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An Outline for **BATIC**:
A Teaching Device for Demonstration of and Experimentation with **B**asic **A**utomata **T**heory **I**n **C**ybernetics and in Communications.

The Annenberg School of Communications, University of Pennsylvania,
1964 (mimeo).

1 Introduction

BATIC is a teaching device for demonstration of and experimentation with "Basic Automata Theory In Cybernetics or Communications".

BATIC can be considered a kind of primitive digital computer, but is not designed to perform any specific arithmetical computations. Its primary purpose is to provide vivid experiences of some behavioral consequences of communication which are the declared subject of cybernetics. Communications and its implications are basic to very many domains of scientific inquiry, a fact which is often not realized and frequently treated only ad abstractum.

BATIC will be of great value in teaching fundamental concepts of cybernetics, general systems theory, simulation processes, communication theory, information theory, abstract design, etc. Especially, BATIC would be of assistance in lectures in any of the communication oriented disciplines such as the social sciences, the behavioral sciences, the biological sciences, and be of help in philosophy of science as well.

BATIC consists essentially of a set of units each of which can be programed and coupled in numerous ways such that the whole can be made to show a great number of behaviors. These behaviors are represented visually, for instance as describing a path through a behavior space of electric lights. Some of the typical processes which can be demonstrated are given in chapters 3 and 4. They range from "transmission of information in the presence of noise" to "corrective behavior" involving feedback and exhibiting various "forms of stability" as a consequence thereof.

BATIC's value is most obvious to educators wishing to demonstrate certain ideas with which they want to concern themselves. Moreover, students can exercise the analysis and synthesis of elementary systems involving communication. BATIC's behavior can, for instance, be recorded and the protocol so obtained be subsequently subjected to analysis. Or, the student can use BATIC to test his solution to given problems by running the specified behavior and communication on BATIC and judge whether it was correctly solved. BATIC could moreover be an interesting educational toy. Its almost inexhaustible combinatorial possibilities leaves much room for experimentation and surprises.

The idea of such a teaching device is not entirely novel. Numerous mechanical computing kits which can be made to perform some elementary algebraical or logical operations are already on the toy market. They are, however, inadequately equipped for the type of problems with which BATIC is concerned. For the principal idea I am indepted to W. Ross Ashby who used in his lectures on cybernetics a "black box" with which he could most competently and vividly demonstrate some basics of the science of communication and control.

The outline for BATIC which follows, refers only to the first few primary components. Although the great instructional value can already be asseverated at this point, experiences should be gained systematically before further additions are suggested. It is, however, intended to include new and more components in order to represent more complex types of communications behavior.

2 Abstractly specified requirement

BATIC's components are required to be capable of embodying at least the following:

a) Several sets each of n binary elements, here denoted by capital letters I, J, K, L, etc. Each set represents n states.

b) A set of mappings μ_u over one step in time defined as follows:

$$\mu_u: \qquad I_e^t \circ J_e^t \longrightarrow K_e^{t+1}$$

$u = 1, 2, \ldots\ldots, n^{nn}, \quad e = x, y, z.$

c) A set of transformations π_v over one step in time each determining a probability distribution over the states in L. The set of probability distributions range from perfect randomness to nearly certainty. In uncertainty measures (Shannon), the set of distributions range from $H(L)=H_{max}$ to approximately $H(L)= 0$.

$$\pi_v: \qquad L^t \longrightarrow L^{t+1}$$

d) A set of mappings λ_w involving no step in time, defined between nay two of the sets named above.

3 An illustrative example

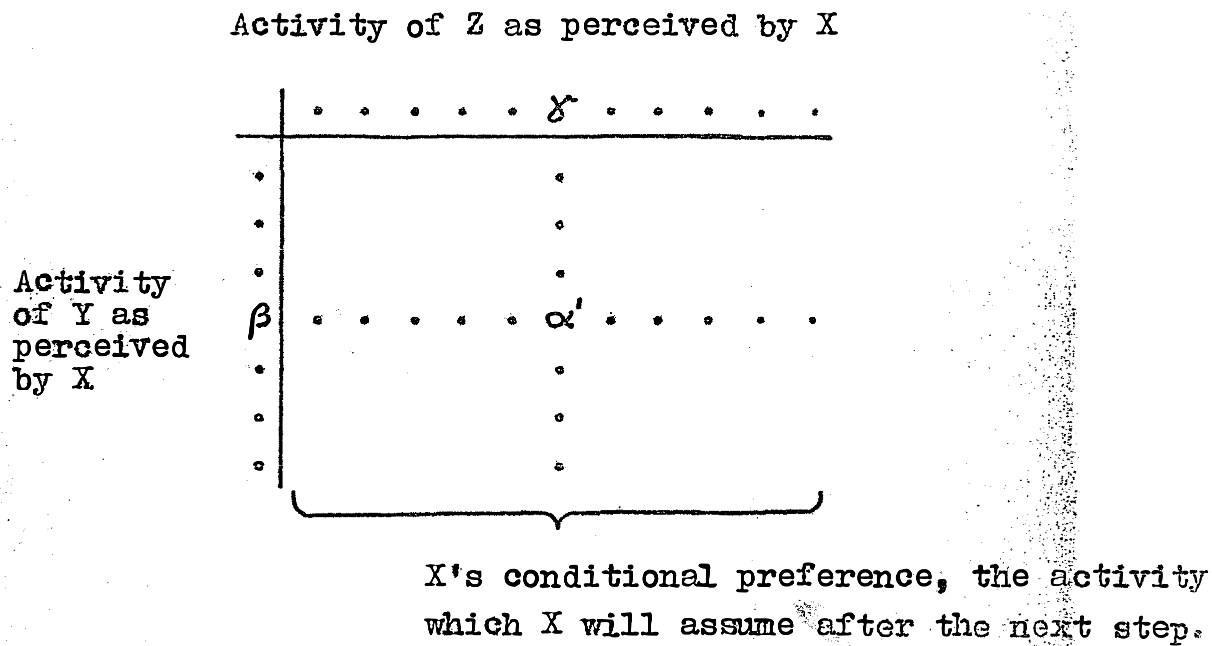
Let a primitive social group be composed of three members X, Y, and Z, interacting with each other through well defined channels of communication in an environmental setting E.

