NR-Router: Non-Regular Electrode Routing with Optimal Pin Selection for Electrowetting-on-Dielectric Chips

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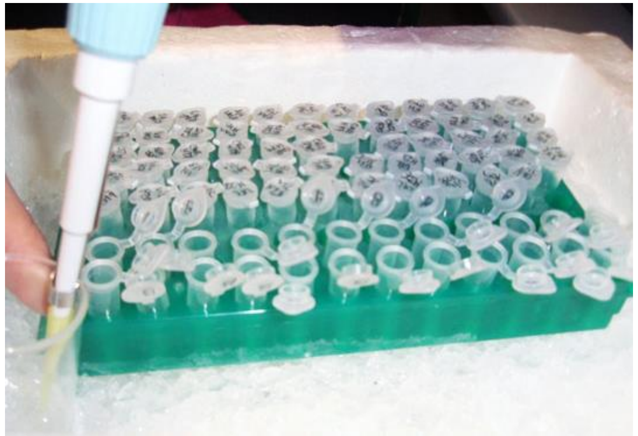
OUTLINE

INTRODUCTION

Paradigm shift in biochemistry



Complex Operations

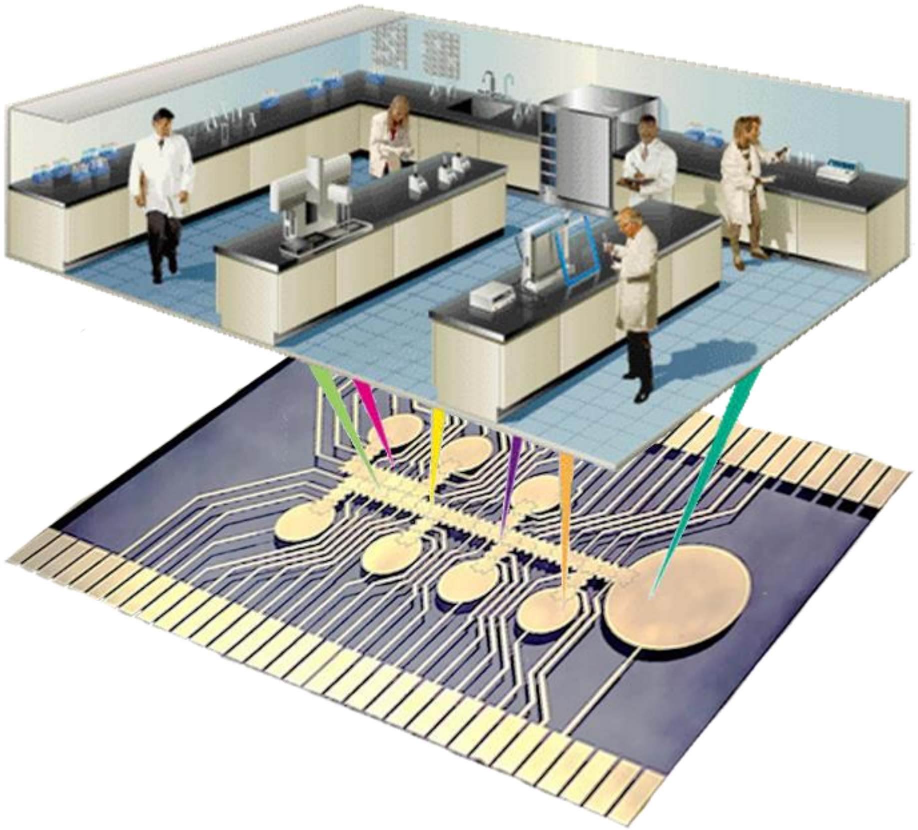
Skilled Technicians

Bulky Equipment

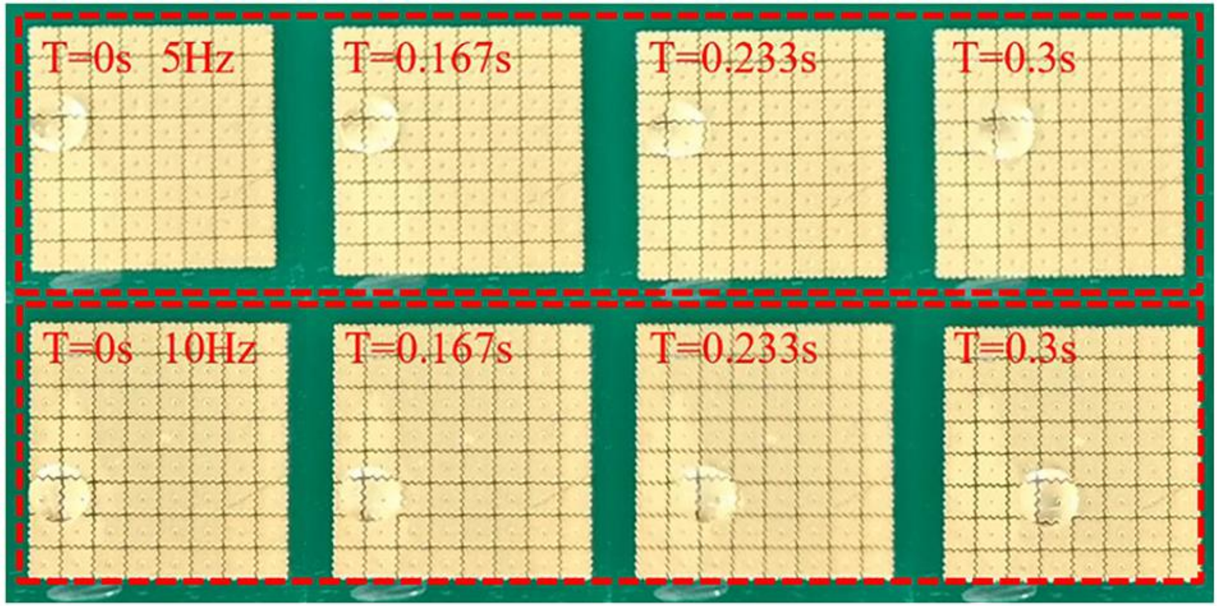
Electrowetting-on-Dielectric (EWOD) (1/2)

- The EWOD can control automatic biochemical experiments through a chip, allowing the low error and reproducibility, avoiding errors caused by humans.

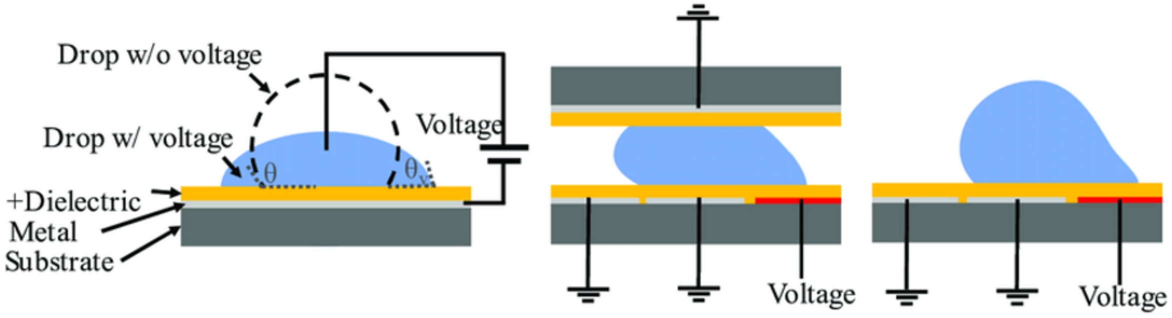
One chip is a laboratory
Low cost
Low error
Fast



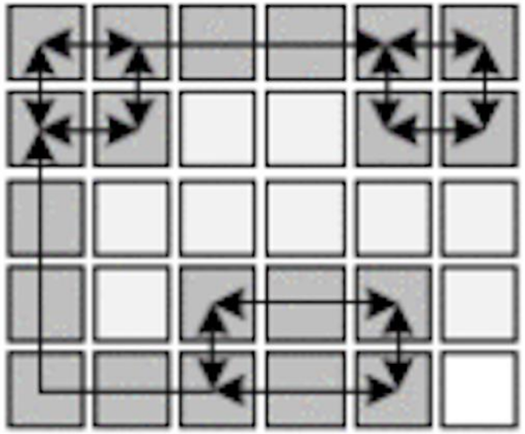
Electrowetting-on-Dielectric (EWOD) (2/2)



(a)



(b)



(c)

The droplet moving path

[1] H.-H. Shen, S.-K. Fan, C.-J. Kim, and D.-J. Yao, "EWOD microfluidic systems for biomedical applications," *Microfluidics and Nanofluidics*, vol. 16, pp. 965-987 (2014).

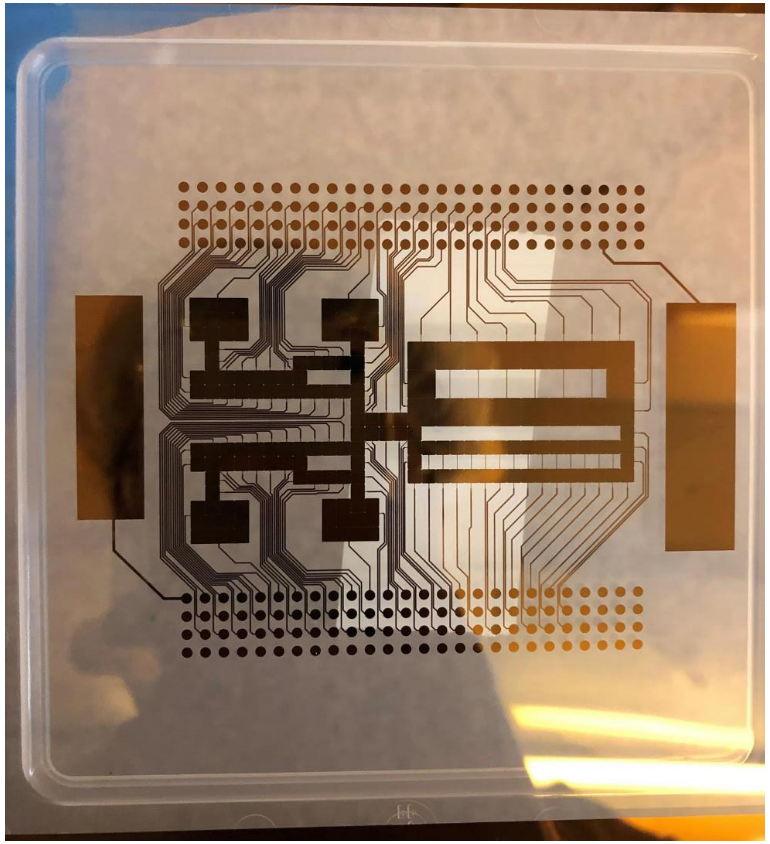
Glass-based EWOD chips with non-regular electrodes (1/3)

- Glass-based EWOD chips allow more reliable droplet operations and facilitating integration of optical sensors for many biochemical applications.

