Exploring Speed and Energy Tradeoffs in Droplet Transport for Digital Microfluidic Biochips

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University of California, Riverside

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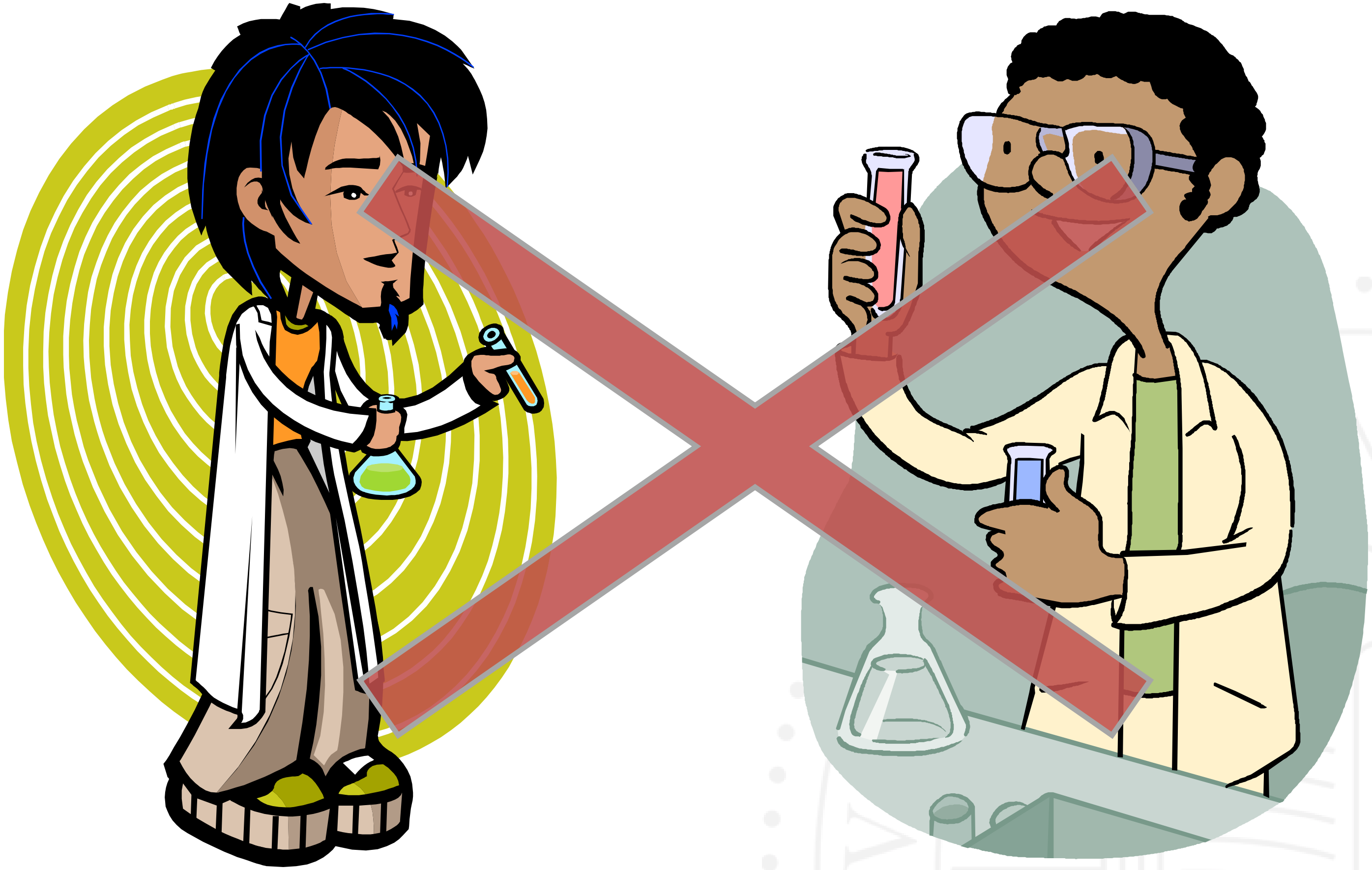
The Bottom Line

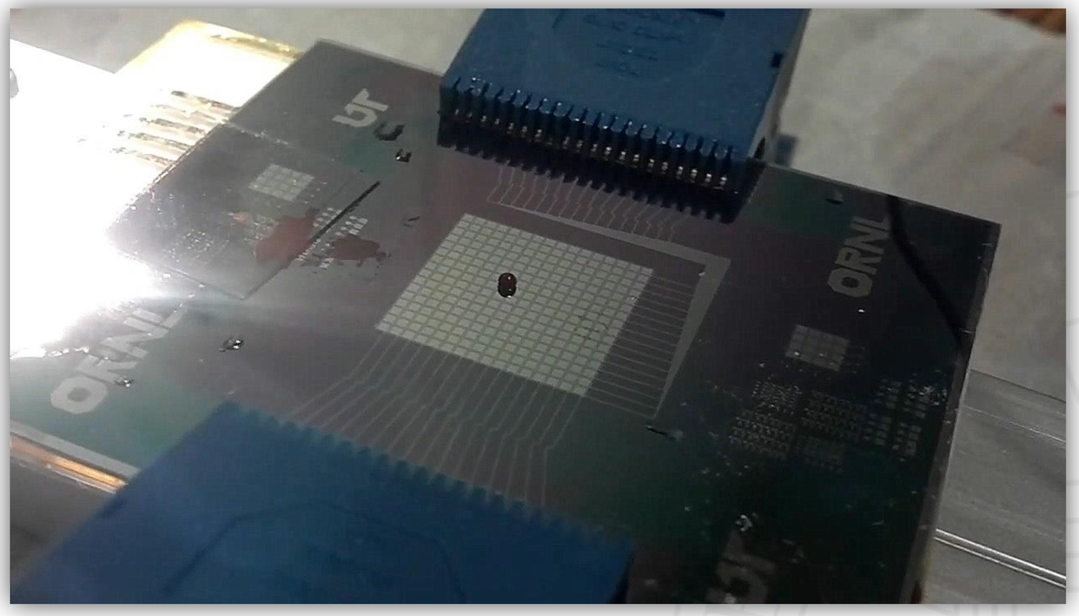


Microfluidics will replace traditional bench-top chemistry

The Future of Chemistry

Microfluidics

"Digital"



Discrete Droplet Based

Miniaturization + Automation
of Biochemistry

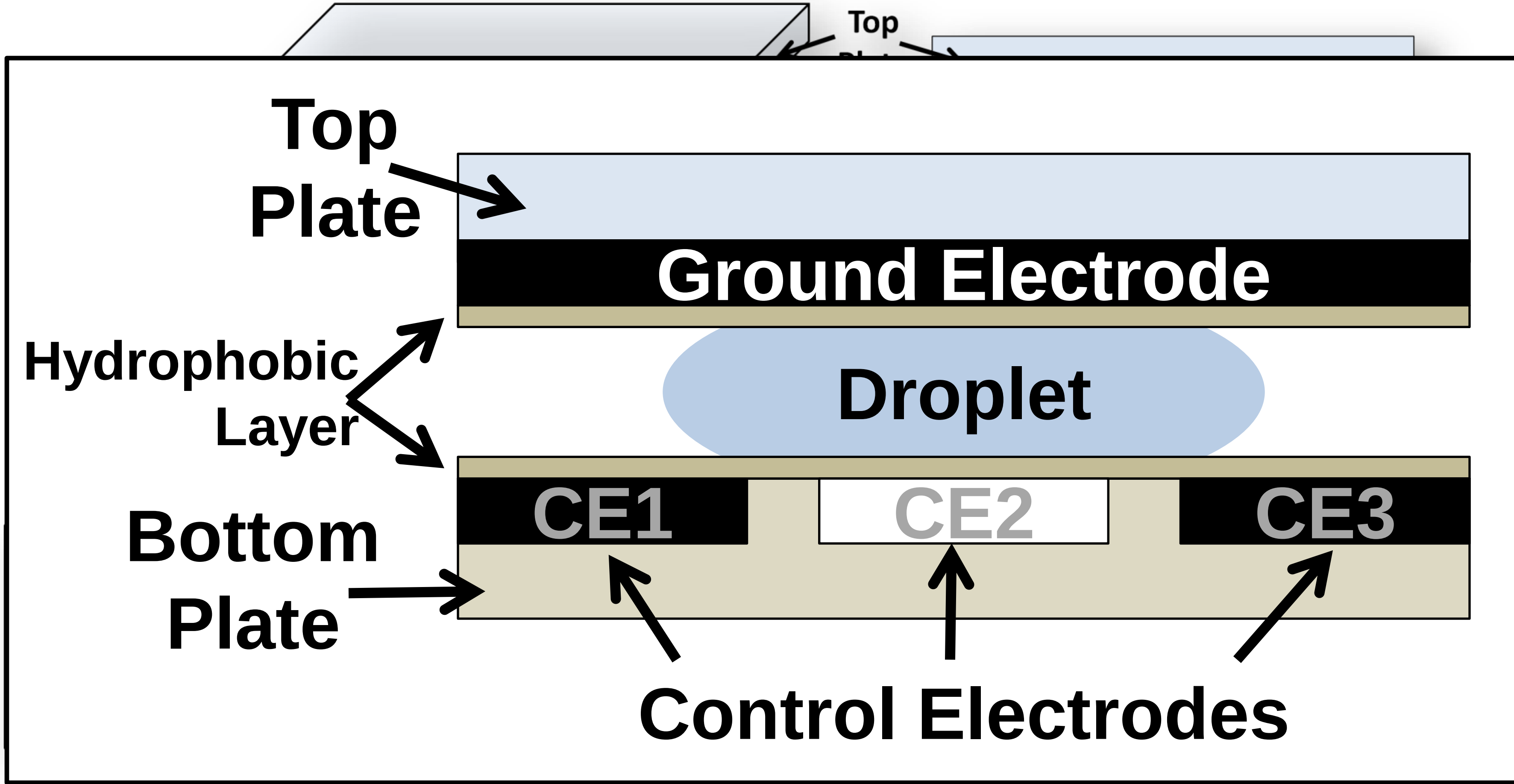
Applications

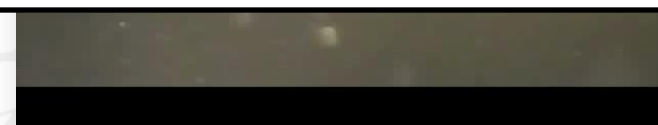
- Biochemical reactions and immunoassays
  - Clinical pathology

- Drug discovery and testing
  - Rapid assay prototyping
- Biochemical terror and hazard detection

