Cellular Automata Designs for Out-of-Plane Nanomagnet Logic

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INTRODUCTION

This paper demonstrates Cellular Automata (CA) designs for out-of-plane Nanomagnet Logic (NML). We show that the regular, near-neighbor interconnection structure of CAs enables magnetologic circuits, where the beneficial characteristics of NML devices (compact, low power operation) can be fully exploited. We also demonstrate how CA rules can be modified to result in fabrication-friendly NML layouts.

NML is one of the promising emerging device technologies, since it offers unique benefits compared to conventional, CMOS-based devices. In NML, nanoscale magnets represent binary information and the information is processed / propagated by magnetic field coupling between appropriately placed single-domain nanomagnets [1]. Interconnection and computation are both done by the same physical mechanism (magnetic field coupling), resulting in compactness and simple construction for simple circuits. Long-range, fast connections are difficult to realize, and any long-range wiring comes at significant penalty in circuit speed and complexity. Since long-range interconnections should be avoided as much as possible, locally-interconnected circuit architectures are the ones that can fully exploit the power of NML circuitry. Cellular Automata (CA) are the prime example of locally-interconnected architectures, and this motivates our present study of CAs realized by NML. We choose out-of-plane NML devices [2] (perpendicular NML, pNML), as their clocked operation makes them a good match to CA architectures.

MODEL OF A ONE-DIMENSIONAL CA

We choose the well-known Rule 30 as a simple demonstration of a one-dimensional CA. This rule often serves as an example to demonstrate emergence of complexity from simple rules, and has practical applications in cryptography as well.

The logic diagram of two cells for this CA is given in Fig 1a. By flipping every second cell upside down, wire crossings can be avoided, greatly simplifying the layout. A pNML-based realization is shown in Fig. 1b. The yellow line around the nanomagnet edges indicates focused-ion-beam (FIB) irradiated regions, which define the input sides of the nanomagnet. Circuits made from such FIB-irradiated nanomagnets can be precisely simulated with compact models calibrated with experiment [3]. Figure 2 shows sample snapshots of such simulations, exhibiting correct evolution of the CA states.

TWO-DIMENSIONAL CAS FOR IMAGE PROCESSING

Noise of a black and white image can be reduced by the following CA algorithm: first assigning a cell for each pixel of the image and subsequently with every CA iteration, each cell assumes the pixel value of the majority of its neighbors (including itself) [4]. In order to ease the layout of the cell, we modified this rule to take into account one neighbor with a double weight. The layout of a 2D pNML-based CA for this operation is remarkably simple, and is shown in Fig 3. Figure 4 demonstrates this NML noise-filtering algorithm for a sample image.

To conclude, we have shown that useful CA templates can be straightforwardly realized by pNML circuits. While the input / output interface will inevitably complicate the design, the magnetic computing part can be indefinitely scaled by tiling the pNML units.

REFERENCES

[1] A. Imre, G. Csaba, L. Ji, A. Orlov, G. H. Bernstein, W. Porod: "Majority Logic Gate for Magnetic Quantum-Dot Cellular Automata," Science 13 Vol. 311. no. 5758, pp. 205 – 208 (2006)

[2] I. Eichwald, A. Bartel, J. Kiermaier, S. Breitkreutz, G. Csaba, D. Schmitt-Landsiedel, and M. Becherer. "Nanomagnetic Logic: error-free, directed signal transmission by an inverter chain." Magnetics, IEEE Transactions on 48, no. 11 (2012): 4332-4335.

[3] S. Breitkreutz, J. Kiermaier, C. Yilmaz, X. Ju, G. Csaba, D. Schmitt-Landsiedel, and M. Becherer. "Nanomagnetic logic: compact modeling of field-coupled computing devices for system investigations." Journal of computational electronics 10, no. 4 (2011): 352-359.

[4] A. Popovici, and D. Popovici. "Cellular automata in image processing." In Fifteenth International Symposium on Mathematical Theory of Networks and Systems, vol. 1. 2002.