Smooth surface topography

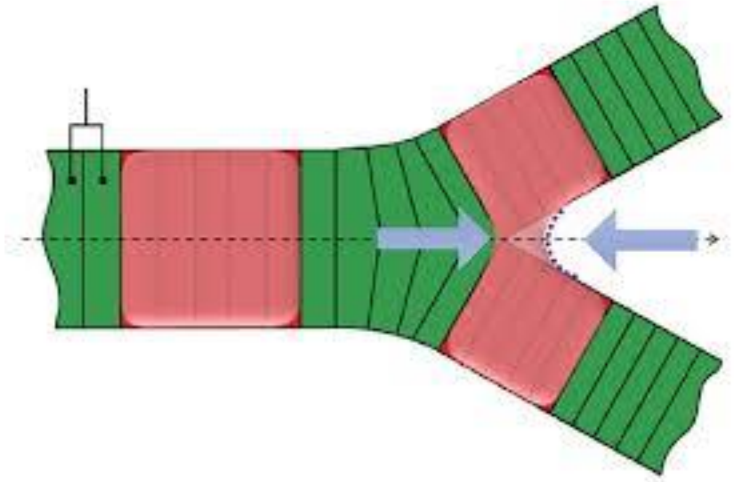
High-resolution electrode

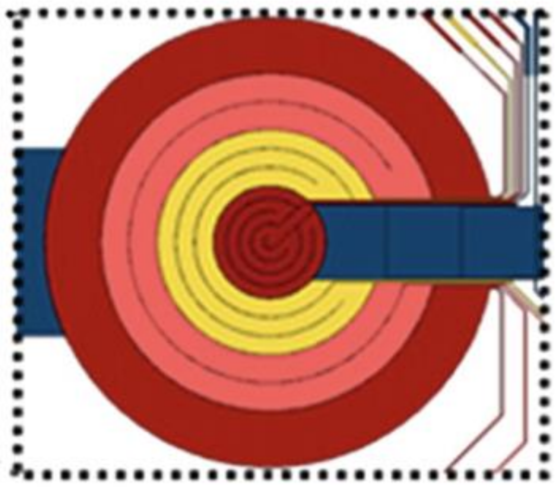
Transparent substrate

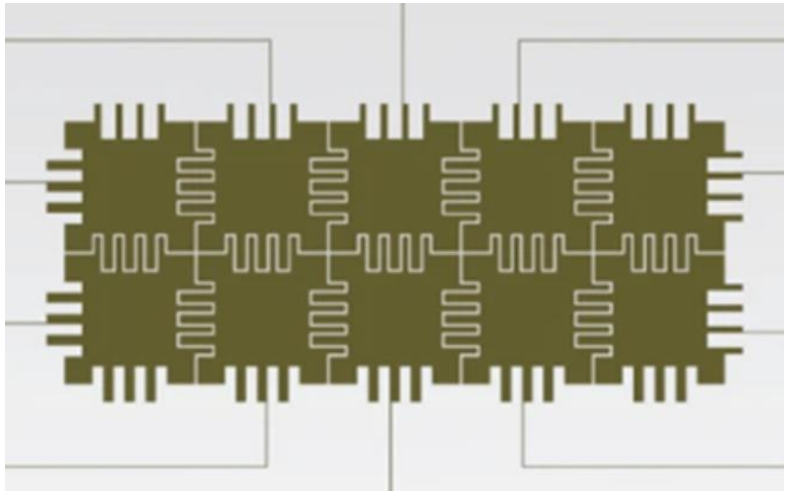


Glass-based EWOD chips with non-regular electrodes (2/3)

- Non-regular electrode designs are utilized in EWOD chips to precisely control droplet volume, and electrodes with a specific shape become necessary for certain applications.



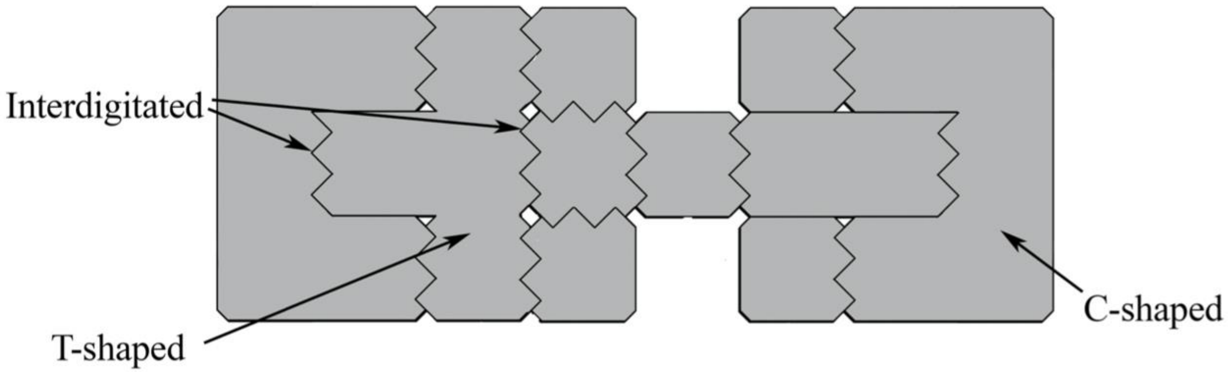




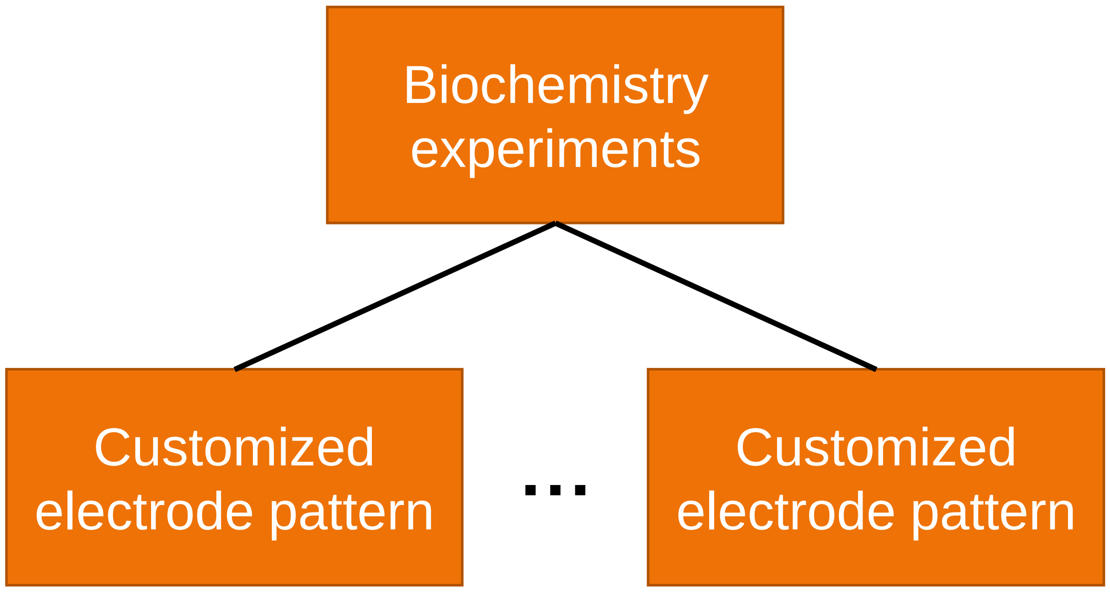
[2] N.-Y.-J.-B. Nikapitiya, M.-M. Nahar, and H. Moon, "Accurate, consistent, and fast droplet splitting and dispensing in electrowetting on dielectric digital microfluidics," *Micro and Nano Systems Letters*, vol. 5, p. 24 (2017).

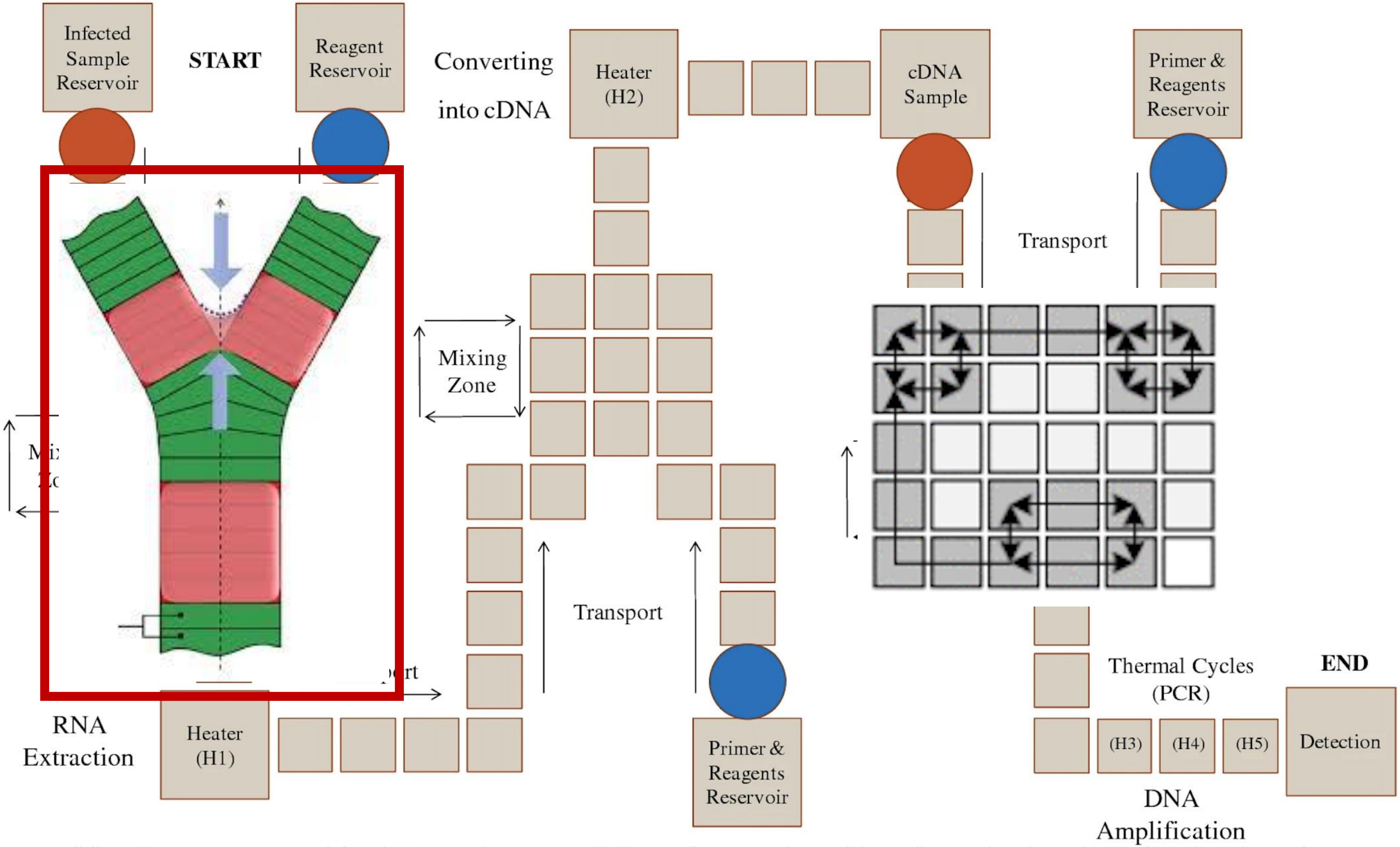
Glass-based EWOD chips with non-regular electrodes (3/3)

- The introduction of customized electrode pattern makes the biochemical experiment modular, which reduces the technical barrier and cost of the experimenters.
- OpenFluidics: Digital Microfluidics Ecosystem.



