CrossRouter: A Droplet Router for Cross-Referencing Digital Microfluidic Biochips

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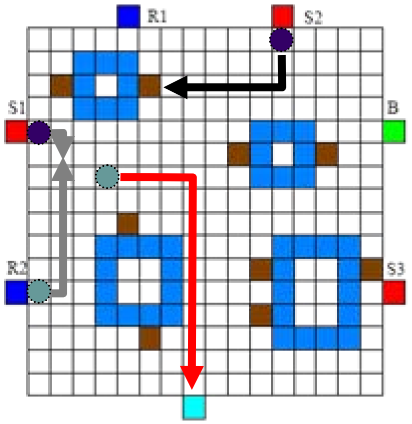
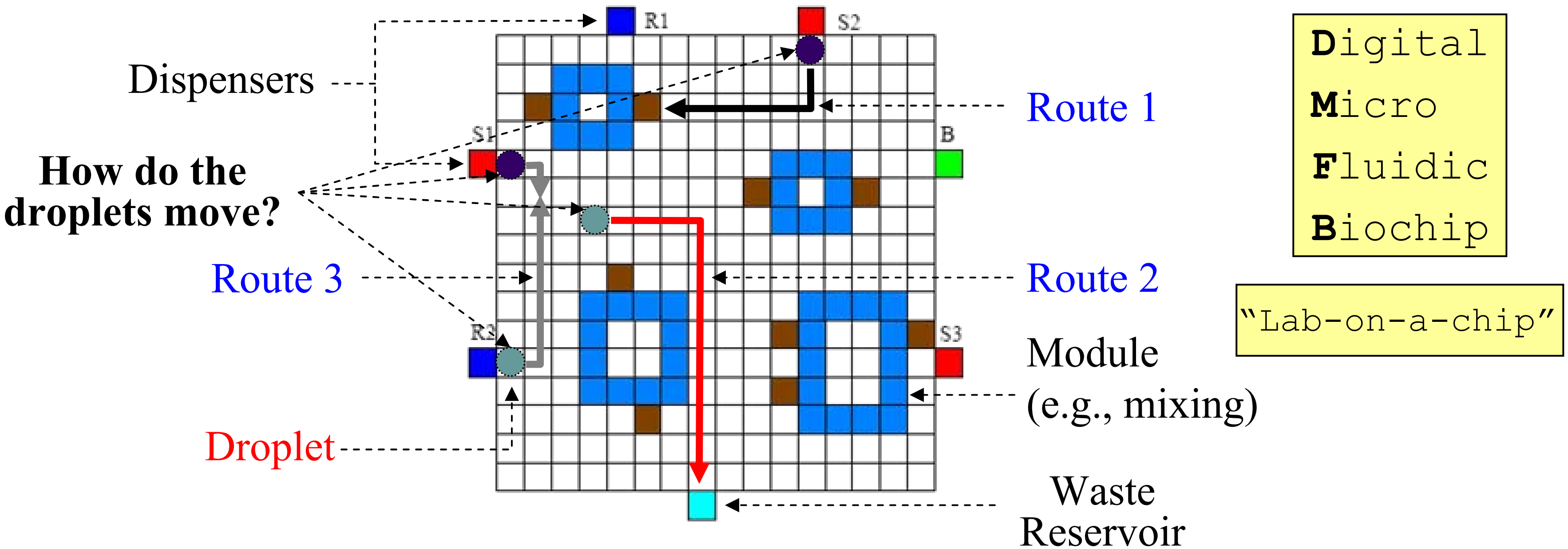
ASP-DAC '10, Taipei, Taiwan
Jan. 20th, 2010

Outline

1. Droplet Routing in Cross-Referencing Biochip
2. Formulation of Droplet Routing
3. CrossRouter: Idea and Implementation
4. Experiment and Evaluation
5. Conclusion



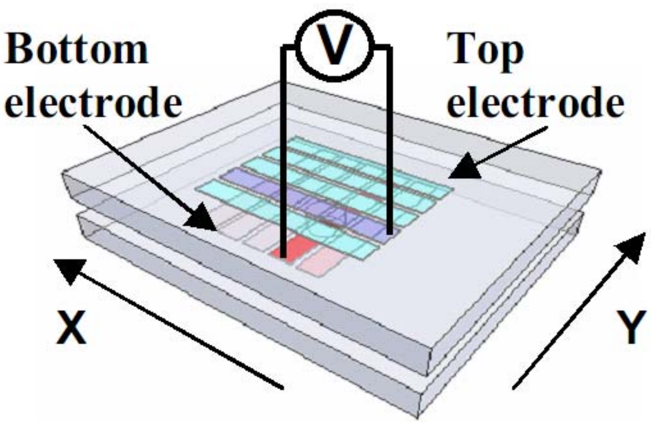
Droplet Routing Problem & Previous Works