- DNA extraction & sequencing

Digital Microfluidic Biochips (DMFB) 101

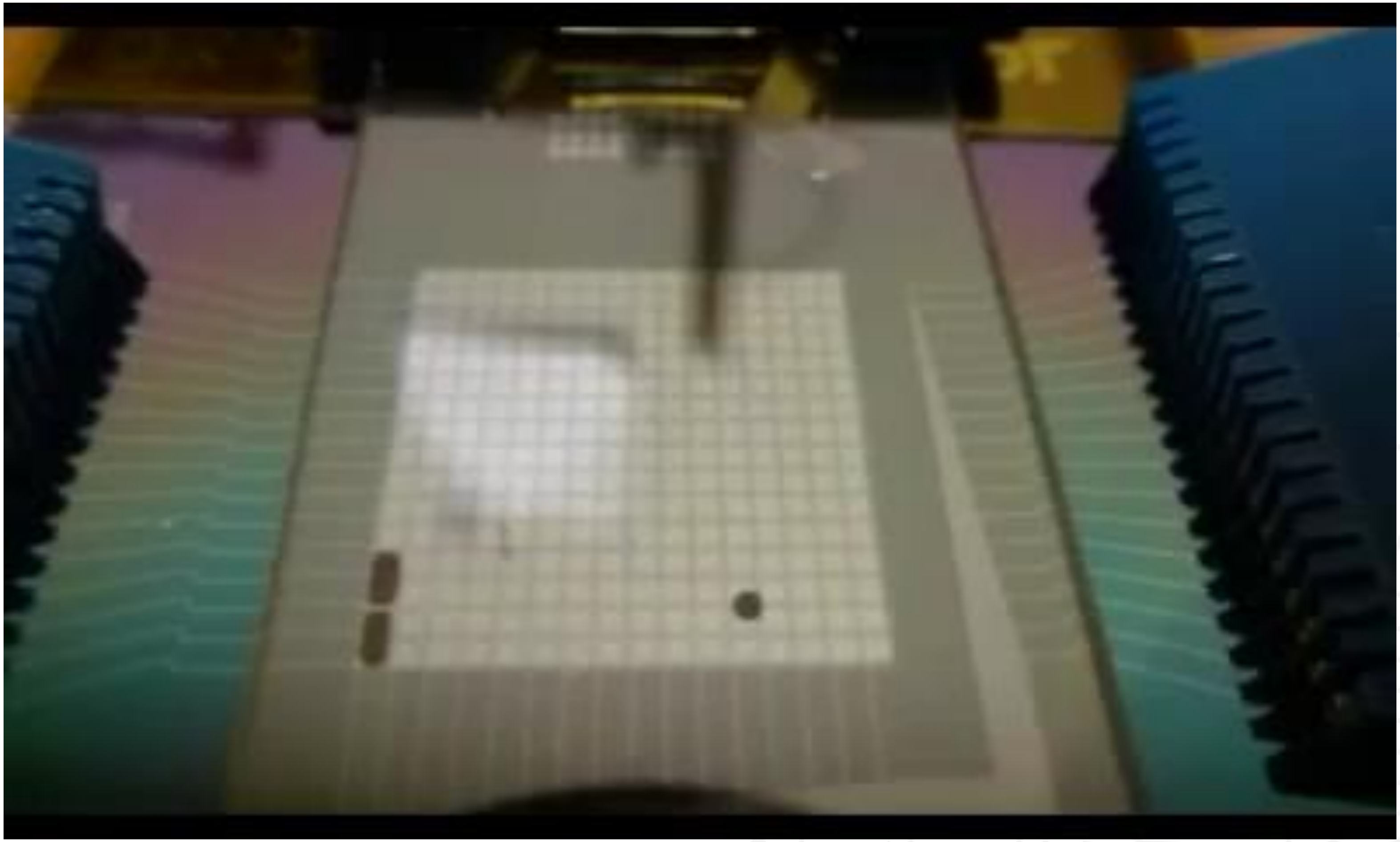




Basic Microfluidic Operations

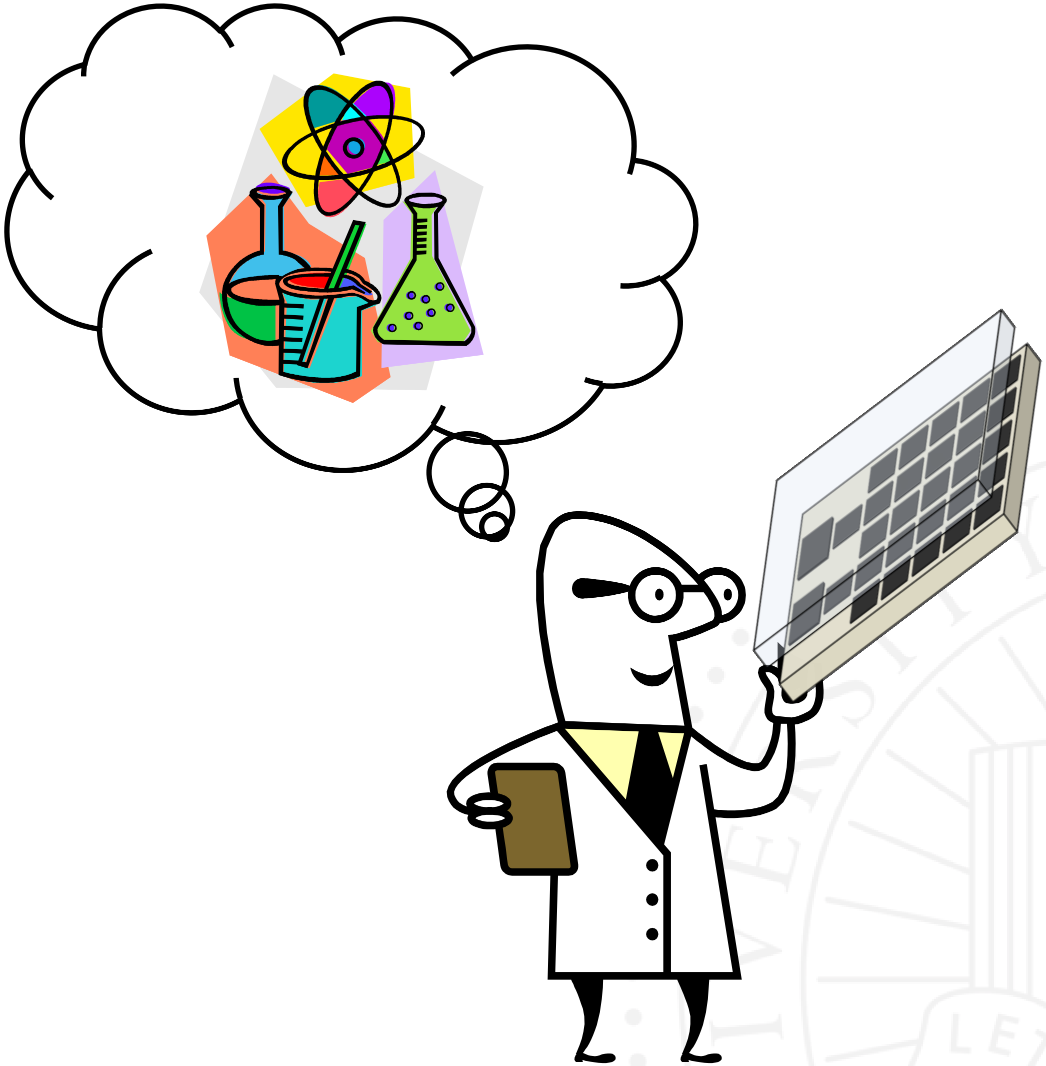
http://microfluidics.ee.duke.edu/

Digital Microfluidic Biochips (DMFB) 101



Droplet Actuation on a Prototype DMFB at the University of Tennessee

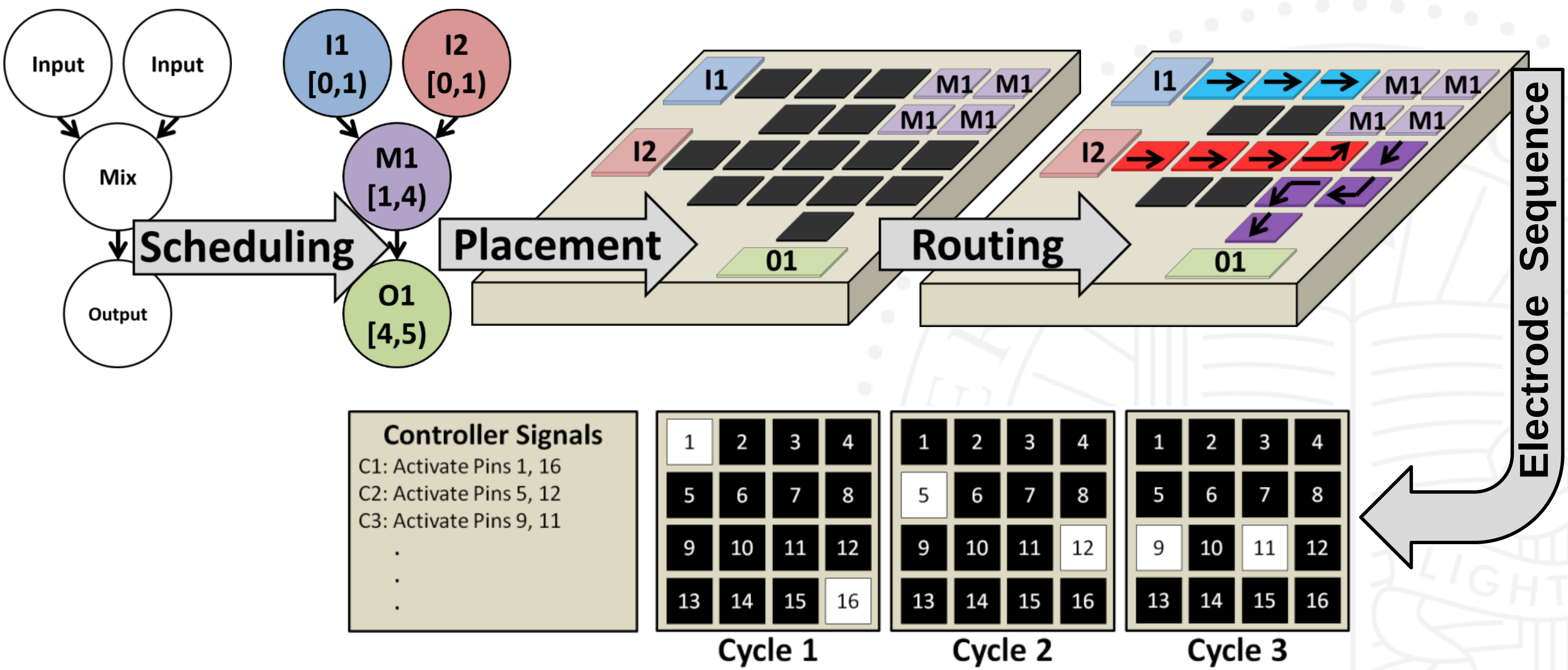
DMFB Mapping



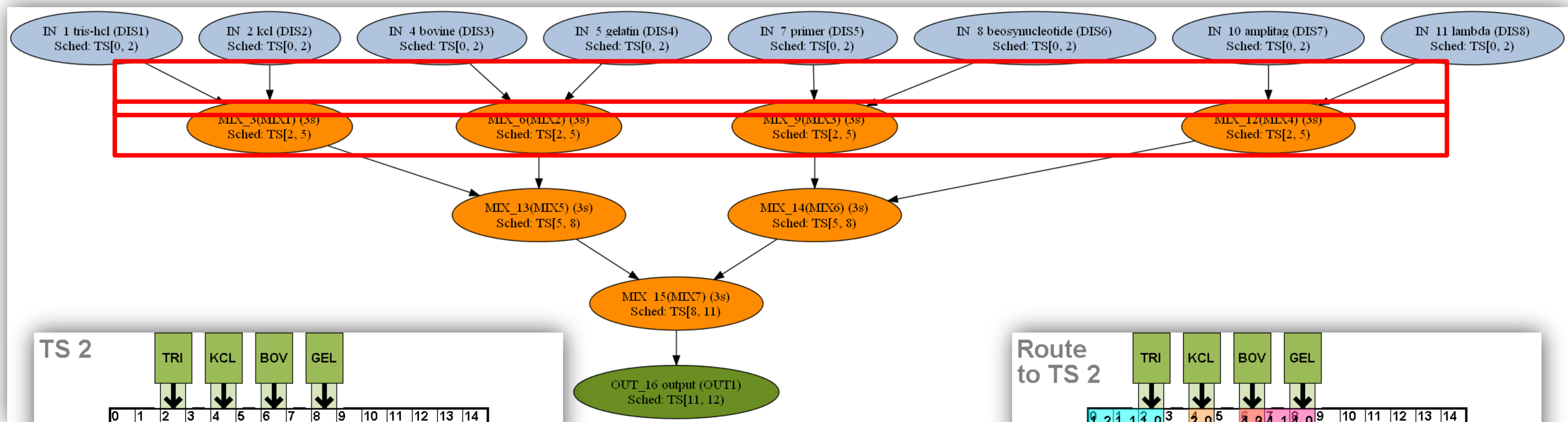
How do I make a reaction run on a DMFB?

CAD Synthesis Flow

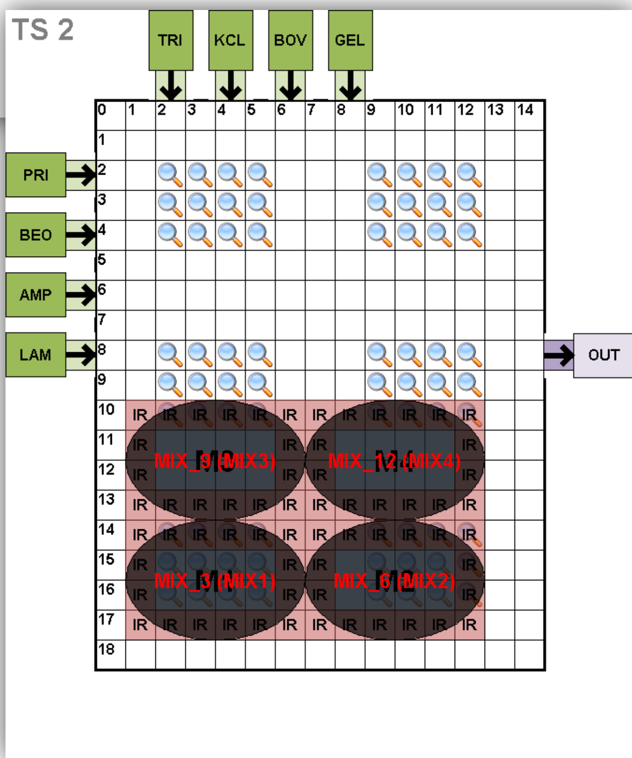
- Synthesis: The process of **mapping** an application to hardware
  - Similar to how applications are mapped to ICs



