# Life evolves in half-chaos of not fully random systems

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## Summary

Important for modeling of products of life, of technology and culture using complex networks, the famous Kauffman's hypothesis „life on the edge of chaos and order" is here deeply reinterpreted in effect of the model extension by functions and states correlation. The presented discovery of "half-chaos" – a state more adequate for describing life, significantly alter the existing basis of many considerations. Half-chaotic systems have the same parameters as chaotic random systems but they exhibit the characteristics of order and chaos simultaneously, previously considered to be mutually exclusive. As superheating, in effect of a large change (after a small disturbance) they become chaotic. Small change, defined by lack of immediate changes, does not lead out of half-chaos. The basis of half-chaos is a short attractor. Discovered "semimodularity" - a form of the half-chaos, gives the image "small lakes of activity in the ice", similar as for systems in Kauffman's "liquid area" on the edge of chaos. There is much more half-chaotic systems than in "liquid area".

**Keywords:** Kauffman networks; complex networks; chaos; life on the edge of chaos; phase transition to chaos; damage spreading; Darwinian mechanism.

## Introduction

Indication of adequate parameters of complex system describing living, technological or social objects is a key for modeling their processes. Kauffman[1,2] has considered autonomous, dynamic, deterministic, complex, random Boolean nets. Typically, fixed number K of inputs to each node of network was used as the main variable in the investigations. A size of damage (change of system function in effect of small permanent disturbation) was the main result. For random networks this result creates two system states – ordered and chaotic. Between them there is a fairly quick transition (near K=2, if signals are equally probable), treated as phase transition. Only in systems in the vicinity of this transition (the liquid area between solid - ordered and gas - chaotic), the changes in the system function (damage) often enough is small. Such small changes are necessary for biological evolution. This is the main basis for the Kauffman's hypothesis: life on the edge of chaos.

This conclusion, however, aroused doubts[3]. Therefore, it has been subjected to deeper analysis presented here, which showed that in expanded model, indicated by Kauffman the liquid area of system space is quite unique and small. Suitable systems for biological evolution can be identified also in other areas. Considering the specific correlation of parameters which Kauffman simplifying took as random, we find systems which simultaneously manifest "mature chaos" and order in similar proportions. The analogy to the phase transition here is more complex - it is rather the "superheating". The distribution of damage size here has two peaks - very small changes (ordered) and very large - close to Derrida balance[4] (mature chaos). There is a big gap between them - immediate changes practically do not appear. This defines in a natural way a small change, which is very important for interpretation. This is previously unknown state of the system, which we call "half-chaos". Half-chaotic systems have parameters which, when these correlations are destroyed by a big change of functioning, create a simple, random chaotic system. Such the big change well models death (elimination) of a living object, which in Kauffman's model was not present. But as long as they evolve accepting only small changes (well modeling evolutionary changes and development), they do not leave the half-chaos. Such the small changes are a base of identity of evolving object and simplify definition of basic Darwinian mechanism.

"Semimodularity" is a discovered in this study form of the half-chaos. It gives a picture of system functioning similar to that indicated by Kauffman for random systems from liquid area, where he places life. The essence of such systems are "small lakes of activity in the ice" (originally: "unfrozen islands")[2], what despite regular, random connection of nodes gives results similar to modularity. In contrast to the liquid area where ice (not changing state nodes) results from the nature of the ordered state, here it is a specific state in the system from the nature of its parameters (s, K - see Methods) chaotic, predetermined non-randomly (through correlation functions and states of nodes). This form of half-chaos is particularly well suited to the description of biological evolution, due to the size distribution of small changes. Generally, the basis of half-chaos turns out to be short attractor in semimodules, or in the entire system when is lack of semimodules.

## Doubts: negative feedbacks & Boolean nets

There are two important doubts that occurred to me during the tracking Kauffman arguments for the hypothesis of life on the edge of chaos. Both are described in more detail in [3].

The first is a way to take account of negative feedback. Such regulatory feedback are generally considered the basis for the stability of living facilities, and their concentration is considered to be significantly increased in relation to the random one. Whereas, the complex structure of the feedbacks for this statistical surplus have been replaced in the model with their proper effect, and it remain only for random share. So simplified model is not able to properly give a statistical picture of a system failure, and conclusions for a stability mechanism can (and seem) significantly differ from reality.

This doubt was the main reason for undertaking the research, which initially aimed to strong raise the share of regulatory mechanisms (met1,2,4ab). It turned out, however, that short attractor is a simpler, more general and more important factor (met4cd, met5,6,7), which does not change importance of regulation (met4a).

The second assumption arousing doubt was the limitation in statistical studies to the two variants of the signal. Boolean network can describe each complex relationship (mechanism), but bringing to two-value description frequent cases where significant signals take more than two variants, generates unrealistic situations, presumably - to skip (Fig.3 in [3]). In the statistical analysis, however, they are not skipped and give a false picture. Adding to the two-value description of the parameter p - probability of one variant, does not solve the problem here. Adoption of $s \geq 2$ equally probable signal variants is an alternative method of model realignment. It seems to be, however, often more adequate. Both methods give different results (Fig.4, 5 in [3]) which significantly increases the importance of correct choice of description.

## Basic assumptions - methods

We use include more than two equally probable signal variants[3]. Symbol s describes their number. I suggest to keep for such networks name "Kauffman network," by which the terms "Boolean network" and "Kauffman network" no longer stay synonymous. In these studies constant K (number of node inputs) for all nodes in the network is used but number k – node outputs, is unrestricted for the nodes in the network and, depending on the method of construction of the network it has different distributions associated with the different network types. The "Random" Erdos-Renyi network (symbol er); scale-free (sf) and sometimes single-scale (ss) are mainly studied (for sf and ss see Fig.2 in [3]). In the figures, the type of network is marked only the second letter. Parameters: network type and s,K (treated as vector) are the main variables in the simulations. Most of the studies are made for s,K = 4,3, also sometimes for s,K = 2,4, that is, for Boolean network. They provide highly chaotic random systems - 'coefficient of change multiplication on one node' [3] $w=K(s-1)/s$ is significantly higher than 1. The number of nodes in the network - N typically is 400, exceptionally is taken 800 or 4000. Synchronous calculation is used, t – is the number of time steps from a disturbance initiation. As the disturbance a permanent change in the value of the function of node for its input state is used at the time t = 0. Parameter tmx - the maximum number of counting steps is chosen arbitrarily, but it is checked whether its increase does not change the results (Extended Data Figs.1, 4, 5). We simulated the process of transformation of the disturbed system on the section tmx, then we compared the resulting state of the system with the undisturbed system. The result A is the number of nodes whose state is different. Change of the system functioning - damage $d = A/N$. The distribution of damage size at the time tmx as P(d) or P(A) (Fig.1) is an especially important result. The boundaries of the peaks: the left of small changes (ordered), and the right of big changes (chaotic) define "a small change". It is a criterion of the acceptance perturbing permanent changes creating the evolution, which is enough (Fig.2) to stay in half-chaos (evolutionary stability of half-chaos). The main result is the "degree of order" q – fraction of effects of a small perturbations (Fig.3) which fit into the range of "a small change of the functioning" at the time tmx. This corresponds to the contents of the left peak, or probability of acceptance of changes in the modeled evolution (lack of elimination).

## More negative feedbacks or modularity

In the presented study to transform part of the feedback from random structure into negative feedback by changing the random function, when the state on the inputs was not used so far was the first methods of correction of random chaotic system. They were **met1** and similar, stronger **met2** with iterative change the pattern. Network s,K = 2,4 and 4,3 was investigated, which suggested from (Fig.5 in [3]) to achieve a Derrida chaotic balance even before the 15-th time step. Initial research for tmx = 60 steps yielded very promising results (Extended Data Fig.1a) - q was significantly increased (especially for s,K = 4,3), the distribution of damage size already contained two peaks separated by a break. A large part of this effect (especially for s,K = 2,4) was the result of deviation from the randomness of node functions, which also may be included[5] to evolution tools. But it turned out (Extended Data Fig.1) that obtained in met2 stability of q usually significantly decreases with the elongation of tmx, practically disappears already for tmx = 1000, only in the case of Boolean networks sf 2,4 this method could be considered to be effective to achieve half-chaos (not tested for evolutionary stability).