Some of the questions which may immediately arize are:
What constraints does a group network impose on the behavior of each of its component members?
What collectively determined behavior will finally evolve if the communicators are long enough in interaction?
Can stability of the group structure be achieved under the assumed conditions? What are the determinants of various types of stability and how will an alteration of these conditions effect the group process?

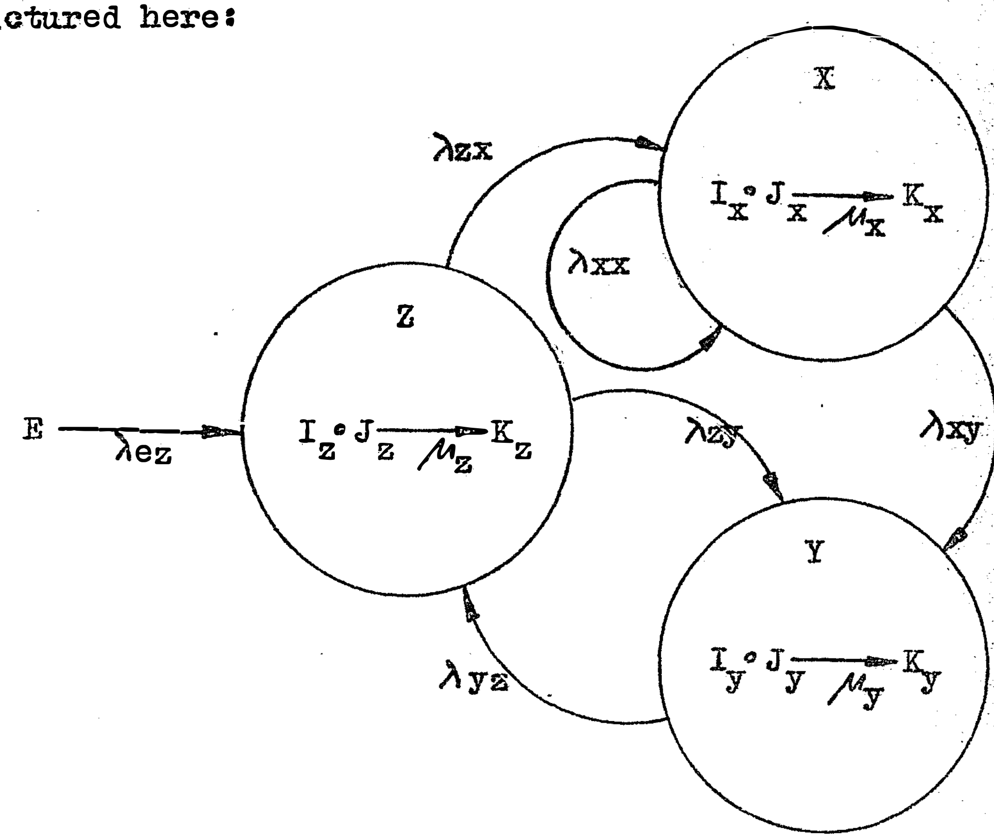
Let the behavior of each of the communicators be characterizable by a set of preferences formulated on the basis of the perceived social context which is composed of the other communicators present activity. A typical preference commitment by one of the communicators could be:

> X: "If Y does β and Z does γ, I prefer to leave the activity α in which I am currently engaged and will do α' "

All such assertions of X's preferential commitments amount in fact to defining a mapping of the general form μ: $I \cdot J \rightarrow K$
Such a mapping can be represented in terms of the following matrix:



The preference commitments of each communicator could then be represented by one of BATIC's components, capable of accepting the respective mapping μ. The communication channels between these components can be realized by the mapping λ_w as defined in the previous chapter. An example of the way a triad of communicators can be represented by BATIC's components is pictured here:



For the sake of simplicity of the illustration it is assumed that each of the communicators correctly perceives what the other is currently doing. This implies that λ is an identity mapping, describing perfect transmission without loss in detail or confusion of perceived activities, and can be omitted from the graphical representation. For the same reason the size n of the repertoire of activities available to each group member may be only three. The concretely specified preferences for the communicators is the following:

Communicator X wants to maintain his activity but does not want to give the appearance of copying the communicator Z. He thus changes if and only if the activity he assumes is identical with the activity of Z. In matrix representation:

$$\mu_x : \quad K_x \begin{array}{c|ccc} & \multicolumn{3}{c}{K_z} \\ & a & b & c \\ \hline a & c & a & a \\ b & b & c & b \\ c & c & c & a \end{array}$$

Communicator Y accepts some sort of majority vote as a criterion for his preference. If X and Z agree in their assumed activity, he will do the same, otherwise he chooses some other activity:

$$\mu_y : \quad K_x \begin{array}{c|ccc} & \multicolumn{3}{c}{K_z} \\ & a & b & c \\ \hline a & a & a & b \\ b & c & b & c \\ c & a & b & c \end{array}$$

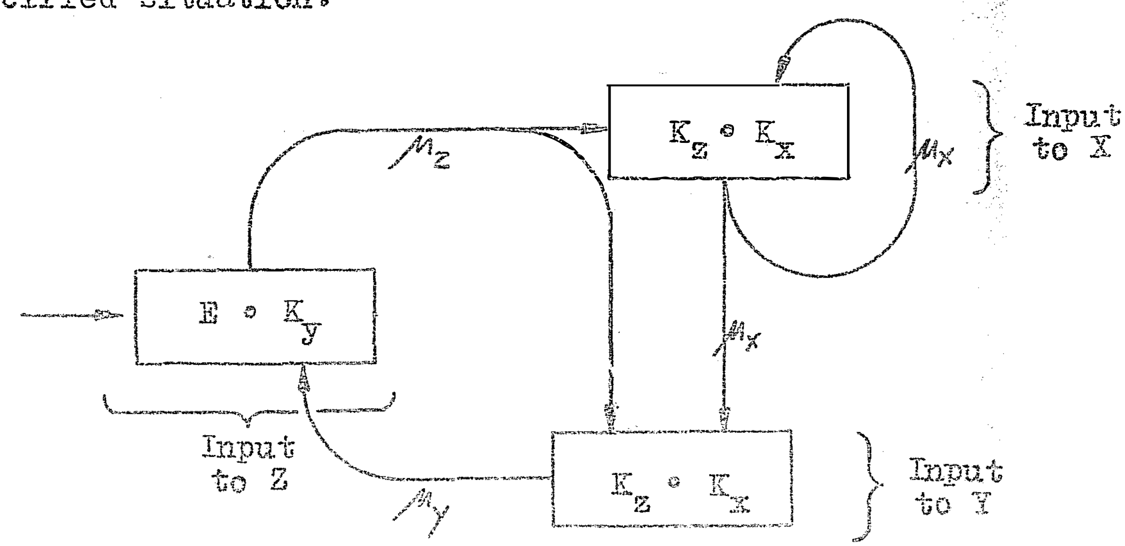
Communicator Z is sensitive to the environmental situation or to the instructions by an experimenter. He does three kinds of things depending on E. (a) he prefers to continue a particular activity whatever X and/or Y does. (b) he prefers some activity which Y does not assume, and (c) he just copies what Y did previously:

