Committee 5
Non-linear Structures in Natural Science and Economics

Draft – January 1, 2000
For Conference Distribution Only

Nonlinear Structures and Dynamics in Nontrivial Chemical Systems

Nicholas G. Rambidi
Head of Department, International Research Institute for Management Science
Professor of Physics Department
Moscow, Russia

The Twenty-second International Conference on the Unity of the Sciences
Seoul, Korea February 9-13, 2000

Abstract

Reaction-diffusion media such as nonlinear biochemical enzymatic systems and chemical oscillators represent striking examples of complex behavior based on primitive structure.

The remarkable feature of biomolecular reaction-diffusion systems based on nonlinear dynamic mechanisms is that they are capable to fulfill functions adequate to information processing operations of high computational complexity.

The key important capability of light-sensitive biomolecular media is that they store input information during rather long period of time.

Periodical process of stored image transformation begins after projecting an image onto thin layer of the medium. Responses of the medium to external stimuli are in the basis of image processing operations performed by the medium.

These image processing operations proved to be similar to the human visual capabilities and dependent on the state of the medium.

Based on responses of reaction-diffusion systems on light excitations the attempt was made to take effective solution for finding path in a labyrinth, one of the most known problems of high computational complexity inherent in information processing by biomolecular and biological entities.

Effective "hardware" system was designed capable of finding path in a labyrinth using fast phase waves.

Keywords : nonlinear reaction-diffusion systems, nonlinear structures and dynamics, behavioral complexity of reaction-diffusion systems, solving problems of high computational complexity, image processing, finding path in a labyrinth.

1. Several basic points of departure.

The world around us is complex. And it is the reality that has been defining our understanding of different phenomena we face everyday. They manifest in the absolutely diverse fields of human activity beginning from complicated engineering designs up to sophisticated economic and social problems.

There is no need to discuss here in the problem oriented paper details of different faces of this multivalued concept (see, for instance [1]). Let us make clear only understanding basic notions that will be used below.

Virtually these notions were formulated in the late seventies. According to [2] complexity concept embraces three basic aspects.

"Static complexity represents essentially the complexity of the subsystems that realize the system, dynamic complexity involves the computational length required by the subsystems interconnection to realize the process, and control complexity represents a measure of computational requirements needed to keep the system behaving in a prescribed fashion."

Problems that would be discussed in the paper have a biological background. There are a lot of chemical and biological systems having similar behavioral characteristics (see details below). They include some tissues of living organisms, assemblies of simple microorganisms, biological membranes, sets of coupled biochemical and chemical reactions with nonlinear kinetics and so on. The term "biomolecular system" will be used below for all this entities.

Following [2] let us consider three basic hypostases of the complexity inherent in biomolecular systems capable of information processing. Given the biological background of the problems discussed let us use terms :

-structural complexity of the system (static),

-behavioral complexity that determined the spatio-temporal evolution of the system performing an information processing operation (dynamic),

-computational complexity of an algorithm describing information processing operations performed (control).

Several approaches to the quantitative definition of complexity are in use now. The notion of algorithmic complexity seems to be the most adequate to the complexity estimation of the dynamic system evolution [3,4]. It is defined as minimal length of the assumed program from some set of programs that describe the process adequately.

Numerical estimations of algorithmic behavioral and structural complexity are not used in the paper. All examples which will be discussed below are chosen in a way when the high (or low) degree of behavioral complexity is evident.

Computational complexity of the algorithm describing the system behavior (complexity of the problem) is a characteristic of the practical opportunities to understand this behavior. It can be expressed as a dependence of computational capabilities (resources) necessary for simulation of the system behavior on some specific system characteristic called the problem size [2-4].

Two basic principles could be set based on experimental experience and theoretical considerations that determine high behavioral complexity of the system. They are :

-nonlinear mechanisms of the system dynamics,

-multilevel structural organization with interactions between levels.

Reaction-diffusion media such as nonlinear biochemical enzymatic systems and chemical oscillators represent striking examples of very complex behavior based on primitive structure.

This paper was designed :

-to give examples and to discuss high behavioral complexity of biomolecular systems based on nonlinear dynamic mechanisms,

-to speculate on the assumption that high behavioral complexity of biomolecular media is in close correlation with their capabilities to solve problems of high computational complexity,

-to give examples of complex computations performed by biomolecular media.

2. Non-linearity and behavioral complexity of biomolecular systems.

Diverse and important examples of high behavioral complexity were shown by non-linear biomolecular and biological systems at different levels of organization (structure).

At the tissue level complex oscillatory processes in a human brain are known. Heart rhythm disturbances and sudden death phenomenon are determined by pathological modes of myocardium excitations [5].

At the level of sell assemblies complex dynamic regimes lead to the ordered spatial evolution, for instance, formation of non uniform circular cell distributions in thin layers of DICTYOSTELLUM DISCOIDEUM media [6].

Complex concentration oscillating modes were found for divers chemical and biochemical reactions in biological membranes and cells, that is at supramolecular level [7].

And finally in biomacromolecules, at the molecular level, complex dynamics could be the origin of collective excitations [8].

One of the basic points for understanding features of information processing system functioning is the correlation between its structural and behavioral complexity. It is quite often assumed, for instance for the case of electronic technical systems, that behavioral complexity should increase proportionally to increasing structural complexity. Nevertheless the correlation between structural and behavioral complexity is not so straightforward. The complication of the system structure do lead in many cases to the more complicated behavior. At the same time some very simple systems (for instance, two oscillators with nonlinear coupling) are known that demonstrate complex behavior in spite of the simplicity of their structure [9].

Chemical reaction-diffusion systems (for instance, Belousov-Zhabotinsky media) demonstrate different complex modes of behavior such as concentration oscillations, waves of switching between different states, traveling concentration pulses, stable dissipate structures and so on [10]. Two examples of temporal evolution of the Belousov-Zhabotinsky system are shown in Fig.1.