These studies demonstrated a high range of results depending on the network type - the network sf is more ordered[6]; network ss and er are more chaotic, similar to the reaction, but er has part k = 0 (Fig.3, Extended Data Figs.1, 2) obstructing observation. The parameters s,K = 2,4 and 4,3 also give a very different picture. The simulation allowed for a deeper look at the process and its determinants, which pointed to the phenomenon of secondary initiation and importance of short attractor. The cases of re-appear at the inputs of disturbed node its inputs state for which the function has been permanently changed are responsible for decline of q with increasing tmx. Such a secondary initiation takes place under different conditions than the previous one and can also lead to great chaotic change. After round of attractor new such cases are no longer present (see below met6 and Extended Data Fig.3a,b).

It seemed that the most natural way to get short attractors is modularity, so the next we provisionally tested, what it gives for stability (**met3**). Here it turned out that a sufficiently small spontaneous attractors can be expected only in so small modules that considering the state of chaos in them losing meaning. Modularity also gave raise q (Extended Data Fig.1c), especially when met2, which increased the share of negative feedback, is used at the same time, however, evolutionary stability was not checked. In the distribution of damage size the typical for half-chaos radical gap between peaks was not observed, only the clear minimum. An increase of q in the experiment met3+met2 with s,K=2,4, almost entirely resulted from non-randomness of functions. Both of these methods and their associated factors (such as non-randomness of functions) belong to the most important methods of producing desired stability by biological evolution, but in both the short attractor is an important factor.

Lack of expected radical effect of regulatory mechanisms in the met2 was sought at a start from a random network. Then we introduced strong regulation in a system with a radically short attractor – point attractor (**met4a**). This time the result was surprisingly strong (Extended Data Fig.2), so we decreased the regulation to the minimum (**met4b**, see also **met5b**, Extended Data Fig.2d), and next regulation was rejected at all (**met4c,d** and later), which showed that the point attractor is sufficient to achieve half-chaos. The result of met4a shows how strong may be the effect of the regulation in half-chaotic system – right peak almost disappears, that is, the probability of entry into chaos as a result of a small system failure (internal cause) is small. This gives a deceptive picture of ordered phase[7,8]. They remain external causes, which model of autonomous network does not take into account from assumption. Adaptation, however, is to the environment, which can vary and the evolution should be tested using open systems, as in [9].

## Point attractor system is half-chaotic

The study of the systems with parameters s,K = 4,3 and 2,4, which is highly chaotic if they were random, but with a given point attractor as extremely short (**met4c,d**), gave clear results - such systems are neither ordered, nor chaotic. Both reaction variants on a small initial perturbation (ordered - a small change in the functioning and chaotic - a big change in the near of Derrida equilibrium - Fig.1) appear in similar proportions (Fig.3). This state was named "half-chaos". In this state, the resultant change in the functioning can be either very small or very large (explosions chaos Extended Data Fig.4), but almost no intermediate changes (Fig.1,Extended Data Figs.2, 4, 5). This defines a small change in the natural way. There remains the problem of the length and condition of the evolution of the half-chaotic system.

Obtaining point attractor is simple, just after the random generation of networks and the states, it is enough to take that for the current state of the node inputs node function gives the current state. For the remain states of the input - functions may be generate randomly. Point attractor in Kauffman terms is a quite frozen system – there is only "ice". The predominance of the ice is a spontaneous property of ordered systems. Obtaining small change after disturbation of half-chaotic, point attractor system, we can expect "a small lake of activity in the ice," which is the essence of the 'liquid' area of random systems, where Kauffman puts life. But such a system ceases to be a point attractor system. It turns out that the vast majority (typically over 99%) of "small changes of functioning" gives also point attractor systems. Evolution may therefore be long, however, such the model is quite extreme and unattractive.

Then we checked for models b and c of the met4 how long can be evolution, if it accumulates small changes, but do not allow the point attractor (**met5**). We received, that it allows to any length of maintenances of the half-chaotic state, which stabilizes its parameters (Fig.2). It is evolutionary stability of half-chaos which was included into half-chaos definition. The system still has significant prevalence of ice (Fig.2c), and there are usually some "small lakes of activity" forming "semimodules." Among the methods used to check the presence and properties of the semimodules (see also Extended Data Fig.5c,d), the most effective was to track of periods of nodes. The set of nodes with the same period in the process ended of accumulation was treated as a local cluster corresponding with semimodule. On average, at the same time occurred about 2 local clusters (Fig.2e). In the evolution, sometimes after many in the meantime accumulated changes, there appeared local clusters very similar in terms of nodes composition - a collection of such local clusters is treated as a global cluster. Methods to identify global clusters are very complex due to the wealth of different circumstances, including merger and disintegration of global clusters during evolution. However, we can say that they are generally quite stable formations, though they often disappear (freeze) and reappear, often in the other company of remaining global clusters, often changing period. Their average number for a complete of initiations presents Fig.2d. It should be emphasized that the structure of the nodes connections in the investigated networks was constant and random, although the randomness had various formulas that define the type of the network. In contrast to the modularity, semimodularity does not rely on varying density of internal and external links, but is the result of the functioning defined by the functions and states of nodes in a given structure. Despite the selection of functions for obtaining initial point attractor state, functions and states of nodes had truly random characteristics.

Simulations met4 and met5 start from the system with point attractor. In the met4 networks sf and er was tested. Number of nodes N = 400 and 4000, section tmx = 200 and 2000 (no variant N = 4000, tmx = 2000). One complete of initialization was tested - for s = 2 (met4d) each node is able to one initiation, for s = 4 there was 3 of the remaining function values. There were gained 48,000 events for each of the three variants of (N,tmx). The differences in the results of these variants were not significant (Fig.1,Extended Data Fig.2), for further research in met5 we used N = 400, tmx = 1000.

We limited met5 to s,K=4,3, but these studies were much more complex. For a long process of accumulation we were studied many completes of initiations, then the same change in function as an initiation has been repeated, but it was separated by many accumulations. Collecting 20 completes (M) of initiations followed one initial (J in Fig.2,Extended Data Figs.3, 4) complete. Only M1,7,13,19 and 20th contained all initiations, allowing them to measure q and other observed variables. In the other completes retrogressive changes were blocked. Parameters q and average time of the latest five "explosion to chaos" are the most important, they demonstrate in Fig.2a,b lack of converging into chaos. They stabilize from complete M7, despite a slightly elevated length of global attractor was forced (not less than 7, and in M20 could not decrease). During the process of accumulation the attractor usually spontaneously decreased and there were happen that the condition for the attractor size block further evolution. Such processes were interrupted, however, in the main series 100 network were obtained, which reached M20.

It turned out that the amount of a shift (in the range of 2-50) of the point of process start (place of the initiation) after each accumulation is an important factor. We assumed shift of 50 steps. The study was much broader and deeper, their complete description can be found in [10]. Additional attempts of evolution referral more towards the boundaries of chaos gave no noticeable nearing - a condition of acceptance of a small change is enough for any long evolution - gives evolutionary stability of half-chaos.

