SOUND VALVE-CONTROL FOR PROGRAMMABLE MICROFLUIDIC DEVICES

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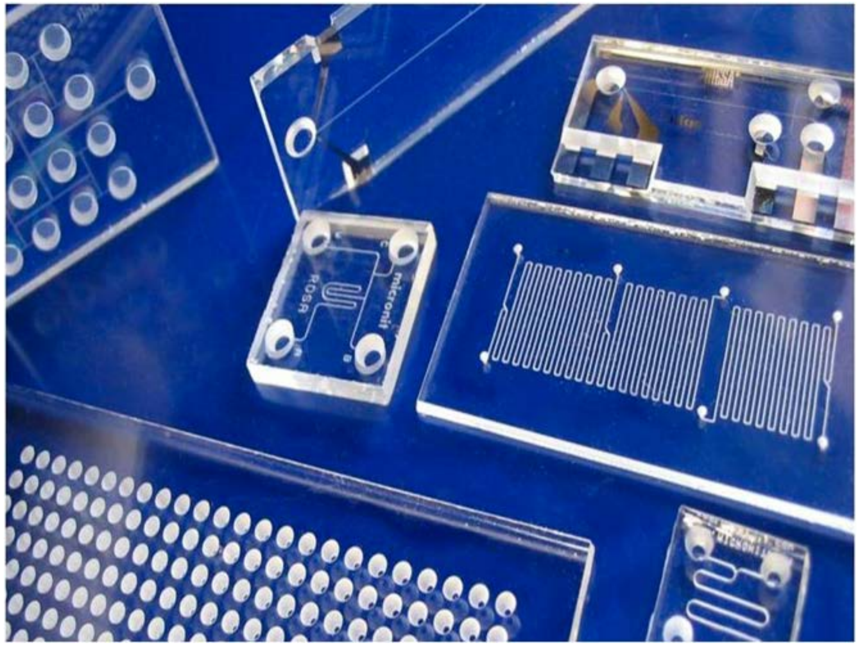
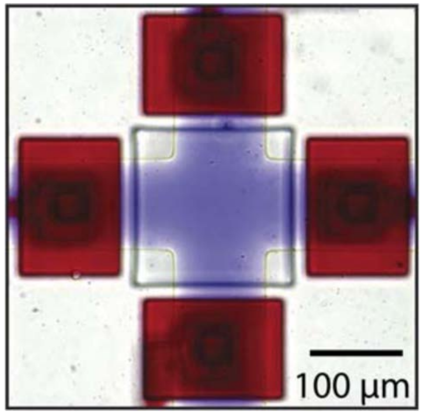
MICROFLUIDIC LABS-ON-CHIP

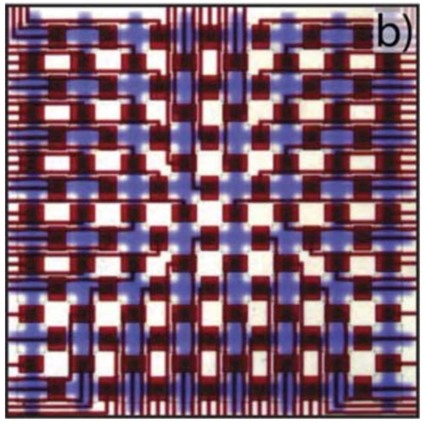


Source: http://miter.mit.edu/articlecommercial-microfluidics-wandering-desert-or-entering-promised-land/

- Reduced sample volume
- High-throughput
- Complex applications: protein crystallization, immunoassays, DNA-synthesizing, etc.

