CYCLIC BEHAVIOR OF RANDOMLY GROWING DIGITAL STRUCTURES IN FINITE RANDOM ENVIRONMENT *

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Introduction

The stability of growth and division of very simple organisms has been considered to be a consequence of the internal organization and information content of its structure. An environment is able to influence the stability of growth and division of any given structure only in a neutral or destructive way. Mutations also belong to this category of influences, because they can be considered as a destruction of the given structure and a replacement of that structure by a new one (in some cases "better" then the former but still new). The environment is usually assumed to be purely random; and long cyclic changes of the environment with the periods many times longer than the one-generation lifetime are, in case of simple organisms, abandoned.

The aim of this paper is to point out the theoretical possibility of influencing the life process stability of simple organisms by cyclic changes of random environment. In this case, the organism, the growth-division process, and the "shape" of the organisms are determined not only by information contained in the organism's internal structure, but also by the environment. Moreover, under these conditions the information contained in the internal structure is only the framework and determines not one but the whole class of organisms. In spite of this, and on the basis of information received from the environment the simulated organisms have a unique and identical (with some infrequent random exceptions) "shape" in each generation.

This paper is the presentation of the results obtained by observation of evolutionary sequences of computer models of simple organisms. The simulated models were not the image of the structure of any living organisms, but the image of behavior, i.e., the models had the possibility of growth by absorbing the "creative material substance" from the environment and the possibility of division. The model presented is very abstract. The results obtained show only the possibility of the real existence of observed environmental influences upon living organisms; but in order to have any biological value, the results should be tested in biological experiments.

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Digital Structure and Growth Process

A Digital Structure (DISTRUC) is a sequence of positive, integer numbers (c_i), $i=1, 2, \ldots, I$. The number I is called the length of DISTRUC, and the ith number is called the i-th place of DISTRUC.

A Digital Structure has the possibilty of growth and division. The growth and division will be called a "life" process of DISTRUC. The growth is performed in the sequence of cycles numbered by i, $t=0, 1, 2, \ldots, T$. After completion of the t-th cycle, DISTRUC is denoted as:

$$(c_i)_t$$

and each place of DISTRUC can be denoted as $c_{i,t}$.

DISTRUC $(c_i)_0$ (for t=0) is called the Basic Structure(BASTRUC). If the growth of the structure is successfully finished, that value of DISTRUC is called the Grown Structure (GSTRUC) and denoted as $(c_i)_T$. The number T is called the Lifetime of Structure (LT). The Basic Structure can be chosen arbitrarily, but usually it is determined by the Grown Structure, directly preceding it.

That Basic Structure which is chosen arbitrarily and does not have a preceding grown structure will be called the Initial Basic Structure (IBSTRUC). Each DISTRUC has a generation number g (a positive integer). For IBSTRUC the generation number is always zero (g=0). The GSTRUC determines BASTRUC in the following way:

$$c_{i,0,g+1} = E\left(\frac{c_{i,T,g}}{2}\right) \text{ for } i=1, 2, \ldots I \qquad (1)$$

where E is the Entier function (for positive numbers, the integral part of the number).

The DISTRUC is growing in each cycle $0<t\leq T$ according to the following equations:

$$\begin{aligned} &\text{for all } i,\ i=1, 2, \ldots, I, I+1 \\ &\text{for } V > 0 \qquad\qquad\qquad\qquad (2) \\ &c_{i,t+1,g} = c_{i,t,g} + R(\text{mod}2) \quad \text{for } i-Q>0 \\ &c_{i,t+1,g} = c_{i,t,g} \quad \text{for } i-Q\leq 0 \end{aligned}$$

where R is a random number, and Q and V are determined for each t in the following way:

$$\text{For } t = 0 \qquad Q = 0$$

$$\text{For } t > 0 \qquad Q = \sum_{k=1}^{I} \prod_{j=1}^{k} q_j$$

where q_j is given by:

If $c_{i,t-1,g} \geqslant 2$ $q_1 = 1$, otherwise $q_1=0$ (3)

If $c_{2,t-1,g} \geqslant 4$ $q_2 = 1$, otherwise $q_2=0$ (4)

If $\frac{c_{3,t-1,g}}{c_{2,t-1,g}} > 3$ $q_3=1$, otherwise $q_3 = 0$ (5)

If $\frac{c_{j,t-1,g}}{c_{j-1,t-1,g}} > S$, $q_j=1$, otherwise $q_j=0$ (6)
for $j = 4, 5, \ldots I$

and $V = \prod_{n=0}^{Q} v_n$

where: $v_0 = 1$, $v_1 = 1$

If $c_{2,t-1,g} \leqslant 7$ $v_2=1$, otherwise $v_2=0$ (7)

If $\frac{c_{3,t-1,g}}{c_{2,t-1,g}} \leqslant 3.5$ $v_3=1$, otherwise $v_3=0$ (8)

If $\frac{c_{n,t-1,g}}{c_{n-1,t-1,g}} \leqslant S+D$ $v_n=1$, otherwise $v_n=0$ (9)
for $n=4, 5, \ldots, I$

Comment

For each t as long as $V_t=1$ and $Q_t<I$, the DSTRUC is growing according to (2), and the cycle t is the cycle of growth. If, in cycle t ($t<T$) $V_t=0$, the process of growth is stopped, DSTRUC "dies"; the state is called degeneration; and $T_d=t$ is called the Time of Degeneration. When $Q_t=I$ and $V_t=1$, DSTRUC is grown, T=t and GSTRUC is ready for division.

Conclusion

From the above, it follows that any sequence of positive integers can be treated as an IBSTRUC but that growth is possible only for those IBSTRUCs which may satisfy the conditions of equations (7-9).