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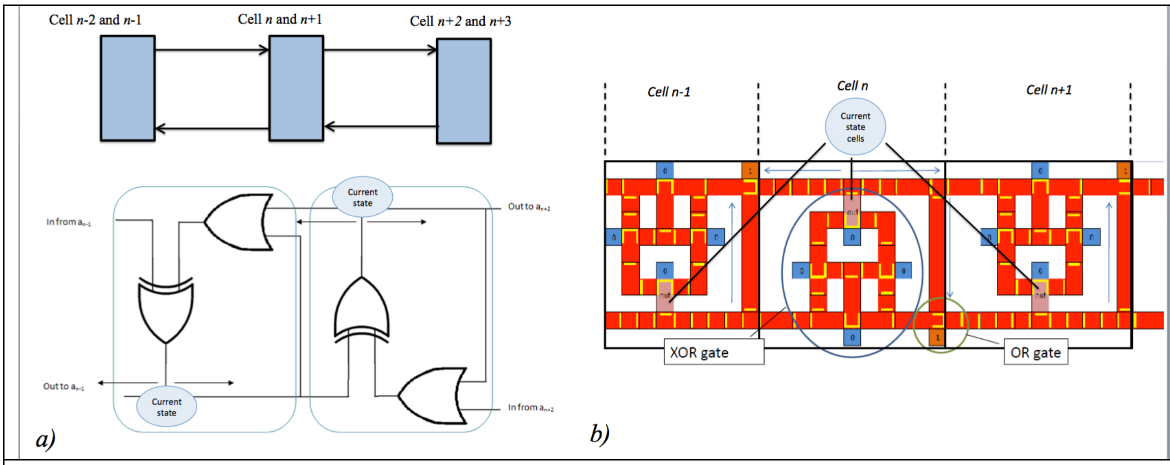

Figure 1. a) Logic diagram of a CA realizing the Rule 30 operation b) is the layout as realized by pNML. The building blocks of the CA are cell pairs in order to make layouting easier.

Figure 2. Snapshots of the Rule 30 CA operation, as simulated by the compact model. Four cell-pairs are shown and white / black colors indicate up / down pointing magnetizations, respectively. A cycle is defined as an up / down external field sequence, which moves the magnetization information one step further along the signal path. One CA rule update takes at most 15 magnetic field cycles.

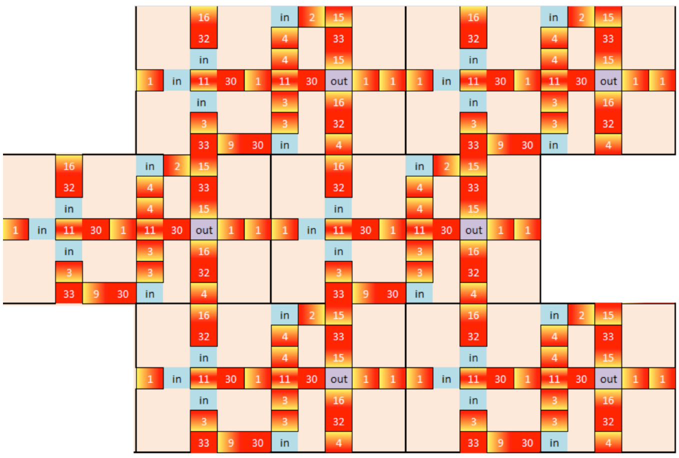

Figure 3. A 2 x 3 cell piece of the noise filtering CA. Nanomagnets labeled as 'out' are the ones representing the pixel values of the binary image.
The noise filtering CA rule substitutes each pixel with the majority of its surrounding pixels. We changed this rule to make the layour easier: one neighbor cell is taken into account with a double weight.

Figure 4. Noise filtering on a test image, as calculated from the compact model of the circuit of Fig 3. The modified CA behaves practically the same way as the original CA rule.