future of advanced cyber-physical microsystems

Professor Jan Madsen
DTU Compute
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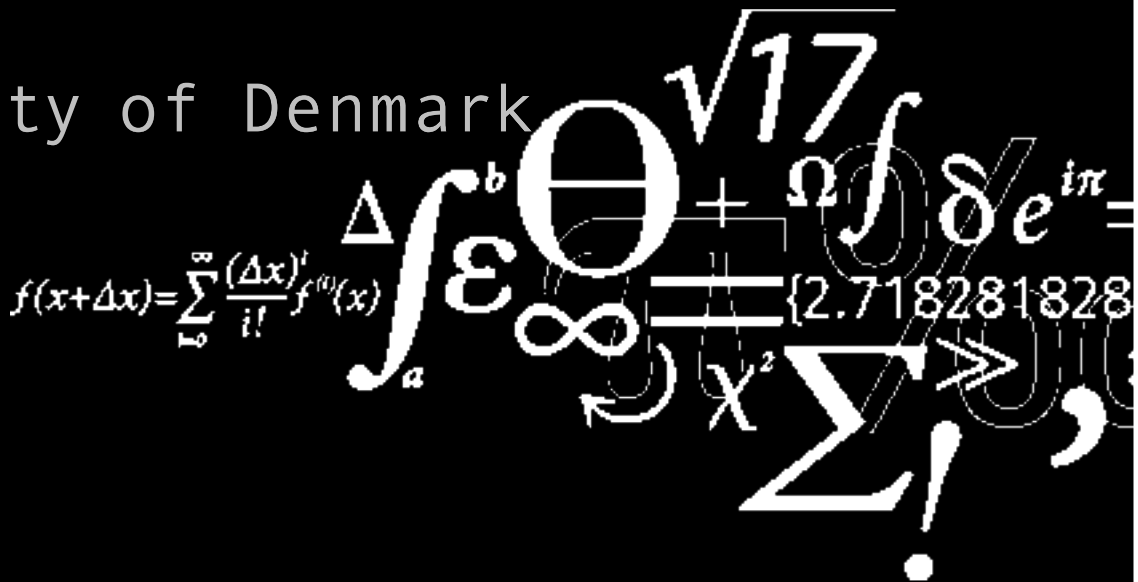
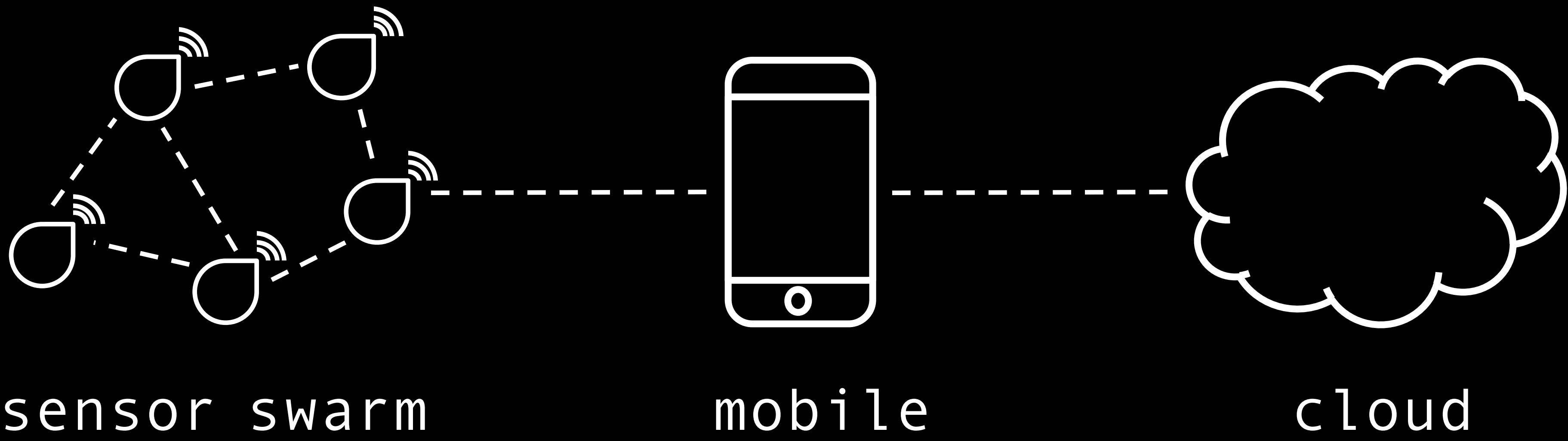
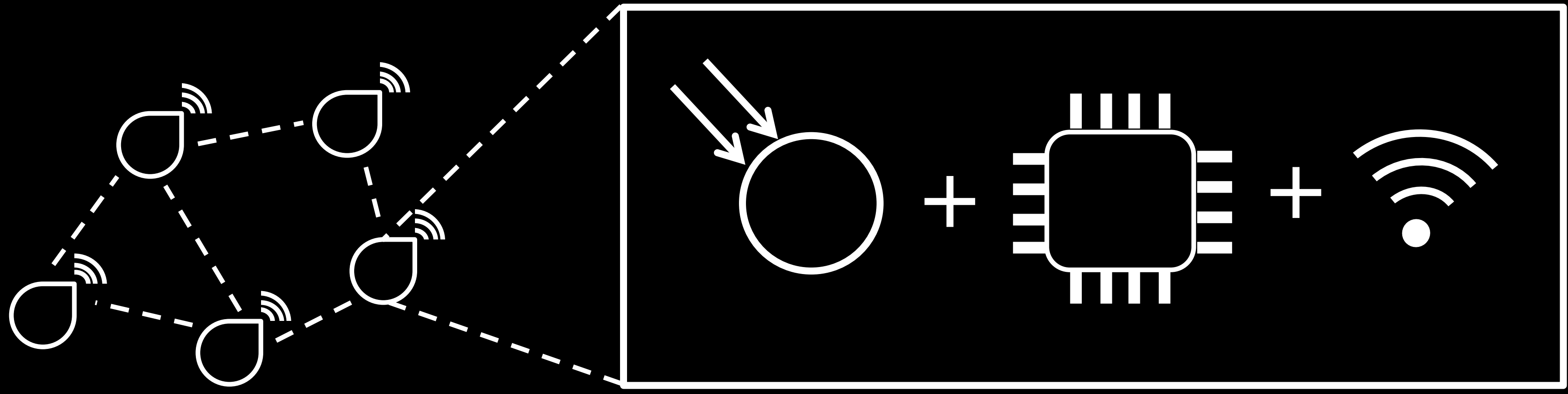


computing

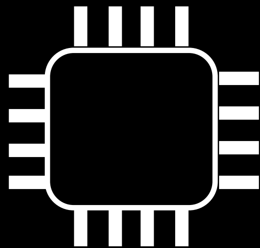


computing



sensor swarm

microsystem

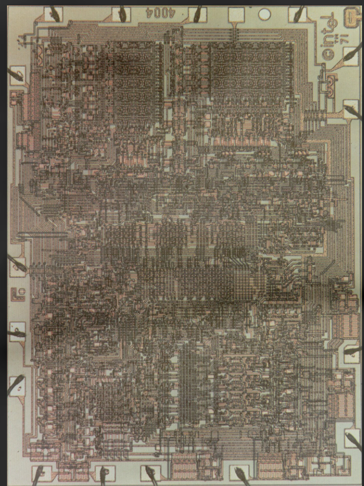


microelectronics

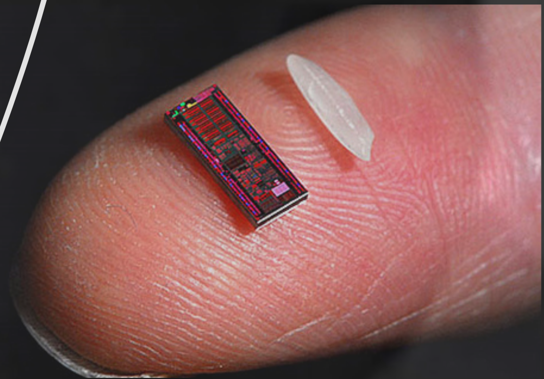
microelectronics

2014: 20.000.000.000

1947: 1



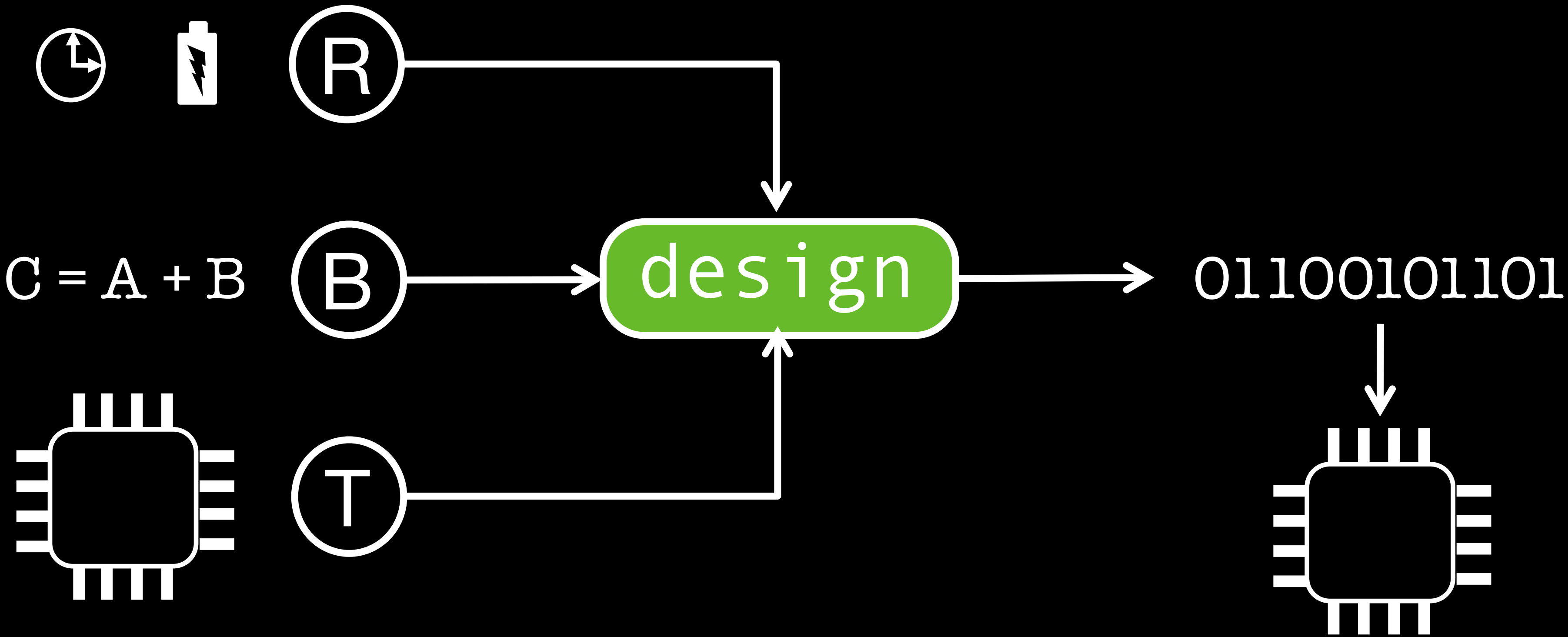
1971: 2.300



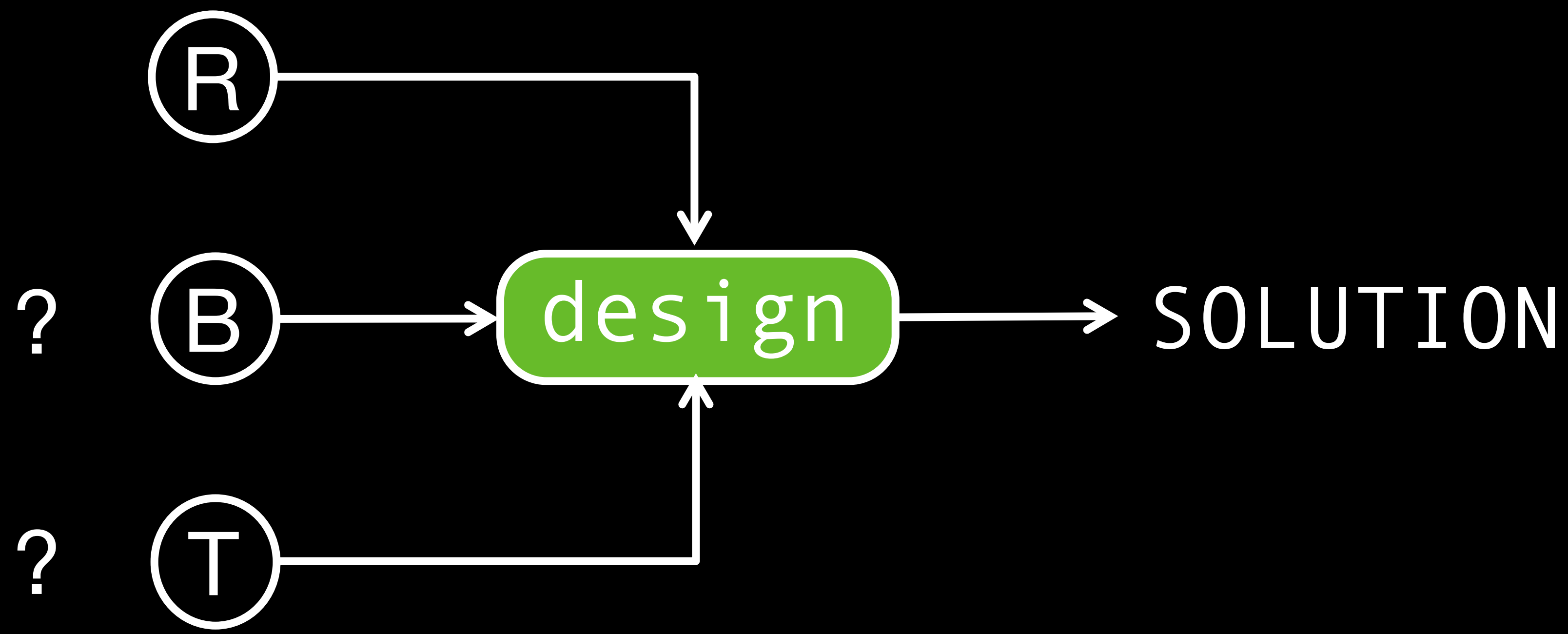
2008: 47.000.000

smaller, faster, cheaper

programming



programming



part 1

- microfluidics
  - motivation
  - technology
  - design
  - applications

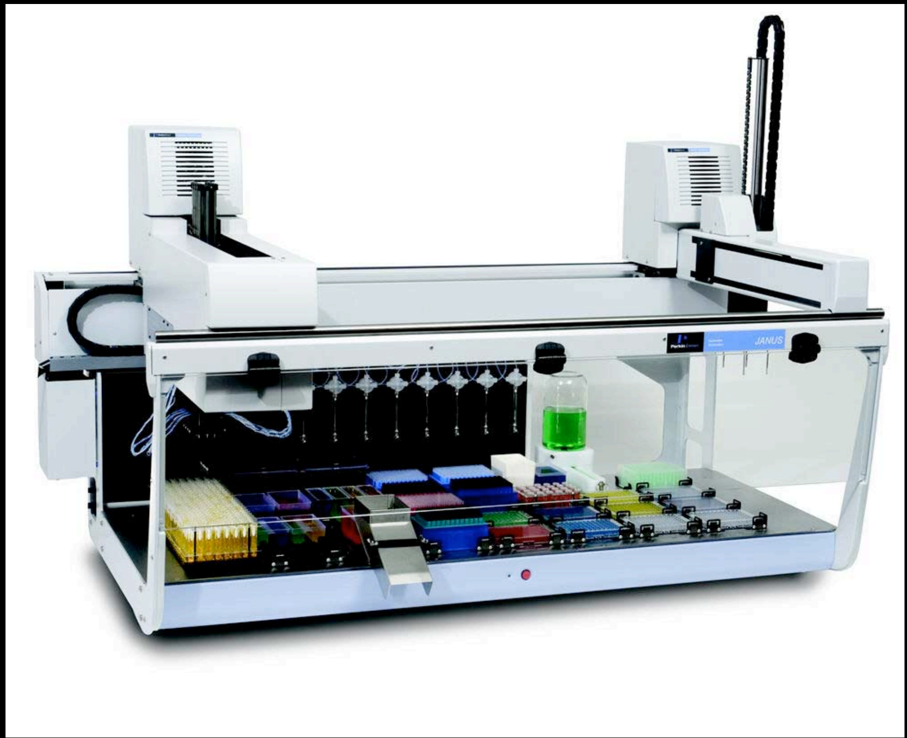
microfluidics

biochemical computing – why?

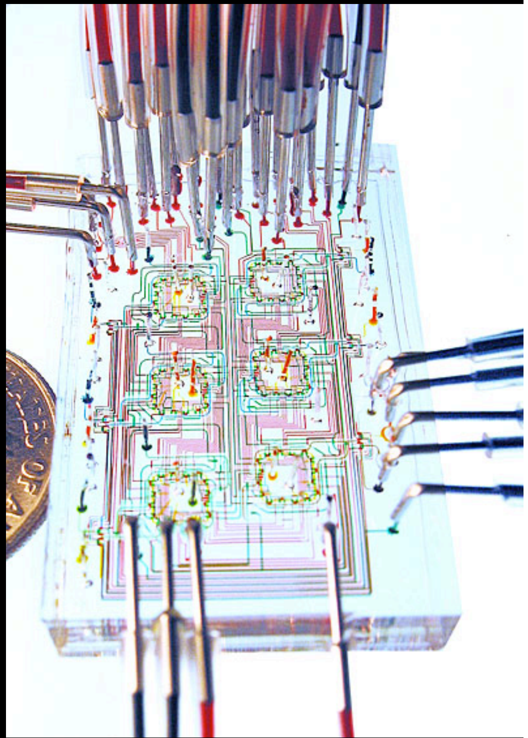
- Biotech
  - DNA analysis
- Medicine
  - Clinical diagnosis
  - Therapeutics
- Ecology
  - Monitoring the quality of air/water/food
- Pharmacy
  - Screening
  - Synthesis of new drugs

biolab

room



table



coin

smaller fluid volumes

4 mL of PCR master mix

$191

100 reactions at 50 μL each =
$1.91 / reaction

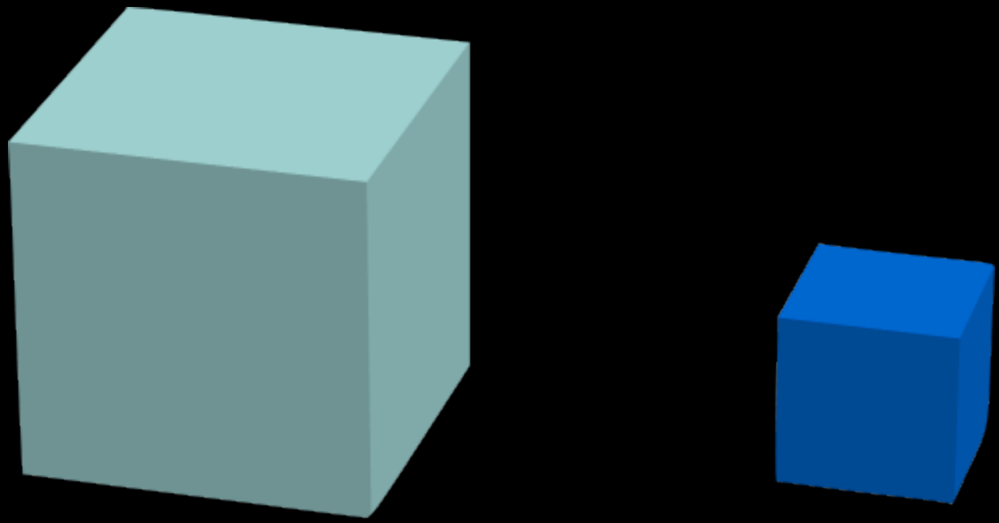
1000 reactions at 5 μL each =
$0.19 / reaction

smaller sample sizes

Milliliters

Microliters

faster reactions



1/2 the size

1/8 the volume

8x the concentration!

64x faster!!!

size matters!

Size matters!

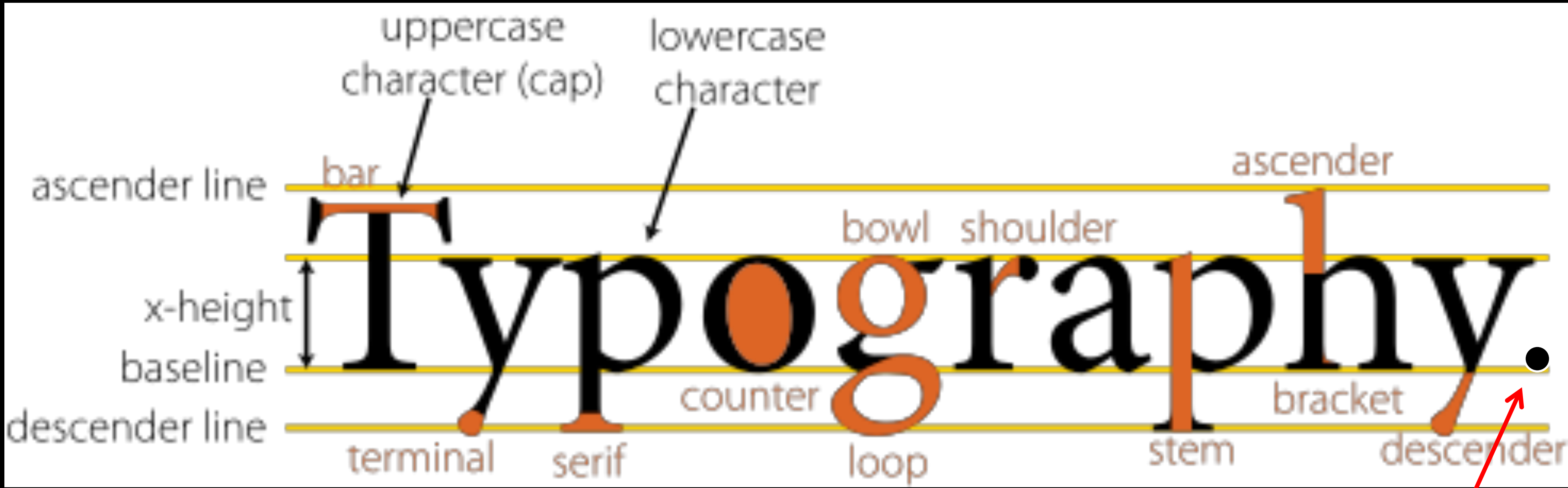
1 Liter – kitchen-sized fluidics!

Size matters!

What's a microliter? 1/1.000.000'th of a Liter

Volume of a poppy seed

Size matters!



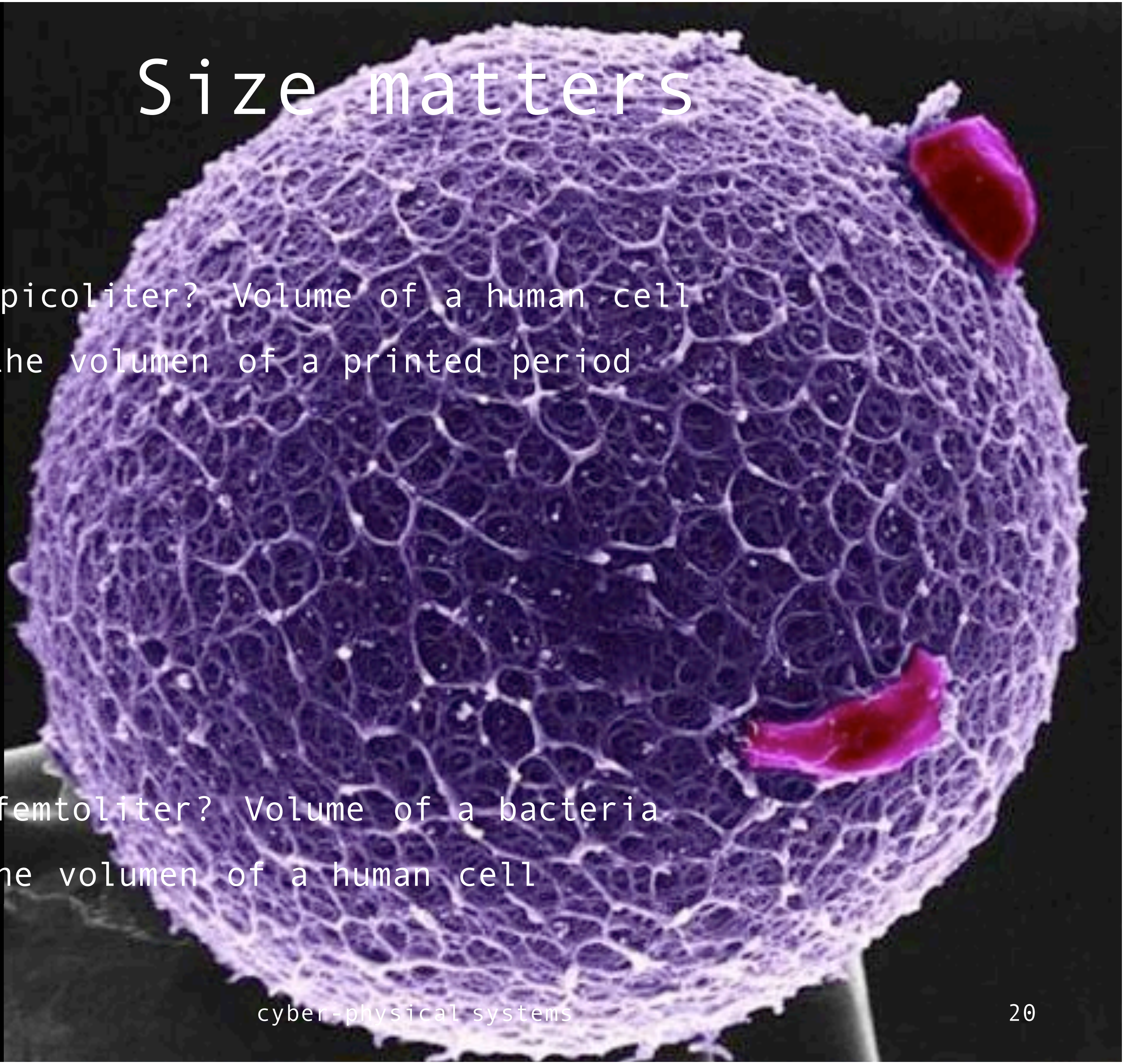
What's a nanoliter? Volume of a laser-printed period