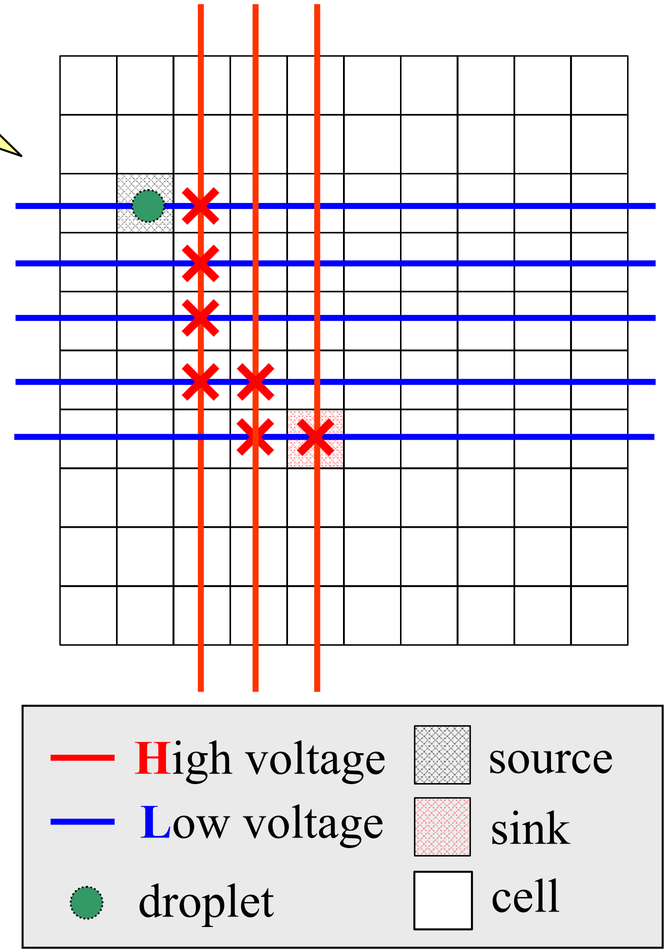
- Similar to Motion Planning in Robotics
  - NP-hard even for only two robots!
- Existing methods
  - A* Search, [Bohringer TCAD'06]
  - OSPF, [Griffith IJRR'05]
  - Pattern Selection, [Su DATE'06]
  - Network-Flow, [Yuh ICCAD'07]
  - Bypassibility, [Cho ISPD'08]
  - Graph-Coloring, [Griffith TCAD'06]
  - Clique-Partitioning, [Xu DATE'07]
  - Progressive ILP, [Yuh DAC'08]

Electrode Manipulation in Cross-Referencing DMFB

Apply a ***sequence*** of ***Voltage Assignment***



(Cite from [1])

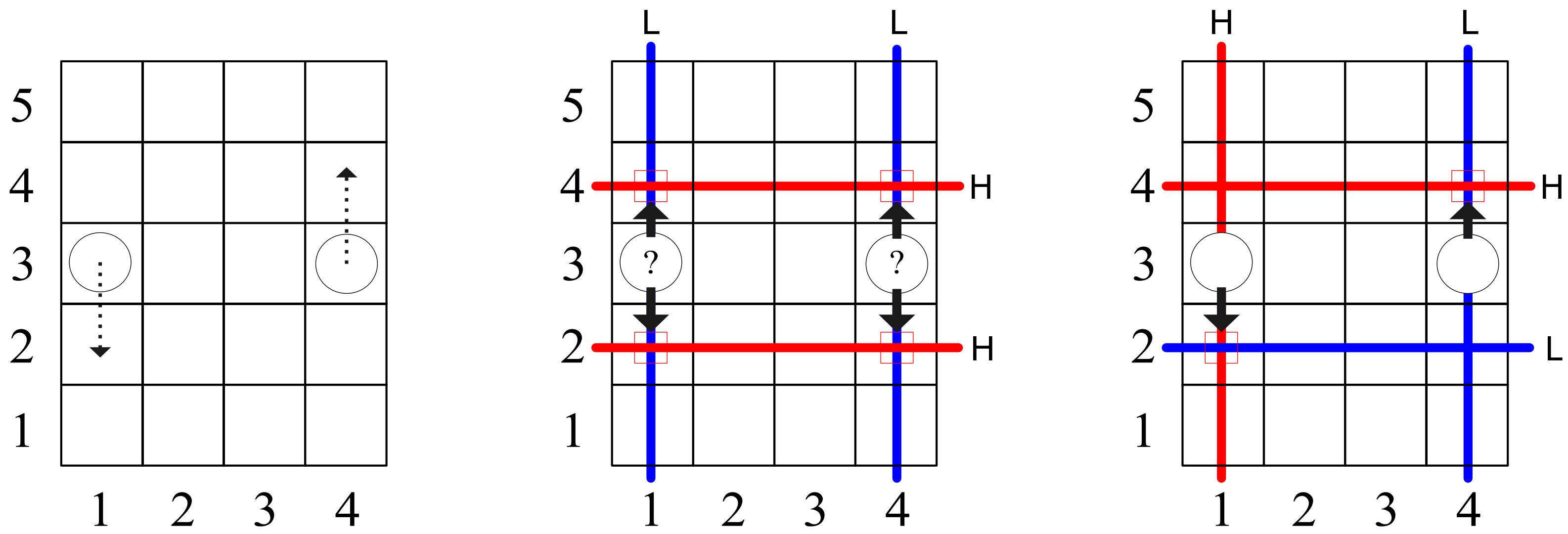


Special and hard problem:

- Routing several droplets simultaneously - *Electrode Interference*

[1] P. Yuh, S. Sapatnekar, C. Yang and Y. Chang, “A progressive-ILP based routing algorithm for cross-referencing biochips”, *Design Automation Conference*, pp.284-289, 2008.

