A High-Performance Online Assay Interpreter for Digital Microfluidic Biochips

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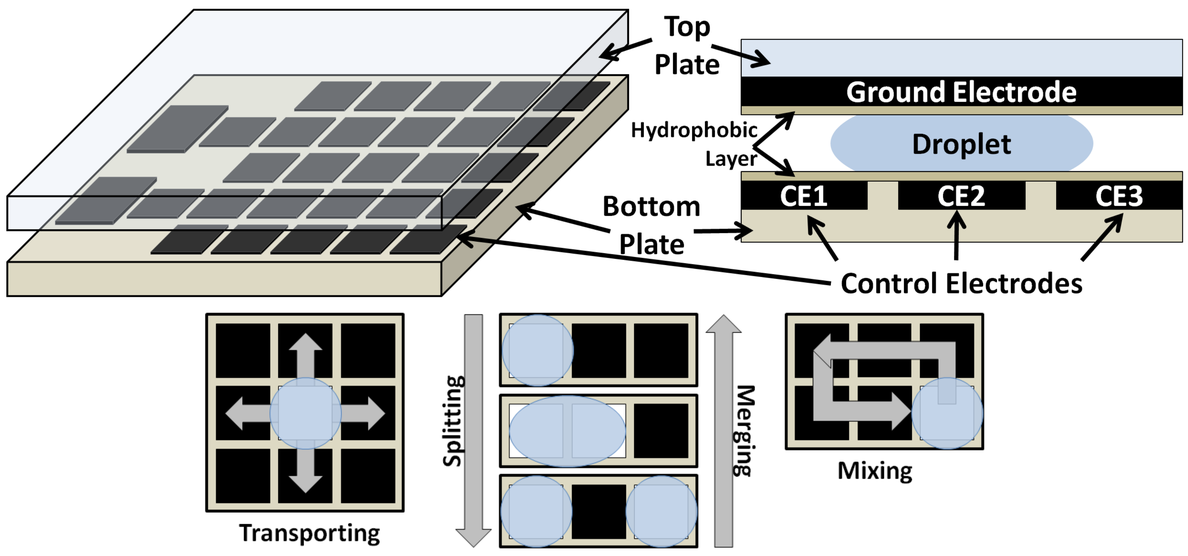
Digital Microfluidic Technology

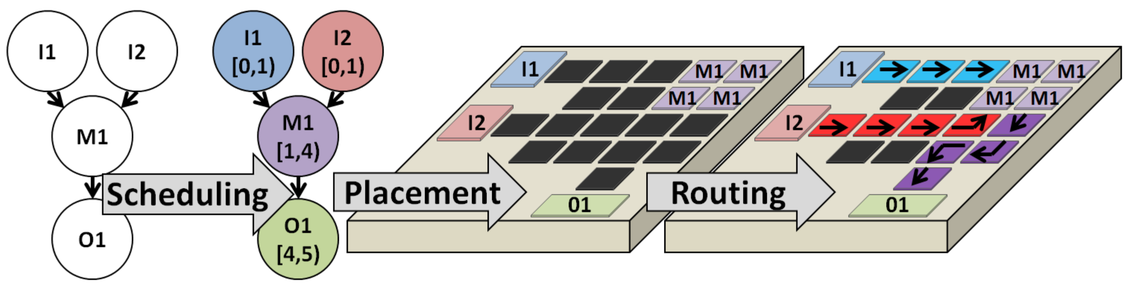
Digital Microfluidic Biochips (DMFBs) are an emerging "lab-on-a-chip (LoC)" technology that perform biochemical reactions by operating on fluidic droplets on the scale of nano-liters.