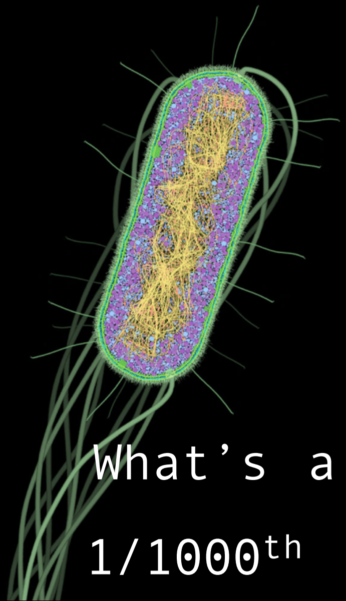
1/1000th the volumen of a poppy seed

Size matters

What's a picoliter? Volume of a human cell

1/1000th the volumen of a printed period

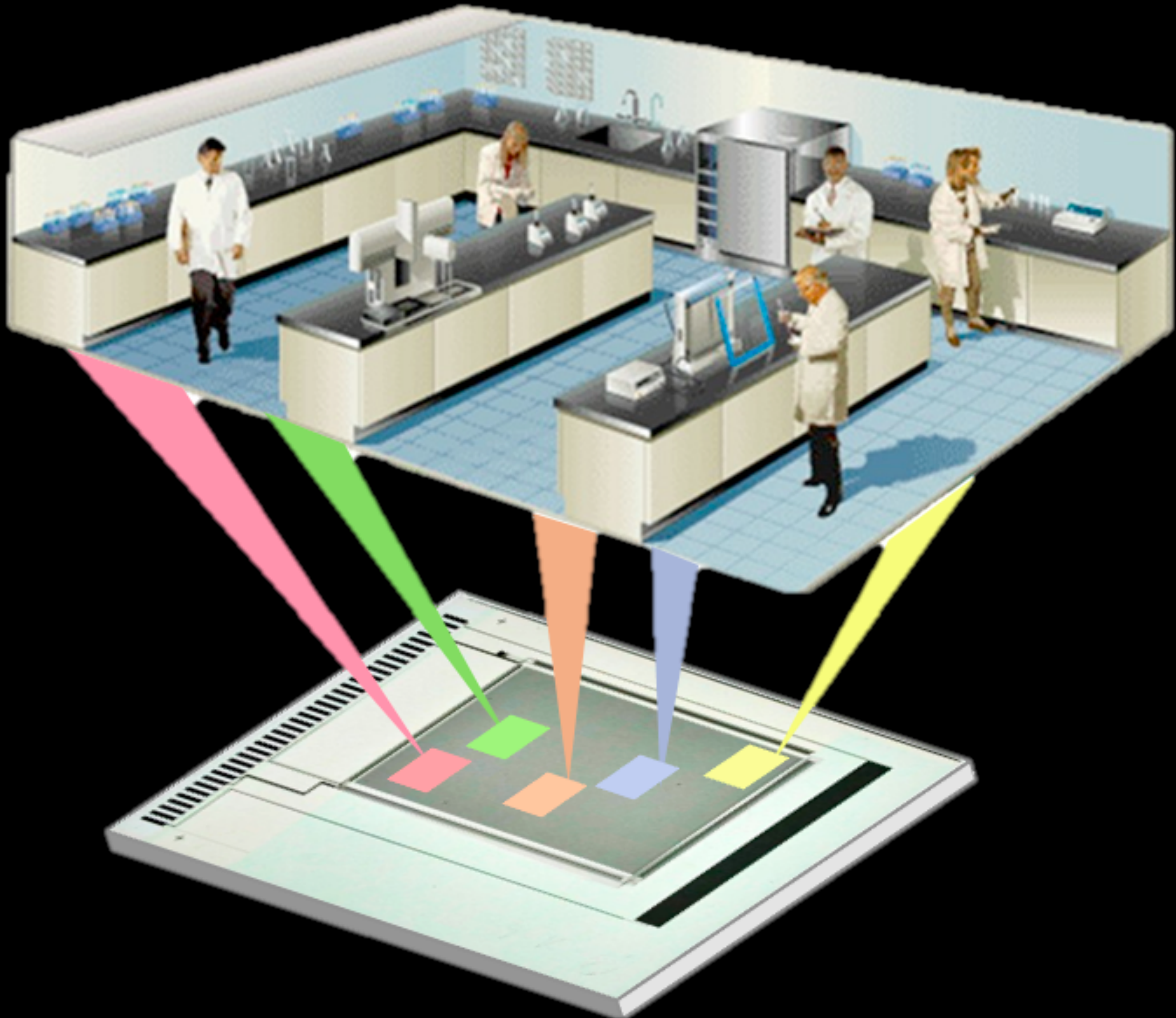




What's a femtoliter? Volume of a bacteria

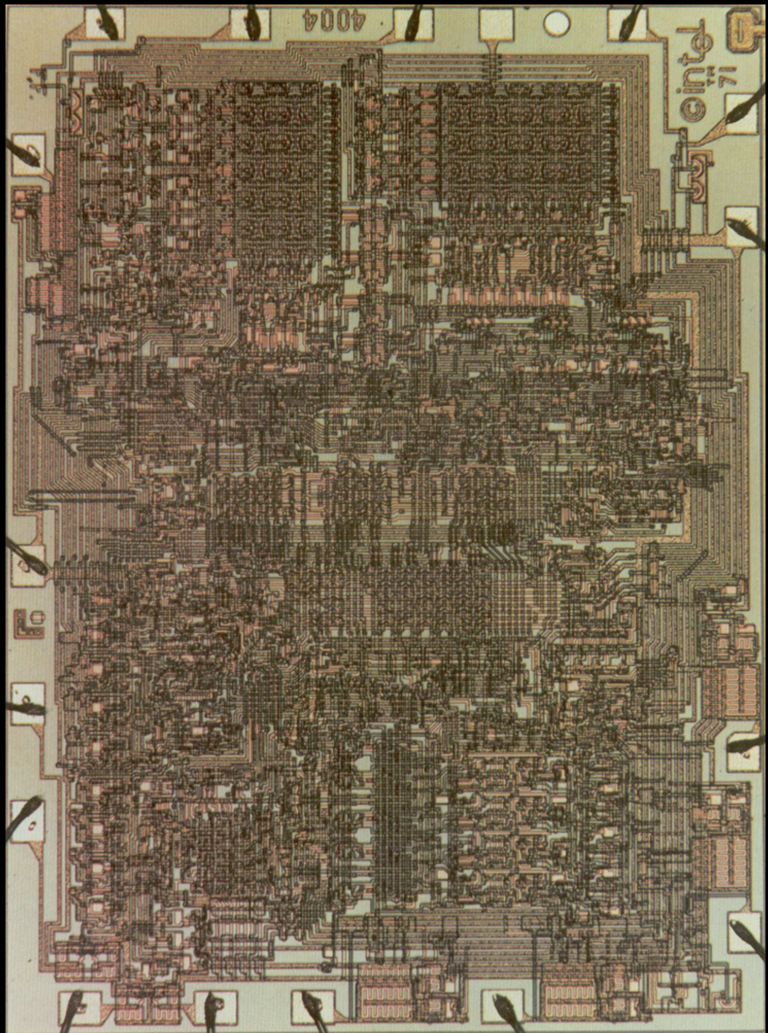
1/1000th the volumen of a human cell

miniaturization



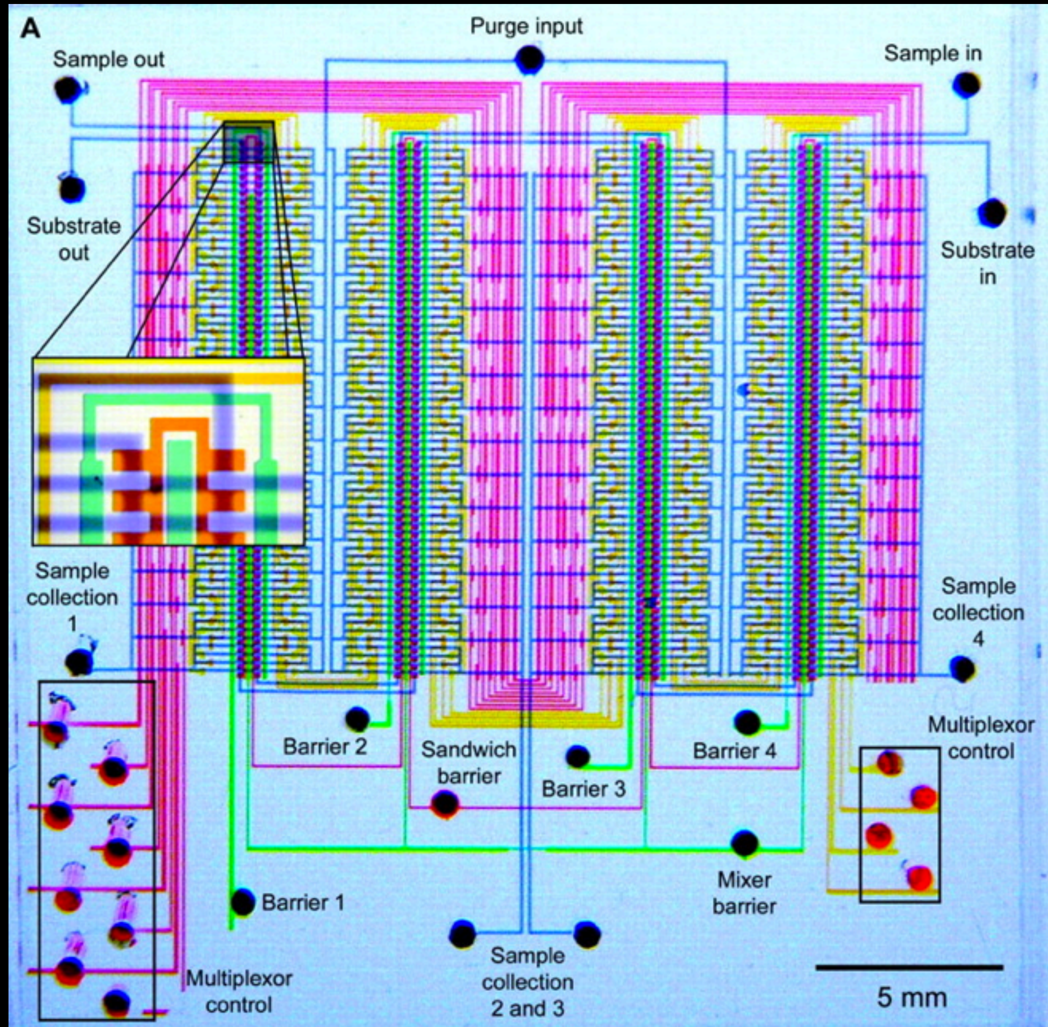
computer v.s. biochip

1971 - 2.300 transistors



Intel 4004 4-bit 10um, 2.300 transistors

2002 - 2.056 valves



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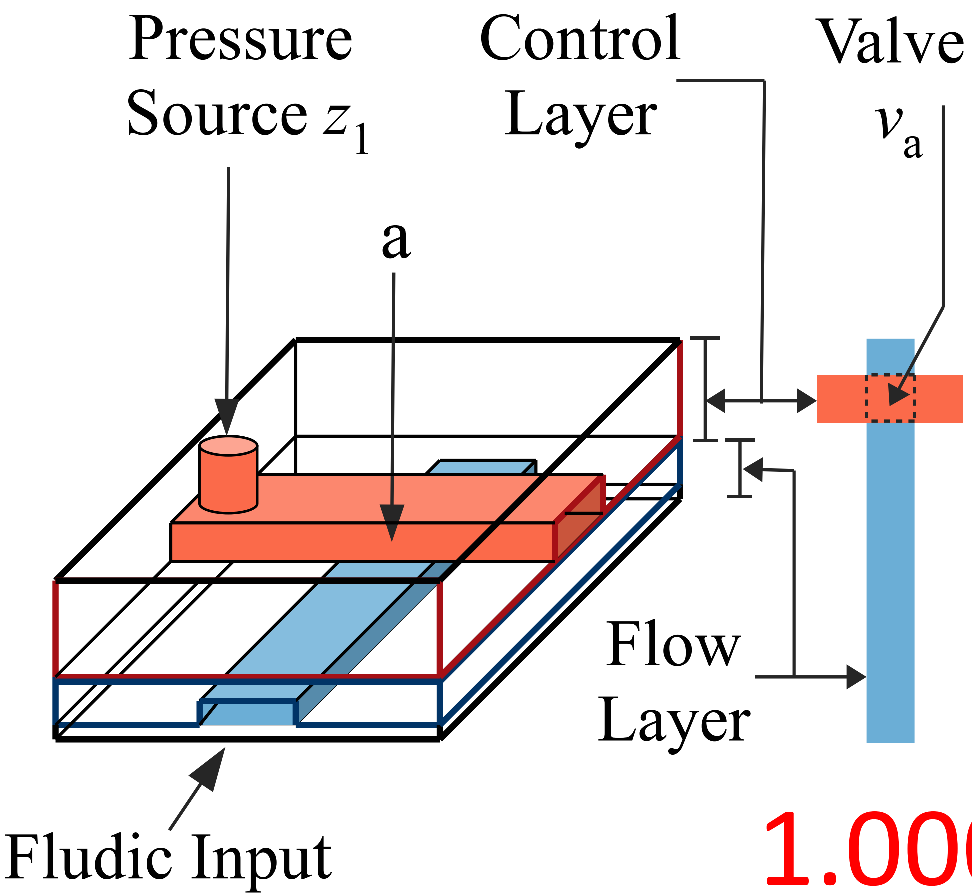
microfluidic technology

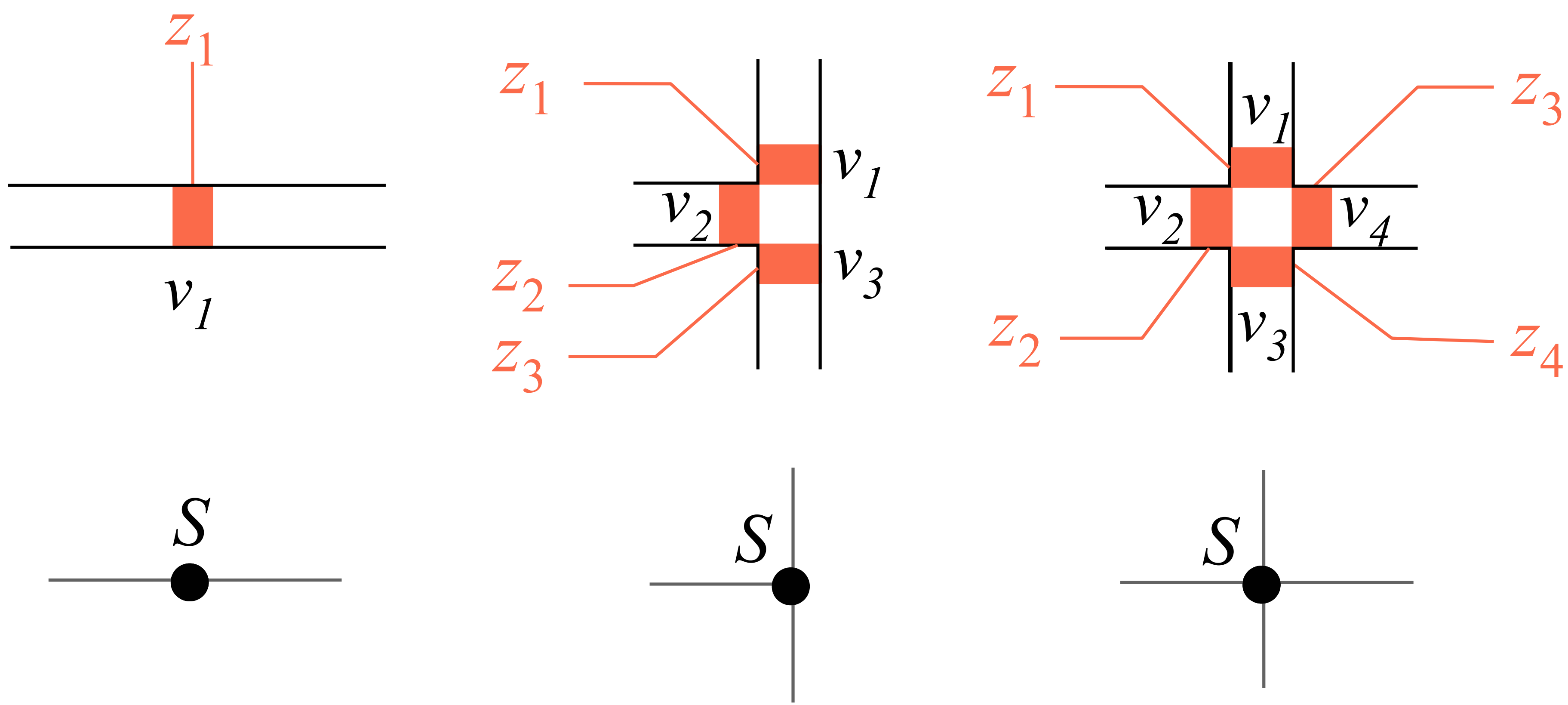
microfluidics



Microfluidic valve
(6 × 6 μm²)

1.000.000 valves / cm²

switch configurations

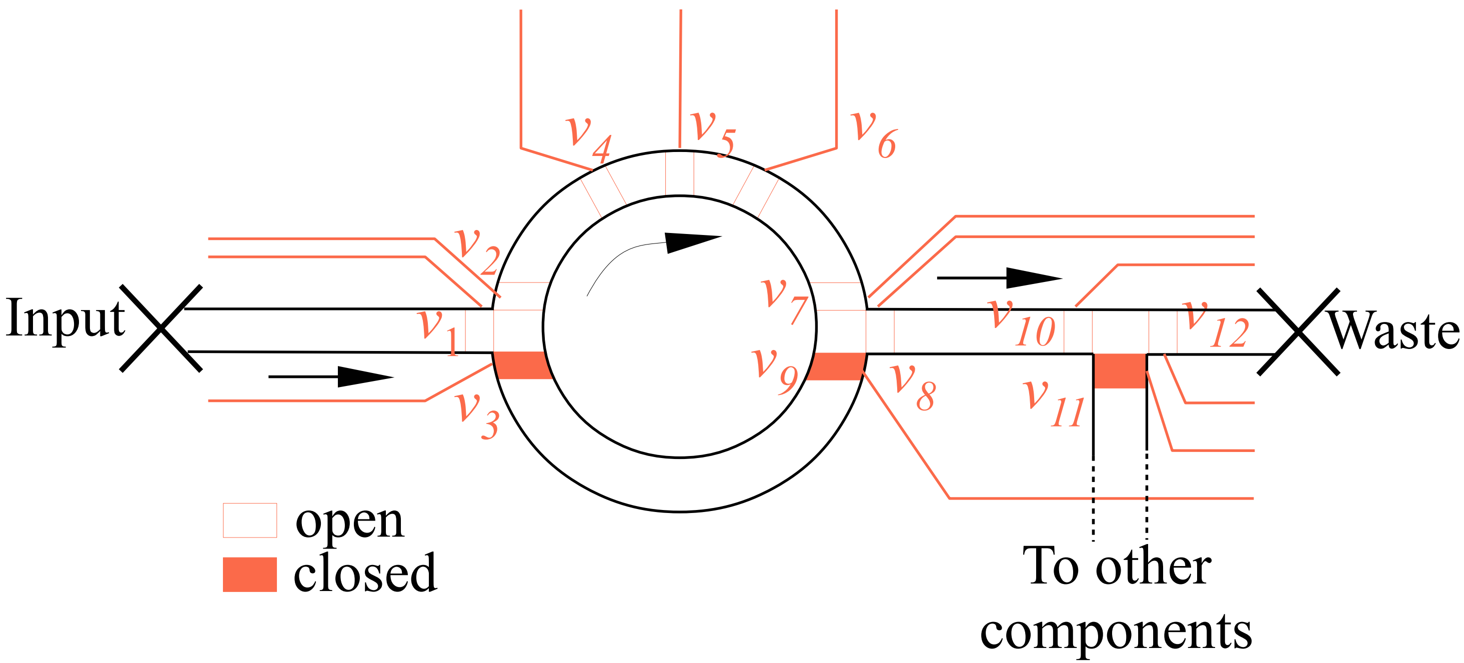


Biochip Architecture

Microfluidic very large scale integration (mVLSI)

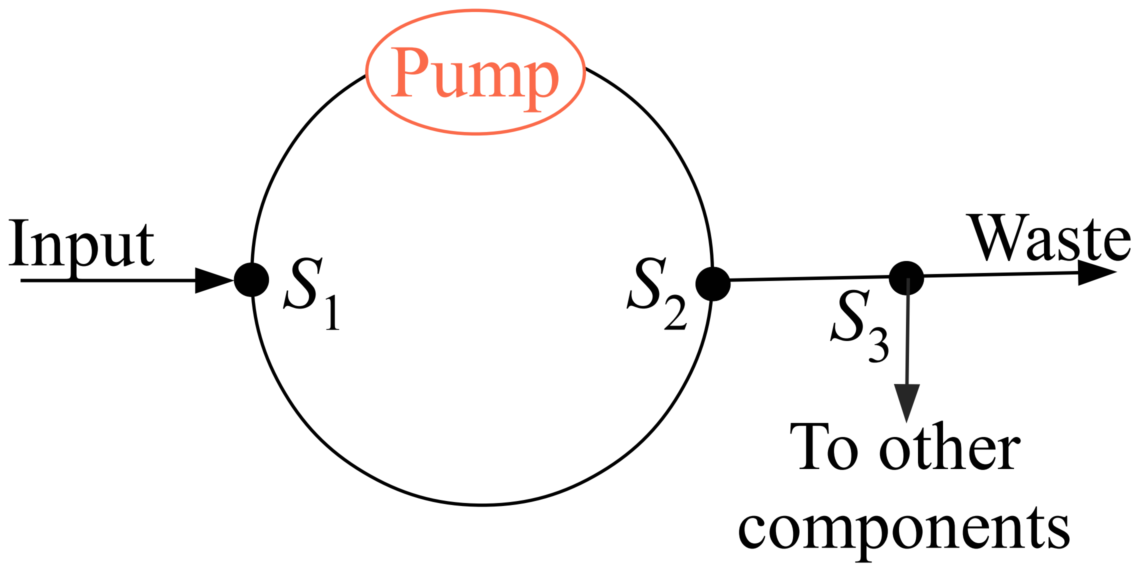
Valves combined to form more complex units, e.g, switches, mixers, multiplexers, micropumps.

Microfluidic mixer

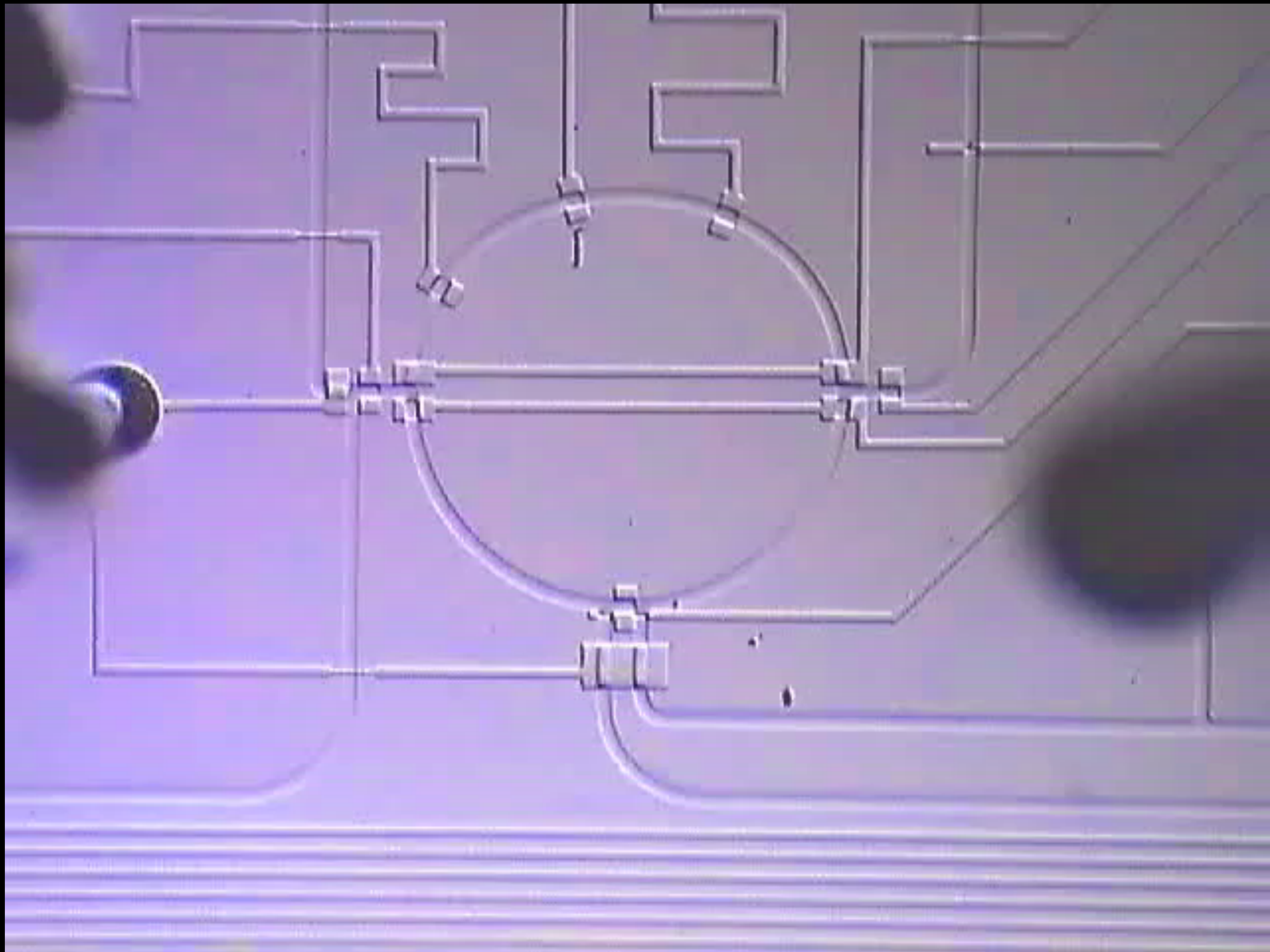


Biochip Architecture

Microfluidic mixer



microfluidics



Microfluidic Mixer: Operational Phases

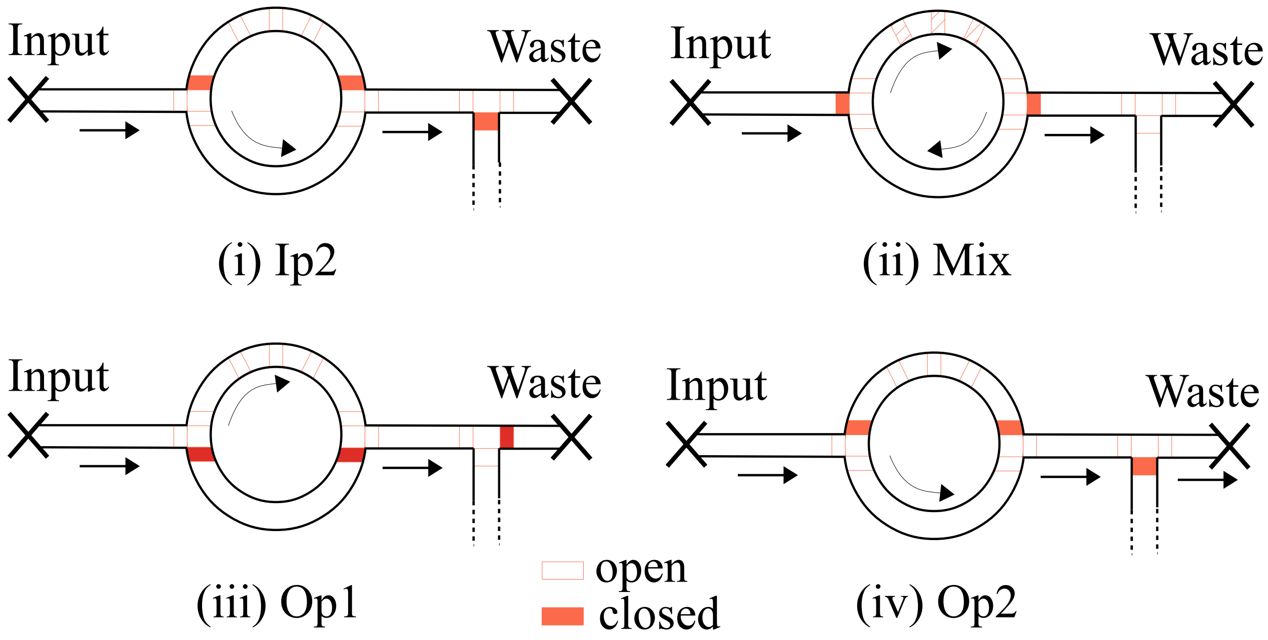
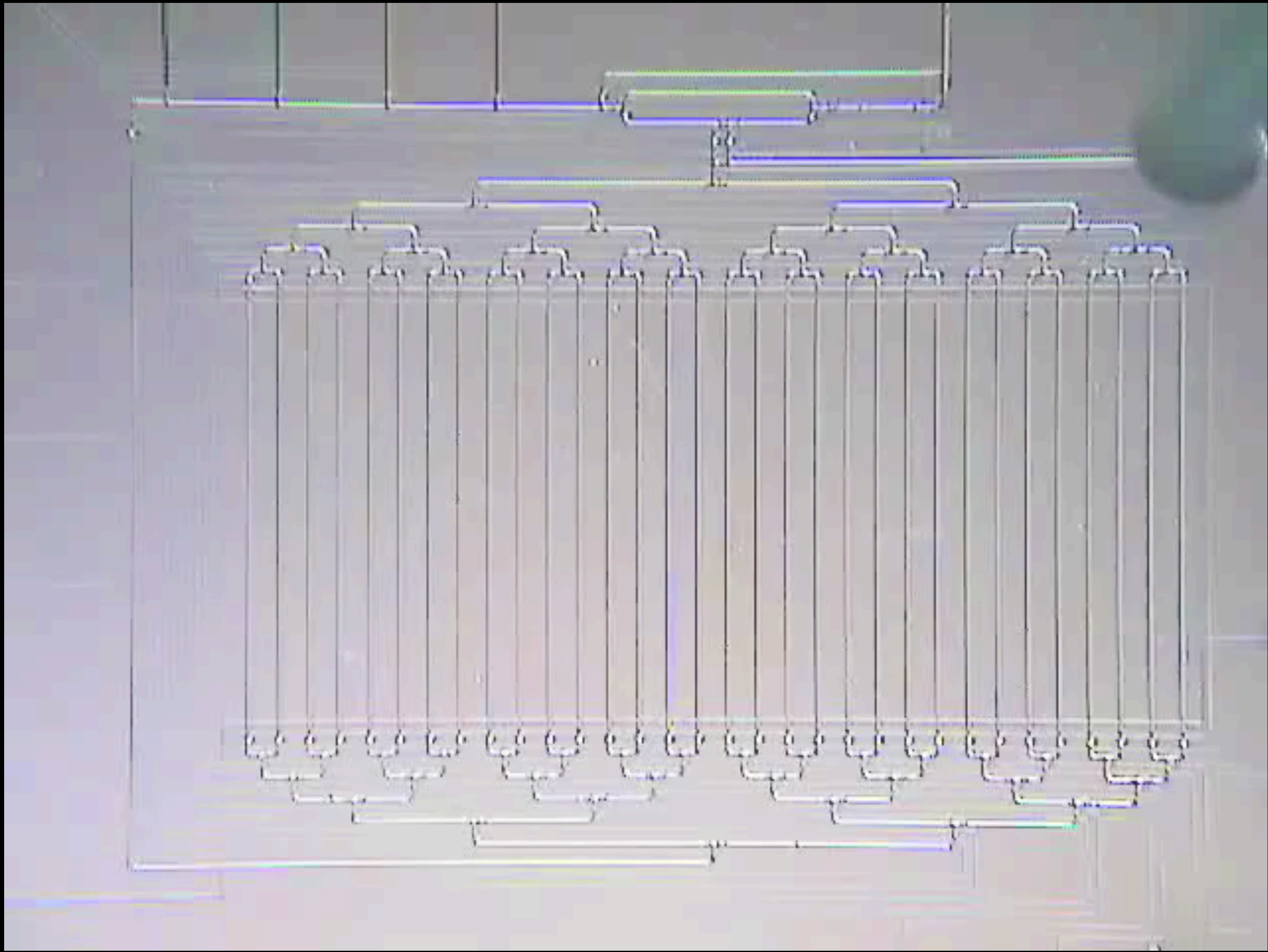


Table 1: Mixer: Control Layer Model

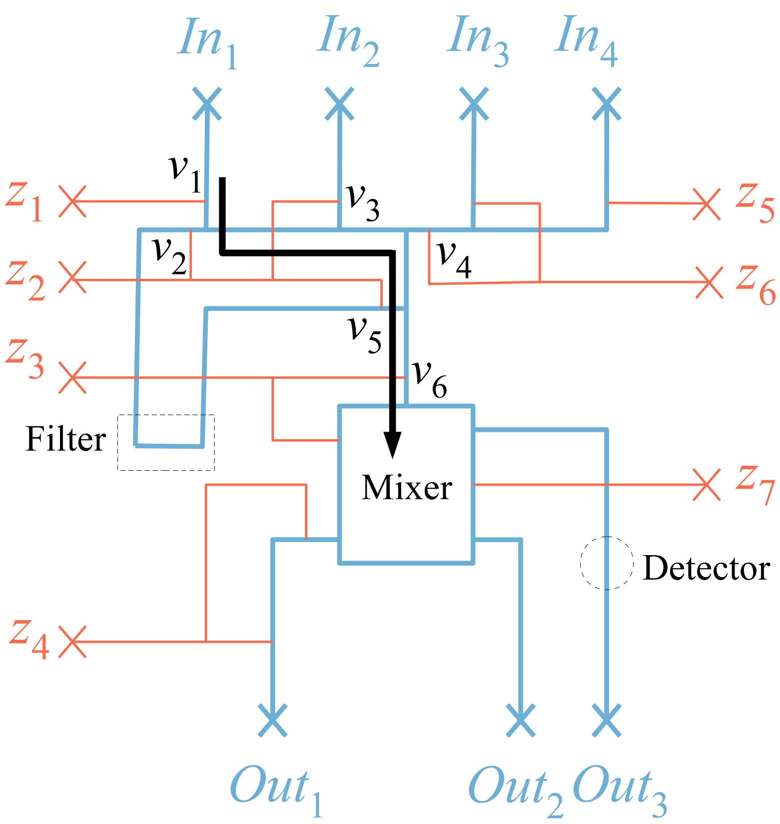
Phase	v_1	v_2	v_3	v_4	v_5	v_6	v_7	v_8	v_9
1. Ip1	0	0	1	0	0	0	0	0	1
2. Ip2	0	1	0	0	0	0	1	0	0
3. Mix	1	0	0	Mix	Mix	Mix	0	1	0
4. Op1	0	0	1	0	0	0	0	0	1
5. Op2	0	1	0	0	0	0	1	0	0

microfluidic storage device

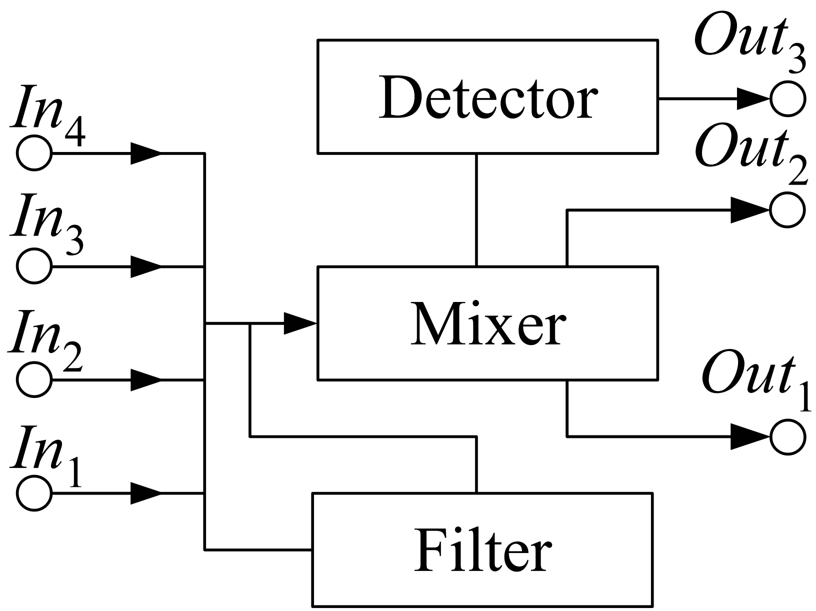


http://groups.csail.mit.edu/cag/biostream/

Flow-Based Biochip Architecture



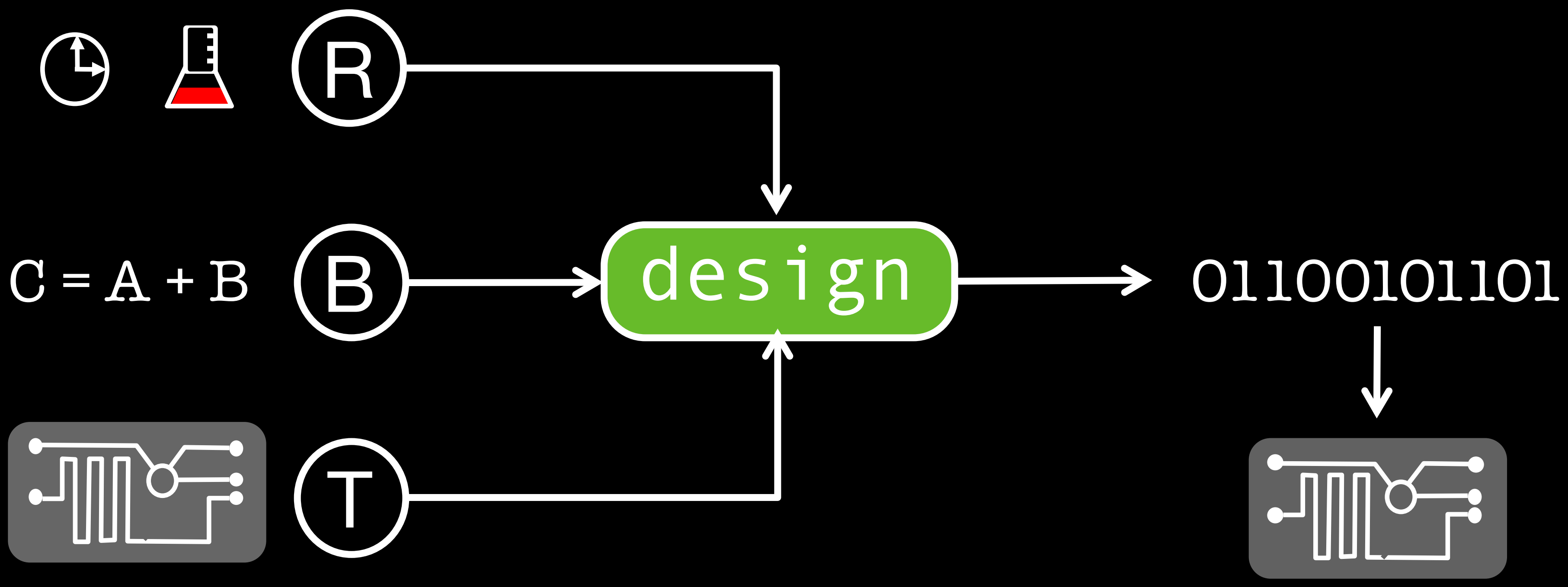
Schematic view



Functional view

microfluidic design

microfluidic design



Biocoder

Plasmid DNA Extraction – Miniprep (Excerpt)

Solutions/reagents:

- Rich medium (LB, YT, or Terrific medium) containing appropriate antibiotic
- Alkaline Lysis Solution I
  (50 mM Glucose, 25 mM Tris-HC (pH 8.0), 10 mM EDTA (pH 8.0))
- freshly prepared Alkaline Lysis Solution II
  (0.2 N NaOH, 1% SDS (w/v))
- Alkaline Lysis Solution III
  (5 M sodium acetate, glacial acetic acid)
- a single colony of transformed bacteria

Equipment:

- Incubator
- Centrifuge
- Sterile 1.5-ml microcentrifuge tubes

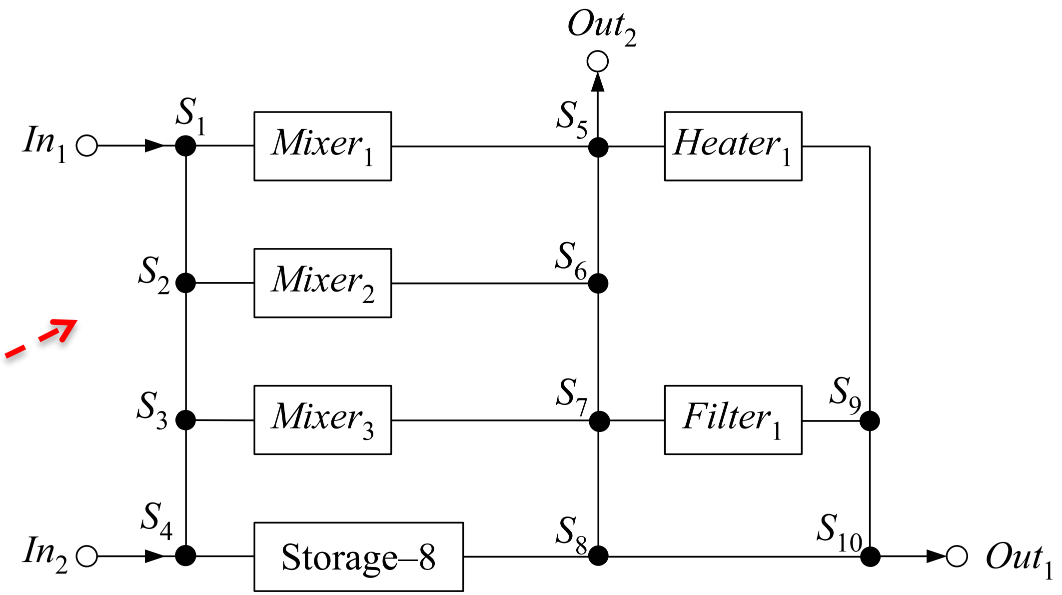
Steps:

1. **Preparation of cells**
   Inoculate 2 ml Rich medium (LB, YT, or Terrific medium) containing appropriate antibiotic with a single colony of transformed bacteria and incubate with shaking for **12 hrs** (overnight) at **37°C**.