Customized electrode pattern for specific function

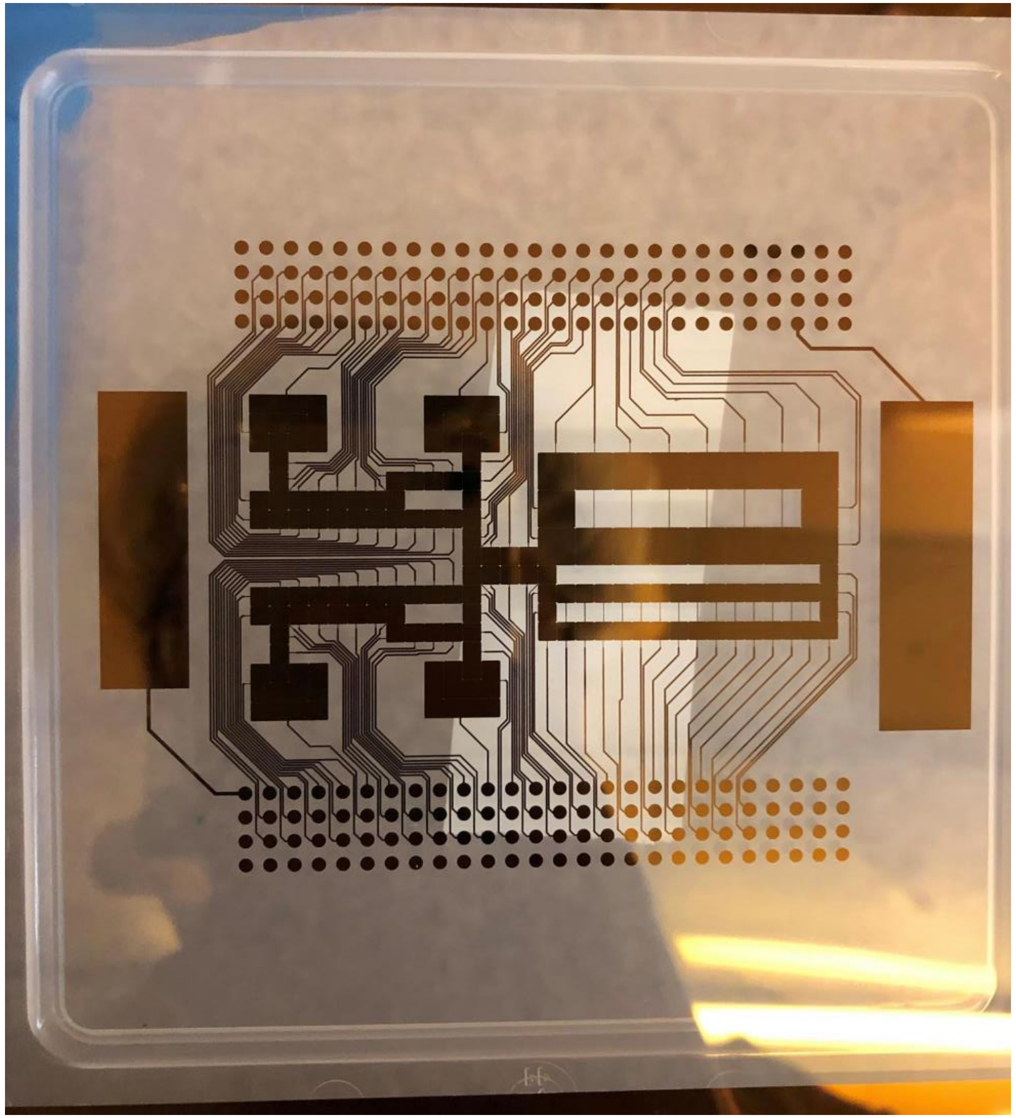




[3] V. Jain, K. Muralidhar,"Electrowetting-on-Dielectric System for COVID-19 Testing," *Transactions of the Indian National Academy of Engineering*, vol. 30, no. 5, pp. 251-254, (2020).

Automatic routing tools

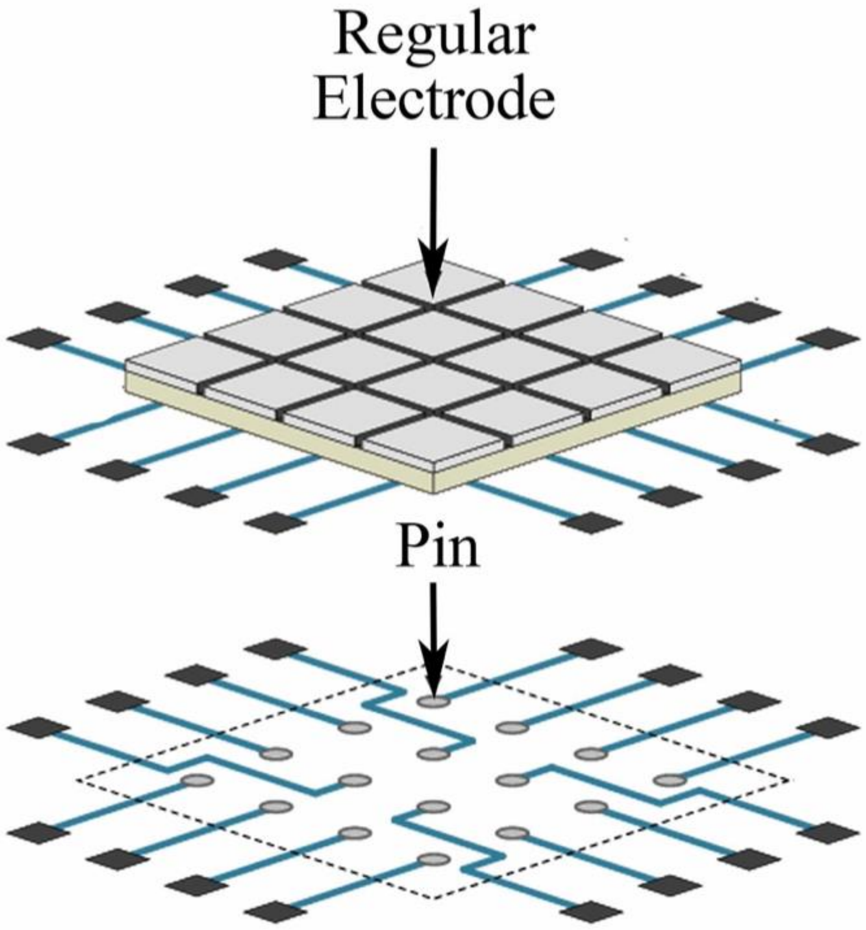
There is no tool to route these chips



RELATED WORK

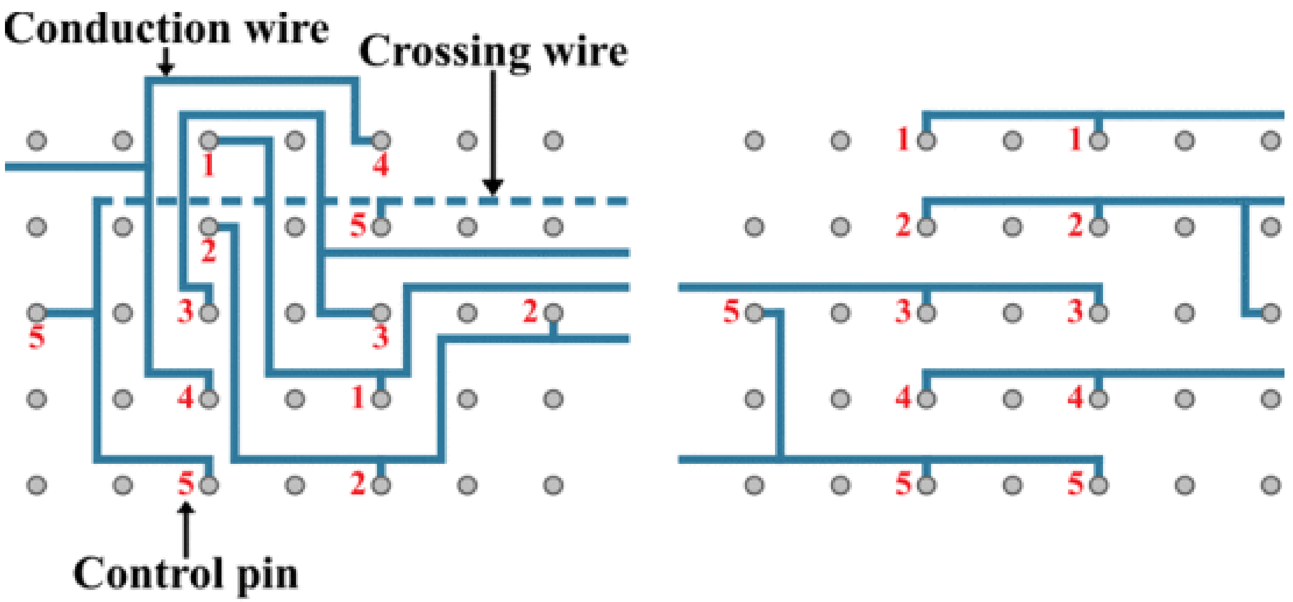
Existing approaches

- Most existing approaches focus on PCB-based EWOD chips with N*N regular electrode 2D-arrays.
- The regular design flow of EWOD chips consists of three major stages:
  I. Electrode addressing
     - Direct addressing
     - Broadcast addressing
  II. Routing
  III. Fabrication



Routing in PCB-based EWOD chips (1/2)

- [4] proposed routing algorithm for broadcast electrode-addressing to assign a single pin to multiple electrodes with the same signal through the network-flow, and successfully route it.

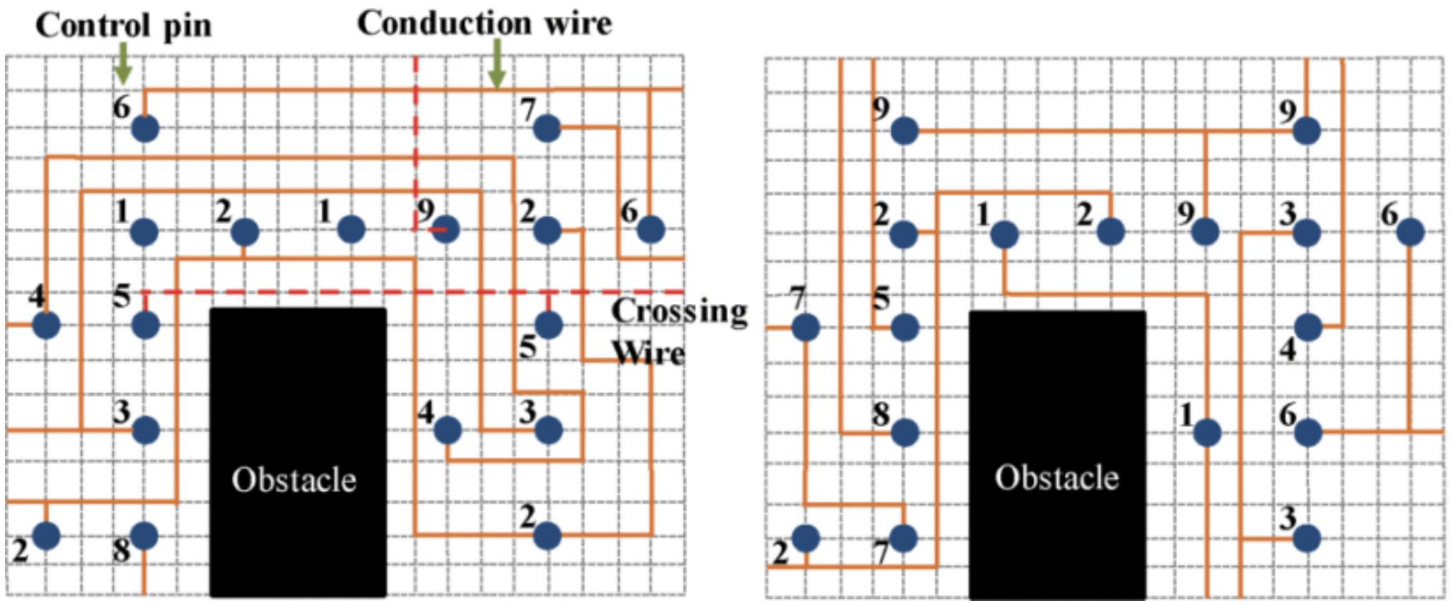


(a) Infeasible routig solution (b) Feasible routing solution

[4] T.-W. Huang, S.-Y. Yeh, and T.-Y.Ho,"A network-flow based pin-count aware routing algorithm for broadcast-addressing ewod chips," *IEEE Transactions on CAD*, vol. 30, no. 12, pp. 1786–1799, (2011).

Routing in PCB-based EWOD chips (2/2)

- [5] propose a novel ILP-based obstacle-avoiding routing algorithm for pin-constrained EWOD-chip designs.

