CELLS)

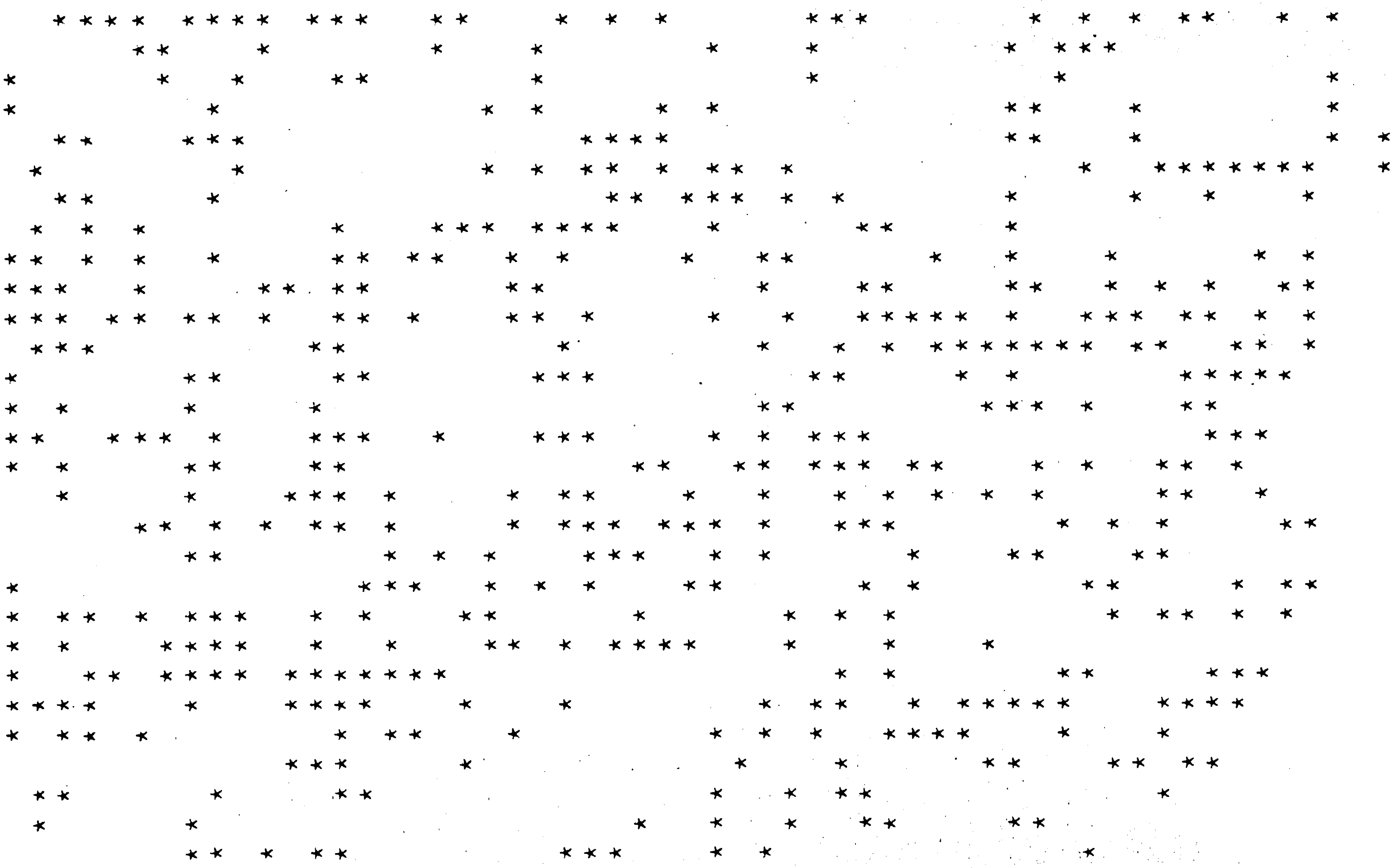
```
                      015AR 4870    UPLEFT  LH     7,UP1
      0228R
015ER 4830                  LH     3,UPM
      022CR
0162R 4860                  LH     6,UPM
      022CR
0166R C8E0                  LHI    14,1
      0001
016AR 48F0                  LH     15,UP1
      0228R
016ER C7F0                  XHI    15,X'FFFF'
      FFFF
0172R 41A0                  BAL    10,TALLY
      00C0R
0176R 0BEE      UPRITE      SHR    14,14
0178R 4870                  LH     7,UP1
      0228R