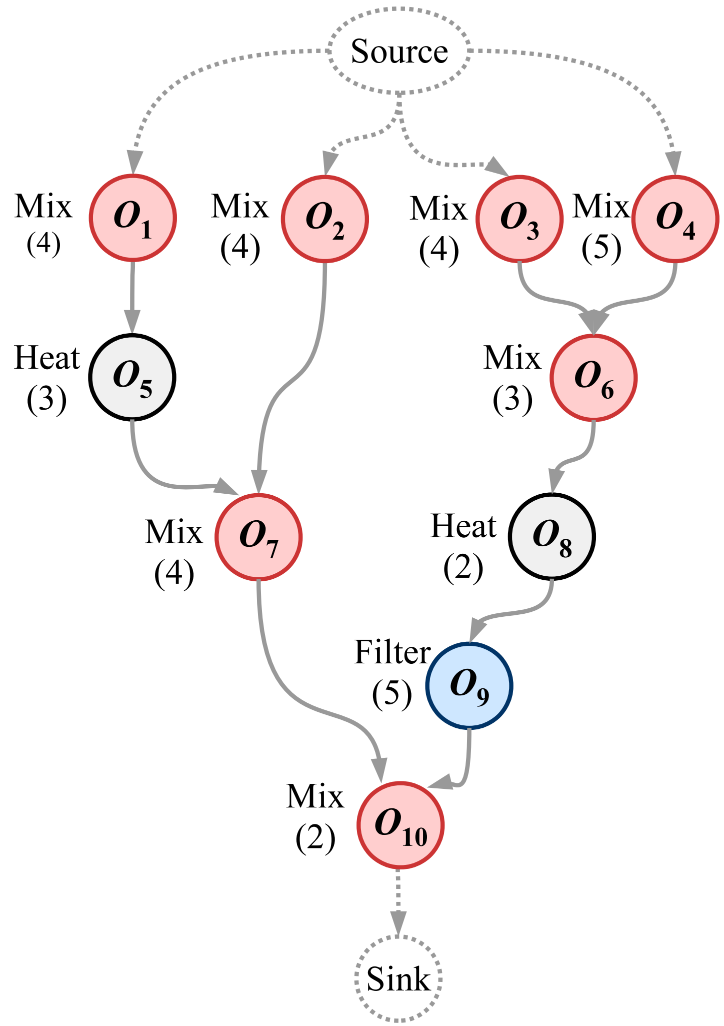
2. Measure out **1.5 ml** of culture into sterile 1.5-ml microcentrifuge tube.
   Centrifuge at maximum speed for **30 secs** at **4°C**; gently aspirate out the supernatant and discard it.
   Leave the pellet as dry as possible.

3. **Lysis of Cells**
   Add **100 µl** of Alkaline Lysis Solution I.
   Resuspend pellet by vortexing or by shaking vigorously.

4. Add **200 µl** of freshly prepared Alkaline Lysis Solution II.
   Close the tube tightly and invert the tube **5 times**.
   Do not vortex!
   Store the tube **on ice**.



Application and Platform Models



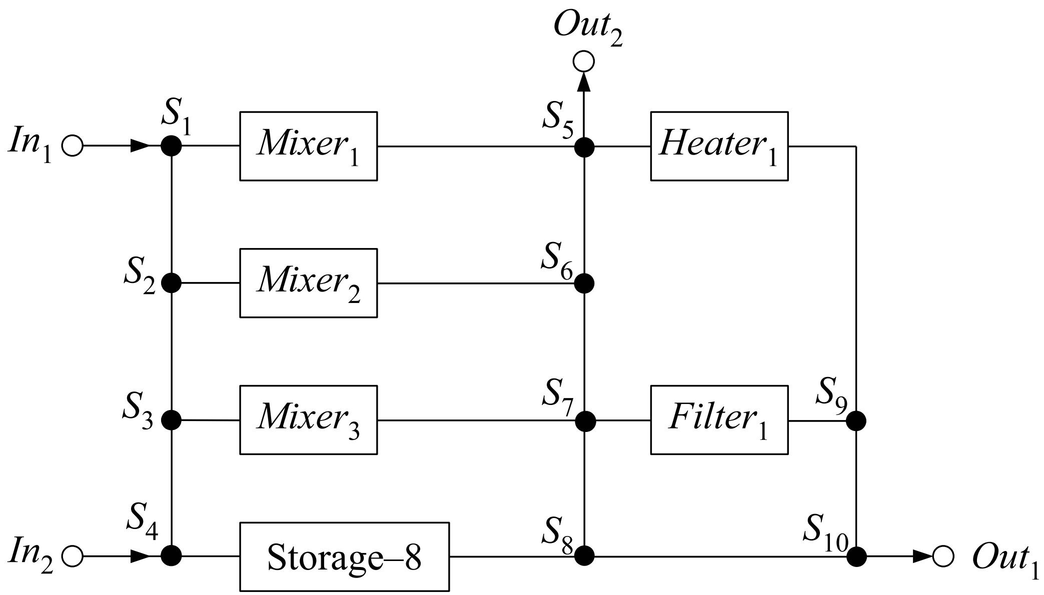
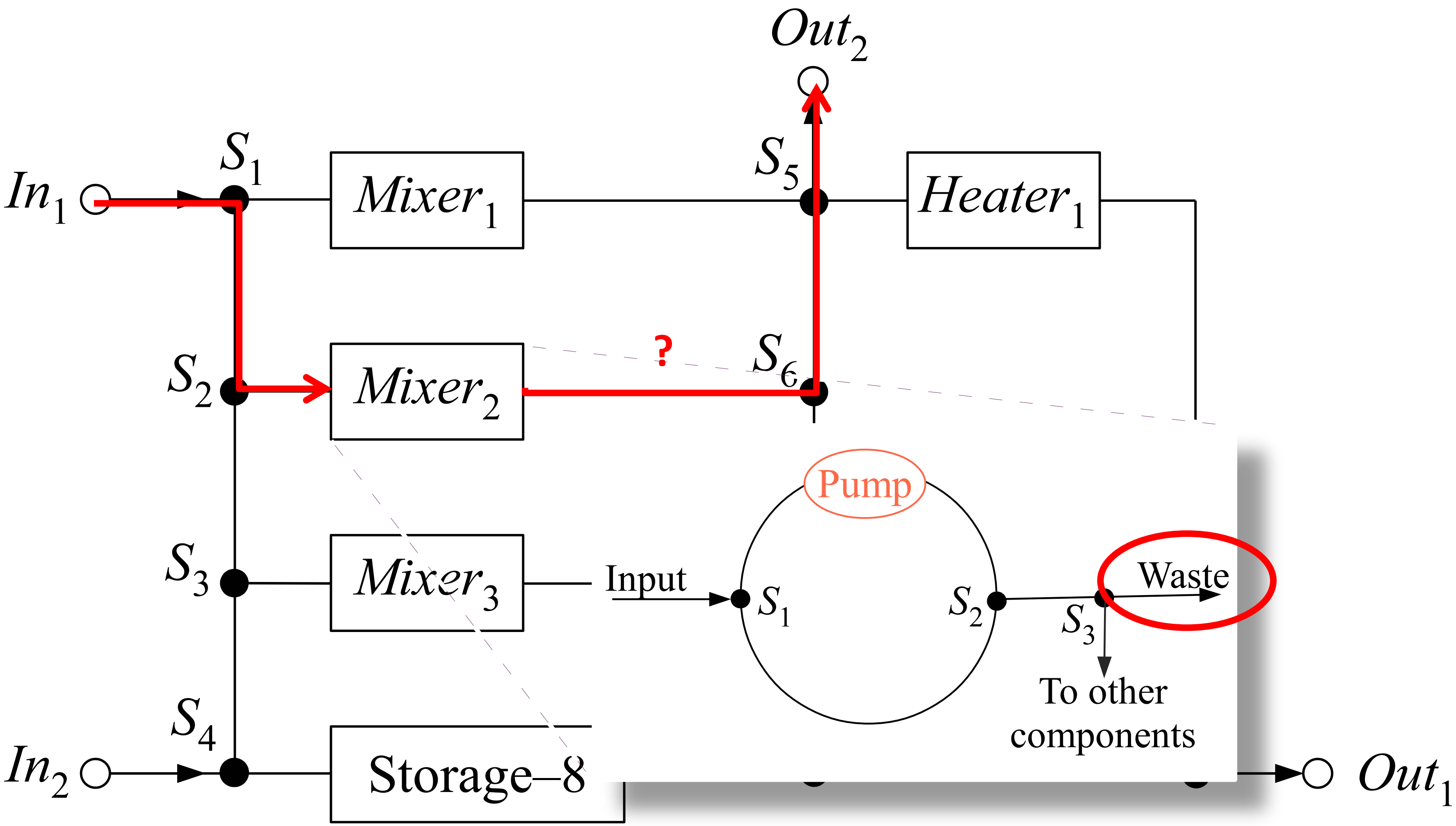


Table 2: Component Library ($\mathcal{L}$): Flow Layer Model

Component	**Phases** (P)	**Execution Time** (C)
Mixer	Ip1/ Ip2/ **Mix**/ Op1/ Op2	0.5s
Filter	Ip/ **Filter**/ Op1/ Op2	20s
Detector	Ip/ **Detect**/ op	5s
Separator	Ip1/ Ip2/ **Separate**/ Op1/ Op2	140s
Heater	Ip/ **Heat**/ Op	20°C/s

Flow paths in the architecture



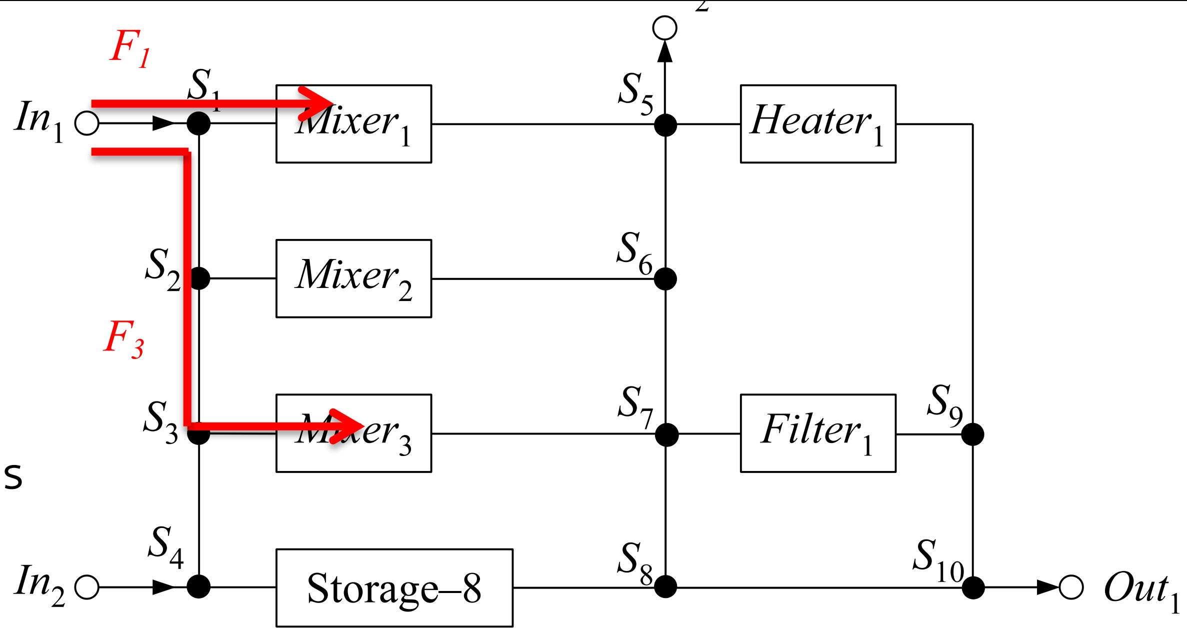
Flow paths in the architecture

- Fluid transport latencies are comparable to operation execution times
- Handling communication is important!
- Enumerate flow paths in the architecture

$F_1 = (In_1, S_1, Mixer_1)$, 2 s	$F_{18} = (Mixer_2, S_6, S_7, S_8, S_{10}, Out_1)$, 3.5 s	*Routing Constraints:*
$F_2 = (In_1, S_1, S_2, Mixer_2)$, 2.5 s	$F_{19} = (Mixer_3, S_7, S_6, S_5, Out_2$, 3 s	
$F_3 = (In_1, S_1, S_2, S_3, Mixer_3)$, 3 s	$F_{20} = (Mixer_3, S_7, S_6, S_5, Heater_1)$, 3 s	$F_1 : F_2 \vee F_3 \vee F_4 \vee F_7 \vee F_{24}$
$F_4 = (In_2, S_4, S_3, S_2, S_1, Mixer_1)$, 3.5 s	$F_{21} = (Mixer_3, S_7, Filter_1)$, 2 s	$F_2 : F_1 \vee F_3 \vee F_4 \vee F_5 \vee F_7 \vee F_{24} \vee F_{25}$
$F_5 = (In_2, S_4, S_3, S_2, Mixer_2)$, 3 s	$F_{22-x} = (Mixer_3, S_7, S_8, Storage\text{-}8)$, 2.5 s	$F_3 : F_1 \vee F_2 \vee F_4 \vee F_5 \vee F_6 \vee F_7 \vee F_{24}$
$F_6 = (In_2, S_4, S_3, Mixer_3)$, 2.5 s	$F_{23} = (Mixer_3, S_7, S_8, S_{10}, Out_1)$, 3 s	$\vee F_{25} \vee F_{26}$
$F_{7-x} = (In_1, S_1, S_2, S_3, S_4, Storage\text{-}8)$, 3.5 s	$F_{24-x} = (Storage\text{-}8, S_4, S_3, S_2, S_1, Mixer_1)$, 3.5 s	$F_4 : F_1 \vee F_2 \vee F_3 \vee F_5 \vee F_6 \vee F_7 \vee F_8$
$F_{8-x} = (In_2, S_4, Storage\text{-}8)$, 2 s	$F_{25-x} = (Storage\text{-}8, S_4, S_3, S_2, Mixer_2$, 3 s	$\vee F_{24} \vee F_{25} \vee F_{26}$
$F_9 = (Mixer_1, S_5, Out_2)$, 2 s	$F_{26-x} = (Storage\text{-}8, S_4, S_3, Mixer_3)$, 2.5 s	$F_5 : F_2 \vee F_3 \vee F_4 \vee F_6 \vee F_7 \vee F_8 \vee F_{24}$
$F_{10} = (Mixer_1, S_5, Heater_1)$, 2 s	$F_{27-x} = (Storage\text{-}8, S_8, S_7, S_6, S_5, Heater_1)$, 3.5 s	$\vee F_{25} \vee F_{26} \vee F_{27}$
$F_{11} = (Mixer_1, S_5, S_6, S_7, Filter_1)$, 3 s	$F_{28-x} = (Storage\text{-}8, S_8, S_7, Filter_1)$, 2.5 s	$F_6 : F_3 \vee F_4 \vee F_5 \vee F_7 \vee F_8 \vee F_{24} \vee F_{25}$
$F_{12-x} = (Mixer_1, S_5, S_6, S_7, S_8, Storage\text{-}8)$, 3.5 s	$F_{29-x} = (Storage\text{-}8, S_8, S_{10}, Out_1)$, 2.5 s	$\vee F_{26}$
$F_{13} = (Mixer_1, S_5, S_6, S_7, S_8, S_{10}, Out_1)$, 4 s	$F_{30-x} = (Heater_1, S_9, S_{10}, S_8, Storage\text{-}8)$, 3 s	$F_7 : F_1 \vee F_2 \vee F_3 \vee F_4 \vee F_5 \vee F_6 \vee F_8$
$F_{14} = (Mixer_2, S_6, S_5, Out_2)$, 2.5 s	$F_{31} = (Heater_1, S_9, S_{10}, Out_1)$, 2.5 s	$\vee F_{24} \vee F_{25} \vee F_{26}$
$F_{15} = (Mixer_2, S_6, S_5, Heater_1)$, 2.5 s	$F_{32-x} = (Filter_1, S_9, S_{10}, S_8, Storage\text{-}8)$, 3 s	...
$F_{16} = (Mixer_2, S_6, S_7, Filter_1)$, 2.5 s	$F_{33} = (Filter_1, S_9, S_{10}, Out_1)$, 2.5 s	$F_{33} : F_{13} \vee F_{18} \vee F_{23} \vee F_{29} \vee F_{30} \vee F_{31}$
$F_{17-x} = (Mixer_2, S_6, S_7, S_8, Storage\text{-}8)$, 3 s		$\vee F_{32}$

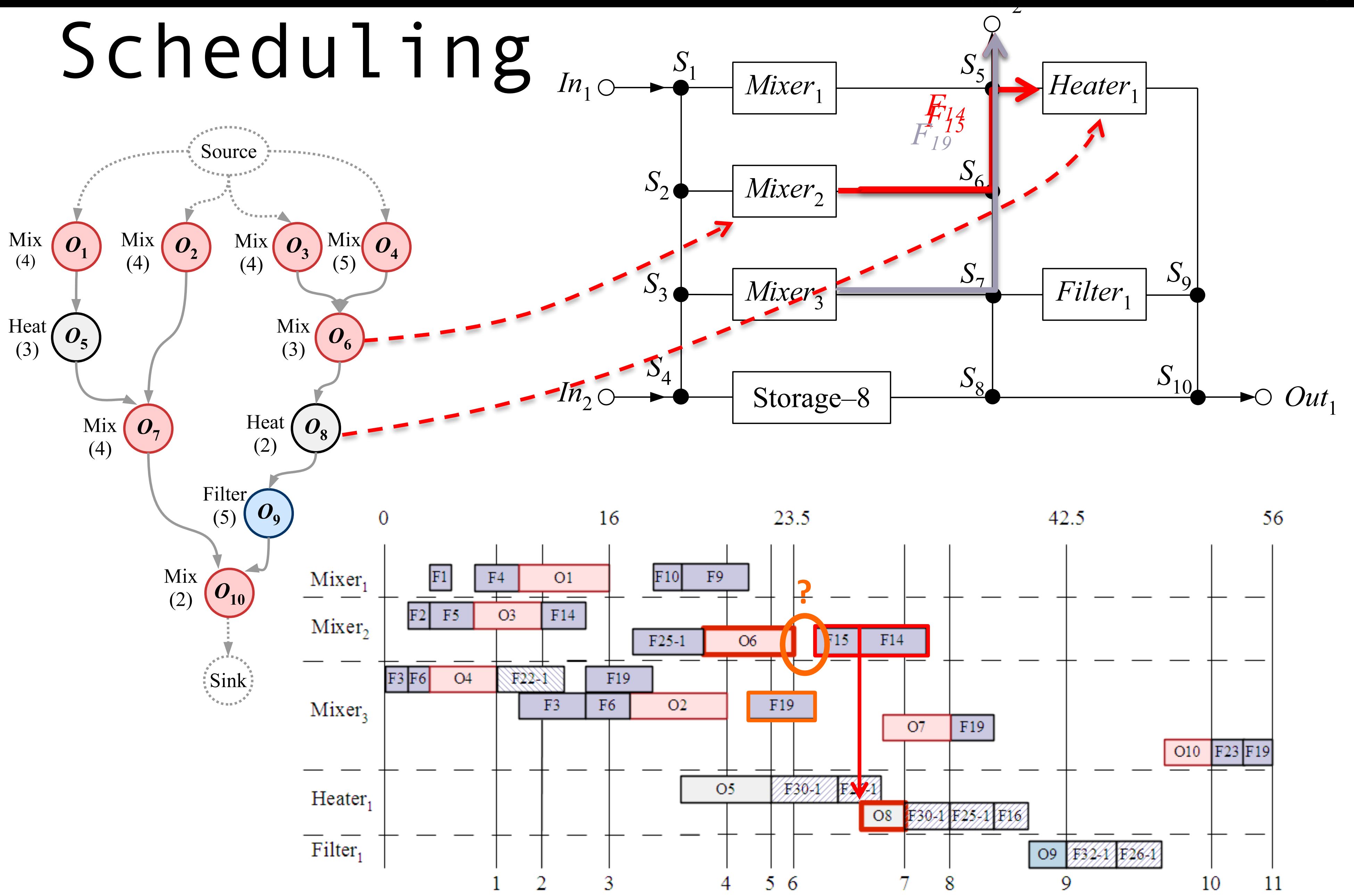
Flow paths

- A flow path is reserved until completion of the operation, resulting in routing constraints



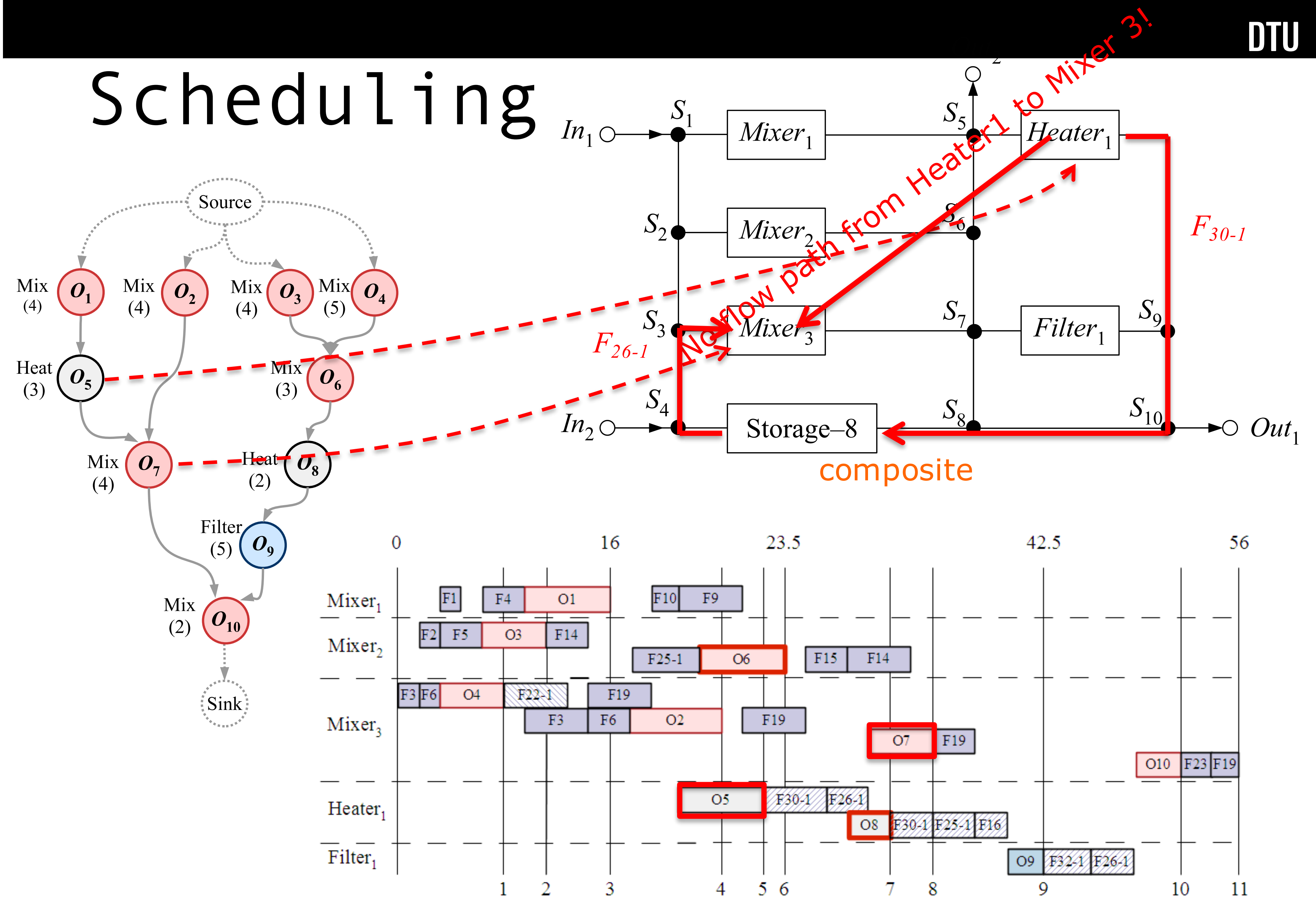
$F_1 = (In_1, S_1, Mixer_1)$, 2 s	$F_{18} = (Mixer_2, S_6, S_7, S_8, S_{10}, Out_1)$, 3.5 s	Routing Constraints:
$F_2 = (In_1, S_1, S_2, Mixer_2)$, 2.5 s	$F_{19} = (Mixer_3, S_7, S_6, S_5, Out_2)$, 3 s	
$F_3 = (In_1, S_1, S_2, S_3, Mixer_3)$, 3 s	$F_{20} = (Mixer_3, S_7, S_6, S_5, Heater_1)$, 3 s	$F_1 : F_2 \vee F_3 \vee F_4 \vee F_7 \vee F_{24}$
$F_4 = (In_2, S_4, S_3, S_2, S_1, Mixer_1)$, 3.5 s	$F_{21} = (Mixer_3, S_7, Filter_1)$, 2 s	$F_2 : F_1 \vee F_3 \vee F_4 \vee F_5 \vee F_7 \vee F_{24} \vee F_{25}$
$F_5 = (In_2, S_4, S_3, S_2, Mixer_2)$, 3 s	$F_{22-x} = (Mixer_3, S_7, S_8, Storage\text{-}8)$, 2.5 s	$F_3 : F_1 \vee F_2 \vee F_4 \vee F_5 \vee F_6 \vee F_7 \vee F_{24}$
$F_6 = (In_2, S_4, S_3, Mixer_3)$, 2.5 s	$F_{23} = (Mixer_3, S_7, S_8, S_{10}, Out_1)$, 3 s	$\vee F_{25} \vee F_{26}$
$F_{7-x} = (In_1, S_1, S_2, S_3, S_4, Storage\text{-}8)$, 3.5 s	$F_{24-x} = (Storage\text{-}8, S_4, S_3, S_2, S_1, Mixer_1)$, 3.5 s	$F_4 : F_1 \vee F_2 \vee F_3 \vee F_5 \vee F_6 \vee F_7 \vee F_8$
$F_{8-x} = (In_2, S_4, Storage\text{-}8)$, 2 s	$F_{25-x} = (Storage\text{-}8, S_4, S_3, S_2, Mixer_2)$, 3 s	$\vee F_{24} \vee F_{25} \vee F_{26}$
$F_9 = (Mixer_1, S_5, Out_2)$, 2 s	$F_{26-x} = (Storage\text{-}8, S_4, S_3, Mixer_3)$, 2.5 s	$F_5 : F_2 \vee F_3 \vee F_4 \vee F_6 \vee F_7 \vee F_8 \vee F_{24}$
$F_{10} = (Mixer_1, S_5, Heater_1)$, 2 s	$F_{27-x} = (Storage\text{-}8, S_8, S_7, S_6, S_5, Heater_1)$, 3.5 s	$\vee F_{25} \vee F_{26} \vee F_{27}$
$F_{11} = (Mixer_1, S_5, S_6, S_7, Filter_1)$, 3 s	$F_{28-x} = (Storage\text{-}8, S_8, S_7, Filter_1)$, 2.5 s	$F_6 : F_3 \vee F_4 \vee F_5 \vee F_7 \vee F_8 \vee F_{24} \vee F_{25}$
$F_{12-x} = (Mixer_1, S_5, S_6, S_7, S_8, Storage\text{-}8)$, 3.5 s	$F_{29-x} = (Storage\text{-}8, S_8, S_{10}, Out_1)$, 2.5 s	$\vee F_{26}$
$F_{13} = (Mixer_1, S_5, S_6, S_7, S_8, S_{10}, Out_1)$, 4 s	$F_{30-x} = (Heater_1, S_9, S_{10}, S_8, Storage\text{-}8)$, 3 s	$F_7 : F_1 \vee F_2 \vee F_3 \vee F_4 \vee F_5 \vee F_6 \vee F_8$
$F_{14} = (Mixer_2, S_6, S_5, Out_2)$, 2.5 s	$F_{31} = (Heater_1, S_9, S_{10}, Out_1)$, 2.5 s	$\vee F_{24} \vee F_{25} \vee F_{26}$
$F_{15} = (Mixer_2, S_6, S_5, Heater_1)$, 2.5 s	$F_{32-x} = (Filter_1, S_9, S_{10}, S_8, Storage\text{-}8)$, 3 s	...
$F_{16} = (Mixer_2, S_6, S_7, Filter_1)$, 2.5 s	$F_{33} = (Filter_1, S_9, S_{10}, Out_1)$, 2.5 s	$F_{33} : F_{13} \vee F_{18} \vee F_{23} \vee F_{29} \vee F_{30} \vee F_{31}$
$F_{17-x} = (Mixer_2, S_6, S_7, S_8, Storage\text{-}8)$, 3 s		$\vee F_{32}$

Scheduling



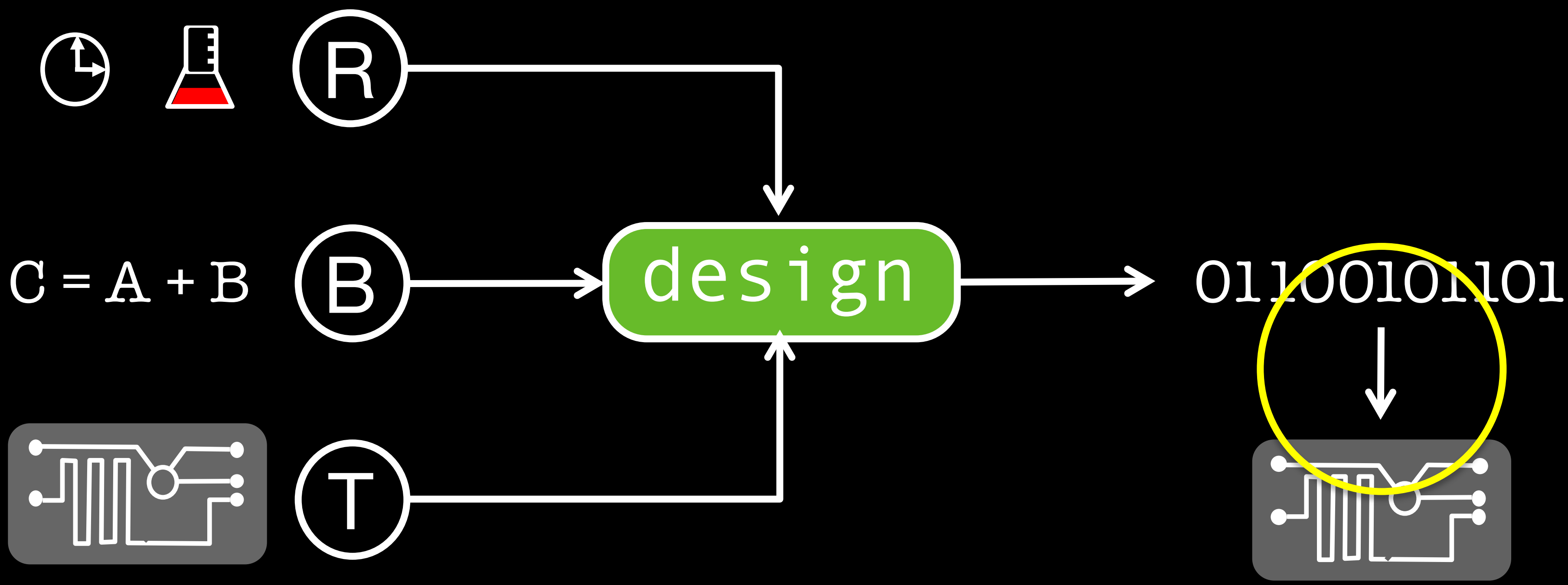
Source
Mix (4)
Mix (4)
Mix (4)
Mix (5)
Heat (3)
Mix (3)
Mix (4)
Heat (2)
Filter (5)
Mix (2)
Sink
O_1 O_2 O_3 O_4 O_5 O_6 O_7 O_8 O_9 O_{10}
In_1
In_2
S_1 S_2 S_3 S_4 S_5 S_6 S_7 S_8 S_9 S_{10}
$Mixer_1$
$Mixer_2$
$Mixer_3$
$Heater_1$
$Filter_1$
Storage–8
Out_1
F_{14}
F_{15}
F_{19}
0
16
23.5
42.5
56
$Mixer_1$
$Mixer_2$
$Mixer_3$
$Heater_1$
$Filter_1$
F1 F4 O1 F10 F9
F2 F5 O3 F14
F25-1 O6 F15 F14
F3 F6 O4 F22-1 F19
F3 F6 O2 F19
O7 F19
O10 F23 F19
O5 F30-1 F25-1
O8 F30-1 F25-1 F16
O9 F32-1 F26-1
?
1 2 3 4 5 6 7 8 9 10 11

