MP Grammars, Reactive Systems and Electric Circuits

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Introduction

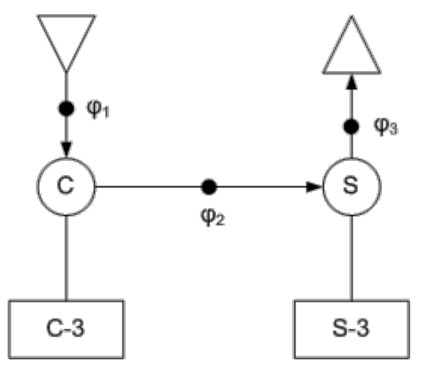
Humankind has been producing a vast amount of data from biological experiments, but their analyze and understand has faced more discreet fate. Hopefully, scientific community is developing methodologies (with inspiration from several fields) to comprehend how these information are tied in biological systems.

A useful tool to realize an event is to reproduce its behavior in a controlled environment, in which individual variables may be observed and isolated from the overall interactions; in fact, it comprises the ideas of analysis and reproducibility, two of the base components of the scientific method. Hence, this work focus on techniques for the implementation in hardware of metabolic process represented in a specific dynamical system (and, in a lesser way, vice-versa).

MP System

$$\begin{cases} x[i+1] &= x[i] + \Delta[i] \\ \Delta[i] &= \mathbb{A}_{\mathcal{V}\times\mathcal{R}} \times \begin{pmatrix} \phi_1(x[i]) \\ \phi_2(x[i]) \\ \phi_3(x[i]) \end{pmatrix} \end{cases}$$

Rules	Regulators
$r_1 : \emptyset \to C$	$\phi_1 = k_1 + k_2 \cdot C$
$r_2 : C \to S$	$\phi_2 = k_3 \cdot C + k_4 \cdot S$
$r_3 : S \to \emptyset$	$\phi_3 = k_5 + k_6 \cdot S$



Electrical Circuits

Electrical Circuits are mathematical models that simplifies the analysis of physical ones; their implementation can be simple since they are component-based (with analogous in the real world).

Generally, electrical circuits are classified in analog and digital depending on the type of input signal they do process—however, the discrepancies go beyond and influence the usages and choices of electrical components used in their design.

The coexistence between electrical circuits and biological systems are recurrent: prostheses, (artificial) neural networks, lab- and cell-on-chips, are examples among several others taking advantage of this existing and fruitful symbiosis.

Problem

1

Demonstrate formal (bidirectional) equivalence between MP systems and:

(a) discrete circuits;

(b) analog circuits.

2

Define a direct and simple procedure to transform:

(a) MP systems to (discrete or analog) circuits;

(b) (discrete or analog) circuits to MP systems.

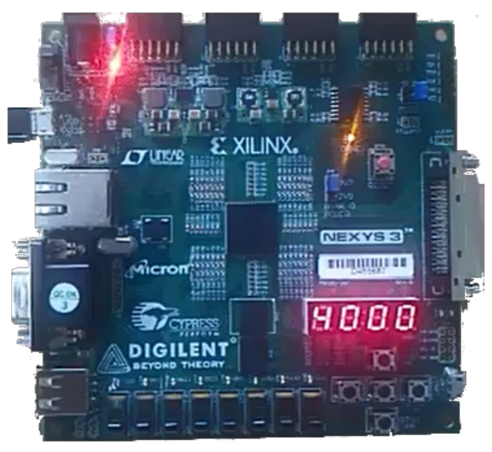
3

Implement diverse MP systems in physical circuits.