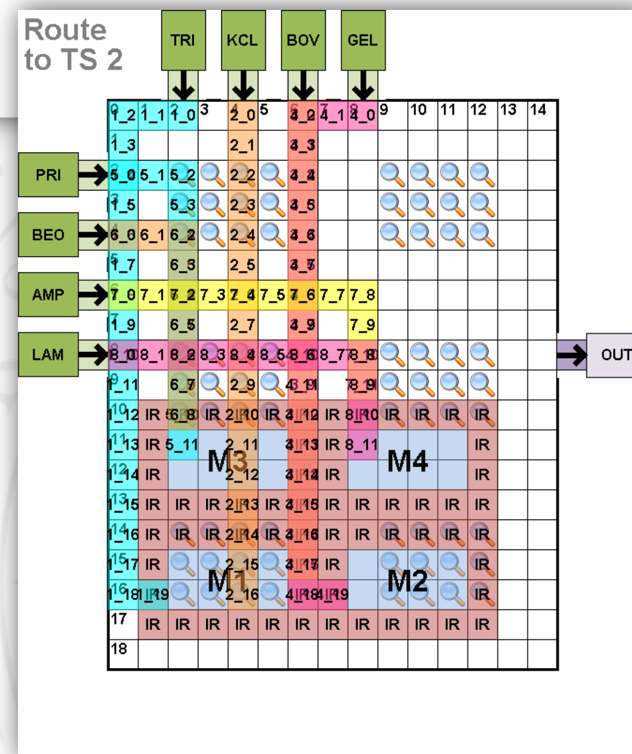
Synthesis Example



1.) Schedule

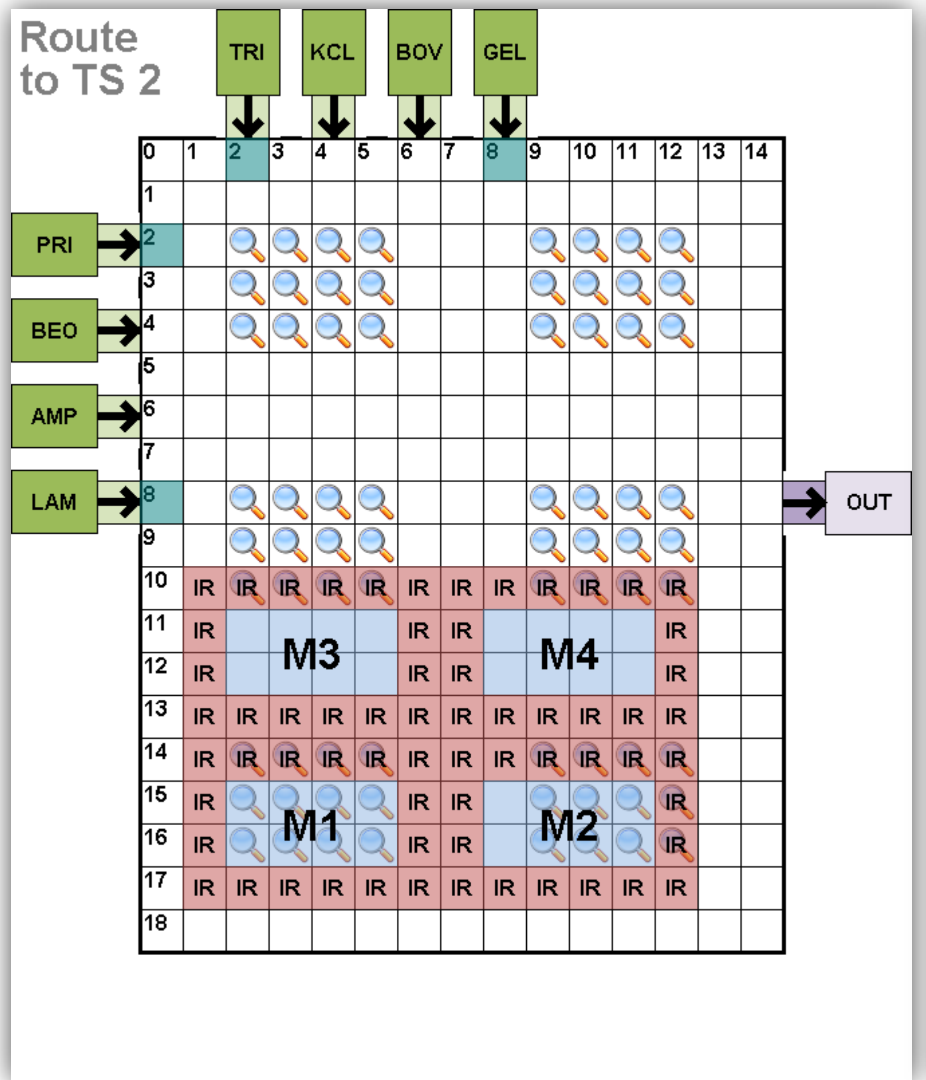


2.) Place

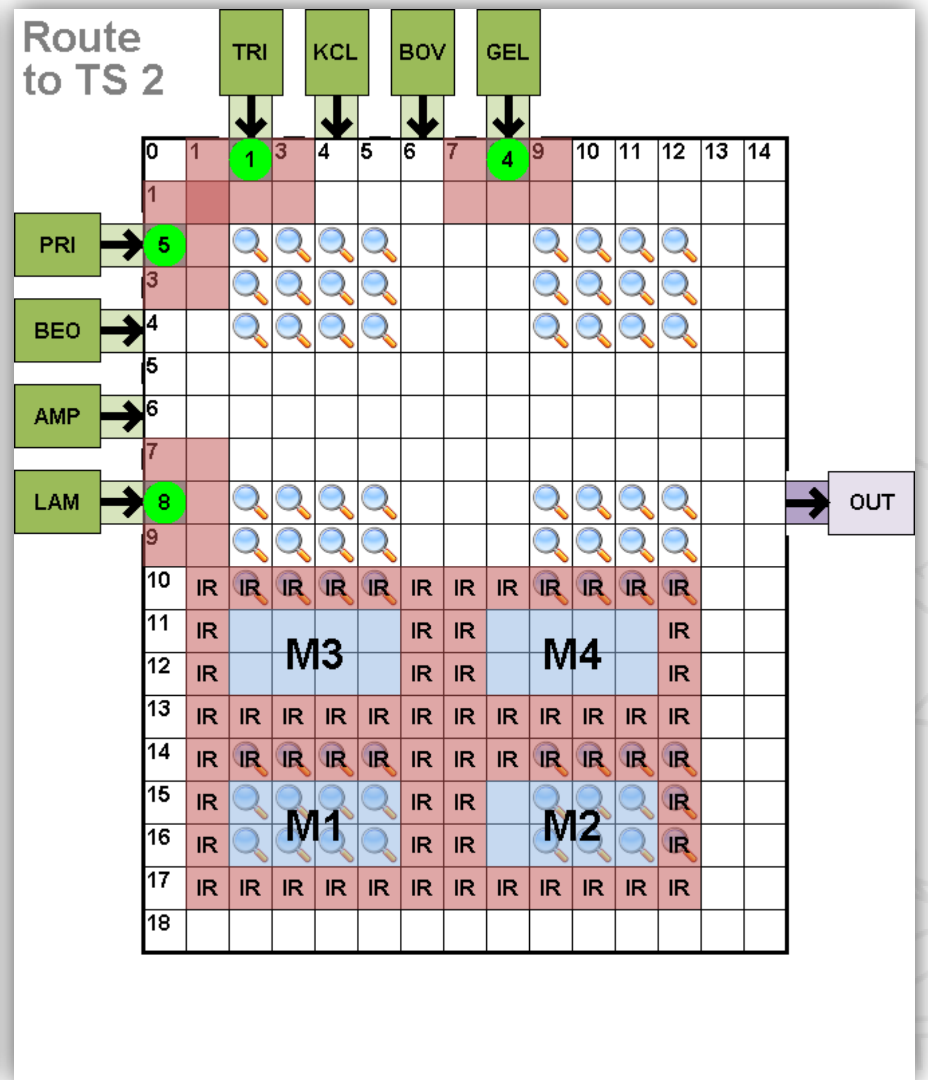


3.) Route

Compaction Example

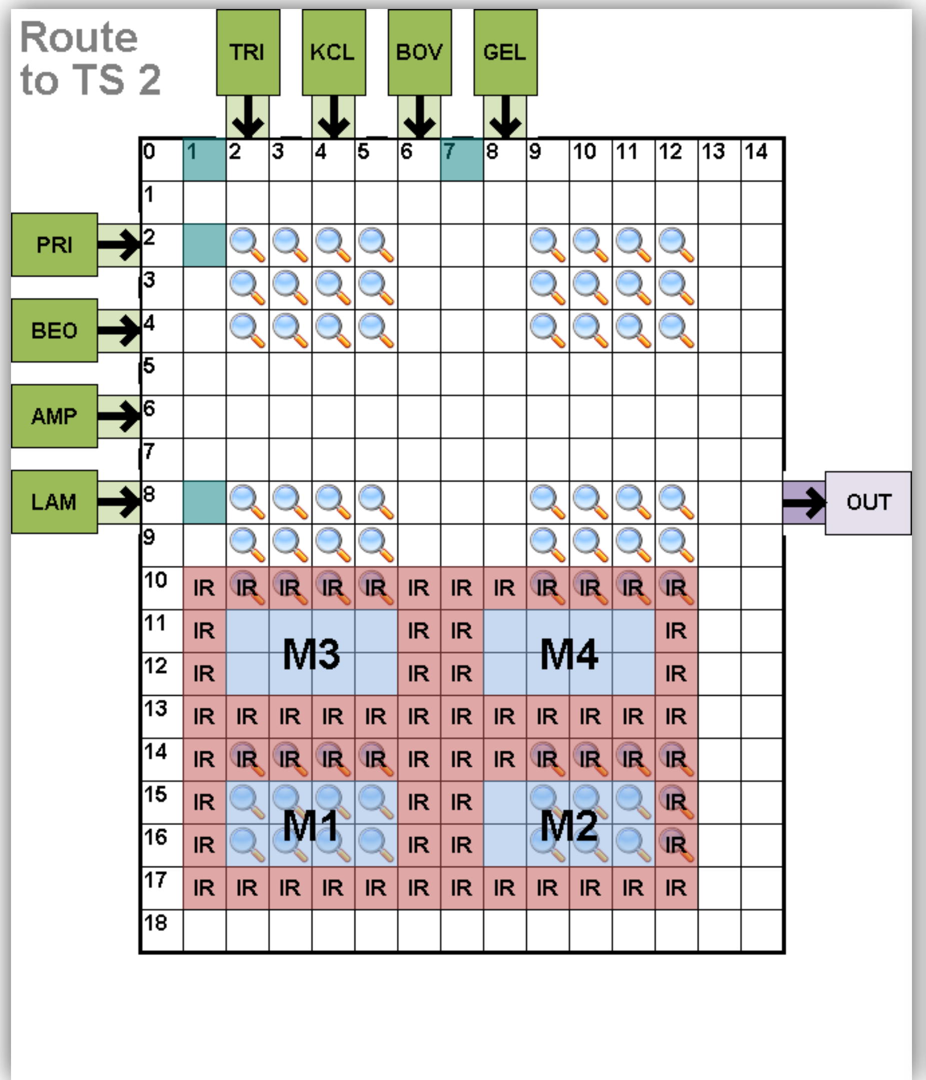


Electrode Activations



Corresponding Droplet Motion

Compaction Example



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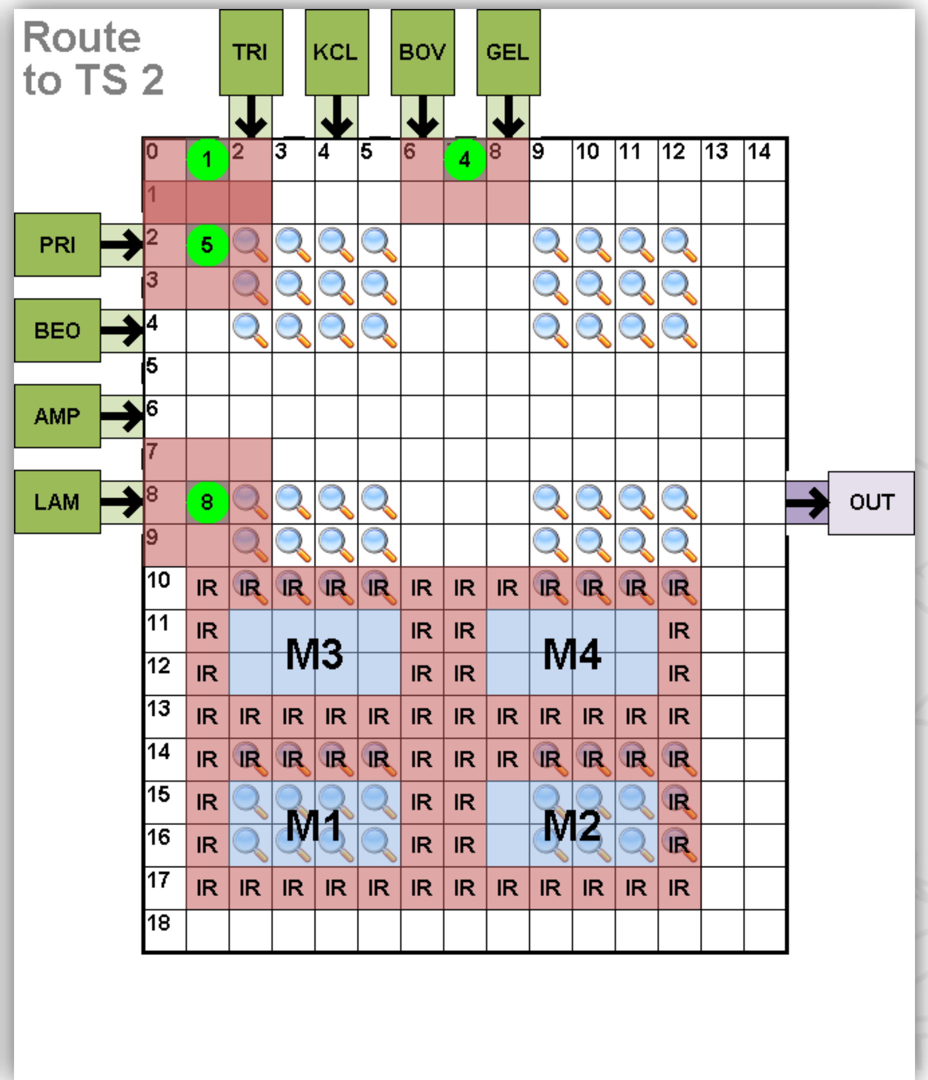
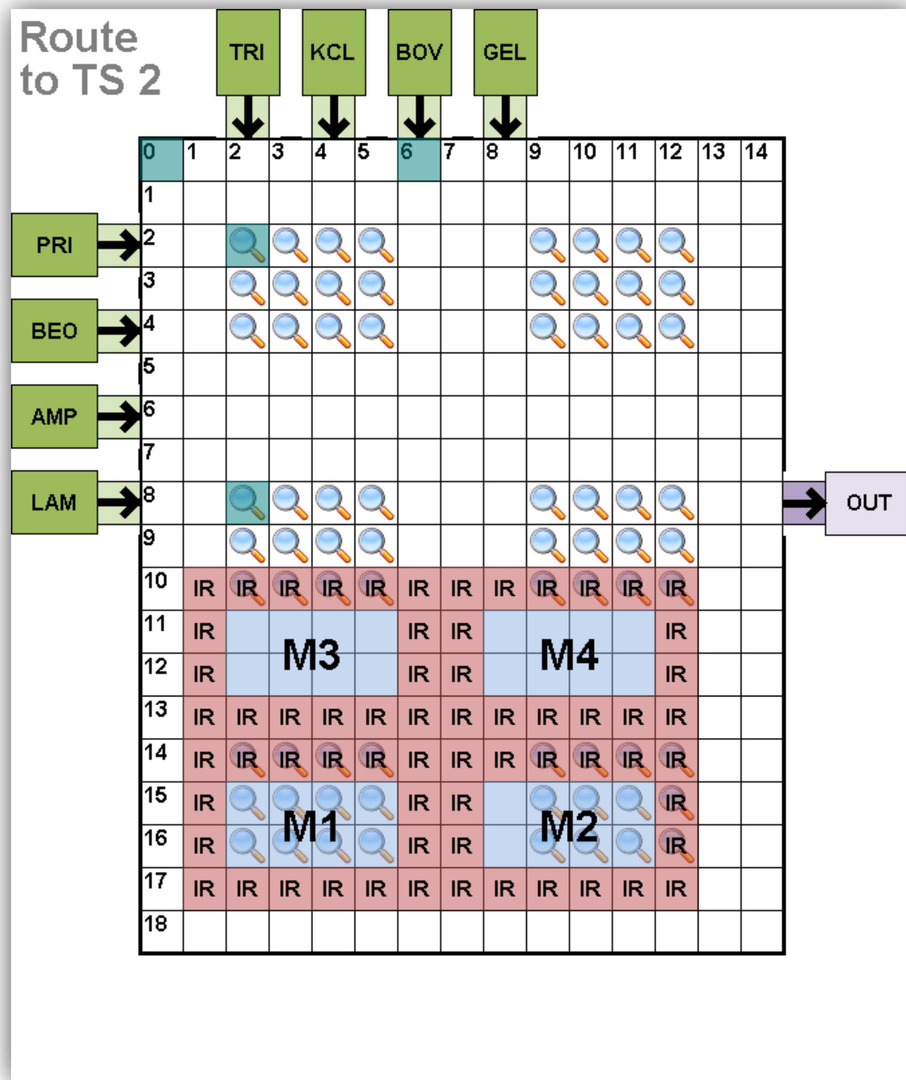


Corresponding Droplet Motion

Compaction Example



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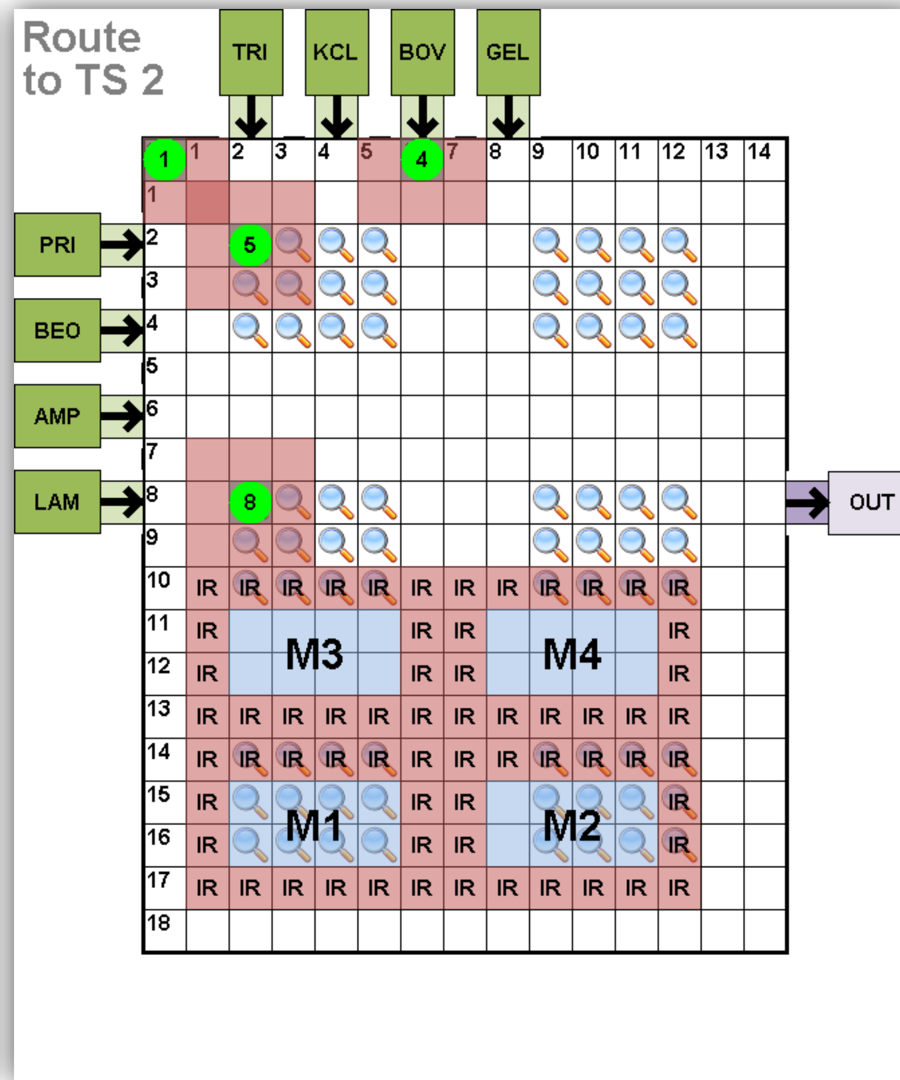