Scheduling

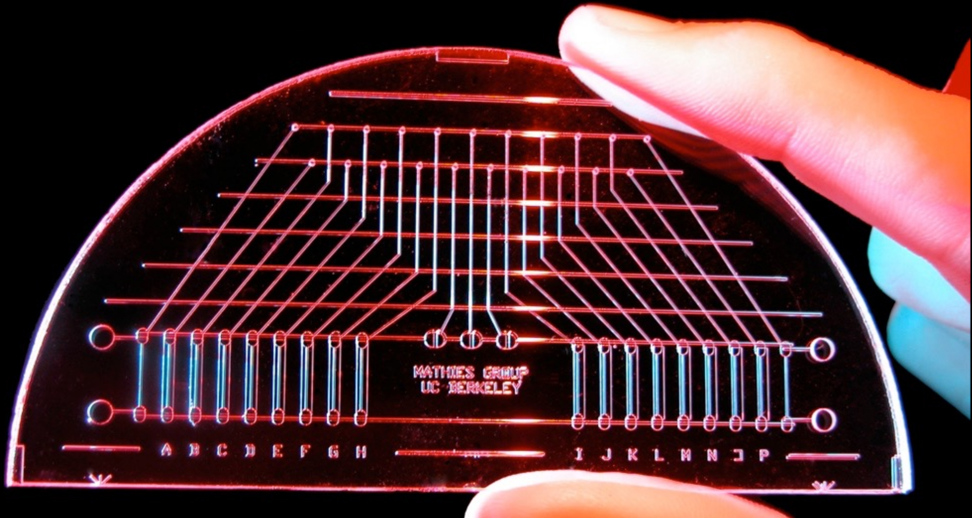

Source
Mix (4) O_1
Mix (4) O_2
Mix (4) O_3
Mix (5) O_4
Heat (3) O_5
Mix (3) O_6
Mix (4) O_7
Heat (2) O_8
Filter (5) O_9
Mix (2) O_{10}
Sink
In_1
In_2
Out_1
S_1 S_2 S_3 S_4 S_5 S_6 S_7 S_8 S_9 S_{10}
$Mixer_1$
$Mixer_2$
$Mixer_3$
$Heater_1$
$Filter_1$
Storage–8
$F_{30\text{-}1}$
$F_{26\text{-}1}$
No flow path from Heater1 to Mixer 3!
composite
0 16 23.5 42.5 56
$Mixer_1$: F1 F4 O1 F10 F9
$Mixer_2$: F2 F5 O3 F14 F25-1 O6 F15 F14
$Mixer_3$: F3 F6 O4 F22-1 F19 F3 F6 O2 F19 O7 F19 O10 F23 F19
$Heater_1$: O5 F30-1 F26-1 O8 F30-1 F25-1 F16
$Filter_1$: O9 F32-1 F26-1
1 2 3 4 5 6 7 8 9 10 11

microfluidic control

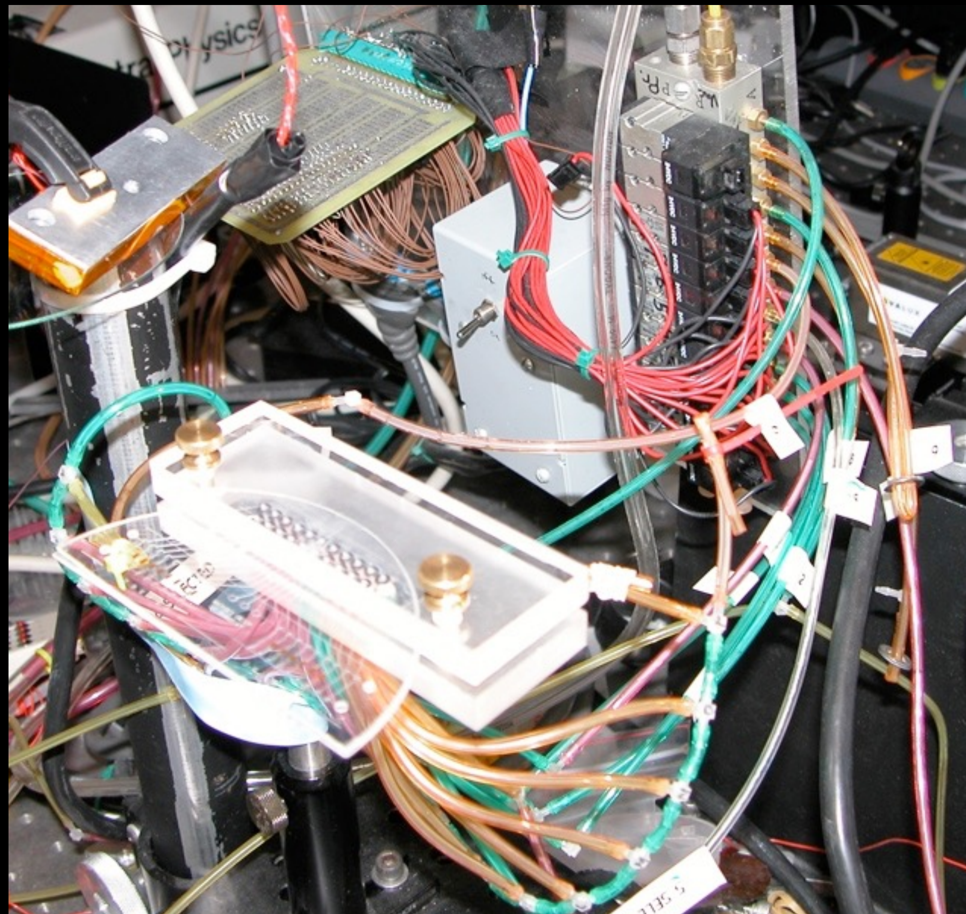
microfluidic control



challenge



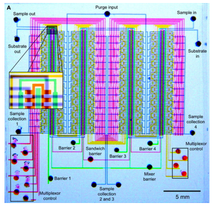
the pretty picture



the reality!

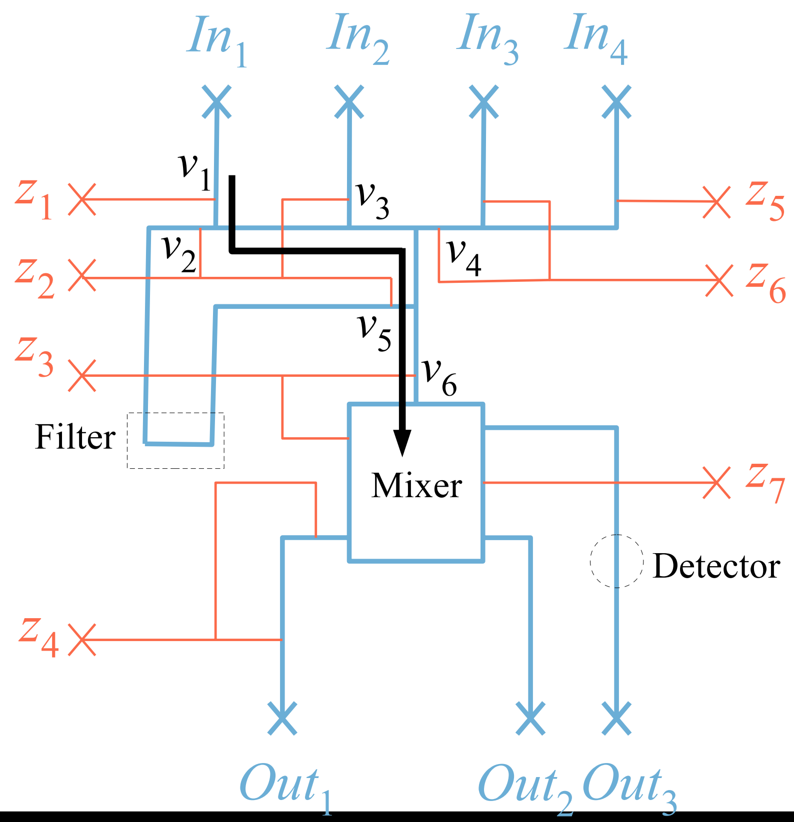
off-chip control

Minimize number of control pins



control synthesis

- Scheduling determines when valves are to be switch on/off
- Control synthesis layouts the control flow layer
- Sharing of control lines?

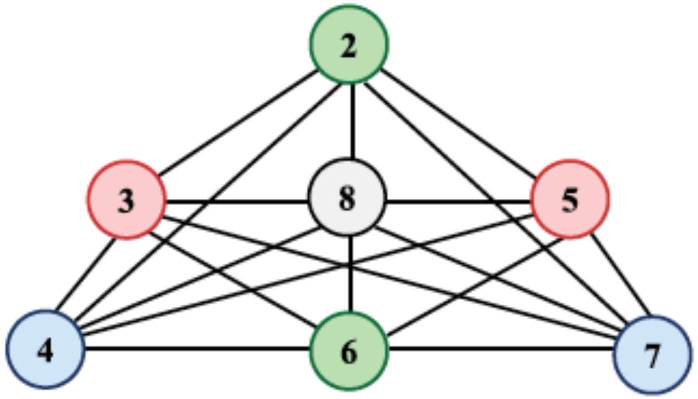


control synthesis

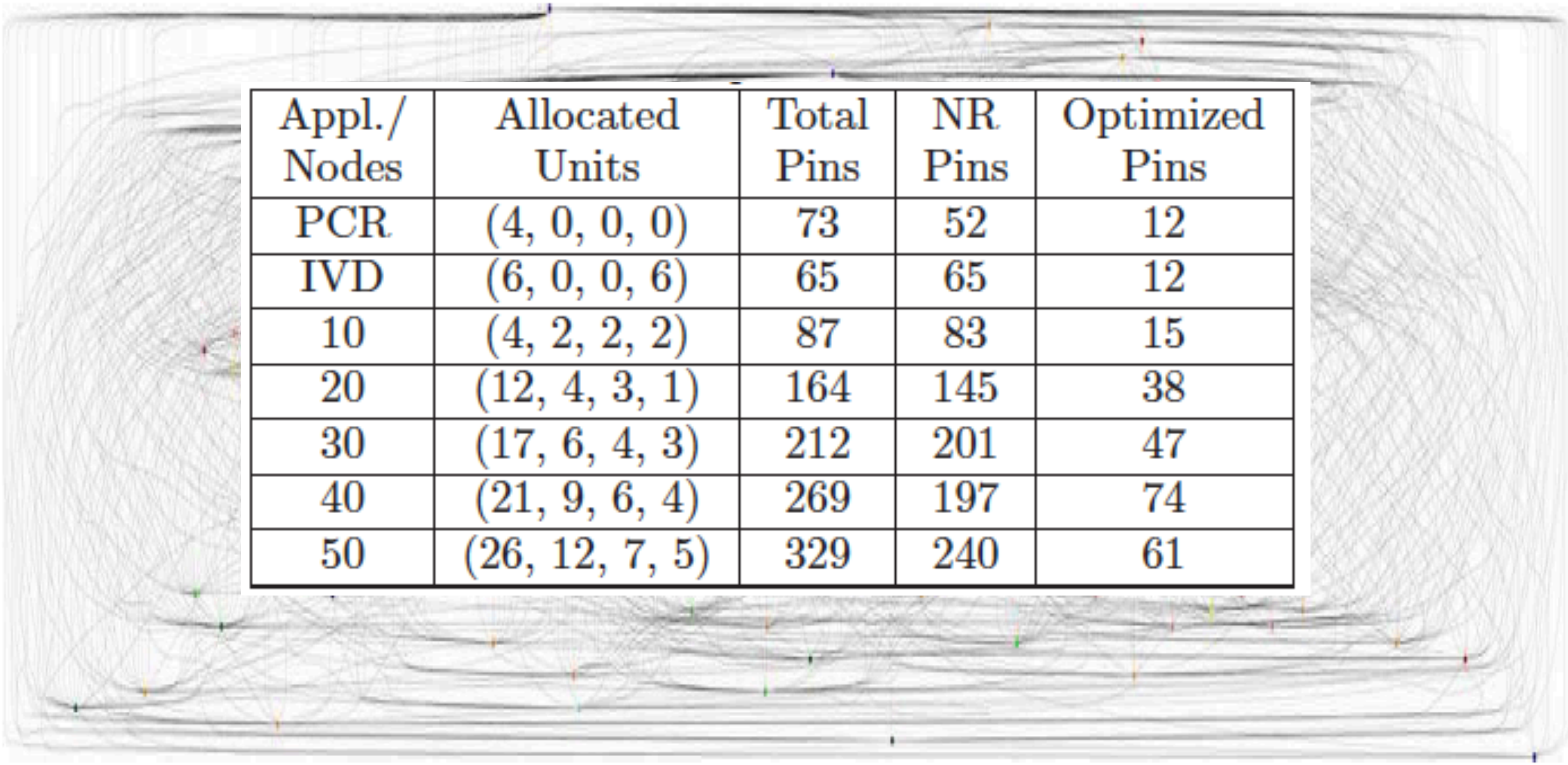
Valve No.	Time Steps (s)					
	0	2	4	5	8	...
1	0	0	X	X	0	...
2	0	0	1	1	0	...
3	0	1	0	0	1	...
4	1	0	0	0	0	...
5	0	1	0	0	1	...
6	0	0	1	1	0	...
7	1	0	0	0	0	...
8	0	0	Mix	Mix	0	...
9	0	0	Mix	Mix	0	...
10	0	0	Mix	Mix	0	...
...	...	...	...	...	...	...
27	0	0	X	X	X	...
28	0	0	1	1	1	...
29	0	1	0	0	0	...

Could be green!

But if all X=0, we can remove the control of this valve

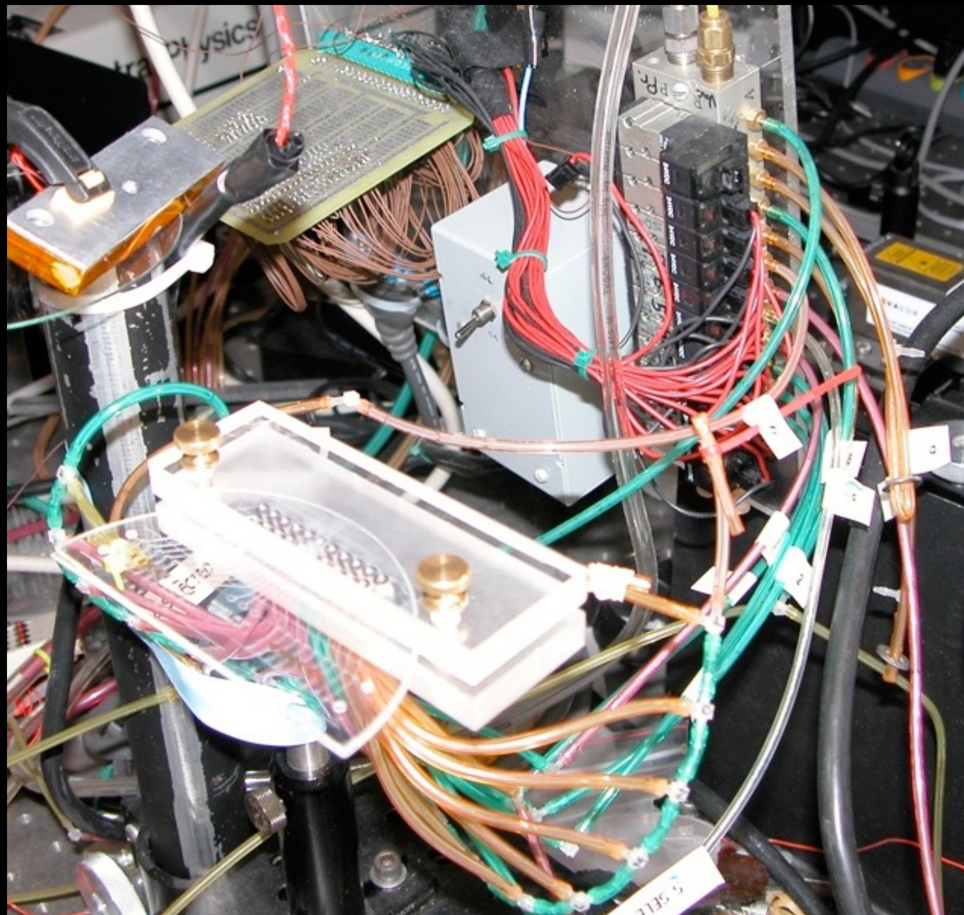


control synthesis



Appl./ Nodes	Allocated Units	Total Pins	NR Pins	Optimized Pins
PCR	(4, 0, 0, 0)	73	52	12
IVD	(6, 0, 0, 6)	65	65	12
10	(4, 2, 2, 2)	87	83	15
20	(12, 4, 3, 1)	164	145	38
30	(17, 6, 4, 3)	212	201	47
40	(21, 9, 6, 4)	269	197	74
50	(26, 12, 7, 5)	329	240	61

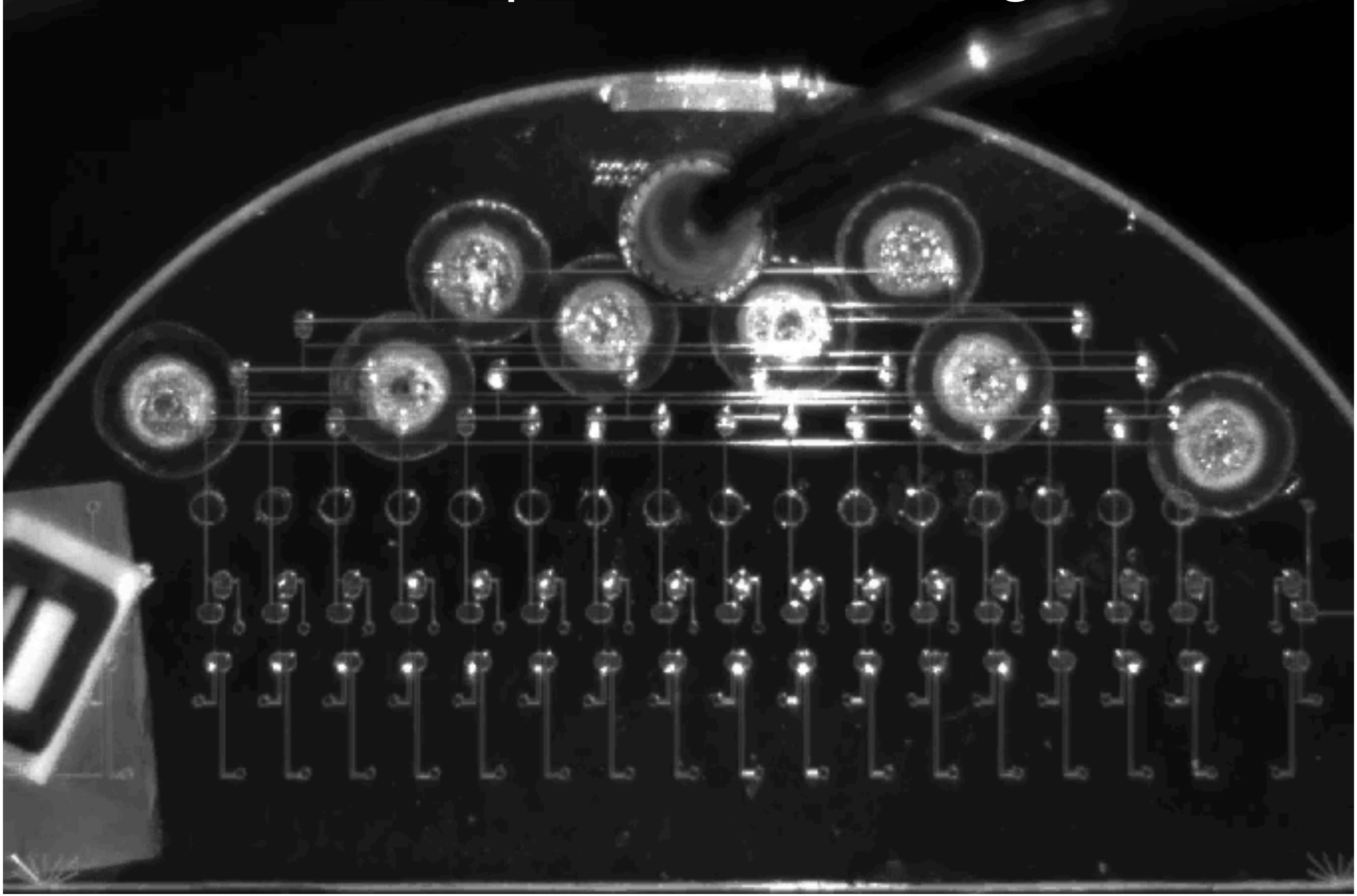
did we solve the problem?



on-chip control?

on-chip bubble logic

DTU



Monolithic membrane valves

Grover, W. H., Skelley, A. M., Liu, C. N., Lagally, E. T., & Mathies, R. A. (2003). Monolithic membrane valves and diaphragm pumps for practical large-scale integration into glass

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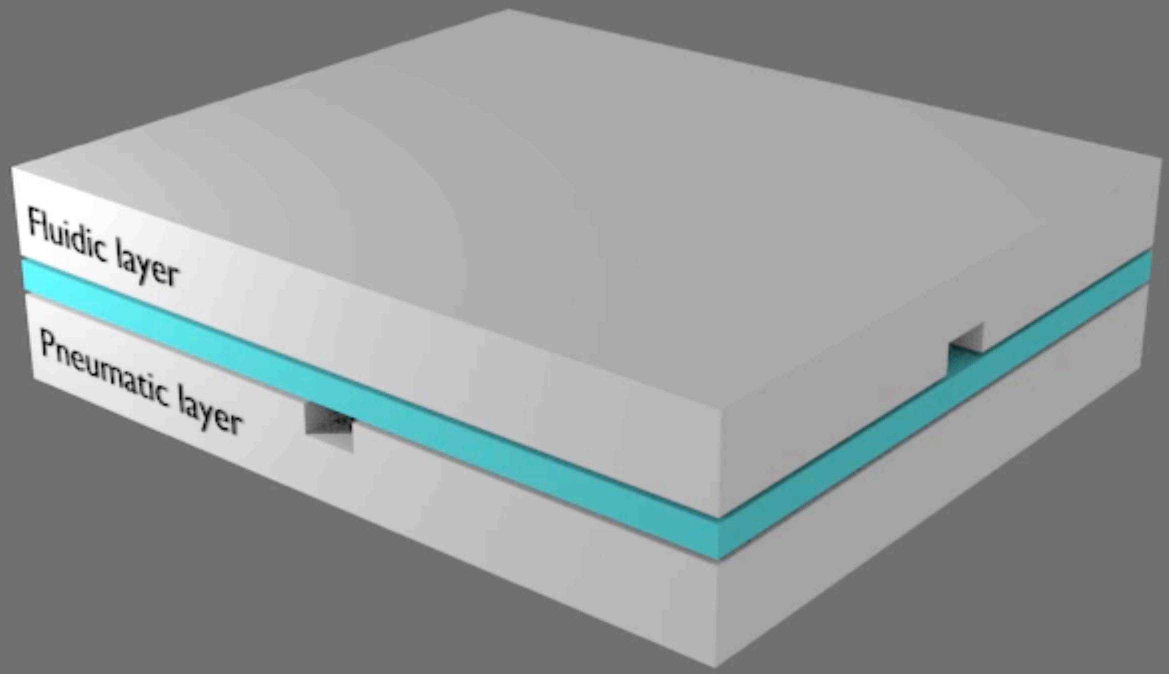

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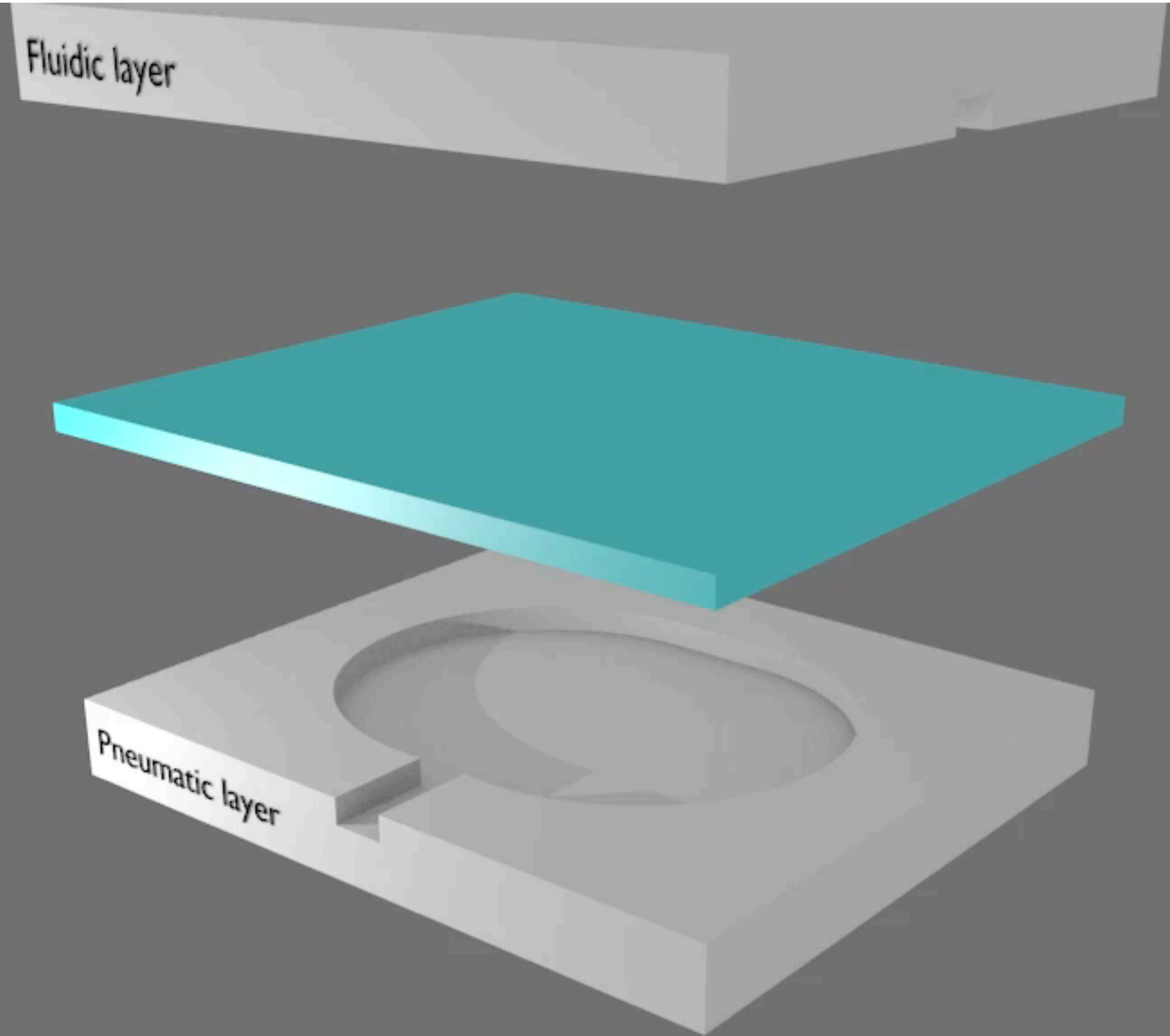

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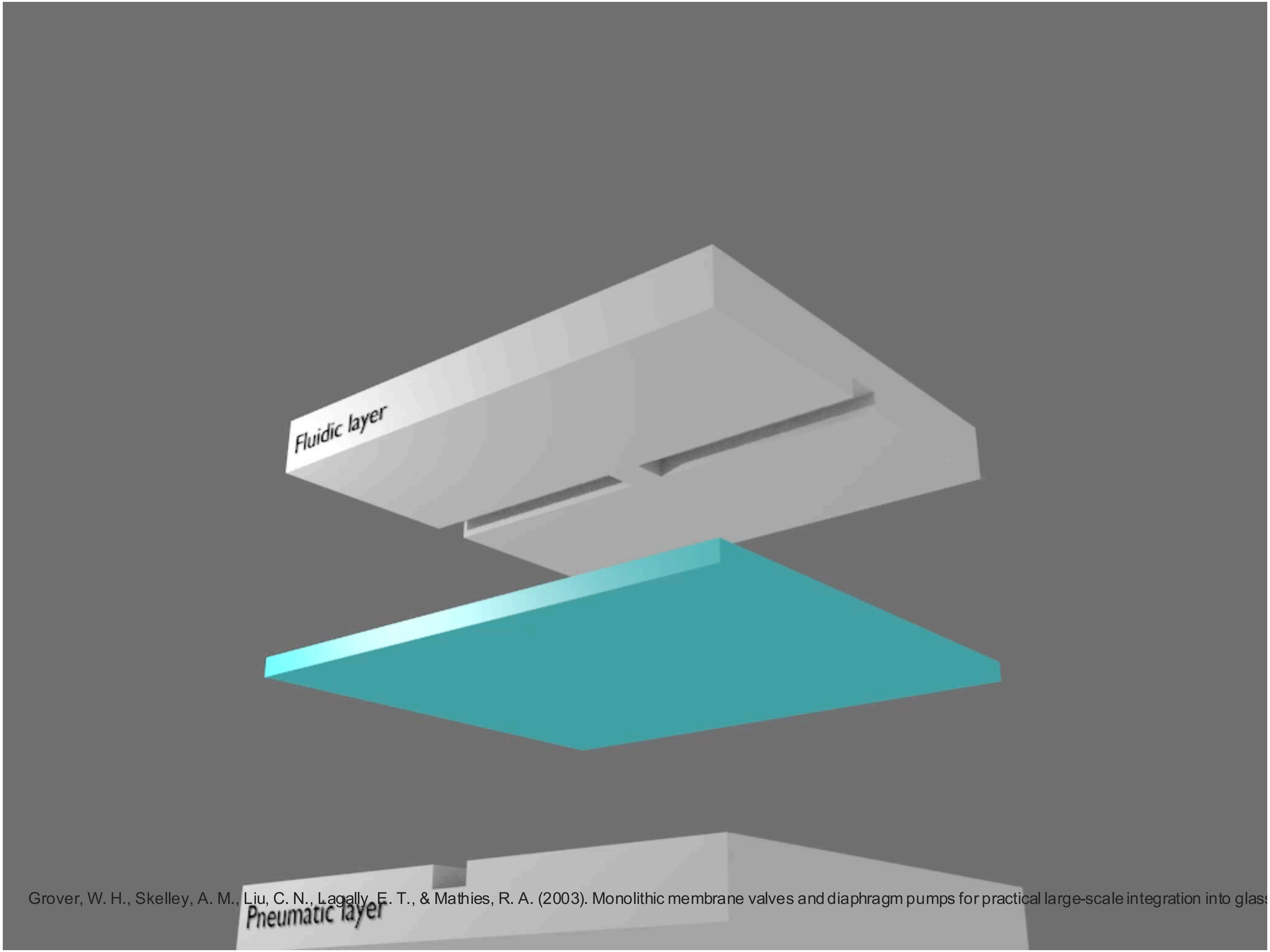

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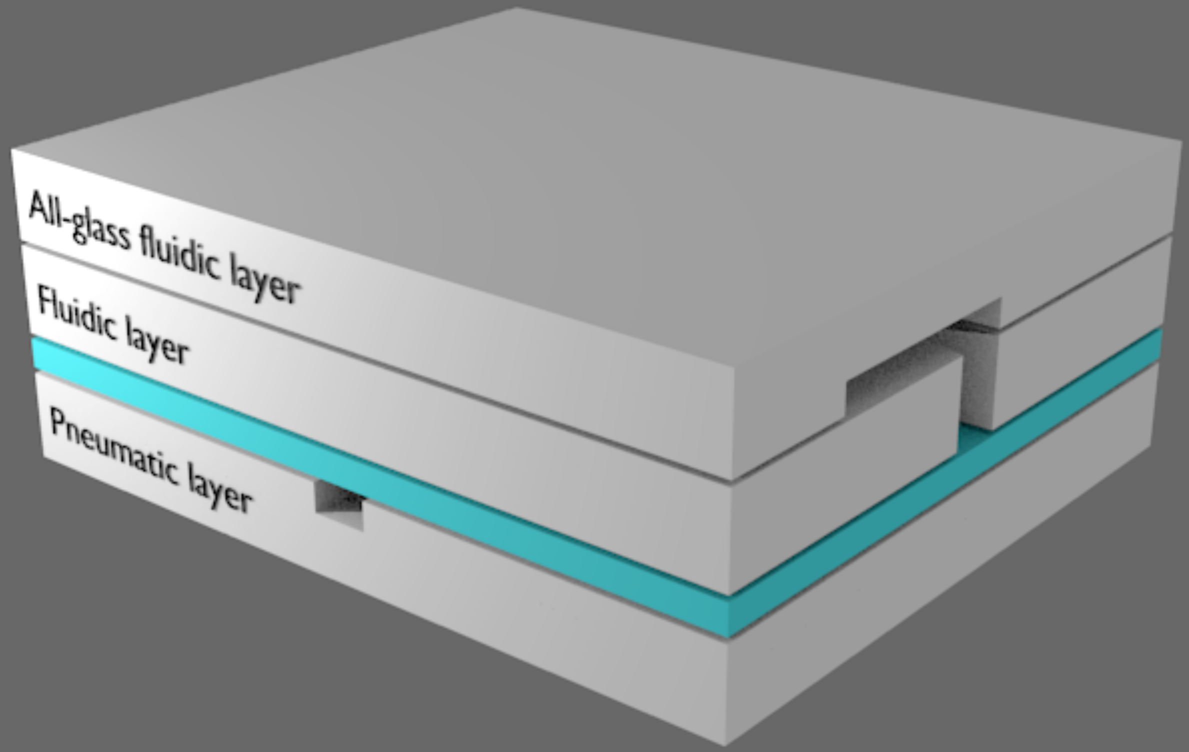