After completion of the growth process and before division a GSTRUC may be able to change its length. The growth process (according to (2)) is applied also to the I+1-th place. From the definition of DISTRUC on the beginning of the growth process:

$$c_{I+1,0,g} = 0$$

The GSTRUC changes its length if and only if:

$$A < P < S+D \qquad (10)$$

where:

$$P = \frac{c_{I+1,T,g}}{c_{I,T,g}} + \frac{D}{2} \; R(\text{mod } 2), \qquad (11)$$

P is called the expanding coefficient,
A is called the stability threshold, and
S and D are parameters determined in the beginning of the process.

If condition (10) is fulfilled

$$I_{g+1} = I_g + 1 \qquad (12)$$

and

$$c_{I,0,g+1} = E\left(\frac{c_{I+1,T,g}}{2}\right) \qquad (13)$$

otherwise

$$I_{g+1} = I_g \qquad (14)$$

Parameters of Process

The set of parameters which describe the growth and division of DISTRUCs can be divided into two subsets:

a. parameters which describe the growth and division process of an individual DISTRUC,
b. parameters common to all DISTRUCs of common origin.

To (a) belong:

1. Sequence (c_i)
2. Length of DISTRUC-I
3. Lifetime-T, or degeneration time-T_d.
4. Expanding coefficient - P.

The sequence (c_i) and length I will be called the "external characteristic" or "shape" of DISTRUC.

To (b) belong:

1. S - basic parameter of growth (6)
2. D - Relative interval of regular growth (9), (11)
3. A - stability threshold (10)
4. L_I - assimilation coefficient
5. L_p - length coefficient

The assimilation coefficient determines the possible speed of DISTRUC growth and also limits the growth of the larger places of DISTRUC in each cycle according to the following relationship:

$$L_I c_{2,0,s} \geqq \sum_{i=1}^{I+1} (c_{i,t+1,g} - c_{i,t,g}) \qquad (15)$$

(c_{i+1} is described by (2)).

The length coefficient determines the maximum length of the DISTRUC that can be accepted by the next generation. It does not influence single length changes of a given DISTRUC, as this length is determined for single DISTRUC by its expanding coefficient and the stability threshold. For each cycle:

$$I_{max\ (accepted)} \leq L_p c_{3,0,g} + 1 \qquad (16)$$

Example:

$L_p = 1$

in generation g, $P_g > A$, $I_{g,0} = 5$, $c_{3,0,g} = 4$

generation g+1, $P_{g+1} \leq A$, $I_{g+1,0} = 6$, $c_{3,0,g+1} = 4$

g+2, $I_{g+2,0} = 5$, (no transmission of length I=6)

but in g+2, $I_{g+2,0} = 6$, (does transmission of length exist) when $c_{3,0,g+1} = 5$ or $P_{g+1} > A$.

From (15) and (16) it follows that the 2nd and 3rd place of BASTRUC influence the possibility of growth speed and the maximum length of DISTRUC.

Environment

The environment is a finite sequence of random numbers (from random number tables). The random sequence is used successively in a cyclic way, starting at an arbitrary position in the sequence. The length of the random sequence N has to be:

$$N << 4 \sum_{g=0}^{G} \sum_{i=1}^{I} c_{i,0,g}$$

This means that N can be arbitrarily large if the number of generations G observed as an evolutionary chain in the experiment is sufficient, i.e., if the experiment lasts sufficiently long.

Behavior of a Single DISTRUC

The only IBSTRUC used in the experiment is:

$c_{1,0,0} = 1$

$c_{2,0,0} = 2$

$c_{3,0,0} = 4$

The I of this IBSTRUC is always 3 (I=3). This IBSTRUC (and other DISTRUCs) will be denoted as:

1, 2, 4

The I value can be read directly from the notation.

The DISTRUC with I=3 is the Minimal DISTRUC i.e., the minimal "living" structure. This follows from (15) and (16) as the structure with I<3 has no possibility of regular growth and division. The value I=3 can be considered as a threshold of "life".

From equations (3) through (5) it follows that the values on places i=1, 2, 3 do not depend on the S or D parameters. Thus, the growth of these places is exactly the same for all DISTRUCs, which could be input into "life" experiments. It underlines the assumed common base for "life" processes in all possible structures.

All parameters which characterize individual structure have the possibility of random changes during the growth process. All these changes influence the possibility of successful growth of DISTRUC; and if the DISTRUC becomes grown (and divides), some of these parameters influence the next generation. The degeneration, which may occur as an effect of random growth, is a selecting factor. The process of changes and selections in the generation sequence of DISTRUCs will be called evolution.

Comparison of Digital Structures

The comparison methods will be introduced for BASTRUCs, as BASTRUC could be considered in some respects as the standard form of DISTRUC. There are four degrees of similarity:

1. Origin similarity (OS)
2. Similarity (SI)
3. Identity (ID)
4. Internal identity (II)

These degrees of similarity could be described as follows:

1. Two DISTRUCs (c_i) and (C_i) have OS if more than half of the places (having numbers larger than 3) if $c_i \neq 0$ and $C_i \neq 0$

   $$c_i = C_i$$

2. Two DISTRUCs have SI if they have OS and have the same length.
3. Two DISTRUCs have ID if they have SI and if

   $$c_i = C_i \text{ for } i=1, 2, \ldots I$$

   ID is the identity of "external characteristics".
4. Two DISTRUCs have II if they have ID and if:
   a. $T_C = T_c$
   b. $P_C = P_c$

Internally identical DISTRUCs have only different generation numbers.