Results

MP System as VHDL

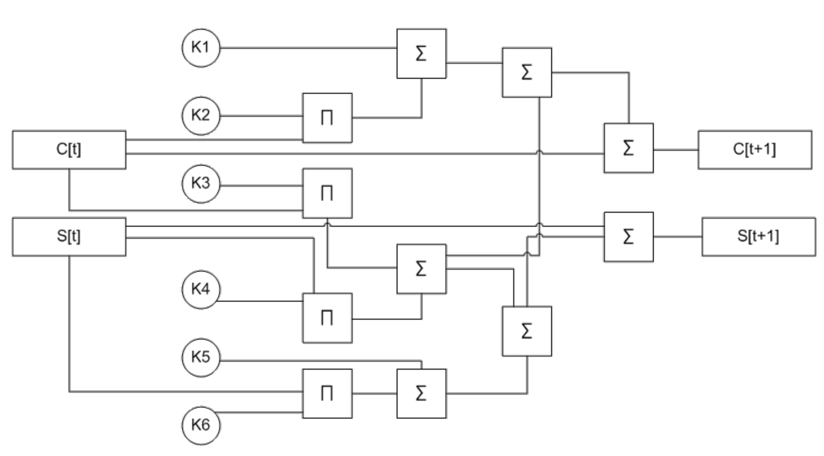
```
-- combinational instructions
should_run <= run;

-- sequential instructions
step: process (step_clock, should_run, resetBook)
    variable rule_1 : ufixed (integer_part_length-1 downto -fractional_part_length);
    variable rule_2 : ufixed (integer_part_length-1 downto -fractional_part_length);
    variable rule_3 : ufixed (integer_part_length-1 downto -fractional_part_length);
    variable cosine_var : ufixed (integer_part_length-1 downto -fractional_part_length);
    variable sine_var : ufixed (integer_part_length-1 downto -fractional_part_length);
begin
    if (rising_edge(step_clock) and should_run = '1') then
        if (resetBook = '1') then
            cosine <= cosine_zero;
            sine <= sine_zero;
        else
            rule_1 := resize(k1 + resize(k2 * cosine, rule_1), rule_1);
            rule_2 := resize(resize(k3 * cosine, rule_2) + resize(k4 * sine, rule_2), rule_2);
            rule_3 := resize(k5 + resize(k6 * sine, rule_3'high, rule_3'low), rule_3);
            cosine_var  := resize(cosine + rule_1 - rule_2, cosine);
            sine_var    := resize(sine + rule_2 - rule_3, sine);
            cosine <= cosine_var;
            sine <= sine_var;
        end if;
    end if;
end process step;
```



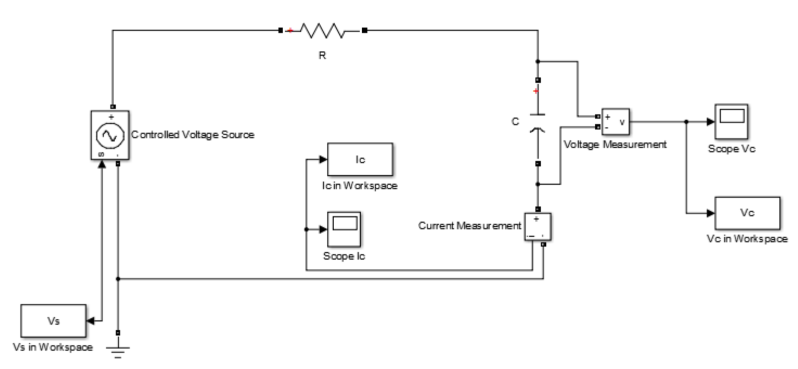
Arithmetic Network of MP System

Inspired by the component list from the hardware synthesis, as well discussions on neural and boolean networks, an arithmetic network of the FPGA implemented was developed.

During the procedure, no optimization on the interconnectivity of the network was performed except by the preference on operations known to have analogues as digital components. As the result, the MP framework highlight as simple summing circuits while the real complexity (multiplications) relied solely on fluxes.



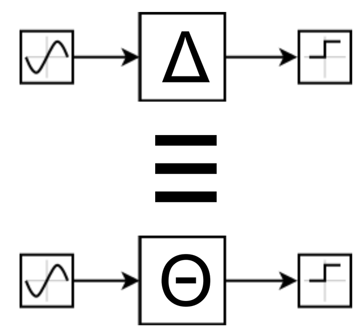
MP System and FFT



Rules	Regulators
$r_0 : \emptyset \to Vc$	$\phi_0 = c_0 \times Ic_1 + c_1 \times Ic_2 + c_2 \times Ic_3 + c_3 \times Ic_4$
$r_1 : Vc \to \emptyset$	$\phi_1 = c_4 \times Vc_3 + c_5 \times Vc_4$
$r_2 : \emptyset \to Ic$	$\phi_2 = c_6 \times Vc_1 + c_7 \times Vc_3 + c_8 \times Vc_4$
$r_3 : Ic \to \emptyset$	$\phi_3 = c_9 \times Vs + c_{10} \times Vc_2 + c_{11} \times Ic_3$
$r_4 : Vc \to Ic$	$\phi_4 = c_{12} \times Vs + c_{13} \times Vc_2 + c_{14} \times Ic_1$
$r_5 : Ic \to Vc$	$\phi_5 = c_{15} \times Ic_4$

Next Steps: Functional Equivalence

If a system is seen as a black box, its internal structure is less important for a external observer than the function transforming the inputs in outputs. In this direction, transfer functions of both classes of MP systems and circuits will be computed in order to use them to demonstrate a functional equivalence between the different representations.



Conclusion

MP systems is a simple way to express correlation among interacting variables in a environment, with successful applications in biological studies. Furthermore, equivalences with structures from bioinformatics has been show.

The results so far indicate the existence of equivalence between mathematical models of metabolism and synthesized electrical circuits, as well as they lead to a manner to easily navigate between the representations. These outcomes are valuable for the current research, but also for the bioengineering field, soon providing it a standard language for bio-electronical developments.

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