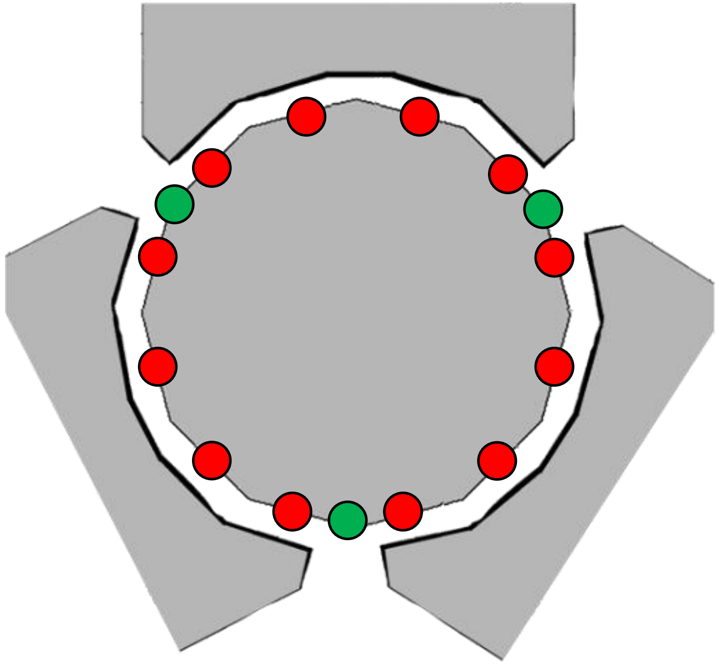


(a) (b)

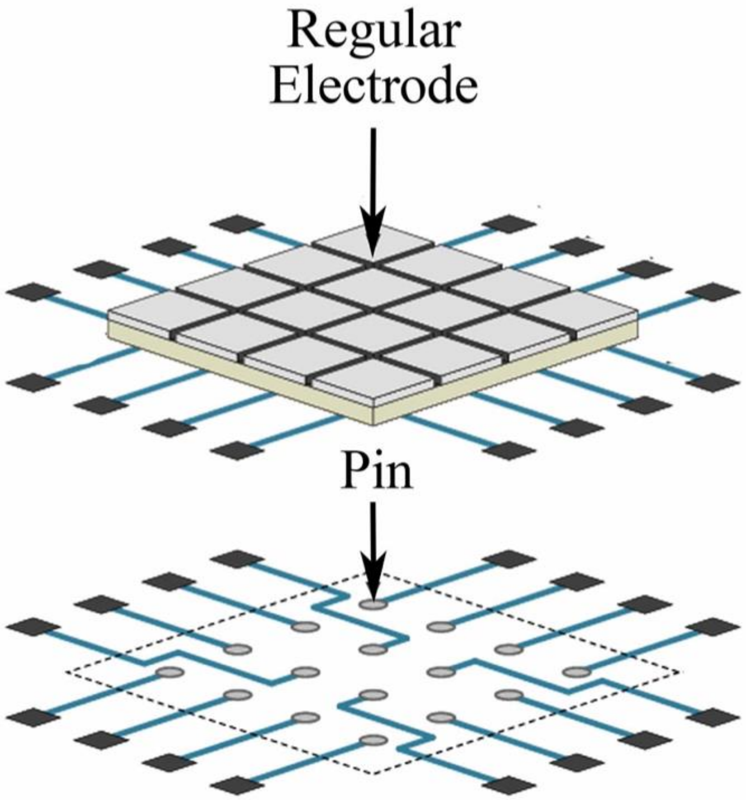
[5] J-W Chang, S-H Yeh, T-W Huang and T.-Y.Ho,"An ILP-Based Routing Algorithm for Pin-Constrained EWOD Chips With Obstacle Avoidance ," *IEEE Transactions on CAD*, vol. 32, no. 11, pp. 1655-1667, (2013).

Pin selection in non-regular electrodes (1/3)

- The number of pins of non-regular electrodes varies, which complexes the problem to select the candidate pins.

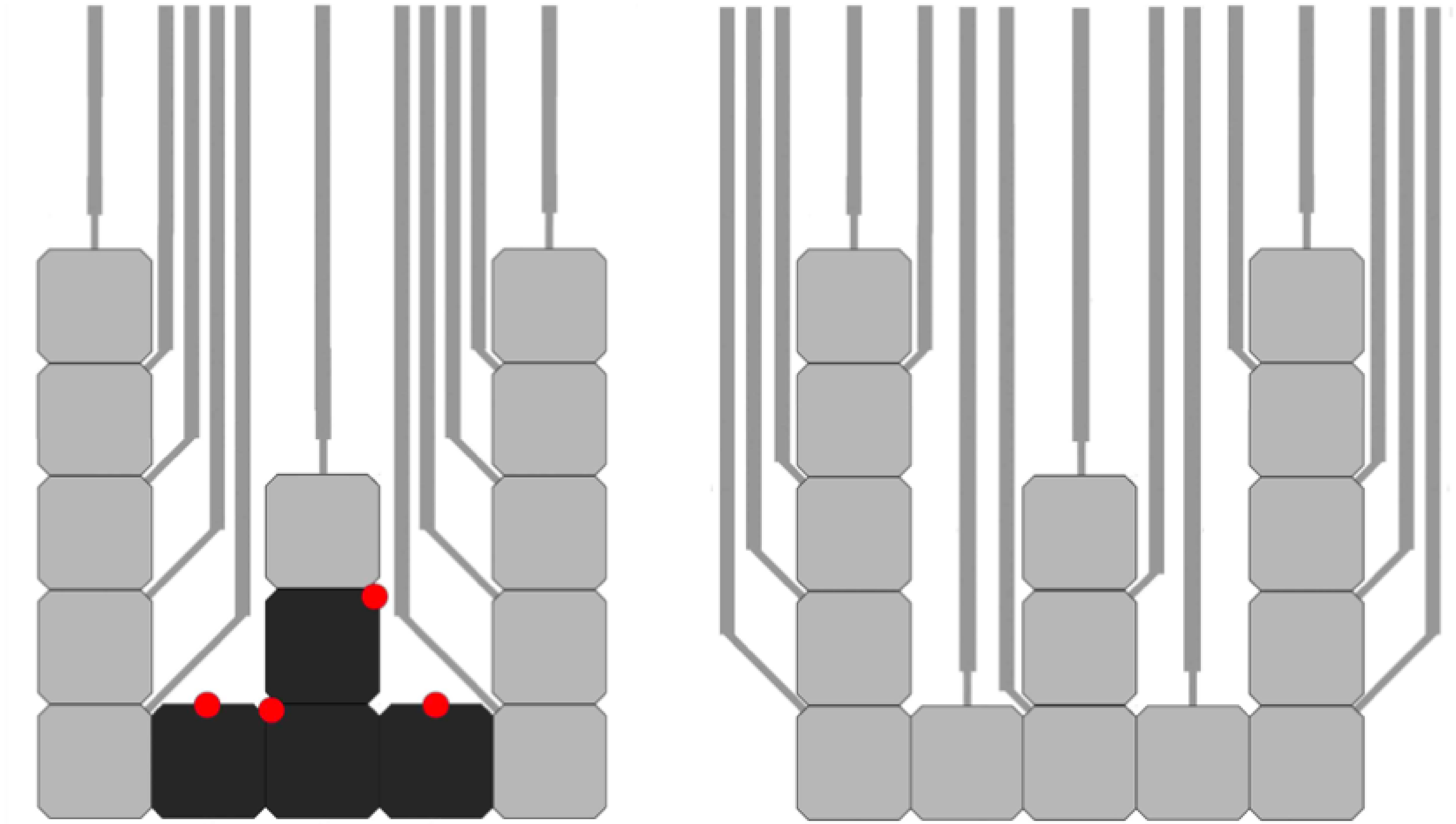


The pin may be anywhere on the boundary of the electrode



Pin selection in non-regular electrodes (2/3)

Failu

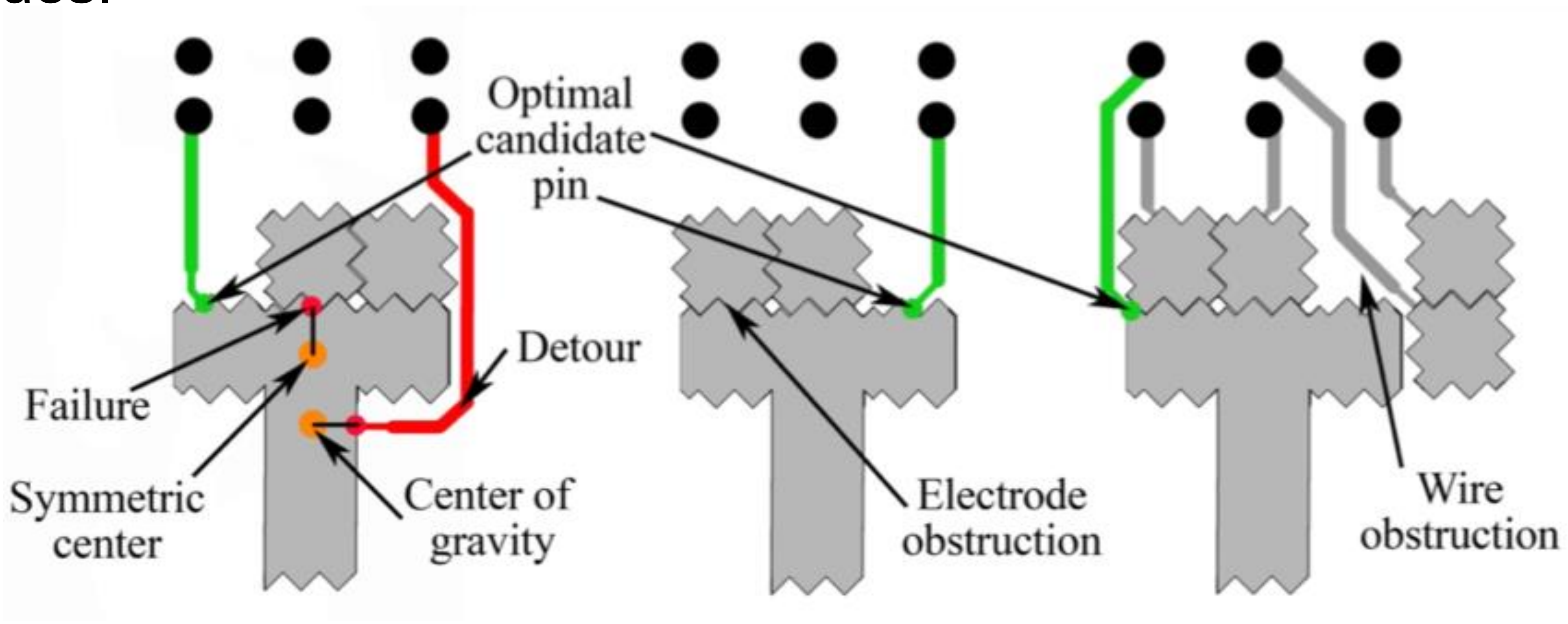


(b)

(c)

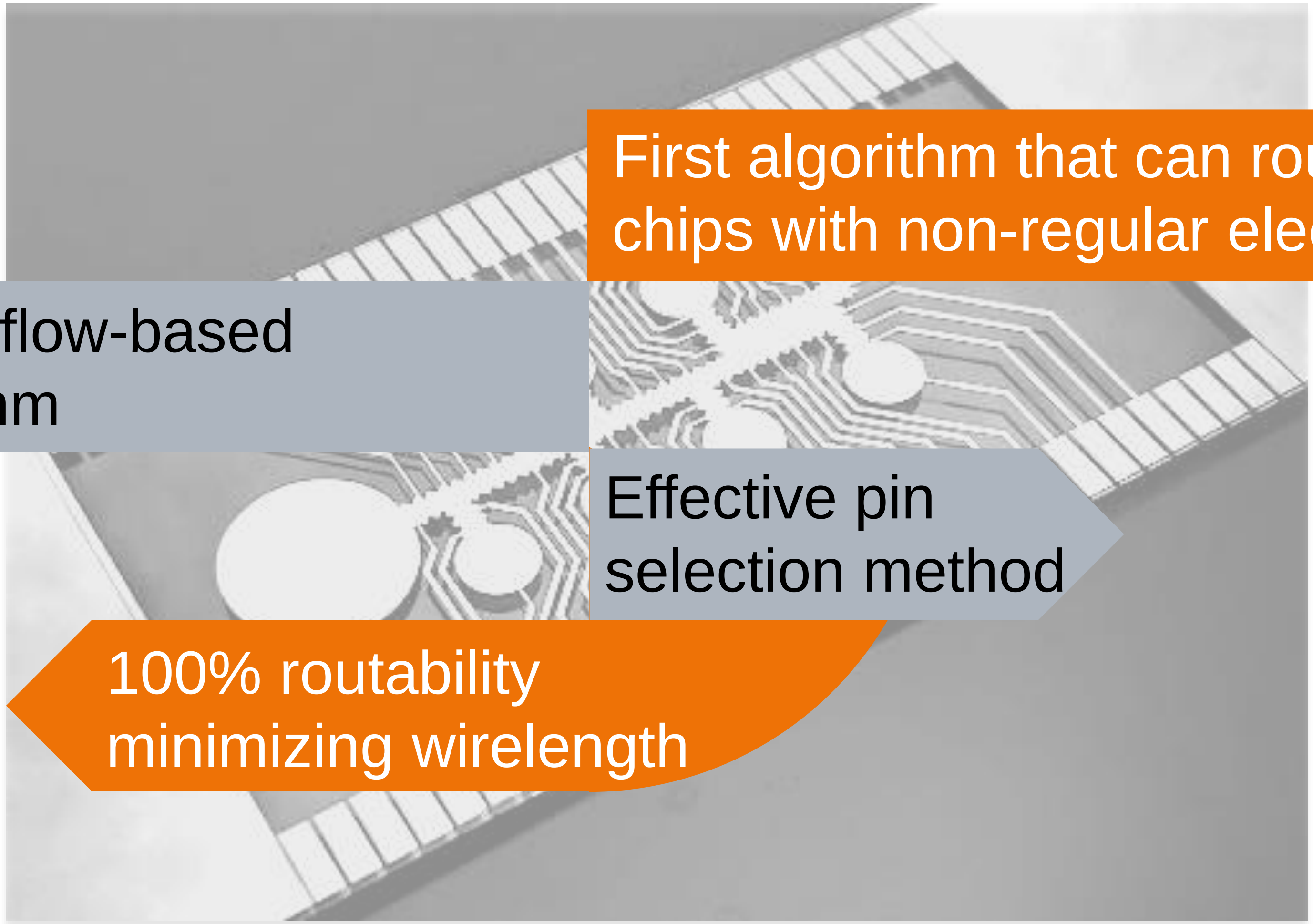
Pin selection in non-regular electrodes (3/3)

- In order to achieve 100% routability and ideal wirelength, all possible pins and routing wires must be considered simultaneously during candidate pin selection.
- The selection of candidate pins becomes much more difficult in non-regular electrodes.