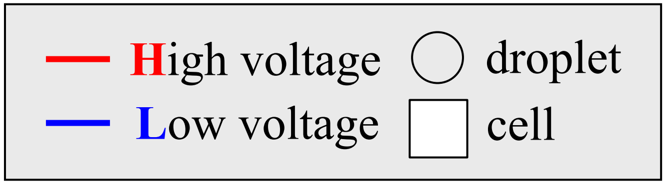
Electrode Interference and Solution



Supposed movements

Electrode Interference

Solution



Example of Routing Result

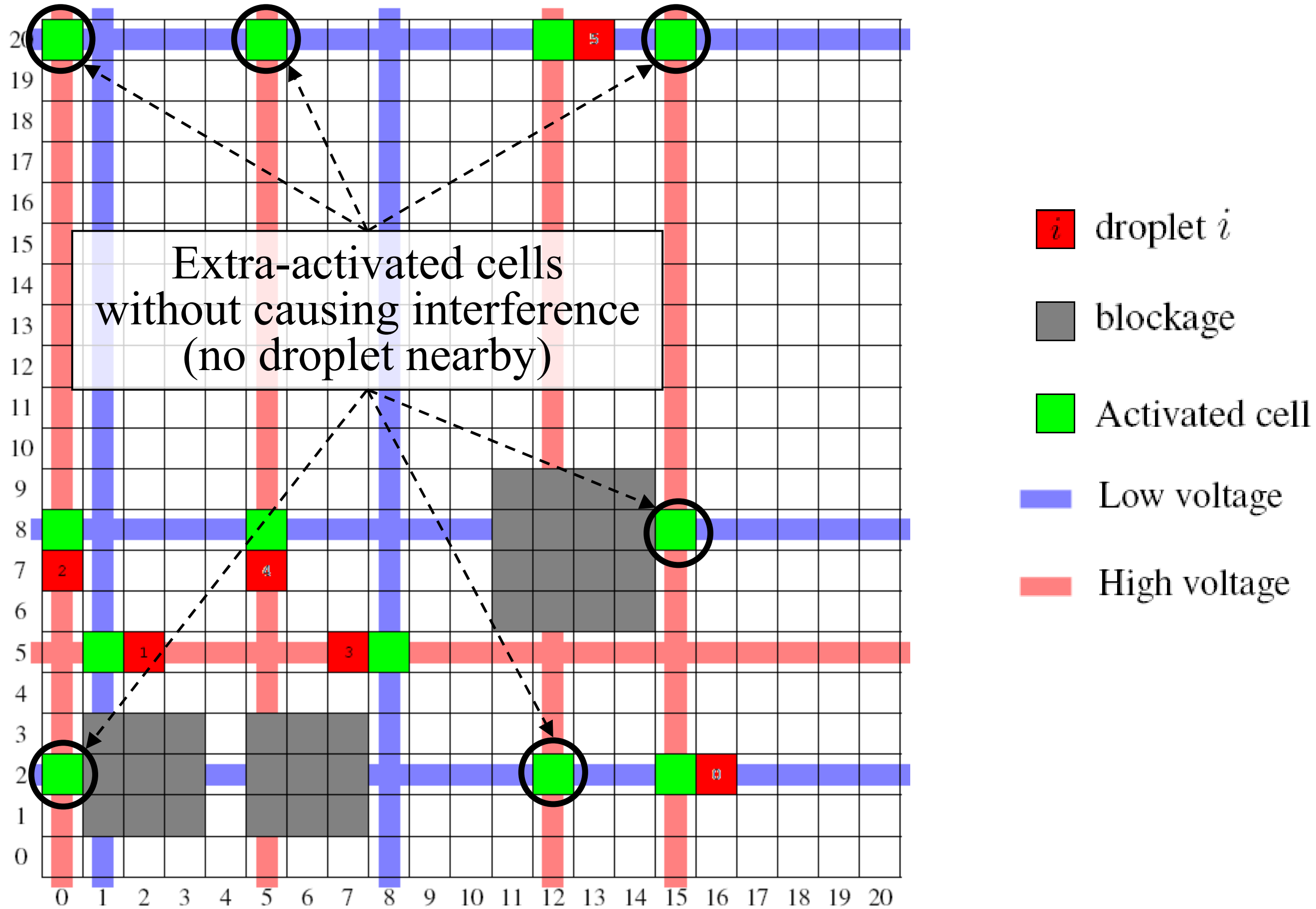


Figure 1: time=0

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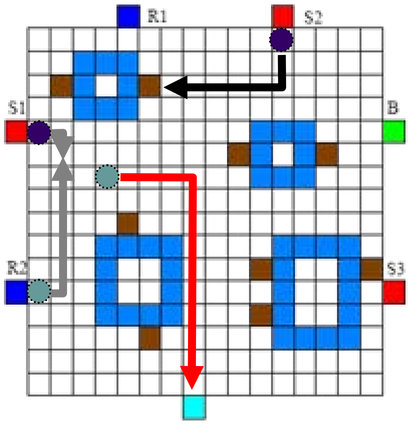


Problem Formulation

- Input:
  - A *WxH* 2D array
  - A netlist of *N* net, either 2-pin or 3-pin
  - *K* blockages
  - Waste disposal location *WAT*
  - Time limit *T*
- Output:
  - A *schedule of voltage assignment* for each time step
  - Fail if cannot finish routing before timing constraint
- Objective:
  - Route all droplets to their destinations
  - Minimize time used
  - (Minimize cell used)
- Constraint…