## Controlled design of half-chaos system

Point attractor, as extremely short, gave sought half-chaos. Extreme, however, is specific, and in the evolution (met5) half-chaos was maintained even when attractor was not found in the range of tmx (Extended Data Fig.5c). It should be checked whether the alone condition of a short attractor, but significantly greater than 1, is sufficient. For that, simulations **met6** causing in the random system a global attractor (of whole network) = 21 was performed. From t = 21 for the unused input states of the node the function value was changed for such as 20 steps backward. We obtained the evolutionarily stable half-chaos even with a high q (Fig.3) for the same parameters and rules of the evolution simulation as in the met5. The primary difference is the shape of the resulting left peak (of small changes) in the distribution of damage size - there are practically only changes of a magnitude A = 0, but A = 1 and A = 2 are present in negligible amounts (Fig.1). This means that practically there are no changes in the functioning and in spite of the acceptance of permanent changes in the functions of nodes, nothing is changed. Such a process is not suitable for modeling of adaptive biological evolution, only for neutral evolution. A total lack of semimodules was found. In half-chaos based on semimodularity as in the met5, the peak of a small damage contains a significant amount of change in the range A = 1 to 4, and also larger changes occur markedly frequent (Fig.1). Semimodularity in met5 explains achieved stability for the larger global attractors - they are assembling of small local attractors (in semimodules) but this solution also should be better checked.

To determine the sufficiency of the semimodular state to obtain stable half-chaos, we have attempted to controlled create it without booting from the point attractor (**met7**). Networks sf, ss and er, s,K=4,3 was studied. First, network of N nodes and their states are randomly generated (dependently on network type). Next, analyzing of the node connections, a collection of semimodules was created and everyone node was assigned to a semimodule or separating them ice. Node created new semimodule when none of its link (input and output) was connected to node belonging to an already existing semimodule. When it was connected to nodes belonging to only one semimodule, it was assigned to this semimodule. When it was connected to the nodes belonging to several semimodules, or if the limit of semimodules (= 10) or the size of the semimodule (= 100 nodes for N = 800, 25 nodes for the study of evolution) was exhausted, the node was assigned to the ice.

Next a trajectory was calculated by appropriately functions selecting. For the current input state, if it was not previously defined, nodes of ice get the value of the function equal to 0 but nodes belonging to semimodules –random value.

A number of additional conditions and adjustments was applied, a full description contain documentation[10], their details are not important here. Initially, short attractor was forced in each semimodule and using this assumption basic investigations were made: (b) – of the semimodularity state (series with N = 800 and tmx= 2000 without evolution roughly corresponding to the met4) and (eb) - the evolution as in the met5 and met6 (series with N = 400, tmx=1000). At the end the necessity of this assumption was verified and surprisingly it occur unnecessary. So the two most important research without the forcing were repeated (called a and ea - as logically simpler).

Examination (J) of the semimodularity with N = 800 mainly relied on checking the q and the distributions of damage size. In the versions b we demanded the global attractor to be greater than 200 when the local attractor could not exceed 100 - the result was in line with the tested vision which explain the admissibility of larger global attractors. In both versions (a and b) it was verified that the statistical properties of non-randomly selected functions are not responsible for the increasing in stability, namely: how such a system behaves after: the acceptance of one large change (X), randomly changing of node states (S), moving the functions to other nodes (T ) and the random generation of new functions (F). In the experiments X, S, T functions retained their statistics. In all these experiments chaos yielded (like X in Fig.3, Extended Data Fig.4b), but it systematically slightly differed from the full version of chaos F (Extended Data Fig.3).

Comparing with the met5, particular for network sf, both peaks of the distribution of damage size have been a little bit changed (Fig.1). Also in distributions of the ice size and the local clusters size the blur arise what caused a marked decreasing of average ice and increasing average size of local clusters (Fig.2c). This shows getting a slightly different state of semimodularity. Like in the met5 and met6, system parameters stabilize from the M7, and the small change as a condition of acceptance is sufficient to any long maintain of half-chaos in the version of semimodularity.

## Conclusion

The hypothesis "Life on the edge of chaos," pointed out an important factor in modeling of biological evolution, of processes in social organizations and technical constructions, however, it was based on too simple model. It gave a picture of damage size distribution with one peak – only small changes and it suggested the strong influence of natural properties of ordered system, known as "order for free" [11]. Such a picture was not very consistent with the observed delicacy of living facilities, not emphasized of regulatory structures, did not contain a model of death necessary for the Darwinian elimination. Necessity of little s = 2 and K in the vicinity of K = 2 also did not seem fit to do observation[12-14].

Deepening the model, allowing complex non-randomness of parameters previously taken as random, led to discovery of half-chaos state - to find areas suitable for the evolution (giving adequate participation of small changes) also in the range of chaotic systems by nature of its parameters. It released with sharp restrictions that were previously typical basis of many considerations[15,16,11,12] - not just K can be greater than two but also s. In the half-chaotic state the peak of great changes that well model death and elimination is also present. After the great change the system becomes forever simply chaotic, but a small change, which receives here a natural definition, retains half-chaos and system identity, then evolution can go on. Half-chaos, together with given initializing changeability, completed by multiplication resulting from demand of long evolution, offers the full basic Darwinian mechanism. Regulatory feedback significantly increase the stability, the classic modularity and narrowing of the function also, which was noticed, but the main and the new condition is the short attractor. They take over the role of explaining the experience[7,16] from "order for free", which in half-chaos lost importance. The reached deeper interpretation of Kauffman hypothesis gives a picture much more consistent with the observation and indicates systems more adequate to the modeling of biological evolution. This significantly alter the existing basis of many considerations and probably their conclusions. Likewise, the description of the systems from 'liquid' region[2], where Kauffman saw living objects - "small lakes of activity in the ice" remains valid for the primary and most appropriate for the evolution half-chaos form - semimodularity discovered in these studies.

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# Figures

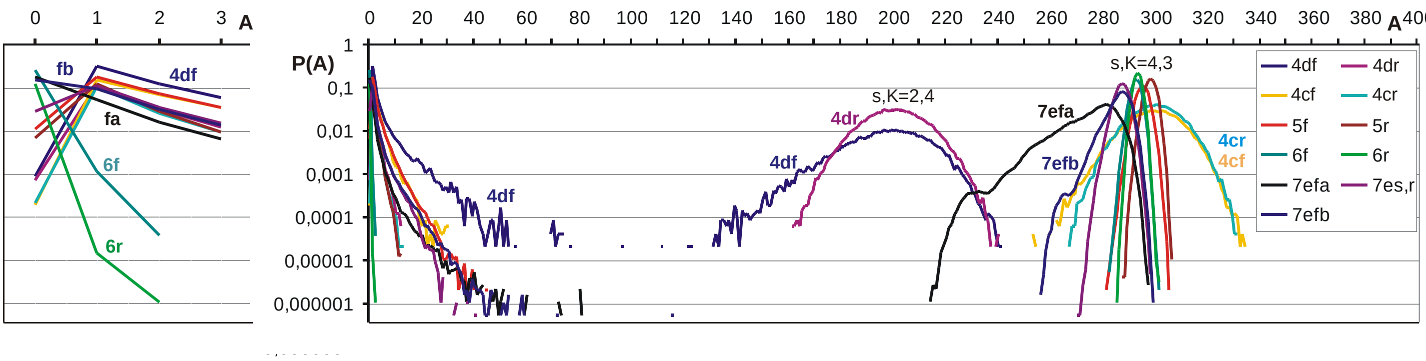



**Fig.1. The main result – distribution of damage size obtained in met4cd, 5, 6 and 7e for N=400.**
Log scales is used because of the large differences in the values and importance of the gap between the peaks - left (small changes - ordered) and right (chaotic changes near Derrida balance, different for s = 2 and 4). The contents of the left peak, i.e. q – degree of order, share of ordered changes summarized in Fig.3 and Extended Data Fig.2d is the basic result of this study, it allows to introduce half-chaos. A clear gap between the peaks naturally defines a small change, which is sufficient to keep half-chaos in the evolution (see also Extended Data Figs.2, 4, 5). The shape of the left peak is especially important for the modeling the biological evolution. The most important first values are shown in more details on the left. An important qualitative distinction of the results from met6 is visible - there is no greater changes in the left peak because it is no semimodularity. Symbol of the method begins a signature, next followed by a second letter of network type. Boolean network (s = 2) is here tested only in the met4d. Results presented here (and in Fig.2) for the met5,6 and 7 (experiments with evolution - except met4) concern the model met4c. They are a sum from completes M7, 13, 19 and 20 of initiation - that is, in the area where they were full and already stabilized (no blocking of reverse changes and no initial J and M1, see Fig.2). Results for the networks ss and er practically overlap (7es,r). Network sf gives clearly different results for the model with forcing of small attractors in the semimodules (fb) and without forcing (fa). They both differ from the others in the left slope of right peak, which is one of the few effects of some additional mechanism (see also Fig.2c).