Experiments

As was mentioned earlier, all experiments were started for IBSTRUC: 1, 2, 4; and only descendants of the structure with this external characteristics, which came into existence in the growth process, were passed on to the further experiments. The evolution was observed for DISTRUCs with the following parameters:

- S: 0.9, 1.2, 1.5, 2.0, 3.0
- D: 0.5, 0.6
- A: 0.8, 1.0 (A=1.0 for S = 3.0 only)
- L_I: 1, 2, 3, 4
- L_P: 1, 2, 3, 4
- $I \leqslant 9$

Two different repetition sequences of random numbers were taken as environmental simulators; and, for both, N = 100. The program was written in FORTRAN PI, part of the Basic Time Sharing System (BTSS) II for the RCA Spectra 70/45. Over two thousand single growth processes were observed. The most interesting fragments of results are presented on Figures A-P.

Description of Figures

The generation numbers g are on the abscissa (g=0 indicates the IBSTRUC). The parts of different evolution sequences are separated by gaps. The small arrows under the abscissa indicate the environmental perturbation (EP) simulated by a skip of several random numbers in random sequence. The values of P(g), T(g), and $c_{i,0}(g)$ (for i=1, 2, ..., I - dotted lines) are presented on the same scale.

The T(g) line is ended in one of three possible ways:

1. With named arrow (e.g., D22). This indicates degeneration of DISTRUC (after 22 cycles in the example).
2. With arrow without a name. This is possible for DISTRUCs with I=9, and means that DISTRUC expanded out of the range of observation (I=9 is the technical limitation caused by an enormous increase of computer time for larger structures, especially for S>1.5).
3. Without arrow. This is only for periodic changes described further.

The P(g) (upper part of the diagrams) is presented in another scale and the stability threshold (dashed, constant value line) is drawn there.

If the single value P or T is out of the scale range, the line is going up out of the scale and the proper value is written for that point. In c_i diagrams except dots (and short lines connecting occasionally more distant dots) the symbols X and + are used. The X means that the I value was changed, and the new c_i started. The + means that two different c_i of the same DISTRUC have the same value.

The figures contain 16 evolution sequences denoted alphabetically as A-P. These sequences are not a representative sample of experimental data, but were selected as a set of examples.

Interpretation

In all experiments, for a sufficiently large number of generations G, one of three possible states were always achieved.

1. Degeneration
2. Periodic evolutionary sequence
3. Number of places I > 9 /out of the range of observations./

The existence of state 3 is the consequence of the technical limitations of experiments (enormous increase of computer time for one generation). It is possible, however, to consider the existence of only the first two states on the basis of following recursive reasoning. It is possible by limiting the value of the length coefficient (L_P = 1) to conduct the experiments only for $I \leqslant 6$. The evolutionary process in this condition has the same qualitative properties as evblution with L_P= 2, or larger.

Working hypotheses: if the value of I is unlimited, there exist only two final states of evolution changes:

1. Degeneration
2. Periodic sequence.

Let us determine first the periodic sequence The evolutionary sequence can be defined as periodic only for a stationary environment (i.e., random numbers input to the experiment in a successive cyclic way (without skips)).

The evolutionary sequence is periodic in a stationary environment if, for certain IBSTR $(c_i)_{0,g'}$, there exists a positive integer F > 0, of such value that:

$$(c_i)_{0,g'} \text{ is II with } (c_i)_{0,g'+kF} \qquad (18)$$

where k = 1, 2, ...

The number F is called the evolutionary sequence period.

If the sequence is periodic, condition (18) is true for each DISTRUC of number g, g'<g<g'+F.

The periodical sequence could start for DISTRUCs of any length. The existence of cyclic behavior of evolutionary sequence is the result of cyclic character of random environment. It is important, however, that length of random sequence N does not influence this type of behavior. It follows, from estimation of number of random environment cycles for one evolutionary sequence period, that this number can be found as:

$$R_C = \left\lceil \frac{4 \sum_{g=g'}^{g'+F-1} \sum_{i=1}^{I} c_{i,0,g} + \frac{c_{I,0,g}}{2}}{N} \right\rceil \qquad (19)$$

where ⌈ ⌉ means "round off to the nearest integer".

For observed periodical sequences A-P, R_c has the following values:

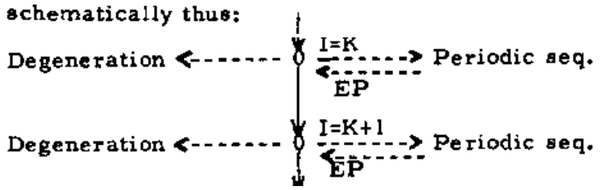
Seq:	B	D	F_1	F_2	G	H_1	H_2	I	M	N	O	P
F:	2	1	2	4	3	8	2	2	8	1	1	1
R_c:	1	3	16	33	10	8	6	6	41	1	32	32

For $R_c > 1$, the environment could be considered as the random number sequence of length:

$$N' = R_c N$$

containing the subcycles of length N.

The periodical evolutionary sequence lasts in a stationary environment, without perturbation, infinitely long. The external perturbance (usually phase shift of random sequence) breaks the periodicity of the sequence. Then the elements of the evolutionary sequence are changing in a random, environmentally unoriented way. The degeneration is a selecting factor, which eliminates nonadaptable structures. Other structures could adapt to the environment in creating another (or the same) periodic sequence after EP. N and O are the examples of finding the periodic sequence of the same period. The end of N is an example of degeneration of a periodic sequence after EP. The influence of External Perturbance can be presented schematically thus:



The expansion and nonperiodic changes could be considered as an unstable state. The example of a long lasting unstable state is P.