PROGRAMMABLE MICROFLUIDIC DEVICE



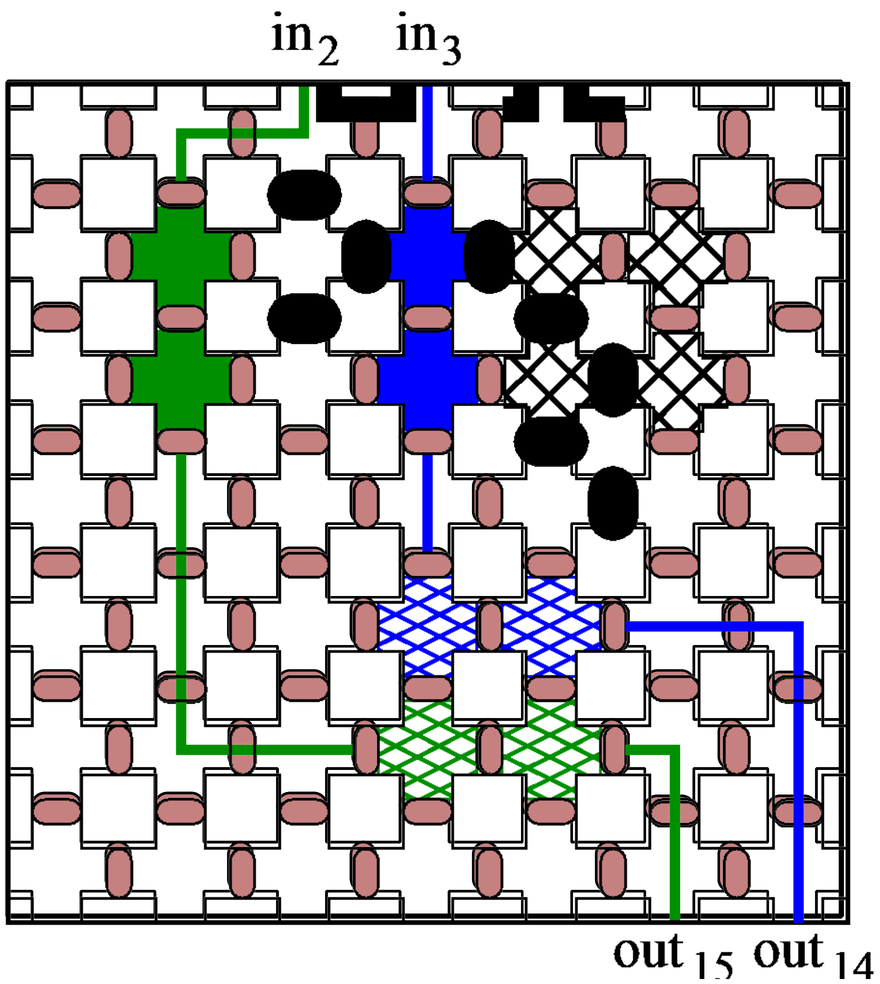


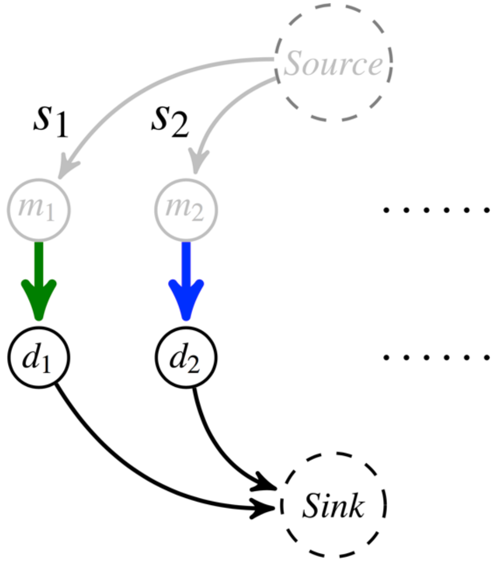
Luis M Fidalgo and Sebastian J Maerkl. A software-programmable microfluidic device for automated biology. *Journal on Lab on a Chip*, 2011.

- Each node consists of four valves (red blocks)
- A node provides a full control of the flow to and from adjacent nodes
- A node is used as reaction vessel

- Realization consists of 64×300 pico-liter nodes
- Controlled by 114 individually addressable valves