017CR CAF0                  AHI    15,2
      0002
0180R C8D0                  LHI    13,1
      0001
0184R 41A0                  BAL    10,TALLY
      00C0R
0188R 0B77      LORITE      SHR    7,7
018AR 48F0                  LH     15,UP1
      0228R
018ER CAF0                  AHI    15,1
      0001
0192R 41A0                  BAL    10,TALLY
      00C0R
0196R C8E0      LOLEFT      LHI    14,1
      0001
019AR 0B77                  SHR    7,7
019CR 48F0                  LH     15,UP
      022AR
01A0R 0BDD                  SHR    13,13
01A2R 41A0                  BAL    10,TALLY
      00C0R
01A6R C500                  CLHI   0,0
      0000
01AAR 4330                  BZ     LOAD
      0000R
01AER 0B77      RBRTH       SHR    7,7
01B0R 0B11                  SHR    1,1
01B2R C820                  LHI    2,1
      0001
01B6R 4830                  LH     3,UP
      022AR
01BAR 0B44      LOP1        SHR    4,4
01BCR C850                  LHI    5,1
      0001
01C0R 4860                  LH     6,UP
      022AR
01C4R D387      LOP2        LB     8,FIELD(7)
      0238R
01C8R 0888                  LHR    8,8
01CAR 4330                  BZ     NULL
      01E6R
```

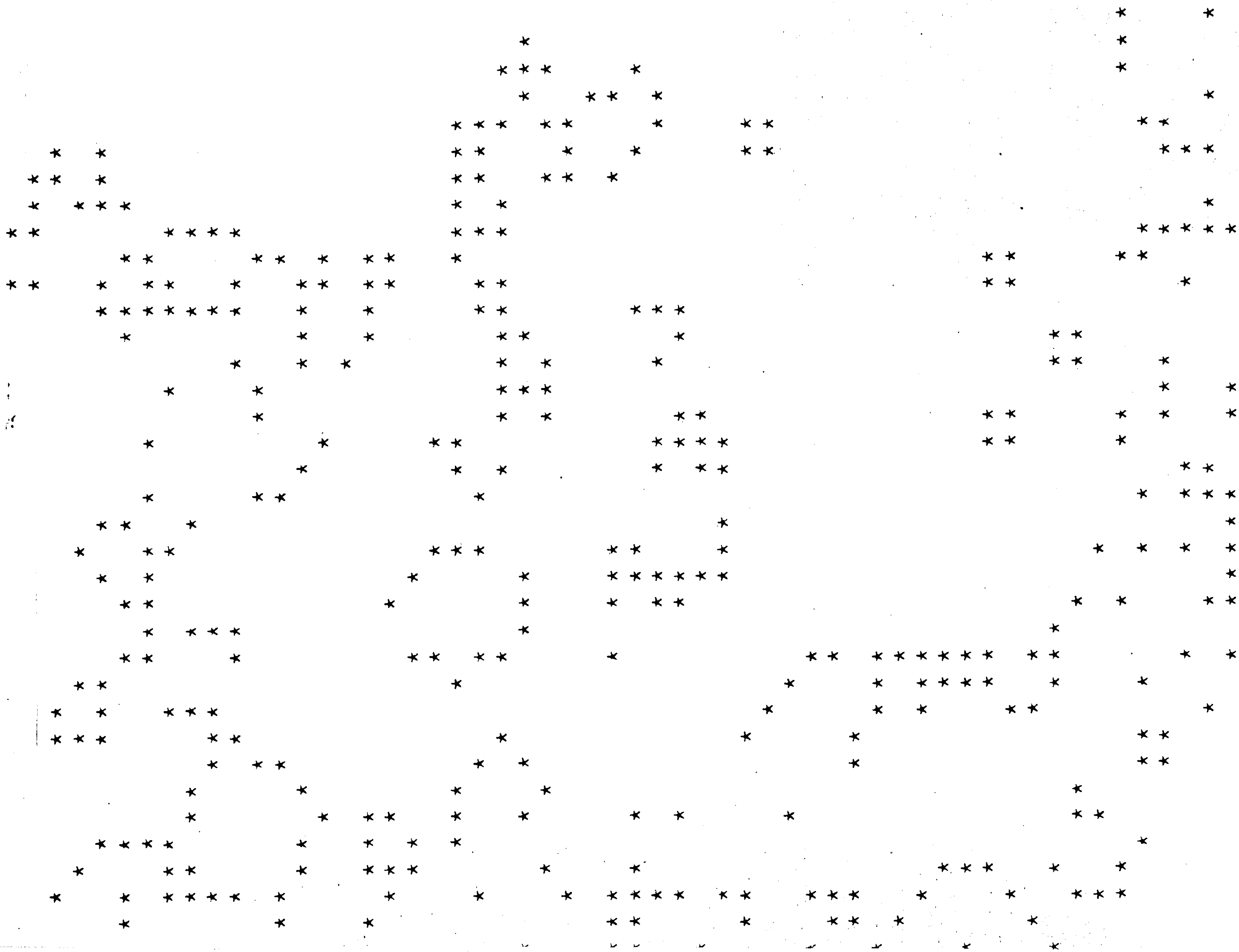
```
               01CER D387              LB     8,COUNT(7)
      0E22R
01D2R C580              CLHI  8,2              RULES FOR
      0002                                      REBIRTH
01D6R 4330              BE    BRTH
      01F6R
01DAR C580              CLHI  8,3
      0003
01DER 4330              BE    BRTH
      01F6R
01E2R 4300              B     DTH
      0202R
01E6R D387     NULL     LB    8,COUNT(7)