It should be noted that the assumption (17) concerning the environment is weak, however, in spite of this, the periodic sequences were always observed after sufficiently long observation without degeneration. If the period sequence is treated as a stable state achieved by the evolutionary sequence it is evident that not all stable states have been founded by one sequence. After each expansion, (in the absence of degeneration) DISTRUC may find the stable state for the just-obtained I value, or may continue the expansion process. The probability of these behaviors are different for just expanded or nonexpanding DISTRUCs.

Any expansion increases the expanding coefficient in the next generation and this property is recursive. That is the reason for the rapid expansions observed in C, F, or H. If the j is a current value of I the above theorem could be formulated as follows:

Theorem 1: for every j, expansion in g generation increases the expected value of P_{g+1}^{j} in the next generation.

This is true as well in the case of expansion limited by the L value.

The beginning of N is an example of this situation. Another two theorems can be proved:

Theorem 2: For S > 1 for sufficiently large I, the probability of degeneration in two DISTRUC which have OS differs arbitrarily little.

Theorem 3: For S > 1, the nonrandom part of P (j) goes to zero with the increase of j.

The conclusion from Theorem 2 is important, since it means that for DISTRUCs of sufficient length the effectiveness of selection is the same. Limitation of a DISTRUCs length (for any given stability threshold > —) is a conclusion from Theorem 3.

Conclusions and Discussions

From the experiment, it follows that randomly growing digital structure could achieve unchangeable "shape" in each evolutionary generation. This unique "shape" achievement is obtainable in spite of the fact that the "shape" of the digital structure is not uniquely predetermined by its internal structure.

The evolutionary sequence of digital structures could behave in a regular way, i.e., the sequence is changing periodically (in the particular case each generation is exactly the same). The periodic changes of evolutionary sequence is the only stable state of an evolutionary sequence. Any non periodic changing evolutionary sequence will achieve this state after a sufficiently large number of generations or X degenerate.

The behavior described above was obtained from a random supplement of creative materials from the environment. The only condition for the environment is that there has to be some cycle arbitrarily long, but many times shorter than the life of evolutionary sequence. From the point of view of one generation, however, (especially for F > 1), the environment could be considered as absolutely nonperiodic and random.

If the extrapolations of this observed behavior could be made to the living organisms, it could be some basis for interpretation of the beginning of life. According to the experiments, a preliving structure could have only the possibility of random (with only the "frame" determined) growth and division. The information to guarantee stability could be achieved from environment. Such a structure would be relatively simple.

Acknowledgement

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Abstract

Computer experiments with a model of a randomly growing structure with the possibility of division are presented. In agreement with the set of conditions, the growing structures are considered as evolutionary sequences.

The randomly growing digital structure could achieve unchangeable "shape" in each evolutionary generation in spite of the lack of complete predetermination of this "shape". The effect was obtained by random supplement of creative materials from the environment. The environment was assumed as random, finite, and repetitive in a cyclic way. For this environment the only stable state of evolutionary sequence is a periodic sequence (in a particular case, the same "shape" in each generation). Other sequences have either to degenerate or, after a number of nonperiodic charges, become periodic.

The model, results obtained from the computer and interpretation are presented.

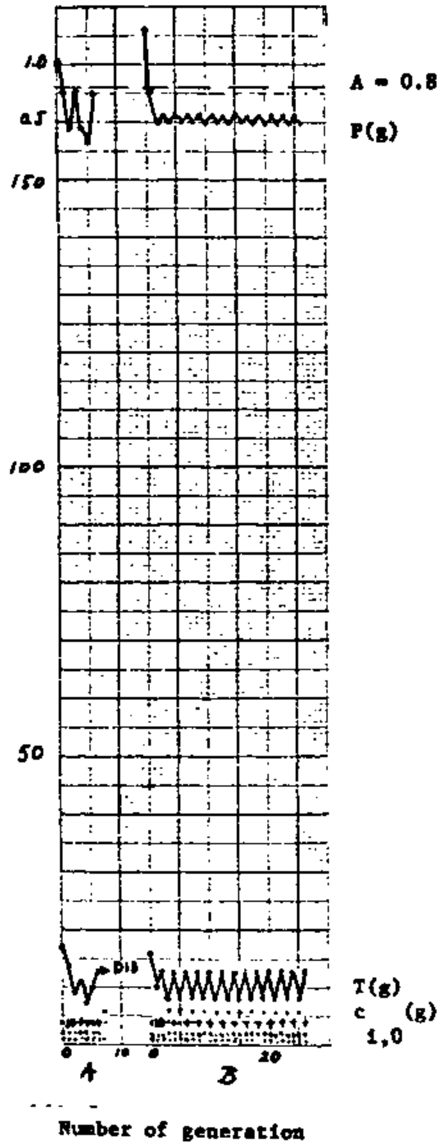


Fig. A - B

Parameters : S=0.9, D=0.6, A=0.8, $L_I = L_P = 3$

Comment :

Fig.A : IBSTR. Degeneration in several generations. Typical for that value of S.