(a) (b) (c)

NR-Router



First algorithm that can route in EWOD chips with non-regular electrodes

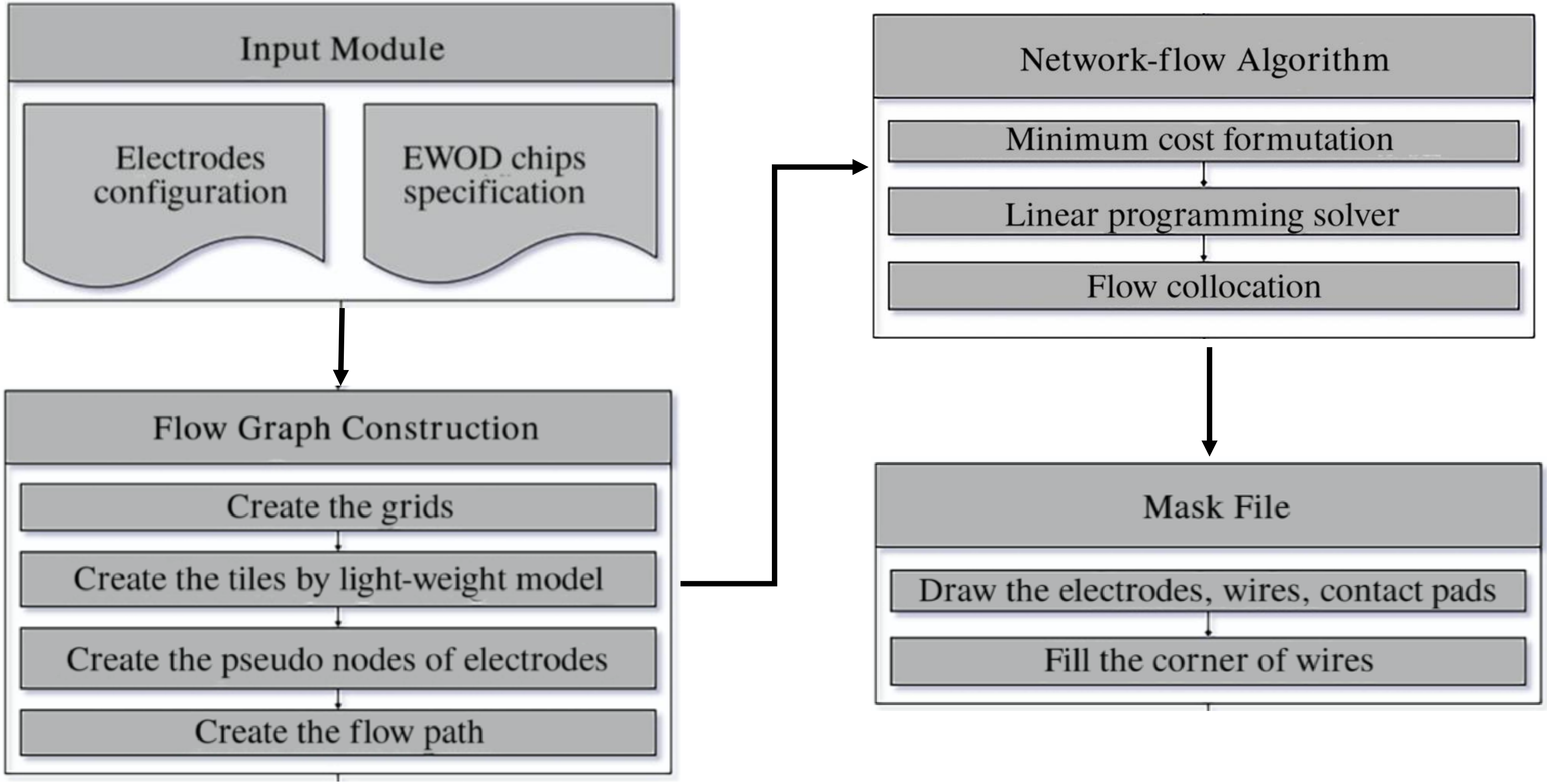
Minimum cost flow-based routing algorithm

Effective pin selection method

100% routability minimizing wirelength

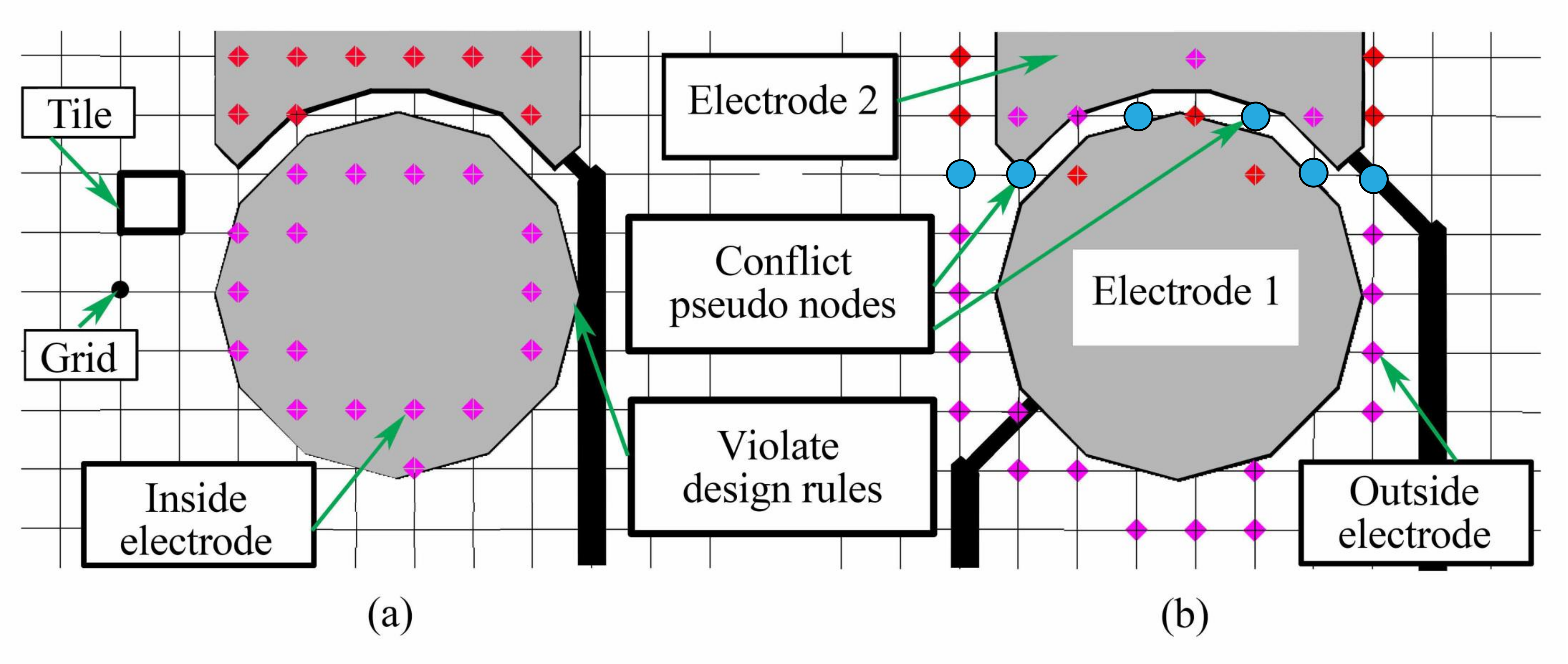
METHODS

Workflow


Input Module
Electrodes configuration
EWOD chips specification
Flow Graph Construction
Create the grids
Create the tiles by light-weight model
Create the pseudo nodes of electrodes
Create the flow path
Network-flow Algorithm
Minimum cost formutation
Linear programming solver
Flow collocation
Mask File
Draw the electrodes, wires, contact pads
Fill the corner of wires

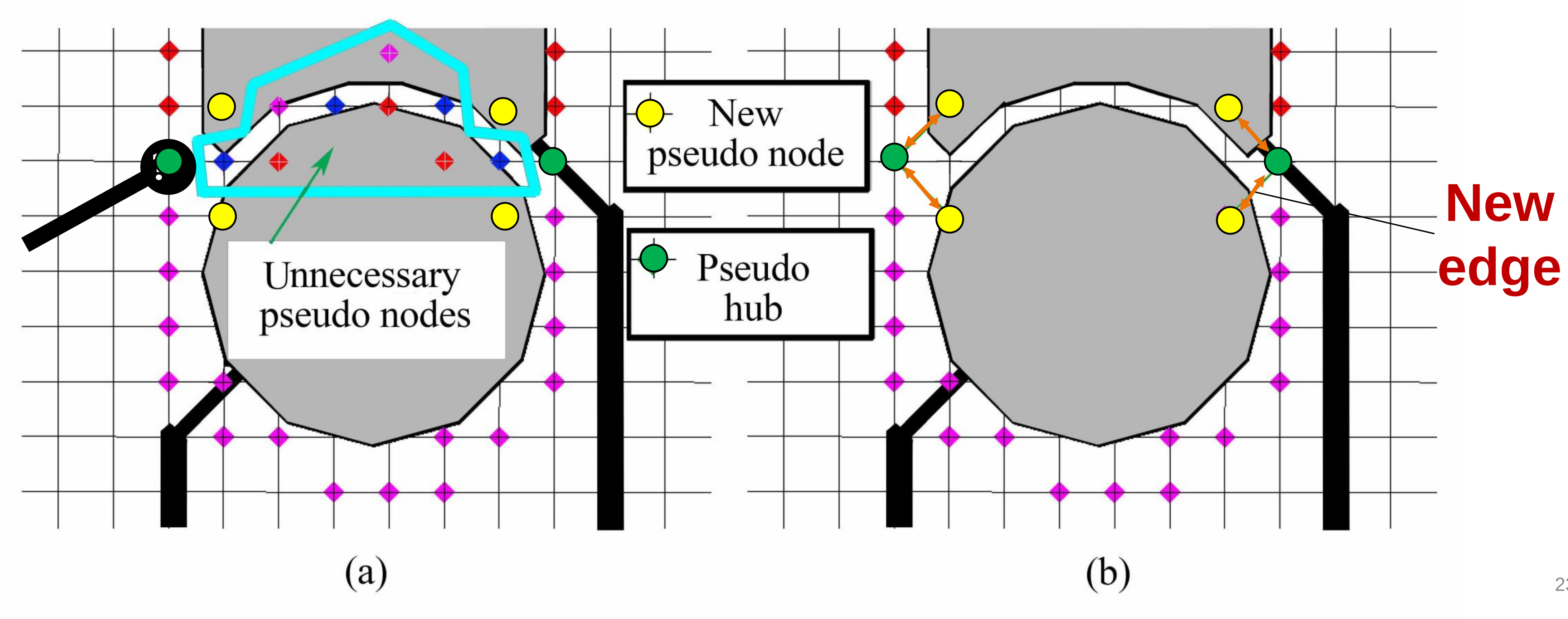
Pseudo node (1/2)

- We consider each electrode as a set composed of pseudo nodes.



