Embryonics: A Macroscopic View of the Cellular Architecture

Daniel Mange, André Stauffer, and Gianluca Tempesti

Logic Systems Laboratory, Swiss Federal Institute of Technology, IN-Ecublens, CH-1015 Lausanne, Switzerland. E-mail: {name.surname}@epfl.ch

Abstract. The ontogenetic development of living beings suggests the design of a new kind of multicellular automaton endowed with novel quasi-biological properties: self-repair and self-replication. In the framework of the Embryonics (embryonic electronics) project, we have developed such an automaton. Its macroscopic architecture is defined by three features: multicellular organization, cellular differentiation, and cellular division. Through a simple example, a stopwatch, we show that the artificial organism possesses the macroscopic properties of self-replication (cloning) and self-repair. In order to cope with the complexity of real problems, the cell will be decomposed into an array of smaller elements, the molecules, themselves defined by three features: multimolecular organization, self-test and self-repair, and finally cellular self-replication, which is the basis of the macroscopic process of cellular division. These microscopic properties are the subject of a companion paper [9].

1 Introduction

1.1 The POE model of bio-inspired systems

Recently, engineers have been allured by certain natural processes, giving birth to such domains as artificial neural networks, evolutionary computation, and embryonic electronics. In analogy to nature, the space of bio-inspired hardware systems can be partitioned along three axes: phylogeny, ontogeny, and epigenesis; we refer to this as the POE model [10](pp. 1-12). The phylogenetic axis involves evolution, the ontogenetic axis involves the development of a single individual from its own genetic material, essentially without environmental interactions, and the epigenetic axis involves learning through environmental interactions that take place after formation of the individual.

1.2 The ontogenetic axis

This paper is devoted to hardware implementations inspired by the ontogenetic processes of living beings. The main process involved in the ontogenetic axis can be summed up as growth, or construction. Ontogenetic hardware exhibits such features as replication and regeneration, which find their use in many applications. Replication can in fact be considered as a special case of growth - this

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process involves the creation of an identical organism by duplicating the genetic material of a mother entity onto a daughter one, thereby creating an exact clone.

Research on ontogenetic hardware systems began with von Neumann's work in the late 1940s on self-replicating machines. This line of research can be divided in two main stages:

- von Neumann [22] and others, Langton [6] and others, Reggia et al. [18], Tempesti [21], and Perrier et al. [16] developed self-replicating automata which are *unicellular* organisms: there is a single genome describing (and contained within) the entire machine.
- Inspired by Arbib [2], [3], Mange et al. [7], [10], Marchal et al. [11], Nussbaum et al. [12], Aarden et al. [1] and Ortega et al. [13], [14], [15], proposed a new architecture called *embryonics*, or embryonic electronics. Drawing inspiration from three features usually associated with the ontogenetic process of living organisms, namely, multicellular organization, cellular differentiation, and cellular division, they introduced a new cellular automaton complex enough for universal computation, yet simple enough for physical implementation through the use of commercially available digital circuits. The embryonics self-replicating machines are *multicellular* artificial organisms, in the sense that each of the several cells comprising the organism contains one copy of the complete genome.

1.3 Objectives and contents

Our final objective is the development of very large scale integrated circuits capable of self-replication and self-repair. These two properties seem particularly desirable for very complex artificial systems meant for hostile (nuclear plants) or inaccessible (space) environments. Self-replication allows the complete reconstruction of the original device in case of a major fault, while self-repair allows a partial reconstruction in case of a minor fault.

This paper is devoted to a macroscopic description of the Embryonics project. Section 2 describes the three architectural features of our artificial organisms: multicellular organization (the organism consists of an array of identical physical elements, the cells), cellular differentiation (each cell contains the complete blueprint of the organism, that is, its genome, and specializes depending on its position within the array), and cellular division (each mother cell generates one or two daughter cells). This last mechanism is the object of a formal description by an L-system. Section 3 shows that the multicellular organism thus defined is capable of self-replication (it can produce a copy of itself) and of self-repair (it can replace one or more faulty cells).

The microscopic study of the cell, which relies on three fundamental features: multimolecular organization (the cell is itself decomposed into an array of physically identical elements, the molecules), fault detection within each molecule and self-repair of the cell (through the replacement of the faulty molecules), and cellular self-replication (each group of molecules forming a mother cell is capable of replicating itself to produce a daughter cell and thus bring about the cellular

division described at the macroscopic level) is described in a companion paper [9]. The outline of this paper constitutes the core of Section 4.