Fig.B : IBSTR. The only observation of periodical changes (P=2) for S=0.9

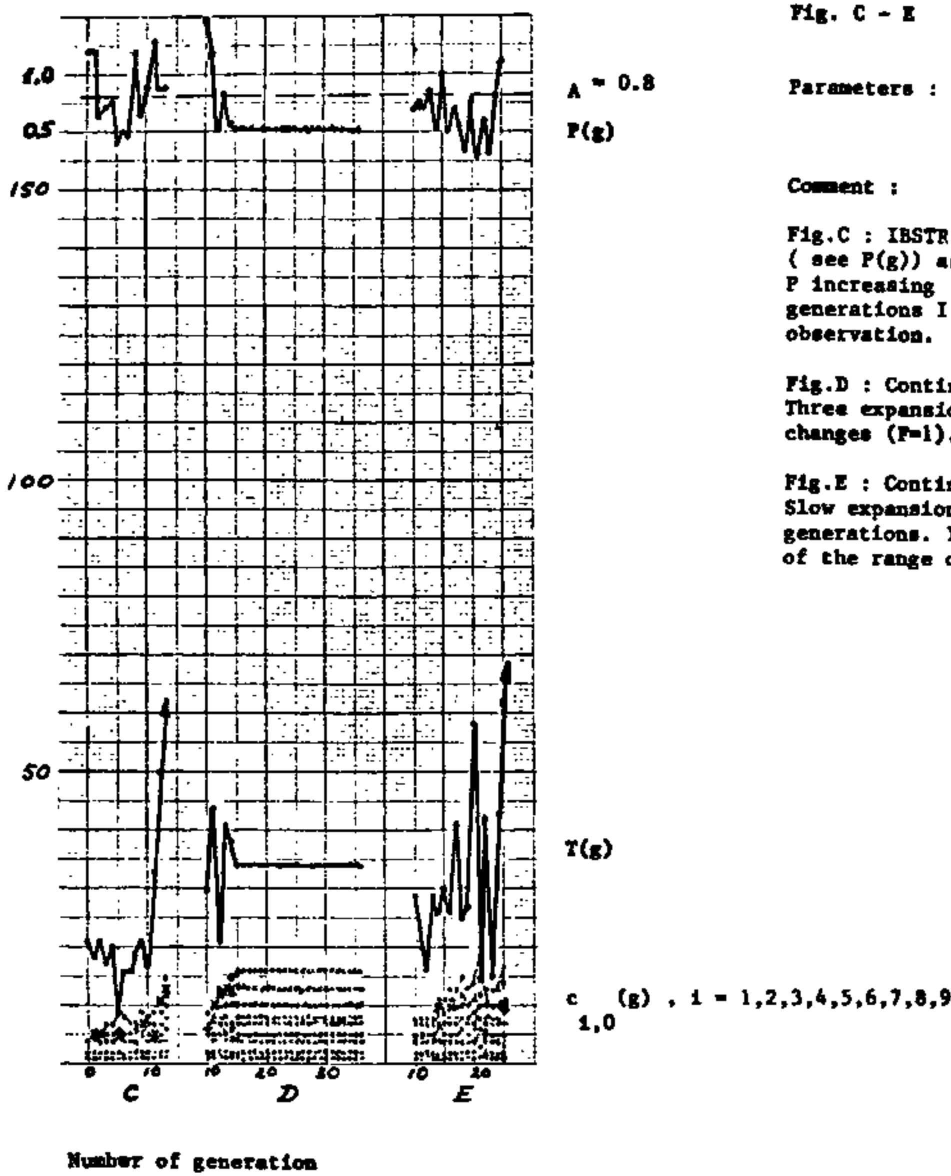


Fig. C - E

Parameters : S=1.2, D=0.5, A=0.8, $L_I = L_P = 3$

Comment :

Fig.C : IBSTR. Rapid successive expansion (see P(g)) as a consequence of recursive P increasing (see Interpretation). In 13 generations I went out of the range of observation.

Fig.D : Continuation of C. 10th generation. Three expansions and after that periodic changes (P=1).

Fig.E : Continuation of C. 10th generation. Slow expansion. Three expansions for 15 generations. In 25th generation I went out of the range of observation.