M_z : E

	K_y: a	b	c
a	b	b	b
b	c	a	b
c	a	b	c

Although the number of activities available to each group member is unrealistically small, and the assumed preference structure extremely primitive, a prediction of the outcome of the interaction process seems almost impossible when the assumptions are stated only verbally. BATIC would now be capable of demonstrating comprehensively what will happen. If the behavior of the communicators is written in terms of a program which is acceptable to BATIC's units, and if these units are coupled according to the assumed communication network, the group behavior can be made observable and reproducable. This offers the possibility of demonstrating some of the fundamental consequences of communication without going into complex mathematical formulations and suggests answers to some of the questions listed earlier. Even with these simple assumptions the computation and presentation of the implied dynamics can become rather painstaking on paper. A brief description of the solution follows.

Simplified diagram of immediate effects of the above specified situation:

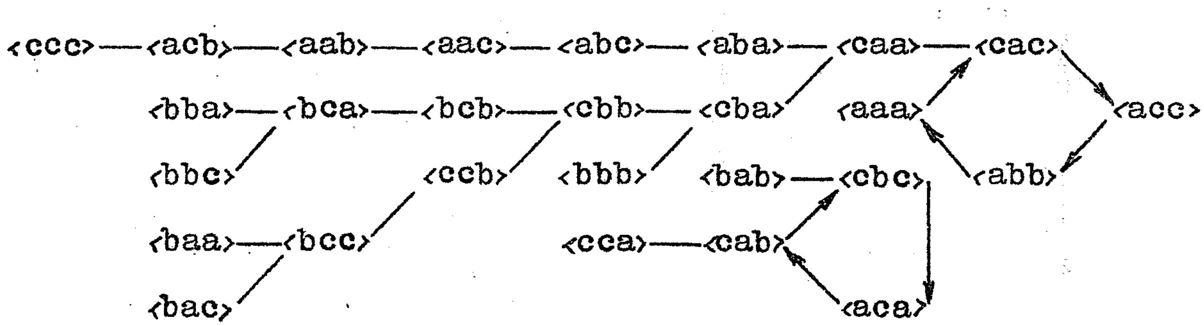


Description of the behavioral consequences:

If the environment E assumes the activity a, i.e. the communicator Z does not accept any information from X or from Y, the group quickly achieves an agreement concerning its collective activity. At least after the second step each member establishes congruency between his preference and his assumed activity.

If E is at b, i.e. the communicator Z is determined to prefer something other then Y does at the moment, such a mutually agreed upon activity can not be accomplished. The pecularities of the communication network and the distribution of preferences forces the group members to change their activity according to a pattern which results in an oscillation of the group behavior. For illustration this behavior may be represented sagittally:

<fgh> is to be read: X assumes "f", Y assumes "g", and Z assumes "h".



The diagram makes clear that the oscillation evolves after at least seven steps. For the communicators Y and Z the change of activities which they assume subsequently ranges over their whole repertoire.

In case E takes c, there are not two equilibria as in the above situations, but five toward which the group may converge depending on their initially assumed activity. In 52% of the cases in which the communicator Z copies the activity which Y occupies, congruence between preference and assumed activity can be accomplished for all members. In the remaining cases the group behavior alternates between two states. The resulting oscillation which imposes on each member a constraint in form of a regular sequence of assumed activities is by far less complex than under the condition that E does b. The finally utilized activities range only over parts of the repertoire of possible activities.

A theoretical interpretation and generalizations from the demonstration seem futile at this point. The contribution BATIC can make for an understanding of the dynamics implicit in given communication structures seem sufficiently clear at this point.

4 Samples of demonstrations

Examples of behavior types which can be demonstrated by BATIC are suggested in this chapter. The demonstrations are represented in terms of the simplified diagrams of immediate effects as used in the previous chapter. That is, notations which would only complicate the picture are omitted. Furthermore the following conventions are adopted:

An arrow without labeled origin pointing to an input I denotes manipulability of that input by an experimenter.

Outputs are denoted K_x, K_y, and K_z respectively.

All sets I and K are observable, sets labeled otherwise are not.

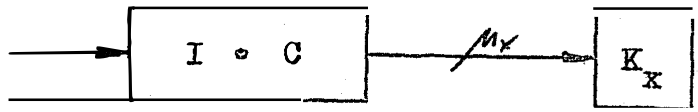
C is reserved to denote a set whose state remains invariant.

All components of product sets are such that their initial state can be determined by the experimenter.

An unnamed arrow denotes an identity mapping λ.