Corresponding Droplet Motion

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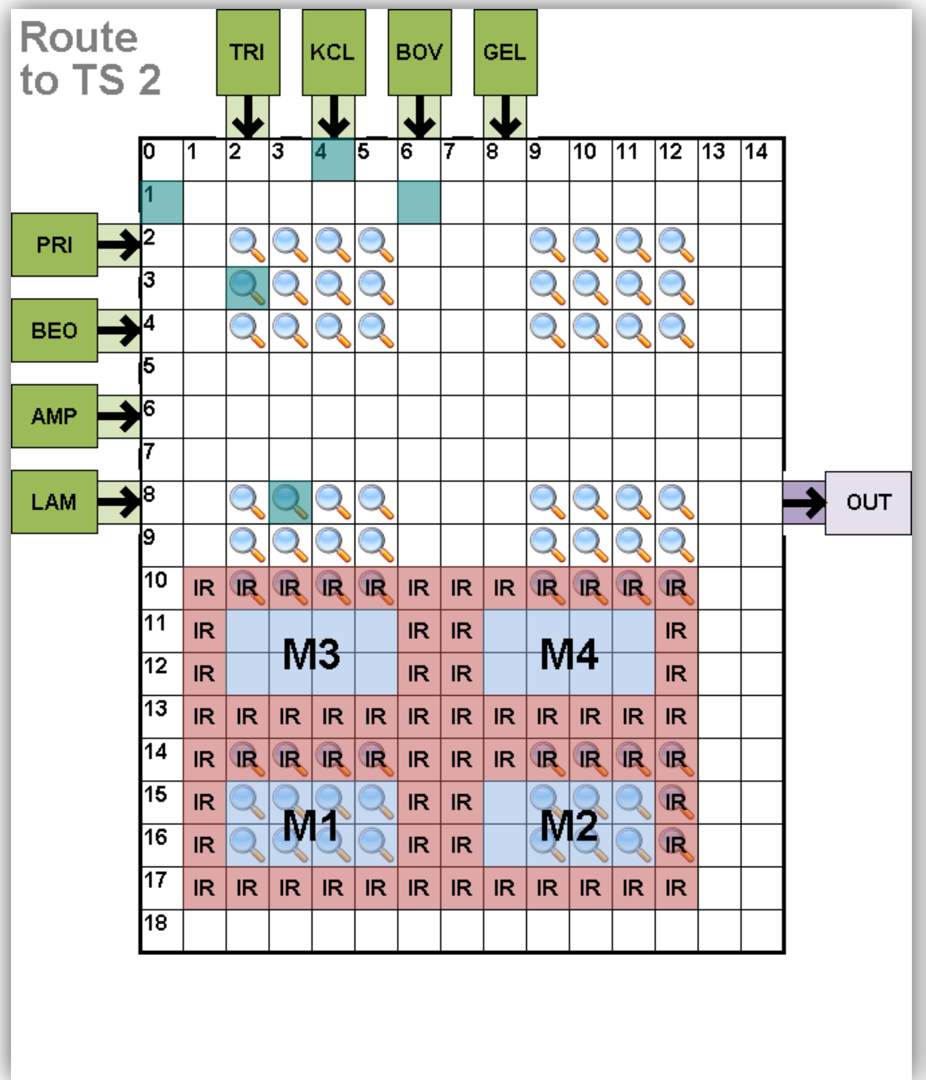

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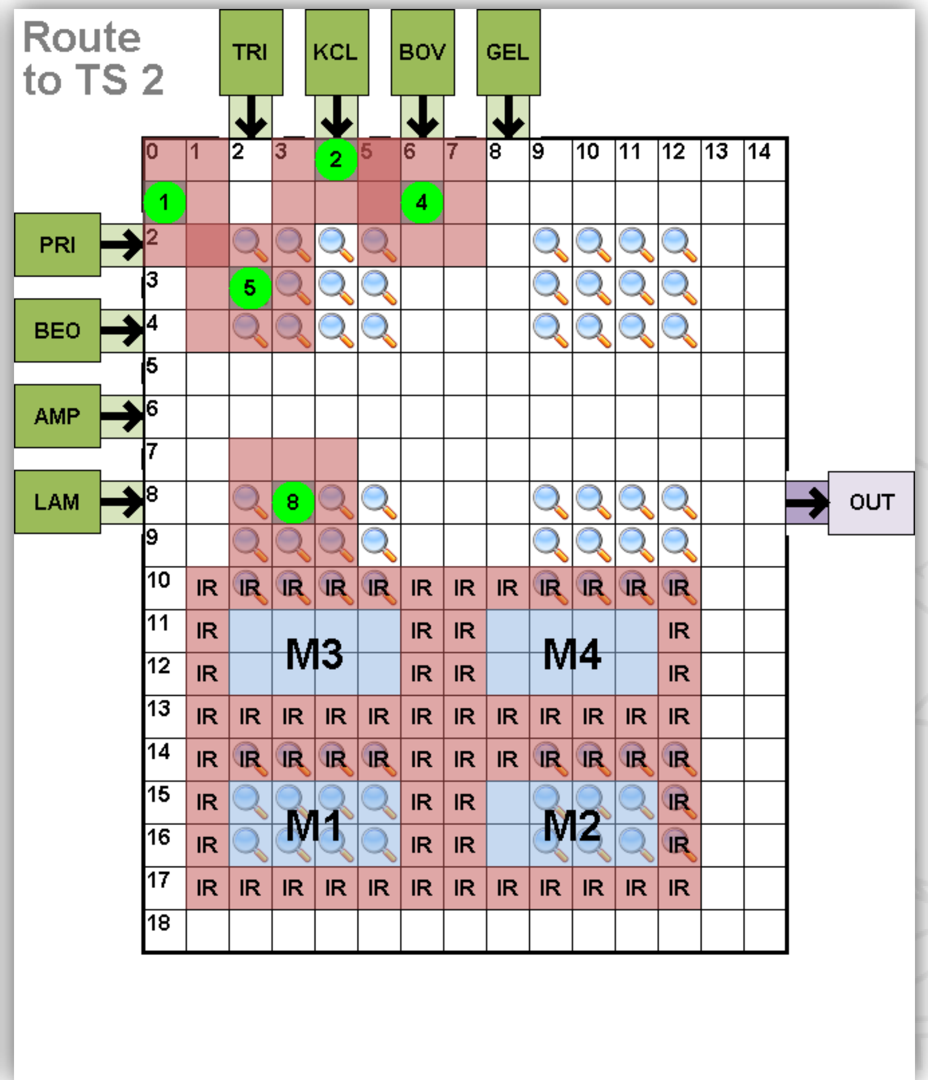
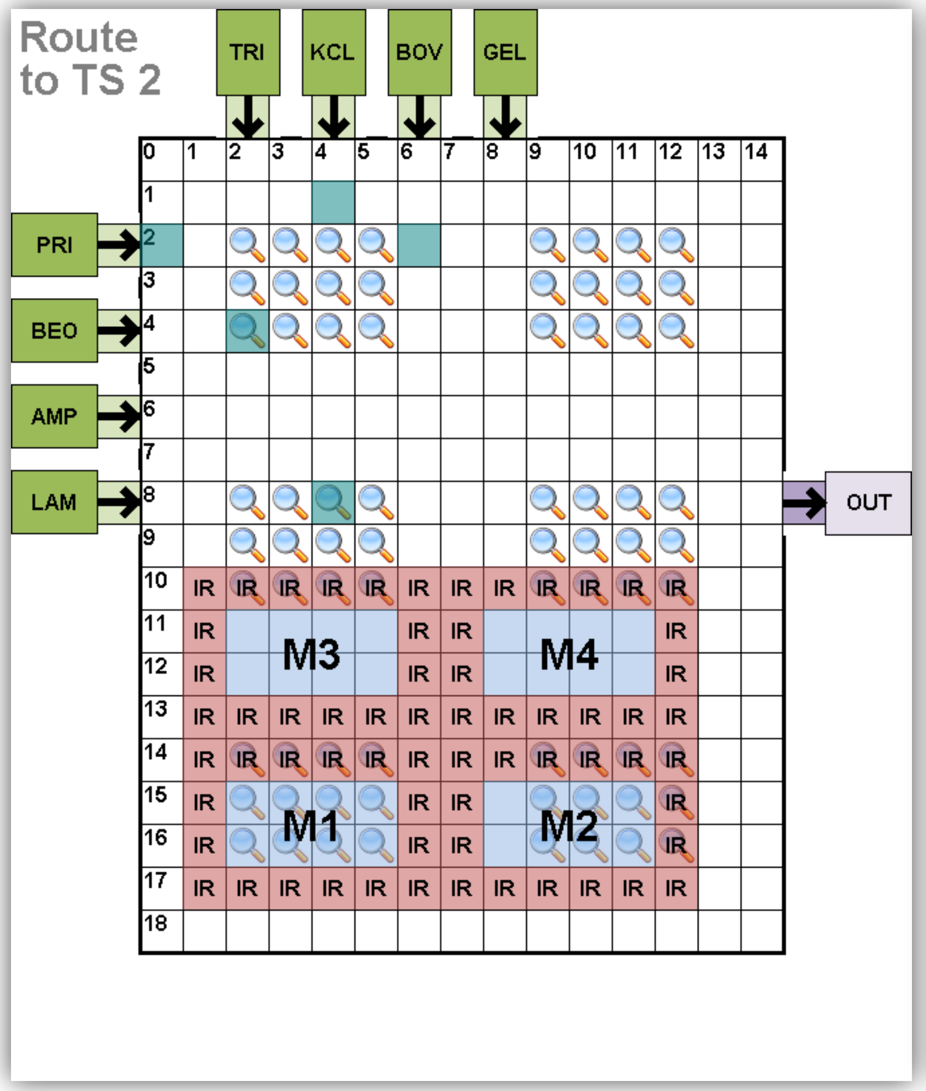


Corresponding Droplet Motion

Compaction Example



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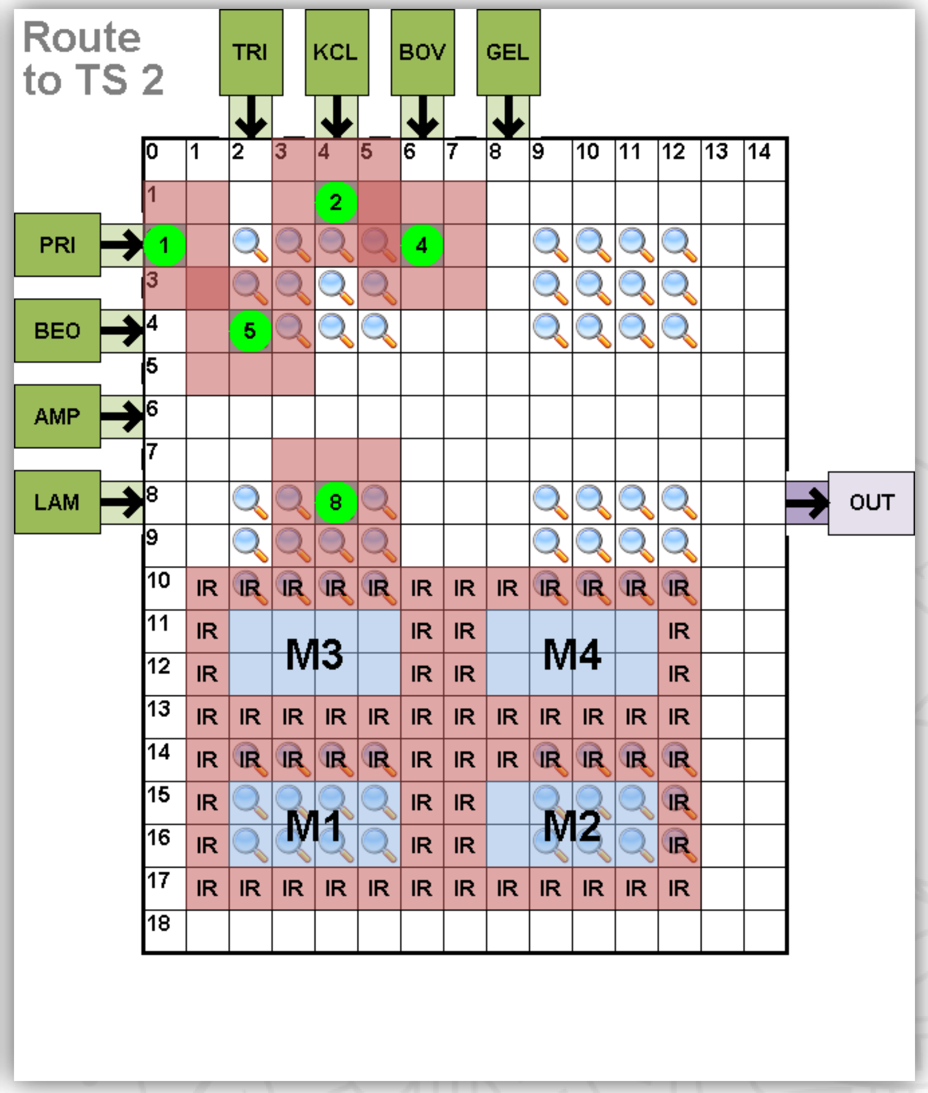

Corresponding Droplet Motion

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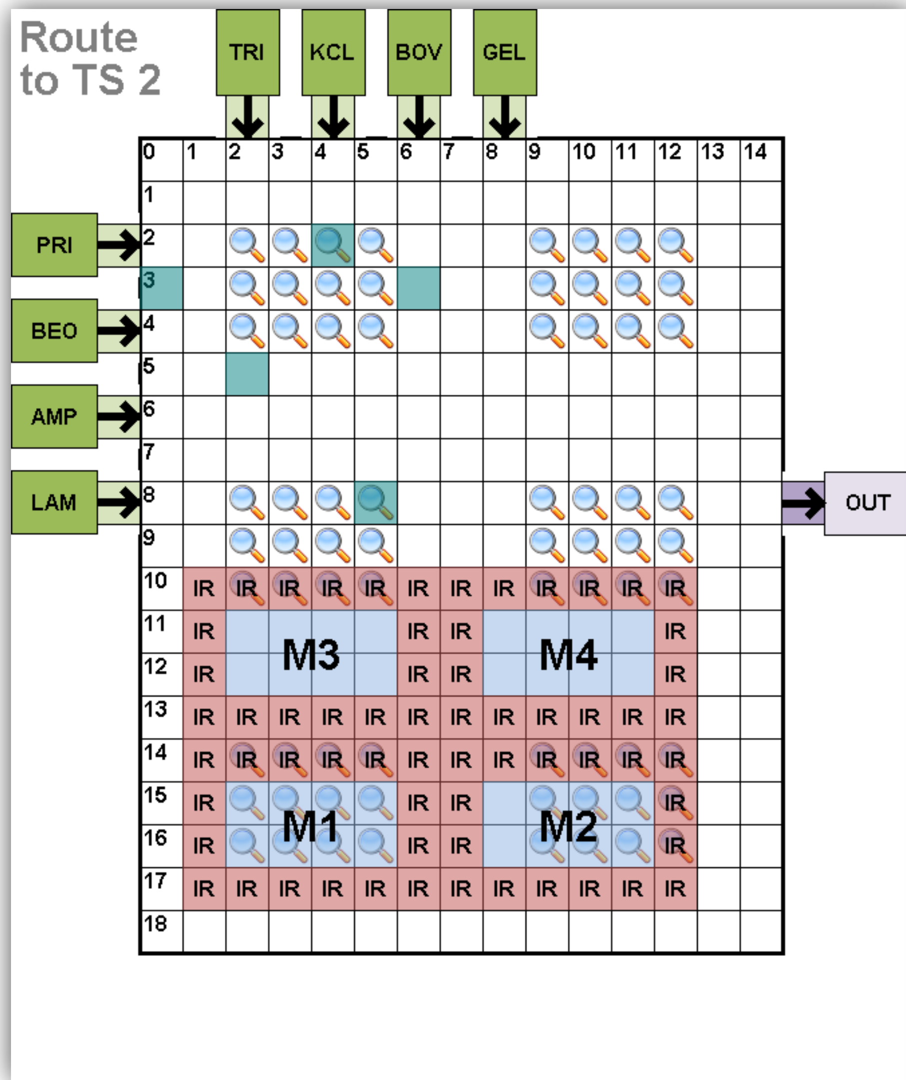