Voltage Assignment – A Snapshot

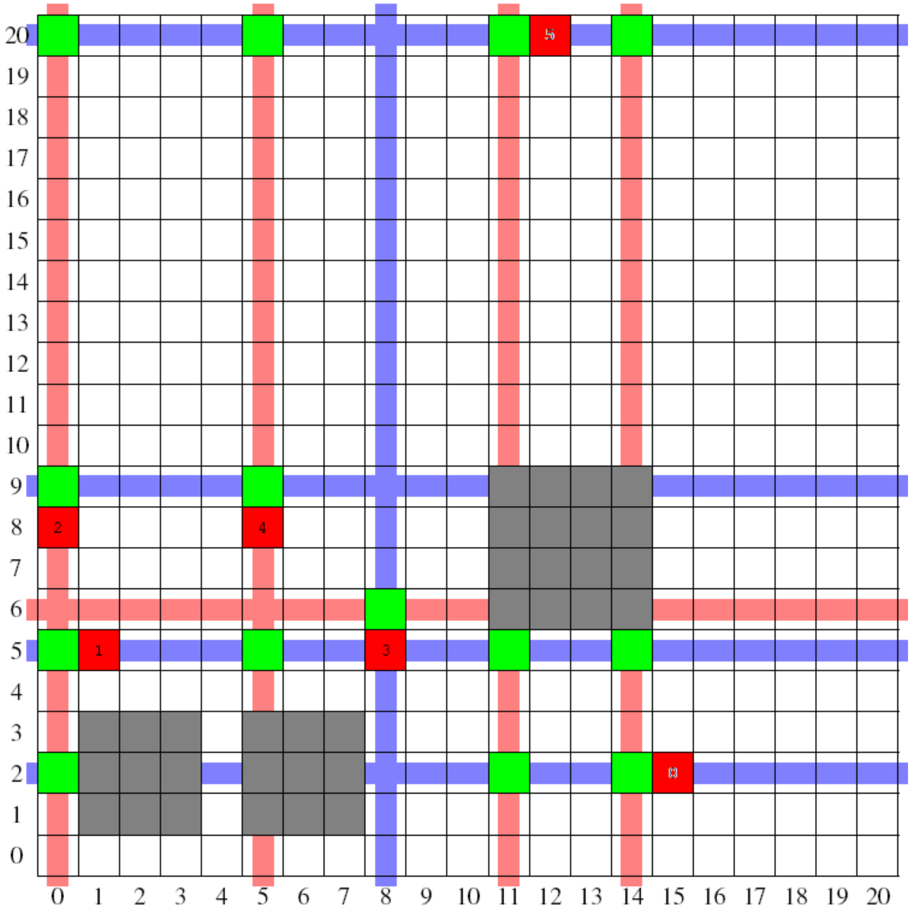


Figure 2: time=1

Voltage assignment for this time step:

(Row)
H: 6
L: 2, 5, 9, 20

(Column)
H: 0, 5, 11, 14
L: 8

Routing Result – Schedule of Voltage Assignment

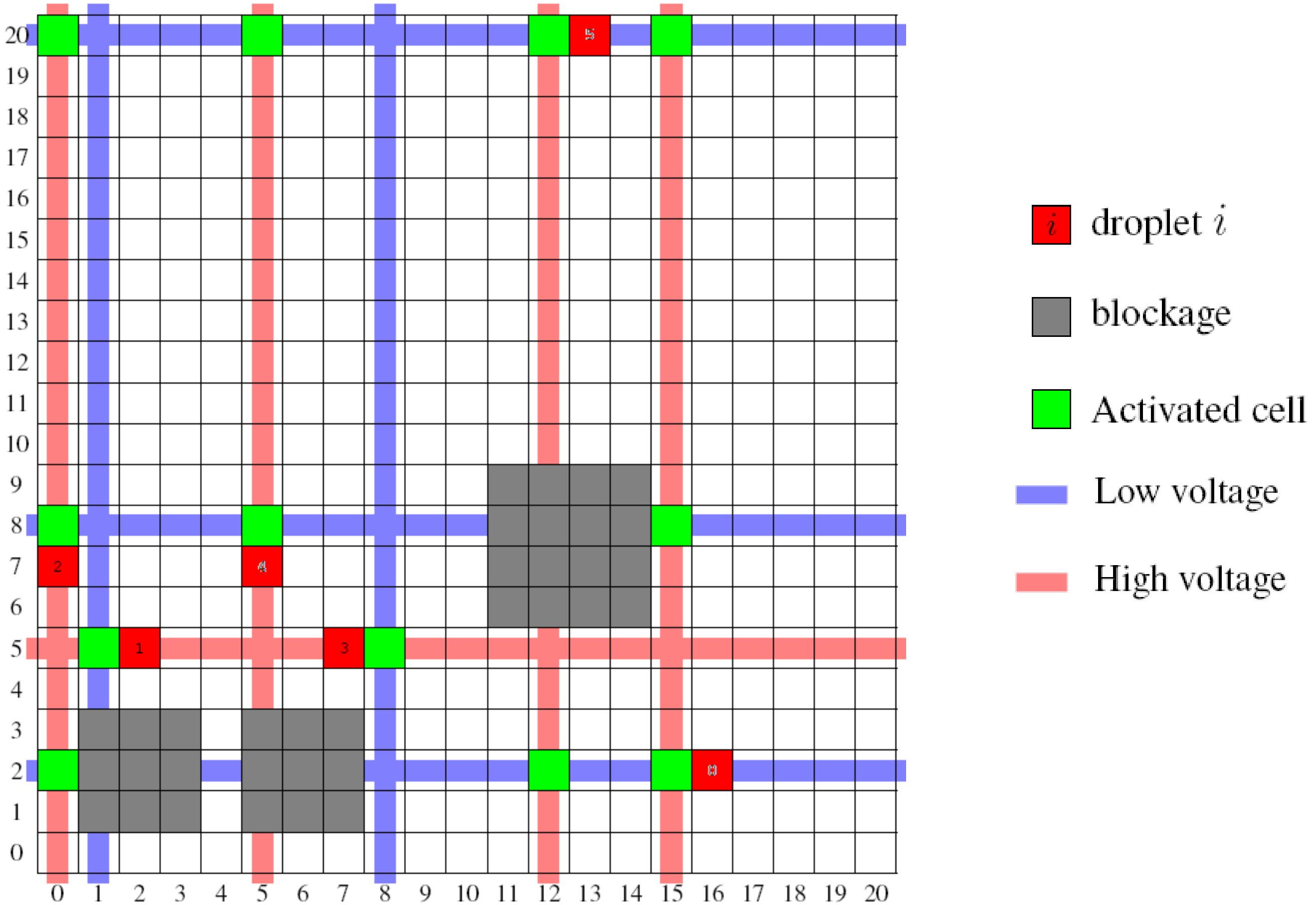
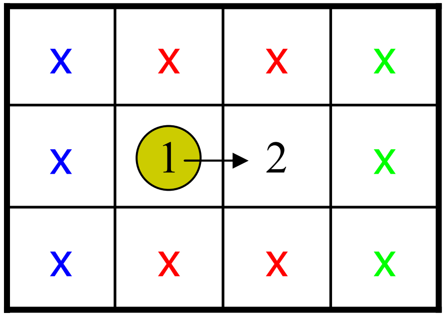


