PhD Thesis

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Chapter 1

Introduction

Chapter 2

Quantum-dot cellular automata

Lent et al. introduced the concept of quantum-dot cellular automata as an alternative computing paradigm in 1993 [1]. Thus the aim was a novel physical scheme to build digital circuits that would overcome some of the limitations of CMOS technology, promising potentially lower power consumption, higher device density, and faster clocking. As the name alludes to, quantum-dot cellular automata (QCA) is built from quantum-dots which are grouped together in cells. Figure 2.1(a) shows a basic QCA cell. Four quantum dots are arranged on the corners of a square. The dots are idealized as perfectly localized single orbitals on a perfectly decoupled non-intrusive medium. Therefore, each dot can be occupied by up to two electrons. In the QCA scheme, however, each cell is occupied by only two electrons in total. The cell is quarter-filled. The electrons tunnel between different dots in a cell, but the dominant energy scale is set by the Coulomb repulsion between the particles. Simply by virtue of the Coulomb repulsion, and ignoring the comparatively small tunnelling for now, the diagonal states, Fig. 2.1(a), are the two energetically preferred electron configurations. In comparison, edge states or doubly occupied quantum dots are unfavourable higher energy states, Fig. 2.1(b). A priori the two diagonal states are energetically degenerate, but this degeneracy can be lifted by introducing an external Coulomb potential, for example a second nearby QCA cell. Then these two states can be identified with logic 0 and 1, as indicated in the figure.

A single cell by itself is, of course, not very interesting. Thus, multiple cells can be positioned next to each other, for example as a straight line of cells, Fig.2.1(c). The approach now again assumes that Coulomb is the driving force and that electron tunnelling between cells is very small and ideally zero. For a straight line of cells, these long-ranging, unscreened Coulomb forces will tend to align the electron configurations of adjacent cells. If the first cell is in logic state 1 then the second cell will also prefer logic state 1 and so will in turn all the other cells in the line. The situation is the same for logic state 0. Therefore, a straight line of cells is similar to a wire not only in geometry, but also in functionality: It transmits a digital signal. The same is true, with slight modifications, for a diagonal

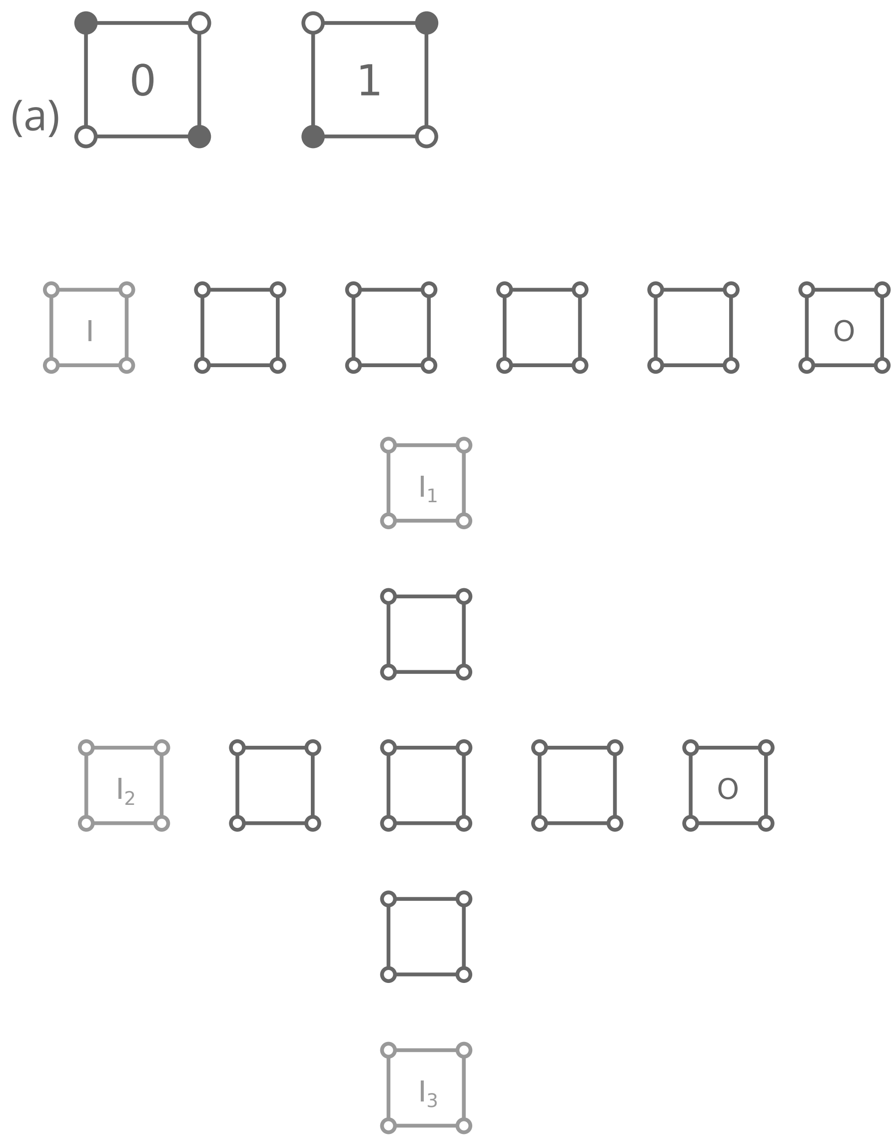

Figure 2.1: ...

line of cells — cells rotated by 45°—, Fig. 2.1(d). In this case the signal alternates from cell to cell, that is, logic 1 will follow logic 0 which followed from logic 0, and this again is simply by virtue of the dominant Coulomb interactions between electrons on different cells. By using an even number of cells the diagonal line of cells works as a wire just as well as a straight line of cells. The pictogram also demonstrates a 90° for the diagonal line of cells which our newly gained intuition for these Coulomb-driven systems expects to pose no problem for signal transmission.

The main idea of the QCA approach becomes apparent: Ideally bistable cells interact with each other solely by Coulomb repulsion. By arranging the cells in clever geometries we can realize interesting functionalities. One such clever geometrical arrangement is the majority gate, Fig. 2.1(e). The gate has three inputs which "vote" on the central cell. The majority wins and sets the single output. The device is commonly operated with one fixed input, for example $I_3 \doteq 0$ or $I_3 \doteq 1$. In the first case, $I_3 \doteq 0$, the device functions as an AND gate for the remaining two inputs, $O = I_1 \wedge I_2$. In the second case, $I_3 \doteq 1$, it is an OR gate with $O = I_1 \vee I_2$. Now, the only missing piece for Boolean algebra is negation, $O = \neg I$. We had already seen that simply arranging cells at an 45° angle as in the diagonal line of cells above negates the signal from cell to cell. The inverter, Fig. 2.1(f) recasts this idea into a more robust layout. With that we have, at least in principle, all the necessary building blocks for Boolean algebra and thus digital circuitry.

Let us note that QCA is a not a cellular automata in a strict mathematical sense, but only by analogy to the idea of interacting cells.

Chapter 3

Approximations

Bibliography

[1] C. S. Lent, P. D. Tougaw, W. Porod, and G. H. Bernstein, "Quantum cellular automata," *Nanotechnology* **4** (1993) 49.