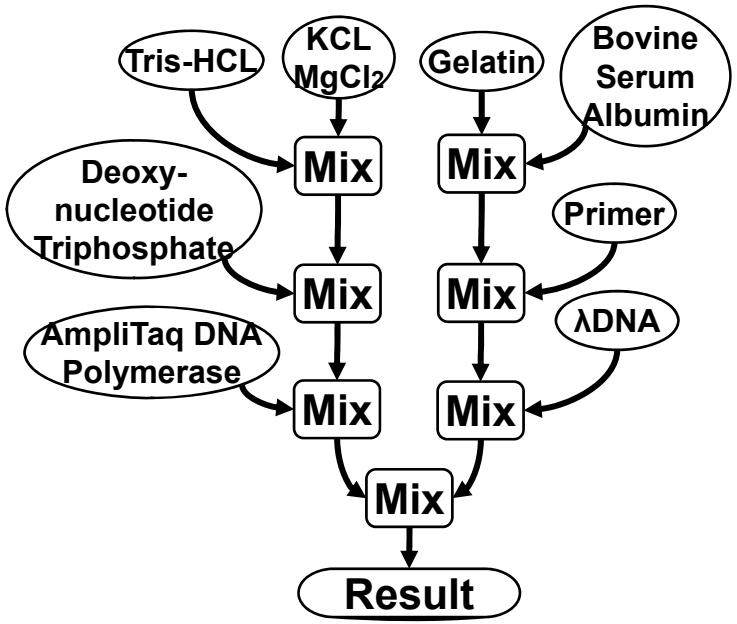
# A High-Performance Droplet Routing Algorithm for Digital Microfluidic Biochips

**Minsik Cho and David Z. Pan**

Dept. of Electrical and Computer Engineering
The University of Texas at Austin
thyeros@cerc.utexas.edu
dpan@ece.utexas.edu
http://www.cerc.utexas.edu/utda

**Sponsored in Part by NSF and IBM Faculty Award**

# Why Biochip?



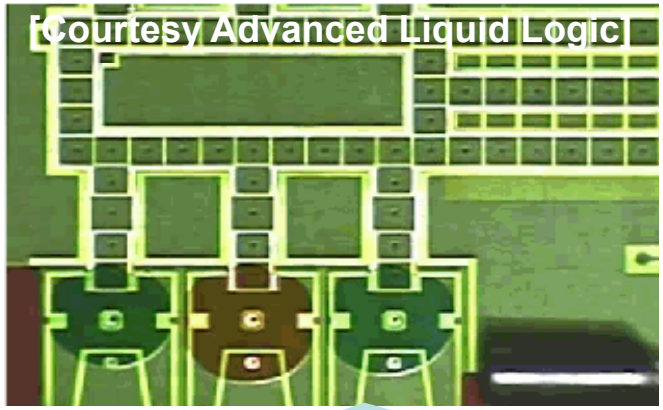

DNA PCR

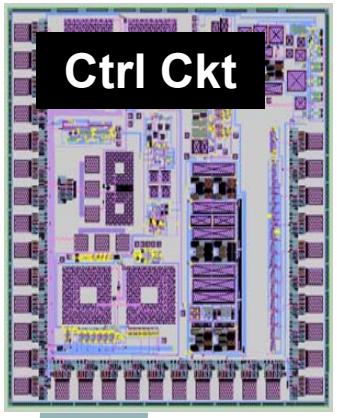
Human Experimenter

Biochip

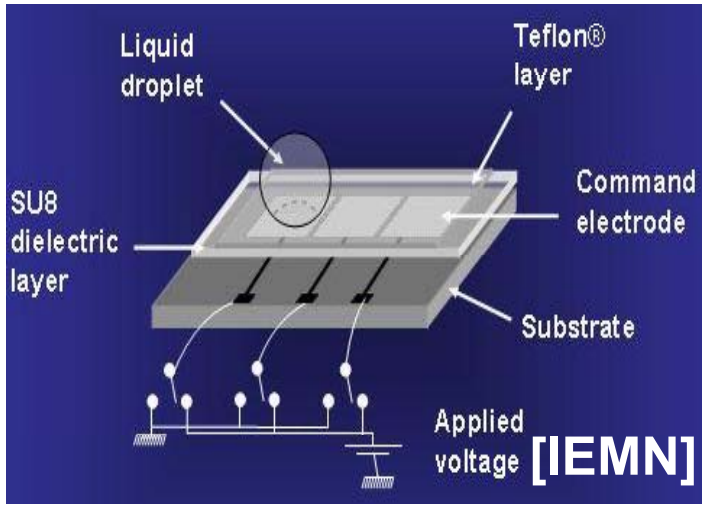
- Economical and high-performance
  - Low cost (less than $2), portable, disposable
  - Fast, automated, error-tolerant (no human involvement)
- Critical applications
  - POC (Point-of-care), anti-bioterrorism, …

# Digital Microfluidic Biochips



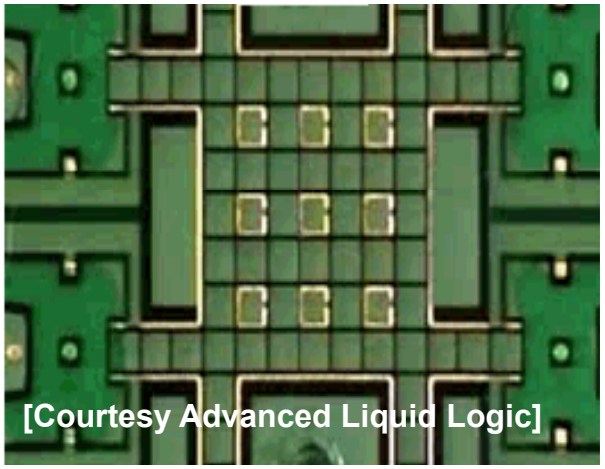

**Preprogrammed voltages for EWOD**

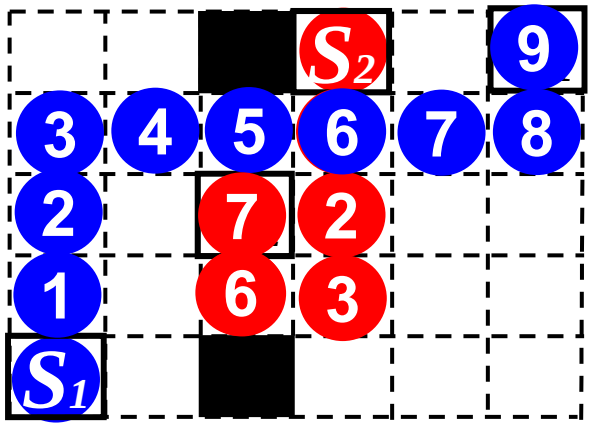



- **Digitized** droplets transported
  - By EWOD (electrowetting-on-dielectric)
    - Electrical modulation of the solid-liquid interfacial tension
  - According to **Preprogrammed Schedule**
    - Traffic control

