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Microfluidics logic gates

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Abstract

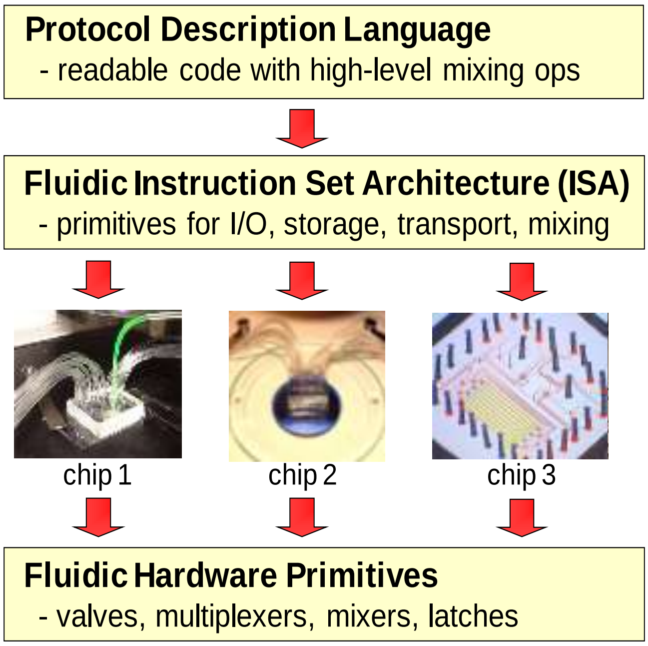
Conventionally, computation is tied to manipulation of information. Microfluidic devices have been designed from the bottom up, where by various fluidic components are combined together to achieve a device that performs a particular application. The microfluidic device may perform only a limited set of operations, such as a liquid transport, separation, or sensing. Then the device is used once and discarded. Microfluidic is the next big thing in VLSI. There are many opportunities for computer scientists in the field of microfluidics. It improves readability, enables automation. With the help of logic gates, MUX, Valves, Mixer, Latch can be formed. We made small fluidic structures here. These structures are used to make logic gates. From these logic gates fluicomputers are created. Fluid is main source which controls the circuits.

Keywords-Microfluidic, logic gates, droplet, lab on chip, VLSI.

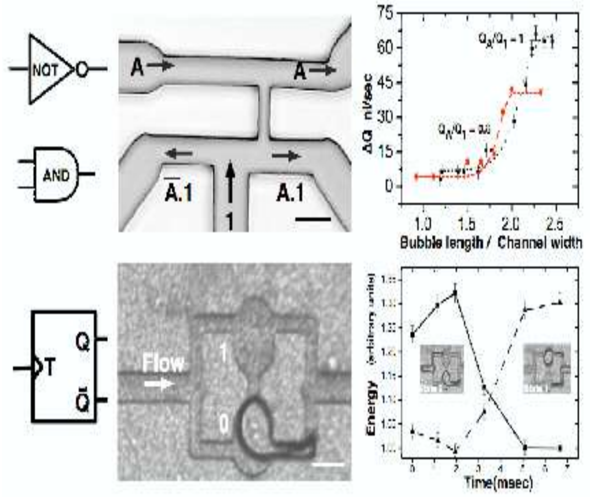
I.INTRODUCTION

Conventionally, computation is tied to manipulation of information. From a physical stand- point, computation can also be understood based on physical constraints due to laws of physics and what implications it has on the physical laws itself. John Wheeler proposed a, connection between physics and computation in his theory of "it from bit"- proposing that all reality is derived from information. Wheeler at length discusses - what can computation and information predict about physics? Can physical laws be derived from computation and information theory - i.e. get "it" (physics) from "bit" (computation).

Historically, microfluidic devices have been designed from the bottom up, where by various fluidic components are combined together to achieve a device that performs a particular application. Thus, just as component-level digital logic design has led to the development of processors and computers, microfluidic system also have been motivated by component level microfluidic devices. However, progress in microfluidic system development has been hampered by the absence of standard commercial components. Thus, many researchers have developed one of a kind valves, mixers, detectors, etc. to pursue short term research goals or to satisfy a specific application. But, these components are not widely available to designers like well-characterized, mass-produced, packaged logic gates. As a result, microfluidic systems built to date are highly specialized to a particular application and are realized in custom technologies that may not be widely available. In addition the general trend in commercial devices has been to fabricate simple, disposable devices that are designed to interface with an expensive box that houses the required control electronics, reagent supply, detectors, and programming. Thus, the microfluidic device may perform only a limited set of operations, such as a liquid transport, separation, or sensing. Then the device is used once and discarded.



