Modern Methods of Performing Logic

Introduction

In our current world, digital logic based on semiconductors has taken over all types of computing. Unfortunately, even though we have been getting better at creating smaller and smaller devices that compute at higher and higher speeds, we are reaching the physical limits of the semiconductors used in the majority of computation. As we get closer and closer to this limit, it becomes necessary to explore other methods of logic that may be used in tandem with or in place of digital logic based on solid-state semiconductors. The following paper attempts to detail a few of the methods currently being explored.

Logic Using Microfluidics

In recent chemistry and biological research, microfluidic devices, in which picoliters of fluids can be precisely controlled inside microscopic channels under very rigid experiment conditions, have made a large impact on efficiency, cost and reliability of experimentation. While their impact in analytical chemistry and bioscience is undeniable, the usefulness of the physics of fluids and bubbles at such a small scale has yet to be fully realized [1].

The microscopic scale of microfluidic devices leads to wildly different fluid dynamics as compared to macroscale fluids. Because these devices operate at low Reynolds numbers, flow resistance within a device can be approximated by a simplified dynamic flow resistance model. When bubbles are introduced into such a system, their impact can be seen in increased flow
resistance according to this model. This model can further be used to predict a bubble’s behavior at a bifurcation: the bubble chooses the branch with highest instantaneous flow given that the bifurcation has a low capillary number ensuring the bubble does not split. The aforementioned increased flow resistance disturbs the flow lines in interconnected channels surrounding the bubble, giving rise to nonlinearity. These nonlinear time-dependent interactions are a result of the introduction of interfacial force terms because of the presence of a free surface at the fluid interfaces and can also be used to create bubble logic gates [1].

Using the hydrodynamics described above, AND/OR bubble logic gates have been constructed that evaluate both AND(·) and OR(+) simultaneously. This gate functions because of the relative widths of the channels. The first bubble that arrives at the junction always enters A+B because being the wider channel, it has less resistance. This increases the output flow resistance of A+B, ensuring that the next bubble that arrives enters A·B [1].

Microfluidic logic gates can also be constructed to allow for an output signal to act as an input signal for multiple gates by splitting bubbles at a T junction which then requires restoration of bubble size. This has been demonstrated by a microfluidic geometry that implements a NOT and AND with gain so that a smaller bubble can switch a larger one. The introduction of a bubble into the main channel allows the injected side flow to be turned on and off dynamically, enabling control of the direction of flow of the large bubble arriving at the bifurcation. This change in injected flow from the main channel is nonlinearly related to the size of the bubble, providing gain [1].

These bubble logic interactions can be sped up and automated using a microheater and flow-focusing geometry to create a thermal electro-bubble generator which can generate
bubbles on demand according to an electric pulse. The type of generation can be used to conduct logic on a larger scale [1].

Further advantages of bubble logic gates include the fact that there are no moving parts which means they can be fabricated from a large variety of materials that are compatible with whatever liquids are chosen to perform the logic. Because the microfluidic device logic mechanisms do not depend on non-Newtonian fluid properties, bubble logic circuits can be designed using a large variety of liquids like water droplets in oil or vice versa. Furthermore, a bubble in a channel can both carry a chemical payload important to the experiment being performed and represent a bit of information, integrating chemistry with computation for process control [1].

**Logic Using Electromechanics**

Electro-mechanic logic has a very long history because some of the very first computers depended on this physics to function. The Enigma machines that appeared in the early- to mid-twentieth century were a series of electro-mechanical rotor cipher machines that were developed to enable the Germans to encrypt their messages throughout World War II and protect their diplomatic and military secrets. This machine was a combination of mechanical and electrical subsystems. The mechanical subsystem included the keyboard, a set of rotors and a stepping component to turn at least one rotor with each key press. The electrical subsystem played into the functionality of the whenever a key was pressed. A key press caused one or more rotors to move to form a new rotor configuration and this mechanical action would complete a circuit. The current flows and circuitry eventually led to the lighting up of one display lamp [2].
Larger electromechanical computers were created by essentially stringing several Enigma machines together. Amongst the first of these computers was the bombe, designed by Alan Turing, used to decipher German Enigma-machine-encrypted secret messages [2].

Even within digital integrated circuits, logic not based on semiconductor physics, in this case electromechanical physics, can be integrated. When dealing with ultralow-power digital integrated circuits, nanoelectromechanical solutions may be used instead of the currently used CMOS transistors (complementary metal-oxide-semiconductor transistors which are known for high noise immunity and low power consumption [3]). In particular, a dual-ended relay design or “seesaw” design demonstrates ideal switching behavior with zero OFF-state leakage and abrupt on/off switching behavior. This zero leakage allows for the minimum required supply voltage to be scaled down even further than for CMOS transistors [4].

Beyond the dimensional advantages of this relay design, the “seesaw” design also provides more reliable operation because electrostatic force (as opposed to spring restoring force) is used for off-switching as well as for on-switching [4].