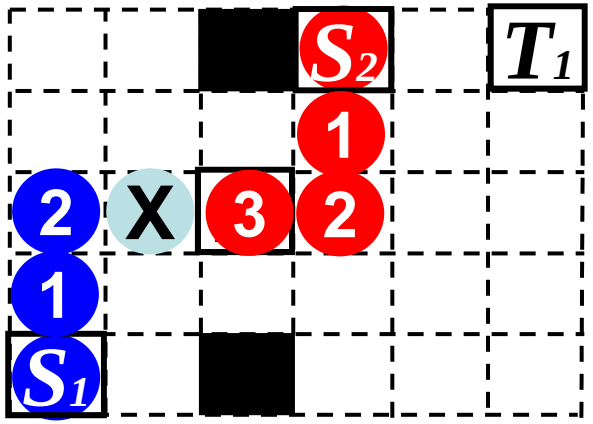
# Microfluidic Biochip Droplet Routing

- **How to program/schedule/route droplets?**
  - Fluidic constraints to prevent collision (keep-off distance)
  - Timing constraints to prevent spoilage
  - NP-Complete



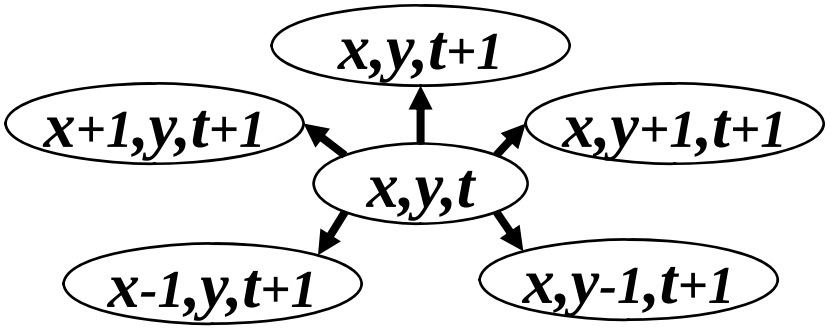

T=9 (good solution)



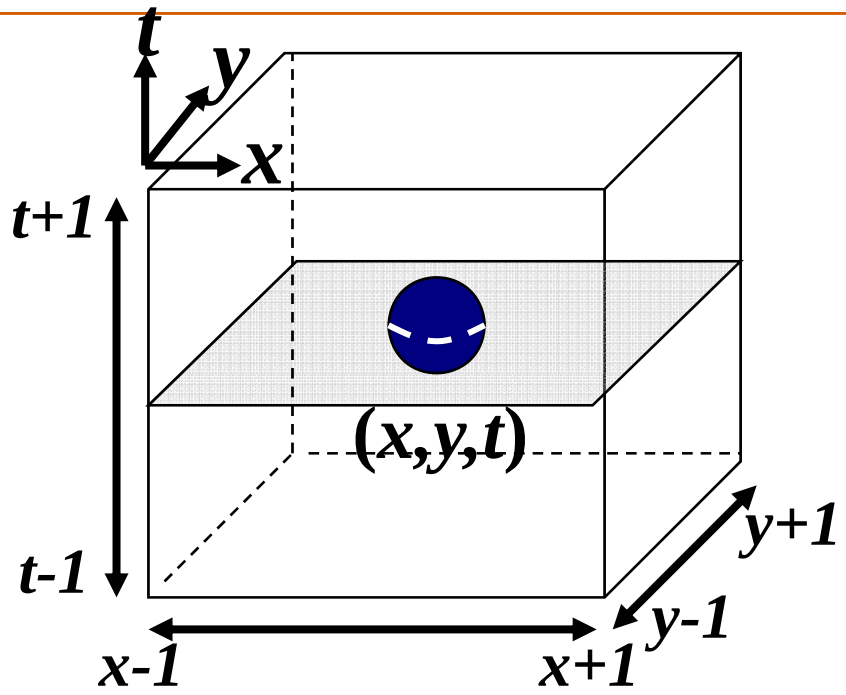

T=?? (infeasible)

- Comparison with VLSI routing
  - Fluidic constraint = Minimum spacing
  - Timing constraint = Required arrival time (RAT)
  - But, **time-multiplexed** movement of droplets

# Modeling and Constraints




**Graph model for simultaneous geometric and temporal scheduling**




- Graph model
  - 5 edges for each node
  - Time causality
- Fluidic cube
  - One droplet inside the cube

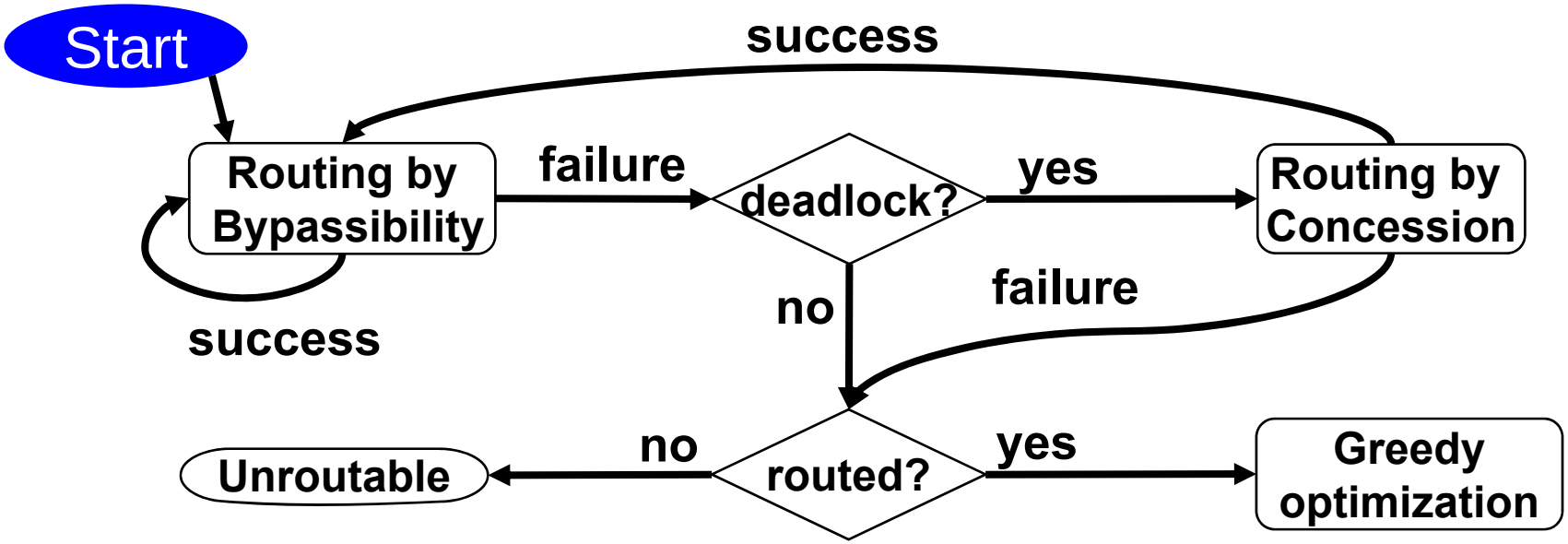
# Current State-of-the Art

- Prioritized A* search [Böhringer TCAD'06]
  - Route shorter droplets first (widely used in VLSI)
- Network flow-based approach [Yuh+ ICCAD'07]
  - Maximize the number of nets routed
  - Min cost-Max flow formulation + prioritized A* search
- OSPF protocol approach [Griffith+ TCAD'06]
  - Have a set of precomputed path, and choose one of them by situation based on OSPF network protocol.
- Two-stage Algorithm [Su+ DATE'06]
  - Generate M shortest paths
  - Random selection
- Progressive ILP based Approach [Yuh+ DAC'08]
  - Similar to VLSI routing
  - Pin constraints

