# Morphogenetic Evolvable Hardware (MG-EHW) Processes and their suitability to Self-repairing Circuits

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**Abstract**

Developmental Evolvable Hardware (DEH) is an emerging field of research that spans the domains of Design Automation, Biomorphic Engineering, Computational Intelligence and Autonomous and Self-repairing Systems. The morphogenetic approach to DEH, inspired by biological processes such as cell signalling and cell behaviour coordination, is a prominent solution aimed towards combating the scalability barrier that exists when generating highly complex circuit solutions. The method is modelled on developmental mechanisms of gene expression observed in natural evolution and implemented at the gate-level on Field Programmable Gate Arrays (FPGAs).

**Keywords:** morphogenesis, evolvable hardware, genetic algorithm, gene regulatory network

## 1 Introduction

Evolvable Hardware (EHW) utilises Evolutionary Computation (EC) techniques to autonomously evolve hardware circuit structures that can be applied to solve real-world circuit design experiments. Driven by a genetic algorithm, an EHW system evolves circuit structures by providing digital blueprints (chromosomes) that are recreated and altered at every generation by genetic operators. The Field Programmable Gate Array (FPGA) architecture allows dynamic reconfiguration of low-level digital resources and remains an ideal platform for EHW simulations.

A Field Programmable Gate Array is a semiconductor device containing configurable logic blocks (CLBs) and programmable interconnects. Configurable logic blocks are self-contained structures whose circuit function can be programmed to replicate basic logic gates (AND, OR, XOR, NOT) or complex combinatorial logic functions like decoders and math functions like bit adders. Many FPGAs also include memory elements, such as flip-flops, and bit-carry logic as part of these programmable logic components. While the placement of components on the FPGA is physically fixed after manufacture, the programmable interconnects functionally associate the collection of logic components together to implement any logical function in the field.

Traditional approaches apply evolutionary algorithms to a Field Programmable Gate Array's configuration bit-stream, however this *direct encoding* approach has not scaled well to large, complex problems [3]. As the size of the evolvable region (no. of utilised CLBs) and circuit complexity increases, the likelihood of traditional, naive approaches to EHW finding a 100% solution decreases. Promisingly, current research focused on biologically inspired growth processes has shown that utilising a developmental design, that is, mapping a combination of genes (genotypes) to a complex structure or organism (phenotype), provides a means to address some of the limits imposed by scalability [1][2][3][4][5]. MG-EHW allows more complex circuit solutions to be developed on commerically viable hardware without restricting the search space (by using the majority of routing resources) and also without introducing unwanted human bias.

## 2 Method and Results

Morphogenesis is the process through which cells coordinate their behaviour and, in nature, is responsible for the generation of complex structures, such as tissues and organs, from relatively simple chromosomes [6]. The MG-EHW system uses a tight coupling between hardware resources and biological processes, mapping individual cells to FPGA CLBs. However, many real-world biological cell behaviours such as changes of cell shape and size, cell fusion and cell death cannot be utilised due to limitations in the Xilinx Virtex's fixed physical layout. Cell behaviours are thus limited to changes in connectivity and function of the low-level logic blocks and are driven by a gene expression model.

Each cell has a copy of the chromosome and all the expressable genes. The genes are expressed based on the probability of simulated polymerase being attracted to the gene's promoter to initiate transcription of the gene coding region. When a gene is expressed it modifies the state of the hardware within the cell (a protein is released in comparative terms). The probability of the gene's promoter attracting polymerase (polymerase binding) is modified by enhancer and repressor regions on the gene that query if a protein is present within the cell (determining if a specific hardware resource is set) and based on this query increase and decrease, respectively, the probability of the promoter attracting polymerase. Cells coordinate behaviour by querying the states of resources in adjacent cells and adjusting polymerase binding probability accordingly.

In previous MG-EHW work [4], the MG-EHW system outperformed a traditional genetic algorithm (GA)-only based approach to circuit evolution in structural complexity experiments (routing of a signal from input to output over varying CLB matrix sizes). Both approaches were unable to successfully evolve a 1-bit Adder in the functional complexity experiment runs. Recent research, exploring the MG-EHW system's suitability to self-repair has extended the system to easily generate 1-bit Adder solutions on varying CLB sizes. Originally, the MG-EHW chromosomes were responsible for representing the entire circuit solution from 0 to 100% from a blank FPGA configuration. This became too much for the chromosomes to represent even with the improvement in scalability provided by morphogenesis.

Nevertheless, a chromosome that generates a circuit solution that is, for example, 87.5% fit can also, due to the dynamic modification nature of MG-EHW, be viewed as a 100% fit solution with 12.5% of fault. By boot-strapping this 87.5% fit circuit as the new initial hardware configuration used in evaluations, the MG-EHW chromosomes can be viewed as repair mechanisms, concentrating their contributions to improving (repairing) the state of the circuit incrementally by substituting the initial blank FPGA configuration for the current highest fitness configuration. This mechanism allows the MG-EHW system to generate 1-bit Adder circuits through minimisation of fault.

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