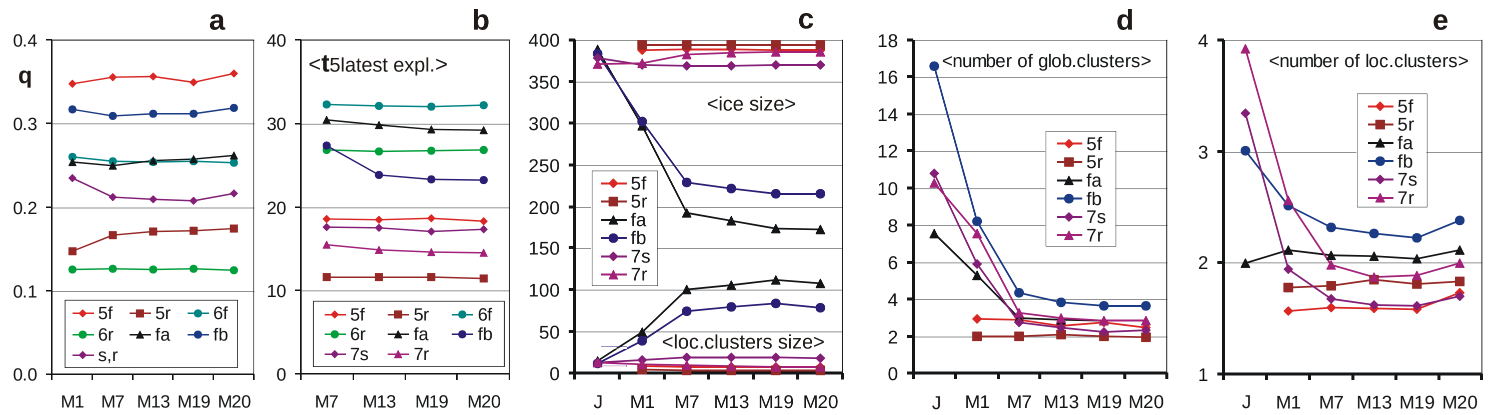
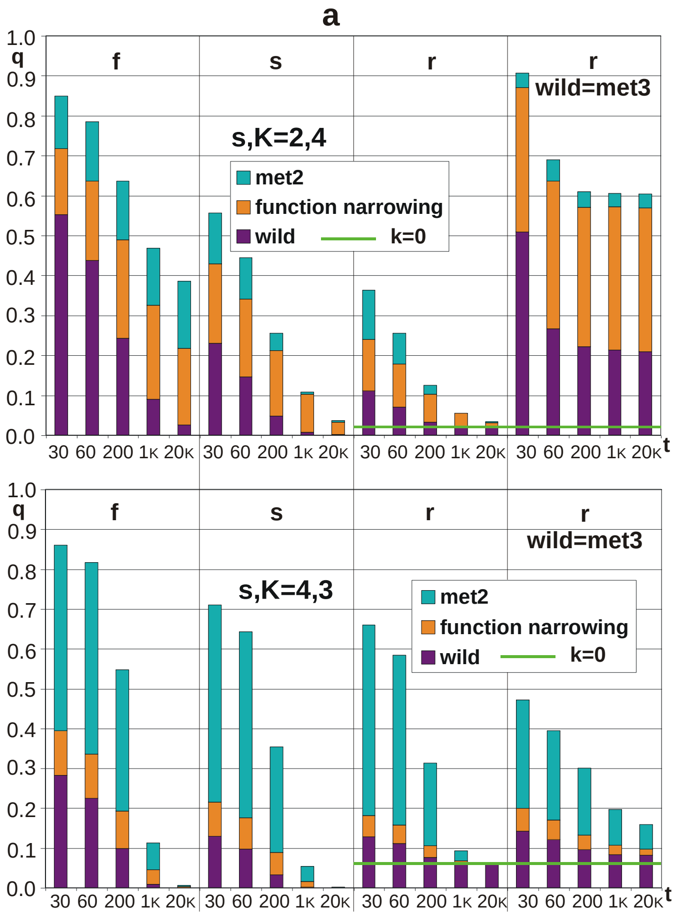



**Fig.2. The variability of basic parameters during evolution in the met5, 6 and 7.**
The similarity of results for these three methods shows similarity of obtained half-chaos, mainly its evolutionary stability, despite the differences in the way of obtaining.
**a -** Stability of parameter q (degree of order of the system, the contents of the left peak in Fig.1) shows lack of moving towards the chaos during the evolution **-** accepting permanent changes in the node functions which give small changes in the functioning (in the range of left peak, additionally excluded global attractors less than 7, and in the M20 also smaller than the already obtained).
**b -** The average time of five latest explosion to the chaos (see also Extended Data Fig.3a,b) does not grow in spite of the above indicated condition on attractors. In the chaotic networks such explosions (see Extended Data Fig.4) happen almost until the not yet exploded processes exist.
**c -** The average size of the ice and local clusters. It makes sense for semimodularity, so not for the met6 where almost always a single local cluster covers the whole network (N = 400). In met7e network sf clearly has a specific derogation, larger in model without forcing of small attractors in semimodules (fa), but it also stabilizes. The mechanism of this derogation has not been elucidated (see also Fig.1, wider recognition in [10]).
**d -** The average number of global clusters. In the met7e it also stabilizes from the M7. In the initial complete of initiation (J), still without accumulation, it is sometimes even greater than the number generated semimodules, which shows, that few so defined clusters may arise within one semimodule. It judges the method of global cluster identification, which is very complex and based on many approximations.
**e -** The average number local clusters is well defined. The initial small dissimilarity of network fa can be seen.