# Proposed Approach

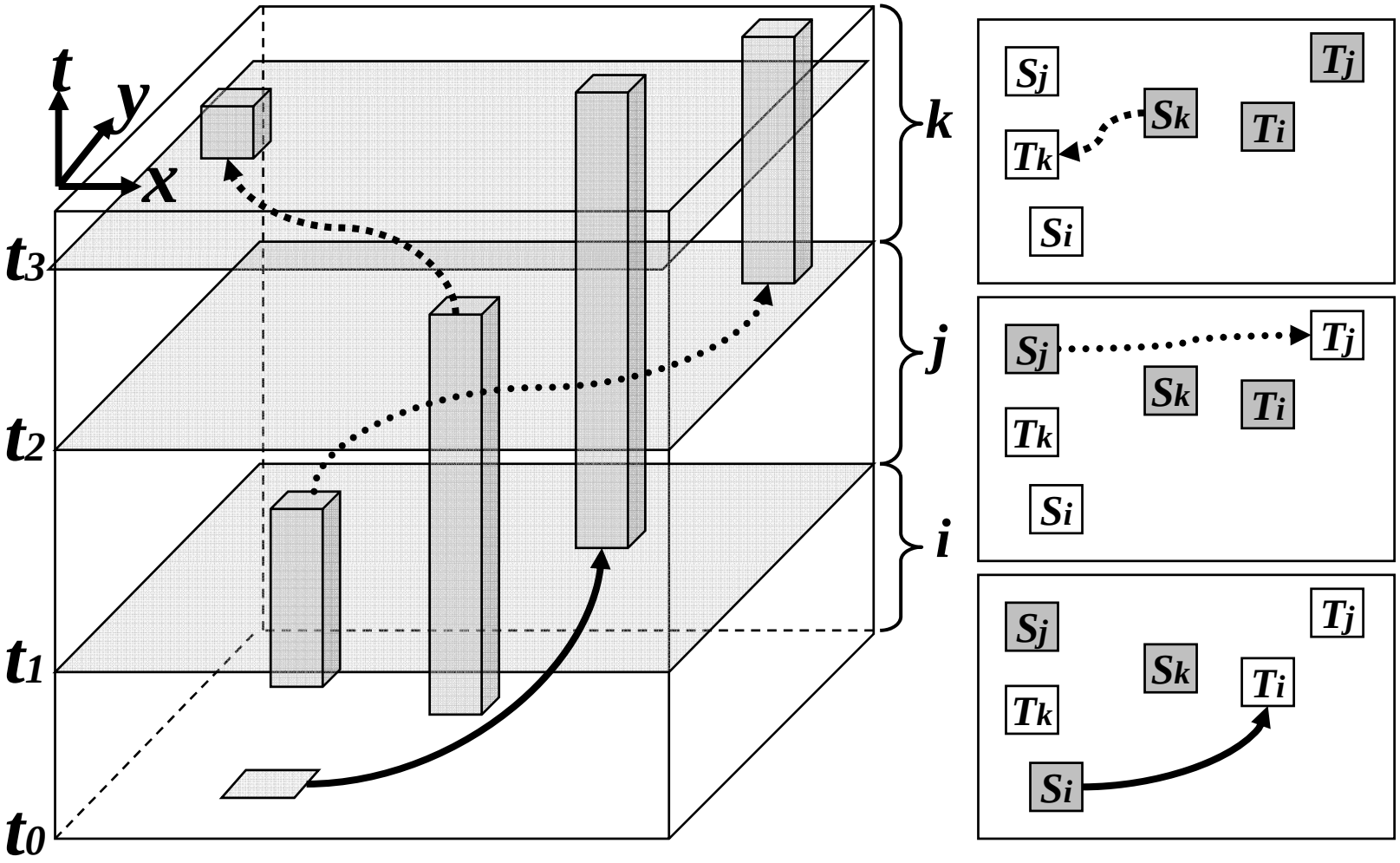
- Time-multiplex resource sharing implies
  - Intermediate paths will be freed up eventually.
- To reduce problem size inspired by Chatin's coloring algorithm
- New concepts to reflect the nature of biochip
  - One droplet movement at a time (the others are frozen)
    - Reduced routing search time
  - **Bypassibility**
    - To route a droplet with minimal impact on feasibility
  - **Concession**
    - To resolve a deadlock
  - **Compaction**
    - To satisfy timing constraint and improve fault-tolerance

# Overall Routing Flow

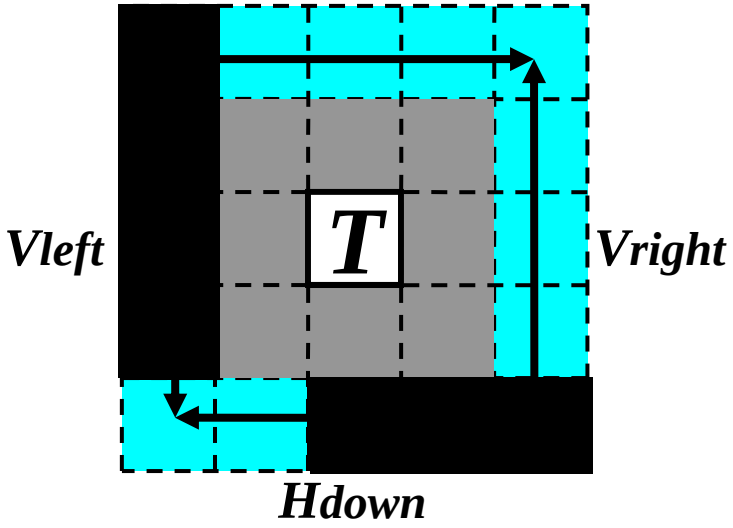



- Reduce the problem size
  - To find out the most complex part of the problem
- First find a feasible solution
  - Greedily improve the solution to meet timing