Figure 1: time=0

Constraints

1. Timing Constraint (Hard constraint)
   - All droplet be moved within time *T*
2. Fluidic Constraint
   - A minimum spacing of one cell should be kept



3. Electrode Constraint
   - While activating some electrodes simultaneously, no interference is caused

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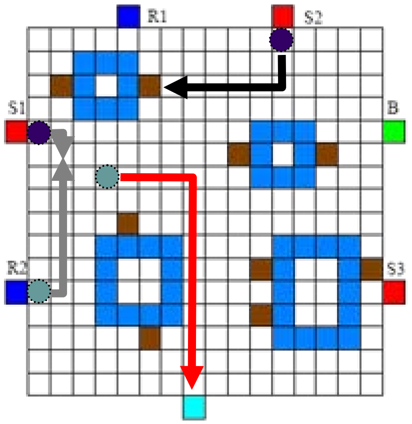
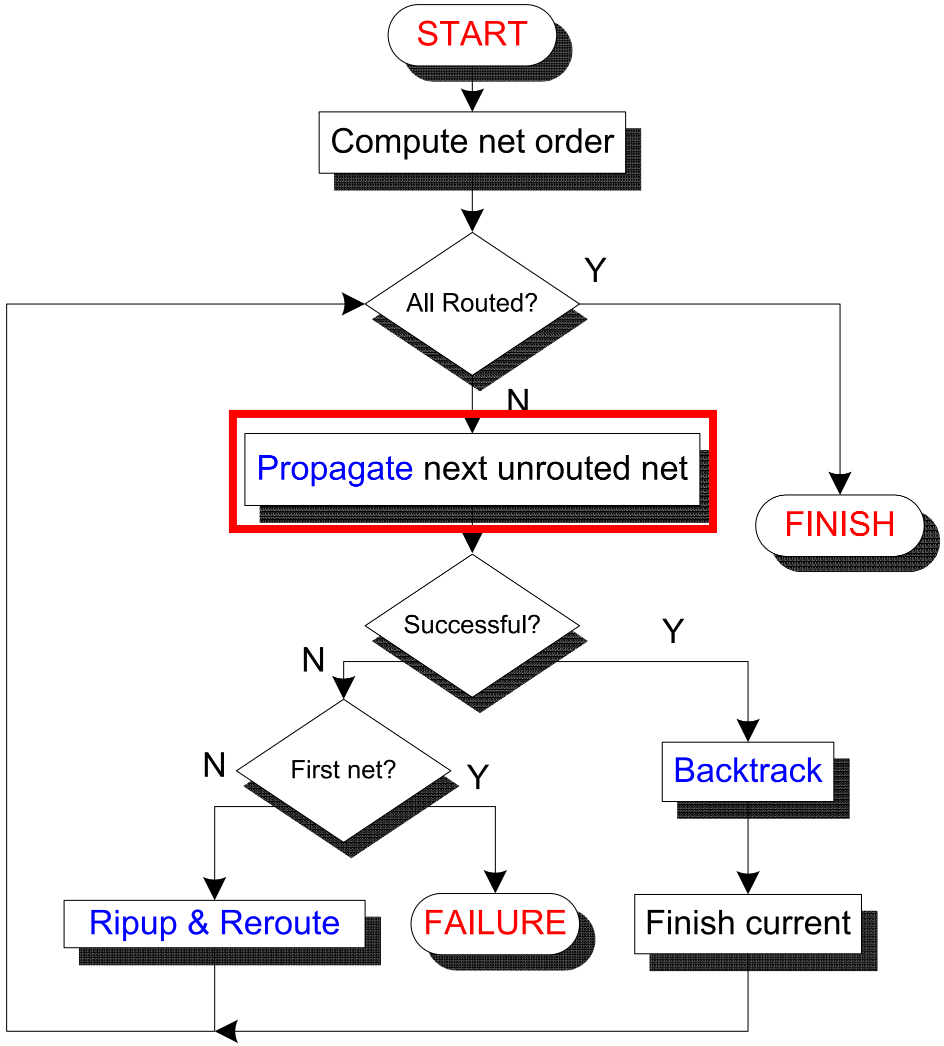
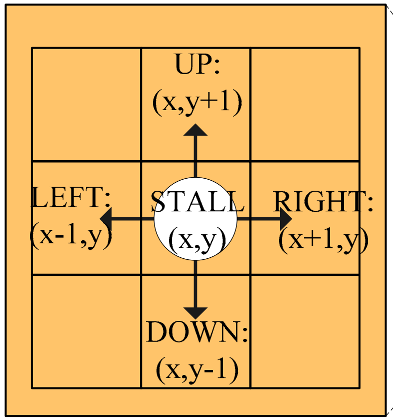