Applications:
- Clinical pathology
- Point of care diagnostics
- Drug discovery
- Proteomics, DNA, PCR, etc.
- Real-time detection of biochemical terror attacks

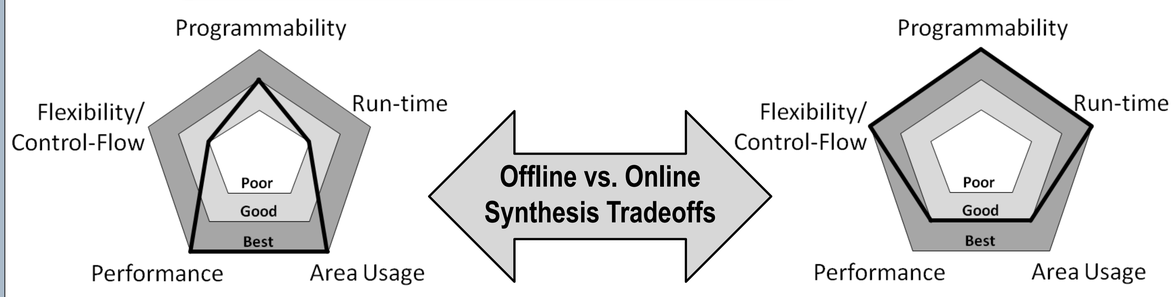
Key advantages:
- Reduced cost
- Reduced reagent and sample sizes
- Increased throughput and efficiency
- Increased sensitivity and accuracy
- Automation and miniaturization



Microfluidic Synthesis



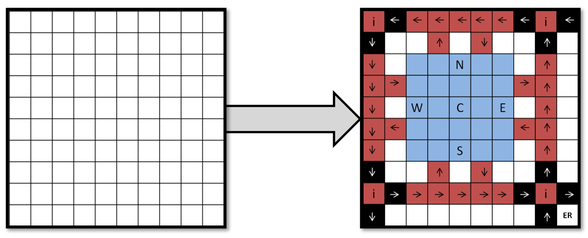
Microfluidic Synthesis Flow



Offline Assay Compilation — **Online Assay Interpretation**

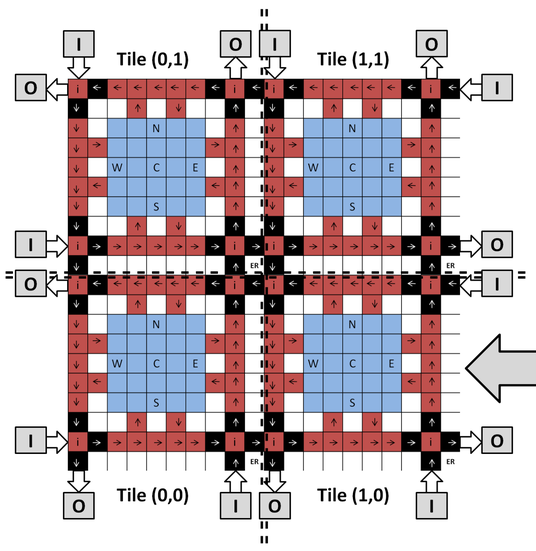
DMFB Topology & Deadlock Free Routing

Application of virtual topology to a tile (10x10 array of cells)

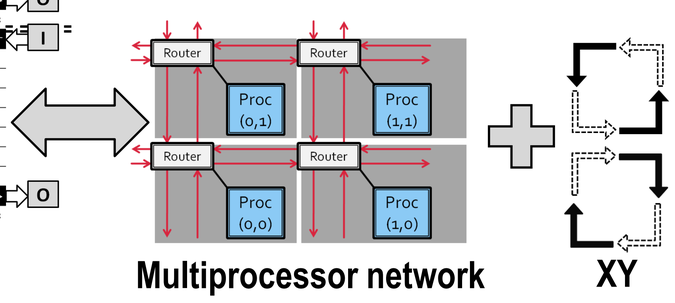


- -Tile arranged like city block
- -Transport limited to1-way streets
- -Operations limited to chambers
- -Similar to multi-proc router