      0E22R
01EAR C580              CLHI  8,3
      0003
01EER 4330              BE    BRTH
      01F6R
01F2R 4300              B     DTH
      0202R
01F6R C880     BRTH     LHI   8,1
      0001
01FAR D287              STB   8,FIELD(7)
      0238R
01FER 4300              B     NEXT
      020AR
0202R C880     DTH      LHI   8,0
      0000
0206R D287              STB   8,FIELD(7)
      0238R
020AR C880     NEXT     LHI   8,0
      0000
020ER D287              STB   8,COUNT(7)
      0E22R
0212R CA70              AHI   7,1
      0001
0216R C140              BXLE  4,LOP2
      01C4R
021AR C110              BXLE  1,LOP1
      01BAR
021ER 41A0              BAL   10,OUTP
      0044R
0222R 4300              B     TESTS
      0100R

0226R 9800     OP       DC    X'9800'
0228R 0038     UP1      DC    56
022AR 0037     UP       DC    55
022CR 0036     UPM      DC    54
022ER 2A2A     EX       DC    X'2A2A'
0230R 2020     BL       DC    X'2020'
0232R 0A0D     LF       DC    X'0A0D'
0233R          CR       EQU   *-1
0234R 0C0C     FF       DC    X'0C0C'
0236R 0001     ONE      DC    X'0001'