REALIZING APPLICATIONS ON PMDS



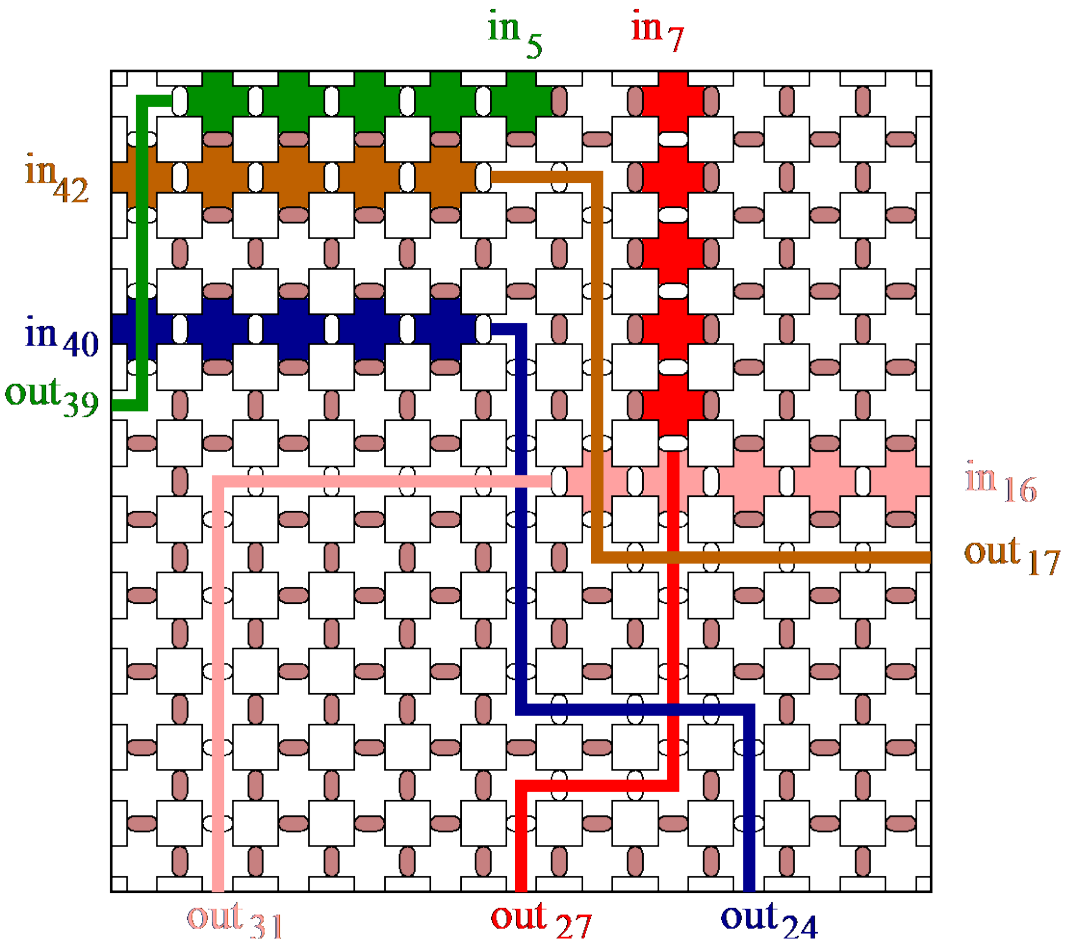


- Considered Task: Control valves
- In order to push the sample through the grid, a continuous *flow path* is required
- In one time step, a sample is pushed one node further in the flow path
- Flow paths must not intersect
- Overall: Push all samples to their target positions by determining flow paths in each required time step

MOTIVATION AND RELATED WORK

- Determining a valve-control is a difficult task because of
  - ☐ limited resources (area, operations, inputs, outputs)
  - ☐ overall time steps should be minimized