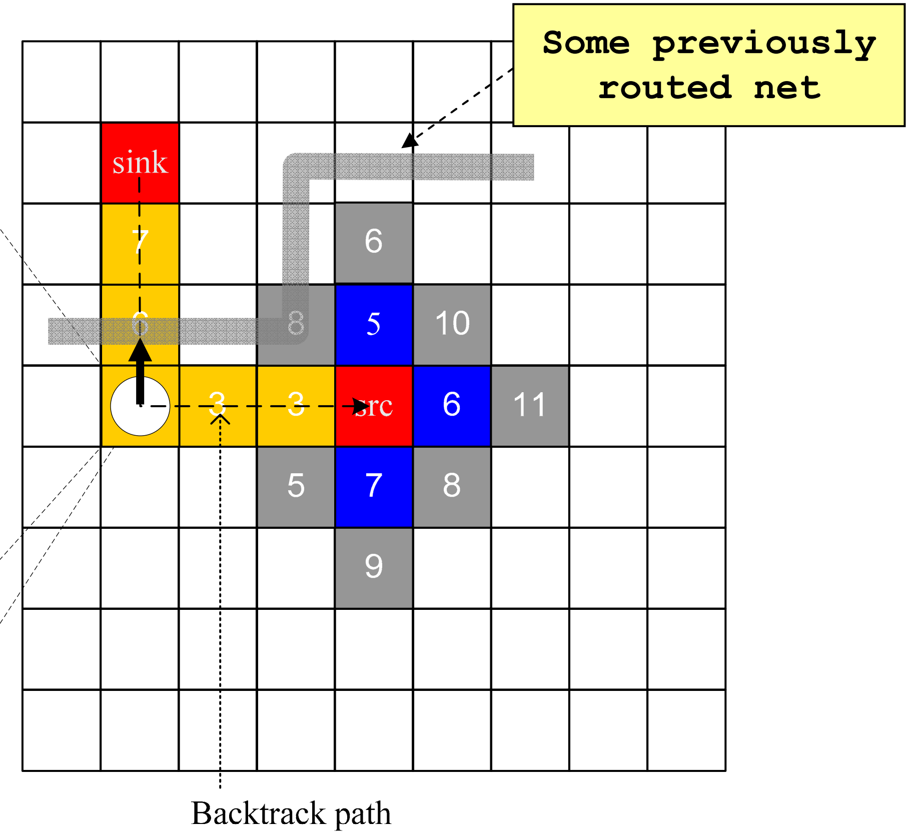
Overview of CrossRouter



Propagation

Five possible movements





Need to perform Fluidic/electrode check!

At P=(2,5), time=3

A 'droplet movement status'

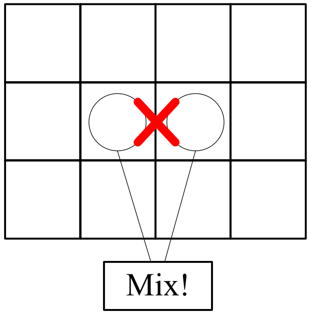
Weight(P,t) = t + MD(P,sink) + U(P) + Len(P,t)

N - #netuse

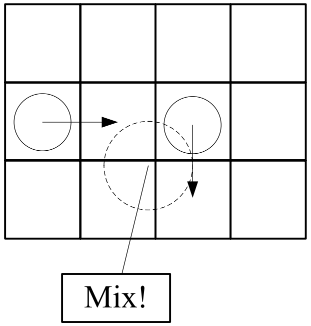
Current path length

Fluidic Constraint

- To avoid unexpected mixing
  - Static fluidic constraint
    - $|x_1^t - x_2^t| >= 2$ or
    - $|y_1^t - y_2^t| >= 2$

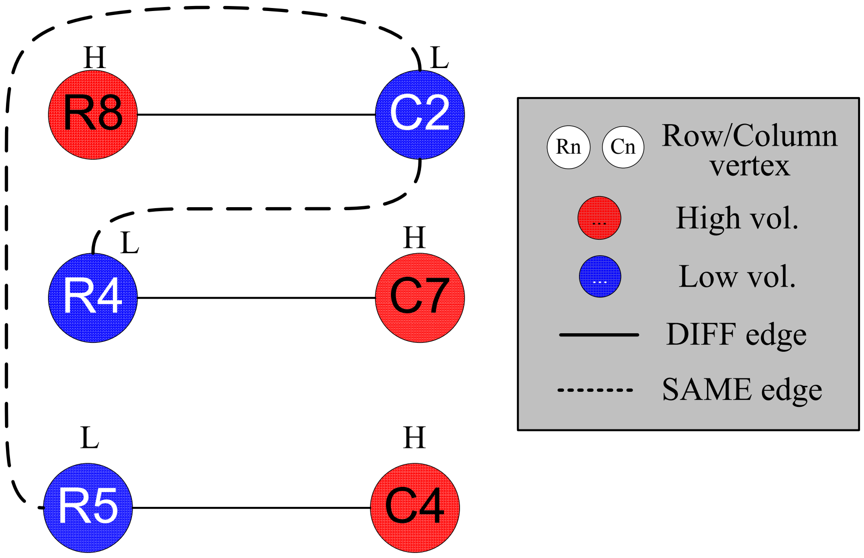


  - Dynamic fluidic constraint
    - $|x_1^{t+1} - x^t_2| >= 2$ or
      $|x_1^t - x_2^{t+1}| >= 2$
    - $|y_1^{t+1} - y_2^t| >= 2$ or
      $|y_1^t - y_2^{t+1}| >= 2$



