Flow resistance for microfluidic logic operations

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Control of relative flow resistance is used for the actuation of both one- and two-input microfluidic "logical gates". By taking advantage of system nonlinearities and despite the linear response of laminar flows associated with these length scales, a number of operators including the NOT, AND, OR, XOR, NOR, and NAND are demonstrated. Because these gates can be actuated simultaneously they can be combined to form more complicated devices such as a half adder. This approach is therefore flexible and illustrates that any macro- or microscale technique that can alter flow resistance can be used as the basis of a fluid-based logical micro-operator. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1764592]

As microfluidic processes are scaled down to smaller and smaller length scales, current techniques for process monitoring will prove ineffective. These approaches will all suffer from the inability to access the vast amounts of data that will be generated in very high-density complex systems. In an effort to avoid such issues, the need for interscale information transport could be obviated by directly performing small length scale "calculations". In an electronic microprocessor for example, decisions are rapidly made within the chip and are not sent out for external processing. Fluidic processors capable of similar operations would enable the scale down of current microfluidic technologies to as yet unachievable sizes and device densities. Fluidic computers will inherently be slower than current electron-based computational tools; however, they will significantly decrease the complexity of microfluidic systems by minimizing information transport across length scales or the need to directly integrate electronics and fluidics.

The use of fluidic systems to perform logical operations is not a new concept.[1] Developed in the 1960's to compete with electronic-based systems, the approach became less prevalent as electronic devices were scaled down to very small sizes that operated at very high frequencies. With the recent advent of microfluidics, the ability to perform logical operations in a seamless and integrated fashion will prove extremely important. Earlier work in fluid-based operators were, for the most part, designed taking advantage of the turbulent flows present at the relatively large length scales which these devices were fabricated. Microscale flows however are dominated by viscous effects where turbulence is not present; therefore, other approaches are required to perform similar fluid-based operations and computations with microscale fluids.

Recent approaches to perform microfluidic logic have included the use of electrochemical reactions to create both an OR and a NAND gate.[2] This approach uses microfluidics as a means of replenishing the necessary reagents and not directly as a means through which to perform the logical operations themselves. And though not logical operators, other work has shown how one can use nonlinearity in the fluid viscosity to create microfluidic memory elements.[3] The need for specialized fluids however can limit the applicability or the direct integration of microfluidic computation with common aqueous bioanalytical systems. In this letter, we demonstrate another approach that takes advantage of nonlinearities in the *system functional response* rather than fluid properties to demonstrate microfluidic logic operation. Specifically, we show the one-inlet one-output NOT operator and five two-input one-output gates, the AND, OR, XOR, NAND, and NOR operators (Table I). These logical gates are the basis of computing; in fact, by combining an XOR gate representing a sum bit and an AND gate representing a carry bit, we can use our approach to realize a half-adder.

For rectangular microchannels, the linear response of the channel flow rate can be expressed as $Q=\Delta P/R$, where ΔP is the pressure drop and R is the flow resistance, proportional to channel length.[4] Using capillary pressure-generated flows leads to equivalent pressure drops across parallel channels, making the channel volumetric flow rate inversely proportional to its resistance only. By then varying the resistance of individual channels in complex flow systems, the overall relative system flow rates can be readily directed, independent of absolute pressure drops.

To actuate our logic gates, a mechanical stylus is used to depress a channel cast in a soft material, sealing the conduit, and effectively reconfiguring the network.[5] This approach requires that the top layer must consist of a flexible elastomer or polymer; as a result, our microsystems are cast in polydimethylsiloxane (PDMS).[6] PDMS provides an excel-

TABLE I. Gates with both single and multiple inputs; table entries represent output.

Input	NOT	AND	OR	XOR	NAND	NOR
(1)	0					
(0)	1					
(0,0)		0	0	0	1	1
(0,1) or (1,0)		0	1	1	1	0
(1,1)		1	1	0	0	0
Relative outlet flow resistance	0.5	0.1	0.1	0.07	0.08	0.25

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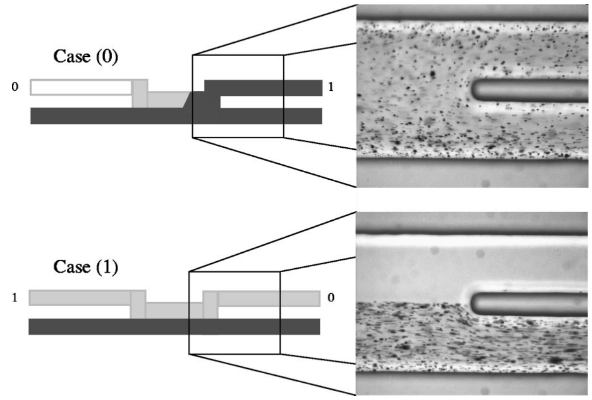