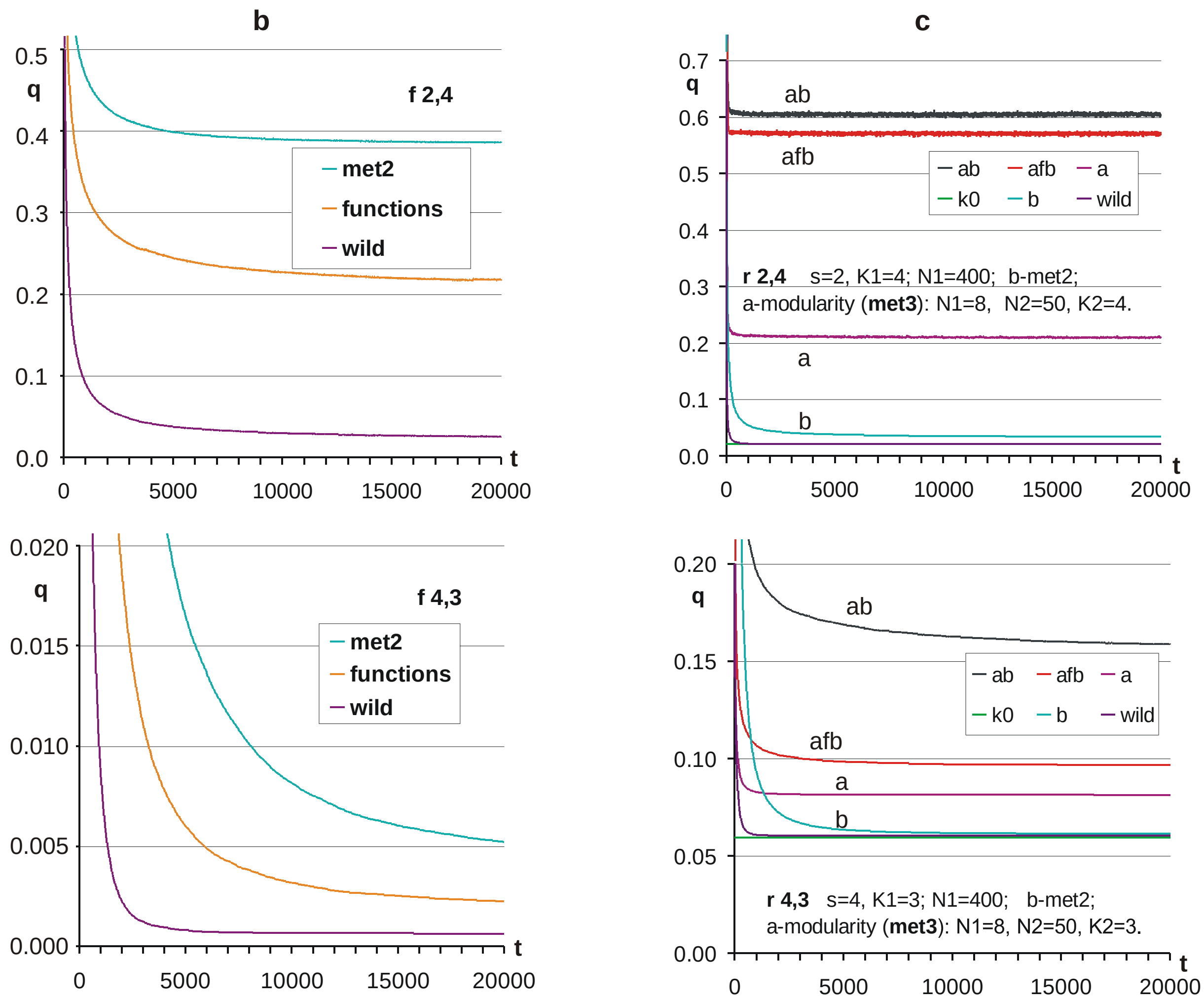

**Fig.3. Half-chaos – fractions of ordered events (q) and chaotic (1-q) in the met4cd, 5, 6 and 7.**
In the range of q order resulting from the absence of output in some nodes (k = 0) in the network er is isolated.
All results presented here concern only the effects of global attractors limitation (met6) or local attractors limitation through semimodularity. Similar juxtaposition for other methods of increasing the q (increasing the share of regulation or modularity) presents Extended Data Fig.2d.
For met4 and met7bJ the results concern the network immediately after generation of half-chaos, for met7bX - after checking complete J and acceptance of one chaotic change, which give a typical chaos. X gives the same picture as in the experiments S, T, F, (see also Extended Data Figs.3, 4). As can be seen, in the case of chaos order q is too small to be visible on the presentation, but in the half-chaos it is a significant and visible. In the remaining methods 5, 6 and 7e result is a sum of the results of M7, M13, M19, and M20, as in Fig.1, means - from the stable field of evolution (see Fig.2). Except met4d (s,K = 2,4) in remain cases s,K = 4,3.

# Extended Data




**Ex.D.Fig.1. Ordered fraction (q) as a function of time (t) after raising the share of negative feedback (met2) and the classic modularity (met3).**
The upper row of all part - s,K=2,4 (Boolean network), lower - s,K=4,3.

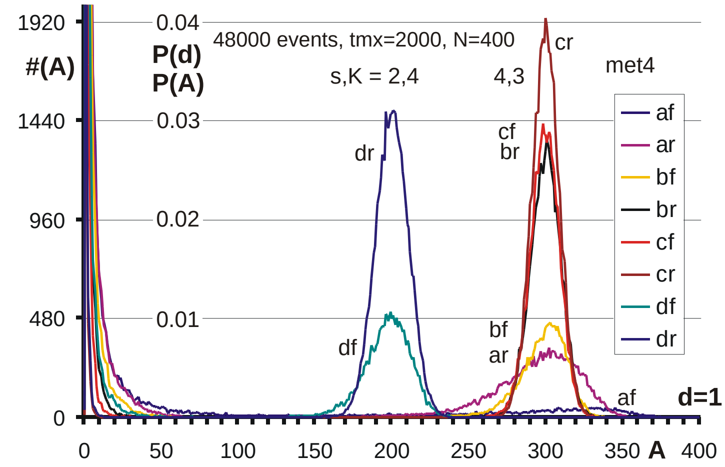
**a** – For some moments t the shares of mechanisms: wild - without interference met2; function narrowing as a side effect of the method; the increased participation of negative feedback by met2. For network er the level of q resulting from participation k = 0 (nodes without outputs) is indicated. In the right column as a wild the modular system resulting in met3 is used, further described in (c) as a curve a. The type of networks sf, ss, er is described by a second letter (as in the other figures) respectively - f, s, r. As can be seen, the results for the simulation parameters s,K=2,4 and 4,3, and network types, differ significantly. For s,K=2,4 the function narrowing is of utmost importance to increase q, but for s,K=4,3 the importance of feedback turns out to be essential. For small t effect of increase q is significant. From these data it can be suspected to achieve half-chaos for: sf 2,4 - the result of functions narrowing and increase of the share of regulatory feedback; and for the assembly of modularity met3 with met2 using nets er - for 2,4 mainly due to the functions narrowing but for 4,3 due to the met2. In the remain 5 presented cases the effect practically disappears already for tmx = 1000, the use of it by living facilities require very rapid multiplication in comparison to the transformation of the construction and metabolism, which seems unattainable. Here evolutionary stability (included into the definition of half-chaos in result of further studies restricting fundamental factors to a short attractor Figs.1, 2, 3) was not examined. The degree of entry into the plateau can be better assessed in **b** and **c**. The network ss gives a close approximation to the network er, but without the confounding effect of k = 0.




**b** – Net sf 4,3 not reached a plateau even at t = 20,000, where q is negligible, but sf 2,4 is almost on plateau q at t = 5000, and this level is high (compare Extended Data Fig.2d).

**c** – The result of modularity (met3) and assembling it with met2. Result of met2 for network er is added, such as in **b**, omitting, however, the share of function narrowing enough presented in **a**. It can be seen that the wild system of network er very quickly descends to the level of q resulting only from k = 0. Also curve b - the result of the met2 only quickly closer to that level, which can also be seen on **a**. Modularity (curve a) gives a clear stable increase of q, and met2 help it (curve ab) to radically increase q, but for s,K = 4,3 appears to fall within the plateau above t = 20,000. For s,K=2,4, almost all large and stable met2 effect results from the function narrowing only. During the study met3 it turn out that sufficiently small spontaneous attractors can be expected only in very small modules (eg .: N1 = 8), so small that considering the state of chaos in them losing meaning. Consideration of chaos in the modules network (N2 = 50 in experiments carried out) have been postponed.