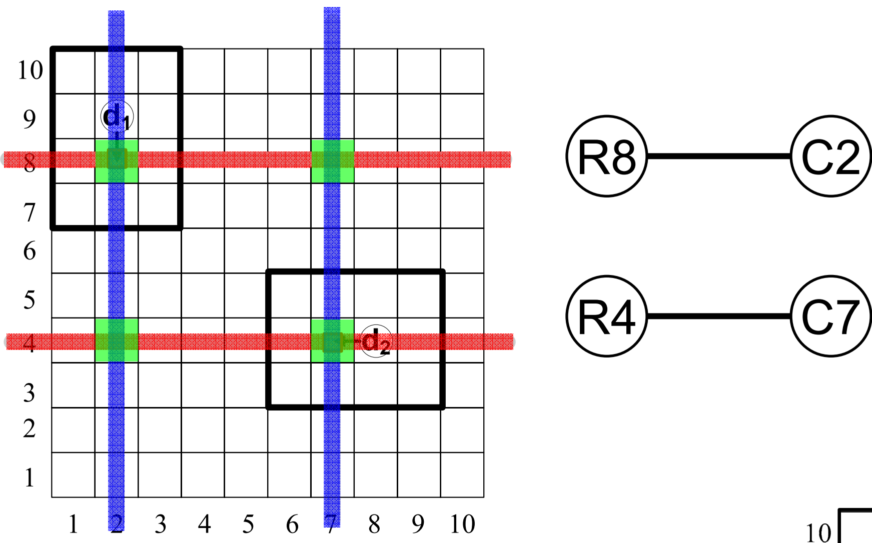
Electrode Constraint

- A crucial part in CrossRouter
- A *constraint graph* is used to determine if the simultaneous movements of a set of droplet is implementable
- Constraint Graph ***G***
  - Vertices are **electrodes** that need to be **assigned** a H/L voltage
  - Two types of edges:
    - **SAME** and **DIFF**
- Two-colorability
  - High->RED Low->BLUE
  - Each coloring corresponds to a voltage assignment



A Constraint Graph and a two-coloring

Constraint Graph by Example

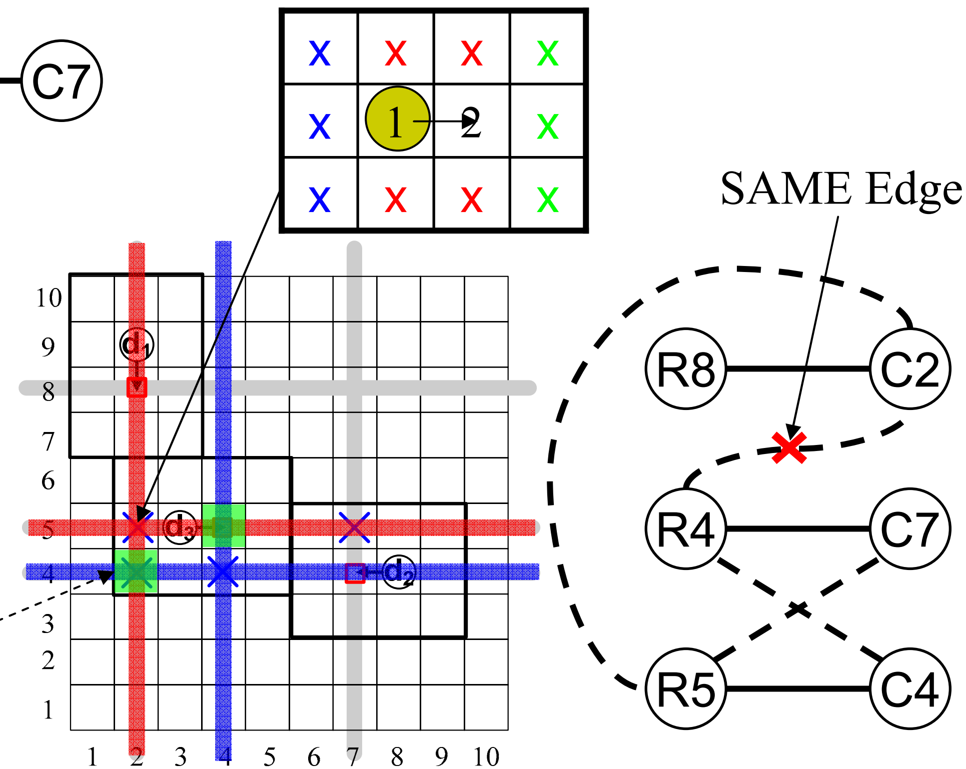


Two colorable components

Scenario: d_3 is NOT present

- Rn Cn Row/Column vertex
- High vol.
- Low vol.
- DIFF edge
- SAME edge
- Activated Cell