It is known [10] that the dynamics of distributed nonlinear chemical system which display sufficiently complicated behavior can be described by a system of nonlinear differential equations of the type :

$$\dot{U}_i(r,t) = F\,[U_1(r,t),\ U_2(r,t),\ \dots,\ U_N(r,t)] + \sum_{j=1}^{N} \Delta\,[D_{ij}\,U_j(r,t)] \qquad (3.1)$$

where $U_i(r,t)$ is the concentration of the ith component of reaction proceeding in the system, A is a control parameter, D_{ij} are diffusion coefficients, and

$$N = 1, 2, 3, , N.$$

The behavior of this system is determined by the complicated nonlinear kinetics of reactions at each spatial point r_k, described by functions

$$F\,[U_1(r,t),\ U_2(r,t),\ \dots,\ U_N(r,t)]$$

and also by diffusion of reaction components.

At the same time these excitable systems can be considered as a realization of a neural network where :

-each point of the medium is a primitive microprocessor,

-the dynamics of microprocessors can be characterized by complicated chemical reactions produced by external excitations,

-short-range interactions between primitive processors occur (in principle, each microvolume is coupled with all others by diffusion, but because of a rather low spreading speed, these interactions proceed with a delay proportional to the distance between microvolumes).

In the general form homogeneous neural nets can be described by a system of integrodifferential equations [19] :

$$\dot{U}_i(r,t) = -\frac{U_i(r,t)}{t_i} + G[-T_i - A + Z_i] = -\frac{U_i(r,t}{t_i} + G\{-T_i - A + \quad (3.2)$$

$$+ \sum_{m=1}^{N} \int \Phi_m [r, x, t, U_1, U_2, \ ,U_N]\, U_m(r,t)\, dx \}$$

where $G[-T_i - A + Z_i]$ is the response function for elements of ith type upon activation by Z_i, T_i is the shift in function G , Φ_m is the function of spatial coupling between active elements.

These integro-differential equations can not generally be represented by the above system of kinetic differential equations (see [20]). However, under some assumptions both of these models prove to be adequate.

The remarkable feature of biomolecular systems based on nonlinear dynamic mechanisms is that they are capable to fulfill functions adequate to information processing operations of high computational complexity. Besides of fantastic intellectual capabilities of a neural system let us mention processes of information replication performed by RNA molecules, recognition at the molecular level inherent in enzyme molecules and so on.

This feature of biomolecular systems is in the basis of pseudo biological information processing paradigm that is an important alternative to the unique von Neumann approach in the contemporary digital computing.

3. Pseudo biological vs. von Neumann information processing paradigms.

Two basic methodological approaches have been defining general ways of developing contemporary computing, i.e. theoretical fundamentals, circuitry approaches, technological incarnations, and software elaboration.

General principles lying in the basis of contemporary computers design were formulated in the early forties by John von Neumann. These principles makes the von Neumann approach indispensable for the elaboration of multipurpose computing systems that are capable of optimum solving engineering and many other problems of relatively low computational complexity.

Regretfully the multipurpose character of the von Neumann computers leads to decreasing of computational efficiency, especially for problems of high computational complexity.

At the same time, when von Neumann has elaborated his paradigm, McCulloch and Pitts [11] offered fundamentally different approach to designing information processing devices. This approach was based on general principles of information processing by biological entities and was called pseudo biological one.

According to ideas of McCulloch and Pitts [11] computational system is designed to be analogous in a sense to human brain. Simple processors (neurons) are constituent parts of the system and each of them is connected to all other processors in some definite manner. Therefore computing capabilities of the system are defined by the predetermined complex structure of the system, not by the stored program. Problems are solved by the system with very high degree of parallelism. At the same time storage of information and information processing capabilities of the system are defined by the character of dynamics inherent in the system.

The relative significance of the von Neumann and McCulloch and Pitts paradigms was different during the last decades depending on the character of those practically important problems that were the most vital at that moment for the progress of human activity.

Virtually the computational complexity of problems was of the decisive importance for the choice of the either paradigm.

The vast variety of divers engineering projects - keystones for industry, developing in the forties and fifties, initiated the impetuous progress of the digital von Neumann computing means. Mathematical and computational basis for these projects could be reduced to the problems of rather low (polynomial) computational complexity

And little by little needs to understand and to control processes in biology, meteorology, economics, social sciences and a number of other fields that was defined by problems of high computational complexity gave rise to attempts to elaborate fundamentally different from von Neumann computational approaches.

The pseudo biological paradigm based on McCulloch and Pitts pioneering work was one of the first in the line.

Neural net approach launched by McCulloch and Pitts was based on two fundamental principles inherent in information processing by biological entities. They are :

-"all-or-none" mode of a single neuron activity, that is a kind of nonlinear dynamic mechanisms,

-giant parallelism of neural connections in a neural nets.

Designers of computing means have been repeatedly facing this paradigm during the last several decades. Nonetheless only nowadays, when problems of high computational complexity do define a number of important aspects of human activity, neural net approaches began to give the practical tangible results at both software and hardware levels (see, for instance, [12-14]).

To make clear the contemporary situation let us return to the roots, that is to the fundamentals of biological information processing [15].

The hereditary information code unique in its designing together with specific information transfer mechanisms provides biological system with stability in the process of reproduction. At the same time the possibilities to modify this information in the process of evolution supply a biological system with the ability to adaptation under changing external stimuli.

The molecular recognition processes ensure the directed information transfer in a biomolecular system and exclude therefore the random search of variants.

The giant parallelism exceeding immensely possible degree of parallelism of contemporary digital semiconductor devices is inherent in biological information processing systems.

Important is the ability to perform as primitive complex logical operations equivalent to a big number of binary ones.

Nonlinear mechanisms of information processing are responsible for a number of complex responses biomolecular and simple biological system to external stimuli equivalent to solving problems of high computational complexity.

And finally the multilevel architecture enables biomolecular and simple biological systems to perform information processing operations of high computational complexity.

These fundamentals are of different importance for solving problems of high computational complexity.

The nonlinear mechanisms inherent in the dynamics of distributed biomolecular systems seem to be the basic fundamental that determined the information processing for problems of high computational complexity (see details in [16-18]).

The second in the line fundamental that gives to the system the ability to solve computationally complex problems is its multilevel organization. The main principles and details of organization were discussed in details by Nikolis (see, for instance [9]).

Coming from these considerations and having in mind speculations of the previous section note that both behavioral complexity of the system and its ability to solve problems of high computational complexity are determined by the same fundamentals of a reaction-diffusion system. Therefore the degree of behavioral complexity could be a decisive point for the choice of a system capable to solve computationally complex problems.