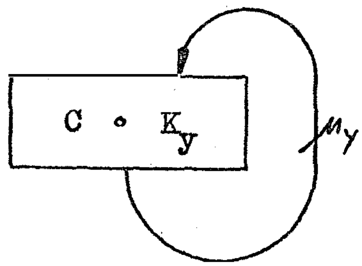
Simple machines:

Simple transducer



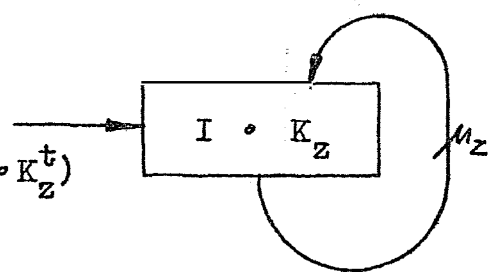
$$K_x^{t+1} = \mu_x(I^t \circ C)$$

Isolated machine



$$K_y^{t+1} = \mu_y(C \circ K_y^t)$$

Machine with input (Ashby's Black Box)

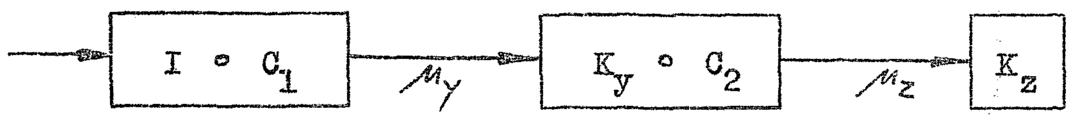


$$K_z^{t+1} = \mu_z(I^t \circ K_z^t)$$

Demonstration of: mapping, simplification, equivocation
the law of irrecoverable variety
confluence
basin
types of stability: stable state, cycle

Coupled systems

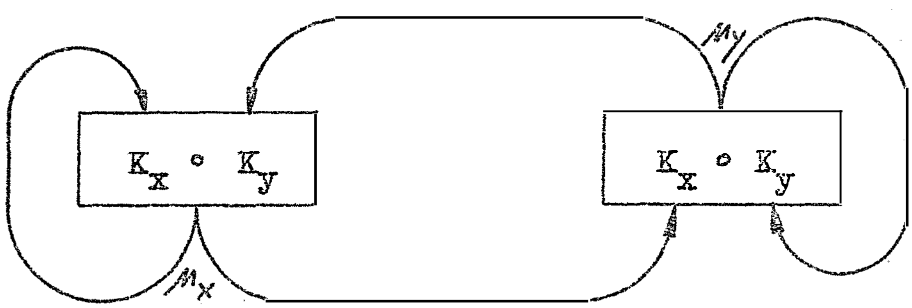
Coupled transducer



$$K_y^{t+1} = \mu_y(I^{t} \circ C_1)$$

$$K_z^{t+2} = \mu_z(\mu_y(I^{t} \circ C_1) \circ C_2)$$

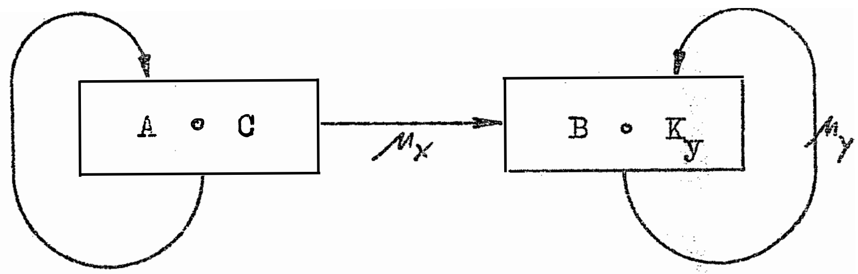
Coupled isolated system



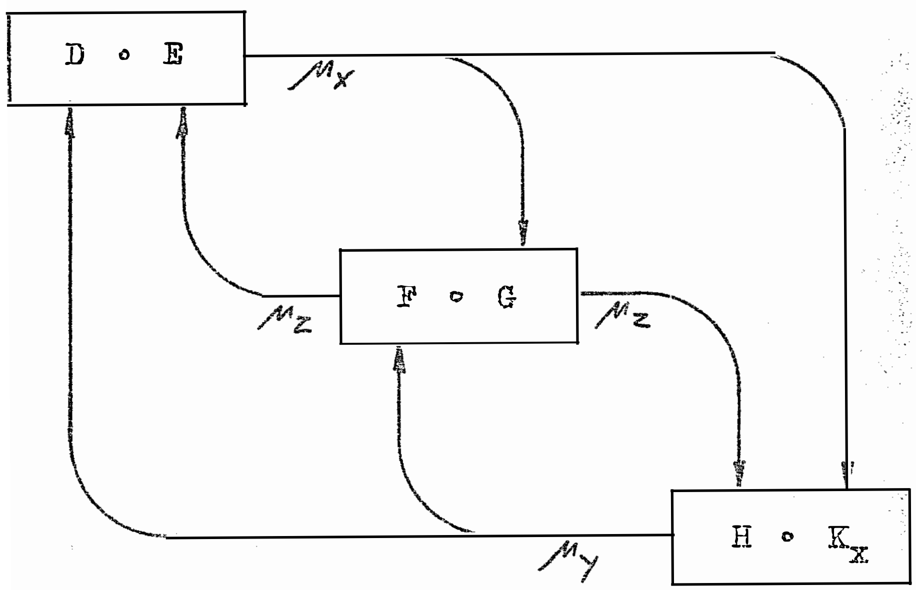
Demonstration of: encoding and decoding
serial transmission
individual equilibria vs. joint equilibr.

Partly observable systems:

Hidden steering

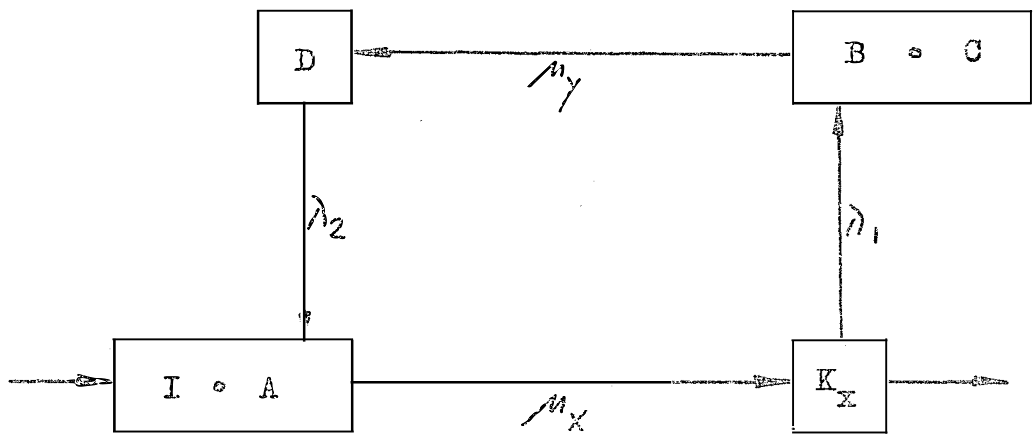


Richly connected network



Demonstration of: memory
hypothetical constructs
invariants and predictability
working from protocol

