Microfluidic Bubble Logic

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We present an all-fluidic universal logic family[1] operating at low Reynolds number in a two-phase flow in microchannel geometries. A bubble traveling in a channel represent a bit, providing us with the capability to simultaneously transport materials and perform logic operations. Nonlinearities are introduced in the system by hydrodynamic bubble-to-bubble interactions. We demonstrate nonlinearity, bistability, cascadability, feedback and signal encoding, all the necessary attributes for a scalable microfluidic computer.

Due to lack of droplet-level control mechanisms, segmented-flow micro-reactors heavily depend on external control. Bubble logic provides an internal flow-control mechanism utilizing physical fluid dynamics providing a route to large scale droplet processors.

Previous attempts at all-fluidic computation used inertial effects[2] (high Reynolds number) or polymer blends[3] (non-Newtonian fluids). Bubble Logic operates at both low Reynolds number and in Newtonian fluids, allowing us to operate at small length scales using common fluids. Nonlinearity in laminar, reversible stokes flow in Bubble Logic is introduced via bubble-to-bubble hydrodynamic interactions.

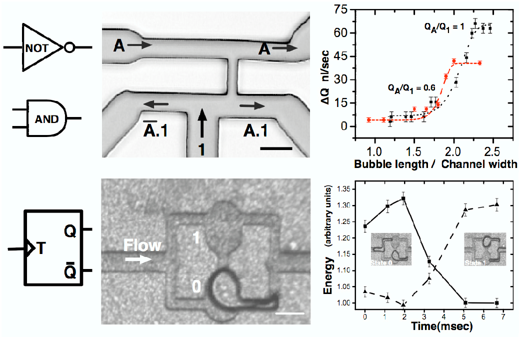

Figura 1. Universal logic and memory. Top row depicts a universal logic gate (AND and NOT) with a plot depicting gain. Bottom row depicts one bit bistable memory, implemented as a toggle flip-flop with a plot of bistability (in surface energy) as a bubble traverses the microfluidic geometry. Scale bar $\sim$ 100 μm.

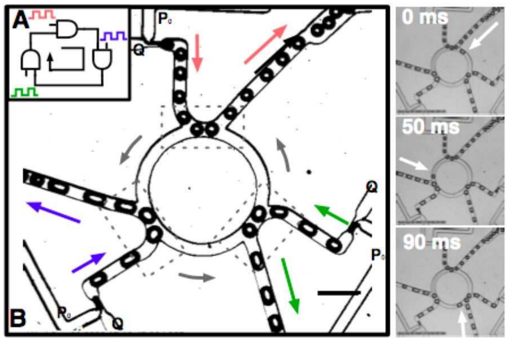

Figura 2. Microfluidic ring oscillator depicting cascading and feedback. Top inset depicts the schematic with three microfluidic AND gates connected in a ring configuration. Righ column depicts a time series of steady state operation of the oscilator at $\sim$ 10 Hz. Scale bar $\sim$ 200 μm.

The devices consists of 2D planar microchannel geometries fabricated using soft-lithography in PDMS bonded to glass. The data presented here is with Nitrogen as a gaseous phase and water (with 2% Tween20 as a surfactant) as the liquid phase. Figure depicts device geometries for universal AND-NOT logic gate and a toggle flip-flop. Propagation time for the logic gates and flip-flop is $\sim$ 10ms. Figure depicts a ring oscillator consisting of three AND gates and a delay line, demonstrating cascading via a feedback circuit.

Bubble Logic provides an all-fluidic means of manipulating both materials and information, merging chemistry and computation.

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[1] Microfluidic Bubble Logic, M Prakash and N Gershenfeld, *Science*, 315, 2007.

[2] A Guide to Fluidics, *Macdonald*, London, 1972.

[3] Microfluidic Memory and Control Devices, A. Groisman, M. Enzelberger and S. R. Quake, *Science*, 300, 2003