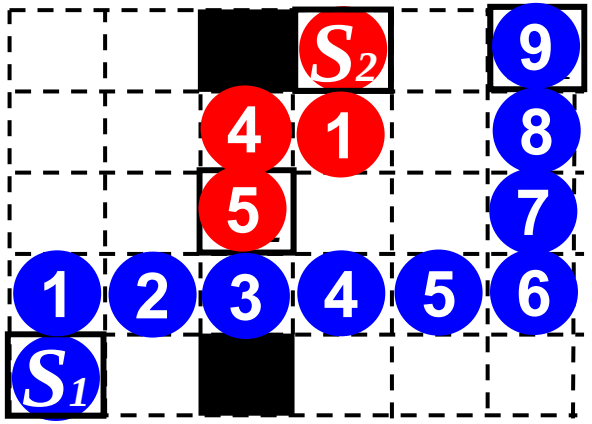
# One Droplet at a Time



# Routing by Bypassibility




Full bypassibility



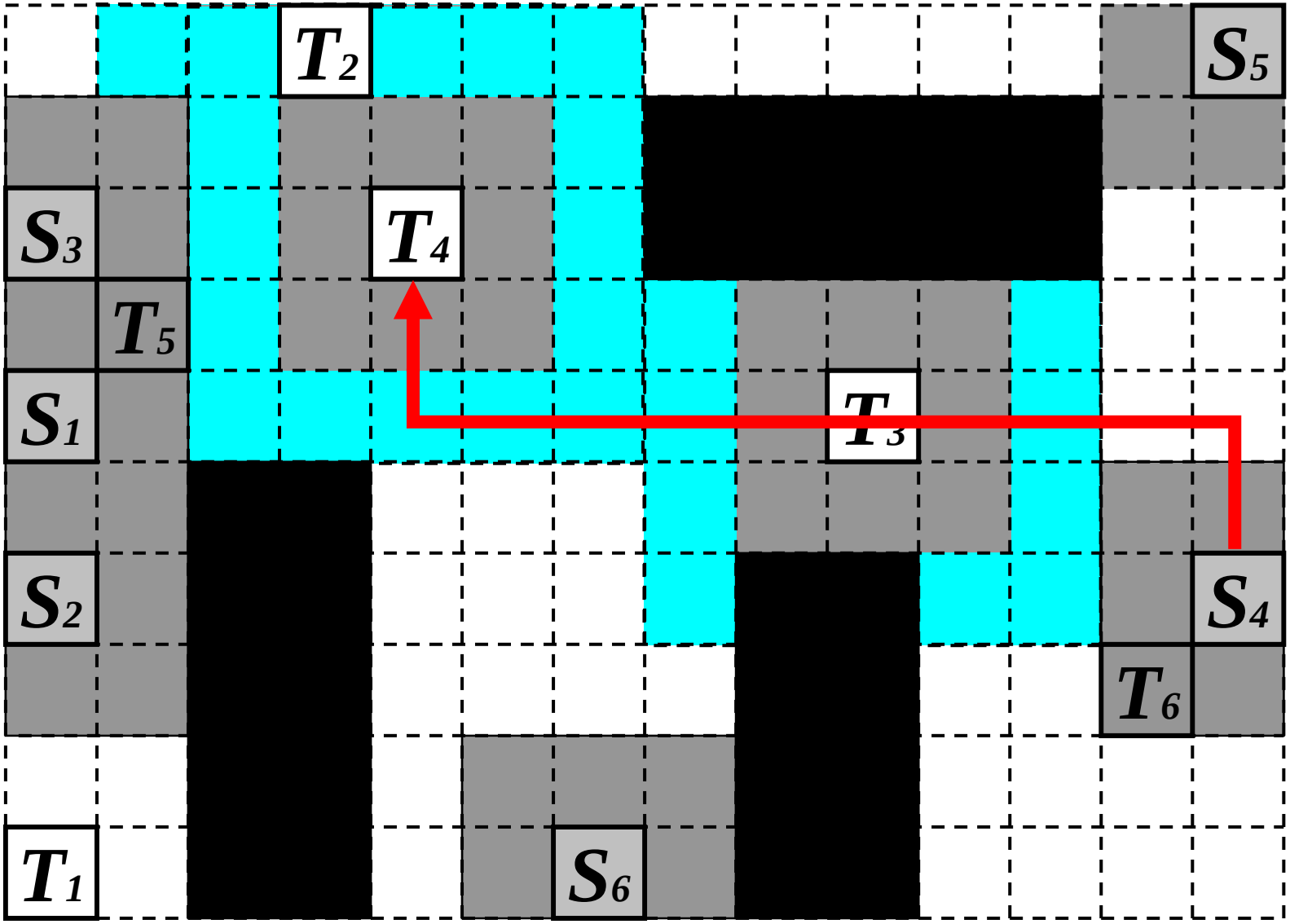

T=9 (optimal solution)

- A routed droplet will block the target regions.
  - **Is there any H/V bypass for the unrouted droplets?**
- Four categories
  - **Ideal**: the target is a waste reservoir.
  - **Full** : both horizontal and vertical bypasses are available.
  - **Half** : only either horizontal or vertical bypasses is available.
  - **No** : no bypass is available.