Simple regulator:



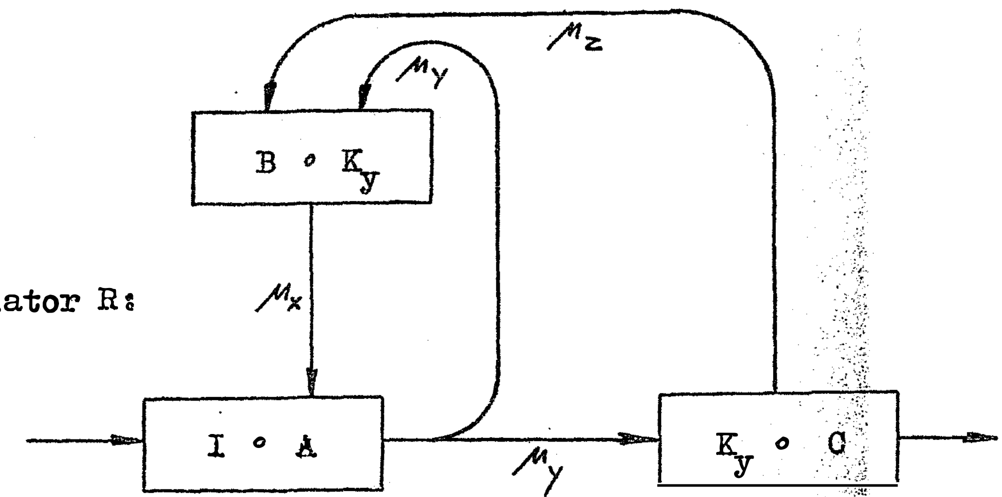
$$K_x^{t+2} = \mu_x(I^{t+1} \circ \lambda_2 \mu_y(\lambda_1(K_x^t) \circ C))$$

Demonstration of: partly observable system
feedback (negative)
memory
equilibrium
state maintenance

Homomorphic systems:

Given:

1) A regulator R:



2) A mapping σ : $K_y \longrightarrow S$

3) A mapping η : $I \longrightarrow H$

4) A mapping $\mathcal{T}$: $H^t \circ S^{t-1} \circ S^{t-2} \circ \ldots\ldots \circ S^{t-n} \longrightarrow S^{t+1}$
which describes the behavior of a machine M.

σ and η is a homomorphism of R into M if:

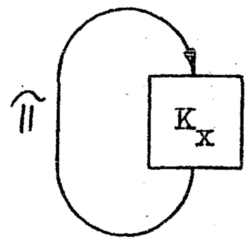
$$\sigma\mu_y(I^t \circ \mu_x(K_y^{t-1} \circ \mu_z(K^{t-2} \circ C))) = \mathcal{T}(\eta(I^t) \circ \sigma(K_y^{t-1}) \circ \sigma(K_y^{t-2}))$$

Demonstration of: isomorphism
homomorphism
analogy
foundations of simulation processes

Markov source:

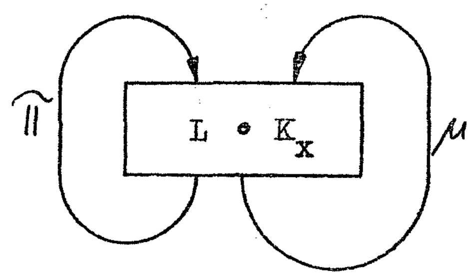
0th order

$$K_x = \widetilde{\Pi}(K_x)$$

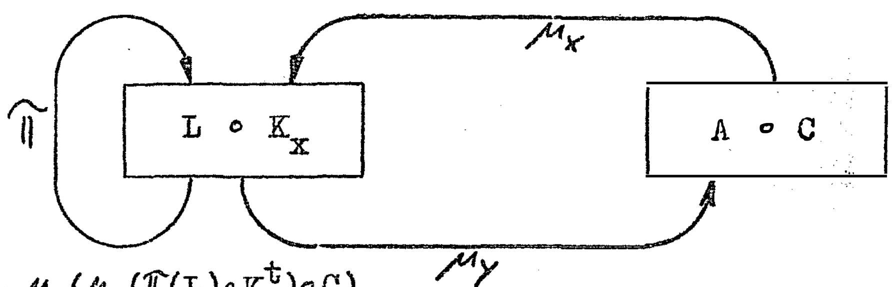


1st order

$$K_x^{t+1} = \mu(\widetilde{\Pi}(L)\circ K_x^t)$$



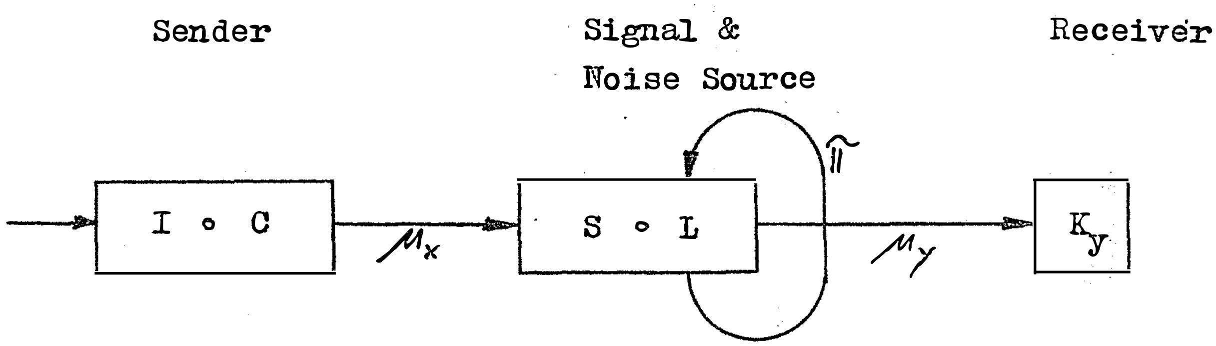
2nd order



$$K_x^{t+2} = \mu_x(\mu_y(\widetilde{\Pi}(L)\circ K_x^t)\circ C)$$

Demonstration of: probability distributions
randomness
regodic and non-ergodic processes
Markov chains
entropie and information
measures of uncertainty