→ Use of automatic design solution

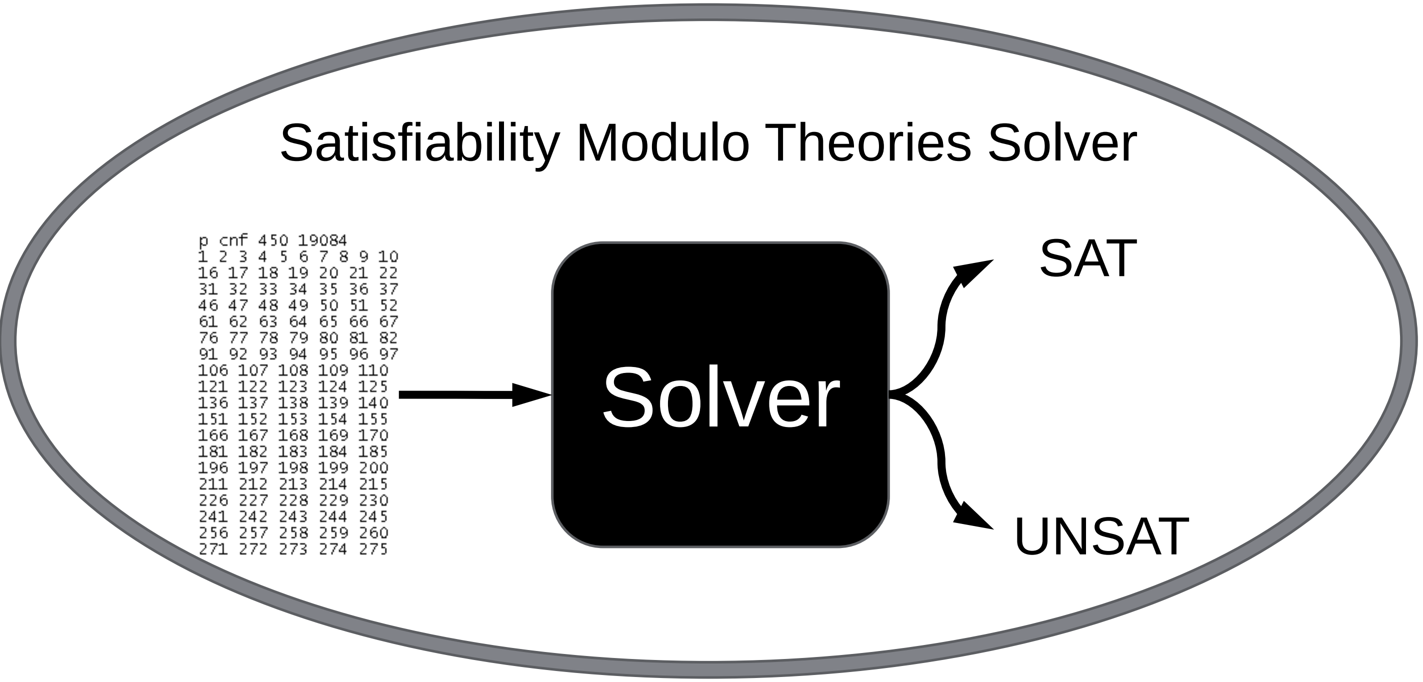


Result obtained from “A routability-driven flow routing algorithm for programmable microfluidic devices” by Yi-Siang Su et al. in *ASP-DAC*, 2016.