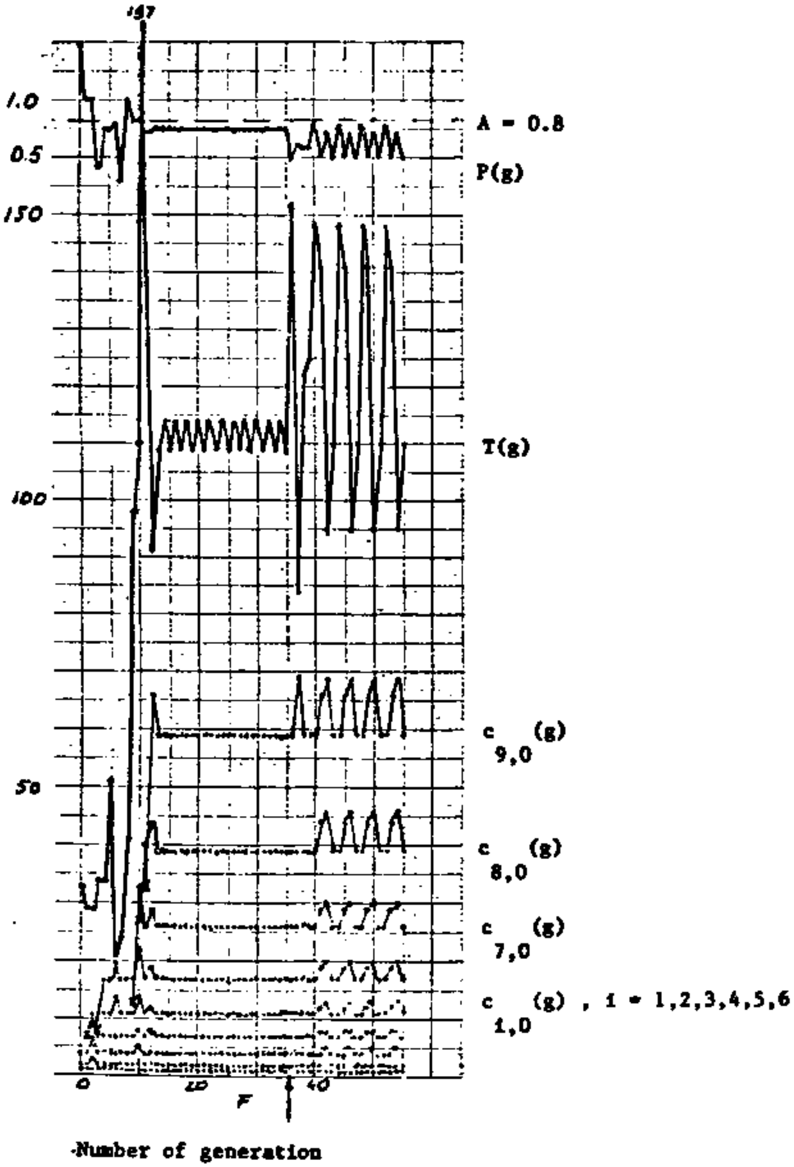


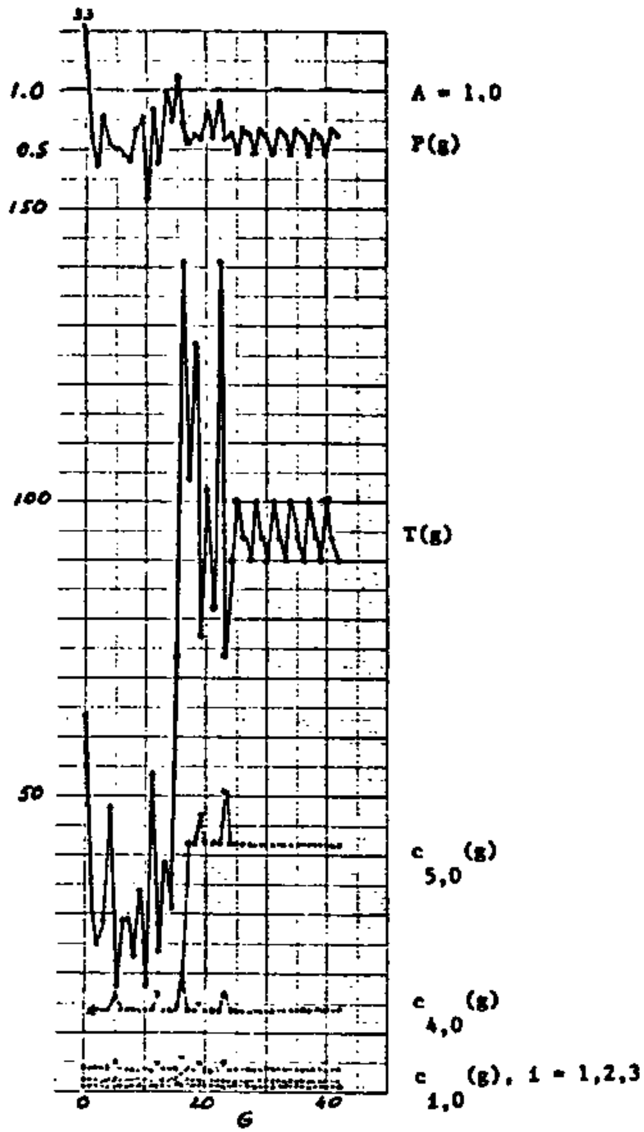
Fig. F

[redacted]

Parameters : S=1.5, D=0.5, A=0.8, L_I=4, L_P=3

comment :

Fig.F : IBSTR. Rapid expansion to I=6 (with recursive P increasing). In 13th generation periodic changes start (F=2). In 36th generation external perturbation (EP) and short nonperiodic changes without expansion. In 40th generation new periodic changes start (F=4)



Number of generation

Fig. G

Parameters : S=3.0, D=0.5, A=1.0, L_I=3, L_P=1

Comment :

Fig. G : IBSTR. Long nonperiodic changes with two separate expansions occur(generations: 0 to 25). In 25th generation periodic changes start (P=3).