“Figure 1. Fluidic Abstraction Layer”



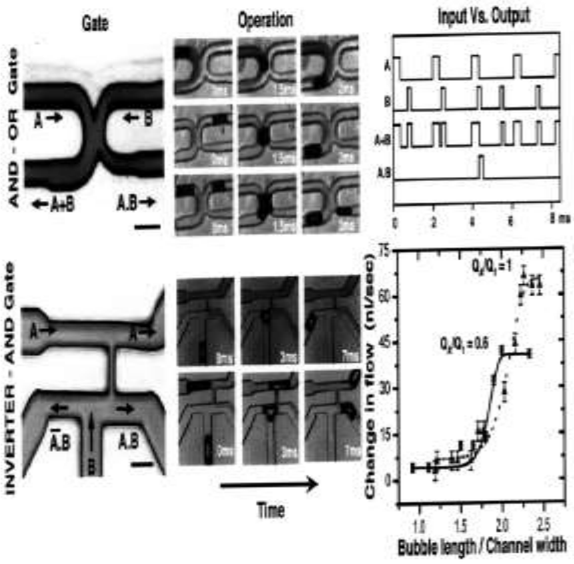
"Figure 2. Universal logic and memory. Top row depicts a universal logic gate (AND and NOT) with a plot depicting gain. Bottom row depicts one bit bistable memory, implemented as a toggle flip-flop with a plot of bistability (in surface energy) as a bubble traverse".

II.UNIVERSAL LOGIC GATES

With an increased flow resistance due to the presence of a bubble in a micro-channel, flow lines in surrounding interconnected channels can be perturbed. These perturbations can hence be used to route another bubble stream resulting in hydrodynamic interactions between bubbles. Navier-Stokes equations describing low Reynolds number flow are linear due to negligible inertial terms. Nonlinearity in such a system arises from the introduction of interfacial force terms from the boundary conditions due to the presence of a free surface at the fluid interfaces. Such nonlinear time-dependent interactions are the basis of our bubble logic gates. We exploit such interactions to build AND, OR and NOT gates, forming a universal Boolean logic set. Since bubbles are neither produced nor destroyed during a bubble logic operation, the number of bubbles is conserved from input to output for a given device. In the implementation described here we use water as the liquid media (with added surfactant 2 % by w/w Tween 20) and nitrogen bubbles. We fabricated planar bubble logic devices in PDMS (poly-dimethyl siloxane) using single-layer soft-lithography and plasma bonding to Pyrex substrates. Fig. 2-1 (top row) shows an AND/OR bubble logic gate which evaluates both AND (.) and OR (+) simultaneously (necessary to satisfy bit conservation).

A single bubble arriving from either A or B at the junction will choose the wider channel, corresponding to A + B. When bubbles arrive from both A and B simultaneously, both output channels contain a bubble (Fig. 2-1 top row, middle column) evaluating both A + B and A -B. The bubble arriving earlier at the junction always enters A + B (the wider channel, with less resistance) increasing the output flow resistance of A + B, thus directing the bubble arriving later to A -B. As shown in the time trace for all four channels of the device (Fig. 2-1 top row, last column), the two bubbles interact only if they arrive within a window TO0 (for this gate To0 - 0.5 ms at Q = 0.25 pl/sec) determined by the residence time of the bubble in the gate geometry. No bubble coalescence was observed in the channels, because of the stabilization of the interface by surfactant molecules.

In any logic family fan-out is necessary for the output signal from one gate to act as an input signal to multiple gates. In the case of bubble logic, this can be simply implemented by splitting bubbles at a T junction into equal parts. Thus gain is necessary to restore signal levels (where the signal is represented by the bubble size) in a logic family. We define gain as the ratio of the volume of the output bubble to the volume of control bubble.



The universal logic gates, toggle flip-flop, ripple counter, synchronizer; ring oscillator and electro-bubble modulator presented in this paper exhibit nonlinearity, bistability, gain, synchronization, cascading, feedback and signal encoding. Having shown the required properties of a scalable logic family, they can be used to create complex microfluidic circuits capable of performing arbitrary fluid process control and computation in an integrated fashion. This can reduce the size, cost and complexity of current microfluidic platforms, and make possible the development of very large scale microfluidic reactors for use in areas including combinatorial chemistry and drug discovery. Long term measurements on droplets in segmented flow micro-reactors require a programmable bistable trap for holding drops for arbitrary periods of time. Toggle flip-flop gate presented here can be used as a passive, reusable trap for the same. Bubble synchronizer presented here can also be used to passively remove any skew in arrival timings of droplets at a junction, necessary for on chip droplet coalescence. The ability to generate bubbles on demand provides a mechanism to encode information and thus program microfluidic bubble circuits. These bubble logic processors, where a bit of information can also carry a chemical payload, merge chemistry and computation.