Development of a **sound** valve-control for PMDs

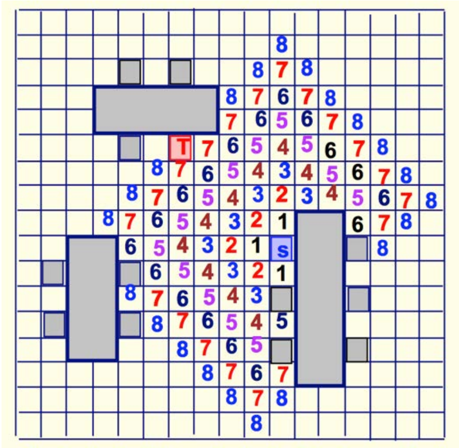
PROPOSED APPROACHES

Exact



Heuristic

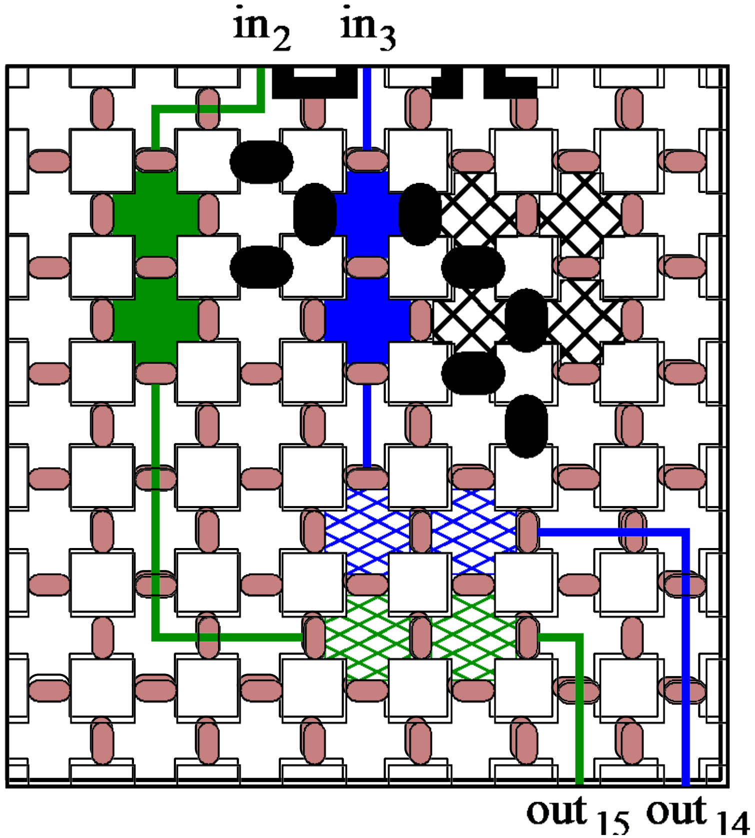
Standard VLSI Maze routing



EXACT: SYMBOLIC FORMULATION

For each sample s and time t:

- Positions: $pos_s^t = \{(pos_s^t[i].x, pos_s^t[i].y) : 0 \leq i < l\}$
- Inputs and Outputs: in_s^t, out_s^t
- Bends: $bend_s^t = \{(bend_s^t[i].x, bend_s^t[i].y) : 0 \leq i < 2 * k\}$



Example:

$pos_s^0 = \{(1,2), (1,1)\}$

$in_s^0 = 2$, $out_s^0 = 15$

$bend_s^0 = \{(2,0), (1,0), (1,5), (5,5)\}$

$pos_s^0 = \{(3,2), (3,1)\}$

$in_s^0 = 3$, $out_s^0 = 14$

$bend_s^0 = \{(3,0), (3,0), (3,4), (6,4)\}$

EXACT: CONSTRAINTS

All samples s have to

- start on their starting position

$$\bigwedge_{s \in S} pos_s^0 = src_s$$

- reach their target at some time t_t

$$\bigwedge_{s \in S} \exists t_t \left(0 \leq t_t < T \land \bigwedge_{t_t \leq t < T} pos_s^t = tgt_s \right)$$

- stay on the grid

$$\bigwedge_{s \in S} \bigwedge_{0 \leq i < l_s} \bigwedge_{0 \leq t < T} 0 \leq pos_s^t[i].x < W \land 0 \leq pos_s^t[i].y < H$$

- can flow to an adjacent node

$$\bigwedge_{s \in S} \bigwedge_{0 \leq t < T} \underbrace{(pos_s^t[0].x = pos_s^{t-1}[0].x \land pos_s^t[0].y = pos_s^{t-1}[0].y - 1)}_{Up_s^t} \lor \underbrace{(\dots)}_{Down_s^t} \lor \underbrace{(\dots)}_{Left_s^t} \lor \underbrace{(\dots)}_{Right_s^t} \lor \underbrace{(\dots)}_{Pause_s^t} .$$

Discussion:

Full consideration how samples can concurrently be pushed on the PMD

→ Results in huge search space

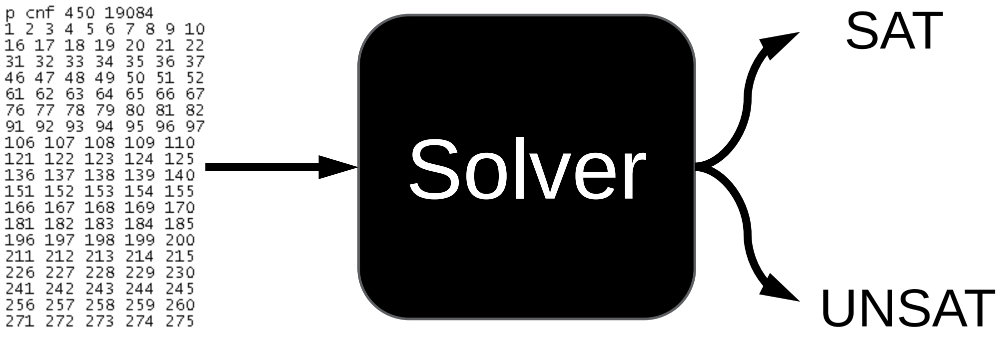
→ Applicable only for small instances

BUT: Useful for evaluating heuristic solutions

PROPOSED APPROACHES

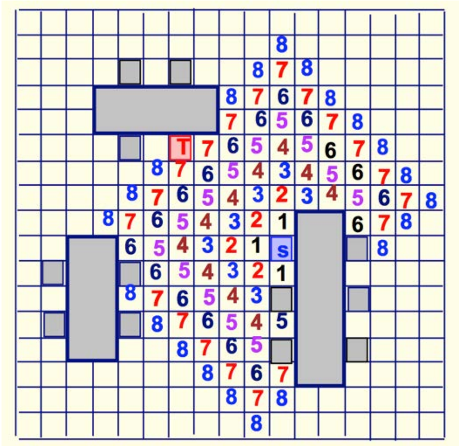
Exact

Satisfiability Modulo Theories Solver



Heuristic

Standard VLSI Maze routing



HEURISTIC

Applied simplifications:

- Samples flow continuously from source to target
- Determine flow path for each sample one after another

Implications:

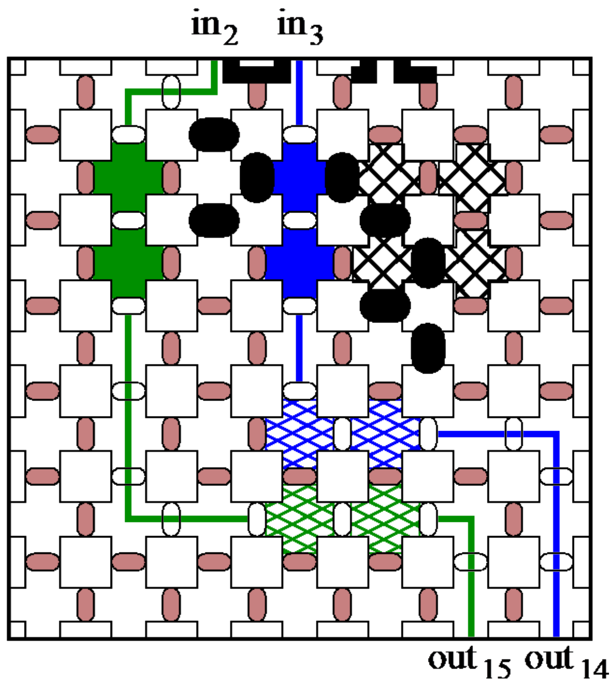
- Cannot guarantee a solution within a certain amount of time steps
- But this solution is still sound!

Procedure:

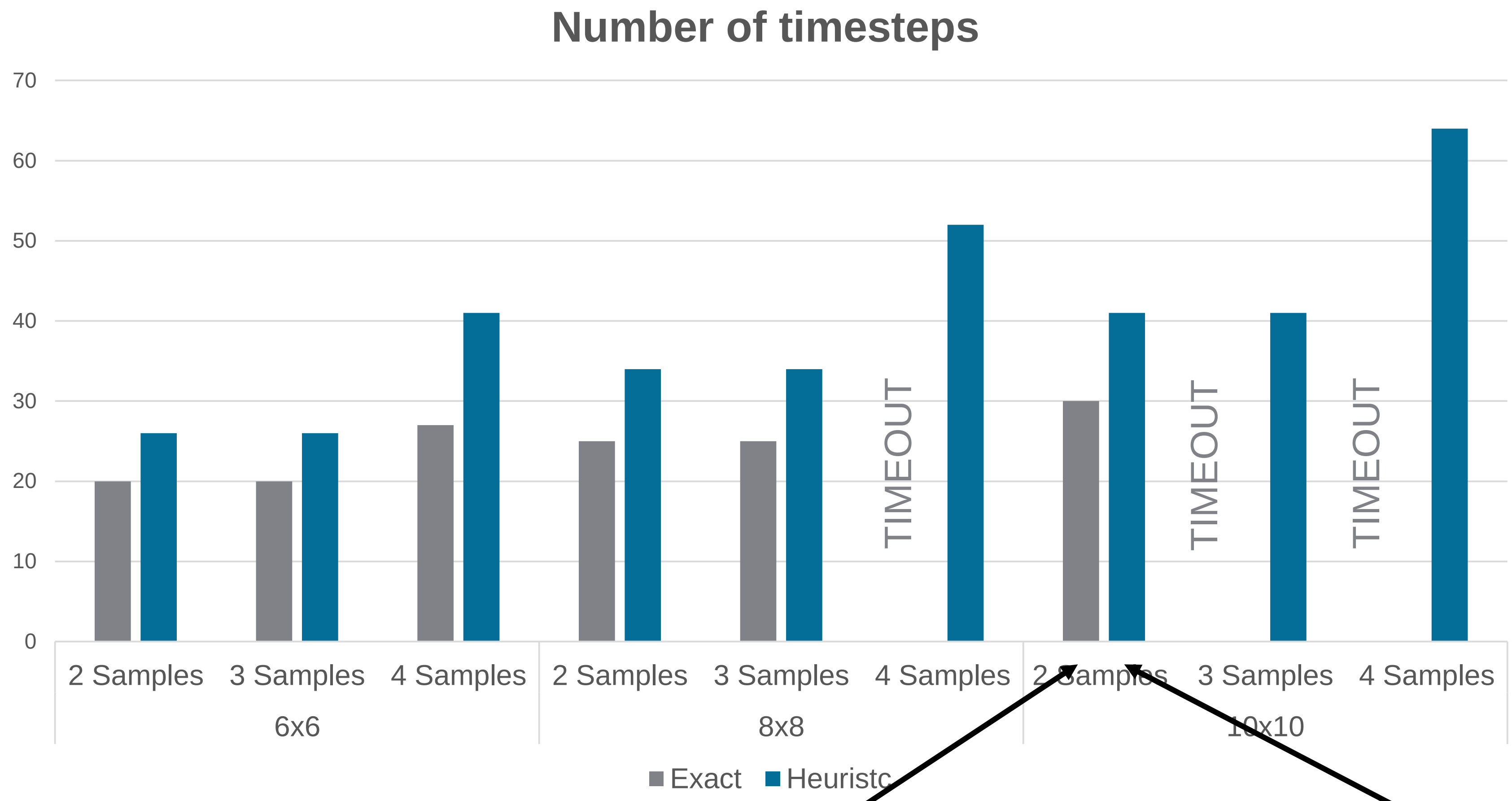
Three sub-paths are required:

- From any input to the ”tail” of the sample source
- From the “head” of the sample source to the “tail” of the sample target
- From the “head” of the sample target to any output

→ Application of a standard routing algorithm, namely **maze routing with a rip-up and reroute method**



EVALUTATION – QUALITY



Required 3 hours

Required 0.092 seconds

EVALUTATION – COMPARISON TO RELATED WORK

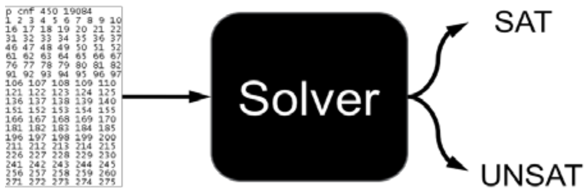
Case
10x10; 5 Samples
10x10; 10 Samples
20x20; 20 Samples
30x30; 30 Samples
40x40; 40 Samples
50x50; 50 Samples

[1] Yi-Siang Su et al., "A routability-driven flow routing algorithm for programmable microfluidic devices" in *ASP-DAC*, 2016.

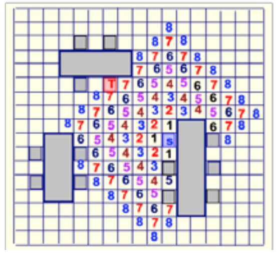
CONCLUSION

Two complementary approaches:

Exact
Satisfiability Modulo Theories Solver



Heuristic
Standard VLSI Maze routing



Limitations:

- Does not consider physical properties (i.e. applied pumping pressure, fluids,…)
- Considers only valve-control

Open Source:

http://www.jku.at/iic/eda/pmd

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