Forbidden cells



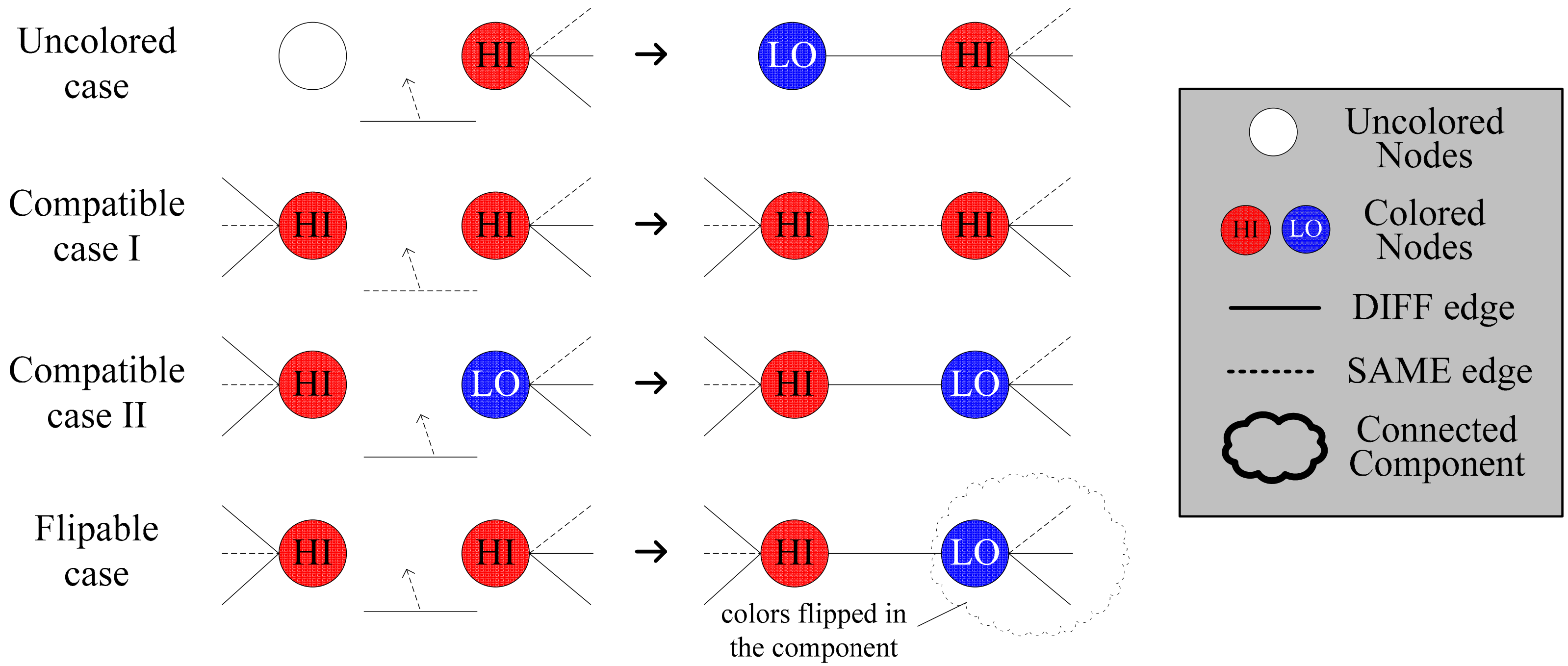
Interference!

NO valid assignment for the graph!

Scenario: d_3 is present

Speed Up Technique - Incremental Coloring

- At every time step, a constraint graph is maintained.
  - No need to construct graph from scratch
  - Incrementally color the nodes
  - Can perform electrode check very efficiently!



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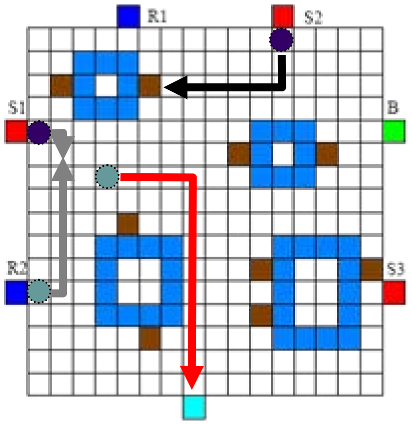
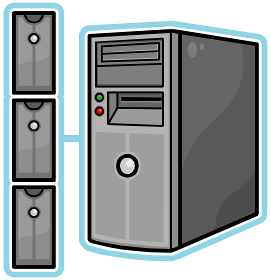


Experiment Setup

- Environment:
  - Implemented in C++ language
  - Run on department's Linux server
    - Intel Pentium IV 3.20GHz
    - 2GB Ram

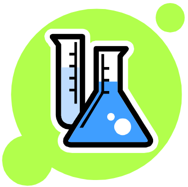


- Benchmarks:
  - Real world benchmark including:
    - *in-vitro, in-vitro2, protein, protein2*
- Compared with two previous works
  - Yuh's Progressive ILP
  - Cho's High Performance Droplet Router (in terms of cell used)

Experimental Result – Comparison I

Circuit	#sub.	Progressive ILP [1]		CrossRouter	
		Max/Average cycle	CPU time (sec.)	Max/Average cycle	CPU time (sec.)
In-vitro_1	11	24/13.09	2.55	20/12.09	0.92
In-vitro_2	15	22/11.00	2.53	19/10.73	1.21
Protein1	64	26/16.15	15.36	20/15.52	7.76
Protein2	78	26/10.23	6.70	20/9.86	2.22
Average		-/12.62	-	-/12.05	-

- The timing constraint of these benchmarks are all 20 steps
- In some subproblems, [1] exceeds the constraint, while CrossRouter completes all with smaller average cycle



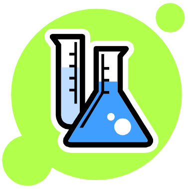
[1] P. Yuh, S. Sapatnekar, C. Yang and Y. Chang, "A progressive-ILP based routing algorithm for cross-referencing biochips", *Design Automation Conference*, pp.284-289, 2008.

Experimental Result – Comparison II

Circuit	# sub.	Size	# cell used	
			HPDRA [2]	CrossRouter
*In-vitro*_1	11	16x16	258	246
*In-vitro*_2	15	14x14	246	250
Protein1	64	21x21	1688	1664
Protein2	78	13x13	963	952
Average			788.75	778

- HPDRA is for direct-addressing DMFB, in which no electrode constraint and thus easier
- We achieve a better cell used rate

  (For *In-vitro*_2, HPDRA found an earlier merging point for a 3-pin net and hence better)



Note: [1] does not provide # cell used

[2] M. Cho and D. Pan, “A high-performance droplet router for digital microfluidic biochips”, *Proceedings of the 2008 International Symposium on Physical Design*, pp.200-206, 2008

Conclusion

- The graph **two-coloring** based method is very succinct and powerful in handling the electrode constraint for droplet routing

- CrossRouter is an efficient router for droplet routing problem on cross-referencing biochip
  - Explores the degree of parallelism of moving droplets
    - Comparing to the state-of-the-art Progressive ILP method, it can solve the problems within timing constraint and achieves shorter routing time
  - Effectively minimizes the cell used during routing
    - Comparing to HPDRA, better cell used rate acquired

Thank You!