Based on these considerations it is natural to broaden the boundaries of the pseudo biological paradigm in comparison with McCulloch and Pitts original approach and particularly :

-to include in the scope of the approach distributed information processing media,

-to use biomolecular information processing systems having more complicated nonlinear dynamics than in the case of McCulloch and Pitts neural networks,

-to look for possibilities of the system multilevel organization.

4. Miraculous Belousov-Zhabotinsky type media : image processing capabilities.

Two remarkable events that happened in early fifties were the starting points for intense investigations in the new thrilling field in between physics, chemistry and biology where systems far from equilibrium demonstrate different and complicated modes of behavior.

Chronologically they were:

-the discovery of periodic regimes in catalytic reaction of the citric acid oxidation by Belousov [10,21],

-the paper "The Chemical Basis of Morphogenesis." [22] published by Alan Turing who first discussed the problem of self organization in far from equilibrium systems.

Later Zhabotinsky [23] performed extensive study of Belousov reaction and developed its very convenient modified version.

These events have initiated intense research activity on complex spatio-temporal behavior in physical, chemical and biological systems during the last several decades and provided the basis for modern theories of biological patterns and forms.

Between different chemical oscillators Belousov-Zhabotinsky type media plays the principal role. The nonlinear dynamics of these media are complex enough to demonstrate diverse and complicated behavior (see two important examples in Fig.1). Therefore they have became the invaluable model systems for excitable media providing deep insights into the properties of nonlinear dynamic chemical and biological systems.

The Belousov-Zhabotinsky type reaction is a catalytic oxidation of some organic substance (mainly malonic acid) by potassium bromate or some other oxidizing agent. The mechanism of this process is complex and is determined by a nonlinear kinetics of intermediate stages of the process and diffusion.

At the same time these media are stable, non-hostile reagents. Furthermore the temperature range and temporal operation scale of the medium dynamics are convenient for investigation with available physical methods.

The Belousov-Zhabotinsky type media based on a light-sensitive catalyst are convenient for investigation purposes. The catalyst in the course of reaction, when the medium goes from one stable state into another, changes its electronic state. As a consequence the reagent changes its color (from red to blue and vice versa). Therefore it is easy to visualize the process and to observe its spatio-temporal evolution.

Practical experimental aspects of information processing by reaction-diffusion media are not considered in the paper. This information detailed enough could be found in [24].

> There is no problem to reproduce some results that will be discussed below using very simple experimental technique. Nevertheless the complication of problems to be solved compels to design more and more sophisticated devices. The most important and decisive point is designing reaction-diffusion media (see [25]).

The key important feature of light-sensitive excitable media is that they store input information during rather long period of time. Periodical process of stored image transformation begins after projecting an image onto thin layer of the medium [26].

This process represents a combination of three interlaced primitive responses to the light excitation :

-consecutive emergence of negative and positive images of an input picture,

-contour enhancement of the image fragments,

-disappearance of small features of the picture.

These primitive responses depending on the state of the medium is shown in Fig.2. It should be stressed that these complex responses are primitive behavioral operations for a reaction-diffusion medium and that they determine the character of primitive information processing operations that could be performed by the medium.

Image processing operations performed by active chemical media proved to be similar to the human visual capabilities and dependent on the state of the medium [26]. There are two main sets of them.

The first of them can be defined as "description of the general features of an object". This set includes such primitive operations as concentration on the general outline of an image (Fig.3A), removing small immaterial features (Fig.3B), "addition to the whole" operations, and, in particular, restoration of an image having defects (Fig.3C).

The second set of image processing operations can be determined as "switching to the details of an image". It includes contour enhancement (Fig.4A), segmentation, that is division of an image into simple parts (Fig.4B), image skeletonizing, italicizing small features of an image (Fig.4C).

In the case of complex images having several levels of brightness primitive image processing operations proved to be complicated combinations of the basic responses of excitable media to the light excitation [27].

It proved to be that in the process of the input image evolution all fragments having different brightness are consecutively enhanced at different stages of evolution.

Processing an image similar to pictures taken from satellites or reconnaissance planes are shown in Fig.5 . It could be seen that the most dark fragments are enhanced first in the process of evolution and after that the most light ones. Therefore the use of excitable media seems to be attractive potential way for the processing of satellite or aerial information.

5. More complicated problem : finding path in a labyrinth.

During the last decades many proposals were made how to take effective solution for finding path in a labyrinth, one of the most known problems of high computational complexity inherent in information processing by biomolecular and biological entities. Proposals were particularly made to use technique attractive enough for solving this problem based on wave processes in reaction-diffusion media. Trigger waves in reaction-diffusion systems spread simultaneously through all paths of the labyrinth in a highly parallel mode. This mode seem to be put into the basis of the computational technique for finding path in a labyrinth. Regretfully the velocity of these waves is extremely low that gave no way for practical implementation of this technique till now.

Effective “hardware” system was designed capable of finding path in a labyrinth using fast phase waves [28].

Three principal points were assumed as a basis for this design. They are the following:

-hybrid architecture that combined information processing reaction-diffusion medium which perform operations of high computational complexity with digital computer carrying out supplementary image processing operations,

-light-sensitive information processing media of Belousov-Zhabotinsky type that enable to simulate the labyrinth and spreading wave evolution by their images stored in the medium and to reduce the problem to the image processing operations,

-fast light-induced phase wave processes that spread through the labyrinth in several seconds instead of hours typical for trigger waves inherent in reaction-diffusion media.

These fundamentals along with additional procedure of testing for labyrinth fragments connectedness gave the opportunity to solve labyrinth problems.

The wave spreading in the labyrinth starting from the point of input to the output is shown in Fig.6 . Since this process is taking place for about 3 - 5 seconds it is easy to record consecutive steps of this spreading. Some of them are shown in Fig.6 .

Taking a set of consecutive images of the wave spreading the basic problem arises : how to use this data for finding a path from the input to output.

In the process of the wave spreading when the wave goes over a branching point the labyrinth is divided into two (or more) fragments. One of these is connected with the output, but other is not. It is easy to find the fragment connected with output initiated the backward wave from the point of output in reaction-diffusion medium. As a result this fragment changes its color and the color of the non connected fragment remains unchanged.

More effective solution is to change this auxiliary reaction-diffusion process by numerical processing the image of the labyrinth at this step of its evolution stored in the memory of the computer, namely to use Paint Bucket operation initiated at the point of output from the labyrinth. This operation changes the color of this fragment to the color of a background. Subtracting the image obtained after Paint Bucket operation from the initial labyrinth image enables to remove fragment not connected with the output.