2 Embryonics' macroscopic features

In the framework of electronics, the environment in which our quasi-biological development occurs consists of a finite (but as large as desired) two-dimensional space of silicon. This space is divided into rows and columns whose intersections define the cells. Since such cells (small processors and their memory) have an identical physical structure, i.e., an identical set of logic operators and of connections, the cellular array is homogeneous. Only the state of a cell, i.e., the contents of its registers, can differentiate it from its neighbors.

2.1 Multicellular organization

The *multicellular organization* divides the artificial organism (ORG) into a finite number of cells (Figure 1), where each cell ($CELL$) realizes a unique function, described by a sub-program called the *gene* of the cell. The same organism can contain multiple cells of the same kind (in the same way as a living being can contain a large number of cells with the same function: nervous cells, skin cells, liver cells, etc.).

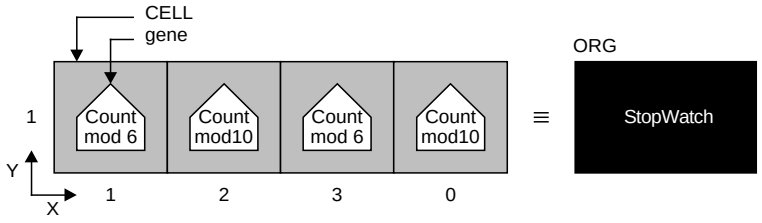

Fig. 1. Multicellular organization of StopWatch.

In this presentation, for clarity's sake, we will confine ourselves to a simple example of a one-dimensional artificial organism: a *StopWatch* implemented with four cells and featuring two distinct genes ("Countmod 10" for counting the units of seconds or minutes, "Countmod 6" for counting the tens of seconds or minutes); the design of these genes is described in detail elsewhere [10](pp. 204-216).

2.2 Cellular differentiation

Let us call *operative genome* (OG) the set of all the genes of an artificial organism, where each gene is a sub-program characterized by a set of instructions

and by its position (its coordinates X, Y). Figure 1 then shows the operative genome of StopWatch, with the corresponding horizontal (X) and vertical (Y) coordinates. Let then each cell contain the entire operative genome (Figure 2a): depending on its position in the array, i.e., its place in the organism, each cell can interpret the operative genome and extract and execute the gene which configures it.

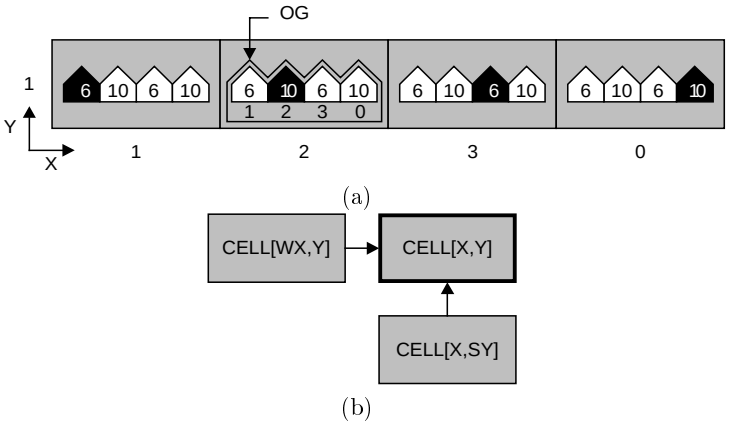

Fig. 2. Cellular differentiation of StopWatch. (a) Global organization; OG: operative genome (genes and coordinates). (b) Central cell $CELL[X, Y]$ with its west neighbor $CELL[WX, Y]$ and its south neighbor $CELL[X, SY]$.

In summary, storing the whole operative genome in each cell makes the cell universal: it can realize any gene of the operative genome, given the proper coordinates, and thus implement *cellular differentiation*.

In every artificial organism, any cell $CELL[X, Y]$ computes its coordinate X by incrementing the coordinate WX of its neighbor immediately to the west (Figure 2b). Likewise, it computes its coordinate Y by incrementing the coordinate SY of its neighbor immediately to the south. To verify the property of self-replication of the organism (see Subsection 3.1), the first, "mother cell" is distinguished by the coordinates $X, Y = 1, 1$, and the last cell is distinguished by the coordinates $X, Y = 0, 1$. In the StopWatch example, the computation of the coordinate X occurs modulo-4 (the organism has four cells on the X axis), while the computation of the coordinate Y, which plays no role outside of self-replication (see Subsection 3.1), occurs modulo-1 (the organism is one-dimensional). Any cell $CELL[OG, X, Y]$ can thus be formally defined by a program (its operative genome OG) and by its two coordinates X, Y. In the case of StopWatch, we have the program of Figure 3.