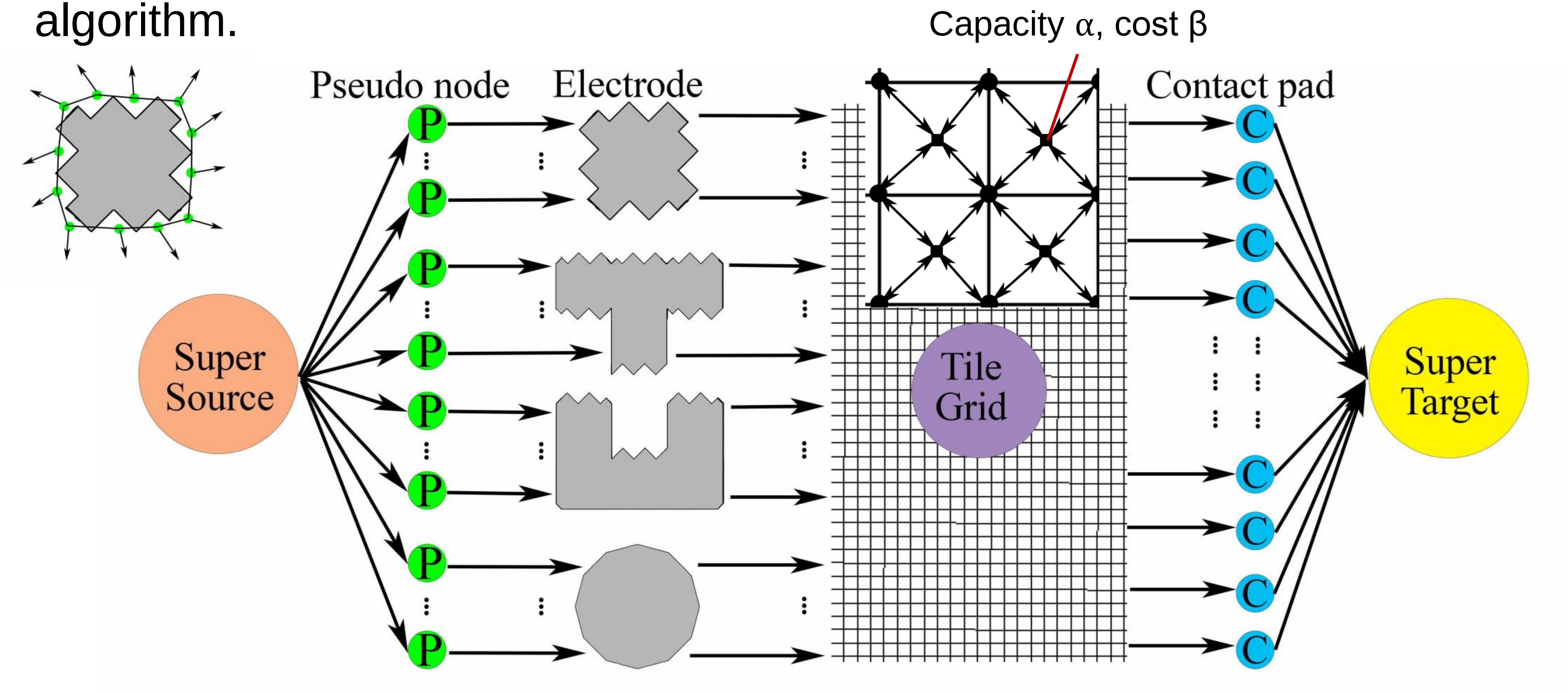
Pseudo node (2/2)

- If any conflict pseudo node has adjacent grids outside the electrodes, the conflict pseudo node becomes the pseudo hub and is removed from the set of pseudo nodes.

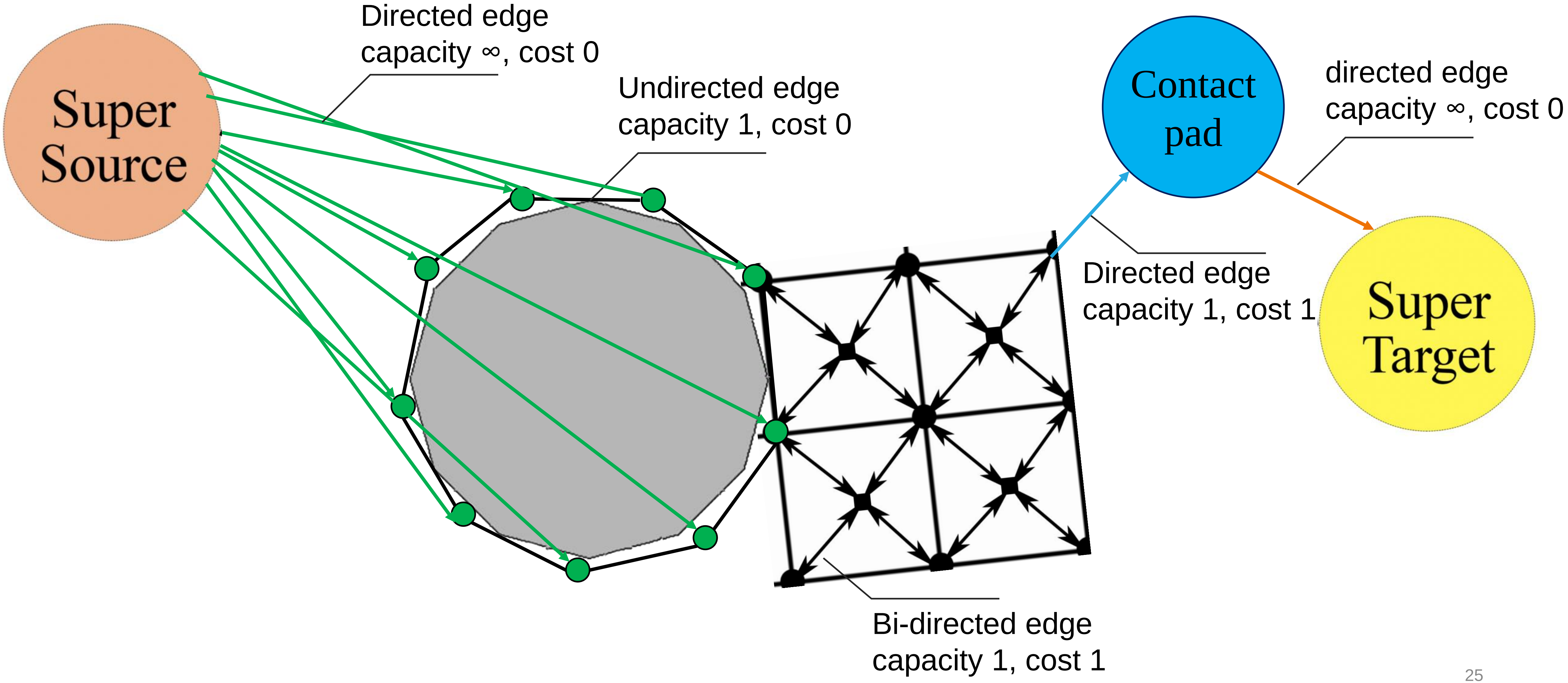


Minimum cost flow graph (1/2)

- The schematic diagram of the flow direction in our minimum cost flow algorithm.

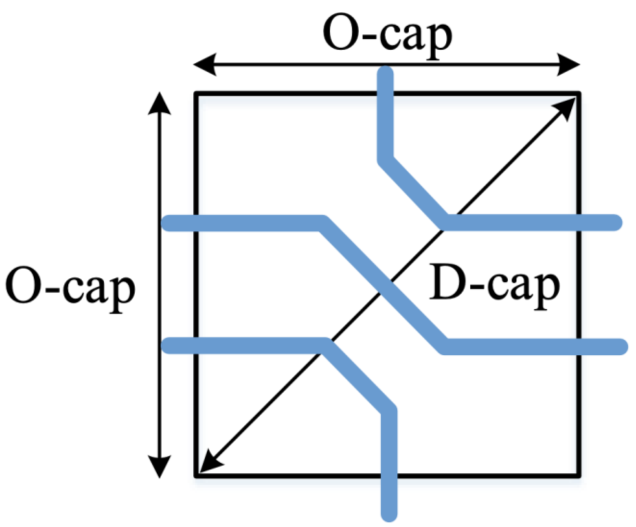


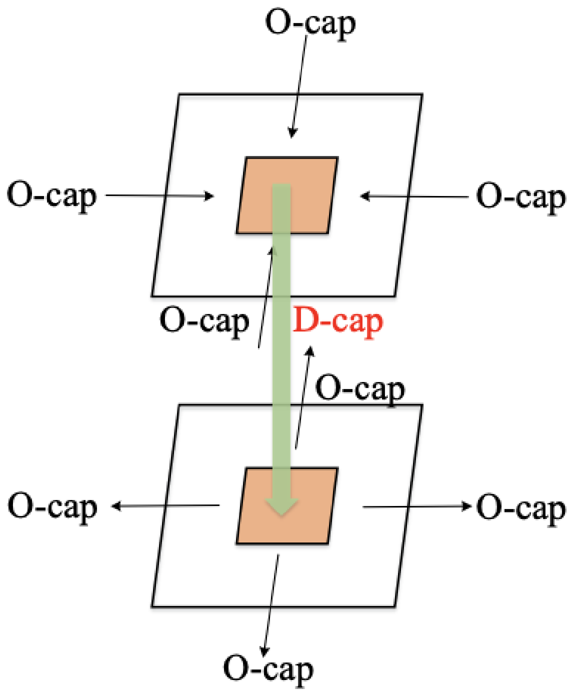
Minimum cost flow graph (2/2)



Light-weight model

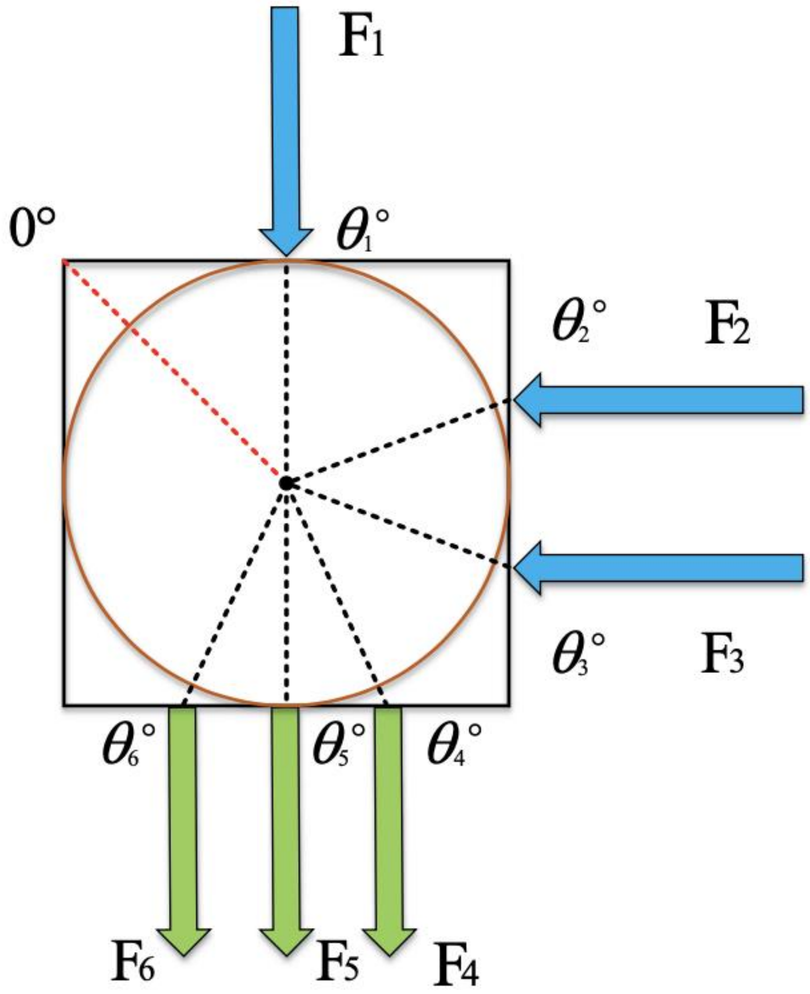
- The flow capacity usually categorized into Orthogonal Capacity (O-cap) and Diagonal Capacity (D-cap).
- The light-weight model can handle the O-cap and D-cap correctly, and reduce memory usage and time consumption of our approach without affecting routability.