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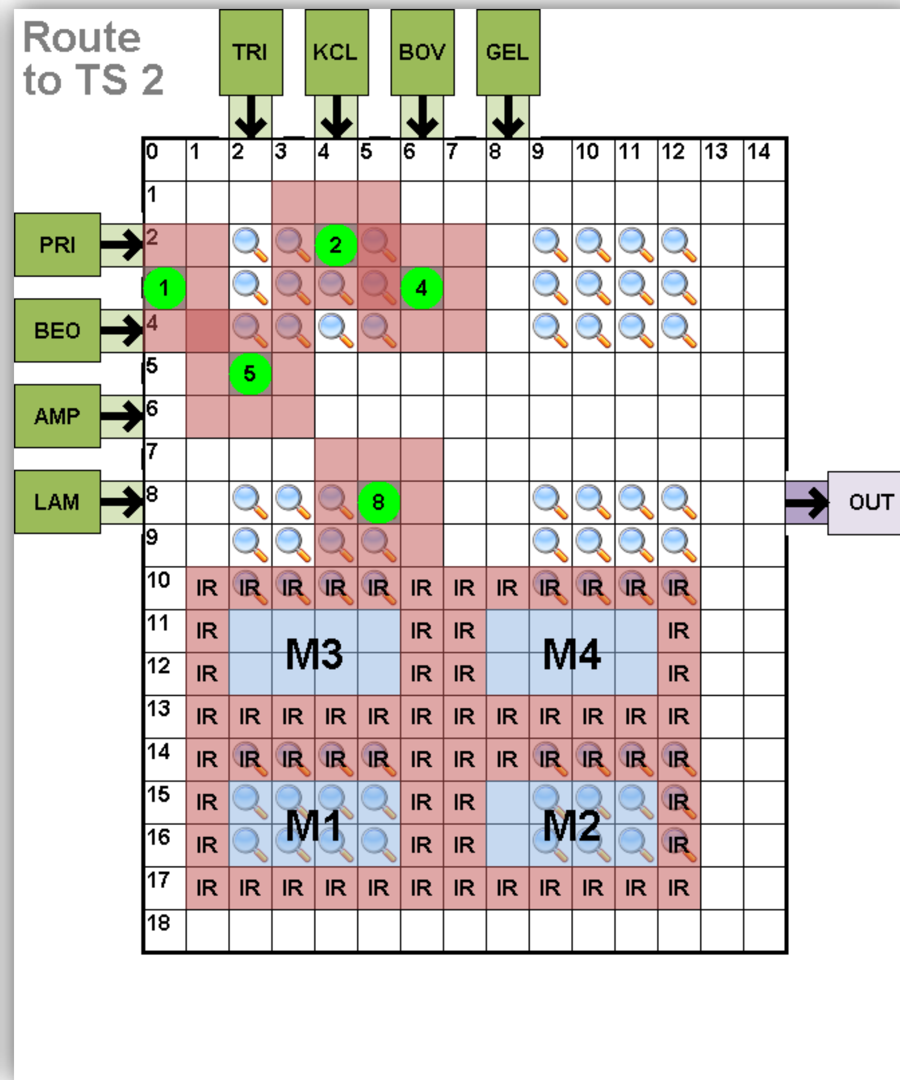

Corresponding Droplet Motion

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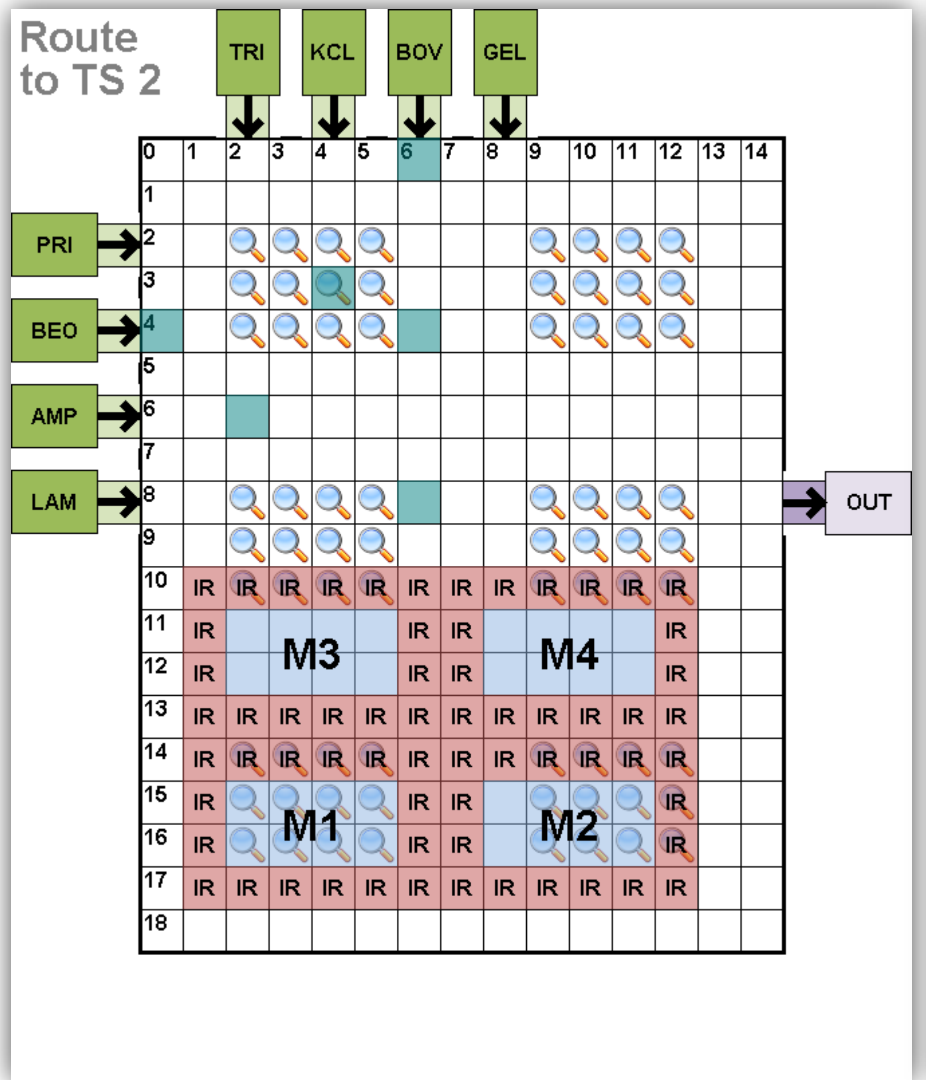

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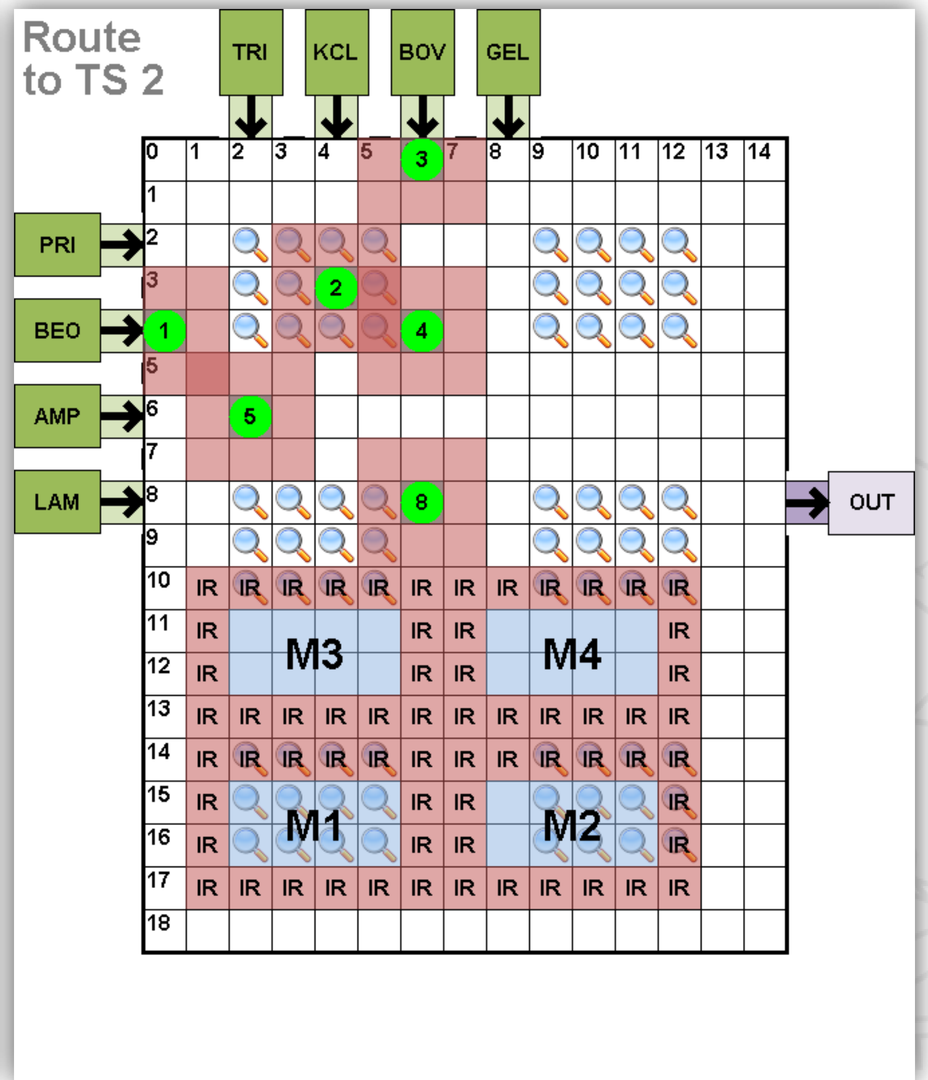

Corresponding Droplet Motion

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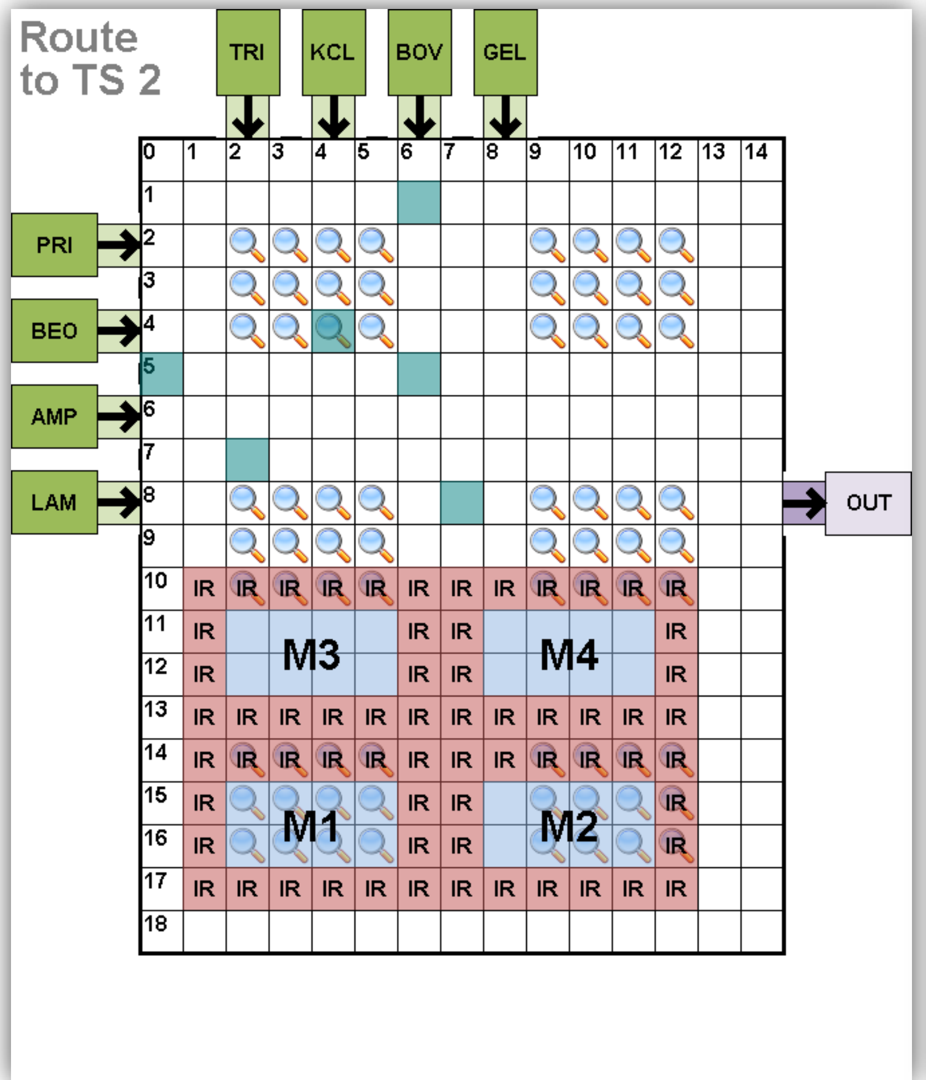

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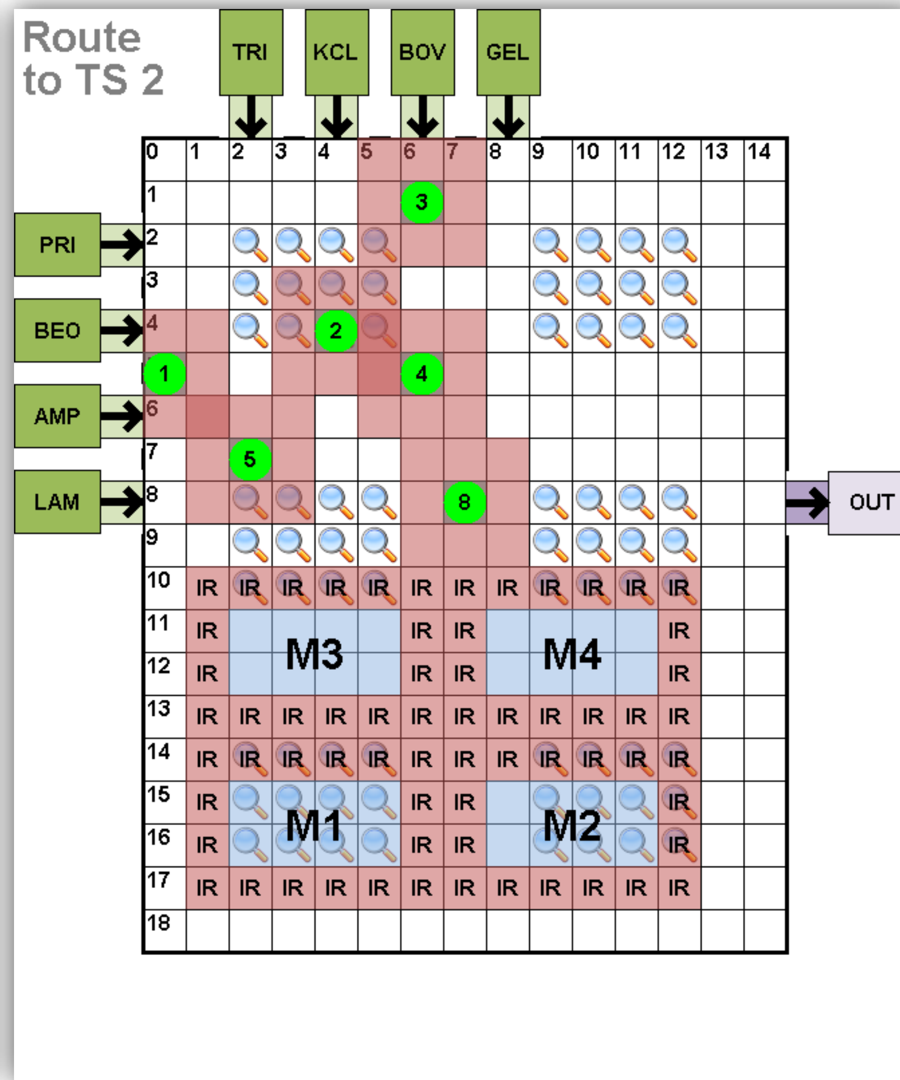