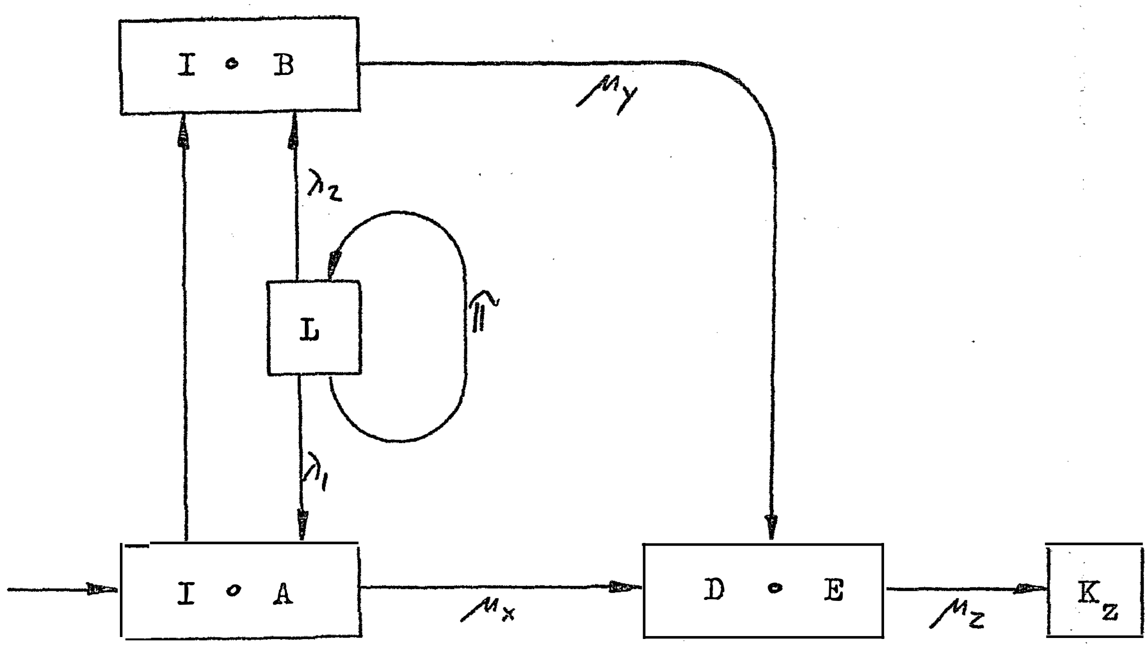
Noisy communication channel:



$$K_y^{t+2} = \mu_y(\mu_x(I^t \circ C) \circ \tilde{\Pi}(L))$$

Demonstration of: decoding and encoding
equivocation
noise
transmission of information
communication
uncertainty measures of transmission

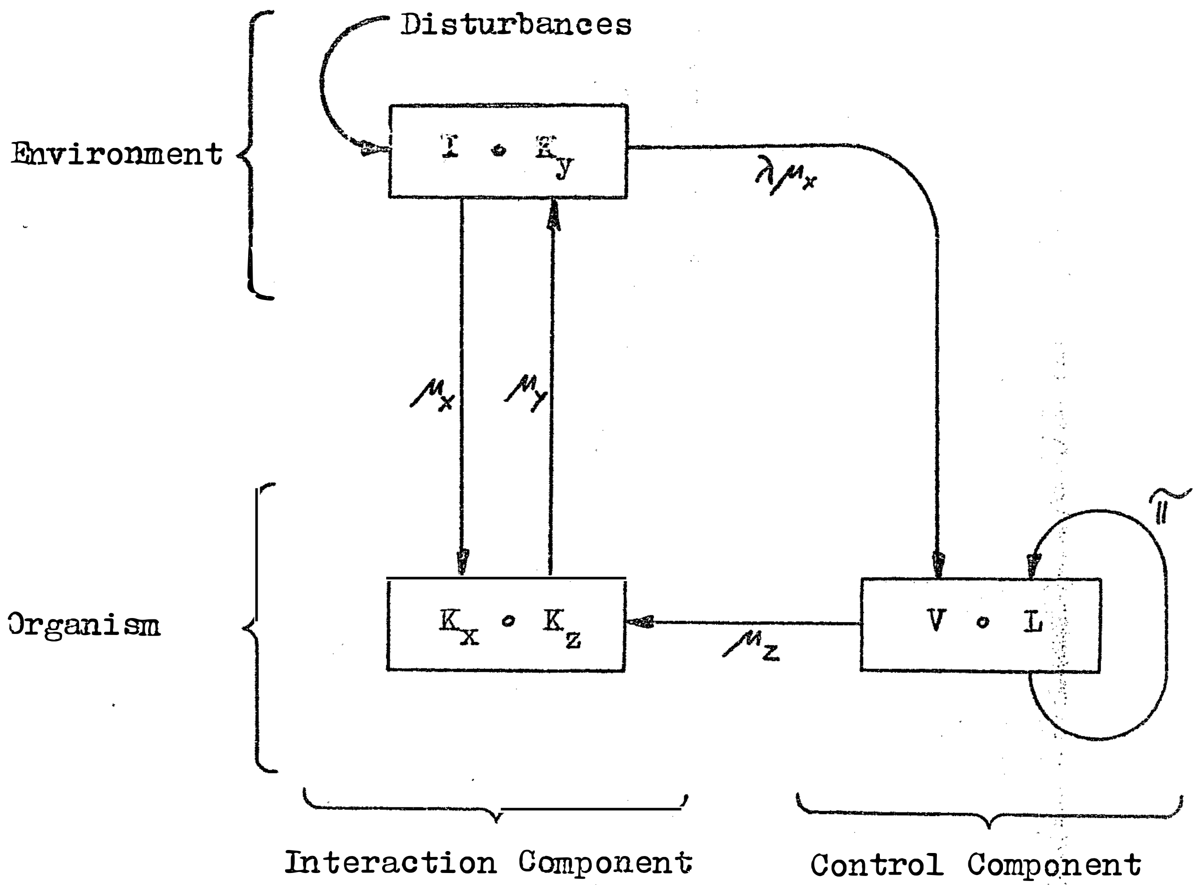
Error correcting channel:



$$K_z^{t+2} = \mu_z(\mu_x(I^t \circ \lambda_1 \widehat{\Pi}(L)) \circ \mu_y(I^t \circ \lambda_2 \widehat{\Pi}(L)))$$

Demonstration of: redundancy
Shannon's 10th theorem
Hamming distance

Homeostatic systems:



μ_z and λ are defined in such a way that $\tilde{\pi}$ becomes effective if and as long as K_x takes a state which is outside the limits acceptable to the organism. $\tilde{\pi}$ becomes ineffective if the "essential values" of the organism are maintained.