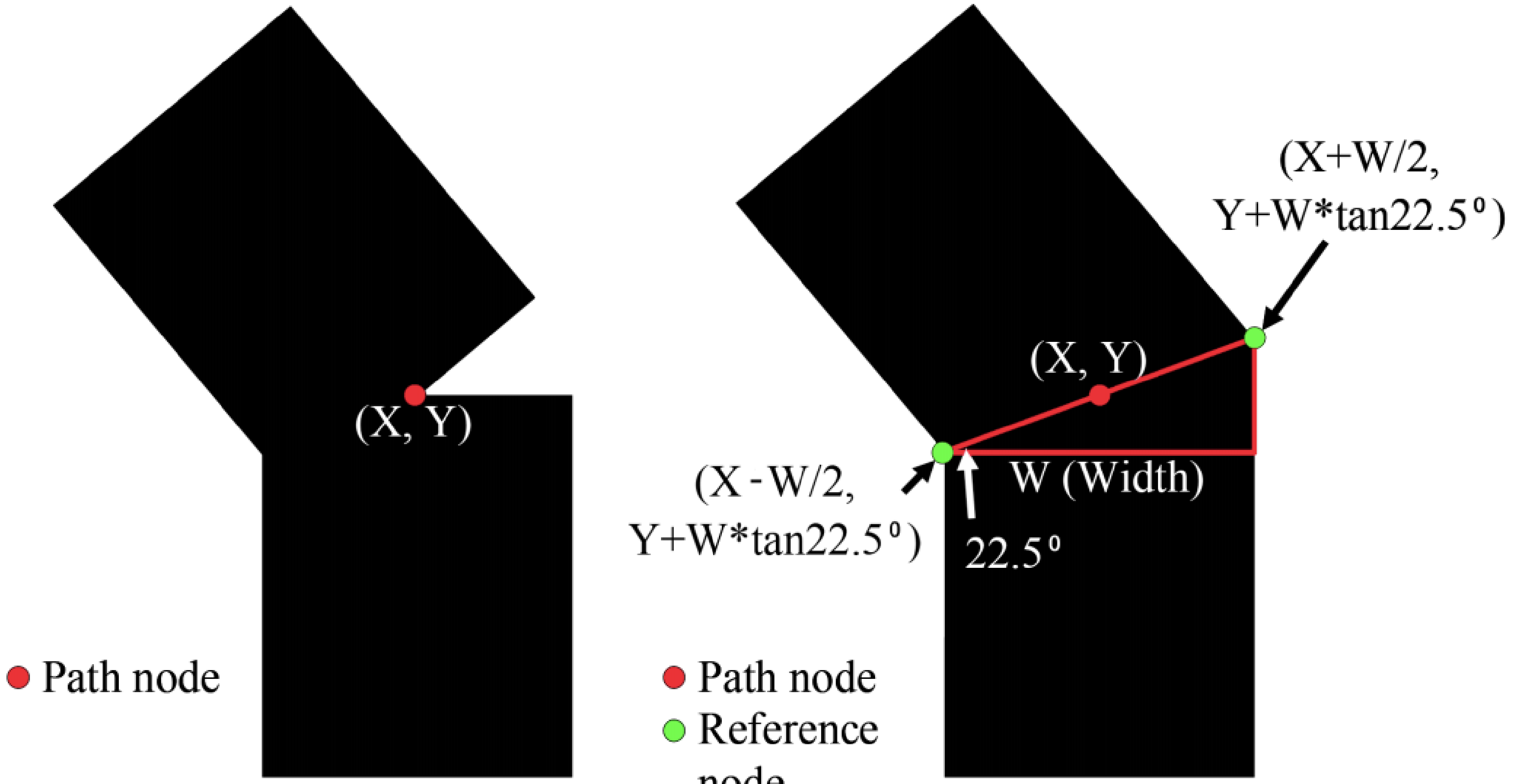


Flow collocation

- The flow collocation is introduced to prevent the flows from crossing over.
- $(F_1, F_6), (F_2, F_5), (F_3, F_4)$



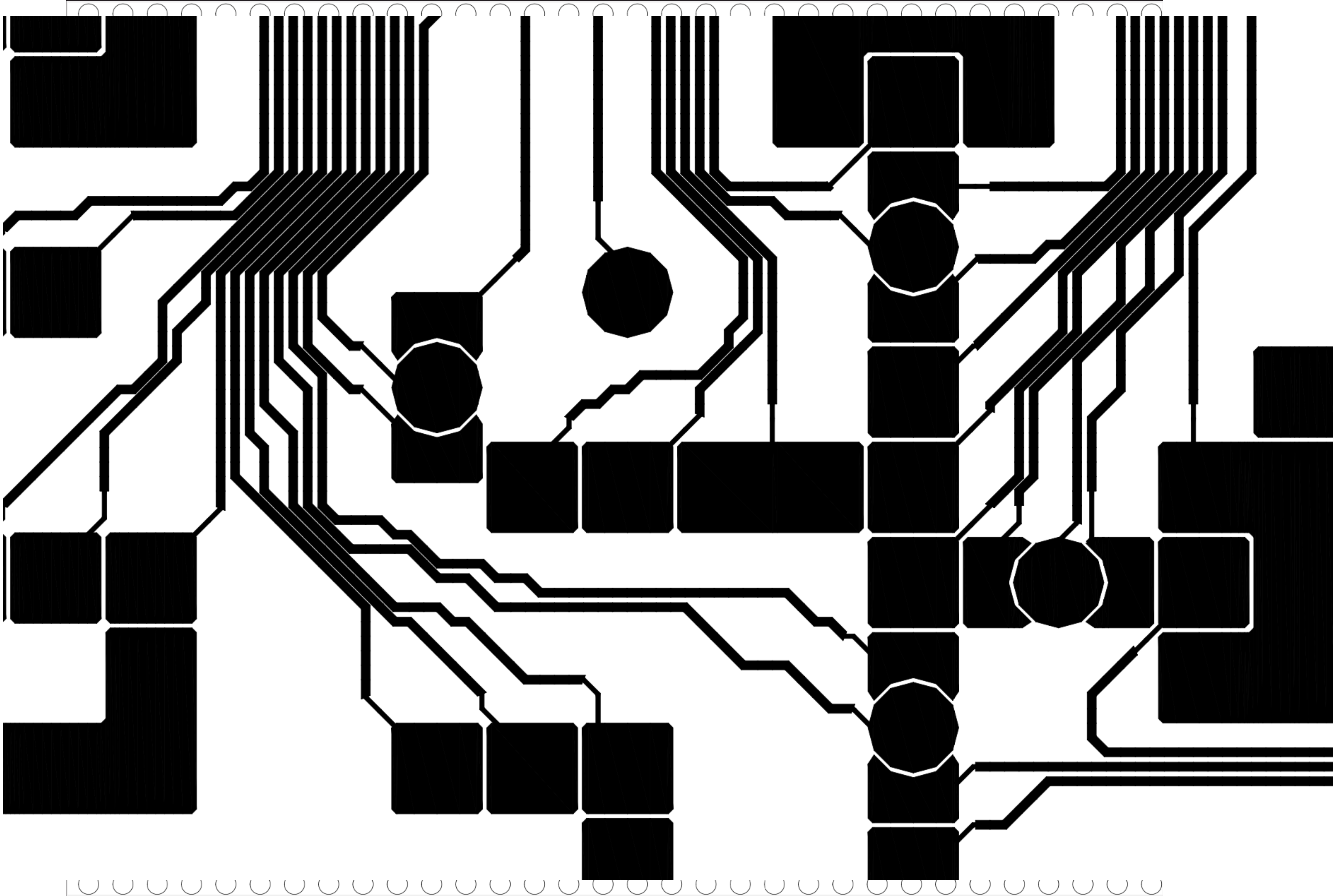
Mask generation

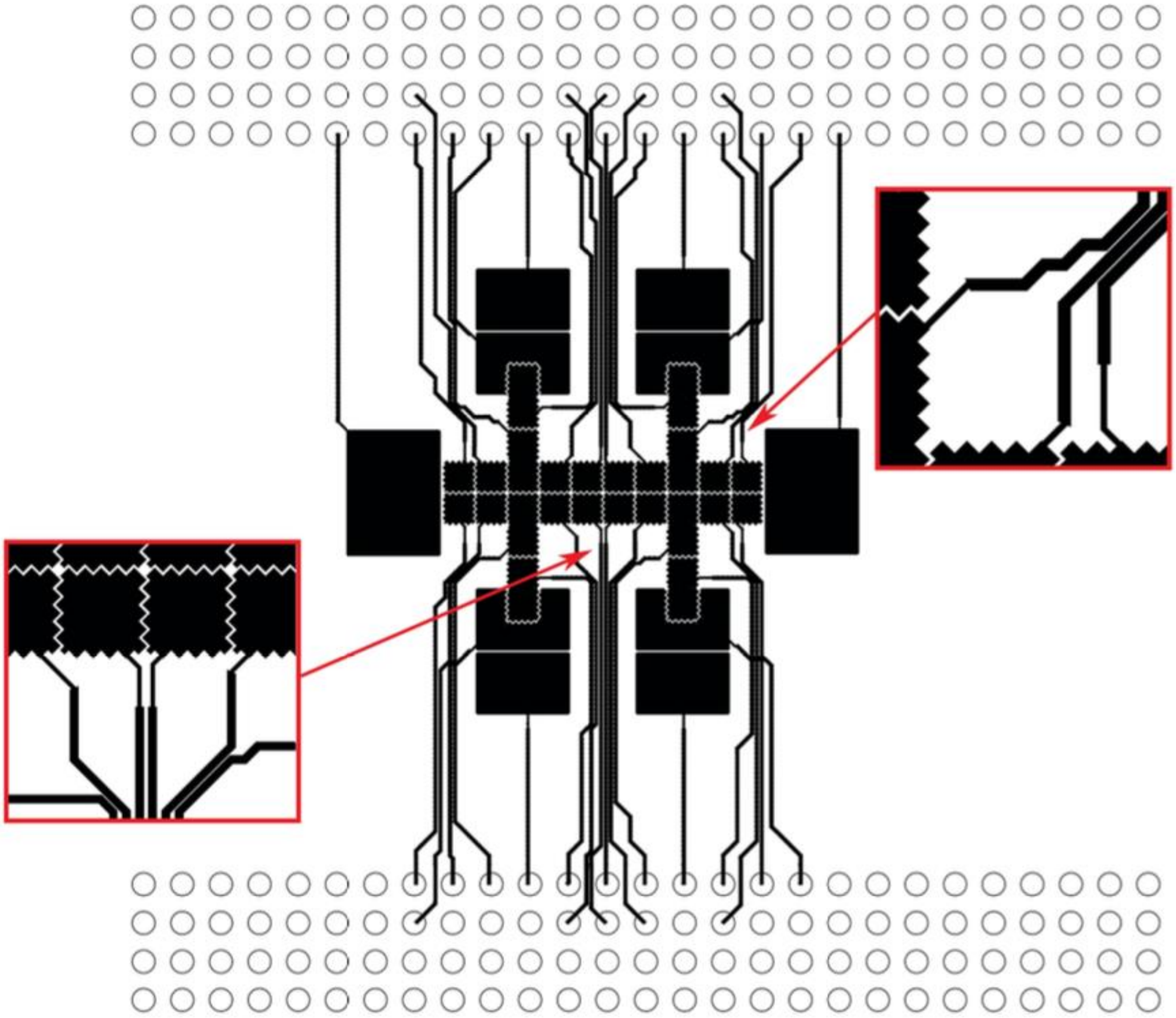


(a) (b)