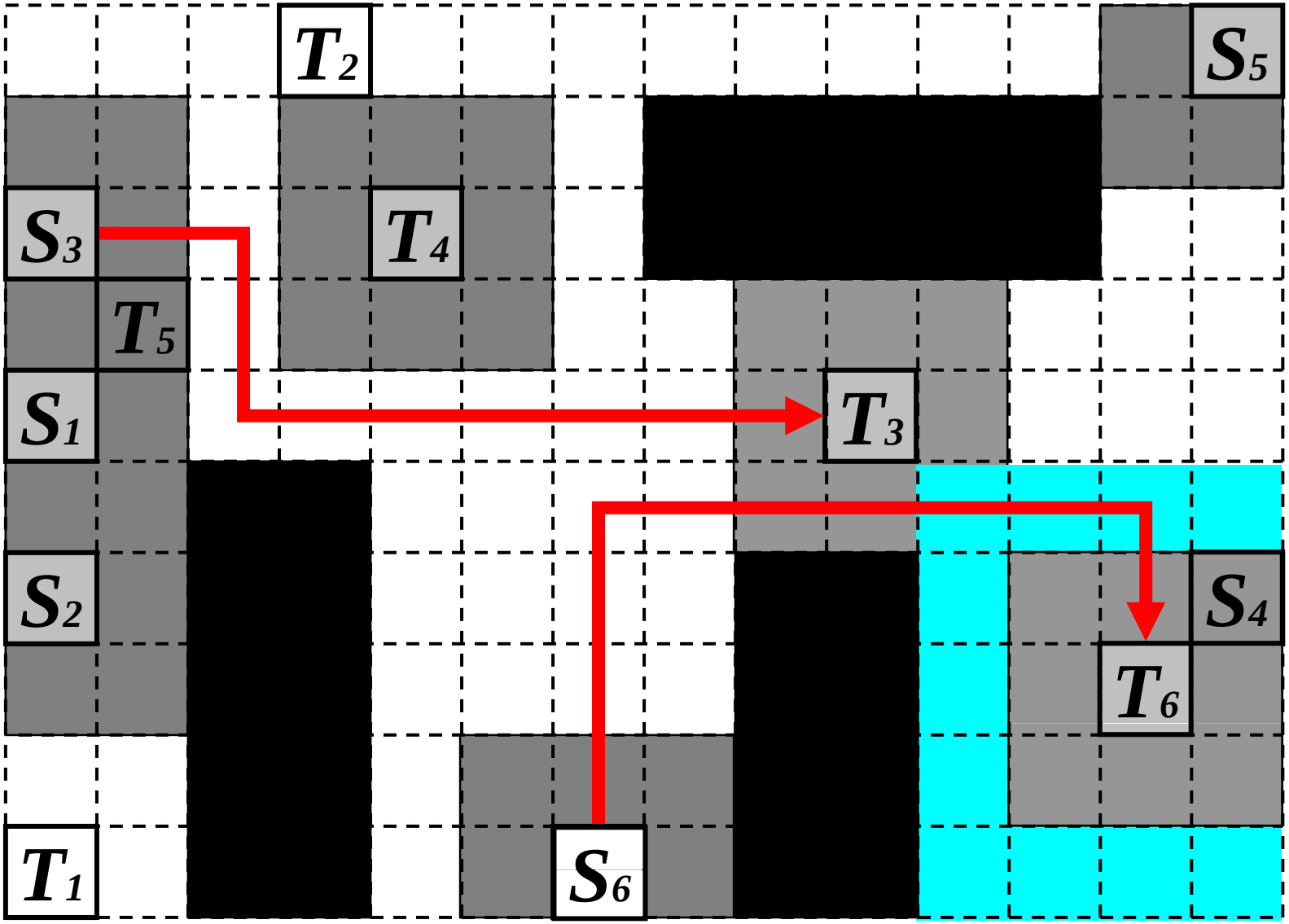
# Routing by Concession

- When there is a deadlock…
  - One droplet needs to back-off
  - One closer to the empty space

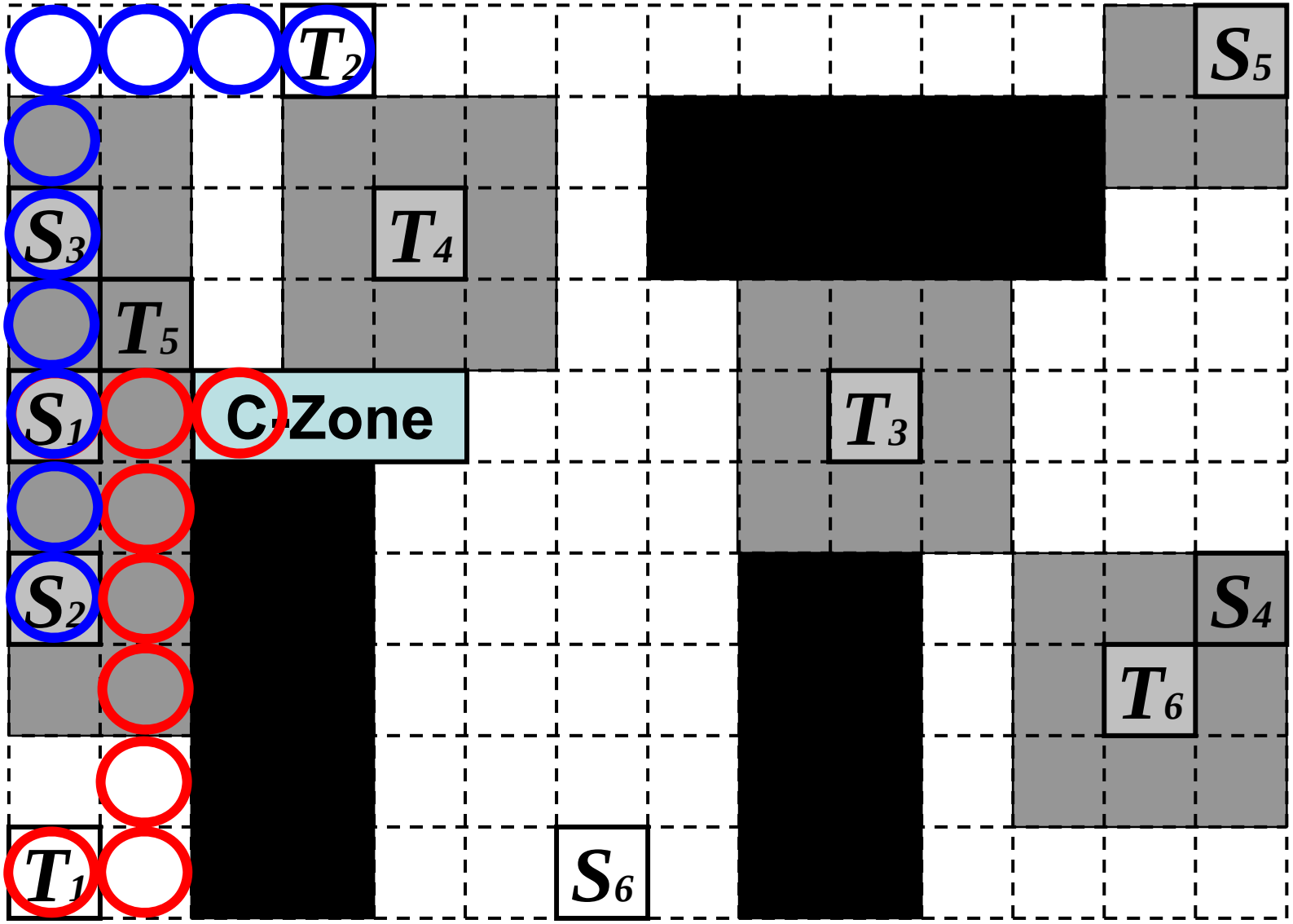
# Toy Example (Bypassibility)