The artificial organism ORG, StopWatch, can be described as the concatenation of four cells ($CELL[OG, X, Y]$ with $X = 1, 2, 3, 0$ and $Y = 1$), and a set

```
X = (WX+1) mod 4
Y = (SY+1) mod 1
case of X:
   X = 1: Countmod 6  (10 minutes)
   X = 2: Countmod 10 (minutes)
   X = 3: Countmod 6  (10 seconds)
   X = 0: Countmod 10 (seconds)
```

Fig. 3. The operative genome OG of StopWatch.

of border conditions ($WX = 0$ to the west of the first cell $CELL[OG, 1, 1]$ and $SY = 1$ to the south of each of the four cells):

$$ORG = CELL[OG, 1, 1], CELL[OG, 2, 1], CELL[OG, 3, 1], CELL[OG, 0, 1] \quad (1)$$

which, in our particular example, becomes:

$$StopWatch = Countmod\,6, Countmod\,10, Countmod\,6, Countmod\,10 \quad (2)$$

2.3 Cellular division

At startup, the mother cell (Figure 4), arbitrarily defined as having the coordinate $X, Y = 1, 1$, holds the one and only copy of the operative genome. After time $t1$, the genome of the mother cell is copied into the neighboring (daughter) cells to the east (the second cell of the desired organism) and to the north (the first cell of the first copy of our original organism). The process then continues until the four cells of StopWatch are completely programmed: in our example, the furthest cell is programmed after time $t3$.

L-systems, originally conceived as a mathematical theory of plant development [17], [4], [5], [19], [20], are naturally suitable for modeling growth processes. The very simple case of the cellular division of StopWatch (Figure 4) can be described by the two-dimensional production of Figure 5a, where $\emptyset$ indicates an empty cell.

From the axiom of Figure 5b, we obtain, through the application of the production (Figure 5a), the successive derivations of Figure 5c, each denoting a step of the cellular division, and thus of the growth, of our cellular organism, StopWatch. We do indeed find, at time $t3$, a complete copy of the artificial organism described by expression (1).

2.4 Genotype, phenotype and ribotype

In biology, all ontogenetic development converts a linear genetic information, the DNA or *genotype*, into a protein (that is, a three-dimensional molecule which constitutes the *phenotype*). The genotype-phenotype transformation is performed by a third entity, the *ribosome*, in charge of decoding the DNA: it

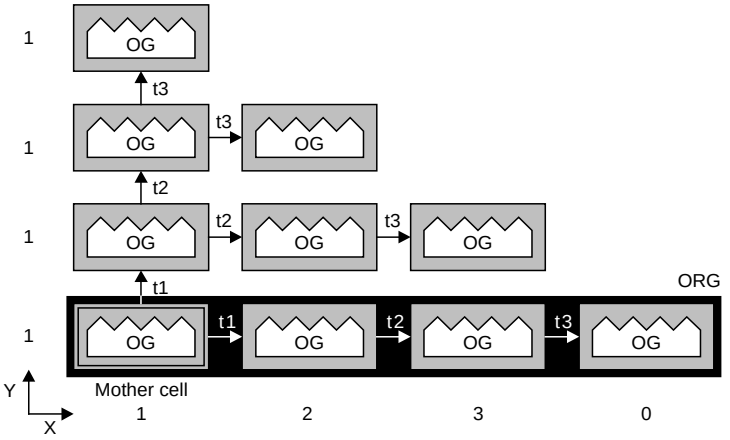

Fig. 4. Cellular division of StopWatch.

is the *ribotype*. The ribosome is, in fact, a special protein, and thus a three-dimensional structure belonging to the same family as the phenotype (Figure 6a)[8]. This relationship can be resumed by:

$$GENOTYPE + RIBOTYPE = PHENOTYPE \tag{3}$$

or, to emphasize the kinship between ribotype and phenotype:

$$RIBOTYPE[GENOTYPE] = PHENOTYPE \tag{4}$$

where $RIBOTYPE$ can be considered as a function of the argument $GENOTYPE$.