0238R          FIELD    DS    3050
0E22R          COUNT    DS    3050
1A0CR                   END
```

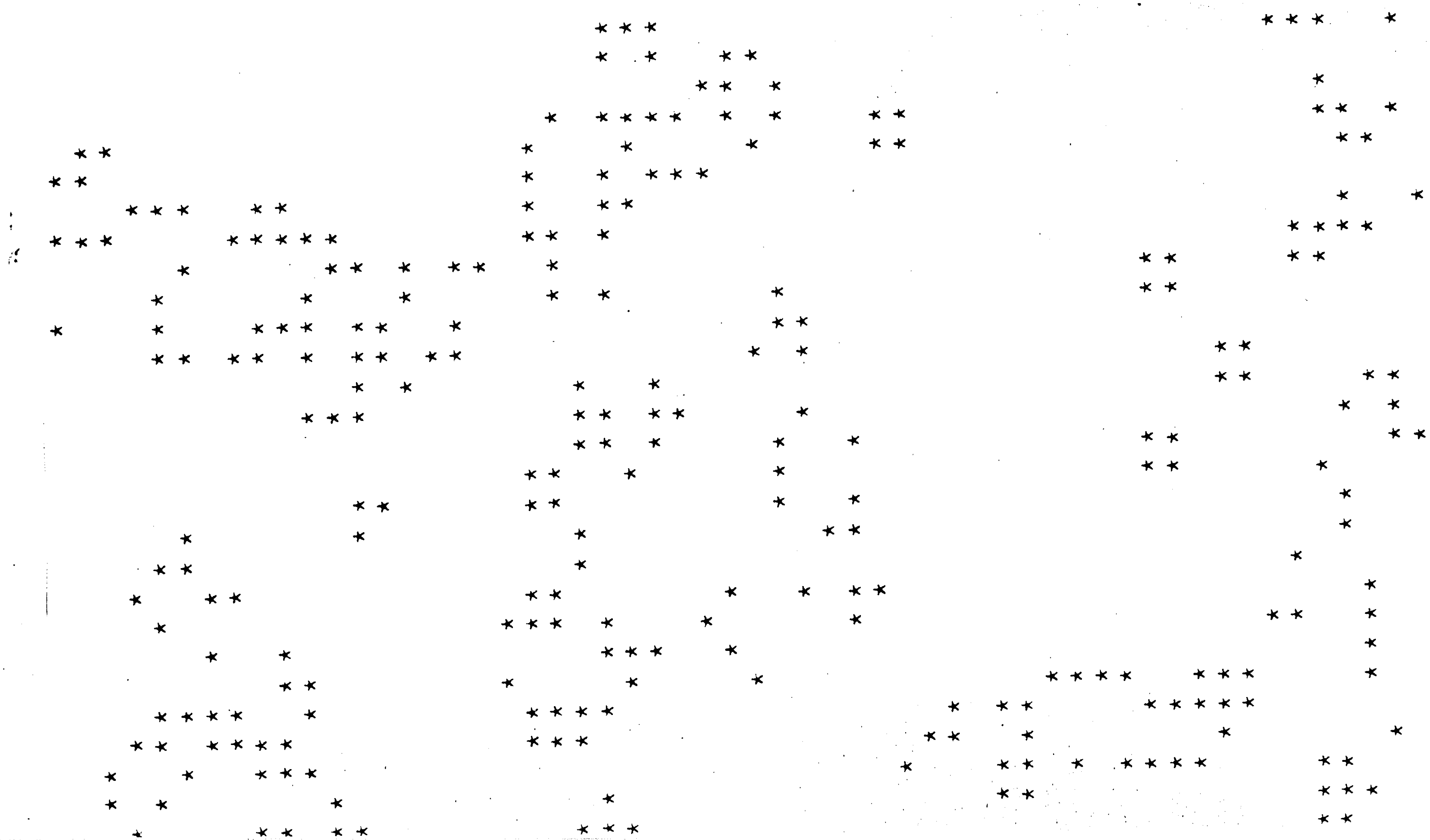
RANDOM INITIAL STATE

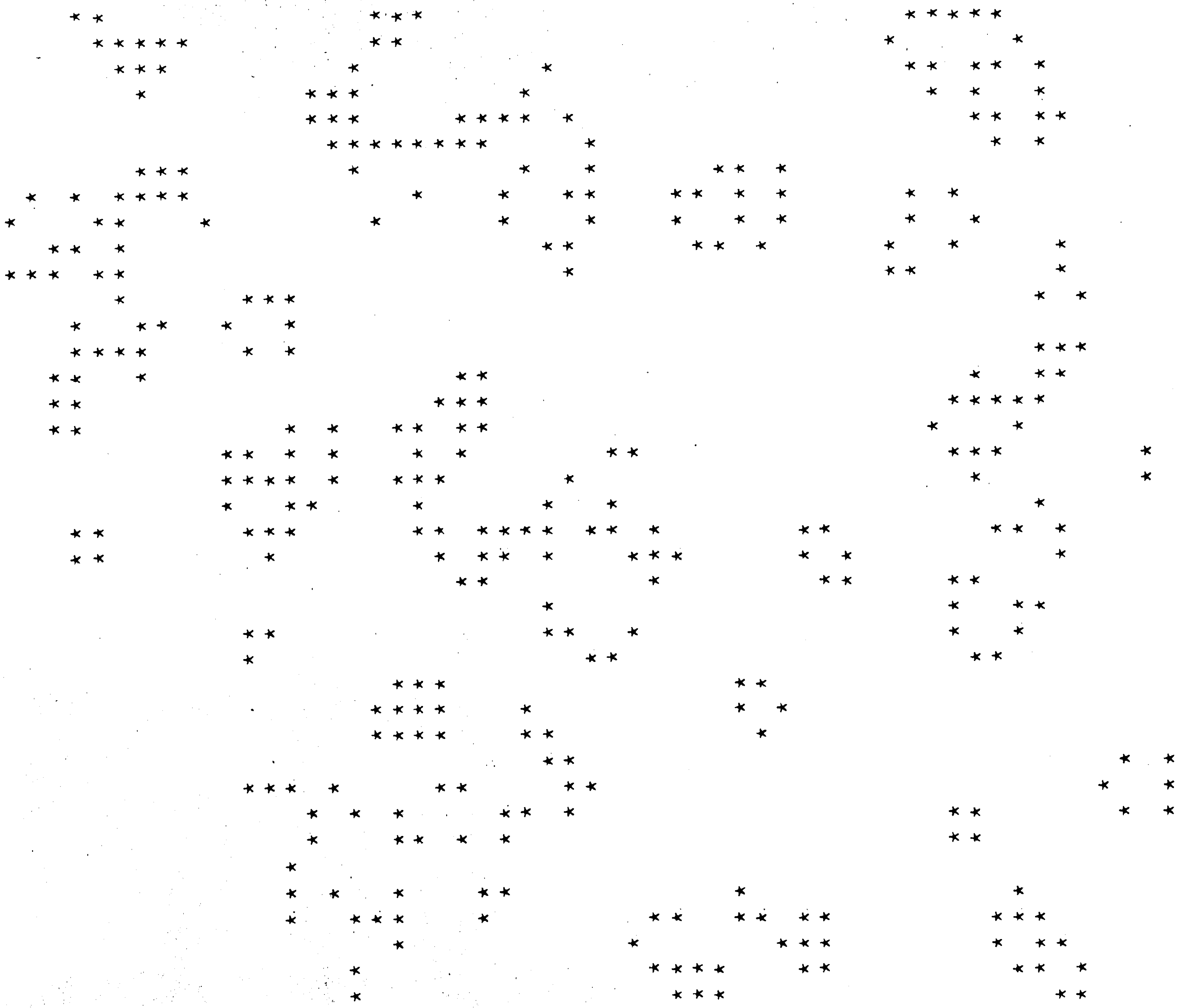


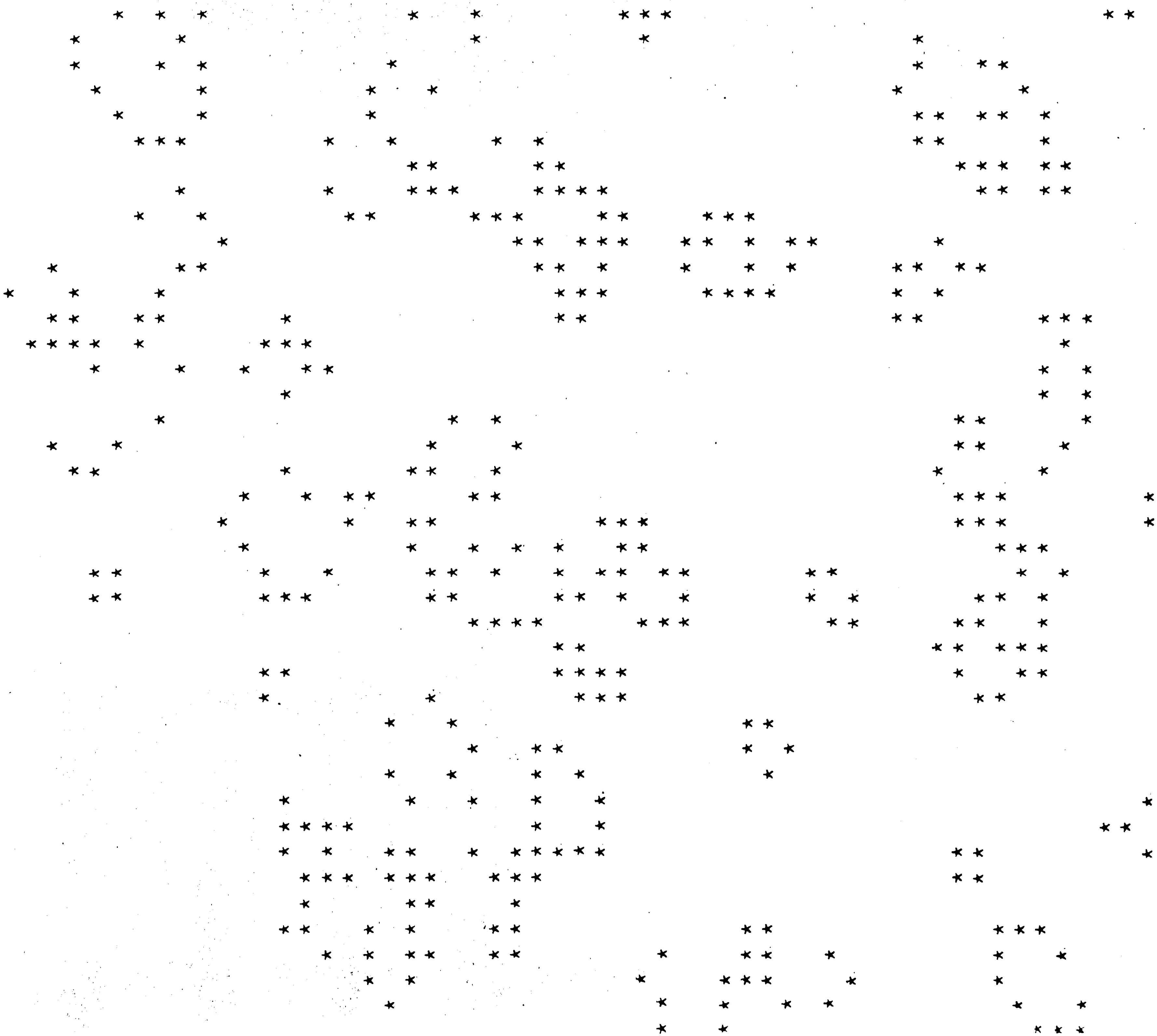
THE BEGINNING OF SELF-ORGANIZATION

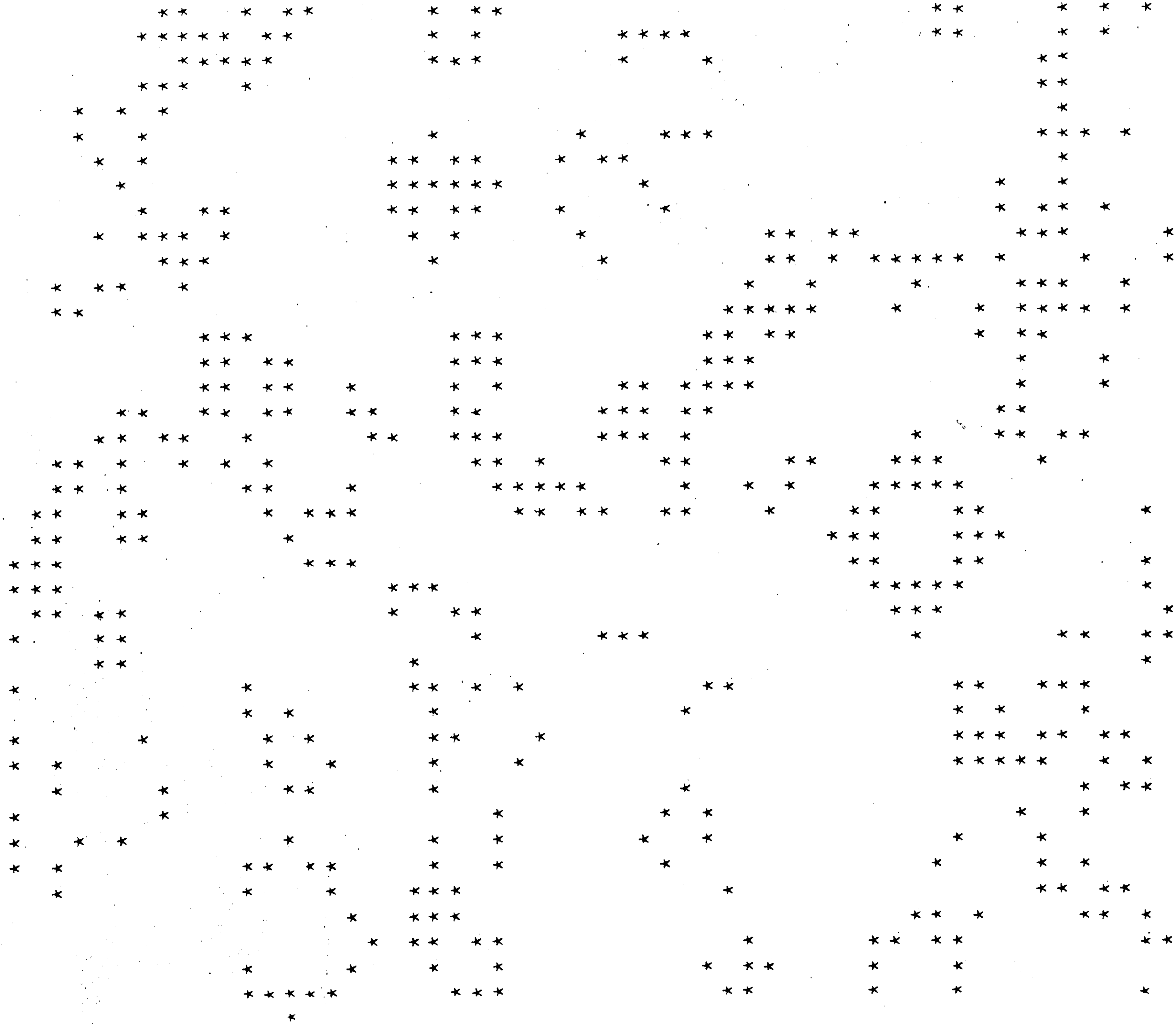












THE r-PENTOMINO

```
*
* * *
  *
```

* * *
*   *
    *

POSITIVE FEEDBACK OF FORM

```
      * *
    *   * *
  * * *   * *
* * *       * *
  *   *   * *
  * *   * *
    *   * *
      *
```