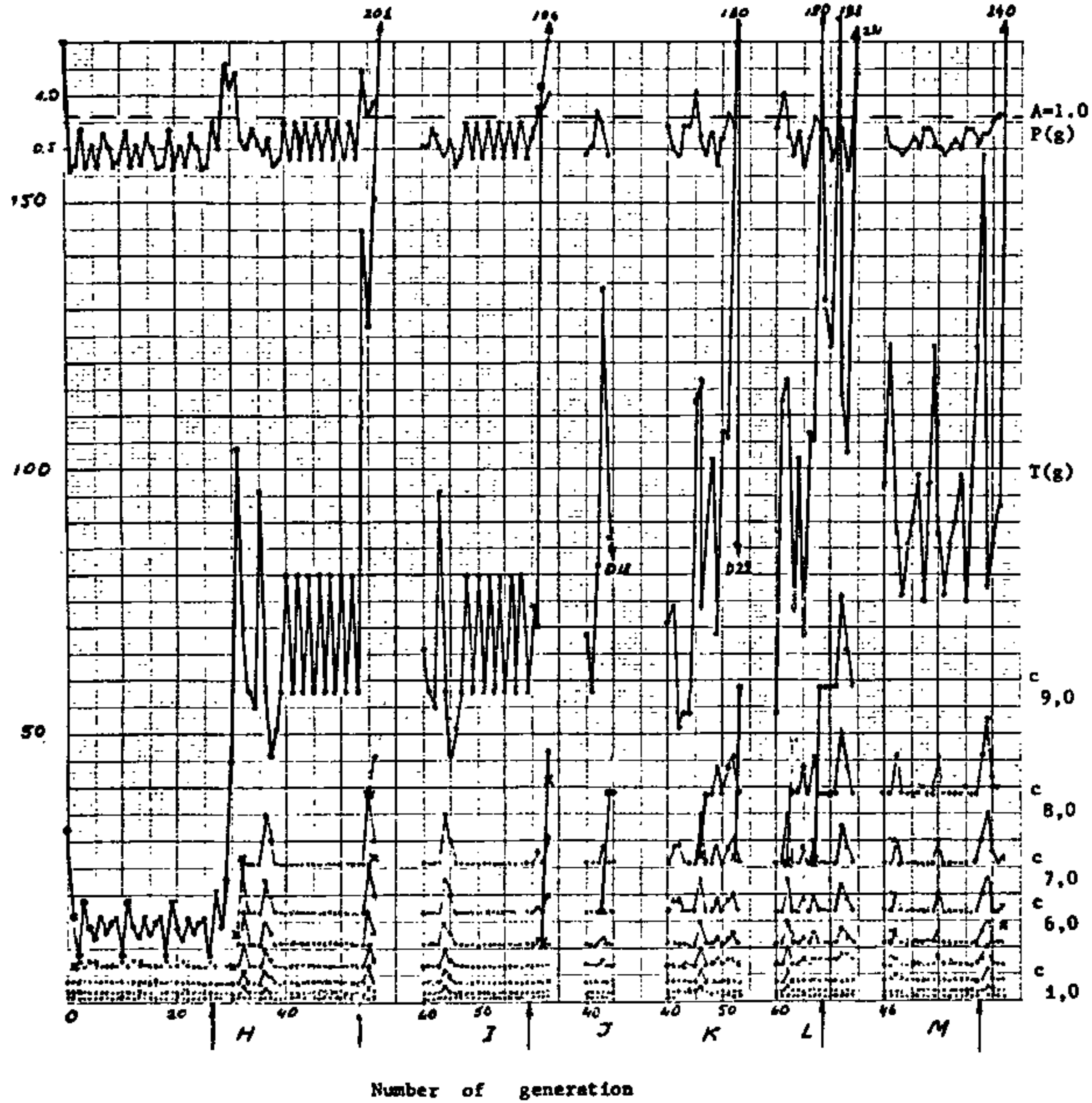
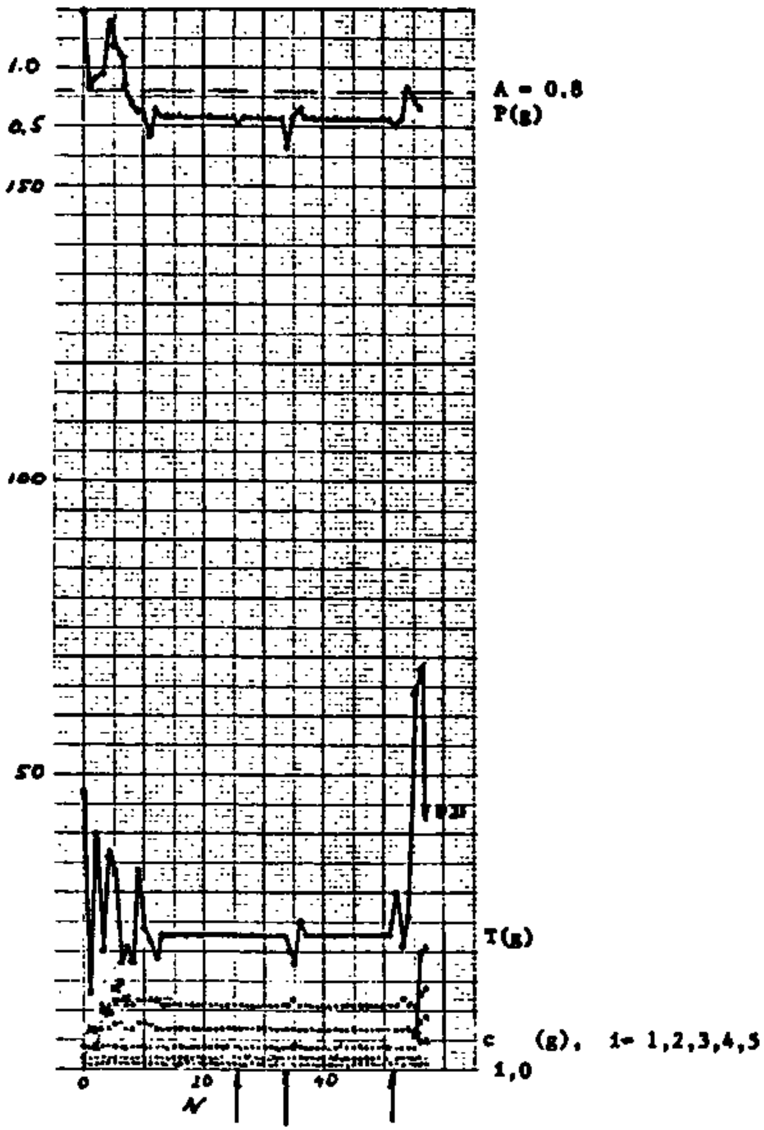


Fig. H - M

Parameters:
S=1.5, D=0.5, A=1.0, L_I=4, L_P=3

Comment:
Fig.H: IBSTR. After a single expansion periodic changes occur (F=8). In 26th generation EP, rapid expansion to I=7; and from 39th generation periodic changes (F=2); in 54th generation EP, and rapid expansion out of the range of observations.
Fig.I: Continuation of H 40th generation; nonperiodic changes and from 42nd -periodic (F=2). In 59th EP and rapid expansion out of the range.
Fig.J: Continuation of H 40th generation. Degeneration in 45th. Compare with fig.I.
Fig.K: Continuation of H 40th generation; nonperiodic changes with two separate expansions. Degeneration in 53rd.
Fig.L: Continuation of H 40th generation; nonperiodic changes with two separate expansions (compare with K). In 48th generation EP ; nonperiodic changes. In 54th generation out of the range.
Fig.M: Continuation of L 46th generation. In 47th, periodic changes start (F=8). In 57th EP and expansion out of the range of observation.