Successive repetition of this procedure at each branching point gives the opportunity to exclude all fragments coming to deadlocks (and to other outputs in general case) and to determine the path from the input to the output.

6. Numerical modeling : from the generation of button textures up to image processing.

The variety of reaction-diffusion simulations performed during the several last decades is rather broad.

The first fundamental work in this field was the paper by great Alan Turing titled "The chemical basis of morphogenesis" [22]. It was the simulations of the biological differentiation processes based on nonlinear kinetic equations describing a set of coupled chemical reactions. It was also one of the first examples shown that nonlinear dynamic mechanisms could be in the basis of high behavioral complexity of the biological system.

This biological line of reaction-diffusion simulations have been continued till now including the broad scope of problems - from models of biological pattern formation such as giraffe or zebra skin patterns up to applications to population dynamics (see, for instance, [29] and references in it).

Similar technique was used for purely practical purposes such as computer graphics (see [30]). It gave the opportunity to generate different reaction-diffusion textures for picturesque buttons, specific art painting and so on. It should be mentioned that high behavioral complexity of reaction-diffusion media revealing in textures seems to be in the basis of the human sense of beauty.

Very important were repeatedly approaches to simulate regimes inherent in Belousov-Zhabotinsky and other reaction-diffusion media. They enabled to calculate different reaction-diffusion patterns including evolution of breathing spots, spiral and labyrinthine patterns (for instance, [31,32])

Three-dimensional reaction-diffusion systems represent fantastic picture of complex behavior [33]. Basic results in this attractive and promising field were obtained by numerical simulations because of big difficulties in obtaining reliable experimental information. Apart from general importance of the field these investigations are indispensable for understanding features of dynamic mechanisms inherent in cardiac muscle and nerve networks activity.

The simulation of image processing capabilities of reaction-diffusion systems is another remarkable direction of investigations [34-36].

Yakhno with coworkers [34,35] used equations (3.2) that describe media having short-range nonlocal interactions. They found out that simulations is capable to describe a number of image processing operations (see, for instance, Fig.7). They embrace :

-contour enhancement,

-transformation of halftone images into high contrast ones,

-image skeletonizing,

-extraction of lines having a given direction,

-calculation of invariant features.

Let us mention that this example shows some practical advantage of numerical simulations of reaction-diffusion system activity in comparison with experimental studies.

Contrary to experimental investigations the numerical simulations give the opportunity to use unreal medium characteristics (for instance, anisotropic coupling functions) and to model regimes that can't be reproduced in experiment. As a result the system proves to be able to perform more sophisticated information processing operations such as enhancement of sharp corners of an image or lines turned to predetermined direction. In other words the following sequence of steps is seen : complication of the medium dynamic characteristics - increasing behavioral complexity - performing more complicated information processing operations.

These simulations are in a good correlation with experimental results. They conform at the theoretical level the close correlation between behavioral complexity of the system and its ability to solve problems of high computational complexity.

Cellular automata technique were an important part of the numerical simulations of reaction-diffusion media.

Between different realization of this technique two directions of the investigations should be mentioned.

Tyson and his coworkers succeeded to simulate complicated modes of Belousov-Zhabotinsky type media (see, for instance, [37] and references to it).

Adamatzky used cellular automata calculations to analyze important characteristics of reaction-diffusion media and potentialities of their practical use ([38] and references to it).

7. Future implications - towards a biomolecular computer.

An attempt was made above to show that high behavioral complexity of the biomolecular systems could be correlated with the ability of the system to solve problems of high computational complexity. The natural further spreading this assumption is to suppose that biomolecular dynamic systems having more complicated behavior than discussed above would be capable of solving much more complicated problems.

Separate considerations show that potential implementations of biomolecular dynamic systems are fare from exhausted.

One of the basic features of these systems is a high degree of self-organization. They display gradualism that is small changes of a dynamic system composition, within definite limits, lead to comparatively small quantitative not qualitative changes in system dynamics. Nonlinear molecular dynamic systems shows also another features necessary for displaying adaptive behavior such as the character of the interaction with an environment, feedback organization and so on. Therefore it seems to be possible to design a system capable of learning.

There are two general ways to realize these advanced capabilities.

First of these is to look for sophisticated dynamic mechanisms that would be capable to increase the behavioral complexity of the system and as a consequence the computational complexity of problems solving by the system.

Experimental data and theoretical considerations show that this approach seems to open new potentialities for practical implementation of complex information processing operations (see, for instance, [39]).

The second of these ways represents designing complicated architectures, particularly multilevel biomolecular information processing systems.

There were a number of theoretical estimations and experimental investigations that open the practical approaches to designing these systems (see [40-45]).

Experimental technique for finding path in a labyrinth [28] is one of the examples of this approach implementation. The main and decisive feature of this system is its two-level character, that is dividing the system into two parts representing the catalyst immobilized on the solid support and all other components of the chemical system in the liquid phase.

This short and superficial enough survey of reaction-diffusion media potentialities shows that this attractive and promising field would give important practical results in not so distant future. And that complexity background is one of keystones for the progress of the field.

References :

1. S. Beer, Managing Modern Complexity: Futures 2, 1970, pp. 245-257.

2. J. Kasti. Connectivity, Complexity, and Catastrophe in Large-Scale Systems, John Wiley & Sons, Chichester-New York-Brisbane-Toronto, 1979, p.44.

3. D. B. Yudin, A. D. Yudin. The Number and the Thought, Znanie, Moscow, 1985, pp. 26-35 (in Russian).

4. Ming Li, P. Vitanyi. An Introduction in Kolmogorov Complexity and Its Applications, Springer-Verlag, New York, 1993.

5. A. T. Winfree, Electrical Turbulence in Three-Dimensional Heart Muscle, Science 266: 1994, pp. 1003-1006.

6. I. Prigogine. FROM BEING TO BECOMING : time and complexity in the physical sciences, W.H.Freeman and company, San Francisco, 1980.

7. A. Goldbetter. Biochemical Oscillations and Cellular Rhythms, Cambridge University Press, Cambridge, 1997.

8. A. S. Davydov. Solitons in molecular systems, Naukova Dumka, Kiev, 1984 (in Russian).

9. J. S. Nicolis. Dynamics of Hierarchical Systems. An Evolutionary Approach, Springer Verlag, Berlin-Heidelberg-New York-Tokyo, 1986.

10. R. J. Field , M. Burger (Eds.). Oscillation and traveling waves in chemical systems. Wiley-Interscience, New York, 1985.

11. W. J. McCulloch, W. Pitts, A logical calculus of the ideas immanent in nervous activity. Bulletin of Mathematical Biophysics 5: 1943, pp. 115-133.

12. R. Niels, G. Hepner, Application of an artificial neural networks to land-cover classification of thematic mapper imagery. Computers and Geosciences 16, 1990, pp. 873-880.

13. S. I. Lee James, D. Nguyen Dziem, C. Lin, Adaptive moving object tracking integrating neural networks and intelligent processing. SPIE seminars Proceedings 1002, 1989, pp. 316-323.

14. T. Trouder, W. Merril, A real-time neural-net estimator of fatigue life, International Joint Conferences on Neural Networks 2, 1990, pp. 59-64.

15. N. G. Rambidi, Biomolecular computer: roots and promises. BioSystems 44, 1997, pp. 1-15.

16. S. Grossberg, Nonlinear Neural Networks: Principles, Mechanisms, and Architectures, Neural Networks 1, 1988, pp. 17-61.

17. S. Grossberg, On the development of feature detectors in the visual cortex with applications in learning and reaction-diffusion systems. Biological Cybernetics 21, 1976, pp. 145-159.

18. N. G. Rambidi, A. V. Maximychev, Molecular image processing devices based on chemical reaction systems. 6: Processing half-tone images and neural network architecture of excitable media. Advanced Materials for Optics and Electronics 7, 1997, pp. 171-182.

19. A. V. Masterov, M. I. Rabinovich, V. N. Tolkov, V. G. Yakhno. Studies of regimes of autowaves and autostructures interaction in neural net like media. V. G, Yakhno (Ed.), Collective dynamics of excitations and structure formation , Institute of Applied Physics of the USSR Academy of Sciences, Gorky, 1988, pp. 89-104 (in Russian).

20. Y. A. Vasilev, Yu. M. Romanovsky, D. S. Chernavsky, V. G. Yakhno. Autowave processes in kinetic systems, Verlag der Wissenschaften, Berlin, 1987.

21. R. Kapral, K. Showalter (Eds.). Chemical waves and patterns, Kluwer Academic Publishers, Dordrecht-Boston-London, 1995.

22. A. M. Turing, The chemical basis of morphogenesis. Philosophical Transactions of the Royal Society London B327, 1952, pp. 37-72.

23. A. M. Zhabotinsky, Periodic processes of malonic acid oxidation in a liquid phase. Biofizika 9, 1964, p. 306, (in Russian).

24. N. G. Rambidi, A. V. Maximychev, A. V. Usatov, Molecular image processing devices based on chemical reaction systems. 1: General principles for implementation. Advanced Materials for Optics and Electronics 4, 1994, pp. 179-190.

25. N. G. Rambidi, T. O.-O. Kuular, E. E. Makhaeva, Information-processing Capabilities of Chemical Reaction-Diffusion Systems. !. Belousov-Zhabotinsky Media in Hydrogel Matrices and on Solid Supports, Advanced Materials for Optics and Electronics 8, 1998, pp. 163-171.

26. N. G. Rambidi, A. V. Maximychev, Molecular image processing devices based on chemical reaction systems. 3: Some operational characteristics of excitable light-sensitive media used for image processing, Advanced Materials for Optics and Electronics 5, 1995, pp. 223-231.

27. N. G. Rambidi, A. V. Maximychev, Molecular image processing devices based on chemical reaction systems. 5: Processing images with several levels of brightness and some application potentialities. Advanced Materials for Optics and Electronics 7, 1997, pp. 161-170.

28. N. G. Rambidi, D. Yakovenchuk, Information-processing capabilities of Chemical Reaction-Diffusion Systems. 2: Finding Path in a Labyrinth Based on Reaction-Diffusion Media. Advanced Materials for Optics and Electronics 8, 1998, pp. 00-00.

29. G. Turk, Generating Textures on Arbitrary Surfaces Using Reaction-Diffusion. Computer Graphics 25, 1991, pp. 289-298.

30. A. Witkin, M. Kass, Reaction-Diffusion Textures. Computer Graphics 25, 1991, pp. 299-308.

31. D. Haim, G. Li, Q. Quyang, W. D. McCormick, H. L. Swinney, A. Hagberg, E. Meron, Breathing spots in reaction-diffusion systems. Physical Review Letters 77, 1996, p. 190.

32. A. Hagberg, E. Meron, From labyrinthine patterns to spiral turbulence. Chaos 4, 1994, p. 477.

33. A. T. Winfree. The Geometry of Excitability. L. Nadel, D. Stein (Eds.), 1992 Lectures in Complex Systems, Addison Wesley Publishing Company, Reading-Menlo Park-New York-Amsterdam-Bonn-Sydney-Singapore-Tokyo-Madrid-Paris-Seul-Milan-MexicoCity-Taipei, 1993.

34. N. S. Bellustin, S. O. Kuznetsov, I. V. Nuidel, V. G. Yakhno, Neural Networks with Close Nonlocal Coupling for Analyzing Composite Images. Neurocomuting 3, 1991, pp. 231-246.

35. S. O. Kuznetsov, I. V. Nuidel, A. I. Panfilov, V. G. Yakhno, Image preprocessing by neuron-like algorithms. SPIE Proceedings 3402, 1998, pp. 479-485.

36. C. B. Price, P. Wambacq, A. Oosterlinck, Image Enhancement and analysis with reaction-diffusion paradigm. IEE Proceedings 137, 1990, pp. 136-145.

37. J. R. Weimar, J. J. Tyson, L. T. Watson, Diffusion and wave propagation in cellular automaton models of excitable media. Physica D 55, 1992, pp. 309-327.

38. A. Adamatzky, Dynamical universal computations in excitable lattices, M. Margenstern, Ed., Proceedings of 2nd International Colloquium Universal Machines and Computations, v. 2, 1998, pp. 194-214.

39. A. S. Mikhailov, Collective dynamics in communicated populations. H. Haken, A. S. Mikhailov (Eds.), Interdisciplinary Approaches to Nonlinear Complex Systems, Springer Verlag, New York, 1993, pp. 89-108.