**Logic Using Vacuum Micro- and Nanoelectronics**

The first devices that truly allowed logic were vacuum tubes used as switches. Unfortunately, the cost and short time to failure of tubes were large limiting factors in implementing vacuum tubes in computation. Nevertheless, a number of computers were built using vacuum tubes to perform Boolean and counting operations were built including, most famously, Colossus which was designed by Tommy Flowers to help in the cryptanalysis of the Lorenz cipher. As solid-state circuits using semiconductors became easier to scale down, vacuum tubes stopped being used in the construction of computers.
Now, as we reach the limits of Moore’s law using semiconductors to perform logic, our greater control over micro- and nano-scale design makes vacuum electronics a more attractive option again. The main advantage a vacuum provides is free space through which electrons can travel much faster with less energy dissipation as compared to any semiconductor where electron scattering inevitably plays a large role. Because there are no physical impediments in a vacuum, faster electron modulation and higher electron energies than semiconductor structures are possible. If put in use, vacuum micro-nanoelectronic devices would be able to operate at higher frequencies, higher power, and wider temperature range as well as in high radiation environments [5].

Another important possible result of vacuum nanoelectronics arises from the device dimensions. At such small dimensions, we begin to observe quantum mechanical effects and as the scale continues to decrease, these quantum mechanical effects become dominant. These effects offer a new set of physical principles that can be utilized to perform logic in ways not possible before. Amongst these quantum mechanical effects, one of the most important is the electron’s ability to quantum mechanically tunnel through energy barriers [5].

The hopeful strength of vacuum electronics comes from both the increased speed of electrons traveling through free space rather than materials and from the possible use of quantum mechanical effects to perform logic in new ways. Even if the quantum mechanical effects were not utilized, the high speed of electrons in vacuum makes vacuum micro-nanoelectronics very useful in high frequency electronics. A need for high frequency processing as well as transfer of larger and larger packets of electronic data via Internet, wireless systems and telephony increases the demands on the bandwidth of these systems. Currently, GaAs, InP,
and GaN based materials produce the highest frequencies in solid-state semiconductor electronics because these materials have higher electron mobility as compared to silicon. Unfortunately, these devices have limited output power and difficulties in harsh environment. Vacuum nanoelectronics devices can take over where such semiconductor limited devices fail [5].

**Logic Using Quantum-dot Cellular Automata**

As mentioned in the previous section, at very small scales, devices begin to demonstrate quantum mechanical effects. This section describes in greater depth how one might use those quantum mechanical effects to perform computation using quantum-dot cellular automata.

This type of computing takes advantage of the Coulomb force that interacts between electrons. Unlike transistor-based electronics which function through the transport of electrons, quantum-dot cellular automata (QCA) operate by the adjustment of electrons in a small limited area of only a few square nanometers. It is implemented by quadratic cells. In these cells, four potential wells are arranged in a square with one well at each corner of the QCA cell. Exactly two electrons are locked in and they can only reside within the potential wells. These four potential wells are connected with electron tunnel junctions which can be opened for electrons to travel through under a particular condition by a clock signal. Due to the Coulomb force between them, the two electrons will try to separate from each other as far as possible. This separation force will result in the electrons residing in diagonally located potential wells because this is the configuration in which they are farthest from each other. Because each square has two diagonals, the electrons can reside in exactly two adjustments in the QCA cell which are interpreted as a binary ‘0’ and binary ‘1’, so each cell can be in one of
two states. This offers a binary system similar to the Boolean logic currently used which interprets high voltage as binary ‘1’ and low voltage as binary ‘0’ [6].

Data propagation can occur between these cells through an exchange of states, by adjusting the electrons in them. The QCA cell transferring its state must have its tunnel junctions closed and the tunnel junctions of the neighboring cell must be open so the electrons can travel through the tunnel junction between the potential wells. As soon as the junctions open, the electrons in the neighboring cell will be pushed as far away from the original cell as possible by the Coulomb force. Because both electrons are also still pushed away from each other, the resultant state will be the same as that of the original cell and the transfer of states is complete. The state of one cell can be quickly propagated to multiple neighboring cells through the same means but the tunnel junctions of all the sequentially neighboring cells must be open at the same time which leads to a much faster transfer as compared to transferring cell by cell. In this way, QCA cell “wires“ are constructed that transport information over long distances [6].

The last elements we need to be able to perform basic logic using QCA cells are logic gates. For QCA cells, the basic gate is a three-input majority voter and it is built from five cells, arranged in a cross. The majority voter takes advantage of the fact that the Coulomb forces of several electrons sum up. Within the cross, the cells on the top, at the left, and at the bottom work as input connections cells. As the Coulomb forces of the electrons of all input cells sum up, the middle cell adjusts to the majority of adjustments of the input connection cells. As a final step, the output cell adjusts to the middle cell and the final state of the majority vote can be obtained from the output cell [6].
The QCA majority voter can be easily turned into more familiar binary gates that current computer science uses like AND and OR gates. For example, the Boolean AND outputs 1 if all inputs are 1, otherwise 0. This can be created using a majority voter by turning the third input into a fixed cell that is always in the 0 state (obtained by setting it to 0 and never opening its electron tunnel junctions). If the other two AND inputs are both 1, the two 1s sum up to strong Coloumb forces and the majority voter turns into an AND gate. The Boolean OR gate is almost exactly the same except that the third input is a fixed cell that is always in the 1 state so that whenever at least one of the other inputs is a 1. In such a way, Boolean logic is possible using QCA cells [6].
References