RESULTS

Benchmark		Test Case 1	Test 1Case 2	Test Case 3	Test Case 4	Test Case 5	Test Case 6	Dilution Function EWOD chip 1	Dilution Function EWOD chip 2	N. Average
Number of Electrodes (N_E)		5	7	13	23	44	88	34	100	
Exhaustive Algorithm	Wirelength (um)	89374	129836	173946	539274	1304753	2183741	593762	2243131	1.0000
	CPU Time(s)	>1 hour	>1 hour	>1 hour	>1 hour	>1 hour	>1 hour	>1 hour	>1 hour	∞
A* Algorithm	Wirelength (um)	128475	182736	397364	1984654	2794854	4395862	2594832	3418597	3.1331
	CPU Time(s)	0.2374	0.5920	1.0943	1.4284	2.5573	3.6716	2.4343	3.5392	3.3724
NR-Router	Wirelength (um)	89374	129836	173946	539274	1304753	2183741	593762	2243131	1.0000
	CPU Time(s)	0.4624	0.4981	0.5244	0.5221	0.6483	0.6739	0.5937	0.6894	1.0000



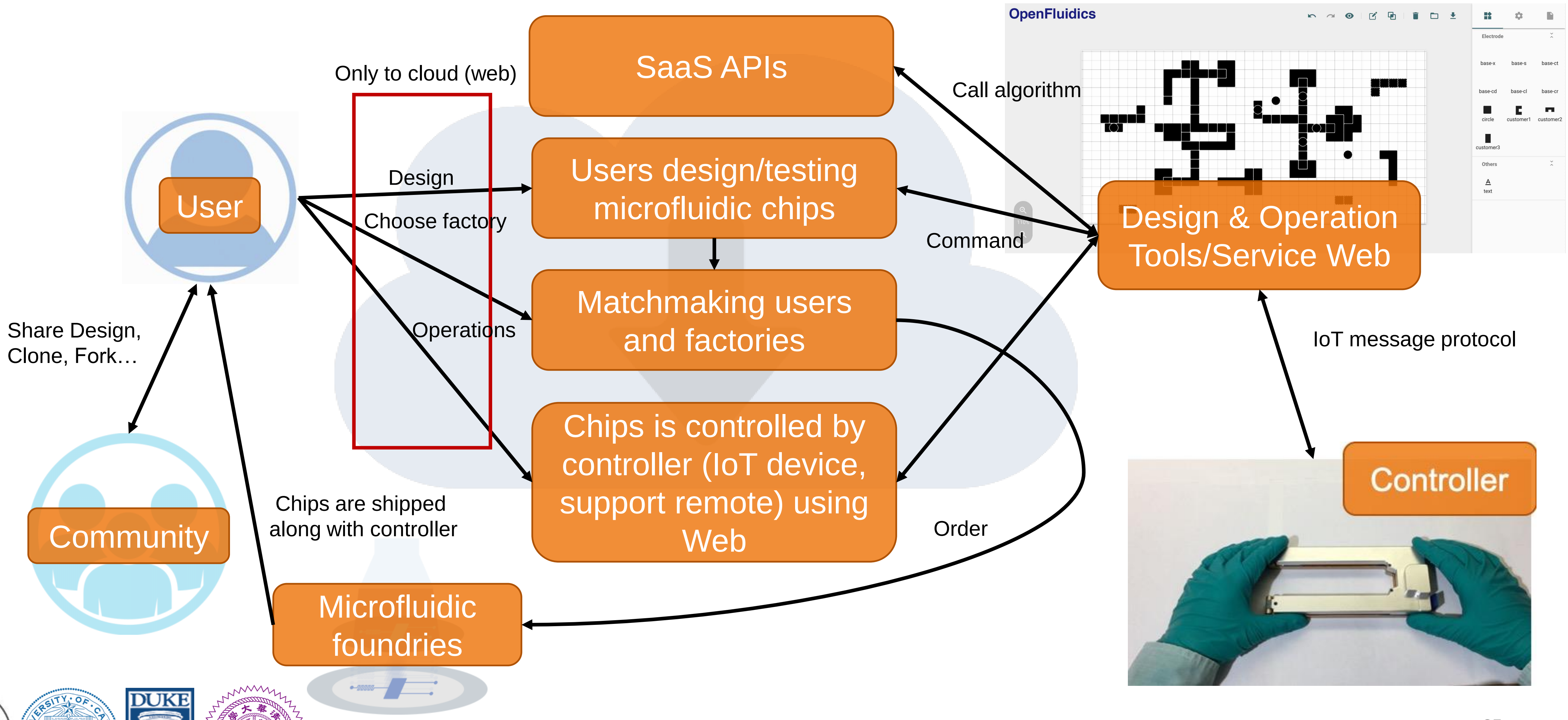


CONCLUSIONS

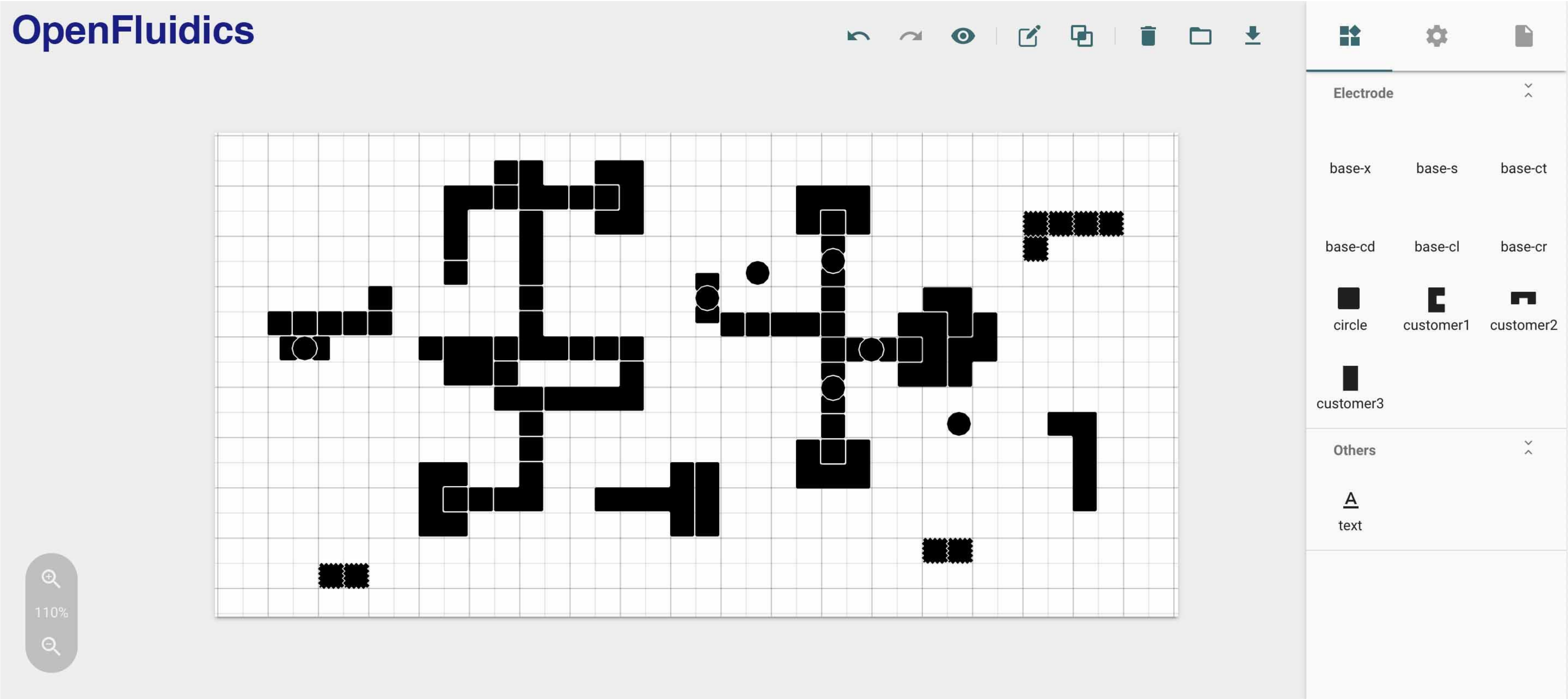
Conclusions

- We proposed NR-Router, the first algorithm that can accurately route in single-layer EWOD chips with non-regular electrodes to the best of our knowledge.
- We lowered the design barriers for single-layer EWOD chips with non-regular electrodes.

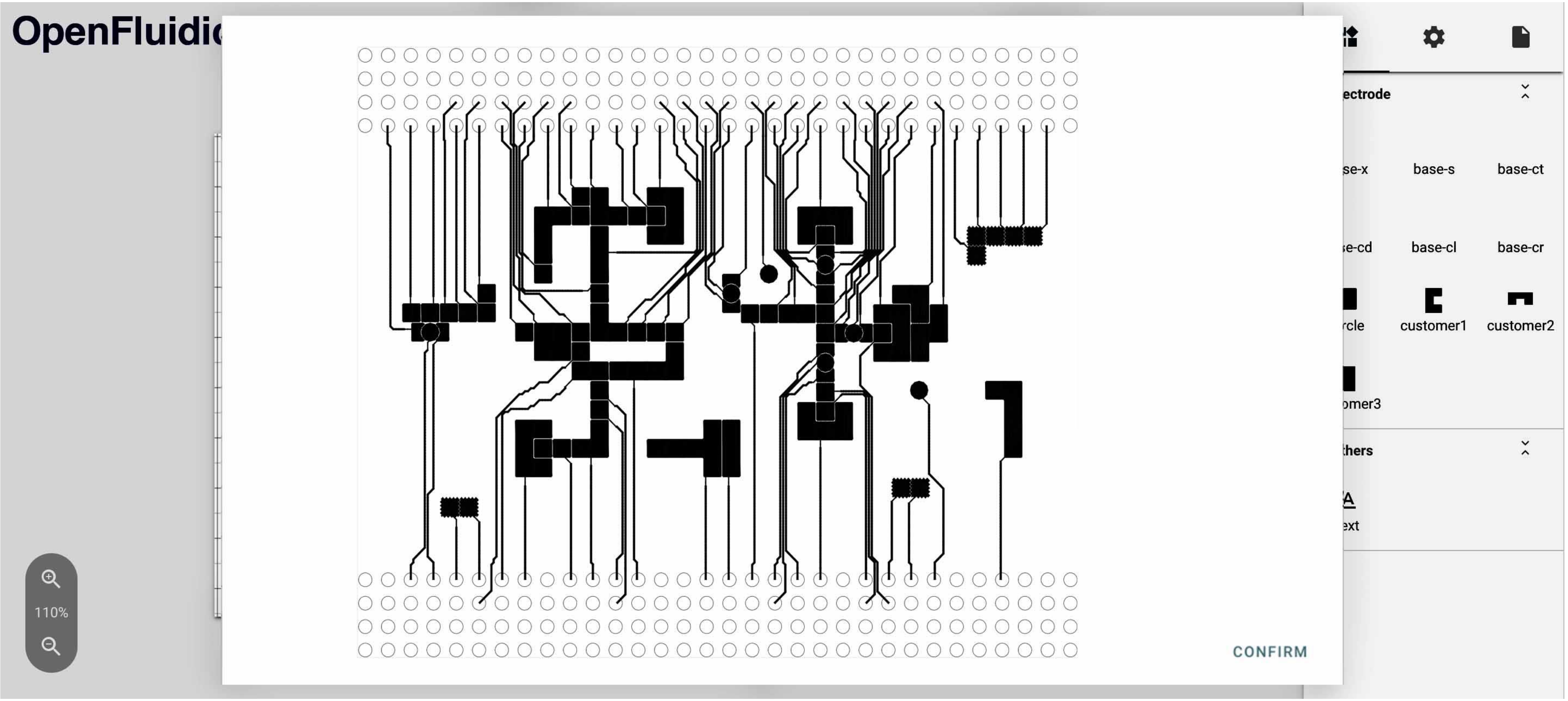
OpenFluidics: Digital Microfluidics Ecosystem (1/3)



OpenFluidics: Digital Microfluidics Ecosystem (2/3)



OpenFluidics: Digital Microfluidics Ecosystem (3/3)



Thanks