Corresponding Droplet Motion

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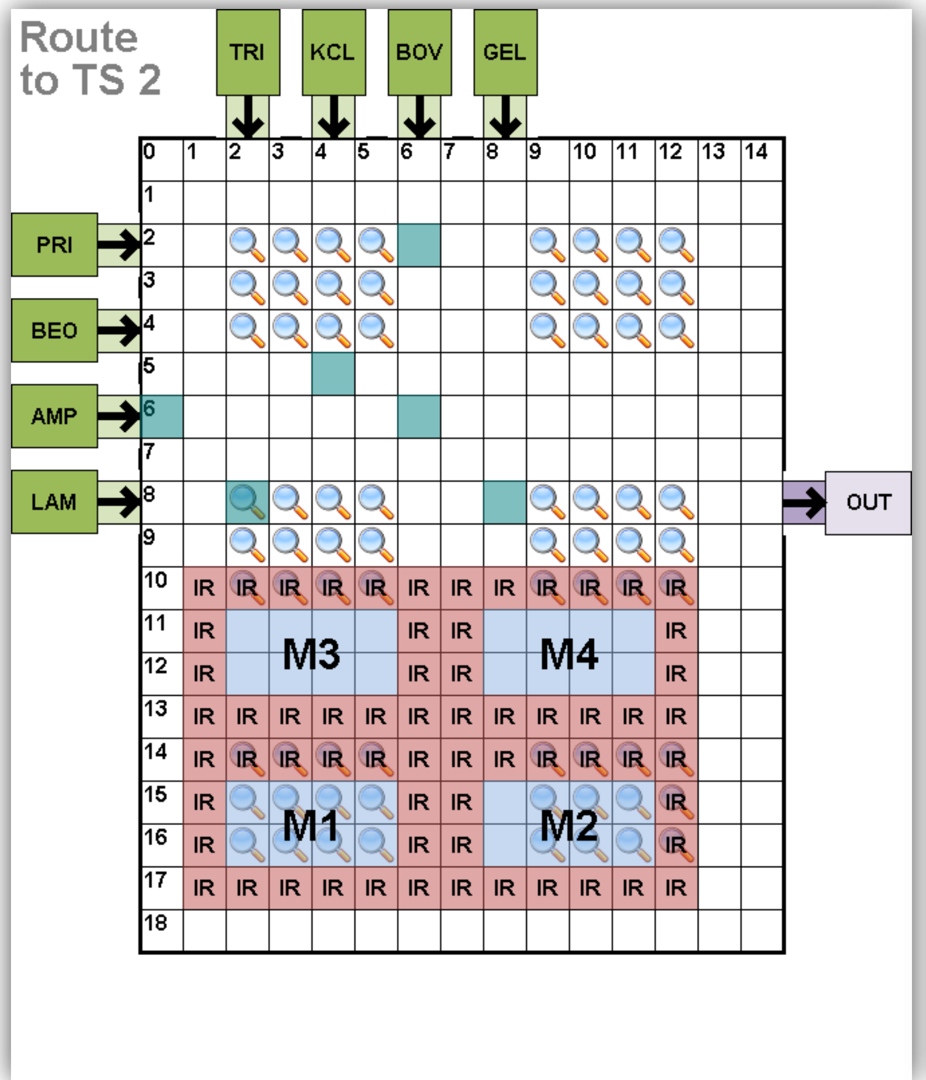

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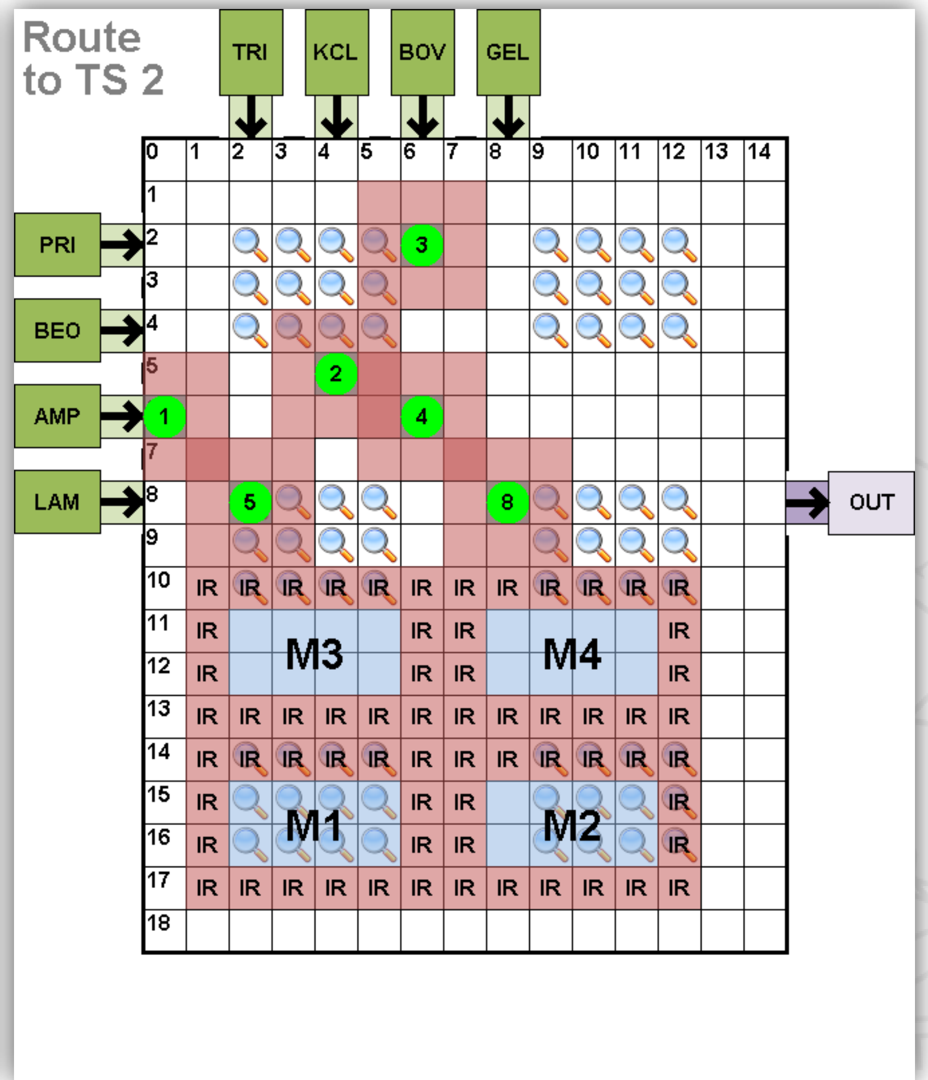

Corresponding Droplet Motion

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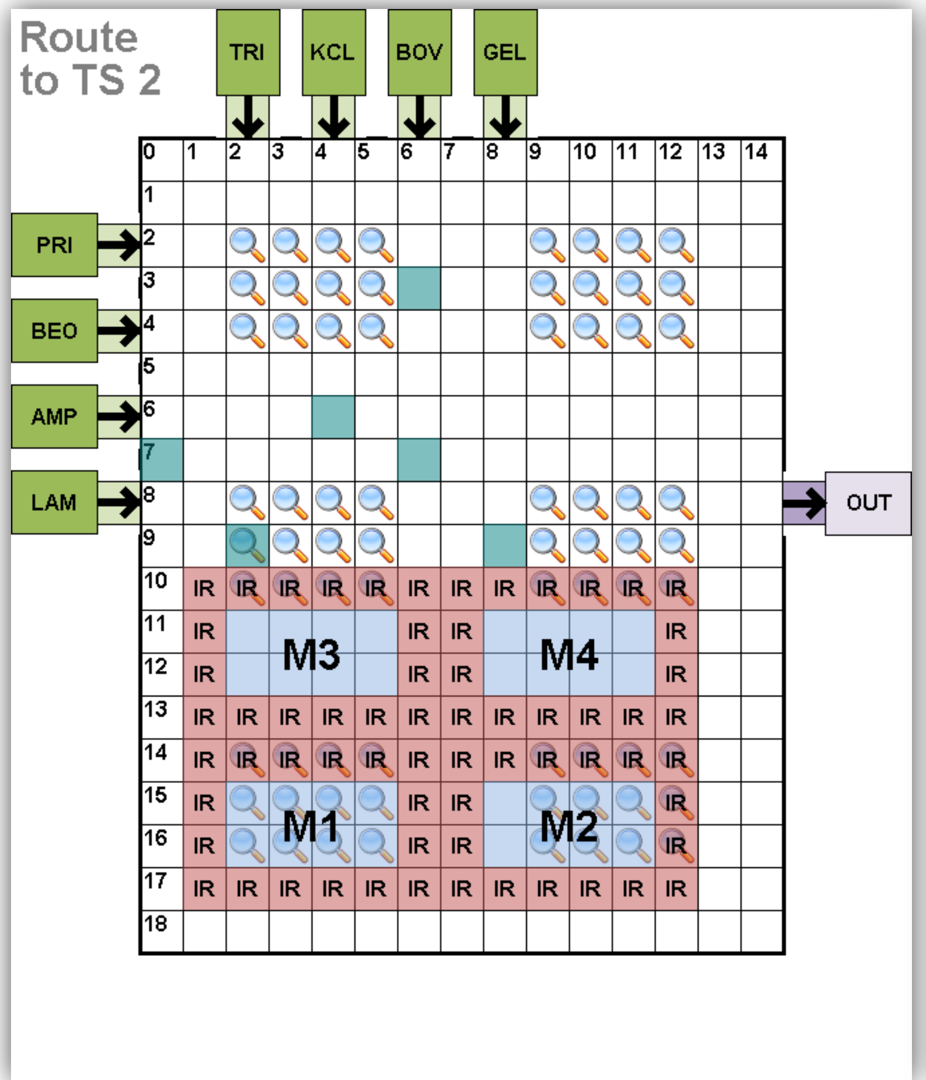

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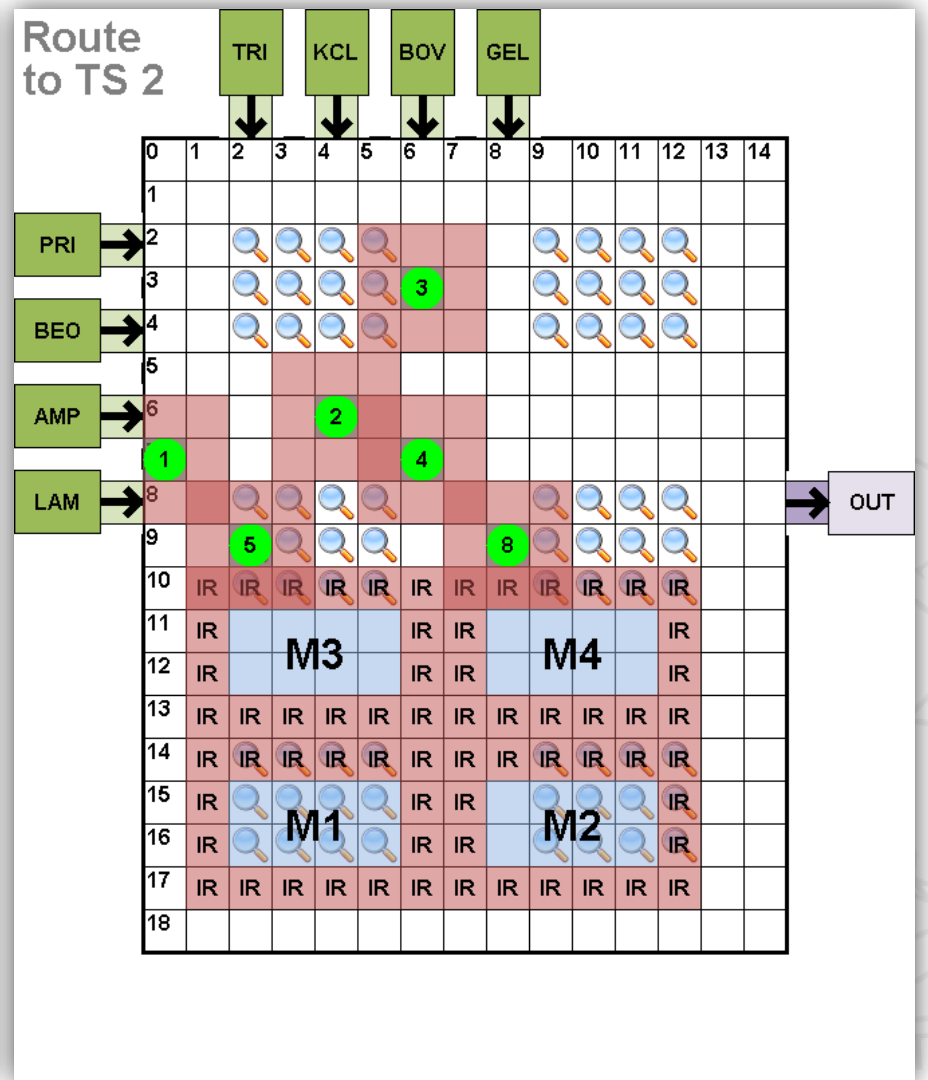

Corresponding Droplet Motion

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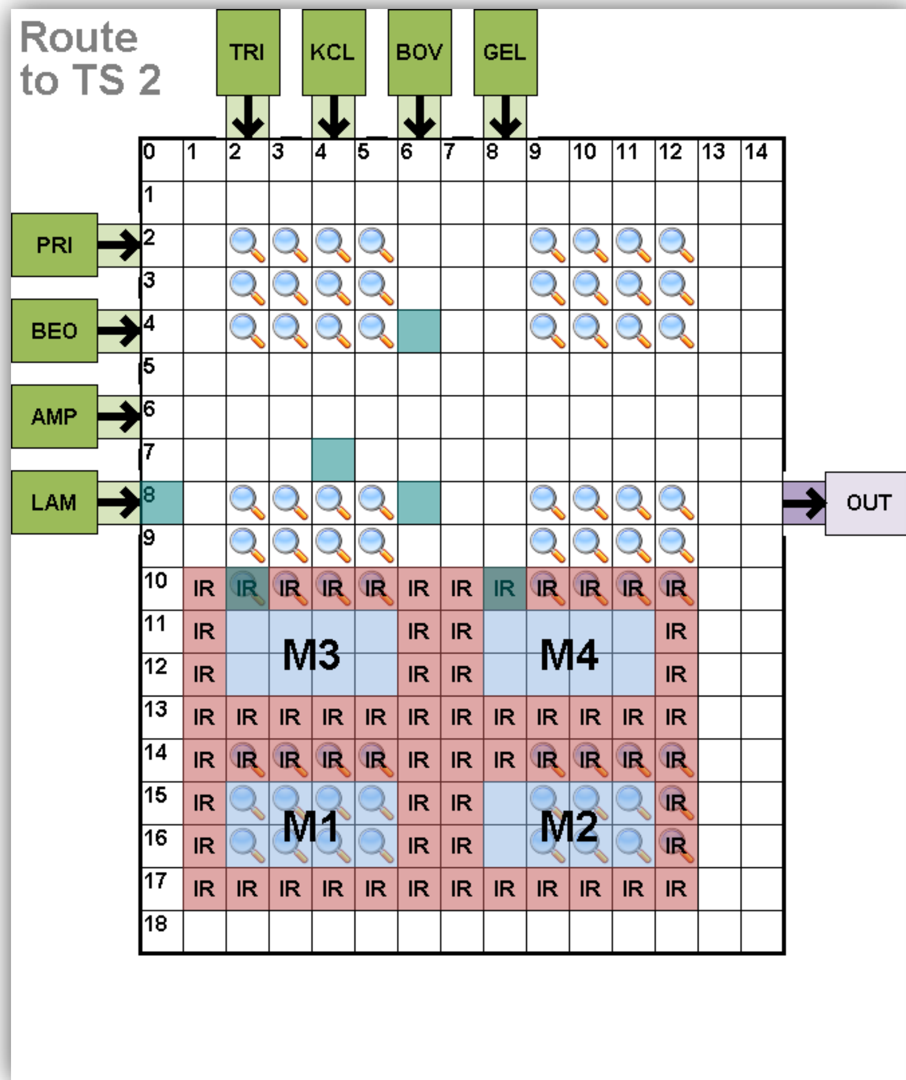