Demonstration of: homeostasis
ultra stability, goal maintenance
creativity and survival
adaptation
probabilistic equilibria

5 Some practical considerations

Without going into technical details of the hardware suitable for BATIC, some requirements derived from the intended usage can be formulated here, and a few construction ideas be suggested. The chapter therefore serves as a very general guide line for the design of BATIC's components.

a The number n of binary elements in each of the sets.

n effects BATIC's instructional value insofar as it restricts the variety within which the device is capable of representing various phenomena. The upper limit of n is largely determined by the way a mapping μ is stored and introduced into the respective components. The number of possible mappings μ_u is n^{nn}, a number which should not be underestimated with respect to its technical realizability. If, for instance, an IBM punch card with 12x8o positions were to represent such a mapping, i.e.

$$n^{nn} \leq 2^{92o},$$

n can not exceed 15. For the instructional purpose so far assumed for BATIC, this is perfectly adequate. n should, however, not be smaller than 8.

b The mapping λ_w

These mappings serve only a connectives, as communication links between BATIC's components, and require no special design. They could be realized simply in form of jump-wires, allowing confluencs according to the definition of a mapping.

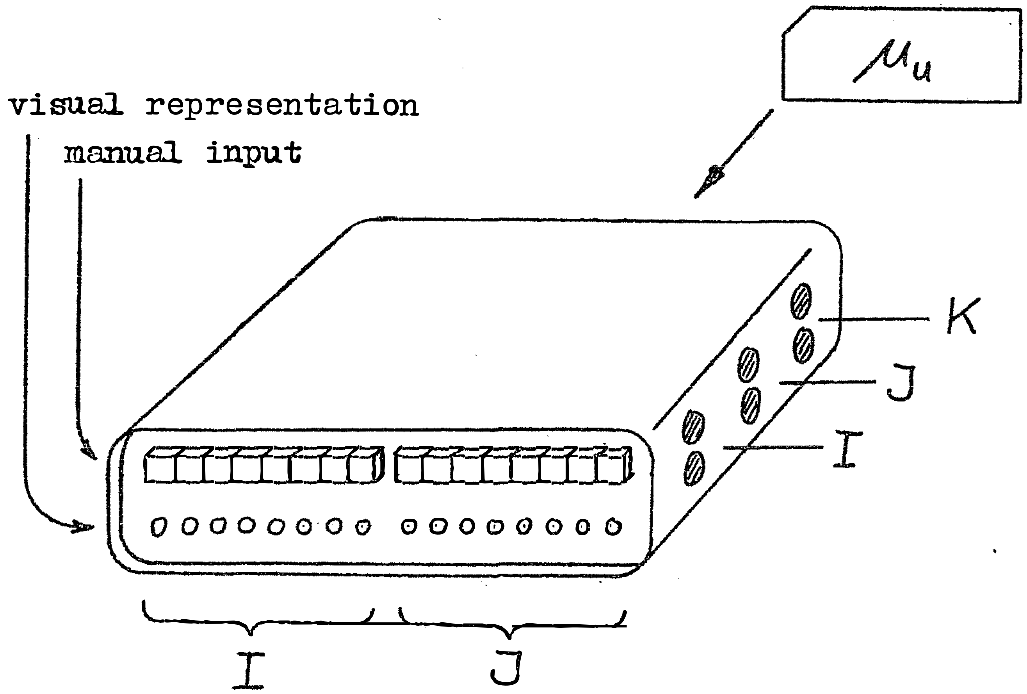
c The unit $I \circ J \longrightarrow K$

Each such units embodies the two inputs, I and J, and the output K, related by one of the set of possible mappings μ_u. In orer to fulfill its minimal objective as a device for demonstrating the behavior of communicatively interlinked components, BATIC necessitates at least three such units.

Each unit takes a "program" which induces a specific mapping μ_u upon its behavior. Whatever the format of this program may be, it is required that it be (1) easily exchangeable such that various demonstrations can be performed without extensive rewiring, and be (2) inexpensively to "write". This seems easily accomplished by any kind of punched card. Such a card could quickly be inserted into the unit under consideration and serve as a program for that unit. If something like an IBM card is used, a low degree of storage efficiency might be quite acceptable provided that a more comprehensive coding schema improves readability and reduces punching errors. When other forms of representing a mapping μ_u are considered, the difficulties arizing in handling the large number of possible programs should not be ignored.

The input I and J for each such unit has to be manipulated in two ways: (1) manually, e.g. by means of control knobs, switches, or even better by an array of push-buttons, and (2) automatically, i.e. by means of a communicative link to one or two other components of BATIC. Note that each set can take always one and only one state at a time, i.e. a former state must be erased as a new one is taken. Since there are two ways of determining the input to a given unit, and since it is required that the experimenter always be able to set the unit's initial state arbitrarily, the manual input has to have preference over the automatic one.

Is is necessary that each input state is represented visually. An arrangement of small lamps may fully satisfy this requirement. The arrangement can consist of two rows, each of n lamps, a square field of $n \times n$ lamps emphasizing the character of the input as a product set, etc. K needs no visual representation on this unit. Needless to say that K must be available at a plug to be conveyed via λ_w to any other input whether of the own or any other unit of BATIC. The unit may be visualized as follows:



d The unit L ⟶ L

The probabilistic transformation $\hat{\Pi}$, defined in L over one step in time is to assume an approximately invariant probability distribution over the states in L. It has already been mentioned that the set of distributions should range from equal probability of all states (perfect randomness) to a distribution in which the probability of one state approaches the value one. As a reasonable minimum, between four and eight such distributions are required for BATIC.

There are numerous ways in which such a probabilistic source can be built. A kind of dice with "variable bias" is an obvious case in point although probably difficult to realize mechanically. A paper tape, bearing punched holes according to the desired frequency of the states, from which the states are selected at random, is a very simple example. More elegant solutions are readily available.