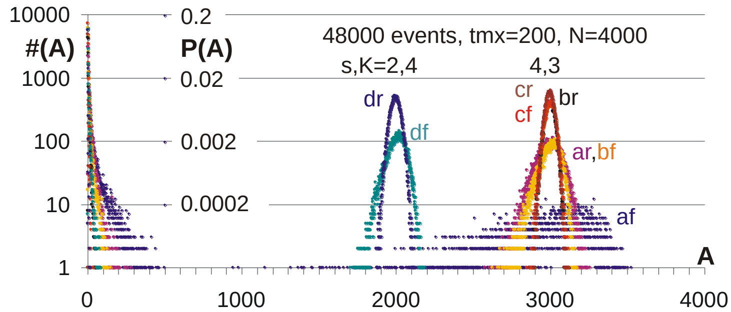
a




b

| peak | af | ar | bf | br | cf | cr | df | dr |
|---|---|---|---|---|---|---|---|---|
| Left | 43270 | 29258 | 32889 | 16851 | 15234 | 6922 | 31017 | 8345 |
| Right | 4730 | 18742 | 15111 | 31149 | 32766 | 41078 | 16983 | 39655 |

c




d


**Ex.D.Fig.2. Increasing regulation or another factor - the point attractor. Primary result of the met4.**

In the met4 removing a presumed cause of the poor performance of the met2, we start with the non-random system, with extremely short attractor – a point attractor: initially, all states are set to 0 and f (0) = 0. The models were tested in the sequence a, b, c (s,K=4,3) and d (s,K=2,4) starting from strong regulation and ending with the lack of regulation in the models c and d. Care was taken that each signal has the same probability in a function of each node.

**Model a** contains a negative feedback with a positive (1) and negative (3) deflection from equilibrium (0) in each of the three input signals. It contains also the leaving of homeostasis into the area of randomness (when deflection is too great or one of the input signals = 2, then the node function is defined randomly). The exact description of this formula is too complex to describe it here, it is available in [10].

**Model b** has a minimal regulation: the condition of the point attractor f (0,0,0) = 0 is supplemented only by condition f (0,0,1) = f (0,1, 0) = f (1,0,0) = 0 that there is no in **model c**.

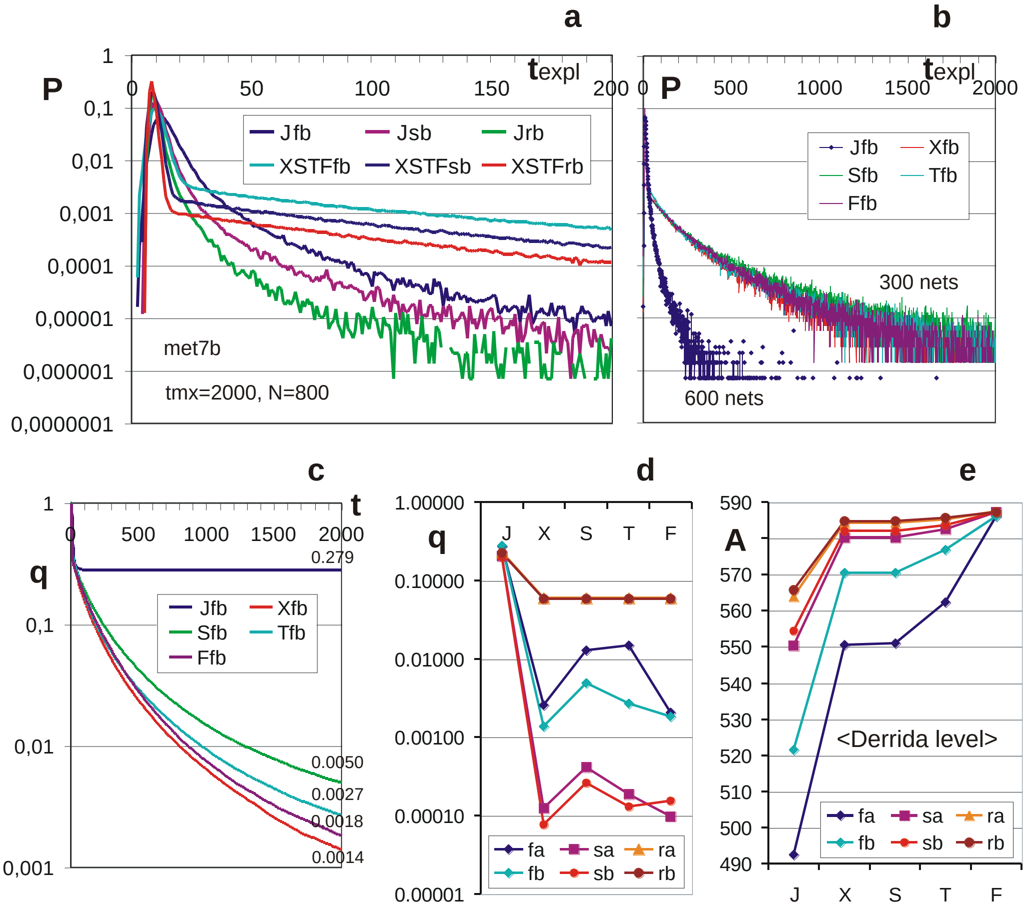
**Model d** of Boolean network (s,K=2,4) has only condition f (0,0,0,0) = 0 similar to model c.

Each model is simulated for three combinations of N,tmx = 400,200; 400,2000; 4000,200 networks sf and er so as to always initiation number was 48,000 in the series. Threshold of small change for N = 400 was set to 100, and for N = 4000 to 800. Each initiation by definition of met4 is made for node state = 0 and for input state = (0,0,0). So only in the model c 3 other function values may be used for initiation. For model a the only one value 2 remains, for b only two values: 2 and 3, which are new states of node without the mandatory fade out of damage at the destination.

**a,c -** The counts #(A) of resulting changes of size A (changed states of nodes in tmx) are shown. Also the scale of the P(A) or P(d) are added. The results in the linear plot a (N=400) for models c and d are also in Fig.1 in log scale. The series shown in c contains 10 times less networks, which gave peaks much narrower (in damage d scale instead of A) than in a. The right peak for models c, b, a, is becoming smaller due to increased regulation, which is reflected in the diagram d as less participation of chaos. Place of right peak in a and c is well designated by Derrida balance (Fig.5 in [3]) (different for s = 2 and s = 4), which is the property of a mature chaos.

**b -** The table of results #(A) for tmx=200 for the same networks as in a for with tmx=2000. The left peak differ only for af by 140 and for df by 2.

**d -** A complementary for Fig.3 juxtaposition of fraction of ordered cases (q) and chaotic cases (1-q) for minor experiments discussed in the article. While Fig.3 lists only the study of impact of small attractor, it is here - the impact of increasing the share of regulation in met2 (only sf 2,4 can be considered in met2 as entry into half-chaos, see Extended Data Fig.1a,b); modularity in met3; assembling of met3 and met2 (Extended Data Fig.1); assembling of point attractor and regulations in met4ab and met5b. In these only met5b examined the evolutionary stability included into the definition of half-chaos. As can be seen, the assembling is more effective than approach alone and should be expected of such a strategy in biological evolution. The case af shows that the way evolution can lead to a state where the half-chaotic system may seem as ordered. Evolution met5b decreased q comparing met4b when met5 (Fig.3) worked in the opposite direction relative to met4c (there are uncertain trends), but the expected strategies of biological evolution its creative aspect is important, not modeled in the presented simulations, too simplified to such a task.




**Ex.D.Fig.3. The difference between half-chaos and chaos in researches met7a and b.** Researches met7a and b (without evolution) were supposed to deeper and more accurately demonstrate the distinctiveness of the achieved state and chaos. In comparison to study the evolution an elevated N = 800 and tmx = 2000 were used. Variant b, over the conditions used in variant a, is forcing small attractors in semimodules and limitations: local attractor ≤100 and global attractor >200 also a shift to the latest start of local attractor <500. Experiment J - immediately after generation of semimodularity (600 networks), and after J further experiments X, S, T, F (300 networks). X - after acceptance of one chaotic change, S - after changing the node states to be random, T - the shift of functions to other nodes, F - after generation of random node functions. Despite the lack possibility of meaningful designation of measurement errors, the reproducibility of the results and the radical behavior otherness of J experiment clearly shows that the obtained state strongly differs from chaos.