Number of generation

Fig. N

Parameters : S=1.5, D=0.5, A=0.8, L_I=4, L_P=1

Comment ;
Fig.N : IBSTRUC. Limited expansion. The P(g) function over the stability threshold (8 times at the beginning) without creation of new iplaced in DSTRUCTs. In 12th generation periodic changes start (F=1).In 25th generation L_P changed to two (L_P=2) and EP. No effects (only small change of P). In 33rd generation L_P changed to one (L_P=1) and EP. Return to the same periodic sequence in 4 generations. In 51st generation EP. Expansion in 55th generation (possible as c_3=5) and degeneration in 57th generation.

* EP - external perturbation

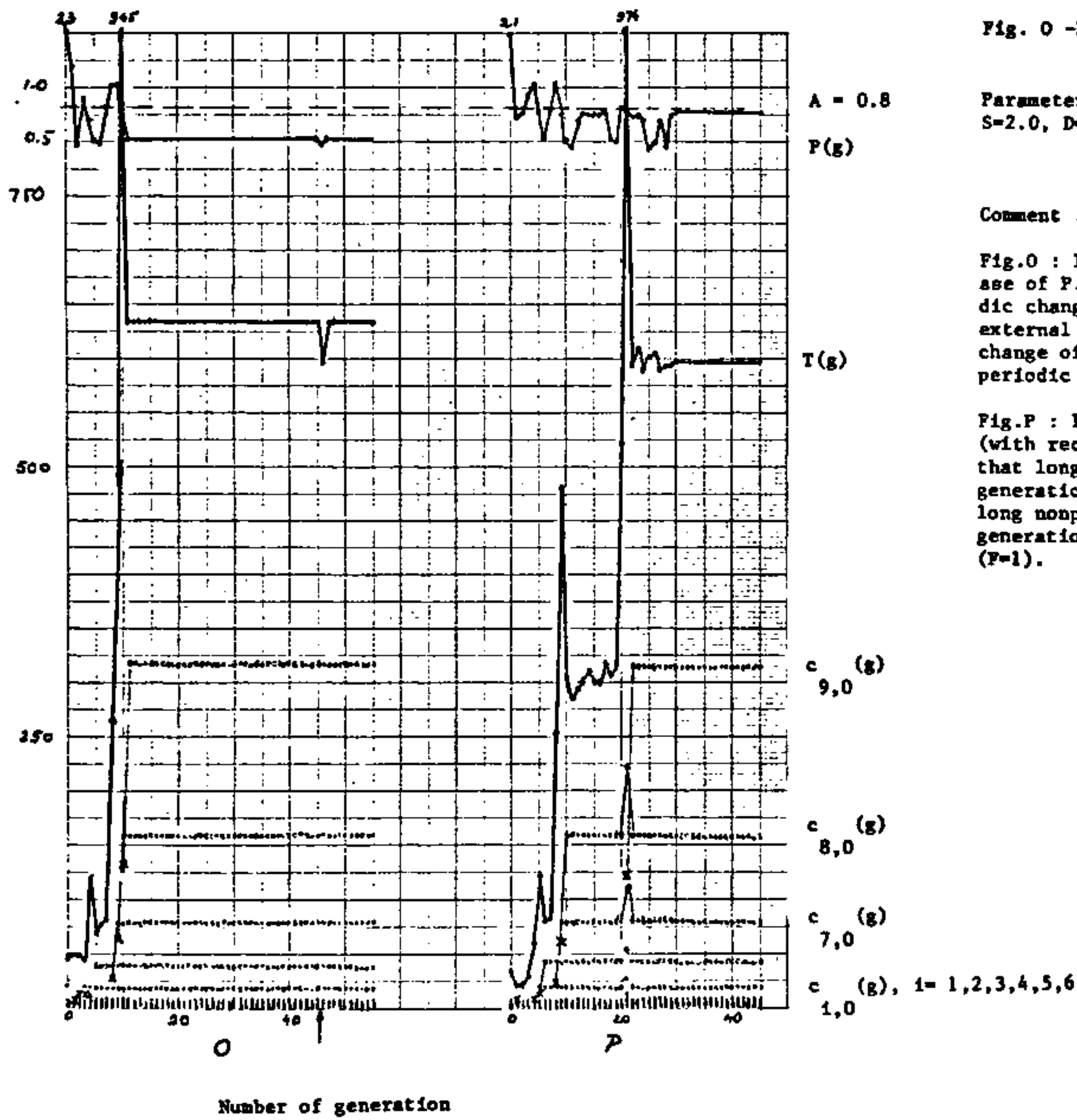


Fig. O -P

Parameters :
S=2.0, D=0.5, A=0.8, $L_I = L_P = 3$

Comment :

Fig.O : IBSTR. Rapid expansion with incre ase of P. In 11th generation start perio dic changes (F=1). In 45th generation external perturbation (EP). Only single change of P and T and return to the periodic sequence

Fig.P : IBSTR. Rapid expansion to I=8 (with recursive P increasing). After that long nonperiodic changes. In 19th generation single expansion to I=9, long nonperiodic changes and in 30th generation starts periodic sequence (F=1).