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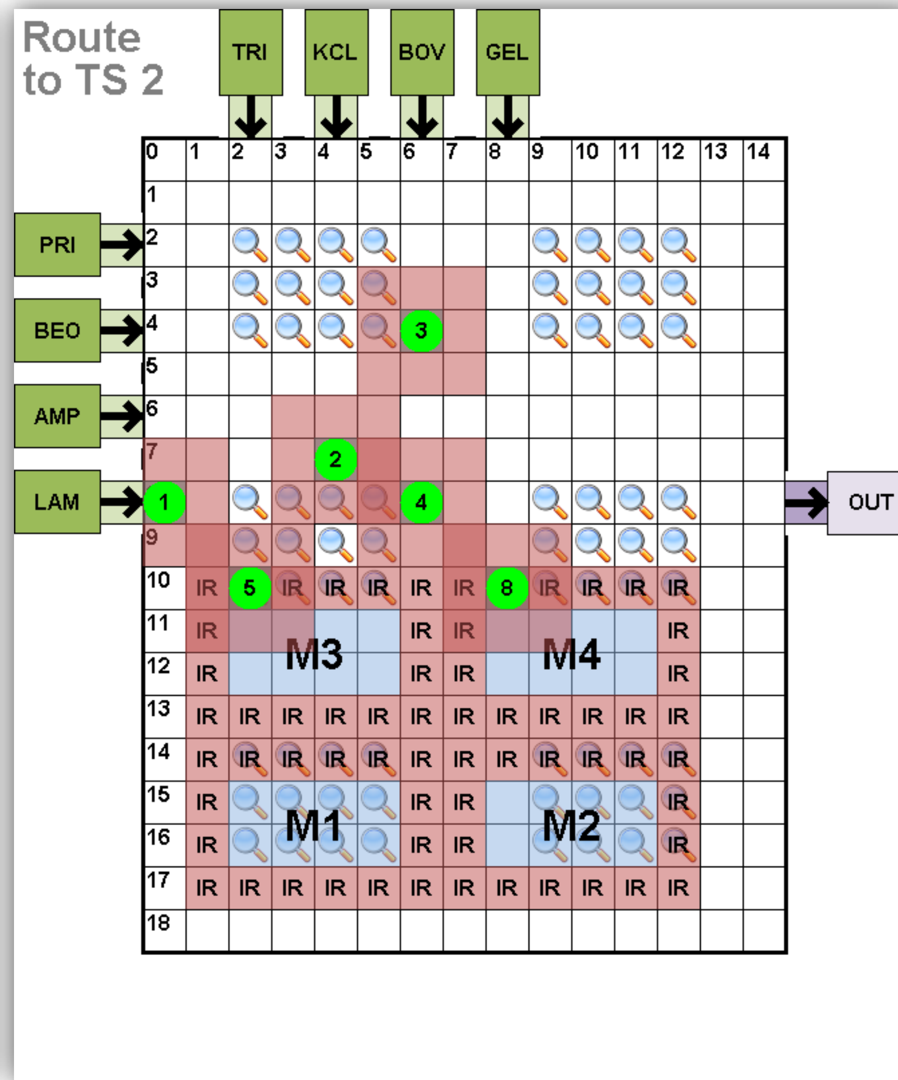

Corresponding Droplet Motion

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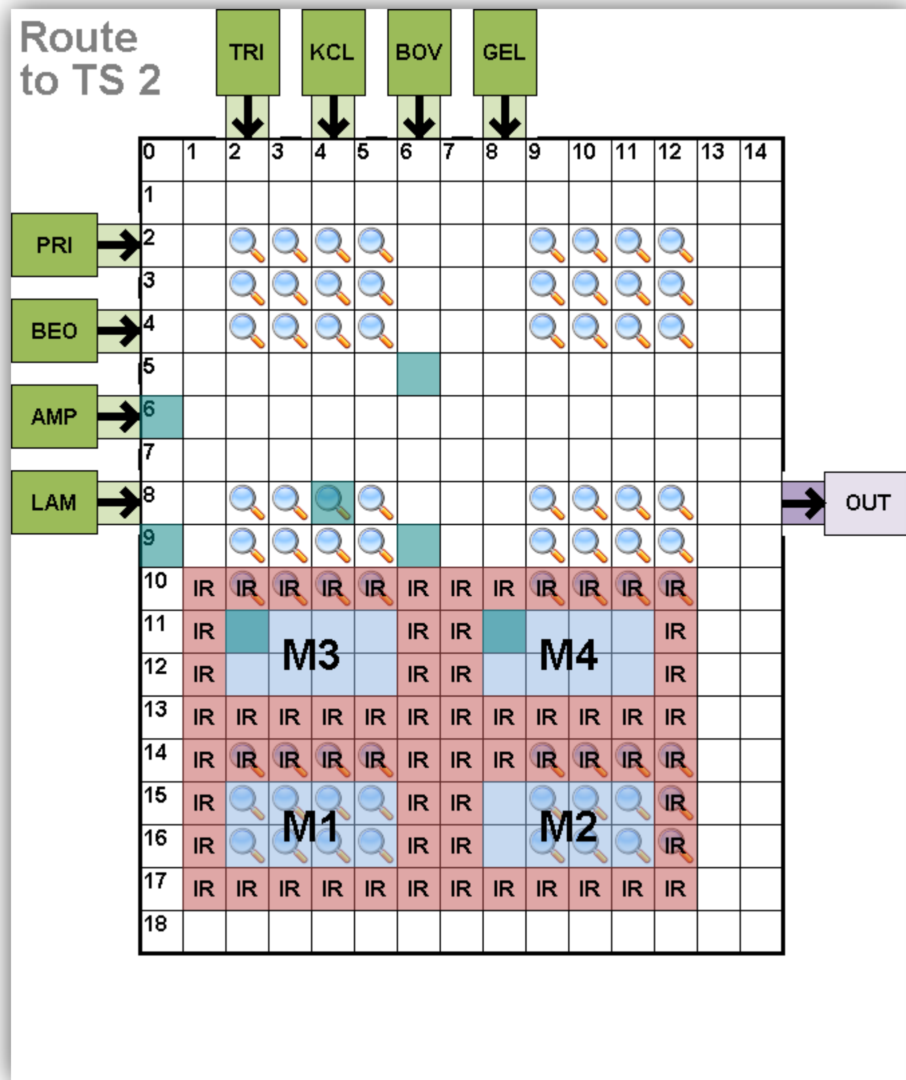

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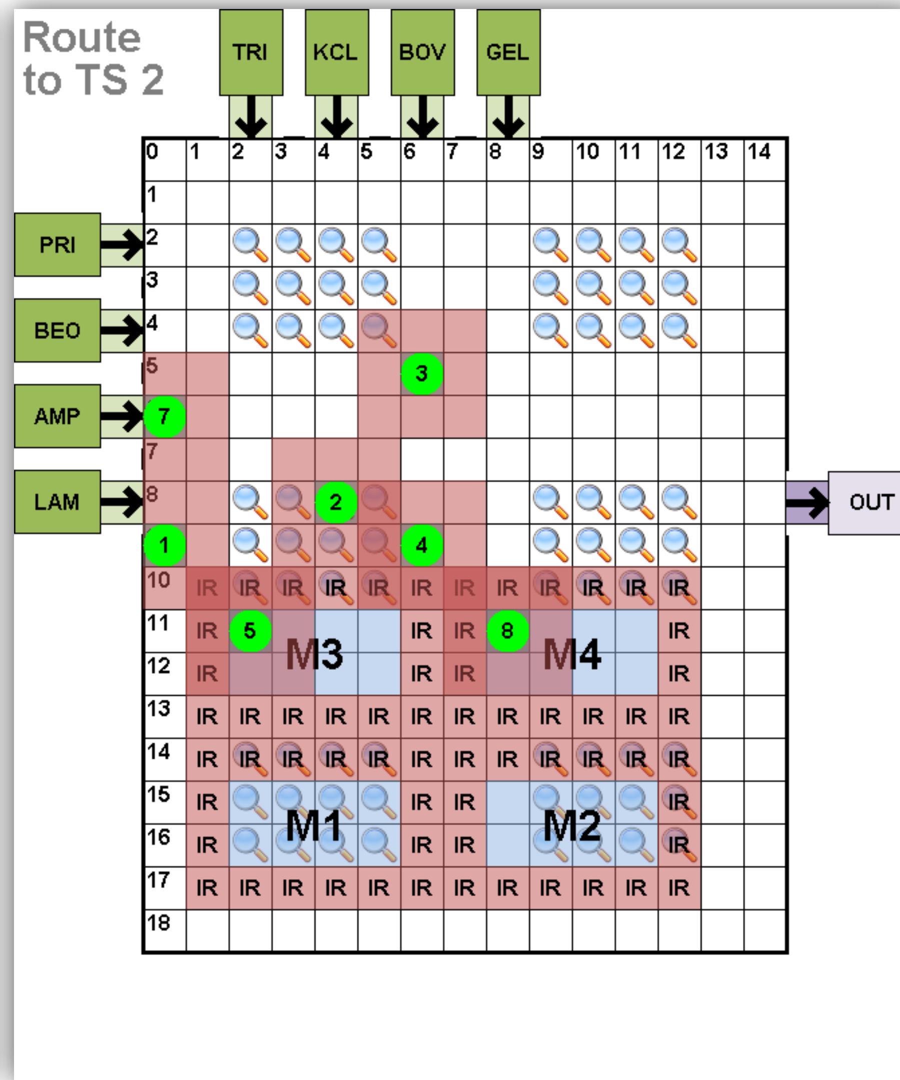

Corresponding Droplet Motion

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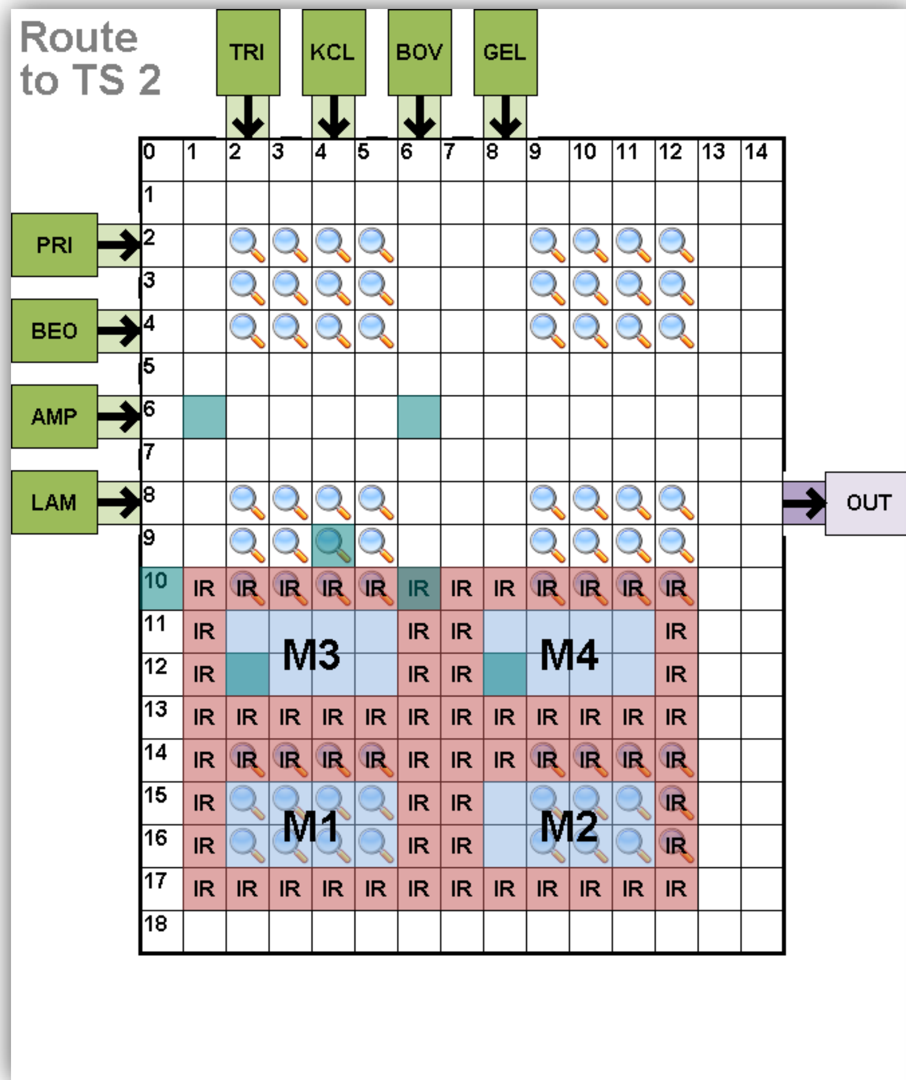

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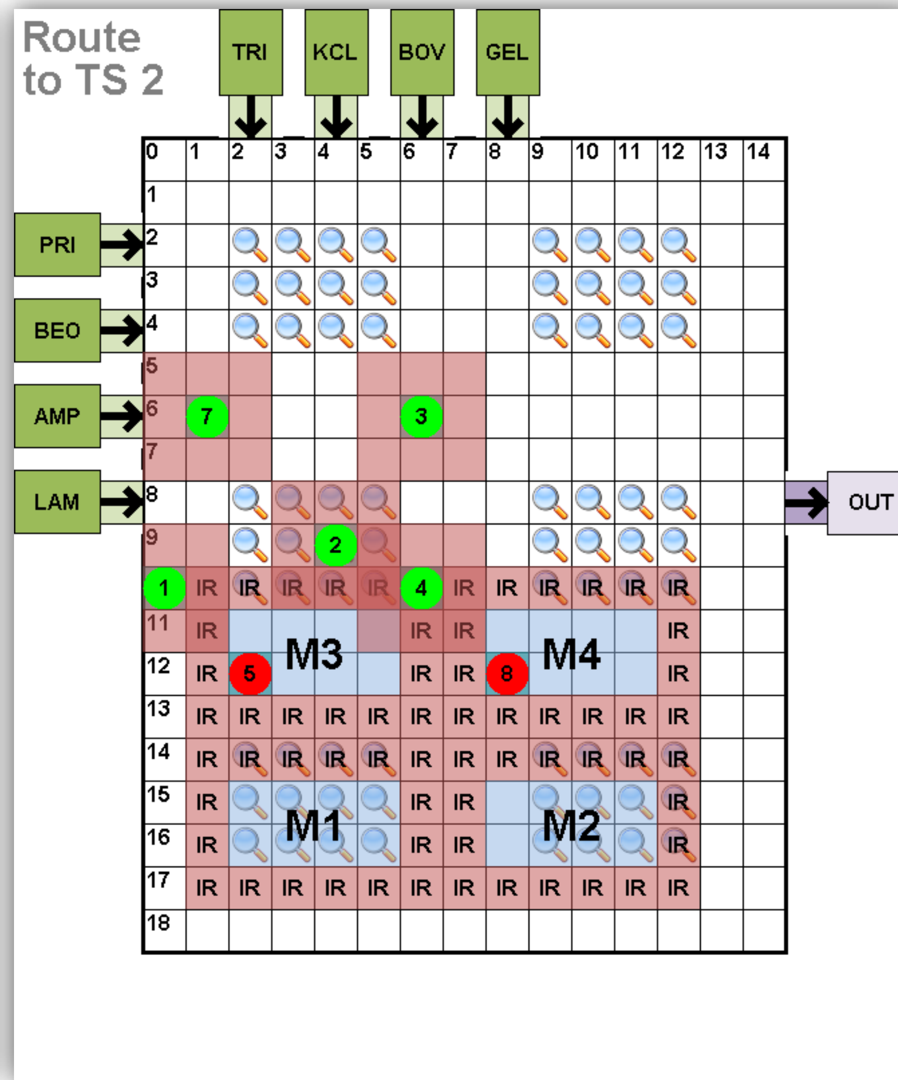