Similarly, our operative genome OG represents the DNA, or genotype, of the artificial organism StopWatch. It is interpreted by multiple processors, the artificial cells $CELL$, which represent the counterpart of the ribotype. The phenotype, that is, the operation of our organism ORG, is the result of the computation executed in parallel by the cells $CELL$ on the program OG. Relation (4) thus becomes, in our case:

$$\sum_{X=1}^{0} CELL[OG, X, 1] = ORG \tag{5}$$

which, for StopWatch and according to expression (1) (Figure 6b), can be written:

$$CELL[OG, 1, 1], CELL[OG, 2, 1], CELL[OG, 3, 1], CELL[OG, 0, 1] = ORG \tag{6}$$

```
                    Ø
Ø                   CELL[OG,WX,(SY+1)mod1],Ø
CELL[OG,WX,SY],Ø -> CELL[OG,WX,SY],CELL[OG,(WX+1)mod4,SY],Ø
```

(a)

```
            Ø                    Ø
            CELL[OG,WX,SY],Ø = CELL[OG,1,1],Ø
```

(b)

```
    Ø
    CELL[OG,1,1],Ø
t1: CELL[OG,1,1],CELL[OG,2,1],Ø

    Ø
    CELL[OG,1,1],Ø
    CELL[OG,1,1],CELL[OG,2,1],Ø
t2: CELL[OG,1,1],CELL[OG,2,1],CELL[OG,3,1],Ø

    Ø
    CELL[OG,1,1],Ø
    CELL[OG,1,1],CELL[OG,2,1],Ø
    CELL[OG,1,1],CELL[OG,2,1],CELL[OG,3,1],Ø
t3: CELL[OG,1,1],CELL[OG,2,1],CELL[OG,3,1],CELL[OG,0,1],Ø
    ⏟                                                  ⏟
                        = ORG
```

(c)

Fig. 5. L-system model of StopWatch. (a) The production. (b) The axiom. (c) The cellular division derivation.

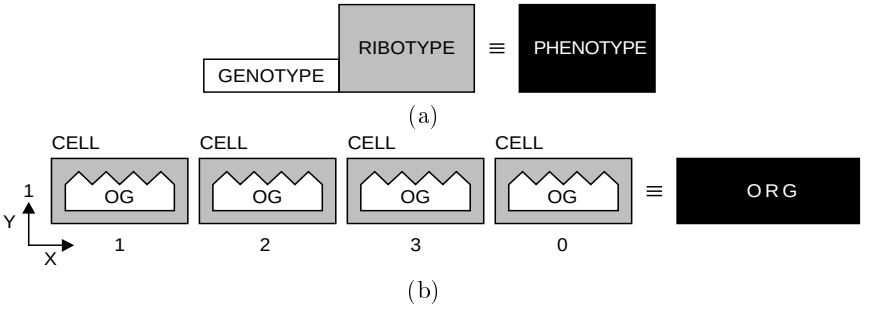

Fig. 6. Genotype-phenotype relationship. (a) The transformation. (b) StopWatch application.

3 Self-replication and self-repair as macroscopic properties

3.1 Organism's self-replication (cloning)

The *self-replication* of an artificial organism, i.e., the production of an exact copy of the original or "cloning", rests on two hypotheses:

- there exists a sufficient number of spare cells (unused cells at the right of the original organism, or at the upper side of the array), at least four in our example (to produce one copy);
- the calculation of the coordinates produces a cycle ($X = 1 \rightarrow 2 \rightarrow 3 \rightarrow 0 \rightarrow 1$ and $Y = 1 \rightarrow 1$ in Figure 7).