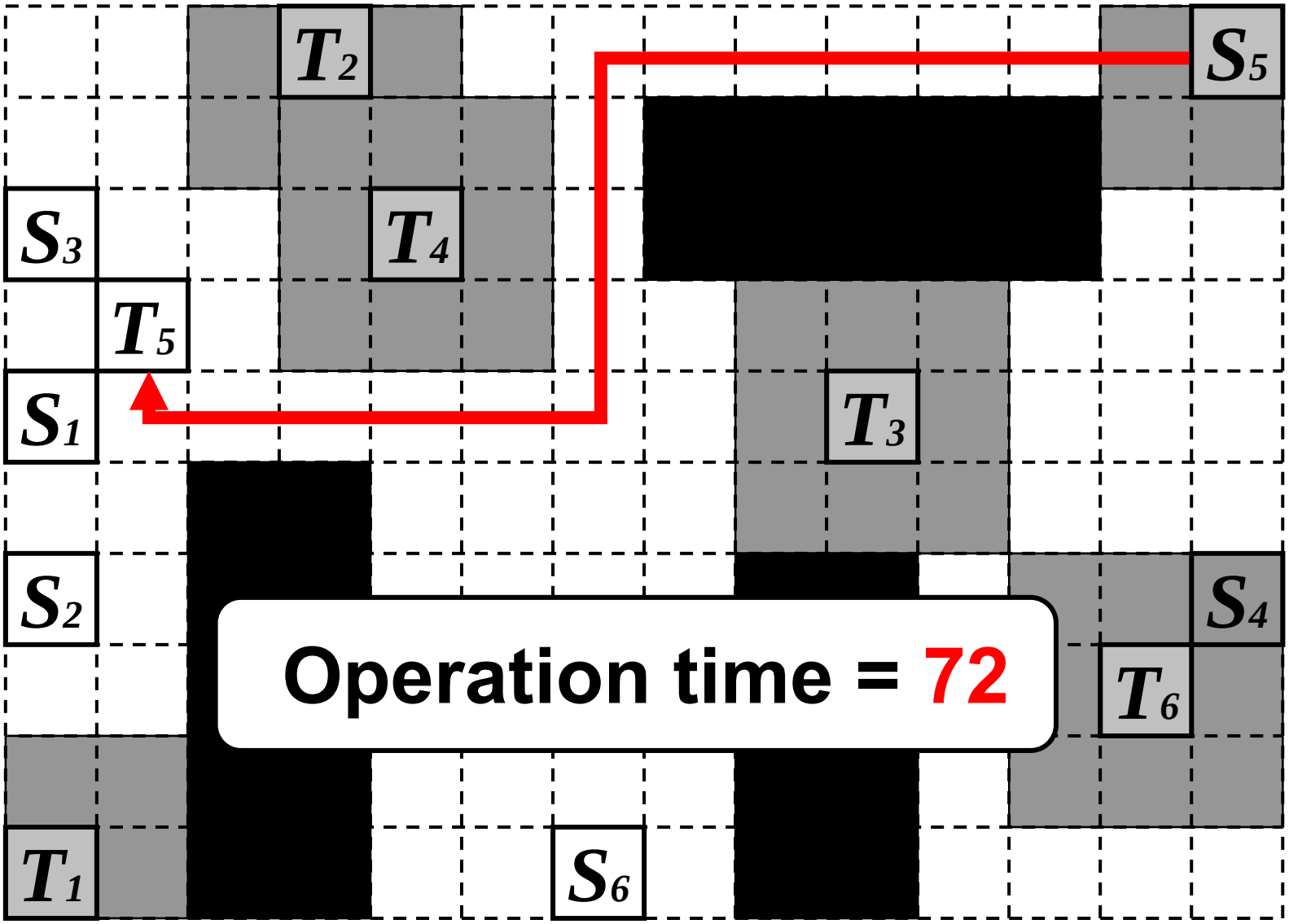
# Toy Example (Bypassibility)



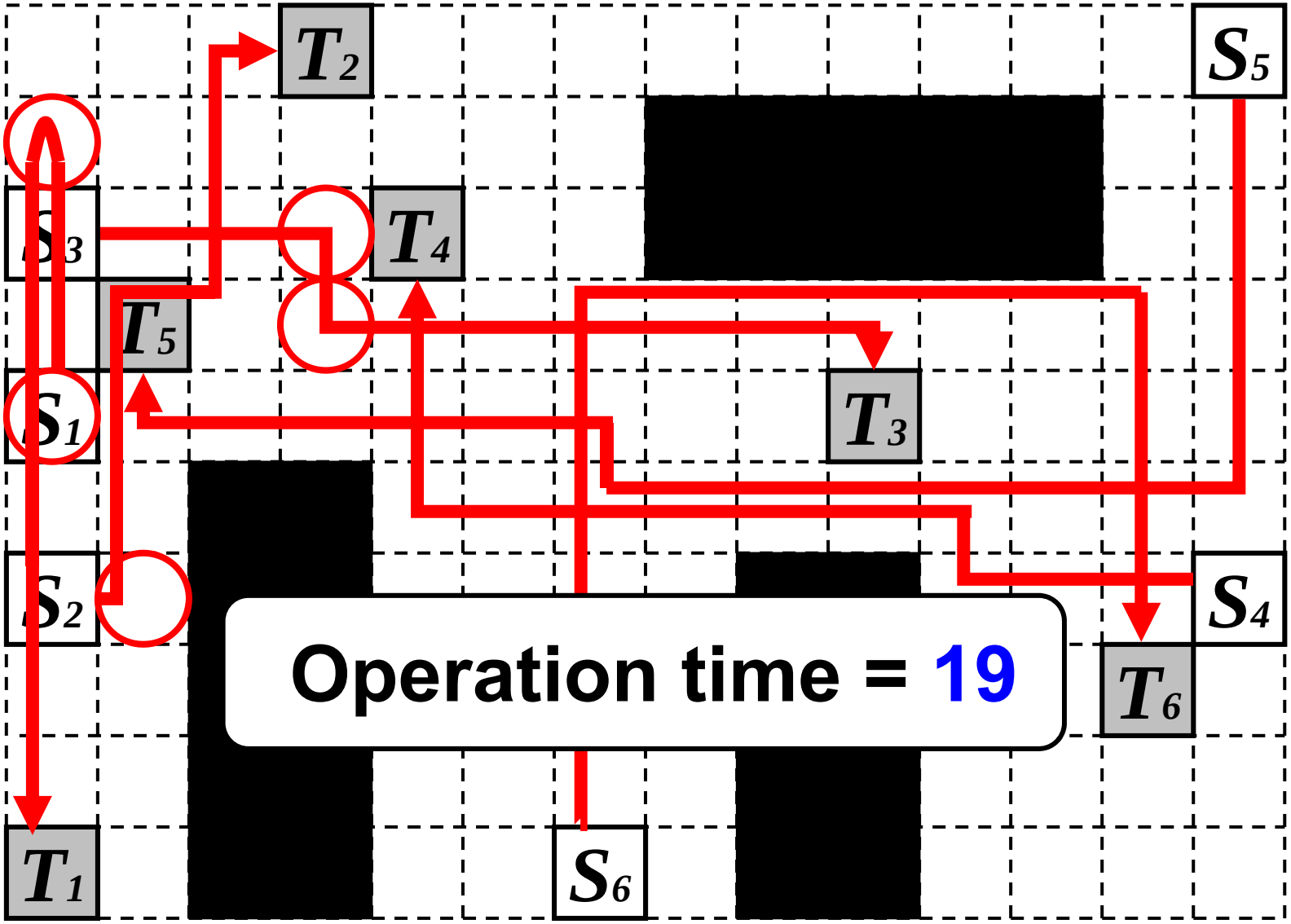
# Toy Example (Concession)



# Toy Example (Bypassibility)



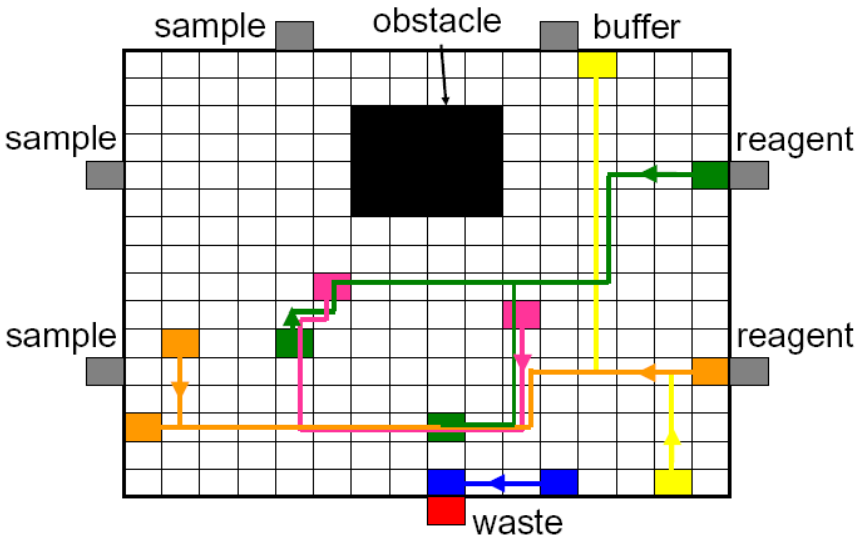
# Toy Example (Greedy Opt.)