**a,b -** Probability of time of explosion to chaos for met7b. This aspect is shown in the graphs of A(t) shown in Extended Data Figs.4, 5 where late explosions resemble the image to the chaotic and increase uncertainty of the appropriate selection of tmx.

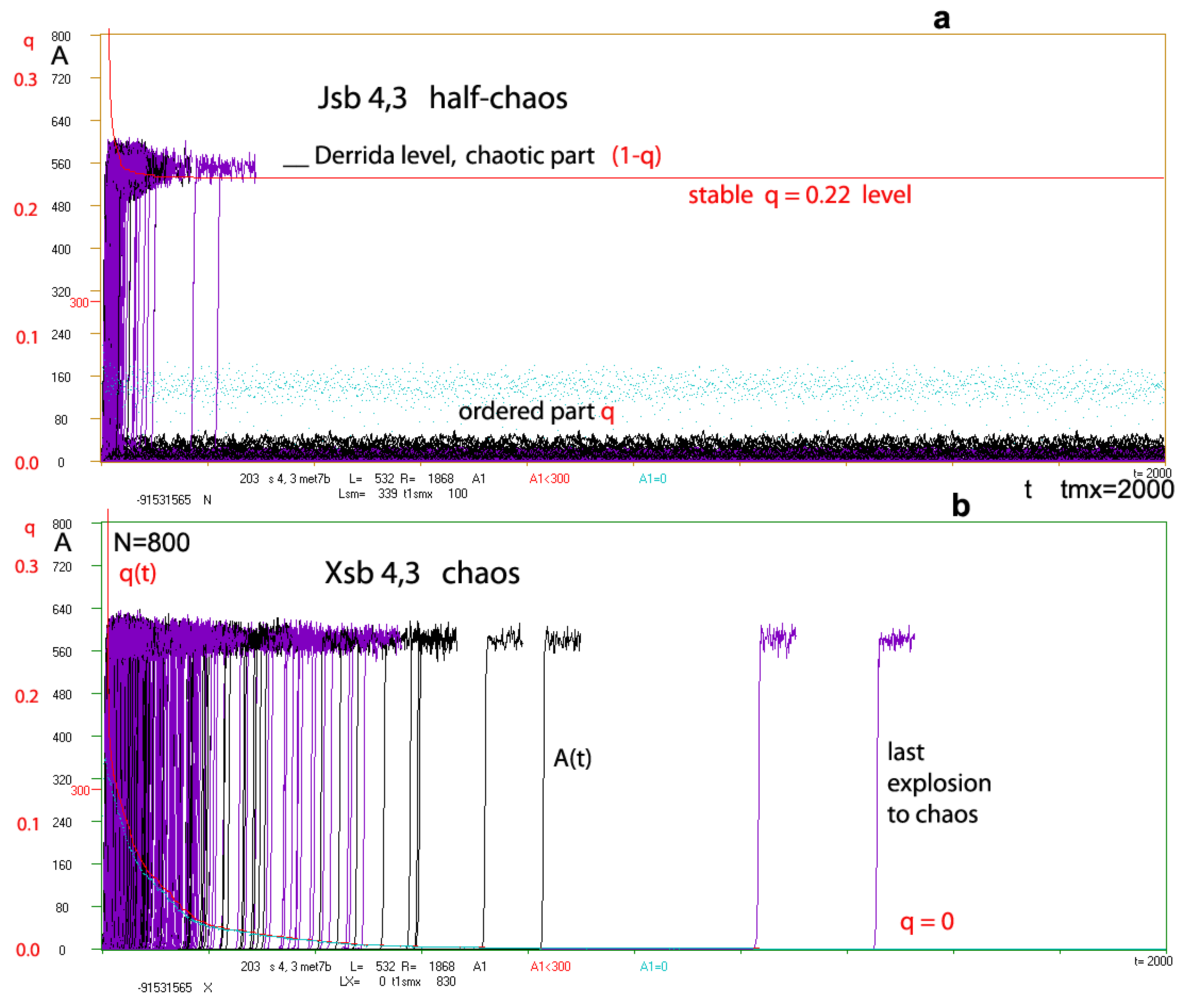
**a -** J and X for network sf, ss and er. For J the probability smoothly decreases with time increasing, for X appeares the collapse near t = 22 and the transition to a much slower decline associated with the presence of chaotic explosion after the secondary initiations. None of the collapse for the J results from the completion of the first round of short local attractor. After this moment there is no explosion as a result of secondary initiation inside the semimodule, which would be happened in the new circumstances. This mechanism is an approximation, since initiations are also held in the icy walls between semimodules, but there damage spreads more difficult, and after penetration into semimodule already subjects to the indicated mechanism. There was a clear difference in the behavior of the tested types of networks - sf has later explosions, in this aspect it is the most similar to the chaos; er has the least of late explosions.

**b -** J, X, S, T, F for network sf. Apart the half-chaotic J, the remaining chaotic X, S, T, F practically overlap. X protrudes somewhat from below, and the S and T – from above. Very late explosions also occur in half-chaos, but they are rare. These are usually cases of especially large global attractors, sometimes not at all found in the range of tmx, furthermore, most of initiation occurs between semimodules in the ice, where damage normally builds up slowly.

**c -** Average q(t) for fb (network sf in met7b) in experiments J, X, S, T, F. Half-chaos in the J is clearly different and quickly stabilizes q, but X, S, T, F drop up to tmx and probably further and are a little bit different. In this measurement the difference may be within a measurement error, which is practically impossible to determine due to the multiplicity of factors, but in d at least the S and T seem to consistently differ from the X and F. Reviewing diagrams A(t) as in Extended Data Fig.4b similarity is noted in the range of X, S and F, but in the case of T there are frequent derogation of different nature, particularly for fa, where the result is strongly disturbed for a few special cases.

**d -** Average q for all the tested types of networks (sf,ss,er) and models (a, b) in all the five experiments J, X, S, T, F. Network er in cases of chaotic hides differences in the occurrence of k = 0. See also the discussion of differences in the description c above.

**e -** Average position for the right peak of chaotic Derrida balance. Particularly large deviation for the Jfa and Jfb is shown in more detail in Fig.1 and Fig.2c. X, S and T behave here the nature of the derogation and the statistical derogation from the randomness of functions, which suggests such a source of visible here differences and determines the magnitude of the impact of functions non-randomness on the results. X and S retain a correlation of functions non-randomness with node place in the structure of the network, which breaks T.