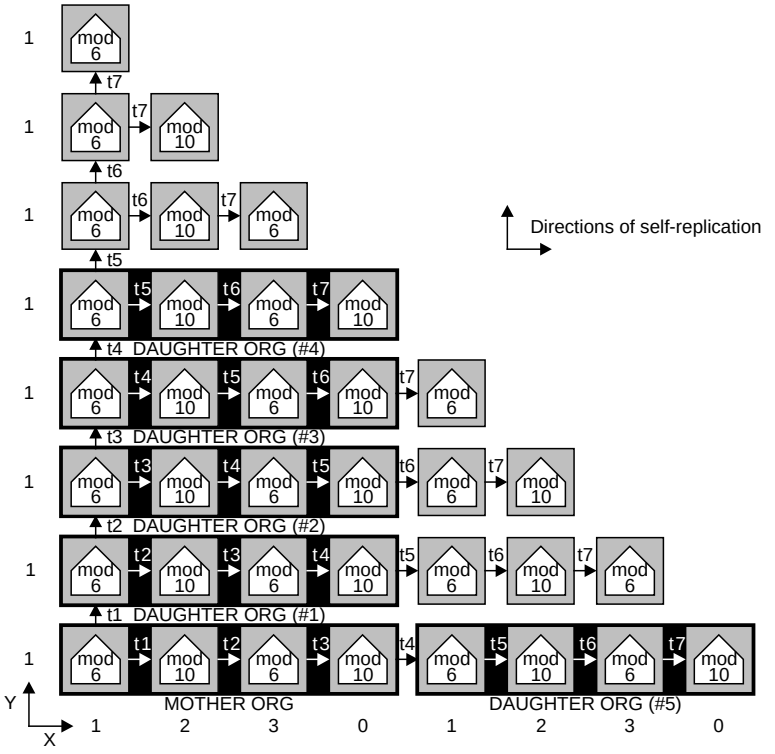

Fig. 7. Self-replication of a 4-cell StopWatch organism in an unlimited homogeneous array of cells.

As the same pattern of coordinates produces the same pattern of genes, self-replication can be easily accomplished if the microprogram of the operative genome OG, associated to the homogeneous array of cells, produces several occurences of the basic pattern of coordinates. In our example (Figure 7), both the repetition of the vertical coordinate pattern ($Y = 1 \rightarrow 1 \rightarrow 1 \rightarrow 1 \rightarrow 1 \rightarrow 1 \rightarrow 1 \rightarrow 1$) and of the horizontal coordinate pattern ($X = 1 \rightarrow 2 \rightarrow 3 \rightarrow 0 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 0$), associated to an unlimited array of cells, produce five copies, the *daughter organisms*, of the original or *mother organism*. Given a sufficiently large

space, the self-replication process can be repeated for any number of specimens in the X and/or Y axes.

Formally, the computation of the different steps of the cellular division described by the L-system of Figure 5c will produce the following sequence of daughter organisms (Figure 7):

- after time $t4$: daughter organism ♯1, in the 2nd row;
- after time $t5$: daughter organism ♯2, in the 3rd row;
- after time $t6$: daughter organism ♯3, in the 4th row;
- after time $t7$: daughter organism ♯4, in the 5th row, and ♯5, in the 1st row.

3.2 Organism's self-repair

In order to demonstrate *self-repair*, we have decided to add spare cells to the right of the original unidimensional organism (Figure 8). These cells may be used not only for self-repair, but also for self-replication.

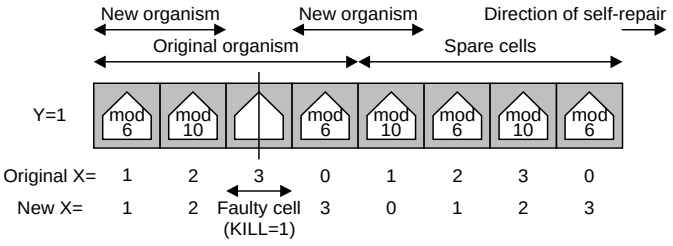

Fig. 8. Self-repair of a 4-cell StopWatch organism with four spare cells and one faulty cell.

The existence of a fault is detected by a $KILL$ signal which is calculated in each cell by a built-in self-test mechanism realized at the molecular level (see the companion paper [9]). The state $KILL = 1$ identifies the faulty cell, and the entire column (if any) to which the faulty cell belongs is considered faulty, and is deactivated (column $X = 3$ in Figure 8). All the functions (X coordinate and gene) of the cells at the right of the column $X = 2$ are shifted by one column to the right. Obviously, this process requires as many spare cells or columns, to the right of the array, as there are faulty cells or columns to repair (four spare cells tolerating four successive faulty cells in the unidimensional example of Figure 8). It also implies that the cell has the capability of bypassing the faulty column and shifting to the right all or part of the original cellular array.

With a sufficient number of cells, it is obviously possible to combine self-repair (or growth if any) in the X direction, and self-replication in both the X and Y directions.

4 Cell's microscopic features

In all living beings, the string of characters which makes up the DNA, i.e., the genome, is executed sequentially by a chemical processor, the *ribosome*. Drawing inspiration from this biological mechanism, we will realize each cell of our artificial organism by means of a small electronic processor, a *binary decision machine*, executing sequentially the instructions of our artificial genome, the operative genome *OG*. In analogy with the ribosome, which is itself decomposed into smaller parts, the molecules, we will embed our artificial cell into an array of programmable logic devices, an FPGA whose basic elements will be considered as our artificial molecules. The detailed design of this molecular architecture is the subject of the companion paper [9].

Acknowledgments

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