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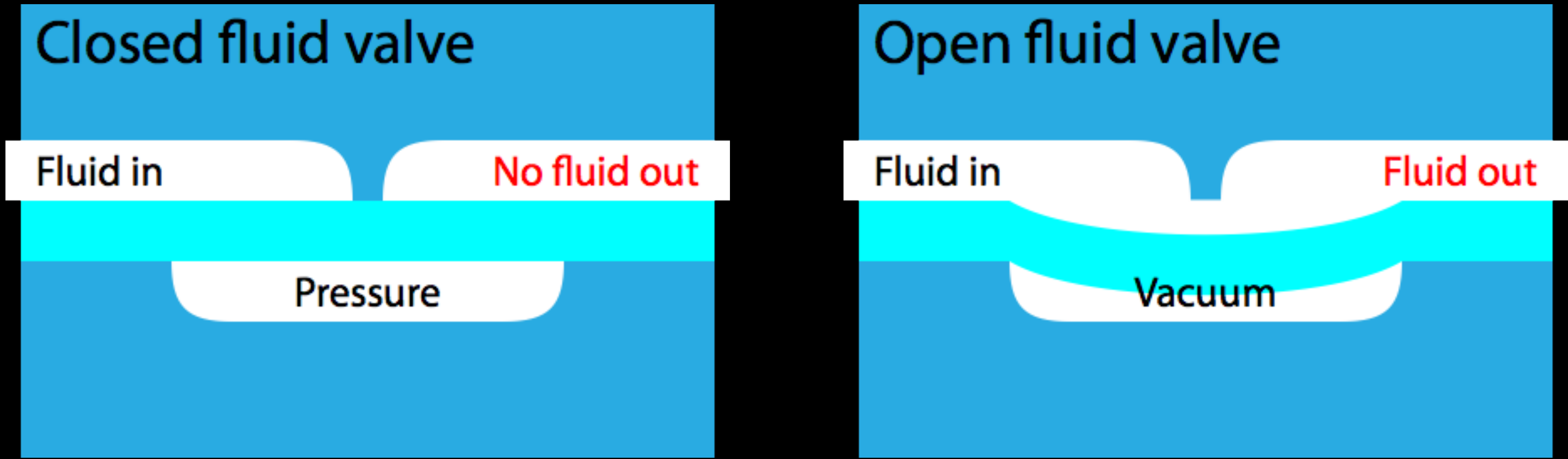
Monolithic membrane valves



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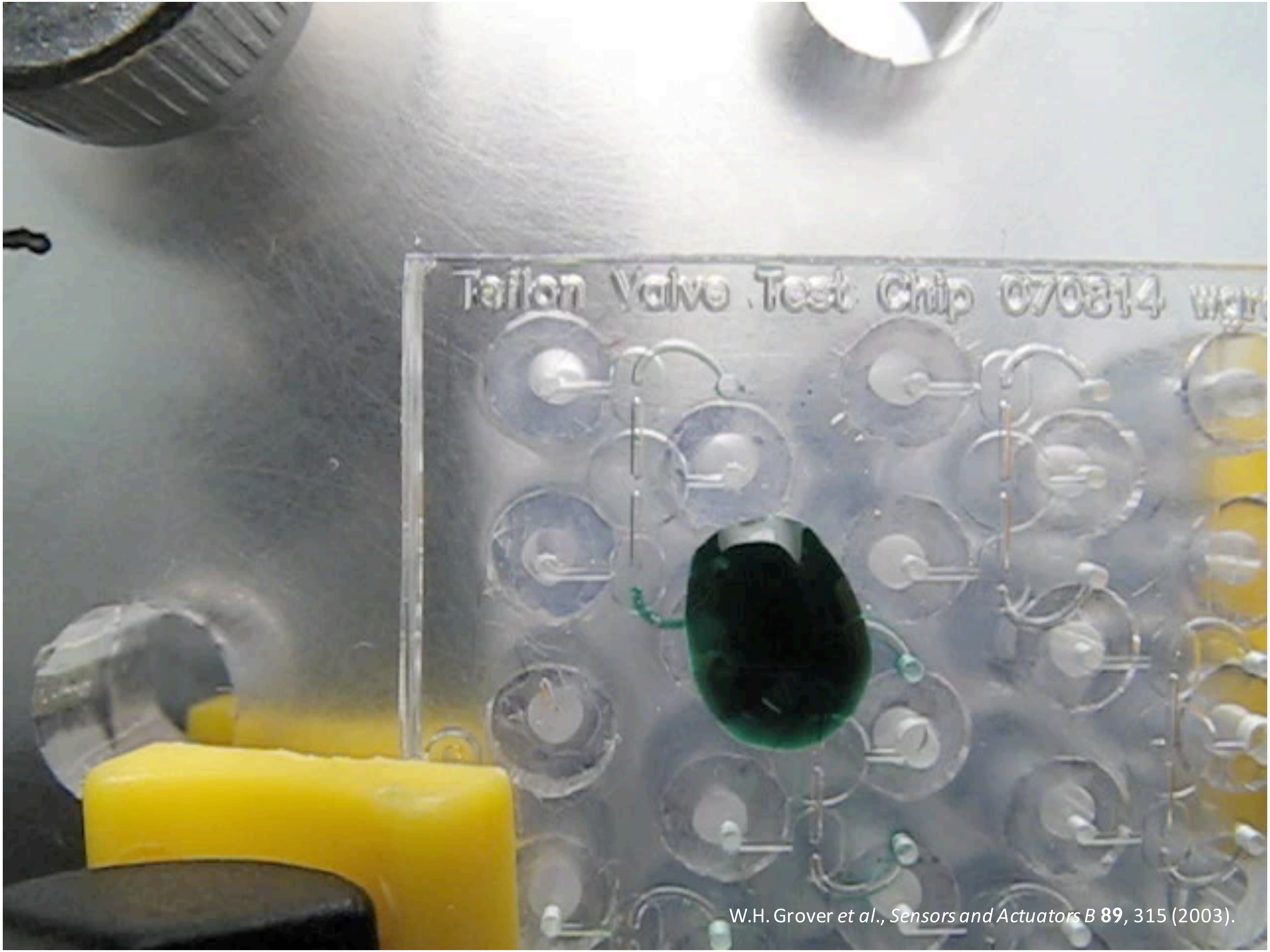
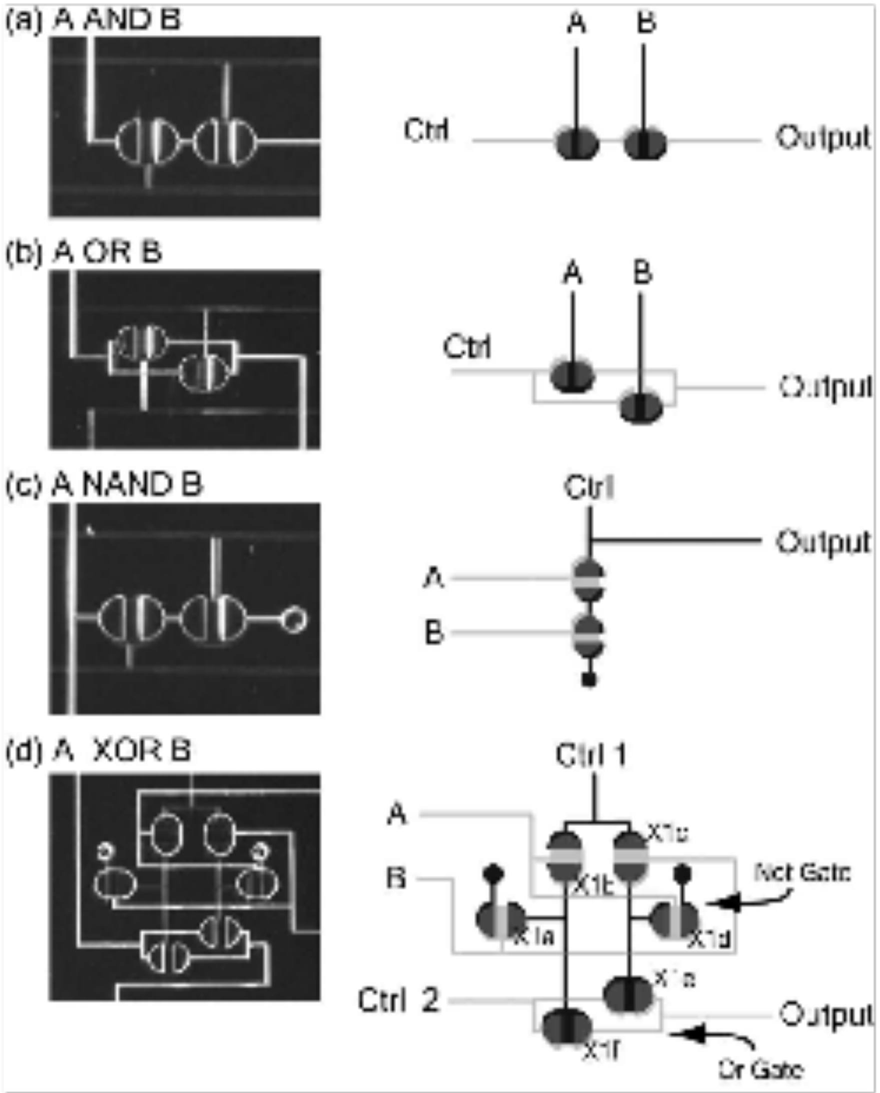


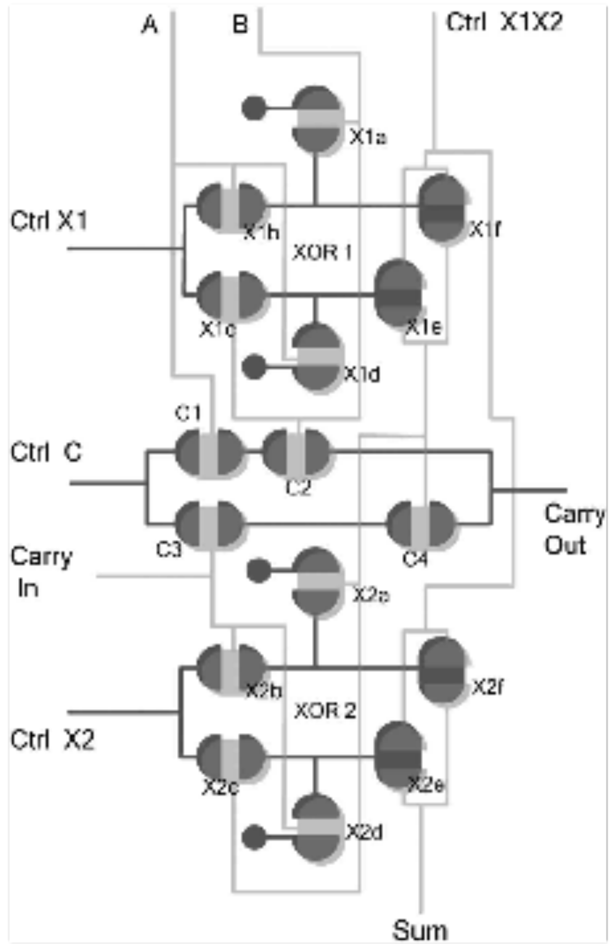
W.H. Grover *et al.*, *Sensors and Actuators B* **89**, 315 (2003).

JOURNAL OF MICROELECTROMECHANICAL SYSTEMS, VOL. 16, NO. 6, DECEMBER 2007

Micropneumatic Digital Logic Structures for Integrated Microdevice Computation and Control

Erik C. Jensen, William H. Grover, and Richard A. Mathies

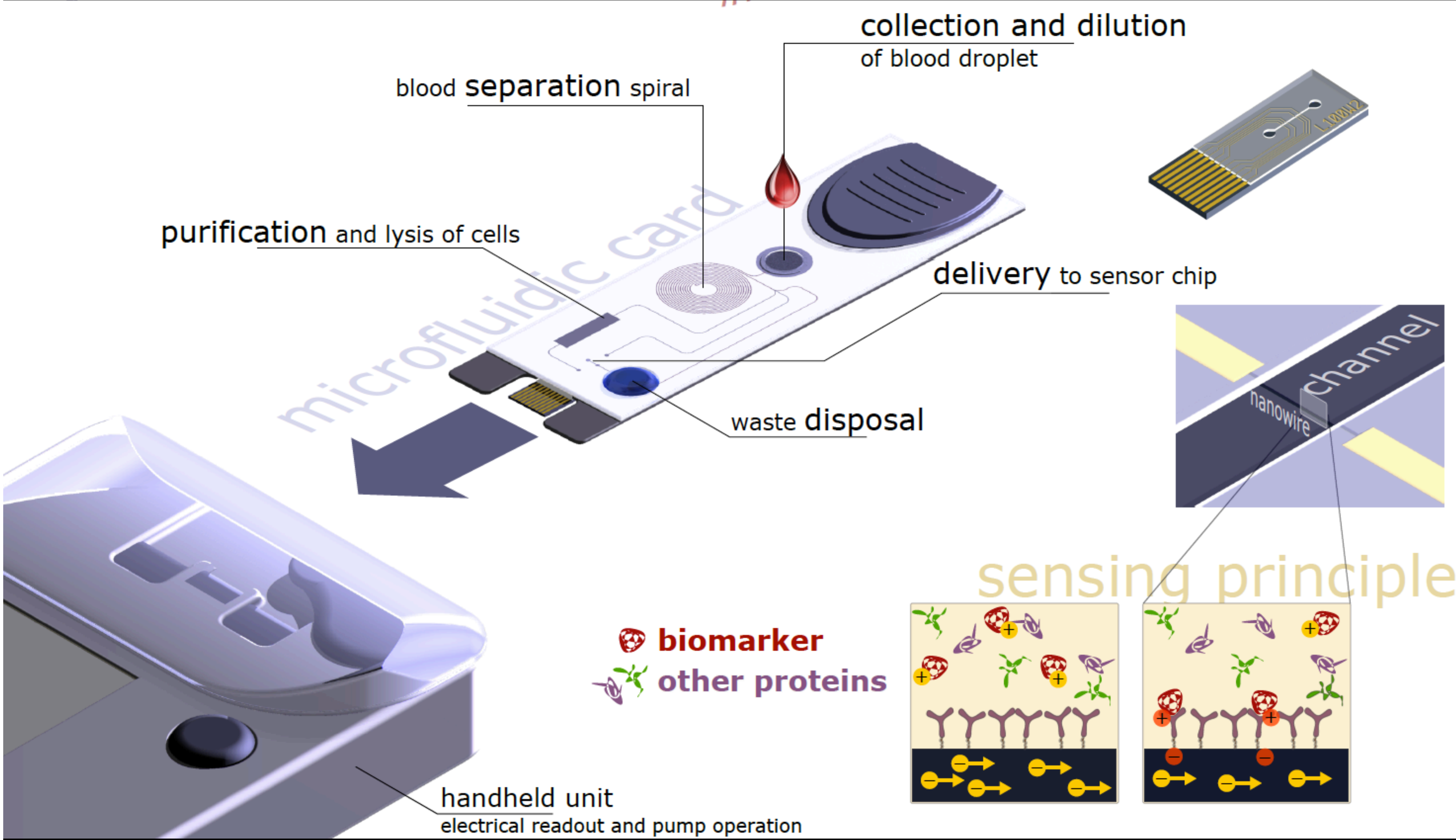





20

integration

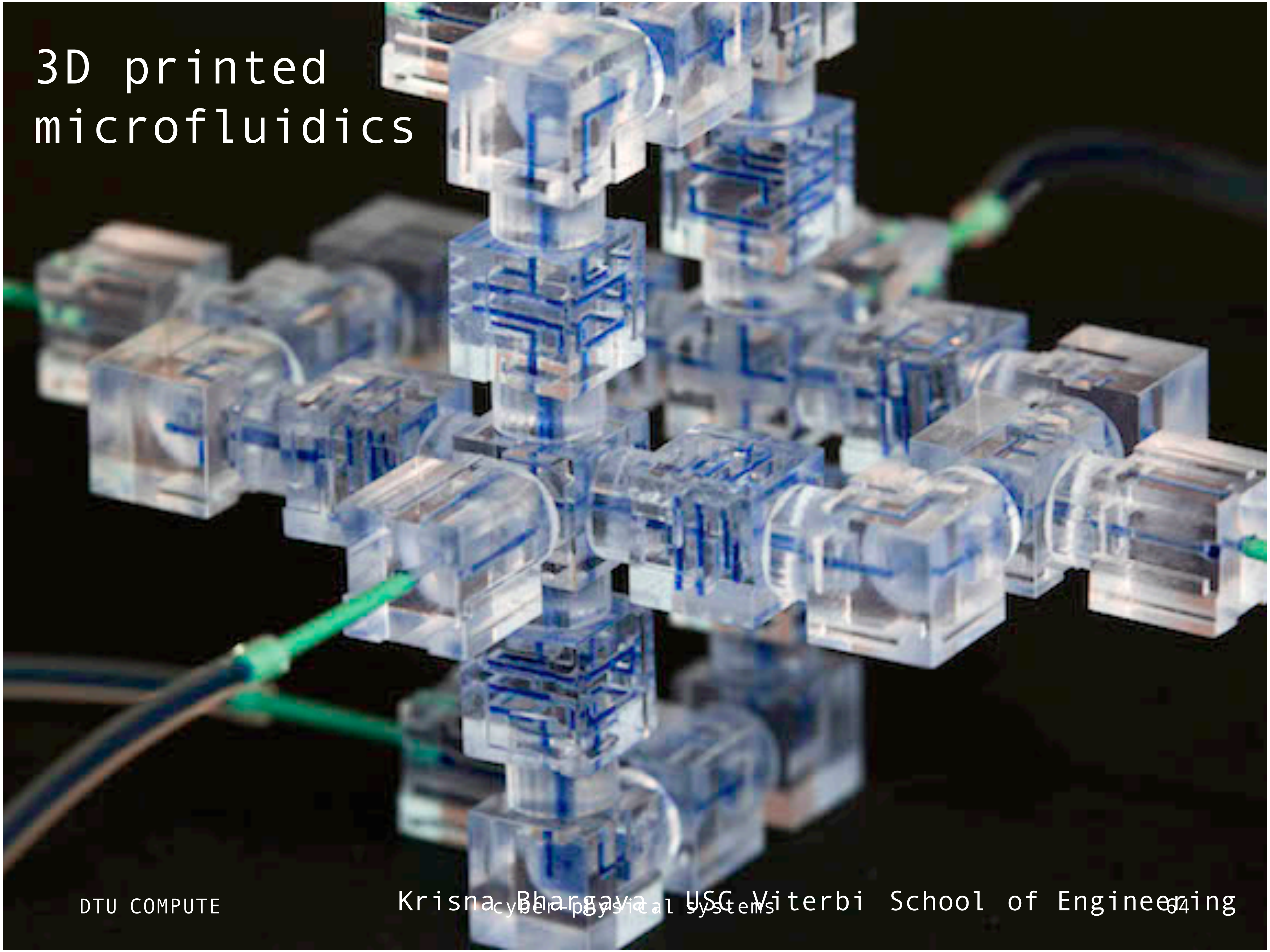
Integration



[Courtesy, Winnie Svendsen, NaBIS, DTU Nanotech]

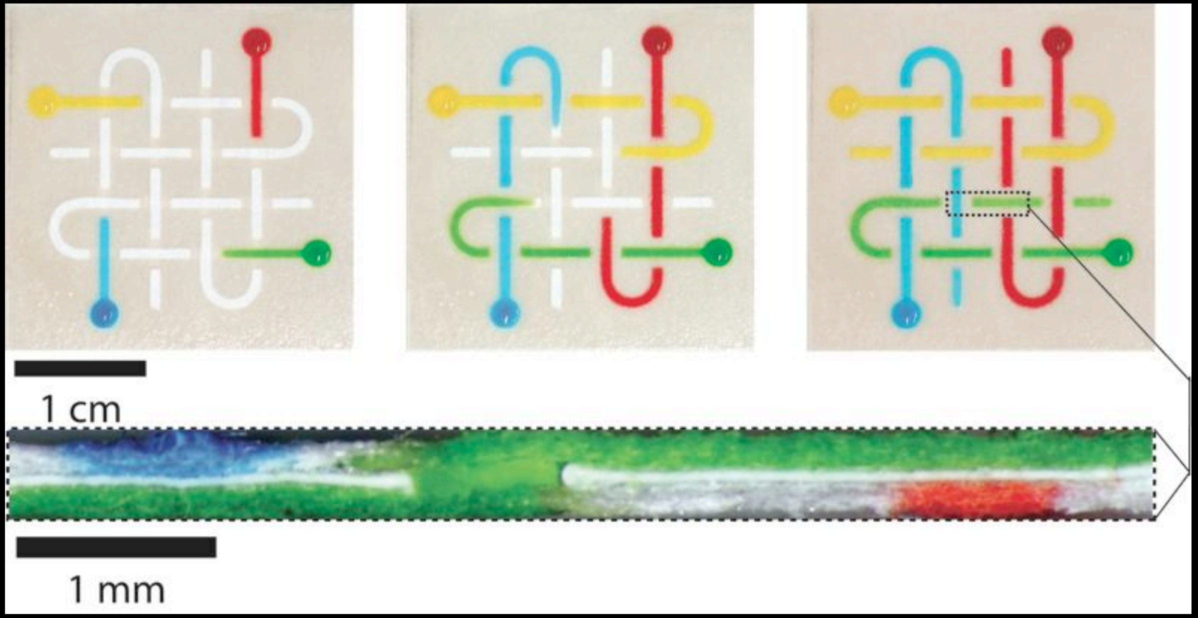
microfluidic technologies

3D printed microfluidics

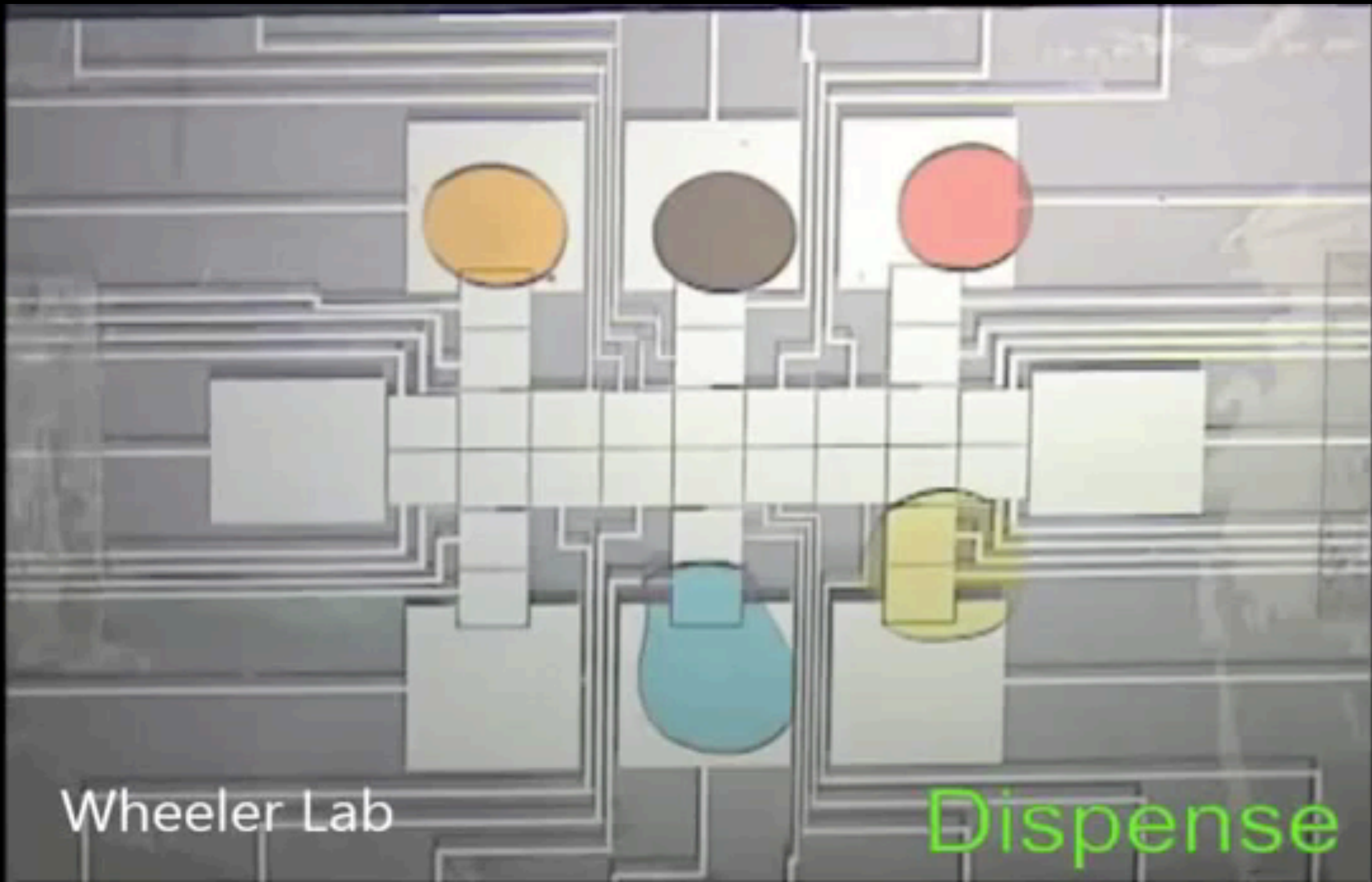


Krisna Bhargava, USC Viterbi School of Engineering

Paper-based microfluidic



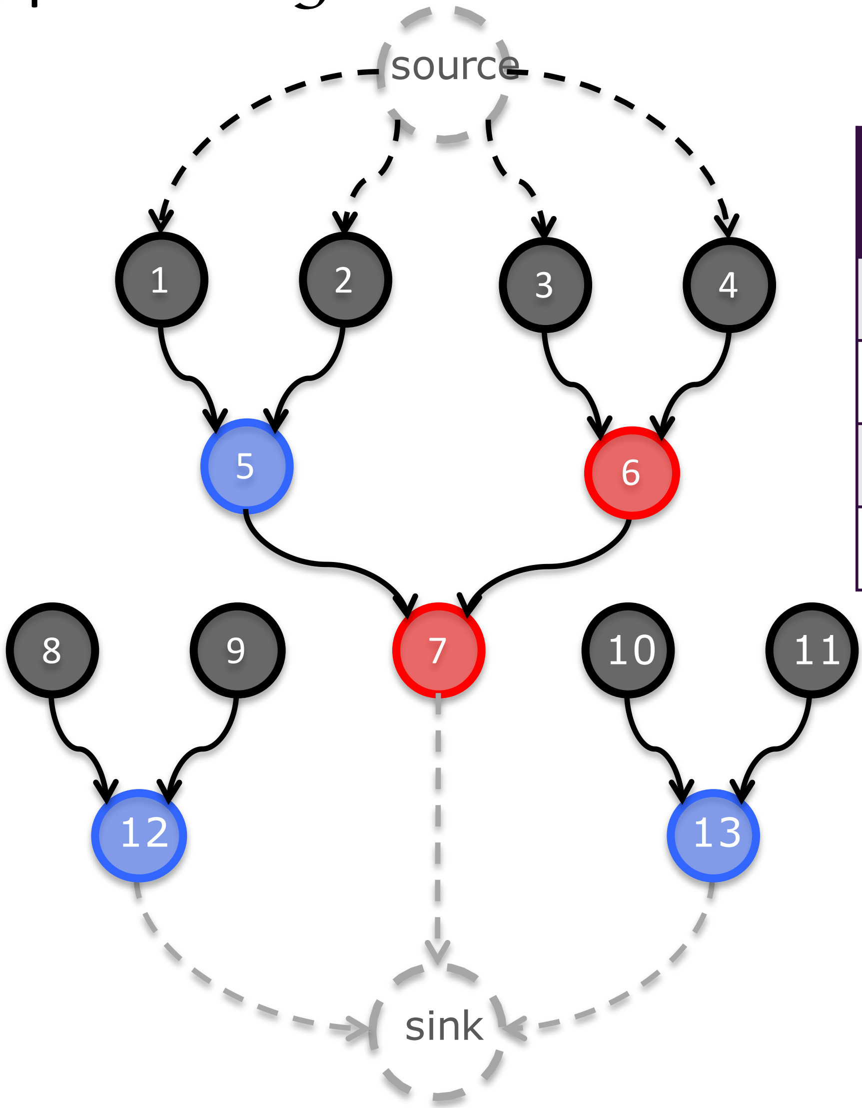
digital microfluidics



Digital microfluidic design

Biochemical application

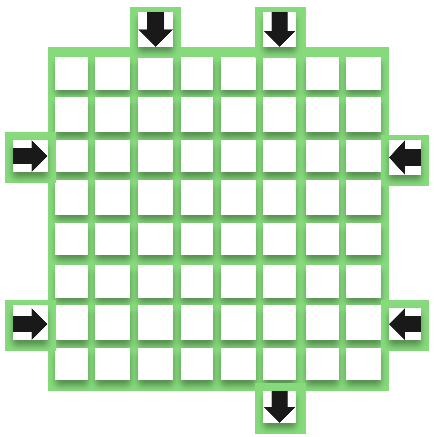
application $\mathcal{G}$



library $\mathcal{L}$

module	Operation	Area (cells)	Time (sec)
M1	Mixing	2x4	3
M2	Mixing	2x2	4
D1	Dilution	2x4	4
D2	Dilution	2x2	5

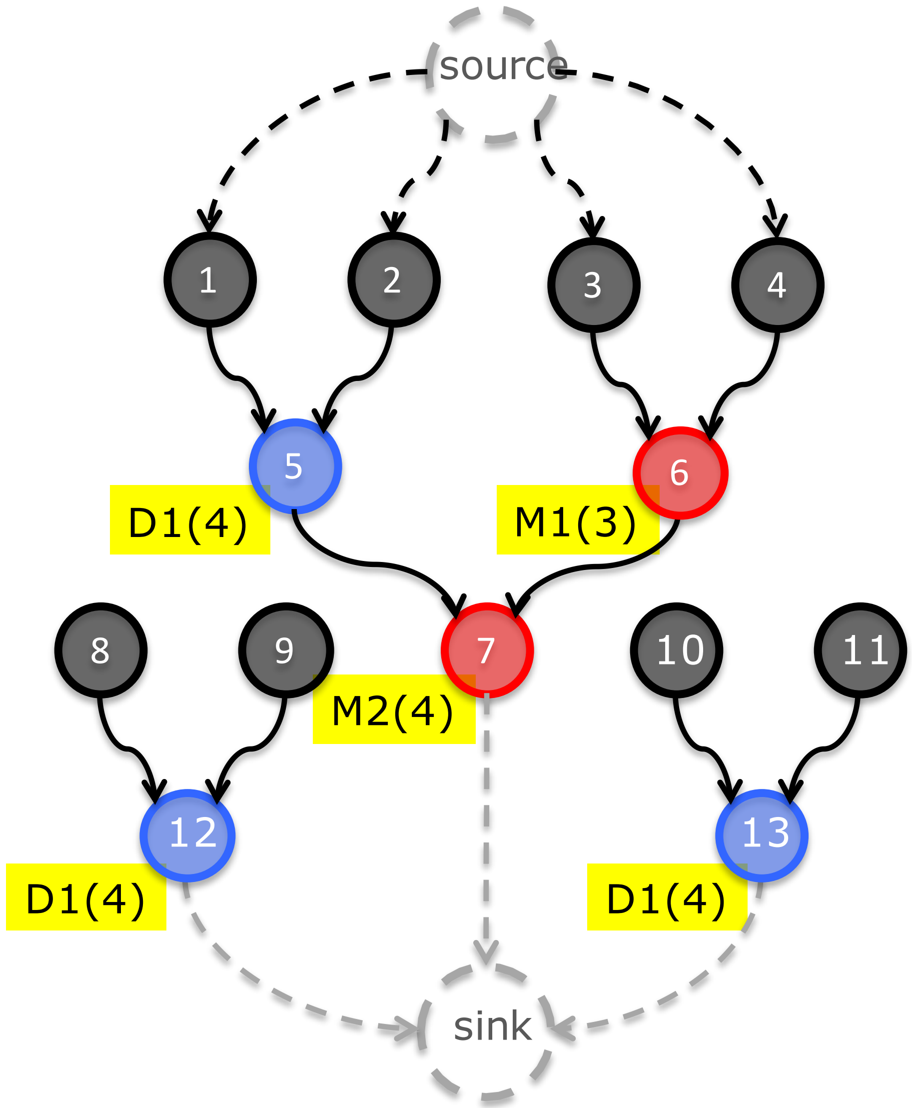
array C



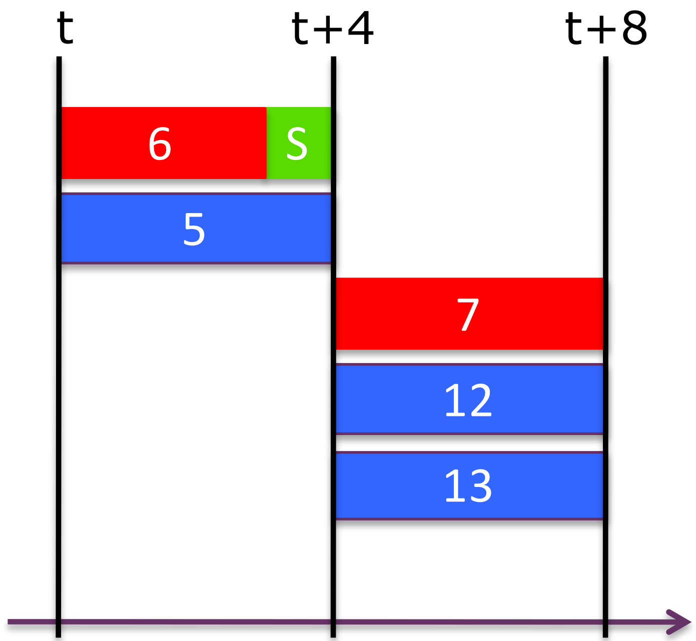
Mapping biochemical applications onto microfluidic biochips