It should be mentioned that a proper selection of the communicative links λ permits not only to rearrange the frequencies within the set of n states, but also to combine frequencies within them additively.

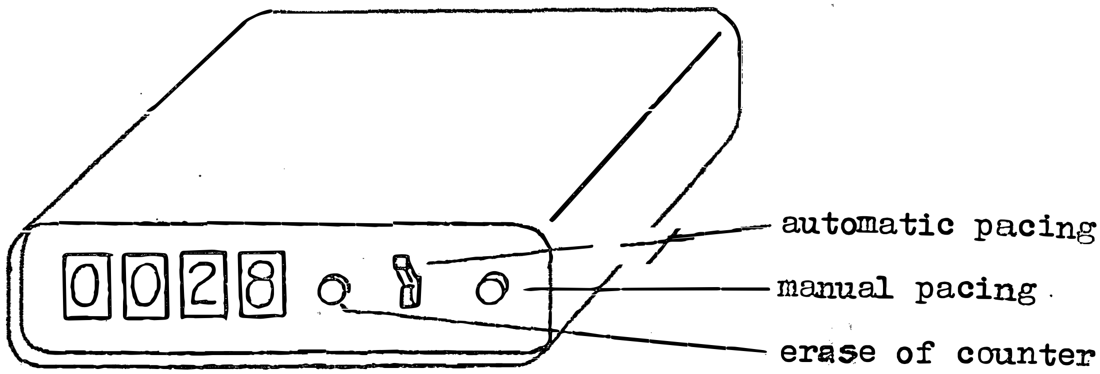
e The pacing component

The mappings μ and π are defined over time. The units which embody one such mapping necessitate coordination so that the step changes occure simultaneously. One of BATIC's components therefore paces the changes each unit is programmed to make.

It is required that the occurence of such steps in time is manually maniplulable. In addition it would be desirable to pace these changes automatically in regular time intervals of about 0.5 to 1 seconds such that the dynamics implicit in communication behavior becomes readily apparent. It is of paramount importance that the change from one state to the next, the occurence of each step be indicated visually or acoustically.

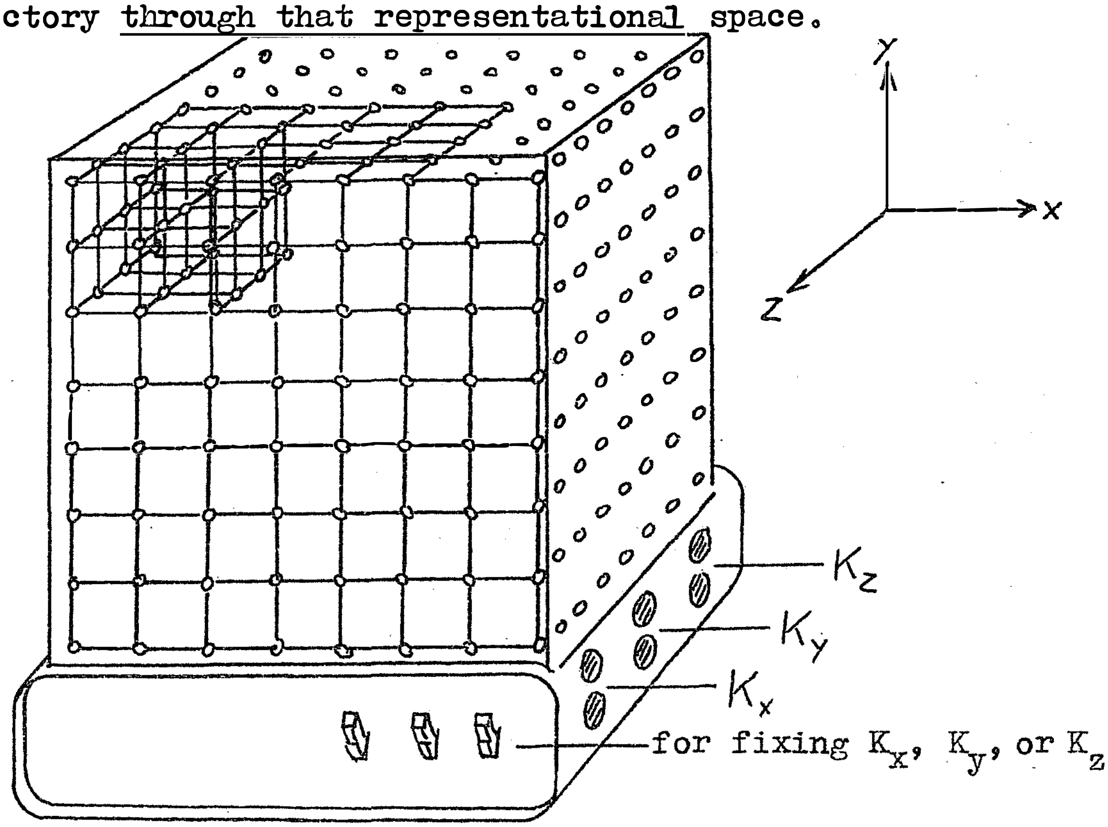
One way of building such a pacing component is to interpolate it with the energy transmission to the coupled units. If the units which embody μ and π are so designed that a short interruption of the energy supply causes the relays to respond and change to the next of the programmed states, then the pacing component is nothing but a switch, when desired operated mechanically. The indication of whether a change has taken place can also be accomplished in numerous ways. Probably most advantageous and sufficiently simple would be a counter the change in state of which could not only indicate that a step occured, but also numerate the states in question. This would greatly assist the protocolling of longer sequences. Such a counter would need not more than three to four digits.

A visualization of this component follows on the next page:



f The representational space $K_x \circ K_y \circ K_z$

When units are coupled it is of great interest to represent their compound state visually, for instance, as an element of the 3-dimensional product set $K_x \circ K_y \circ K_z$ of n^3 light bulbs. Each light then represents a triple state of BATIC. If states with less then three components are to be represented, or a behavior is to be projected onto fewer dimensions, an invariant value must be supplied to the remaining sets. In either case the behavior of BATIC's coupled units will appear as a trajectory through that representational space.



g A possible total view in working condition: