BIO-INSPIRED DATA AND SIGNALS CELLULAR SYSTEMS

André Stauffer, Daniel Mange and Joël Rossier
Logic Systems Laboratory, Ecole polytechnique fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland

Keywords: Self-organization, configuration, cloning, cicatrization, regeneration.

Abstract: Living organisms are endowed with three structural principles: multicellular architecture, cellular division, and cellular differentiation. Implemented in digital according to these principles, our data and signals cellular systems present self-organizing mechanisms like configuration, cloning, cicatrization, and regeneration. These mechanisms are made of simple processes such as growth, load, branching, repair, reset, and kill. The data processed in the self-organizing mechanisms and the signals triggering their underlying processes constitute the core of this paper.

1 INTRODUCTION

Borrowing three structural principles (multicellular architecture, cellular division, and cellular differentiation) from living organisms, we have already shown how to grow cellular systems thanks to two algorithms: an algorithm for cellular differentiation, based on coordinate calculation, and an algorithm for cellular division (Mange et al., 2004). These cellular systems are endowed with self-organizing properties like configuration, cloning, cicatrization, and regeneration (Stauffer et al., 2005).

In a previous work (Stauffer et al., 2006), the configuration mechanisms (structural and functional growth), the cloning mechanisms (cellular and organismic growth), the cicatrization mechanism (cellular self-repair), and the regeneration mechanism (organismic self-repair) were already devised as the result of simple processes like growth, load, branching, repair, reset, and kill. The goal of this paper is to point out the data processed in these mechanisms and the signals triggering their underlying processes. Starting with a minimal system, a cell made up of six molecules, Section 2 will introduce digital simulations to describe the data and the signals involved in the self-organizing mechanisms and the corresponding processes. We define then a small organism made of three cells, the "SOS" acronym, as an application example for the simulation of our mechanisms and processes (Section 3). A brief conclusion (Section 4) summarizes our paper and opens new research avenues.

2 SELF-ORGANIZING MECHANISMS

2.1 Structural Configuration

The goal of the *structural configuration mechanism* is to define the boundaries of the cell as well as the living mode or spare mode of its constituting molecules. This mechanism is made up of a *structural growth process* followed by a *load process*. For a better understanding of these processes, we apply them to a minimal system, a cell made up of six molecules arranged as an array of two rows by three columns, the third column involving two spare molecules dedicated to self-repair.

The *growth process* starts when an external *growth signal* is applied to the lower left molecule of the cell (Fig. 1a) and this molecule selects the corresponding eastward data input (Fig. 1b). According to the *structural configuration data* or *structural genome*, each molecule of the cell generates then successively an internal *growth signal* and selects an input (Fig. 2), in order to create a data path among the molecules of the cell (Fig. 1b-g). When the connection path between the molecules closes, the lower left molecule delivers a *close signal* to the nearest left neighbor cell (Fig. 1h). The structural configuration data is now moving around the data path and ready to be transmitted to neighboring cells.

The *load process* is triggered by the *close signal* applied to the lower right molecule of the cell (Fig. 3a). A *load signal* propagates then westward and northward through the cell (Fig. 3b-d) and each of

Stauffer A., Mange D. and Rossier J. (2008).
BIO-INSPIRED DATA AND SIGNALS CELLULAR SYSTEMS.
In *Proceedings of the First International Conference on Bio-inspired Systems and Signal Processing*, pages 203-207
DOI: 10.5220/0001057402030207

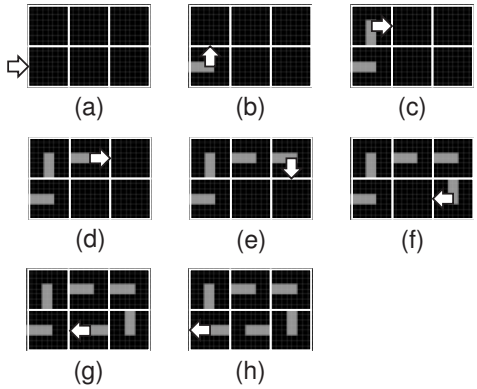

Figure 1: Structural growth process of a minimal system, a cell made up of six molecules. (a) External growth signal is applied to the lower left molecule. (b-g) Generation of internal growth signals to build the structural data path. (h) Closed path and close signal delivered to the nearest left neighbor cell.

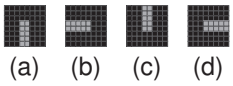

Figure 2: Data input selection. (a) Northward. (b) Eastward. (c) Southward. (d) Westward.

its molecules acquire a *molecular mode* (Fig. 4) and a *molecular type* (Fig. 5). We finally obtain an homogeneous tissue of molecules defining both the boundaries of the cell and the position of its *living mode* and *spare mode* molecules (Fig. 3e). This tissue is ready for being configured by the functional configuration data.

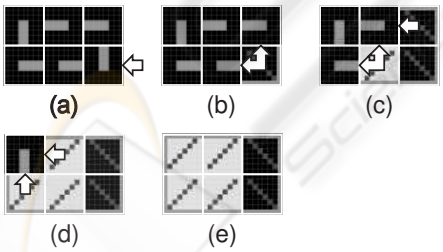

Figure 3: Load process. (a) External close signal applied to the lower right molecule by the nearest right neighbor cell. (b-e) Generation of internal load signals propagating westward and northward to store the molecular modes and types of the cell.

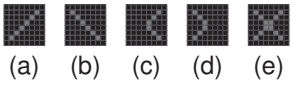

Figure 4: Molecular modes. (a) Living. (b) Spare. (c) Faulty. (d) Repair. (e) Dead.

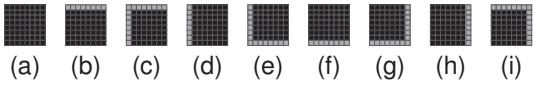

Figure 5: Molecular types. (a) Internal. (b) Top. (c) Top-left. (d) Left. (e) Bottom-left. (f) Bottom. (g) Bottom-right. (h) Right. (i) Top-right.

2.2 Functional Configuration

The goal of the *functional configuration mechanism* is to store in the homogeneous tissue, which already contains structural data (Fig. 3e), the functional data needed by the specifications of the current application. This mechanism is a *functional growth process*, performed only on the molecules in the *living mode* while the molecules in the *spare mode* are simply bypassed. It starts with an external *growth signal* applied to the lower left living molecule (Fig. 6a). According to the *functional configuration data* or *functional genome*, the living molecules then successively generate an internal *growth signal*, select an input, and create a path among the living molecules of the cell (Fig. 6b-f). The functional configuration data is now moving around the data path and ready to be transmitted to neighboring cells.

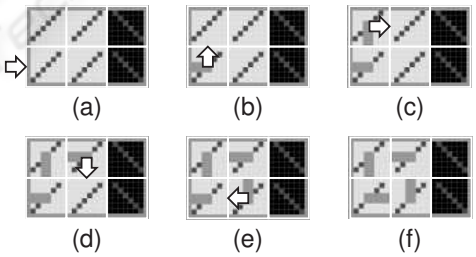

Figure 6: Functional configuration of the cell performed as a functional growth process applied to the living molecules. (a) External growth signal is applied to the lower left molecule. (b-e) Generation of internal growth signals in order to build the functional data path. (f) Closed functional data path.

2.3 Cloning

The *cloning mechanism* or *self-replication mechanism* is implemented at the cellular level in order to build a multicellular organism and at the organismic level in order to generate a population of organisms. This mechanism suppose that there exists a sufficient number of molecules in the array to contain at least one copy of the additional cell or of the additional organism. It corresponds to a *branching process* which

takes place when the structural and the functional configuration mechanisms deliver northward and eastward growth signals on the borders of the cell during the corresponding growth processes (Fig. 7).

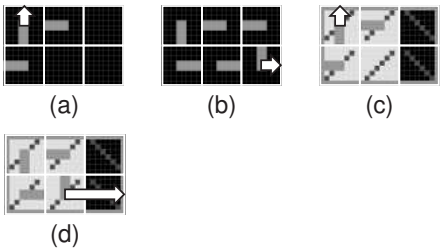

Figure 7: Generation of growth signals triggering the cloning mechanism. (a) Northward structural branching process. (b) Eastward structural branching process. (c) Northward functional branching process. (d) Eastward functional branching process.

2.4 Cicatrization

Fig. 6f, shows the normal behavior of a healthy minimal cell, i.e. a cell without any faulty molecule. A molecule is considered as faulty, or in the *faulty mode*, if some built-in self-test detects a lethal malfunction. Starting with the normal behavior of Fig. 6f, we suppose that two molecules will become suddenly faulty (Fig. 8a): (1) The lower left molecule, which is in the *living mode*. (2) The upper right molecule, which is in the *spare mode*. While there is no change for the upper right molecule, which is just no more able to play the role of a spare molecule, the lower left one triggers a *cicatrization mechanism*. This mechanism is made up of a *repair process* involving eastward propagating *repair signals* (Fig. 8b-c) followed by a *reset process* performed with westward and northward propagating internal *reset signals* (Fig. 8d-g). This tissue, comprising now two molecules in the *faulty mode* and two molecules in the *repair mode*, is ready for being reconfigured by the functional configuration data. This implies a *functional growth process* bypassing the faulty molecules (Fig. 9).

2.5 Regeneration

Our minimal system comprises a single spare molecule per row and tolerates therefore only one faulty molecule in each row. A second faulty molecule in the same row will cause the death of the whole cell, and the start of a *regeneration mechanism*. Fig. 10 illustrates the *repair process* and *kill process* involved in this mechanism. Starting with the normal behavior of the cicatrized cell (Fig. 9f), a new

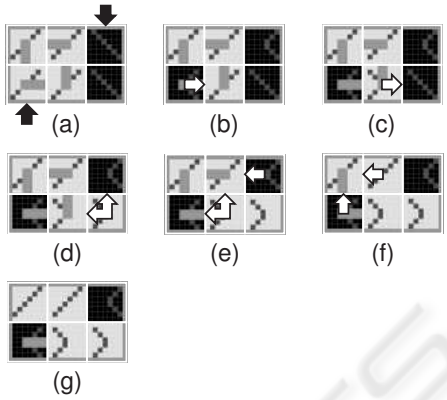

Figure 8: Cicatrization mechanism performed as a repair process followed by a reset process. (a) Living and spare molecules becoming faulty. (b-c) Generation of repair signals propagating eastward. (d-f) Generation of internal reset signals propagating westward and northward. (g) Cell, comprising two faulty and two repair molecules, ready for functional reconfiguration.

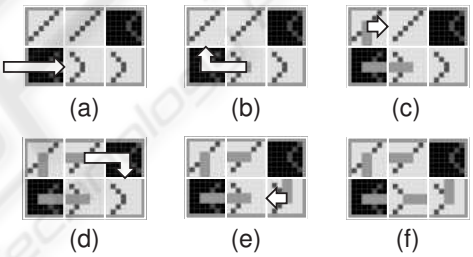

Figure 9: Functional reconfiguration of the living and repair molecules. (a) External growth signal bypassing the lower left faulty molecule. (b-e) Generation of internal growth signals to build a functional data path bypassing the faulty molecules. (f) Closed functional data path within the living and repair molecules.

molecule, the upper middle one, becomes faulty. In a first step, the new faulty molecule sends a *repair signal* eastward, in order to look for a spare molecule, able to replace it (Fig. 10b). In a second step, the supposed spare molecule, which is in fact a faulty one, enters the lethal *dead mode* and triggers *kill signals* which propagate northward, westward and southward (Fig. 10c-f). Finally in Fig. 10g, all the molecules of the array are dead as well as our minimal system.

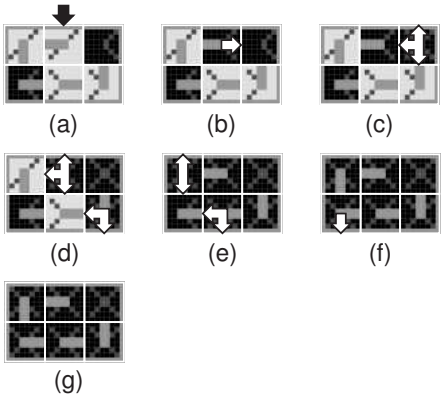

Figure 10: Regeneration mechanism performed as a repair process followed by a kill process. (a) Living molecule becoming faulty. (b) Eastward repair signal. (c-f) Generation of internal and external kill signals propagating northward, westward and southward. (g) Cell made up six dead molecules.

3 SOS ACRONYM APPLICATION

3.1 Structural Configuration, Functional Configuration and Cloning

Even if our final goal is the self-organization of complex bio-inspired data and signals cellular systems, we will use an extremely simplified application example, the display of the "SOS" acronym, in order to illustrate its basic mechanisms. The system that displays the acronym can be considered as a one-dimensional artificial organism composed of three cells (Fig. 11). Each cell is identified by a X coordinate, ranging from 1 to 3. For coordinate values $X = 1$ and $X = 3$, the cell implements the S character, for $X = 2$, it implements the O character. Such a cell, capable of displaying either the S or the O character, is a *totipotent cell* comprising $4 \times 6 = 24$ molecules.

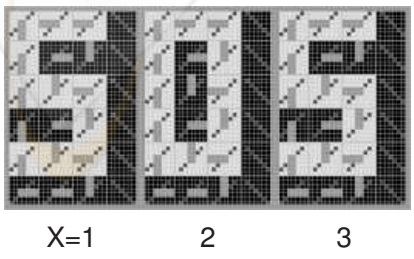

Figure 11: One-dimensional organism composed of three cells resulting from the structural configuration, functional configuration and cloning mechanisms applied to a totipotent cell.

In order to build the multicellular organism of Fig. 11, the structural configuration mechanism, the functional configuration mechanism, and the cloning mechanism are applied at the cellular level. Starting with the structural and functional configuration data of the totipotent cell, these mechanisms generate successively the three cells $X = 1$ to $X = 3$ of the organism "SOS".

3.2 Cicatrization and Functional Reconfiguration

The cicatrization mechanism (or cellular self-repair) results from the introduction in each cell of one column of spare molecules (Fig. 11), defined by the structural configuration of the totipotent cell, and the automatic detection of faulty molecules. Thanks to this mechanism, each of the two faulty molecules of the middle cell (Fig. 12) is deactivated, isolated from the network, and replaced by the nearest right molecule, which will itself be replaced by the nearest right molecule, and so on until a spare molecule is reached. The functional reconfiguration mechanism takes then place in order to regenerate the O character of the organism "SOS". As shown in Fig. 12, the regenerated character presents some graphical distortion.

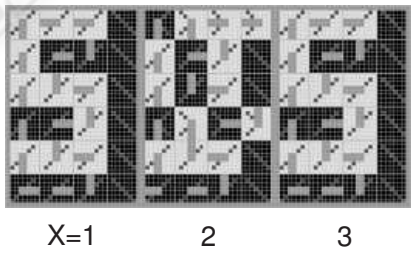

Figure 12: Graphical distortion resulting from the cicatrization and reconfiguration mechanisms applied to the middle cell of the organism.

3.3 Regeneration

The totipotent cell of the organism "SOS" having only one spare column allows only one faulty molecule per row. When a second one is detected, the regeneration mechanism (or organismic self-repair) takes place and the entire column of all cells to which the faulty cell belongs is considered faulty and is deactivated (column $X = 2$ in Fig. 13; in this simple example, the column of cells is reduced to a single cell). All the functions (X coordinate and configuration) of the cells to the right of the column $X = 1$ are shifted by one column to the right. Obviously, this process requires as

many spare cells to the right of the array as there are faulty cells to repair. As shown in Fig. 13, the reparation of one faulty cell needs one spare cell to the right and leaves a scar in the organism “SOS”.

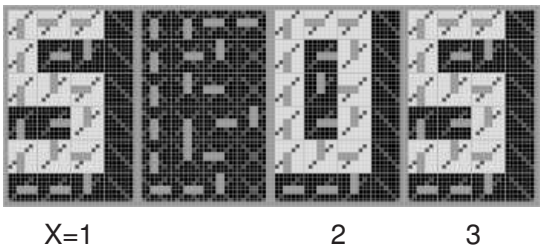

Figure 13: Scar resulting from the regeneration mechanism applied to the organism.

4 CONCLUSIONS

The self-organizing mechanisms are made of simple processes like growth, load, branching, repair, reset, and kill. They allow the data and signals cellular systems to possess three bio-inspired properties: (1) Cloning or self-replication at cellular and organismic levels. (2) Cicatrization or self-repair at the cellular level. (3) Regeneration or self-repair at the organismic level.

Starting with a very simple system, a cell made of six molecules, we realized digital simulations in order to describe the data and signals involved in the self-organizing mechanisms. The “SOS” acronym, an organism made of three cells, was introduced as an application example for the simulation of our mechanisms and processes.

The functional configuration mechanism presented here will be implemented in the *ubichip* (Upegui et al., 2007), a programmable circuit that draws inspiration from the multi-cellular structure of complex biological organisms.

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