- Allocation $\mathcal{A}$
  - Determine modules $\mathcal{M}_k$ from library $\mathcal{L}$
- Binding $\mathcal{B}$
  - Assign each operation O_i to a module $\mathcal{M}_k$
- Schedule $\mathcal{S}$
  - Determine start time t_i^{start} of each operation O_i
- Placement $\mathcal{P}$
  - Place modules on the $m \times n$ array
- Synthesis Ψ
  - Given $<\mathcal{G}, \mathcal{C}, \mathcal{L}>$, find $\Psi = <\mathcal{A},\mathcal{B},\mathcal{S},\mathcal{P}>$ which minimize the schedule length $\delta_{\mathcal{G}}$

Scheduling

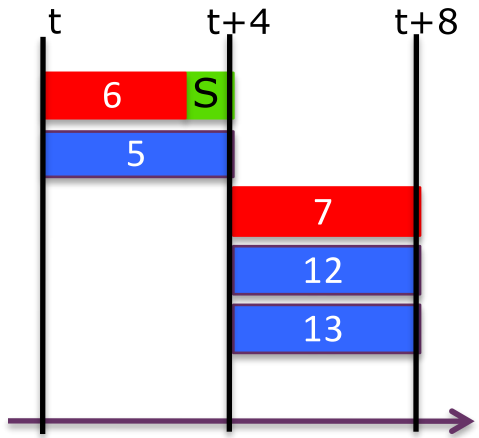


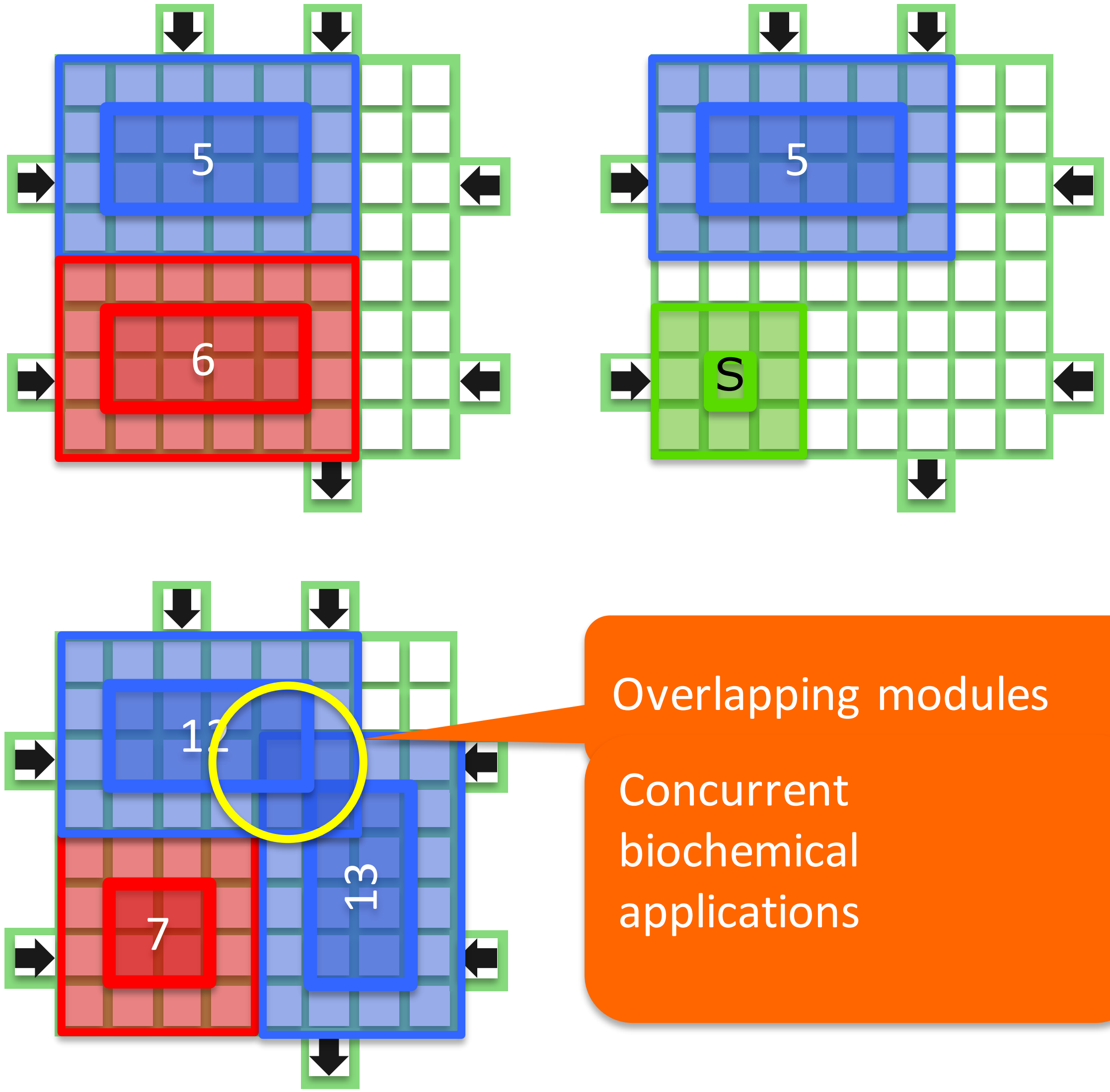
source
1
2
3
4
5
6
D1(4)
M1(3)
8
9
7
10
11
M2(4)
12
13
D1(4)
D1(4)
sink



t
t+4
t+8
6
S
5
7
12
13

Scheduling

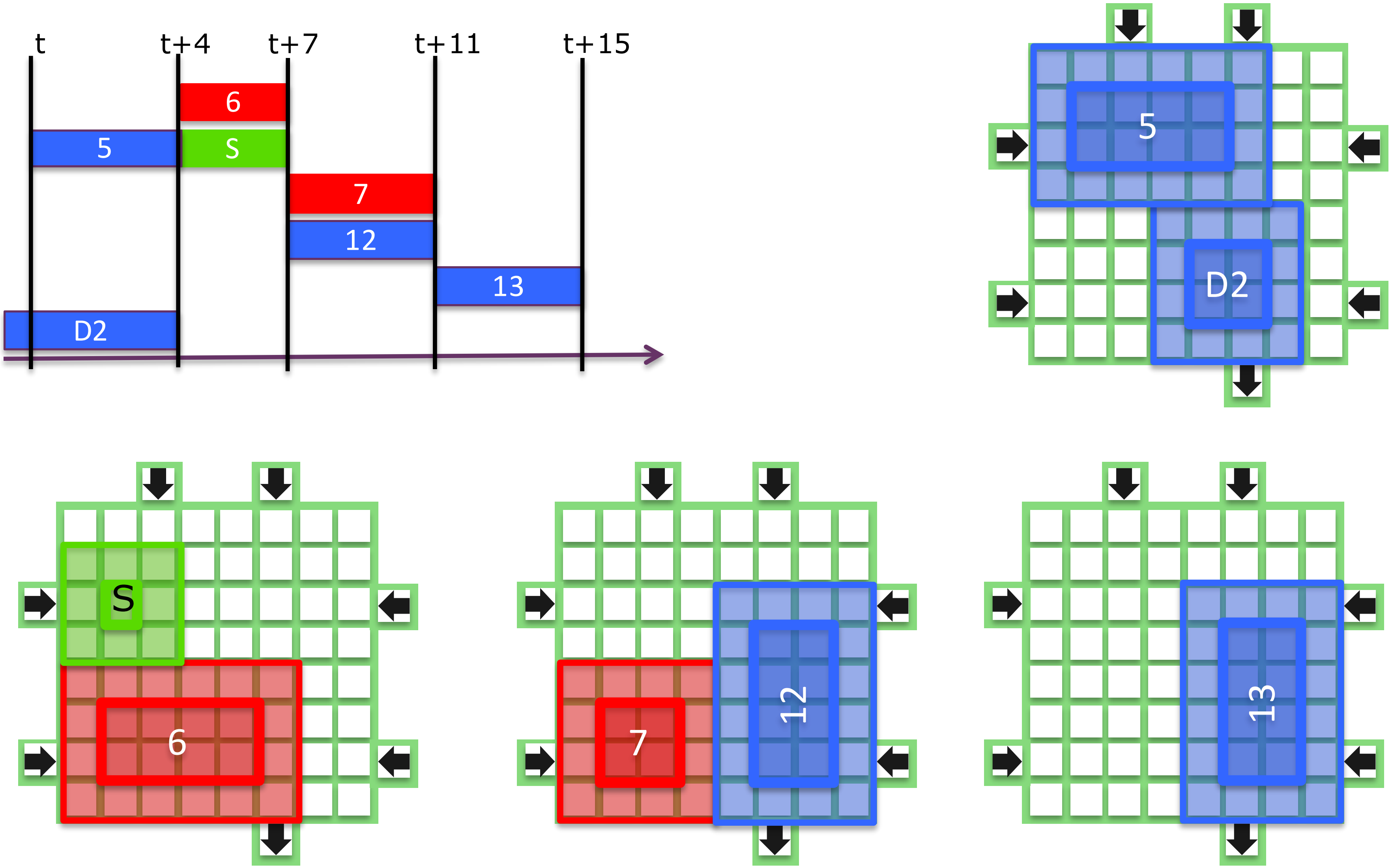




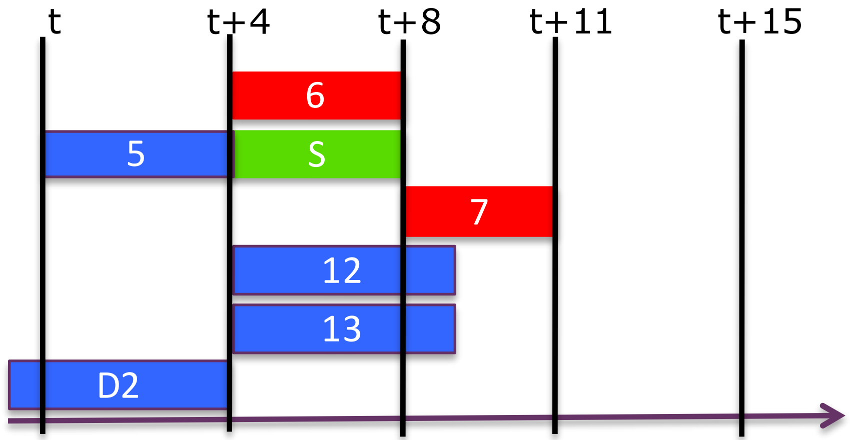
Overlapping modules

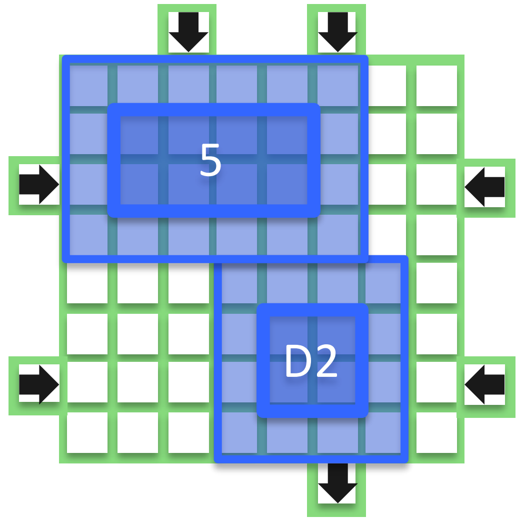
Concurrent biochemical applications

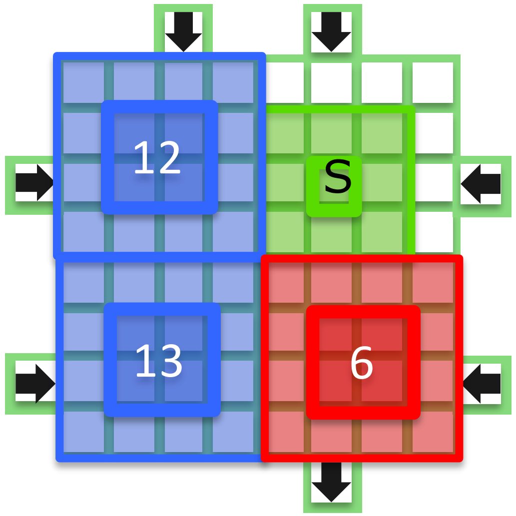
Scheduling with placement

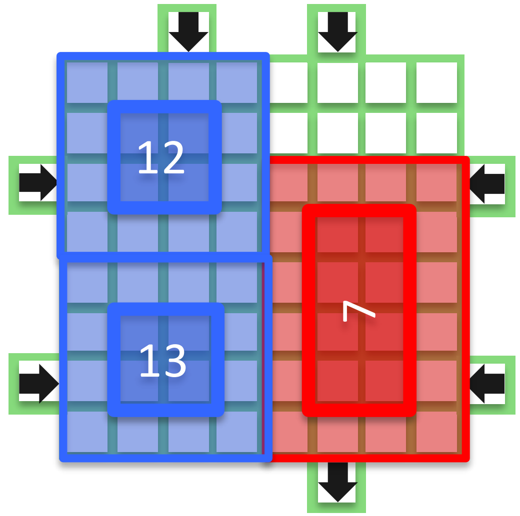


Scheduling with placement

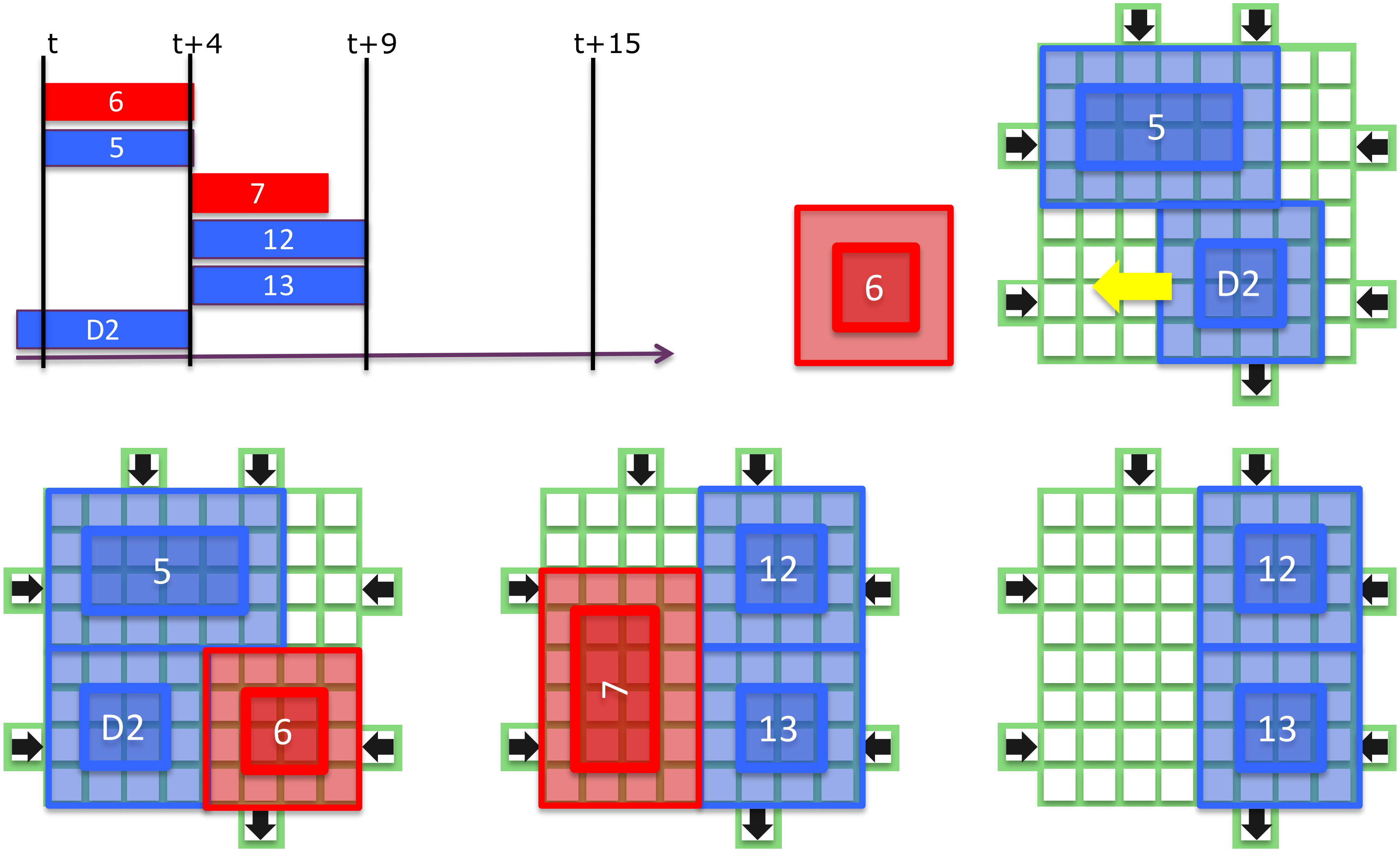




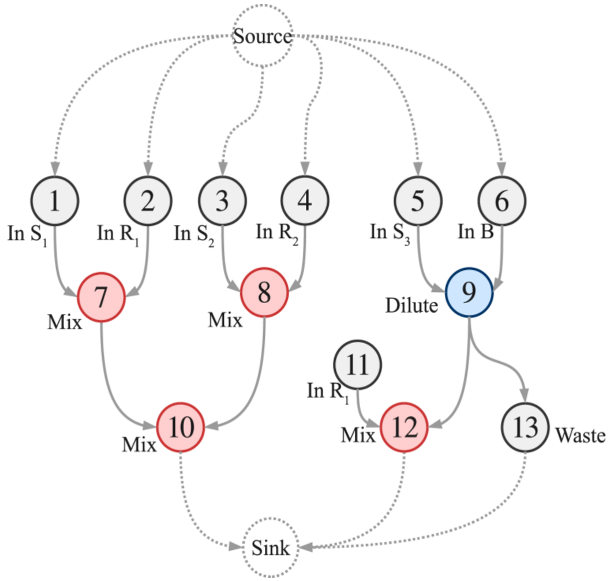




Scheduling with dynamic placement



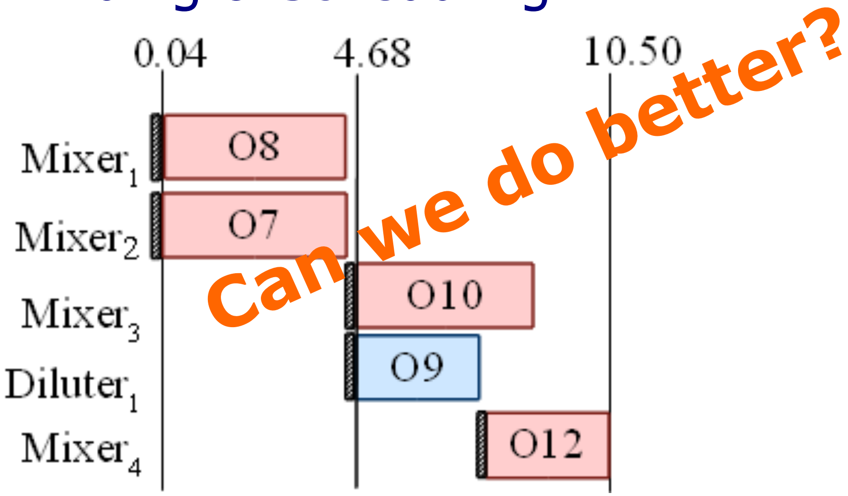
module-based design tasks



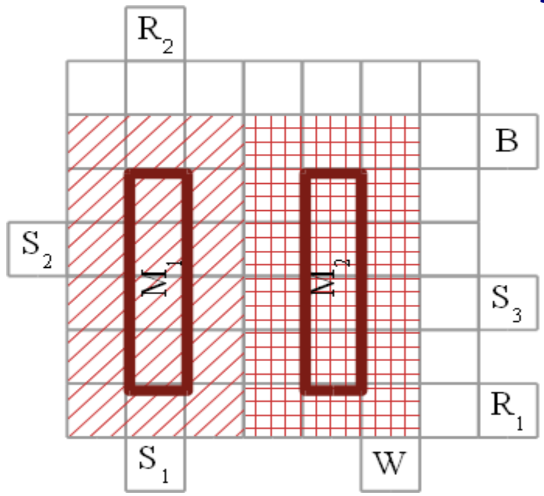
Allocation

Operation	Area(cells)	Time(s)
Mix/Dlt	2x4	2.8
Mix/Dlt	1x4	4.6
Mix/Dlt	2x3	5.6
Mix/Dlt	2x2	9.96