# Experimental Setup

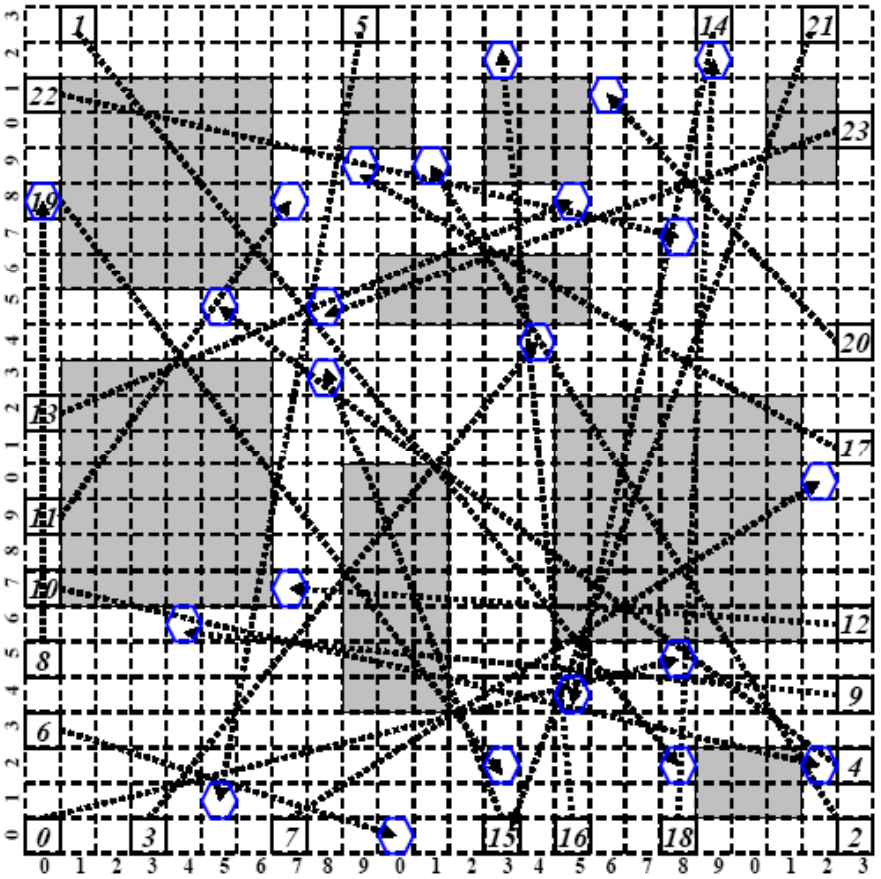
- Implemented in C++ and tested on Intel Dual Core 2.6GHz Linux with 4GB
- Two benchmarks
  - Suite1: 4 widely used benchmarks
    - Relatively small and easy
    - Max # of droplets: 6
  - Suite2: 30 synthetic benchmarks
    - Large scale and complex with multiple blockages
    - Max # of droplets: 48 with 30% of areas blocked
- Comparison
  - Prioritized A* search [TCAD'06]
  - Two-stage algorithm [DATE'06]
  - Network flow based routing [ICCAD'07]

# Comparison between Suite1 and Suite2



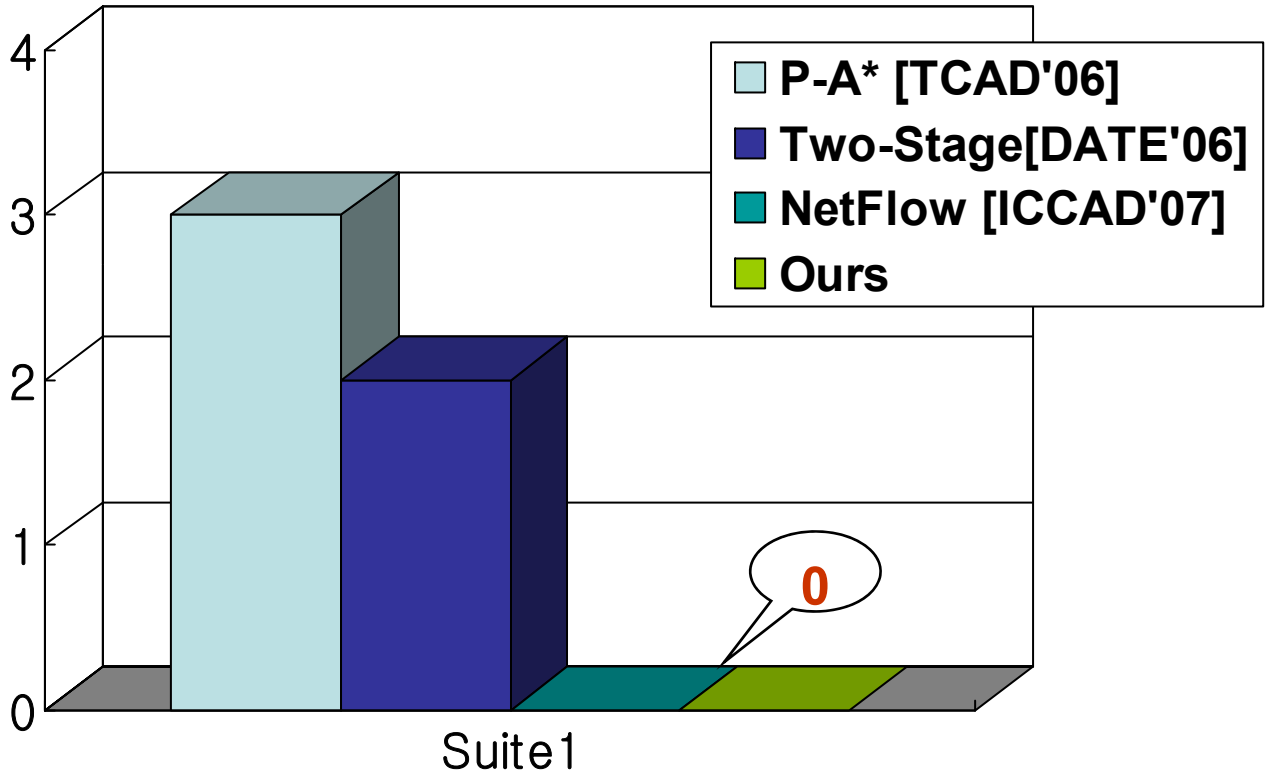

[Yuh+ ICCAD'07]