Tiled topology showing chambers, streets, intersections, rotaries and I/Os

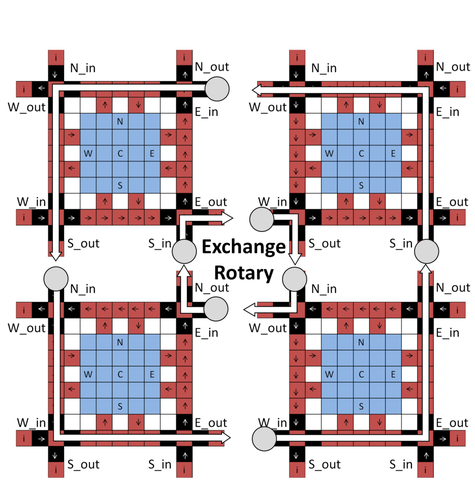


- -Similar to multi-proc network
- -Known methods for deadlock-free routing in multi-proc networks
- - Droplets travel from chamber to chamber via XY routing, which prevents deadlock by prohibiting turns in potential cycles

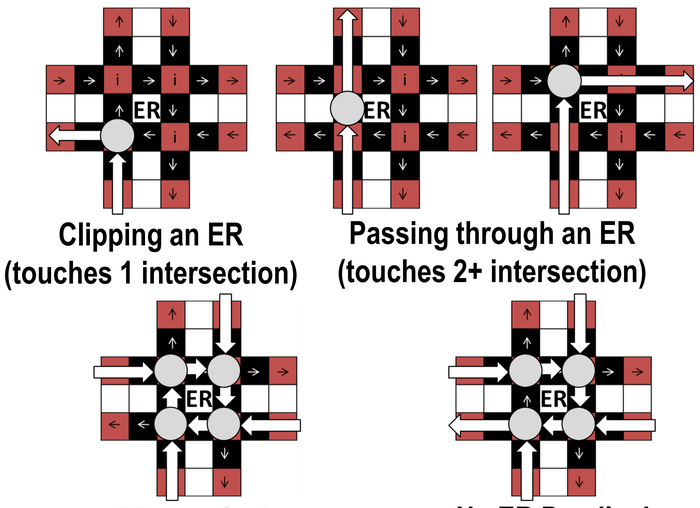


Preventing Droplet Deadlock in Rotaries

An Exchange Rotary (ER) is the clockwise inner loop which allows droplets to move from one tile to its neighbor tiles.



Exchange Rotary

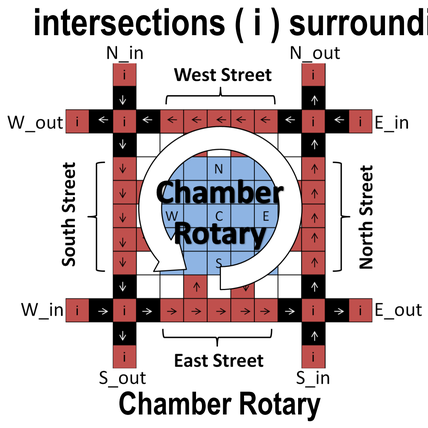


Clipping an ER (touches 1 intersection) — Passing through an ER (touches 2+ intersection)

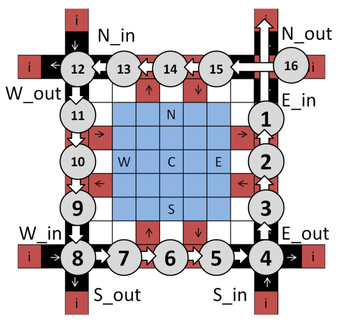
ER Deadlock — No ER Deadlock

ER deadlock occurs when four droplets attempt to *pass through* the ER simultaneously. <u>ER deadlock is prevented by allowing, at most, three droplets that wish to *pass through* the ER to enter concurrently.</u>

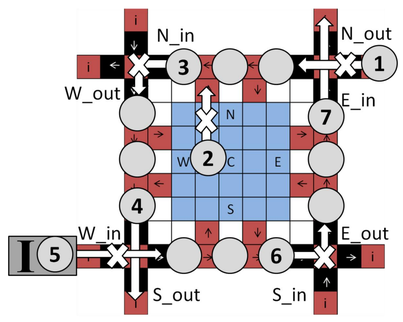
A Chamber Rotary (CR) is formed by the four streets (→, ↓, ←, ↑) and intersections (i) surrounding the work chamber.