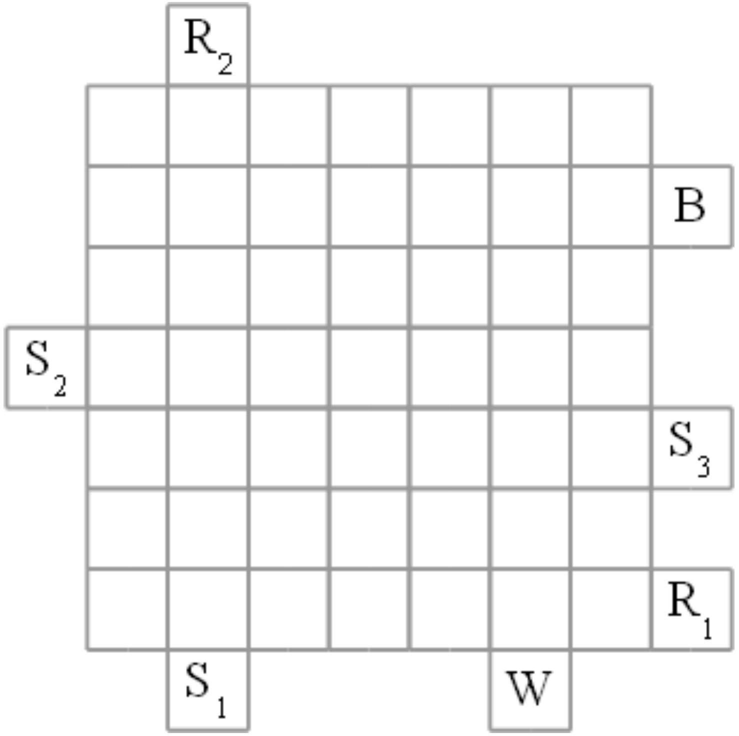
Binding & Scheduling

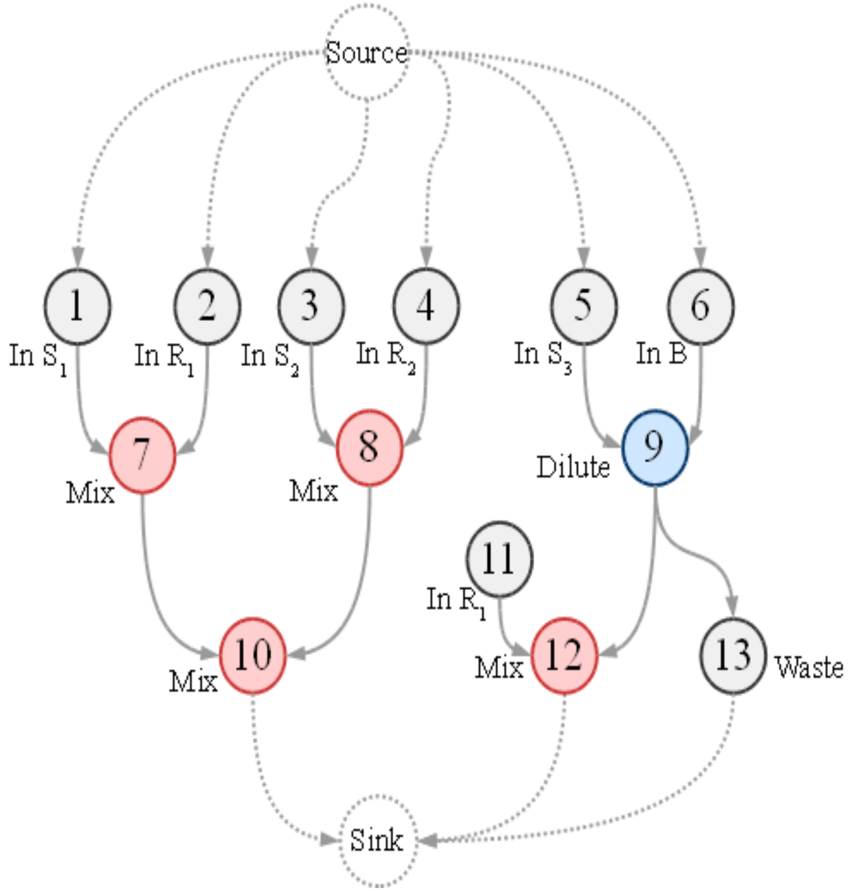


Placement & Routing



routing-based synthesis



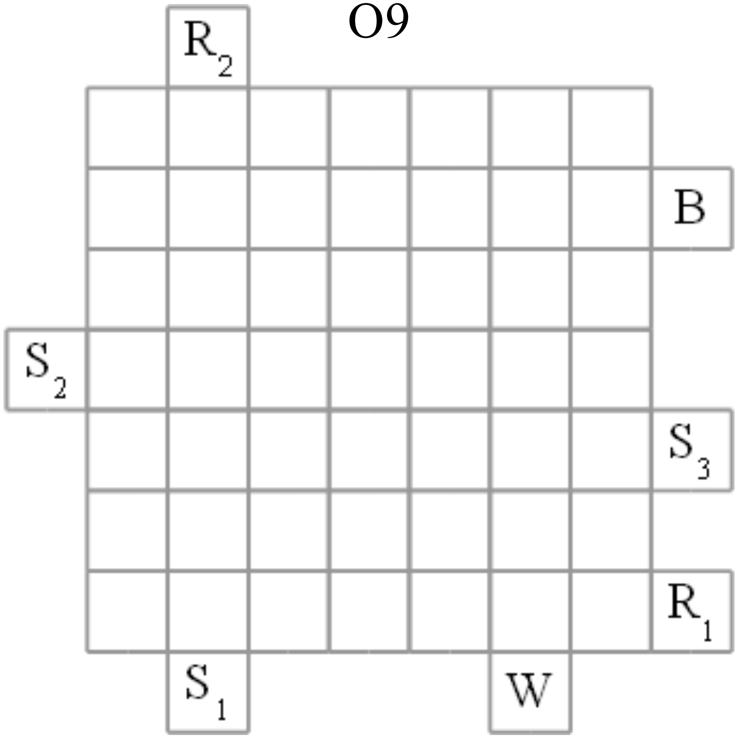


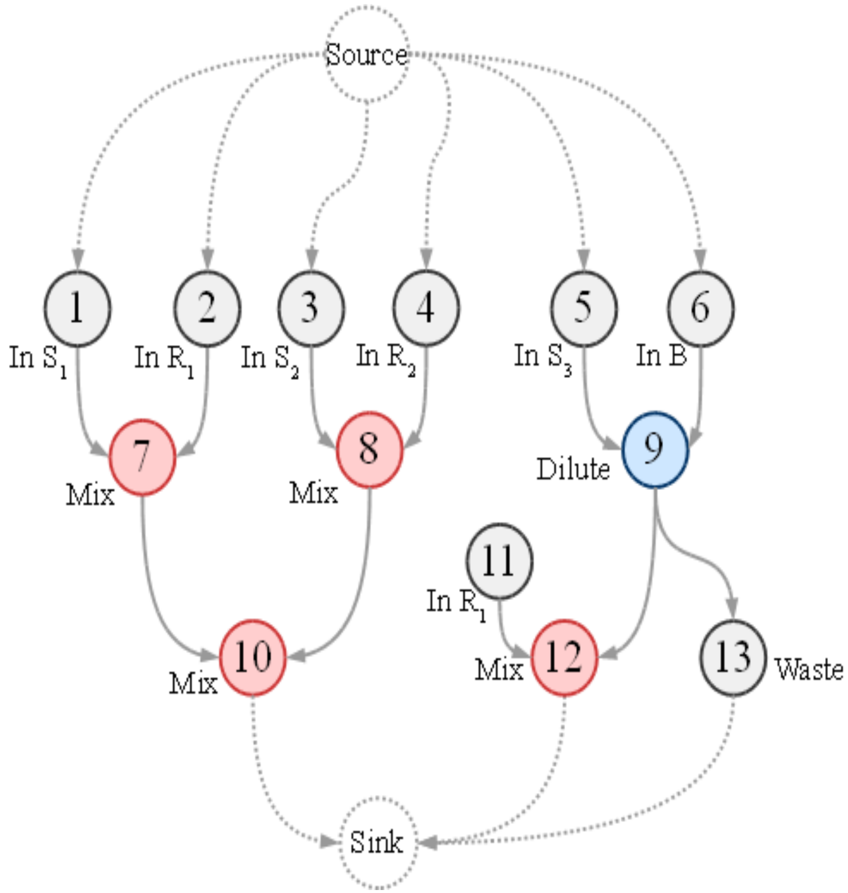
routing-based synthesis

O7

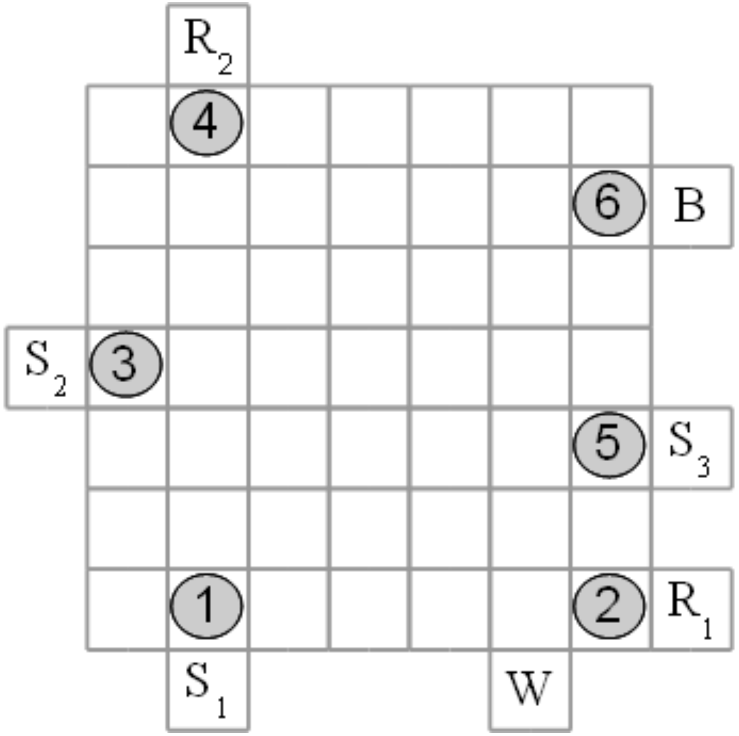
O8

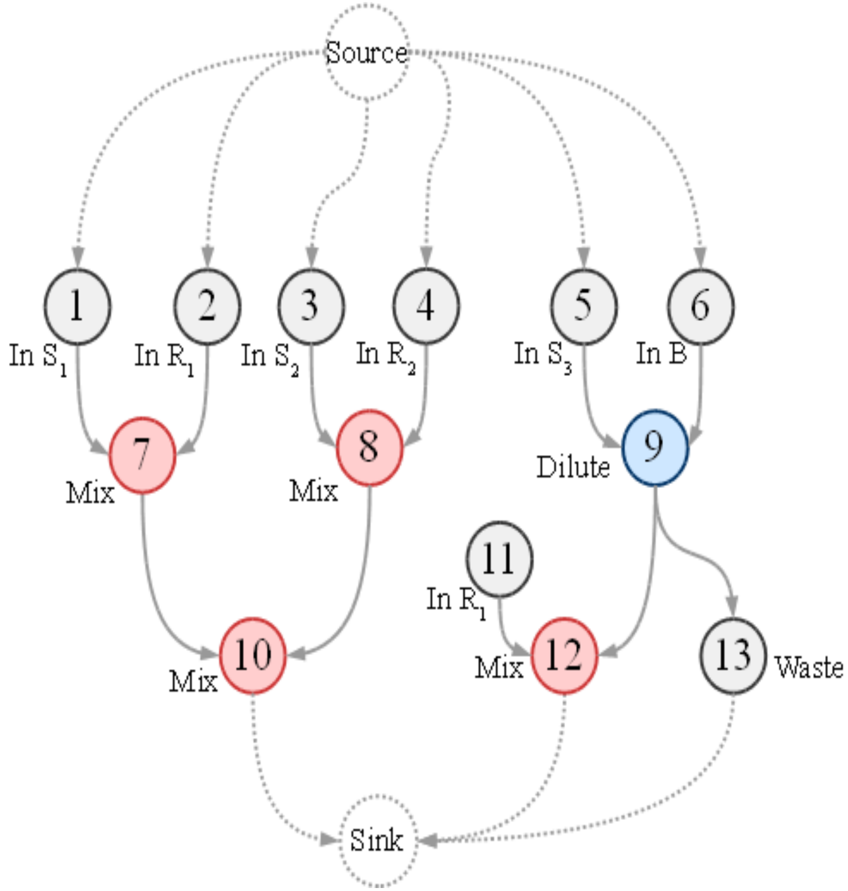
O9



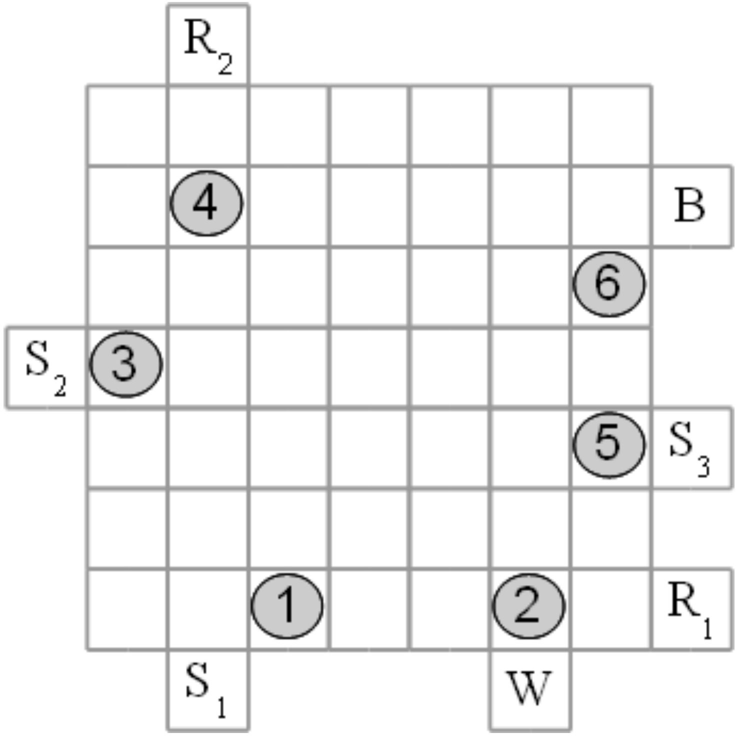


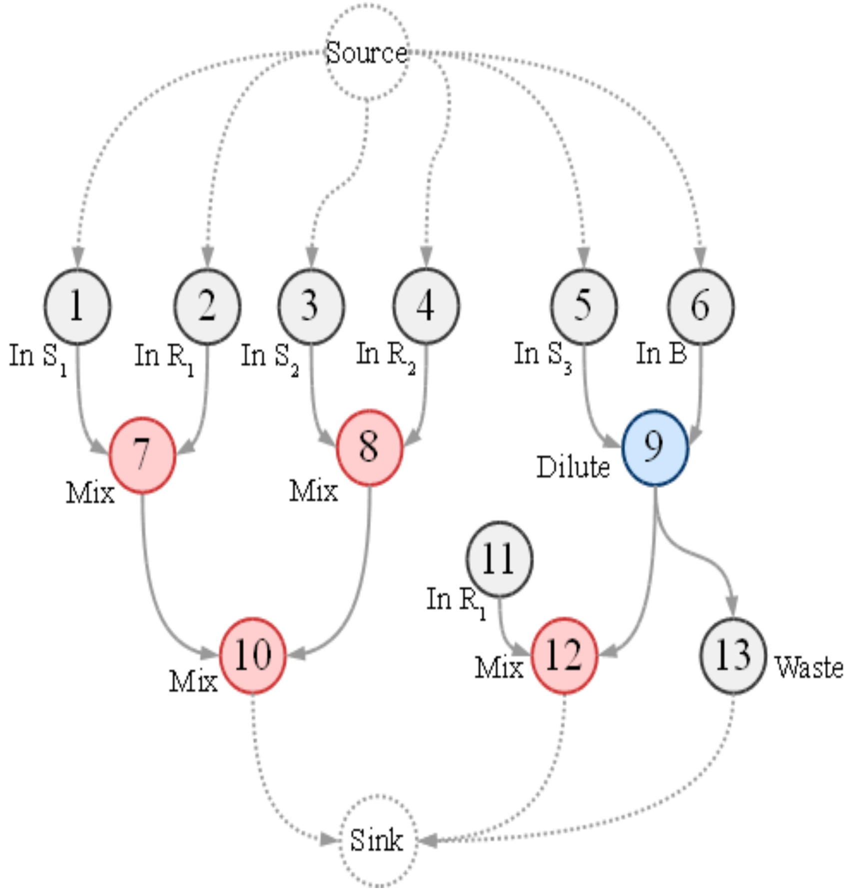
routing-based synthesis



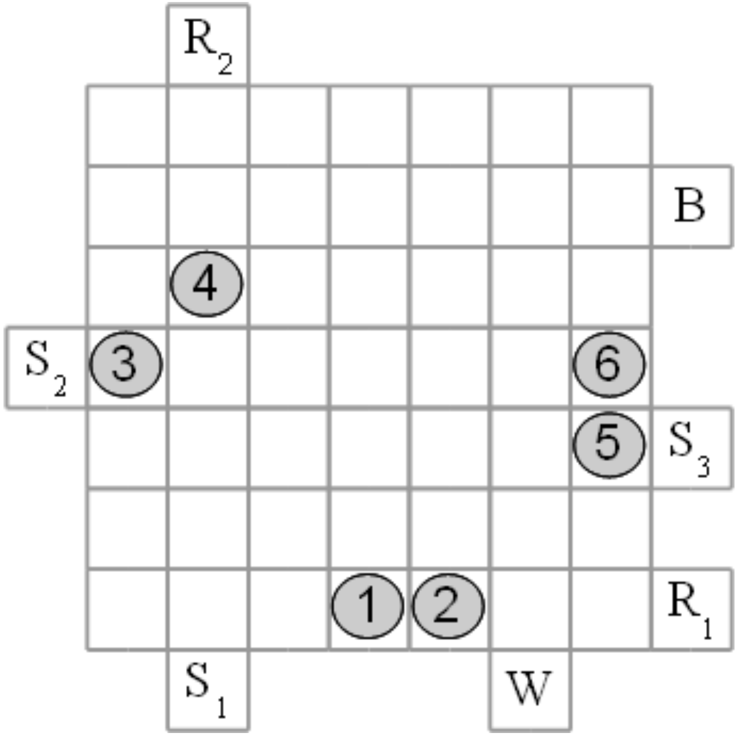


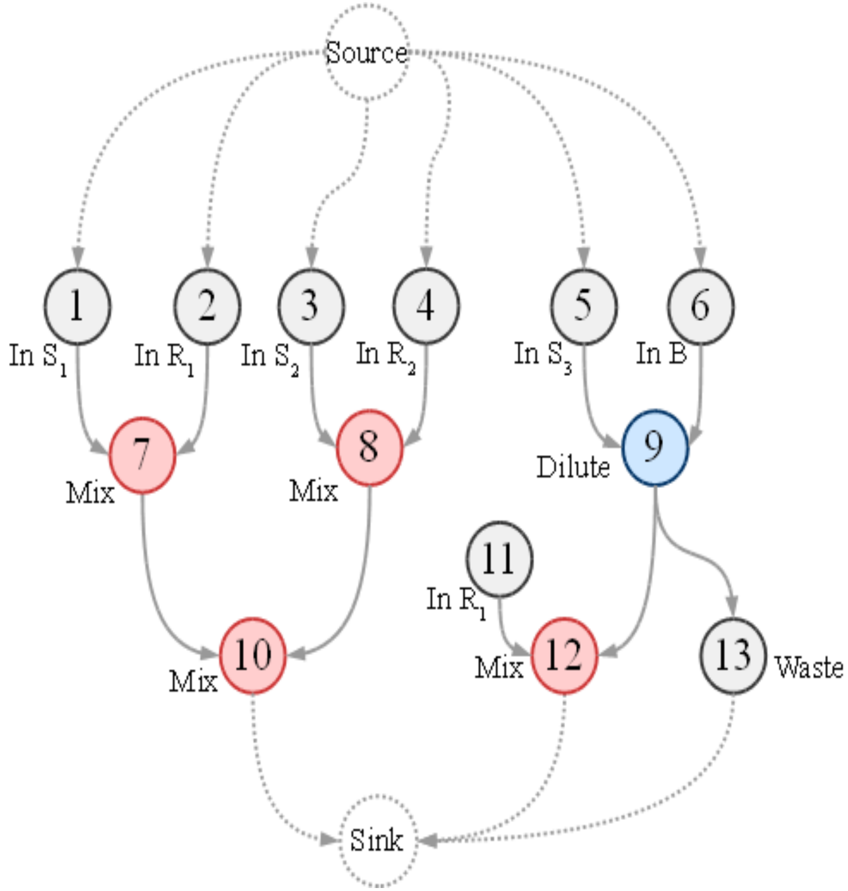
routing-based synthesis



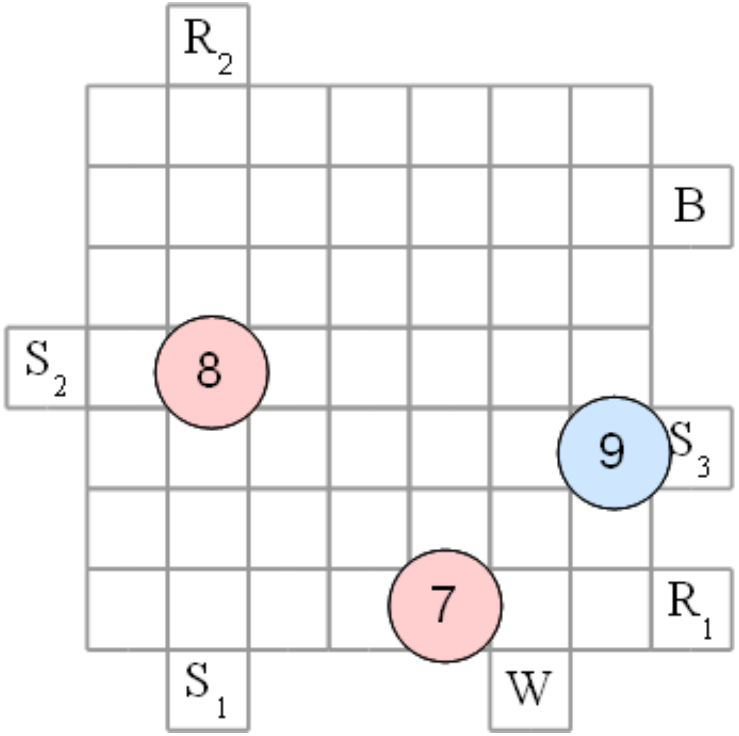


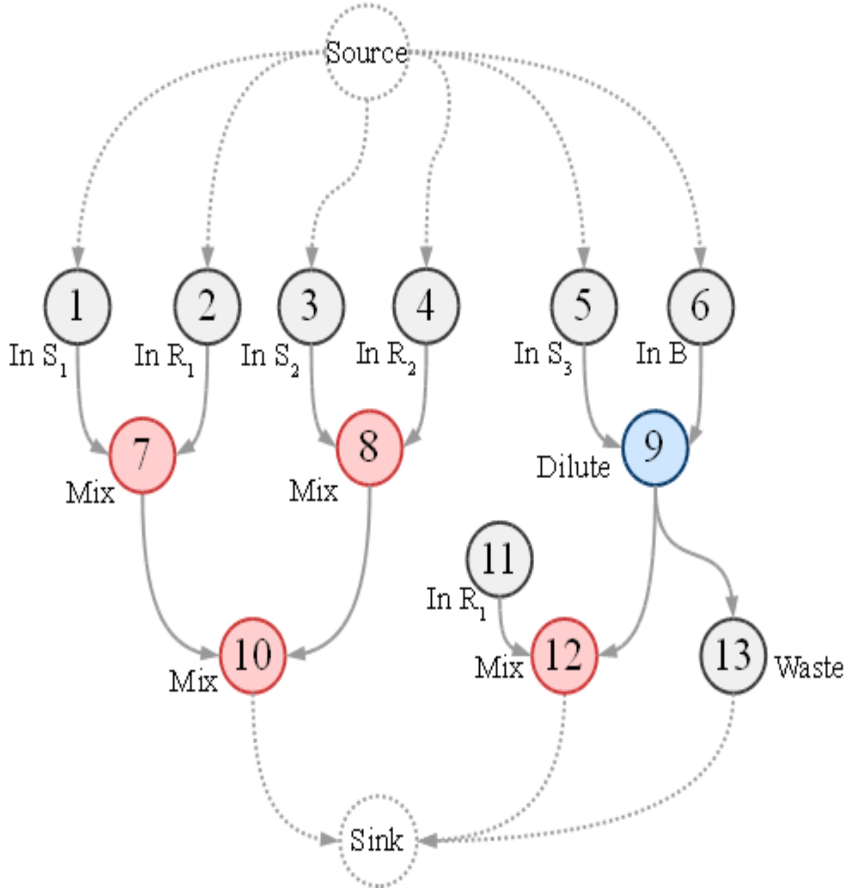
routing-based synthesis



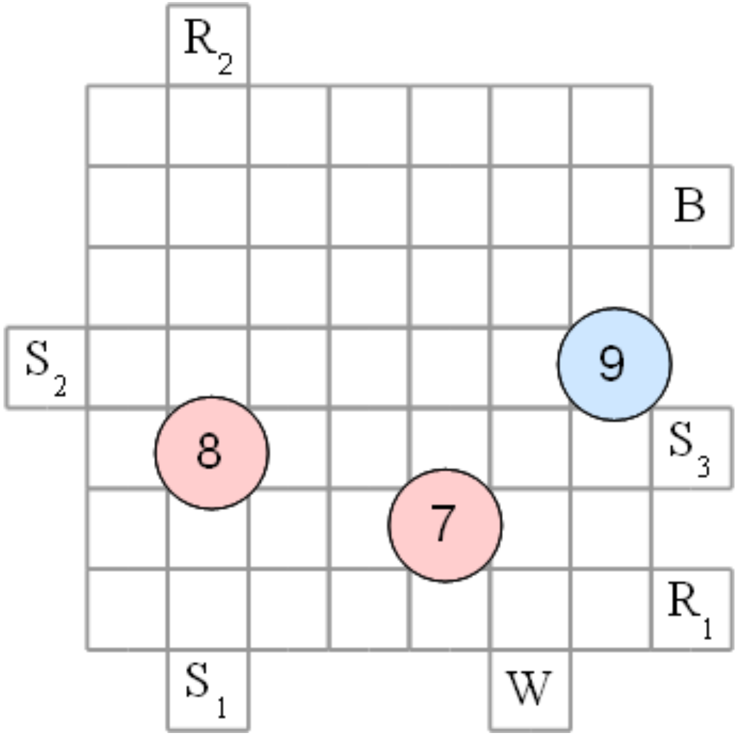


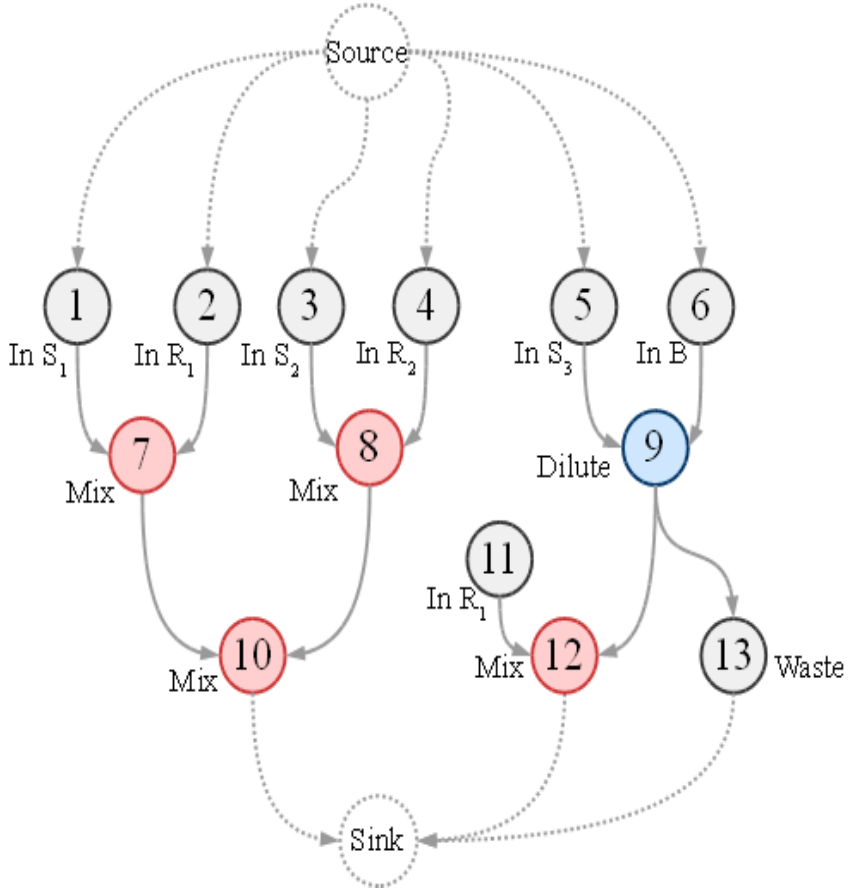
routing-based synthesis



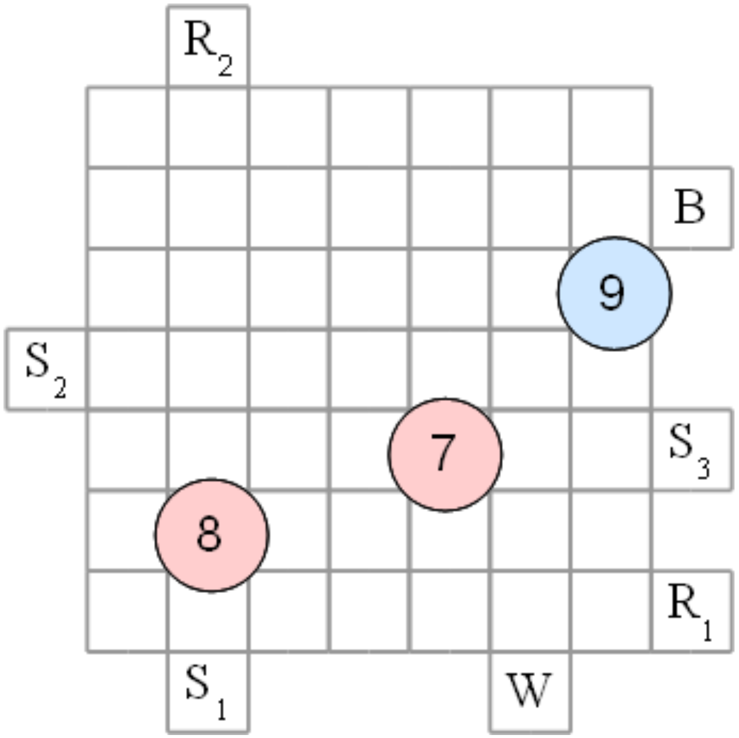


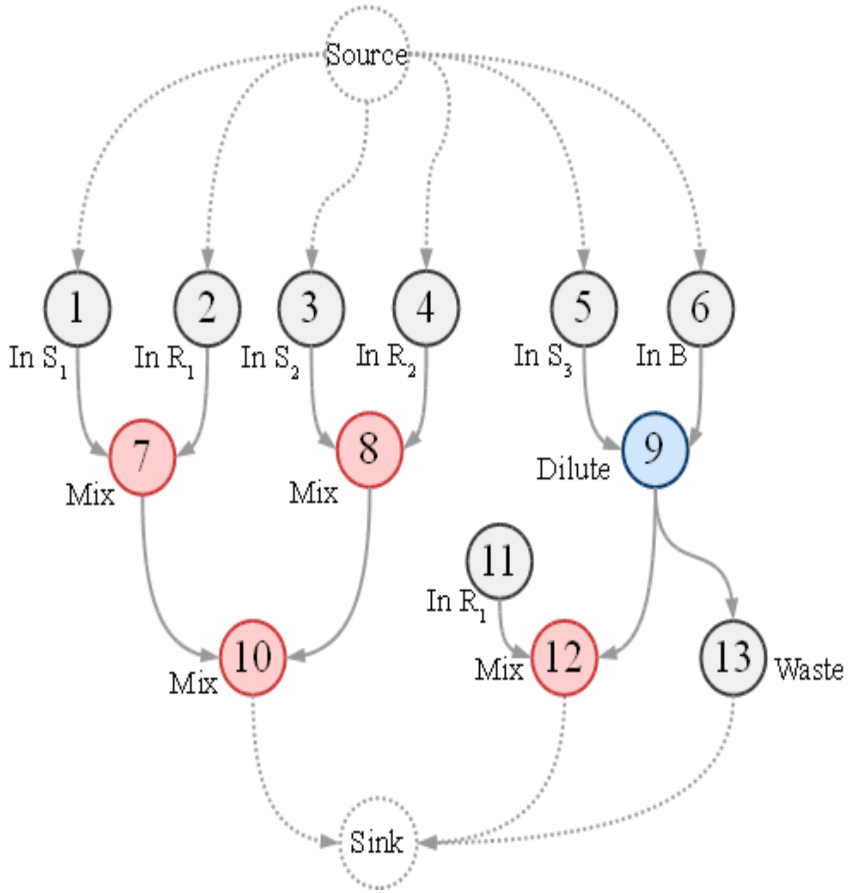
routing-based synthesis



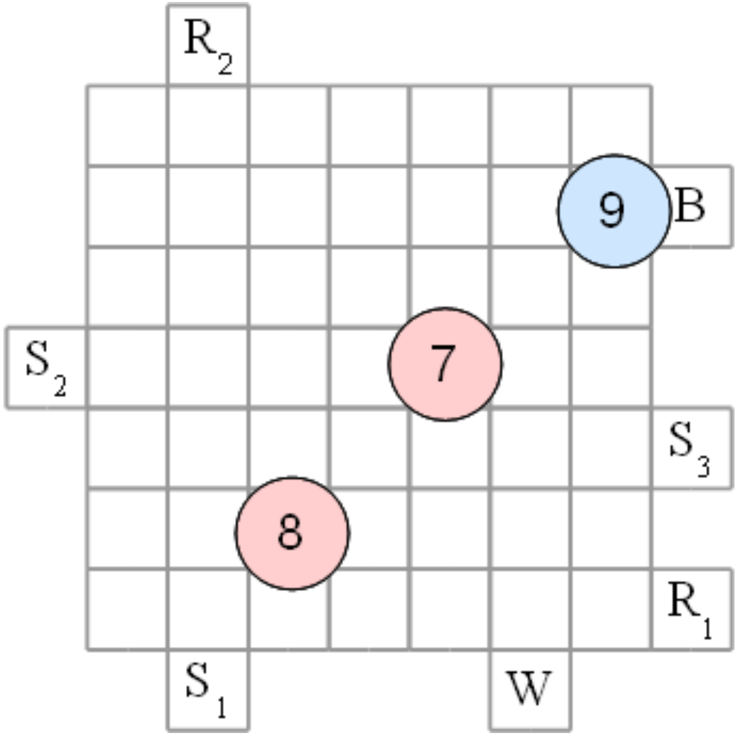


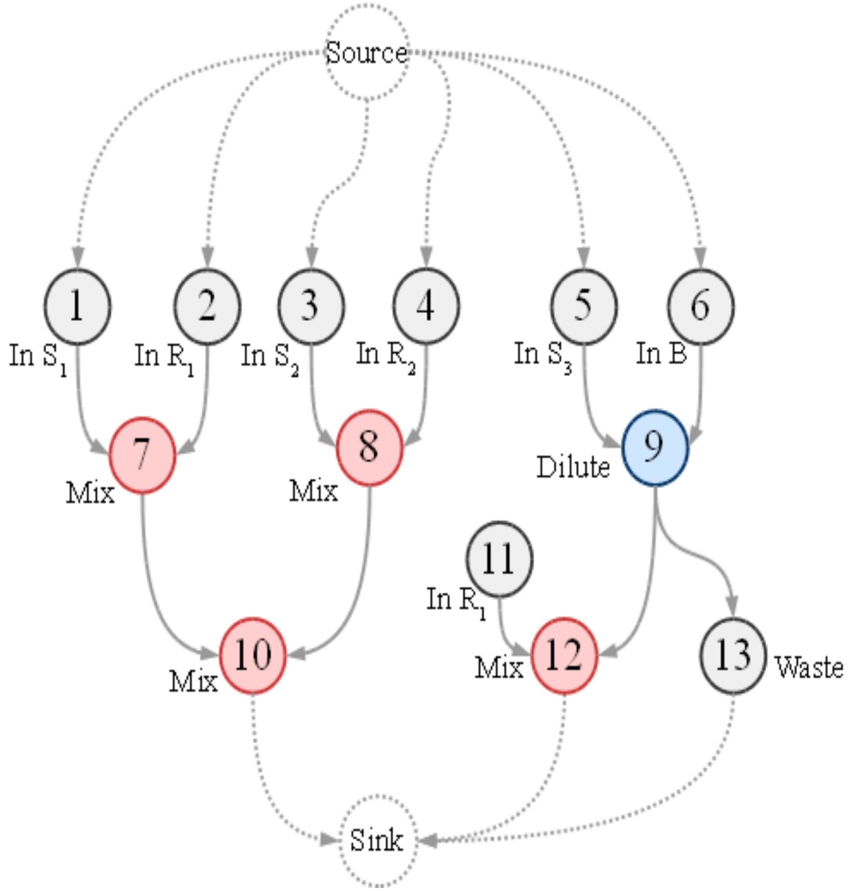
routing-based synthesis



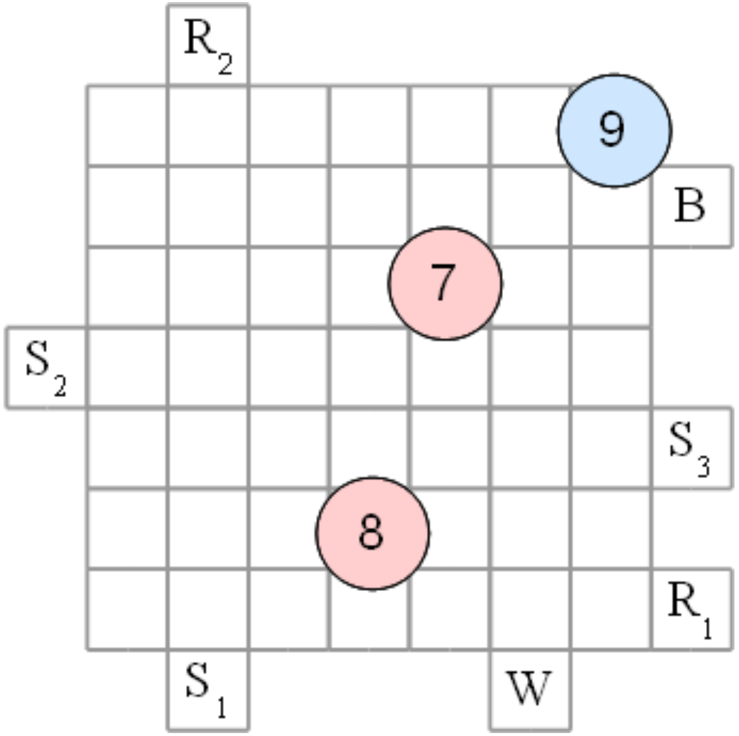


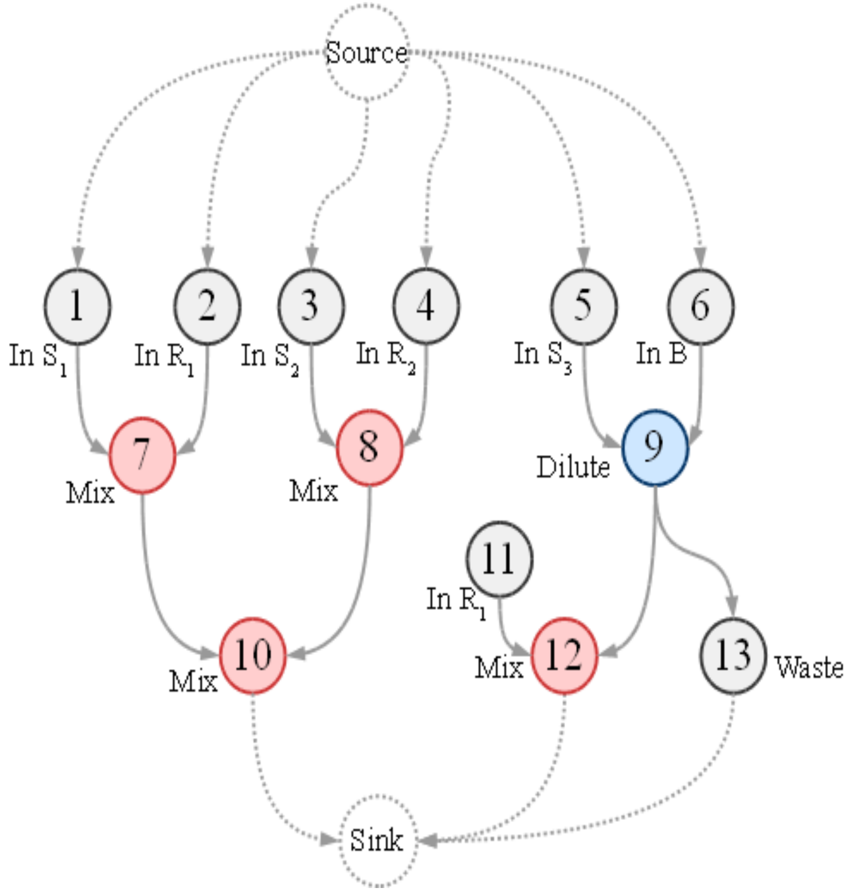
routing-based synthesis



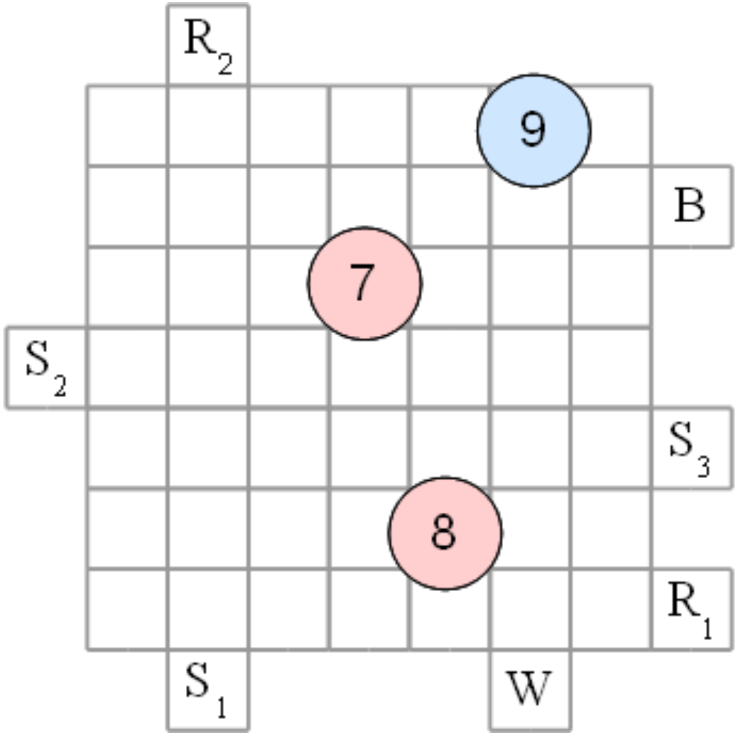


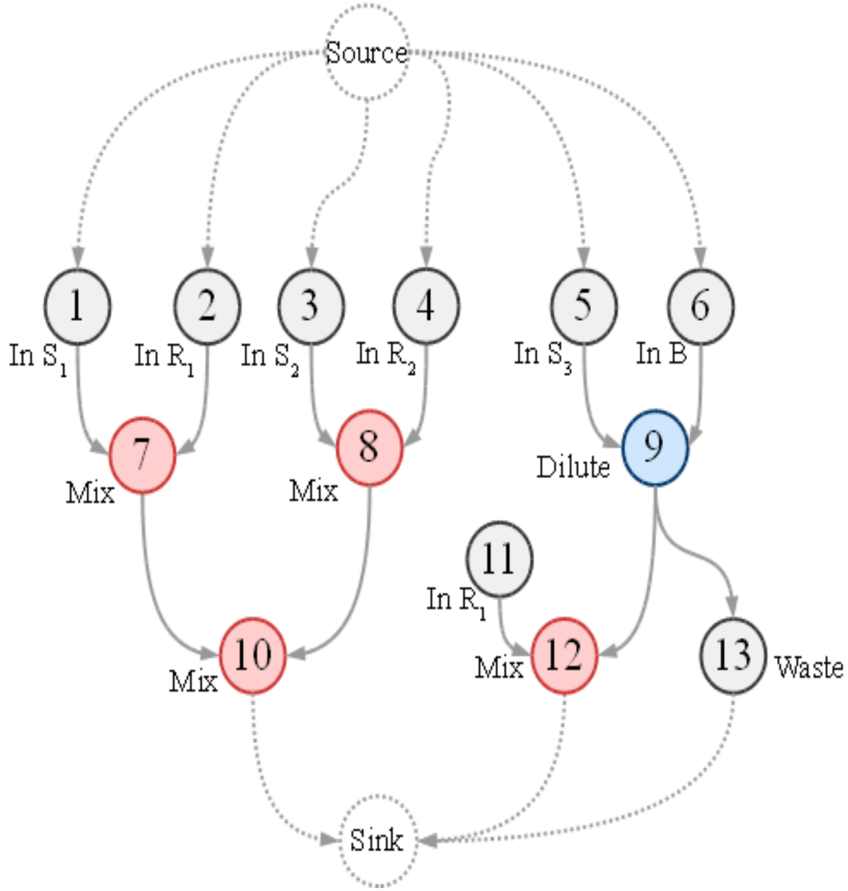
routing-based synthesis



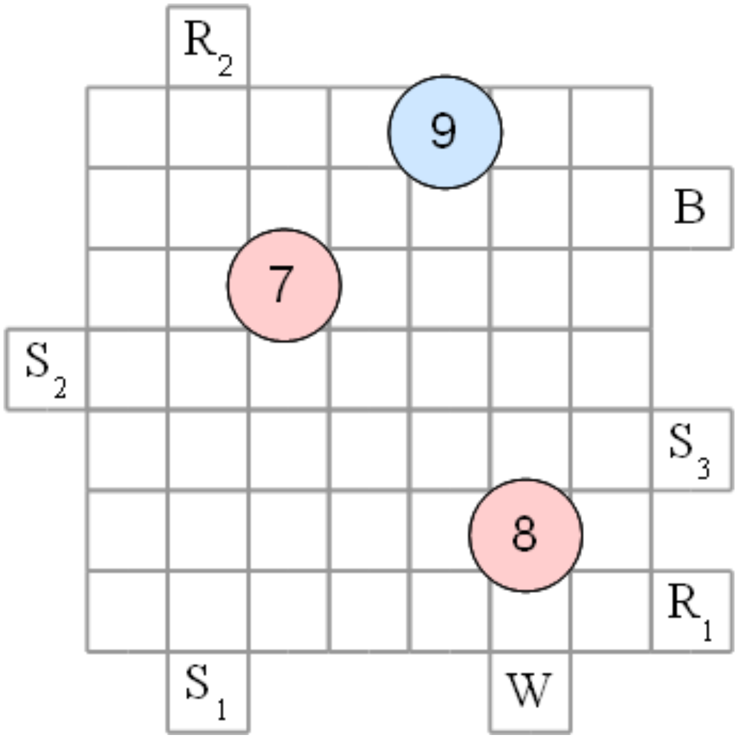


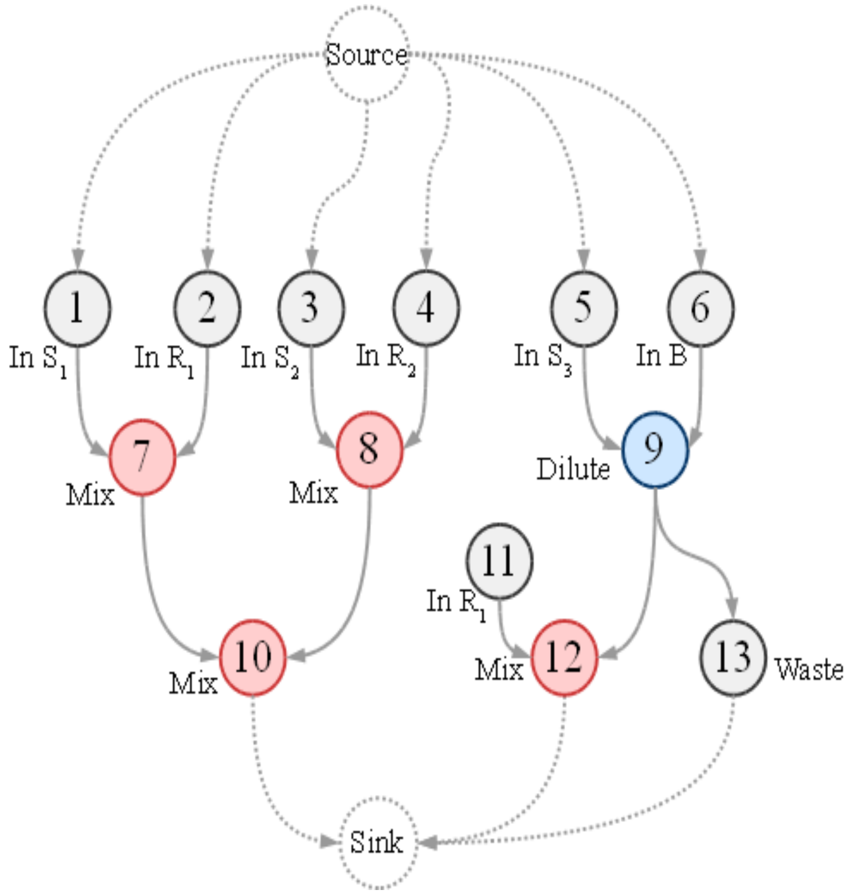
routing-based synthesis



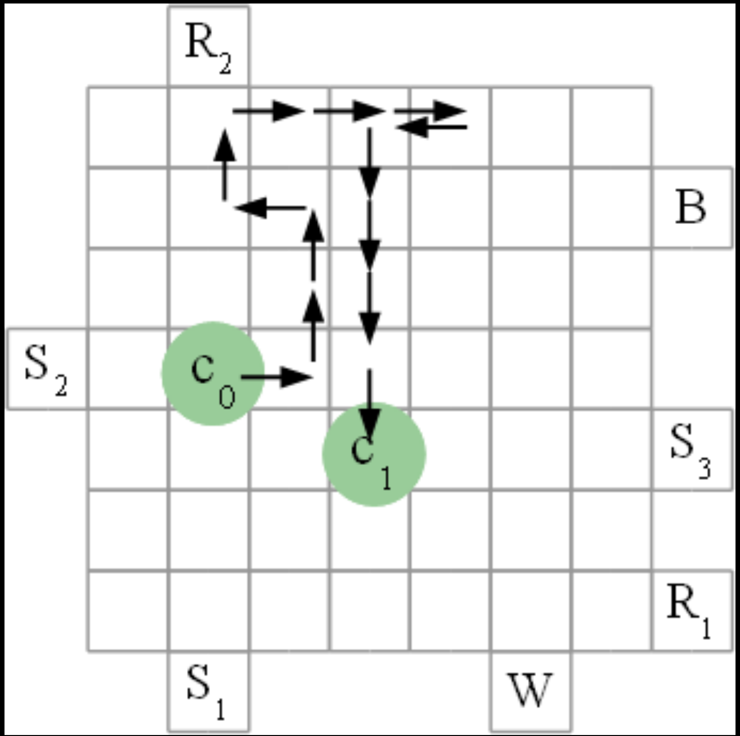


routing-based synthesis



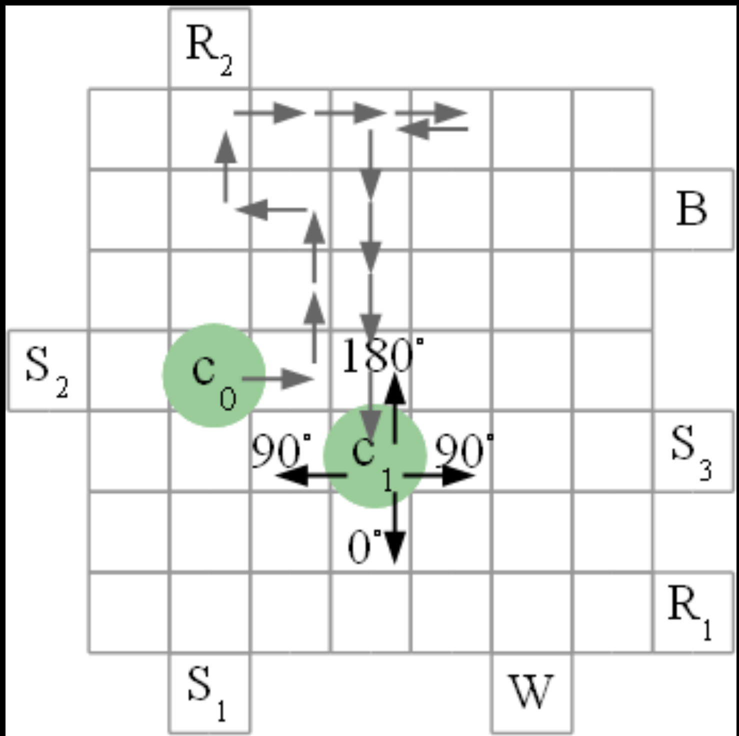


when will the operations complete?



- For module-based synthesis we know the completion time from the module library.
- But now there are no modules, the droplets can move anywhere.
  - How can we find out the operation completion times?

characterizing operations



- If the droplet does not move: very slow mixing by diffusion
- If the droplet moves, how long does it take to complete?
- Mixing percentages:

  p^0, p^{90}, p^{180} ?

characterizing operations

Operation	Area(cells)	Time(s)
Mix/Dlt	2x4	2.8
Mix/Dlt	1x4	4.6
Mix/Dlt	2x3	5.6
Mix/Dlt	2x2	9.96

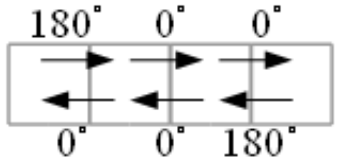
- We know how long an operation takes on modules
- Starting from this, can determine the percentages?

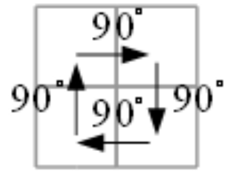
decomposing modules

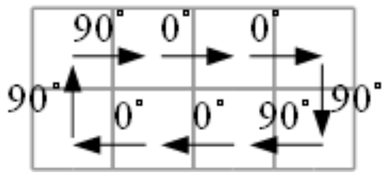
Operation	Area(cells)	Time(s)
Mix/Dlt	2x4	2.8
Mix/Dlt	1x4	4.6
Mix/Dlt	2x3	5.6
Mix/Dlt	2x2	9.96

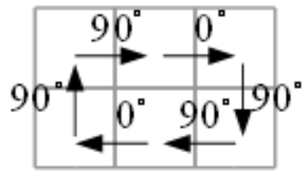
Safe, conservative estimates

p^{90} = 0.1%, p^{180} = -0.5%,
p^{0} = 0.29% and 0.58%



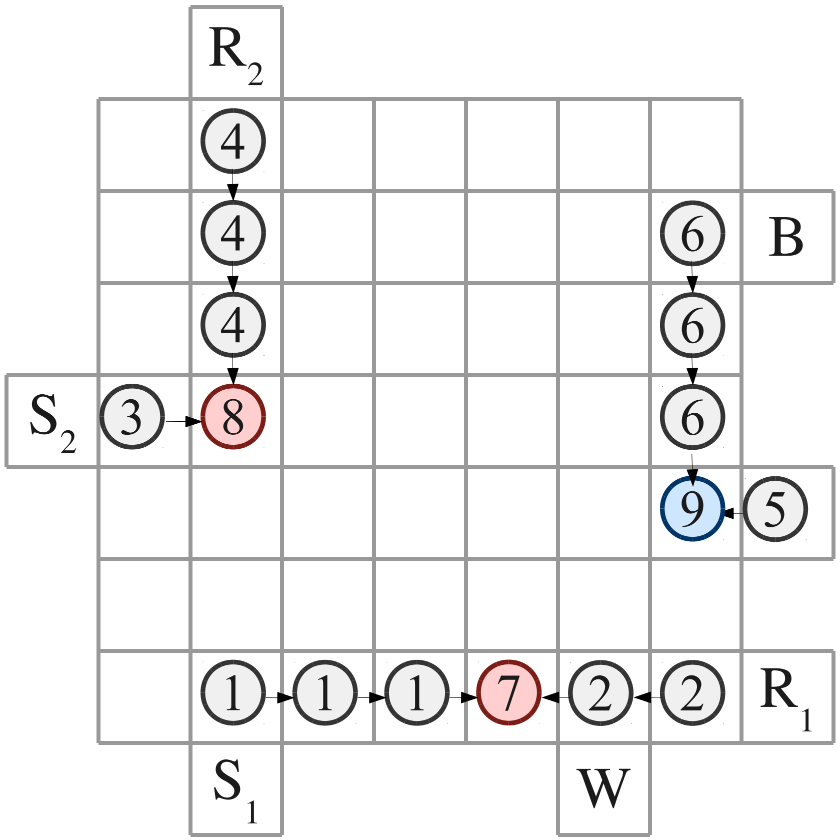


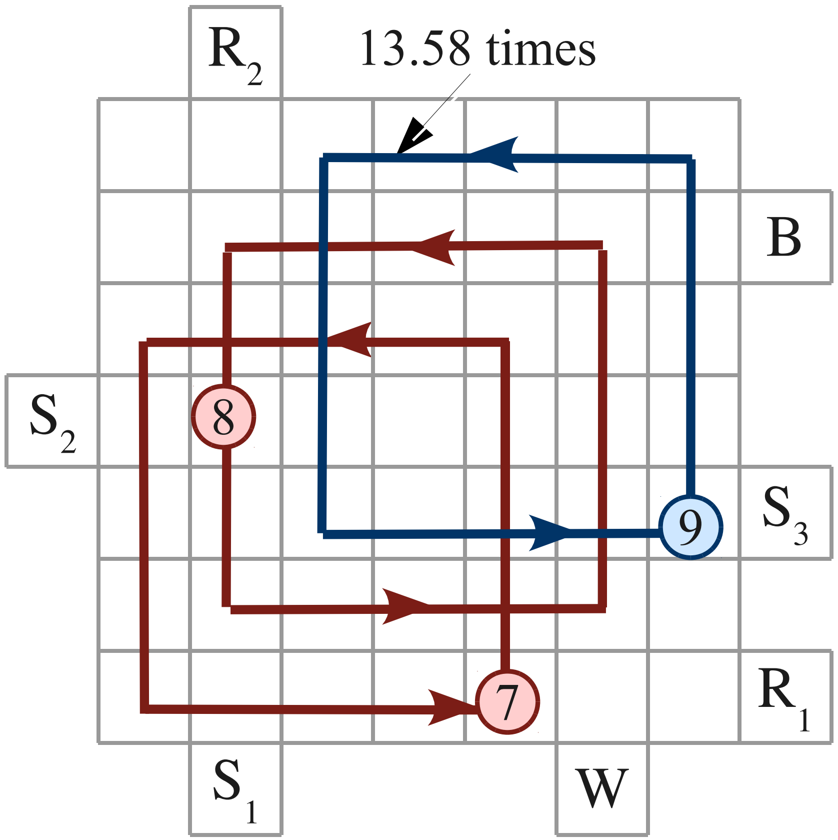




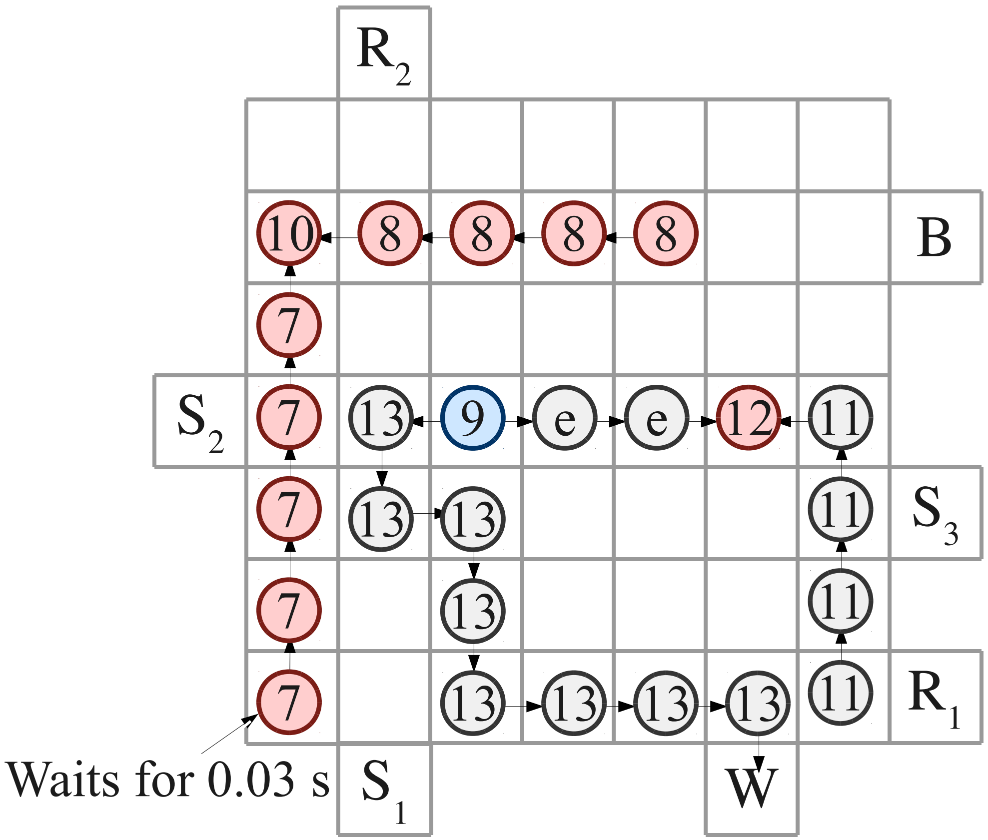
Moving a droplet one cell takes 0.01 s.

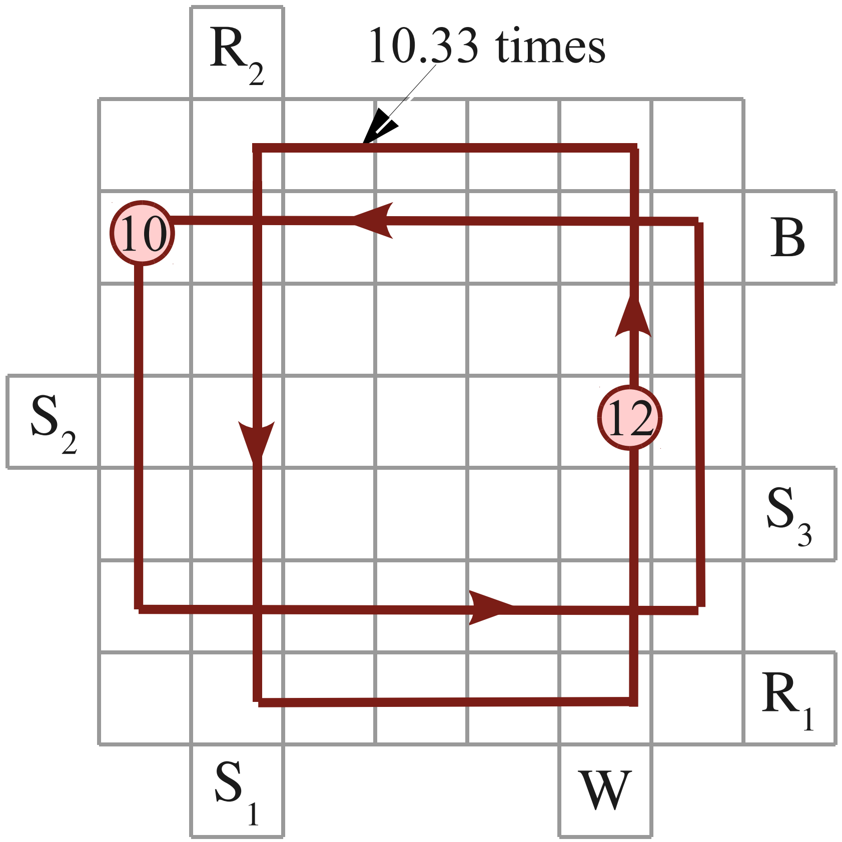
routing-based synthesis





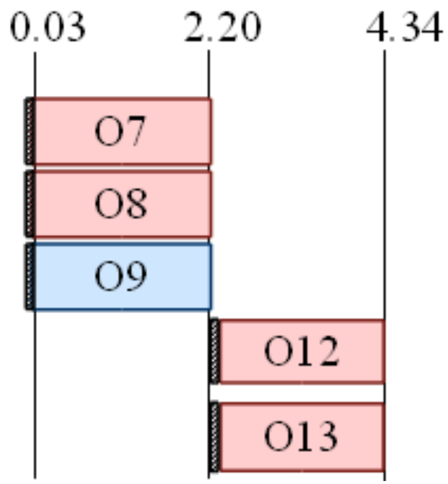
routing-based synthesis



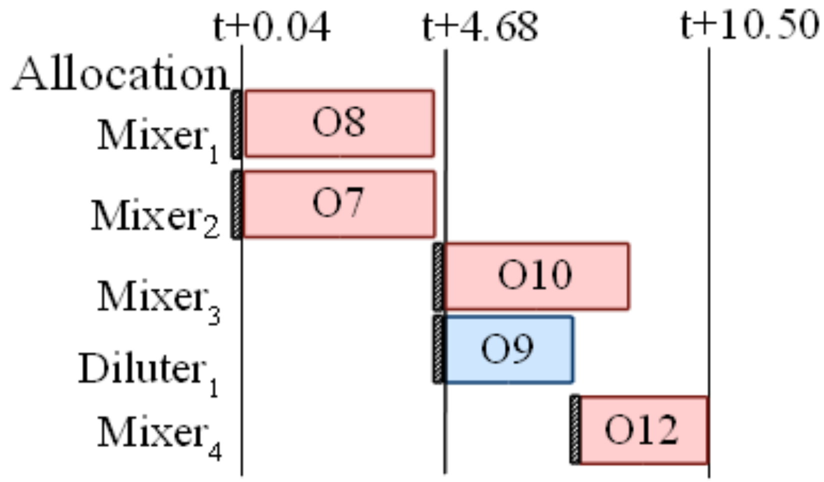


routing- vs. module-based

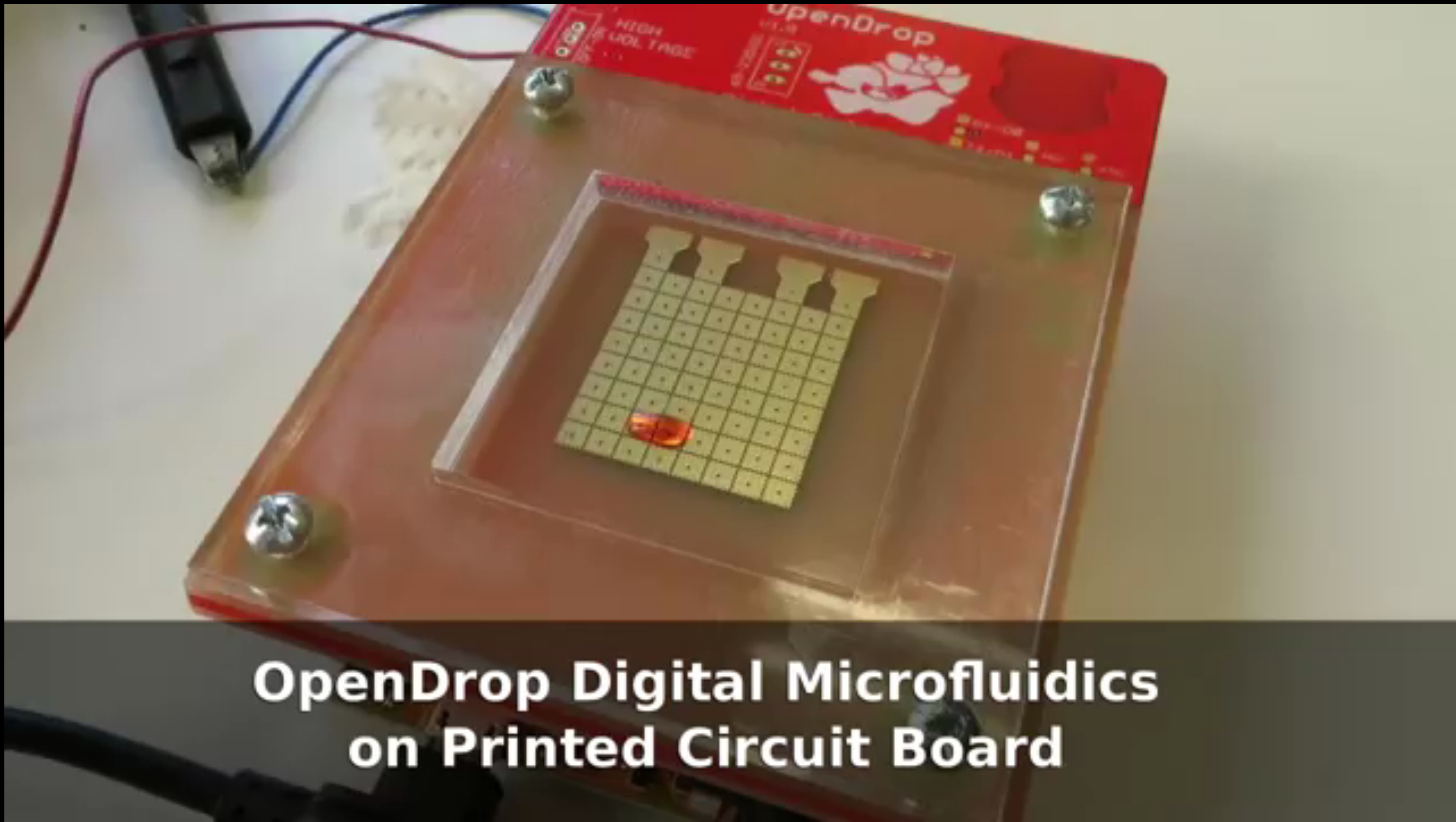
Routing-Based Synthesis



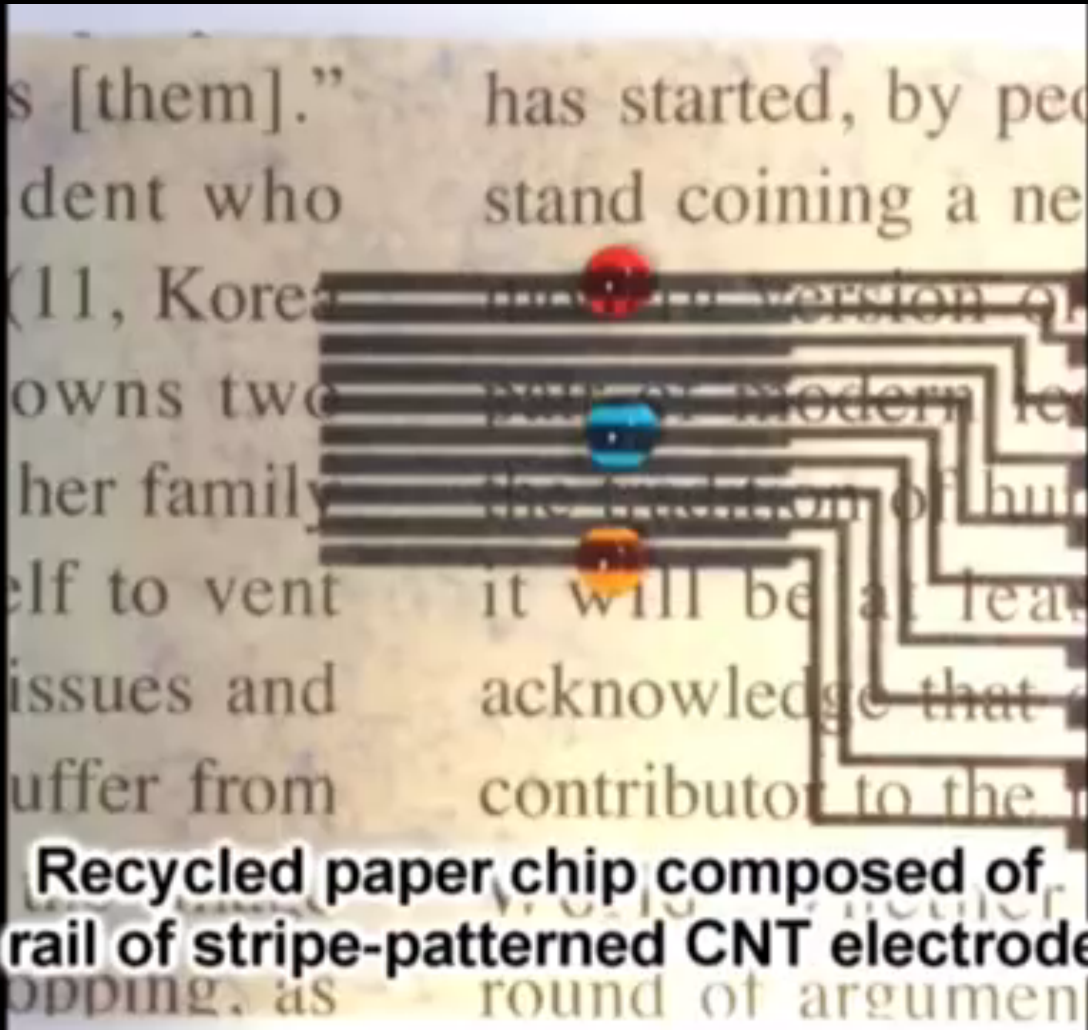
Module-Based Synthesis



OpenDrop


OpenDrop
HIGH VOLTAGE
OpenDrop Digital Microfluidics
on Printed Circuit Board

digital microfluidics on paper!



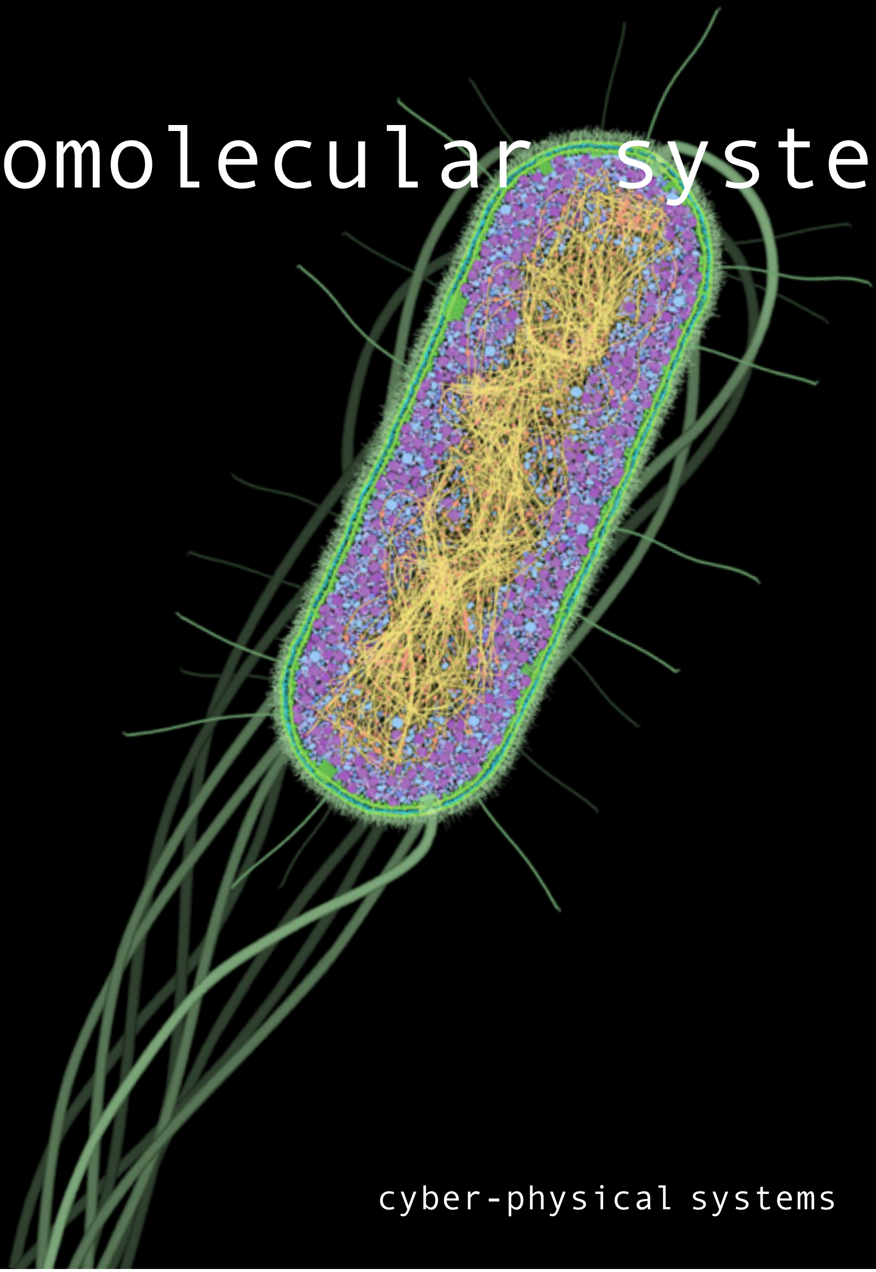
summary part 1

- microelectronic

- microfluidic
  - continous flow microfluidics biochips
  - on-chip control
  - digital microfluidics biochips

part 2

- micromolecular systems



biochip books

- fault-tolerant digital microfluidic biochips
  - Paul Pop, Mirela Alistart, Elena Stuart, Jan Madsen
  - Springer 2015

- Microfluidic very large scale integration (VLSI): modeling, simulation, testing, compilation and physical synthesis
  - Paul Pop,Wajid Hassan Minhass, Jan Madsen, Seetal Potluri
  - Springer 2016

thank you for your attention!

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