40. A. Hjelmfelt, F. W. Schneider, J. Ross, Pattern Recognition in Coupled Chemical Kinetic Systems. Science 260, 1993, pp. 335-337.

41. A. Hjelmfelt, J. Ross, Pattern Recognition, chaos, and multiplicity in neural networks of excitable systems. Proceedings of the National Academy of Sciences USA 91, 1994, pp. 63-67.

42. I. R. Epstein, Experimental and theoretical studies of coupled chemical oscillators. Reaction Kinetic and Catalysis Letters 42, 1990, pp. 241-252.

43. J. P. Laplante, T. Erneux, Propagation failure and multiple steady states in an array of diffusion coupled flow reactors. Physica A 188, 1992, pp. 89-98.

44. J. P. Laplante, M. Pemberton, A. Hjelmfelt, J. Ross, Experiments on Pattern Recognition by Chemical Kinetics. Journal of Physical Chemistry 99, 1995, pp. 10063-10065.

45. Dechert, K.P. Zeyer, D. Lebender, F. W. Schneider, Recognition of Phase patterns in a Chemical Reactor Network. Journal of Physical Chemistry 100, 1996, pp. 19043-19048.

Figure legends

Fig.1. Two modes of a Belousov-Zhabotinsky reaction in thin (pseudo two dimensional) layers of the reagent. A - the process of trigger waves spreading corresponding to the switching of the medium from one stable state to another. B - the emission of circular waves from point-wise sources and their further evolution.

Here and in the following figures gray arrows show steps of the image transformation by the reaction-diffusion medium, black arrows correspond to input of an initial image into medium.

Fig.2. Temporal evolution of simple images (initial images are to the left) in thin layers of light-sensitive Belousov-Zhabotinsky type media depending of the state of the medium (A1 - A3), and on the character of the input image (A - B).

Fig.3. Some details of the temporal evolution of images in light-sensitive Belousov-Zhabotinsky type media and results of primitive image processing operations performed by the medium. A - smoothing of immaterial features of the image, B - removing of small features, C - defect repair. (initial images are in the first row above, results are in the last row at the bottom)

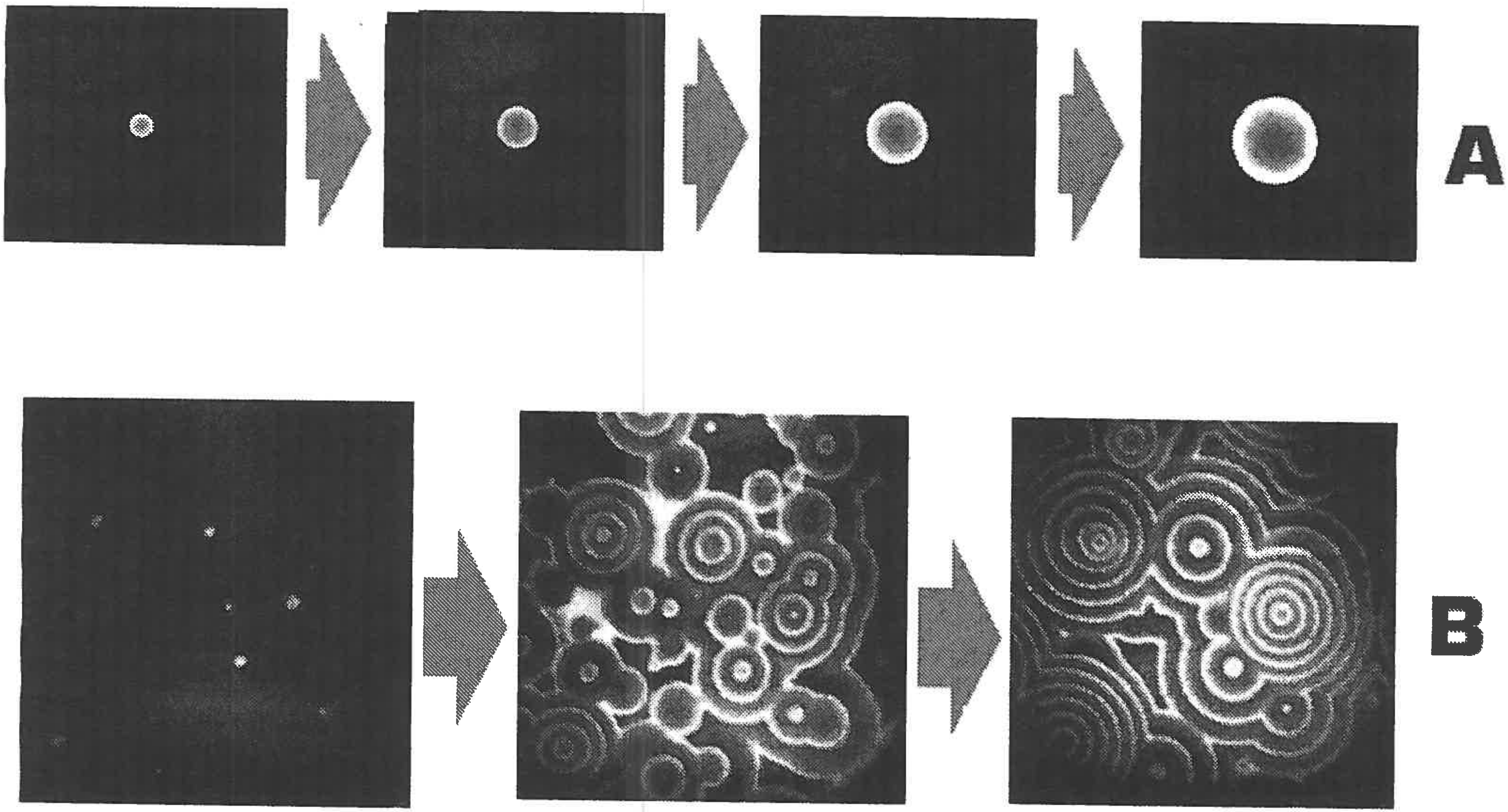
Fig.4. Some details of the temporal evolution of images in light-sensitive Belousov-Zhabotinsky type media and results of primitive image processing operations performed by the medium. A - contour enhancement, B - segmentation of the image, C - enhancement of small features. (initial images are in the first row above, results are in the last row at the bottom)

