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Embryonics:
Growing Large-Scale Cellular Arrays of Processors

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Concepts inspired by the developmental processes of living organisms can help address some of the issues related to the implementation of large arrays of processors in next-generation electronics.

Molecular-scale integrated circuits will provide hardware designers with an astounding amount of computational resources. However, current design methodologies, which already struggle to exploit the resources available today, are ill-suited to cope with the complexity and high fault rates of these novel technologies. Nature, on the other hand, has evolved ways to cope with complexity and fault sensitivity: a human being consists of approximately 60 trillion ($60x10^{12}$) cells, ceaselessly operating throughout the lifetime of the organism. Faults occur at a very high rate, but are (in the majority of cases) successfully detected and repaired with little or no effect on the organism. It is then legitimate to wonder if it is possible to draw inspiration from nature to find ways to cope with the complexity of molecular-scale electronics.

One of the basic mechanisms behind the resilience of biological organisms is *cellular division*, i.e., the ability of the cells to self-replicate, and indeed the idea of self-replicating computing machines has a long history, starting in the 1950s with the seminal work of John von Neumann[1] and continuing in the 1980s with the research of Chris Langton[2]. More recently, the predicted features of nanoelectronic devices have sparked a renewed interest in the topic[3–6]. Our own research[7–10] addresses in particular the development of self-replication approaches that can be integrated within complex digital systems able to operate in the presence of faulty components.

Our research has then focused on a transposition of biological mechanisms to the world of computer hardware: the growth and operation of all living beings are directed by the interpretation, in each of their cells, of a chemical program, the DNA string or genome, and this process is the source of inspiration for our *Embryonics* (embryonic electronics) project. Our final objective is the design of highly robust integrated circuits endowed with properties usually associated with the living world: self-repair (cicatrization) and self-replication.

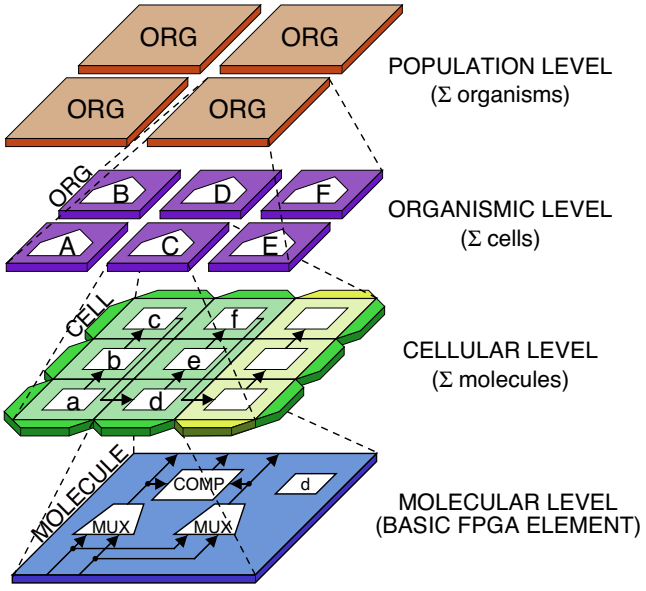

Figure 1. *The four hierarchical levels of organization of an Embryonics system.*

Even if our ultimate goal is the development of mechanisms that will be applied to nanoelectronics, our approach has been implemented using conventional digital logic. The Embryonics architecture is based on four hierarchical levels of organization (Figure 1): 1) the basic primitive of our system is the *molecule*, defined here as a multiplexer-based element of a novel programmable circuit; 2) a finite set of molecules makes up a *cell*, essentially a small processor with an associated memory; 3) a finite set of cells makes up an *organism*, an application-specific multiprocessor system; 4) the organism can itself replicate, giving rise to a *population* of identical organisms.

In more detail, at the molecular level of our system we have developed a set of custom Field-Programmable Gate Arrays (FPGA)[7,9] that include dedicated mechanisms for the implementation of self-replication and fault tolerance. To obtain the desired behaviour, we developed novel self-replication algorithms (e.g., the Tom Thumb algorithm[8]) and tested our approach on

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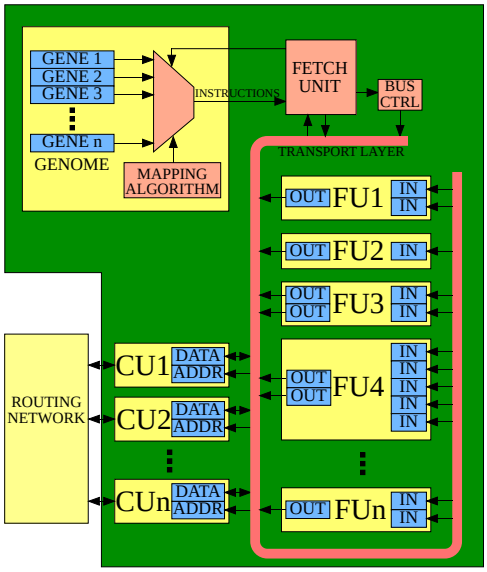

Figure 2. *Schematic architecture of a MOVE-based cellular processor, where the instructions (the genome) are accessed on the basis of a developmental mapping algorithm and are used to control the flow of data between the functional units (FU) within the cell and between the cells via the communication units (CU) and an adaptive routing network.*

complex, processor-scale circuits[10]. While we emphatically do *not* claim that the functionality of our FPGAs corresponds to the molecular components of future devices (contrary to what the terminology might suggest), we believe that the mechanisms we have developed could be useful in that context.

For the cellular level of our systems, our research has led us to define a family of processor architectures based on the MOVE paradigm[11,12]. These architectures provide the versatility required for the implementation of bio-inspired systems, while their modularity and compactness simplify the application of evolutionary and developmental algorithms. These features are vital for the higher levels of our hierarchy, where organisms (and possibly populations) are designed to execute specific applications, exploiting the dynamic behaviour of bio-inspired systems and taking into account the possibility of faulty components.

In summary, bio-inspired mechanisms can bring useful insights on how to design extremely complex computing systems. Notably, processes such as growth and cicatrization could be useful paradigms for systems implemented in next-generation electronics. The novel algorithms and architectures we have developed represent a step forward in this direction, but additional research will be needed to verify the efficiency and usefulness of biologically-inspired approaches in the context of the design of complex real-world computational systems.

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