Chamber Rotary



CR Deadlock



No CR Deadlock

CR deadlock occurs when no droplet in the CR can move in the counter-clockwise CR loop without interfering with another droplet. <u>To prevent CR deadlock, no droplet may enter an ER unless there is an open spot for it on the destination CR street.</u>

Evaluation of DTP on Low-Powered Intel Atom™

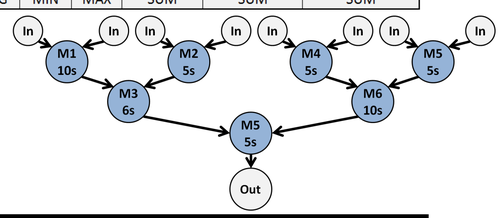
Routed a common "PCR" benchmark with 5 routing sub-problems:
- -Online computation time for entire benchmark is only 13.83ms (10.6s for Offline)
- -Online routing spends 2.23ms, at most, computing routes during any routing cycle (if this number is less than 10ms (100Hz DMFB), routes can be computed in real-time, providing maximum flexibility and fault-tolerance potential)
- -Offline routing time is 15 cycles (0.15s if 100Hz DMFB) shorter than online

PCR Routing Results - Offline Method

Routing Sub-Problem	Can Compact	Route #	Route Comp. (ms)	Route Length (# cycles)	Route Description
1	YES	1	618	4	In->M5
		2	582	4	In->M5
		3	859	12	In->M4
		4	576	4	In->M4
		5	916	13	In->M1
		6	584	4	In->M1
		7	572	4	In->M2
		8	587	4	In->M2
2	NO	9	793	7	M4->M6
		10	833	10	M5->M6
3	YES	11	709	6	M1->M3
		12	911	12	M2->M3
4	YES	13	662	4	M3->M7
		14	807	6	M6->M7
5	YES	15	655	4	M7->Out
		SUMS:	10664	98	
		COMPACTED SUM:		52	

PCR Routing Results - Online Method

Routing Sub-Problem	Cyclic Routing Computation (ms)			Routing Sub-Problem Stats			
	Avg	Min	Max	Route Comp. (ms)	Longest Route (# cycles)	Route Lengths (# cycles)	Route Description
1	0.17	0.00	2.23	4.85	7	6, 6, 6, 6, 7, 7, 7, 7	In->M(1, 1, 2, 4, 2, 4, 5, 5)
2	0.20	0.12	0.37	5.89	30	12, 30, 30	M5->M6, M4->M6, M2->S2
3	0.13	0.09	0.23	1.62	12	12	S2->M3
4	0.09	0.06	0.14	1.07	12	12	M6->M7
5	0.02	0.00	0.11	0.41	6	6	M7->Out
TOTALS:	0.12	0.00	2.23	13.83	67	154	-
	AVG	MIN	MAX	SUM	SUM	SUM	



Performed routing stress test on DMFBs of varying size. 5 droplets were input at each input port, traveled to 2 random chambers each, and then output at a random output port.

Random Traffic Stress Test - Online Method

DMFB Size (# Chambers)	General Simulation/Routing Stats			Cyclic Routing Computation		
	# Droplets/ #Routes	Completion Time (s)	Total Computation Time (ms)	Avg (ms)	Min (ms)	Max (ms)
2x2	40/120	2.19	235.77	1.08	0.02	4.86
3x3	60/180	2.33	514.88	2.21	0.02	8.23
4x4	80/240	2.26	809.57	3.58	0.03	12.13
8x8	160/480	3.69	2780.24	7.53	0.03	36.39

- -2x2 & 3x3 can run in real-time on a 100Hz DMFB driven by the Atom™
- -4x4 & 8x8 are too complex for the Atom™ to compute in real-time, but can quickly route up to 160 droplets simultaneously in less than 4s

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