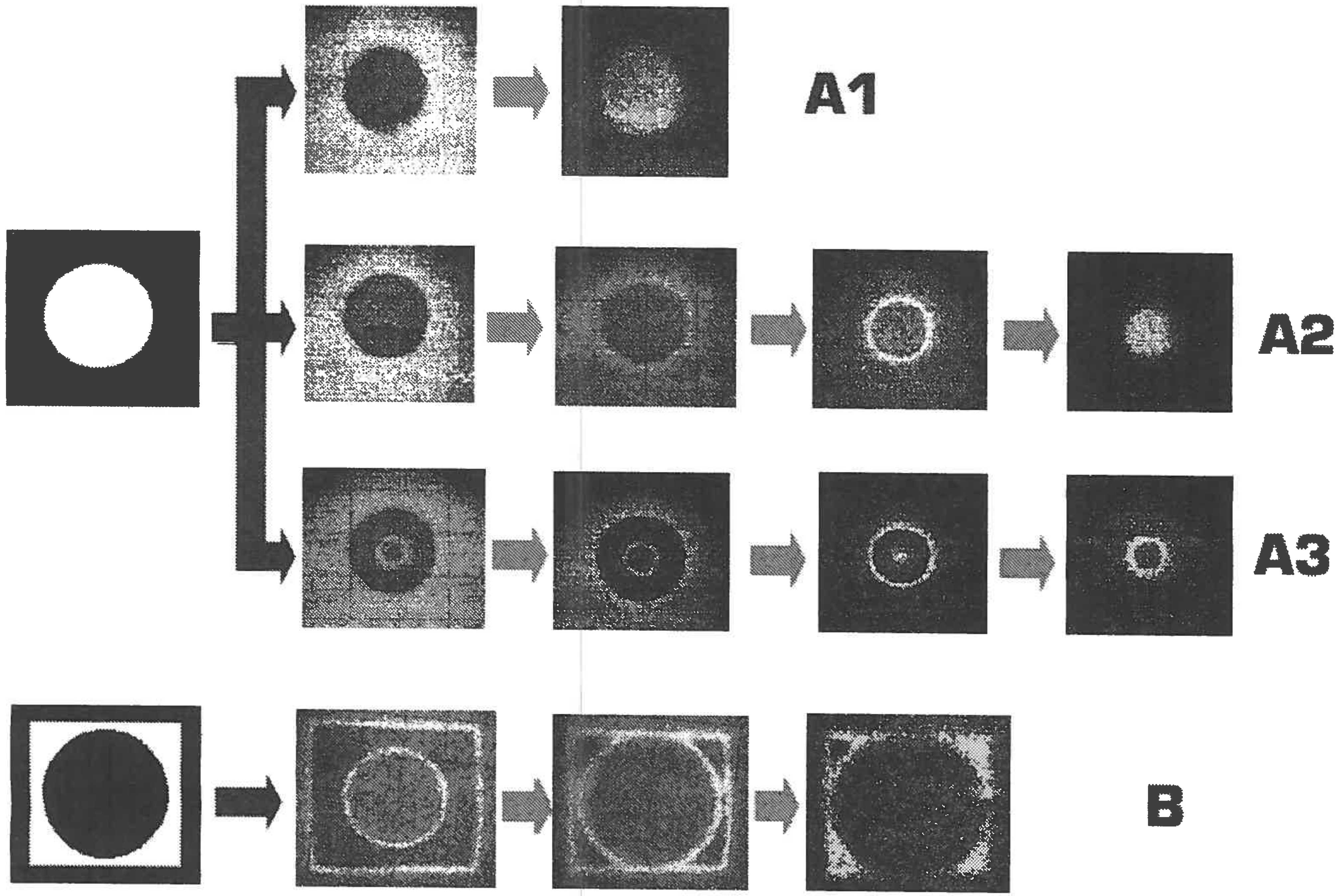
Fig.5. Evolution of artificial aerial picture in a light-sensitive Belousov-Zhabotinsky type medium.

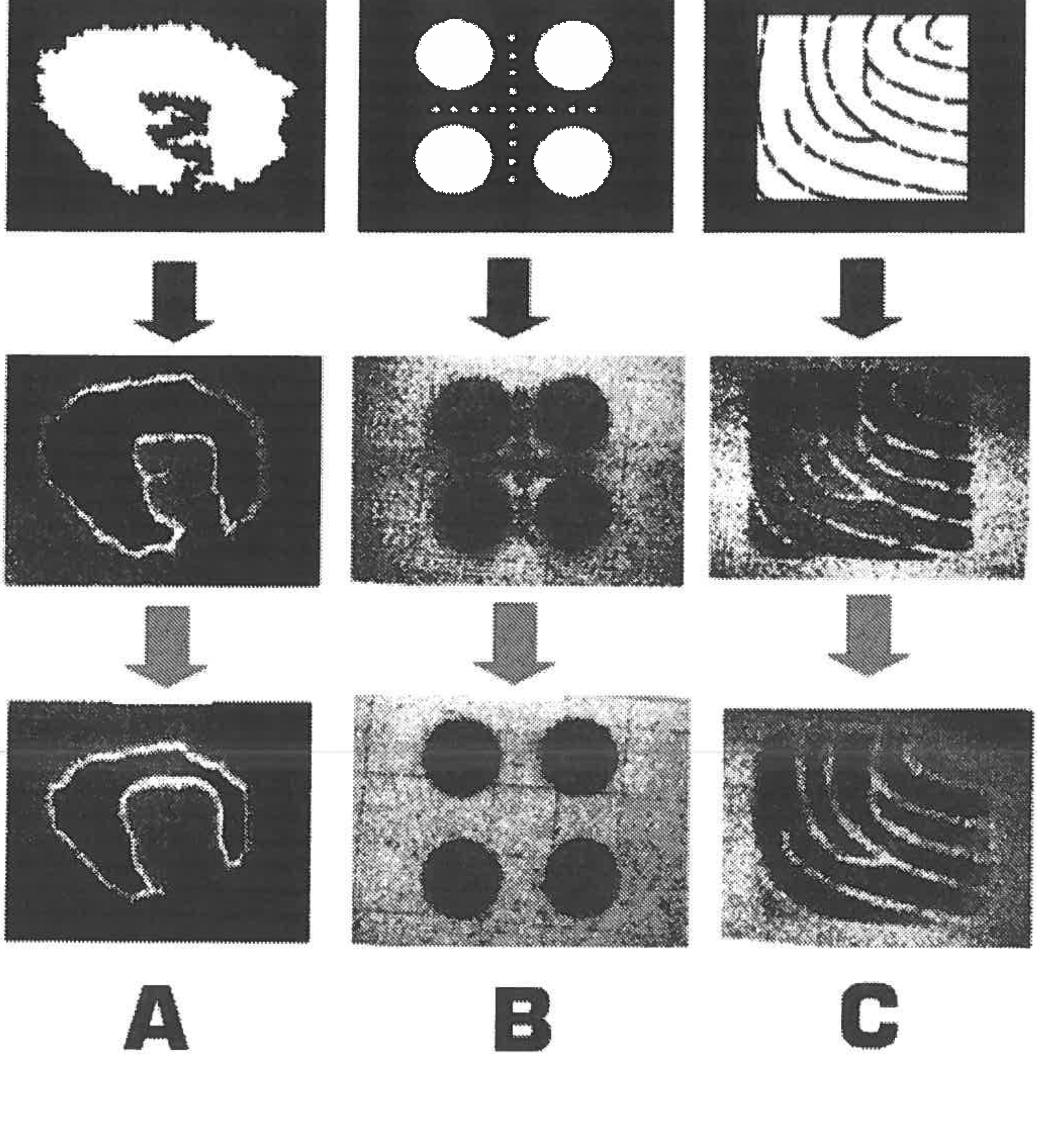
Fig.6. The spreading of a phase wave in a labyrinth and finding the shortest way from input to the output. Initial labyrinth image is shown at the left above, above to the right is initial image combined with nonuniform background that initiate a phase wave. Filling the fragment of the labyrinth connected with the output by the white color is shown in dotted brackets (left). Image of the labyrinth after subtracting of the fragment non connected with the output is in the dotted