FIG. 1. Illustration and experimental realization of a microfluid-based NOT gate where the 100 μm outlet channels fabricated in PDMS are shown.

lent material platform for device construction, as it is not only flexible but gas permeable, biocompatibile, inexpensive, and microfluidic networks can be quickly replicated from a permanent reusable master with fidelity on the order of single nanometers. The lower-resolution limit is therefore dictated by the resolution of photolithography, currently less than 100 nm. Our networks are created by first transferring the pattern of a shadow mask to a negative photoresist film spun upon a silicon wafer to a depth of approximately 50 μm. A two-part mixture of PDMS is then poured, cured upon the silicon master, then removed and placed in contact with glass to form our channels. To differentiate flows and provide a logic gate output identifier, an insoluble dye was added to one of the input aqueous streams. This dyed stream remains separate from the other streams indicating that the lack of diffusive mixing present in microfluidic flows is an important aspect of our design. By controlling the relative inlet flow fractions of fluid, the outlet flow fractions are specified and used as the basis of our multilogic gate design. To control the outlet gate resistance, outlet channel lengths were scaled appropriately (see Table I).

To demonstrate this technique, we first fabricate a simple NOT gate as shown in Fig. 1 where the dyed fluid determines whether a given output operator is “1” or “0.” Input to this design is performed by allowing flow, “1,” or by turning off flow, “0,” to the upper inlet stream while keeping a constant-flow bottom inlet stream. Here, also, can be seen the simplicity of the approach: With the input stream off, the output stream is dyed; when the input stream is switched on however, the outlet stream is clear. In this system, the dyed output flow fraction which provides the nonlinear system functional response can be expressed as $\zeta=1/(1+n)$, where n is the relative volumetric flow rate of the constant to control streams. With an input control channel of the same resistance as the constant channel, n can take a value of 0 or 1, leading to ζ of 1 or $1/2$.

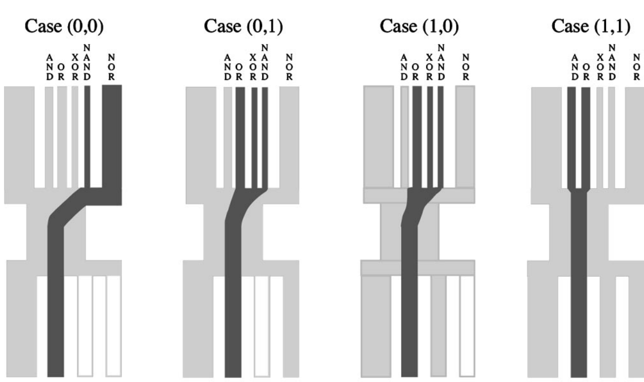

FIG. 2. Multigate design where the output channel width reflects its relative flow resistance (see Table I) and not the actual width. Note that with all five logic gates actuated simultaneously, combination of the XOR and AND gates constitutes a half-adder.

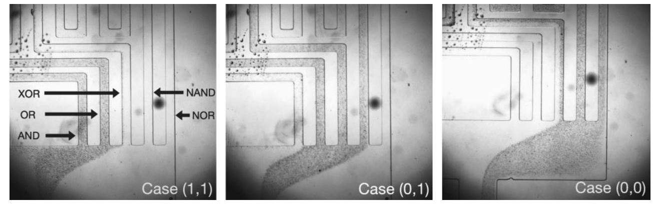

FIG. 3. Experimental realization of the illustration of Fig. 2 where only the outlet channels are shown. Note some spillover into the XOR gate.

We can extend the approach from a simple one-input one-output gate to the more complicated two-input one-output logical operators. This is illustrated in Fig. 2 where the dyed and undyed fluids are flowing from the bottom to the top of the device and four cases are shown corresponding to the four possible input states of a two-input logical operator. Once again, the dyed fluid determines whether a given output operator is “1” or “0”; however, in this design, a number of the logical operators listed in Table I are “computed” simultaneously. Figure 2 has four inlets with two constant and two control streams with input again performed by turning on flow, “1,” or by turning off flow, “0” to the control channels. As indicated in this illustration, as each input flow is turned off, the remaining outlet flows broaden, encompassing more of the outlet logical operator channels. In this case and because the relative input flow rates are identical, $\zeta=1/(3+n)$ where the dyed fraction can now take on values of $1/3$, $1/4$, and $1/5$ as n goes from 0 to 2. A working demonstration of this is shown in Fig. 3.

The creation of logical gates using microfluidics demonstrates that nonlinear system responses can be achieved with laminar inherently linear microfluidic flows. One drawback of the current approach however is that the output (in this case dye) cannot be used to directly actuate subsequent fluid-based logical operators, limiting the direct scaling of the technique to create fluid-based computers. Despite this, the approach can clearly be used with any technique or sensor that modifies the subsequent flow resistance within a channel, such as the integration of environmentally sensitive gels that could turn the input flows on or off within microfluidic networks.[7]

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