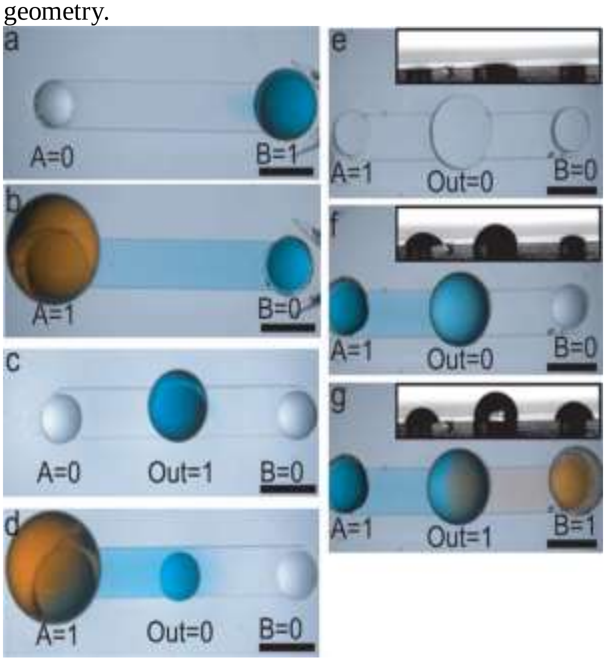
III.MICROFLUIDIC LOGIC GATES

AND/NOT GATE

Here we consider the AND/NOT Boolean logic gate implemented in two-phase microfluidic circuits. Since "Bubble Logic" is a conservative logic scheme, bits can't be created or destroyed in the channels at will (which is the case for electronic logic schemes). Thus any non-conservative logic gate, for e.g. a AND gate needs to be integrated with another gate to suffice for conservative property of the bits. This also provides multiple logic operations in a single step performed in a gate, outputs of which can be utilized individually.

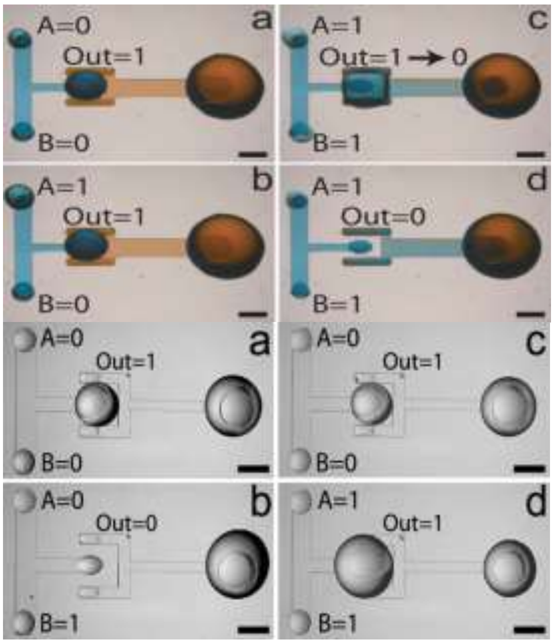
Fluidic logic elements can be traced back to the 1950s; however, most of the early constructs depended on turbulent and multi-stable flow states, 11 which are not scalable due to the low Reynolds numbers that are typically observed in microfluidic channels. More recent efforts using microfluidics have employed fluidic resistance,12 electrochemistry,13 pneumatics,14 channel geometry,15 multiphase flow,16 and chemistry17 to create logic elements. Many of these approaches rely on continuous flow and are unable to create more integrated constructs due to different input/output (e.g. pressure/dye). Additionally, the electronic components used to input and read out signals are often more complex than the devices themselves. For many applications, it would be advantageous for fluidic logic elements to use consistent signal input/output and require minimal supporting equipment. While liquid-based logic devices are not likely to compete with solid-state technologies in terms of computational power, they offer a facile method for implementing autonomous control in microfluidic systems. We have developed a new class of fluidic logic gates that use a consistent input/output (droplet/droplet), visual signal transduction (droplet/no droplet), and allows several gates to be connected in series. The method is based on a previously reported passive pumping technique that uses the pressure differential between surfaces with different radii of curvature. Importantly, the method can be implemented via ubiquitous pipetting (either manual or automated). OR/AND gates require an output of 1 only if at least one of the inputs is 1. In the present system, this would require liquid to be pumped to a port were there is originally no droplet. While a larger droplet has traditionally been used as a low pressure sink in the passive pumping method, it is not a necessity. For the OR/AND gates, we create an output port with a radius larger than that of the input droplet. The curvature of the meniscus in the outlet port is large enough to drive fluid flow to the outlet from the inlet, provided a sufficiently small input droplet is used. The resulting fluid flow then displaces the air/liquid interface from within the port to above the port to form a droplet. A functional AND gate is shown in Fig. 4e–g and a movie of the operating gate can be

seen in movie 1 of the ESI.{ The same design can be used as an OR gate or an AND gate by simply changing the size or number of droplets that are used to define an input of 1, which implies that the passive pumping logic devices are to some extent programmable. That is to say, the size of the input and priming droplets can be varied to change the type of gate that is created with a given channel geometry.