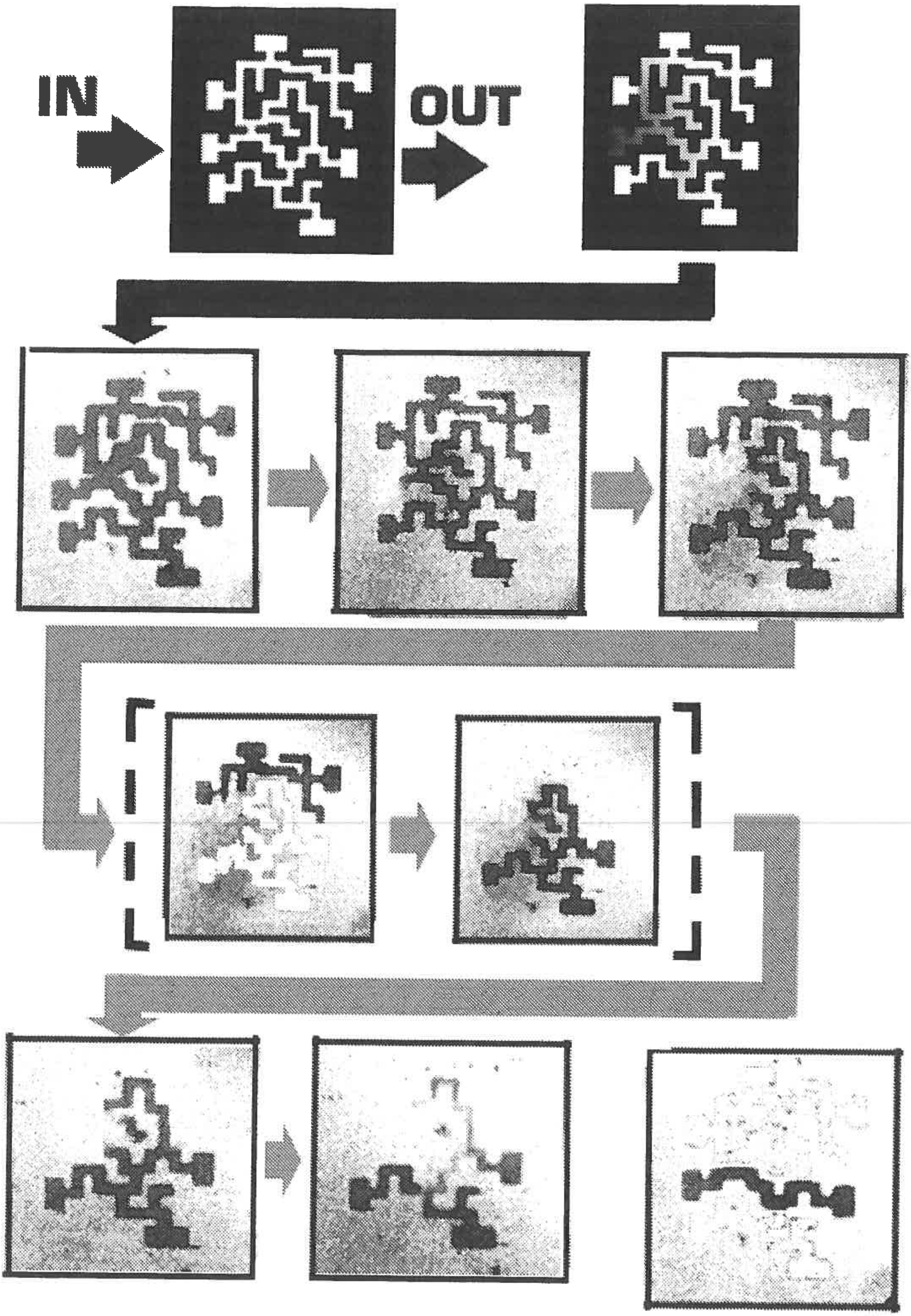
brackets to the right. The shortest way from input to the output is shown in the right bottom corner of the figure.

Fig.7. Numerical simulations of image processing operations based on reaction-diffusion equations. Initial half-tone image is sown in upper part of the picture. Results of simulation different due to divers choice of coupling functions and shifts are : enhancement of thin and thick contour, contrast enhancement, enhancement of lines having different slope and corners of the image, skeleton of the image.


A
B


A1
A2
A3
B


A
B
C


IN
OUT