**Much More Complex For Future Design**



# Experimental Results

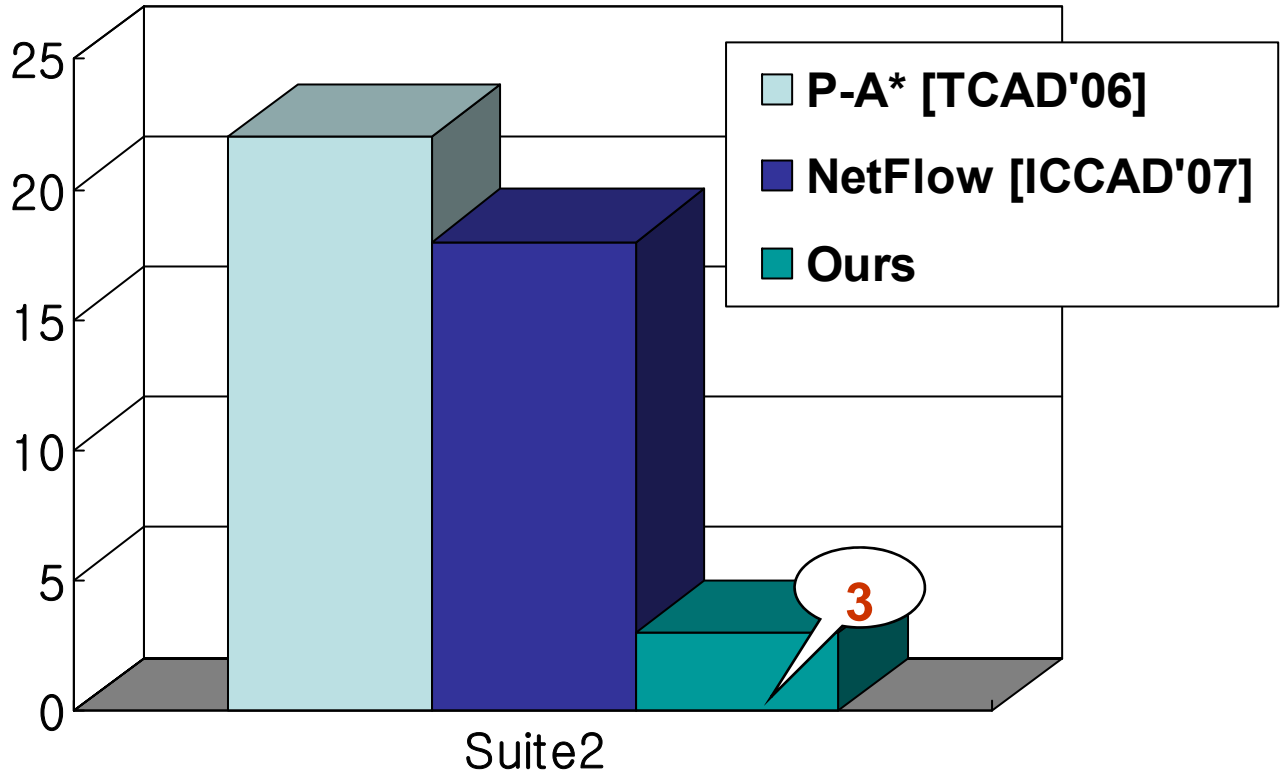
**Number of failed designs**




- Total 4 designs
- Completed the most number of designs

# Experimental Results

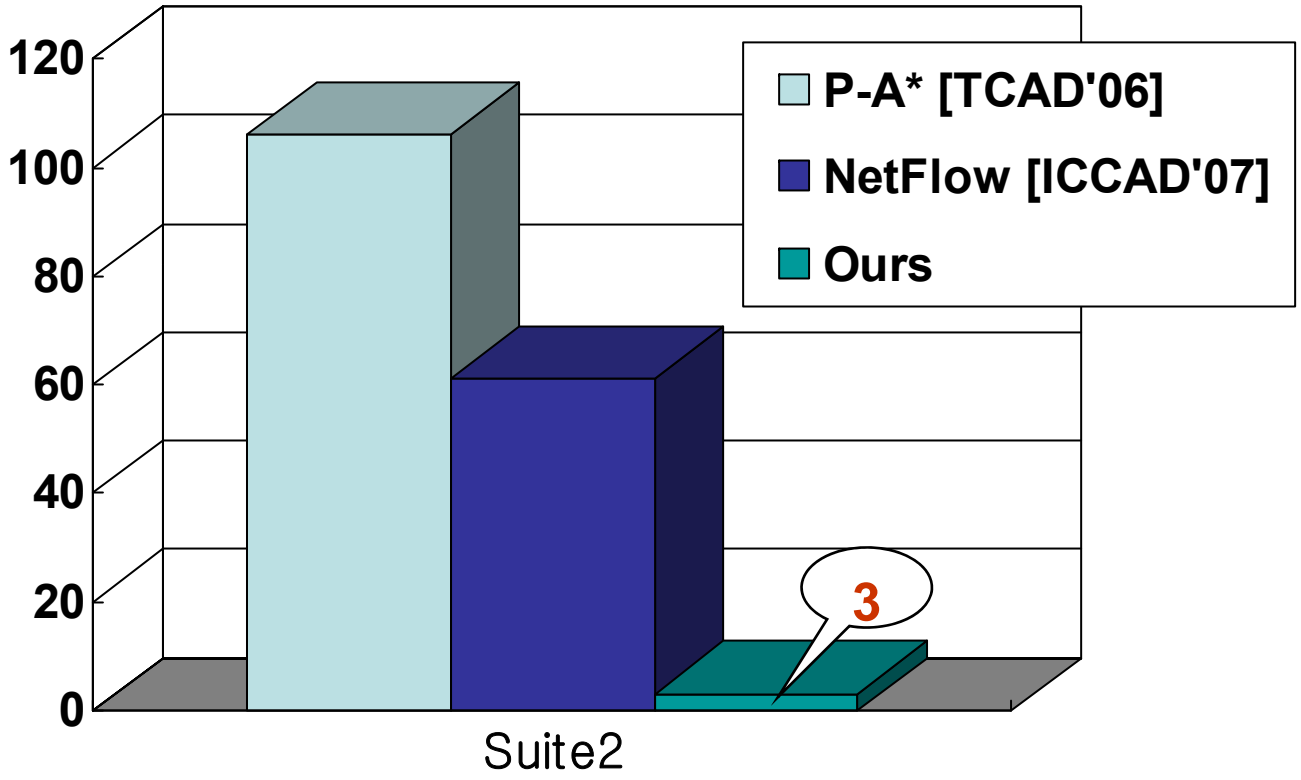
**Number of failed designs**




- Total 30 designs
- Completed the most number of designs

# Experimental Results

**Number of the unrouted droplets**




- Total 864 droplets (30 designs)
- Outperforms the previous works by wide margin

# Conclusion

- New digital microfluidic biochip routing algorithm
  - Multiple concepts to leverage time multiplexed resource sharing
- Outperforms the previous works by wide margin
- Ping-Hung Yuh, Prof. Chia-Lin Yang, and Prof. Yao-Wen Chang (NTU)
  - Providing the results of network flow-based on algorithm in ICCAD'07 on benchmark suite2

## Thank you!!