"Figure 4. Microfluidic inverter, AND, and NOR gates".

A NAND gate can be constructed by arranging two channels near one another. The main channel contains three ports for the two inputs and the output. The output port is primed with a droplet prior to placing any input droplets and a second channel is placed in close proximity to the output droplet. If any input droplets are placed, they will increase the size of the output droplet. If only one input droplet is placed, the output droplet will grow in size but will not overlap with the inlets of the second channel. However, if there are droplets placed on both inputs, the output droplet will grow large enough to overlap with the inlet of the second channel. The output droplet will then be pumped away through the secondary channel, leaving an output of 0. The NAND gate can be operated as a NOR gate by increasing the size of the priming output droplet or the input droplet. A sequence of images showing a functioning NAND gate is shown in Fig. 5, which can also be seen as a video (movie 2, ESI{). An XNOR gate can be formed by modifying the secondary channel of the NAND/NOR design to have a high fluidic resistance. The output of the XNOR gate is primed with a droplet, as with the NAND/NOR configuration. A single input droplet is sufficient to create fluid contact between the two channels and will lead to the droplet being pumped away, though at a slower rate than in the case of the NOR gate. The addition of a second input droplet can then be used to increase the output droplet volume such that it is larger than the sink, provided that the output droplet grows much faster than the sink droplet. Thus, the output droplet remains only if the inputs are 0/0 or 1/1. Fig. 5 shows the operation of the XNOR gate. The main channel is 250 mm tall while the secondary channel is only 40 mm tall, providing significantly higher fluidic resistance. The gate is set by placing a 1.2 ml droplet on the output port and a 2.5 ml droplet on the sink. Input droplets with a volume of 0.9 ml were used to operate the gate. The input ports to the secondary channel are shorter than on the NAND gate in order to maintain a droplet shape after the output overlaps with the secondary channel ports.



"Figure 5. Microfluidic NAND and XNOR gates".

Multi-channel designs can also be used to merge and split individual droplets. Fig. 5 shows a three-channel design that can be used to either split an individual droplet or merge two separate droplets. The output droplet of the central channel can be split between the two side channels if its curvature is smaller than both of the outer channels (Fig. 5a–c and movie 3, ESI). Alternatively, the central droplet can be used to mix the two droplets from the outer channels if the curvature of the central droplet is larger than both the outer droplets (Fig 4d–f and movie 4, ESI). A number of channels can be connected in series by using the output of a preceding channel as the input for next channel, as shown in Fig. 5 (movie 5, ESI). In addition to potentially enabling several gates to be connected in series, the cascading nature of some of the gates confers a degree of temporal control over subsequent pumping steps. That is, a set amount of time is required for the initial input droplet(s) to be pumped through a given channel before the output droplet will reach a critical size to carry out the next pumping step.

IV.CONCLUSION

Microfluidic lab-on-a-chip devices, where picoliter of fluids can be precisely manipulated in microscopic channels under controlled reaction conditions, have revolutionized analytical chemistry and biosciences. Recent advances in elastomeric pneumatic microvalves and large-scale integration have enabled complex process control for a wide variety (3, 4) of applications in single-phase microreactors. However, pneumatic elastomeric microvalves require external macroscopic solenoids for their operation, and cascadability and feedback (where a signal acts on it) are currently lacking in microfluidic control architectures.

Microfluidic is the next big thing in VLSI. There are many opportunities for computer scientists in the field of microfluidics. It improves readability, enables automation. With the help of logic gates, MUX, Valves, Mixer, Latch can be formed. We made small fluidic structures here. These structures are used to make logic gates. From these logic gates fluidic computers are created. Fluid is main source which controls the circuits.

The fluidic abstraction layers for programmable microfluidics consist of General-purpose chips, Fluidic ISA, BioStream language, and mixing algorithms. In abstract machine, all samples have unit volume. Abstract layers can Input/output a sample. They Store a sample. Also operates on a sample. The challenge for a digital architecture is fluid loss. Because no chip is perfect and eventually it will lose some volume over time. The causes are imprecise valves, adhesion to channels, evaporation.

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