**Ex.D.Fig.4. Half-chaos and chaos in the presentation of A(t) from simulation of a complete of small permanent disturbances on example of met7b J and X for network ss.**

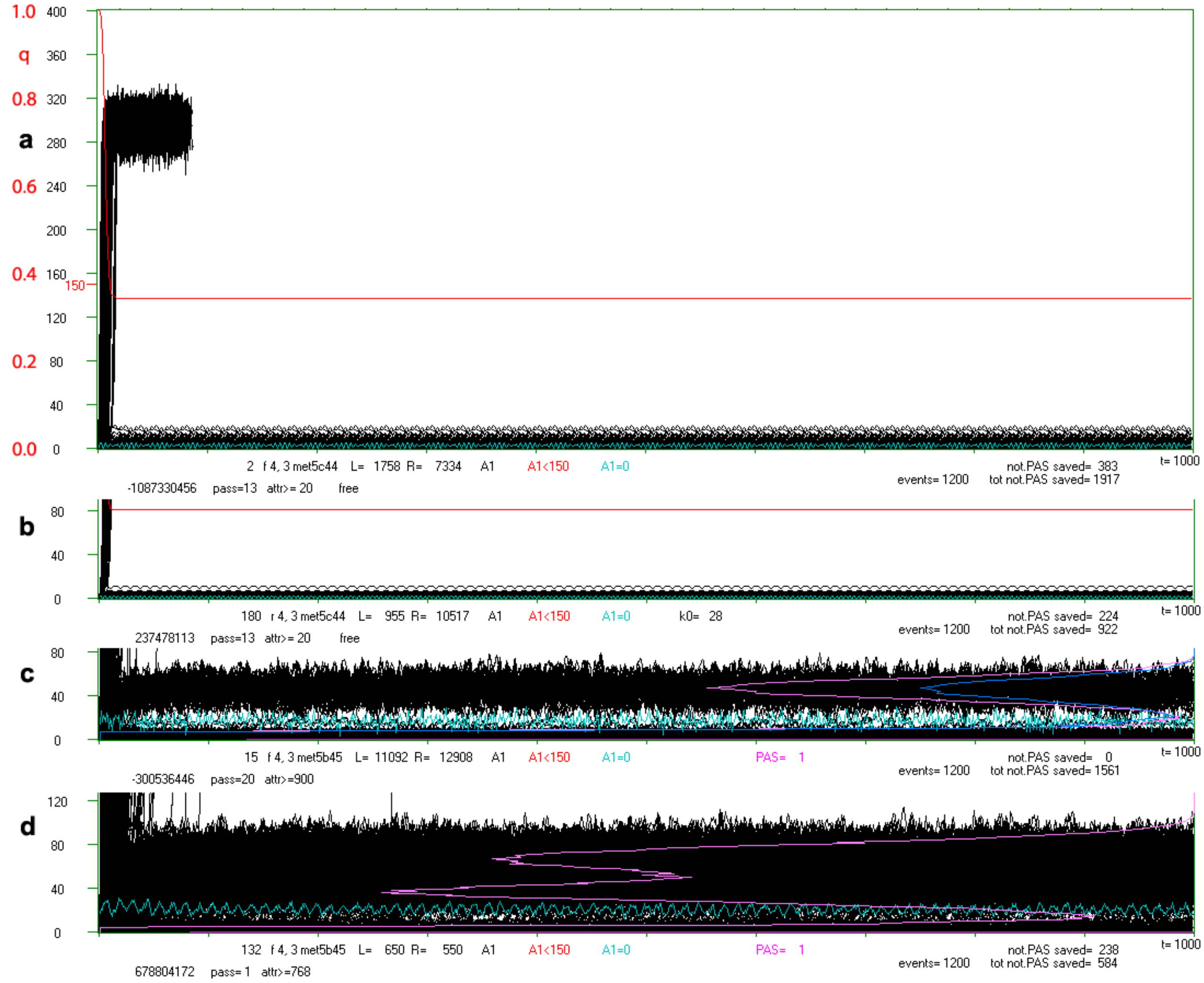
This is a presentation observed dynamically during simulation on the screen pixels. The details should be watch in enough magnification. In met7b N = 800, tmx = 2000 was used. A rectangle has the dimension of 400*1000 pixels, so or each axis one pixel shows 2 values. In Extended Data Fig.5, which this figure is a description of forms, N = 400 and tmx = 1000 is used, so there unit on the axes corresponds to a pixel. The vertical axis is originally scaled in the A - number of the nodes states different than in the pattern. The horizontal axis is the number of steps t of simulation of network function. After each initiation by small permanent change, the state A(t) was drawn with a continuous line on the screen after every step of calculation. For initiation of node in the semimodule black color is used, and for initiation in the walls between semimodules - purple. In met5 shown in Extended Data Fig.5 this distinction was not known and always black was used. To optimize the simulation a counting after 70 steps from the explosion to chaos (crossing over the threshold, here = 300, marked in red on the left) was stopped - there the process has no chance to return.

As can be seen, the transition to chaos in the vicinity Derrida balance is not slow, but rapid in several to over a dozen steps, where A increases drastically, so - "explosion." After deflection from a small value to say - A = 80 no longer the returns happened (as checked without optimization, see [10]).

After the end of initiation complete, the red curve q(t) was added to the figure. In met7 it is originally scaled by the A as the number of initiation, which do not exceed the threshold = 300, but there is 3N=2400 of initiations. In met5 in a Extended Data Fig.5 q(t) is divided by the number =3 of initiation by node, so that q=1 for A=N. Red description of the left has been added for readability and here q(t) is the share of processes that in the time t did not pass the threshold.

**a** – Half-chaos, experiment J for network ss model b. There was 600 of such simulations for each type of networks sf, ss, er and models a and b of met7. The red curve q(t) quickly stabilizes at a high level q=0.22. In the lower part of the graph many trajectories are visible (there are L = 532 of 2400) that a little over t=200 no longer explode. So R = 1868 processes from the very beginning went to chaos - a Derrida balance.

**b** - Chaos on example of experiment X performed immediately after the measurement of the J illustrated above in the a. There was 300 of such simulations for each type of networks sf, ss, er and models a and b of met7 and for each experiment of X, S, T, F. Here, q(t) is steadily decreased until all the processes are not 'exploded'. At the end there is exact LX = 0 of their, means q = 0. Blue points describe the number of processes that currently have A = 0, i.e. damage fade out, but for the X the secondary initiations lead to their explosion.




**Ex.D.Fig.5. Simulations met5 (changes accumulation) in the presentation of A(t).**

Except red description q on the left each drawing was created dynamically on the screen during the simulation of one full complete of initiation without blocking of reverse initial changes. It is accurate to the pixel. Description of the presentation elements in Extended Data Fig.4.

**a -** Full typical image for the M13 met5c (met5 in other figures, model c from met4), network sf. Almost an immediate end of the explosions to the chaos can be seen. At the top - the state of chaos in the Derrida balance (short due to optimization by interrupting the counting after 70 steps, as in Extended Data Fig.4). At the bottom - a repeating pattern in accordance with the global attractor marked on the top frame (pattern network state as in tmx before the first initiation of the complete). Here L and R under the lower frame is the sum from the beginning of the network simulation. In this complete 383 initial changes were accumulated of 1200 tested, but accepted changes defining q (not exceeding the threshold = 150) were a little bit more (with global attractor<7).

**b -** Typical image of network er simulation in met5c. The upper part of the almost identical to a is cut. The level of q(t) is lower, the belt at the bottom - clearly thinner, the time of latest explosion to chaos - shorter.

**c, d -** The lower part of the image for met5b (with minimal regulation). Here the level of q(t) was much higher than in a. In the model b, the width of the lower belt is greater due to the possibility of regulation. Simulations slightly different model than in Extended Data Fig.2d - here without blocking of reverse changes, but with the condition non-decreasing of global attractor and accumulation of changes not less than A = 3, the shift of beginning = 2 but not 50. In these simulations, a distribution of damage size A <150 was studied on section from t = 600 to tmx for a given complete of initiations (purple curve on the right frame) and the sum of the completes in the final complete M20 (blue curve in c). It is one of several ways to look for proof of the semimodules existence. As can be seen, in both (c,d) shown cases in these distributions the significant peaks are visible. They are responsible for stimulating one (in the c M20) or two (in d M1) hypothetical semimodules. Under the scope of these peaks there is a clear gap in the minimum of distribution. An interpretation of these peaks can vary, they are not proof of the semimodules existence, which was shown later watching nodes states repeating, but they are a strong premise.

The q level here is high: in c q = 0.46 and in d q = 0.55. In c the attractor was not found at the beginning of the complete (attr> = 900), and because it could not decrease, no one accumulation happened (not.PAS saved = 0). It does not mean, however, that there is no here acceptable (A <150) cases (there are 220), which indicates q and wide black belt below the A = 150.