Corresponding Droplet Motion

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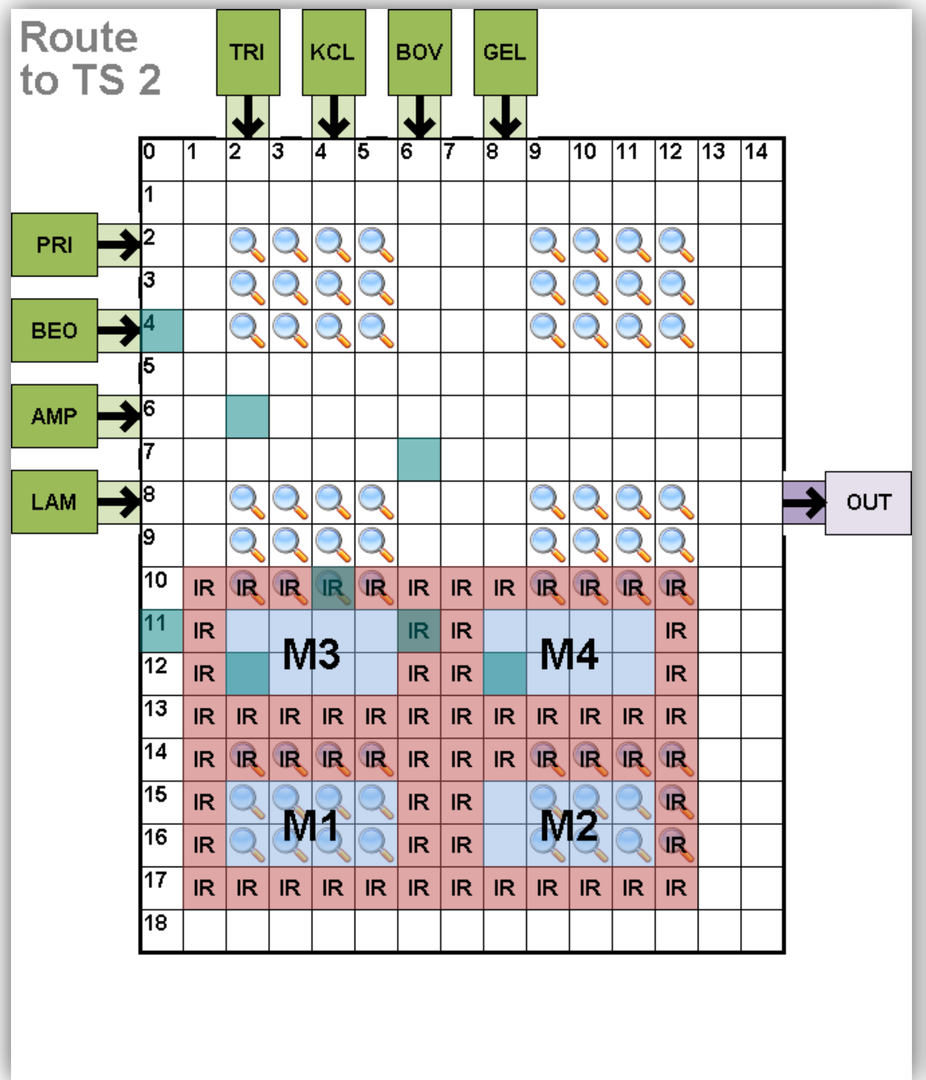

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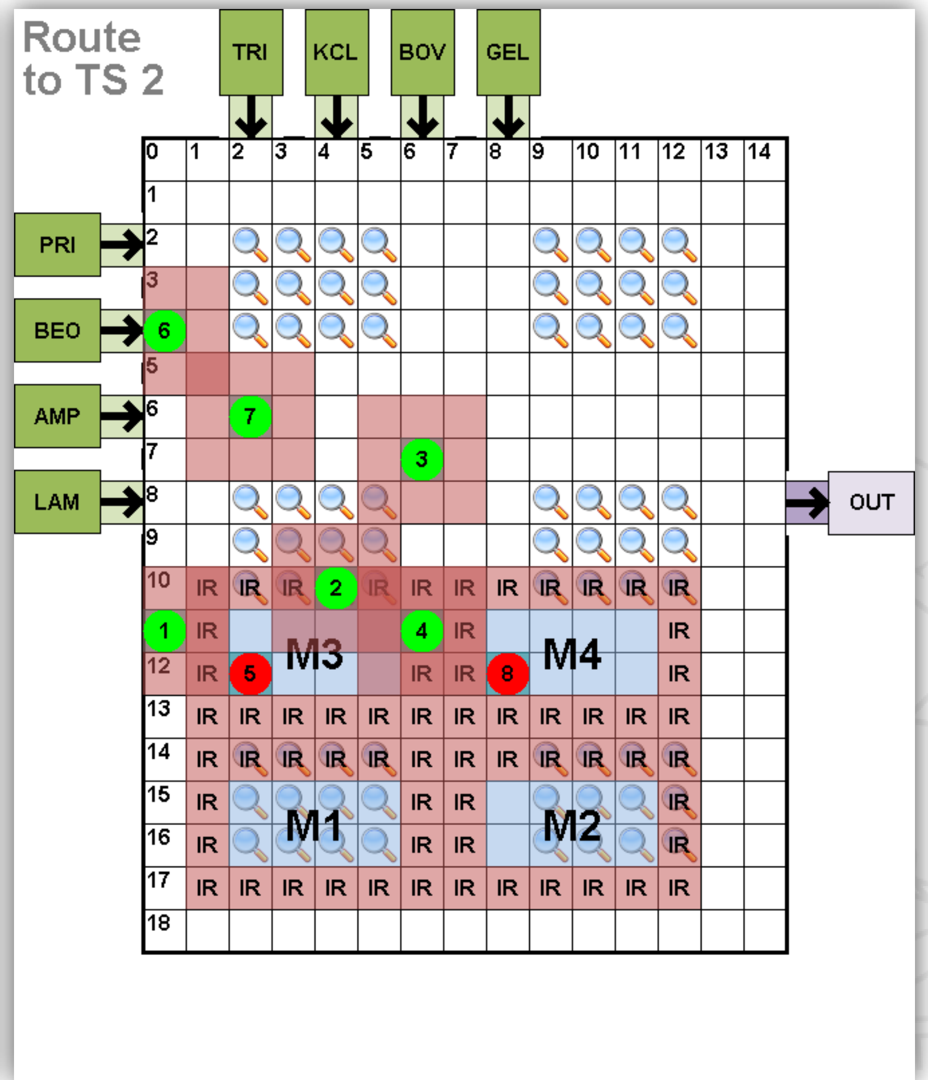

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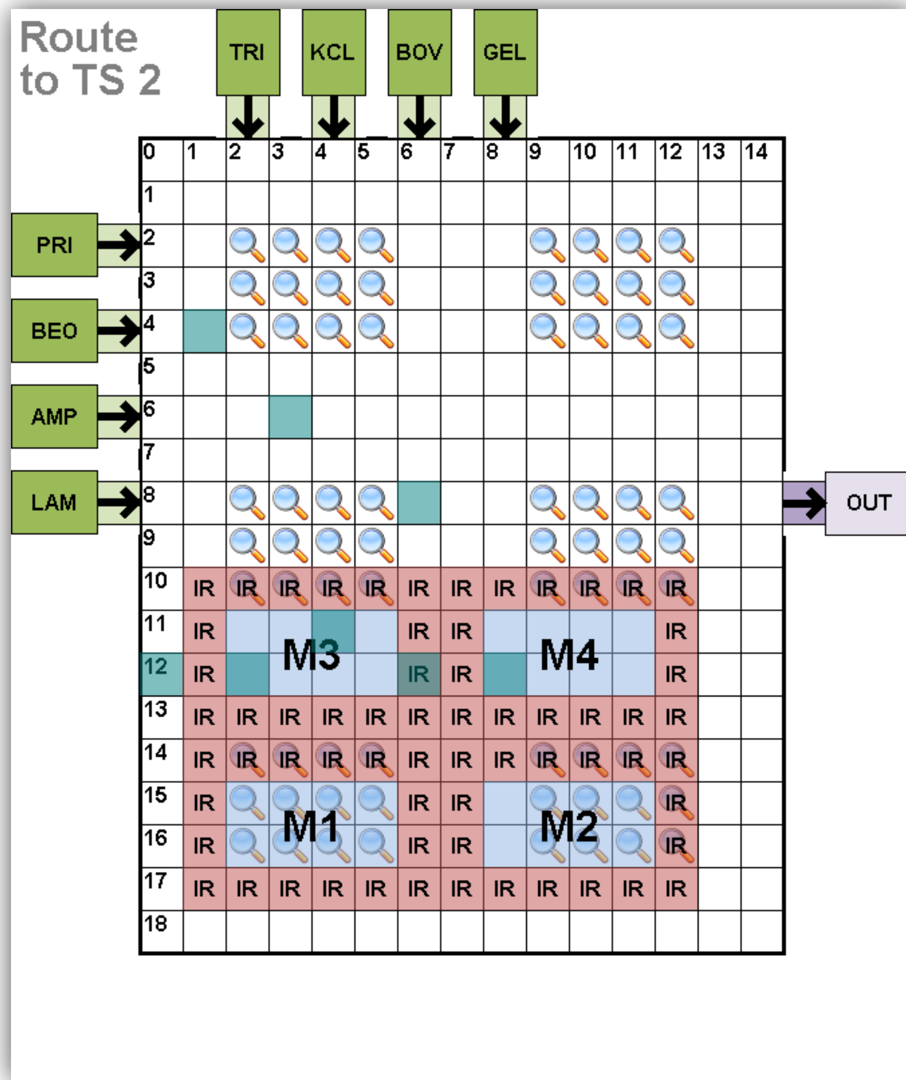

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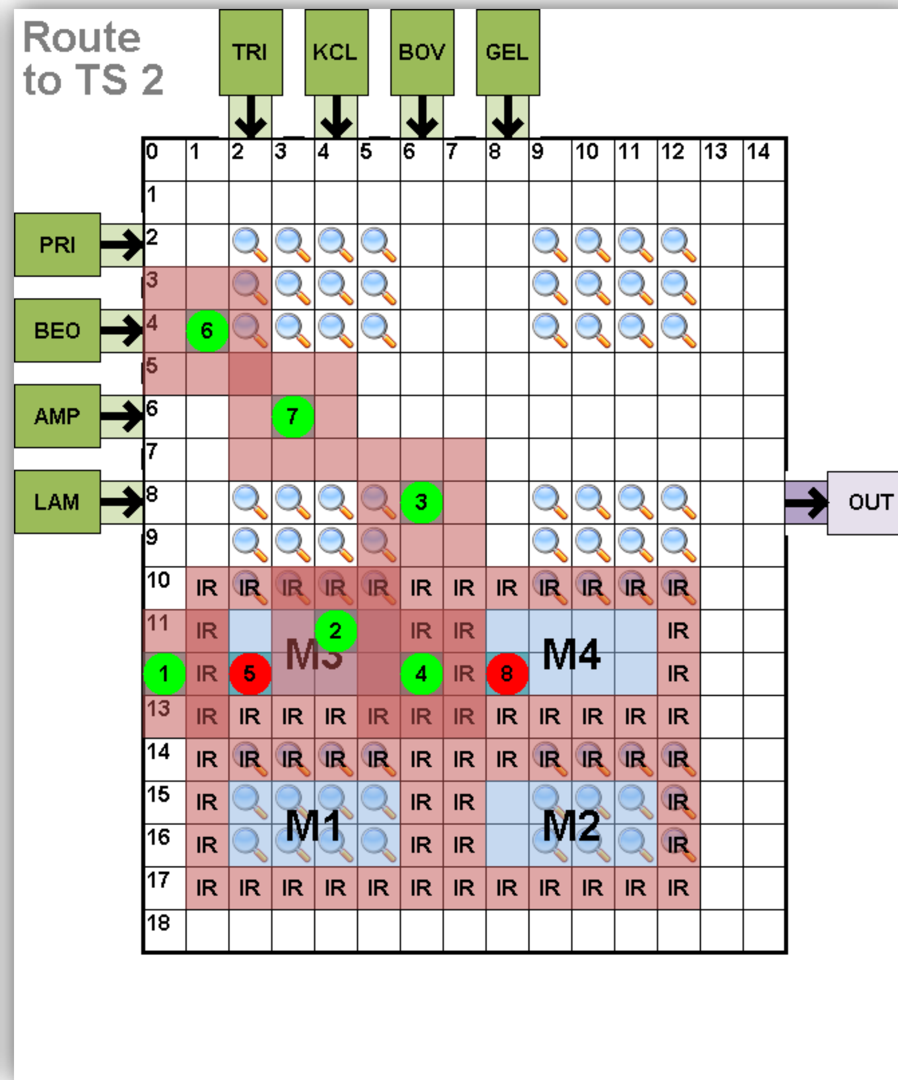

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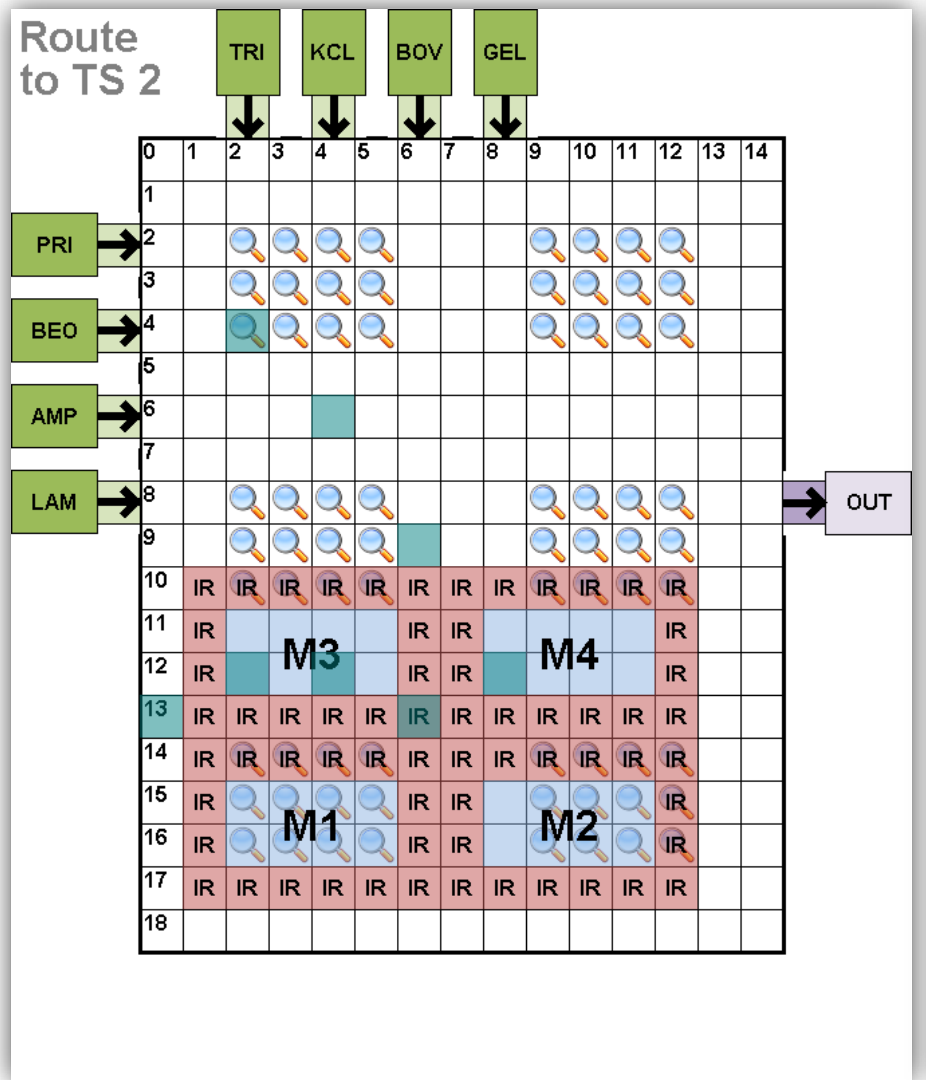

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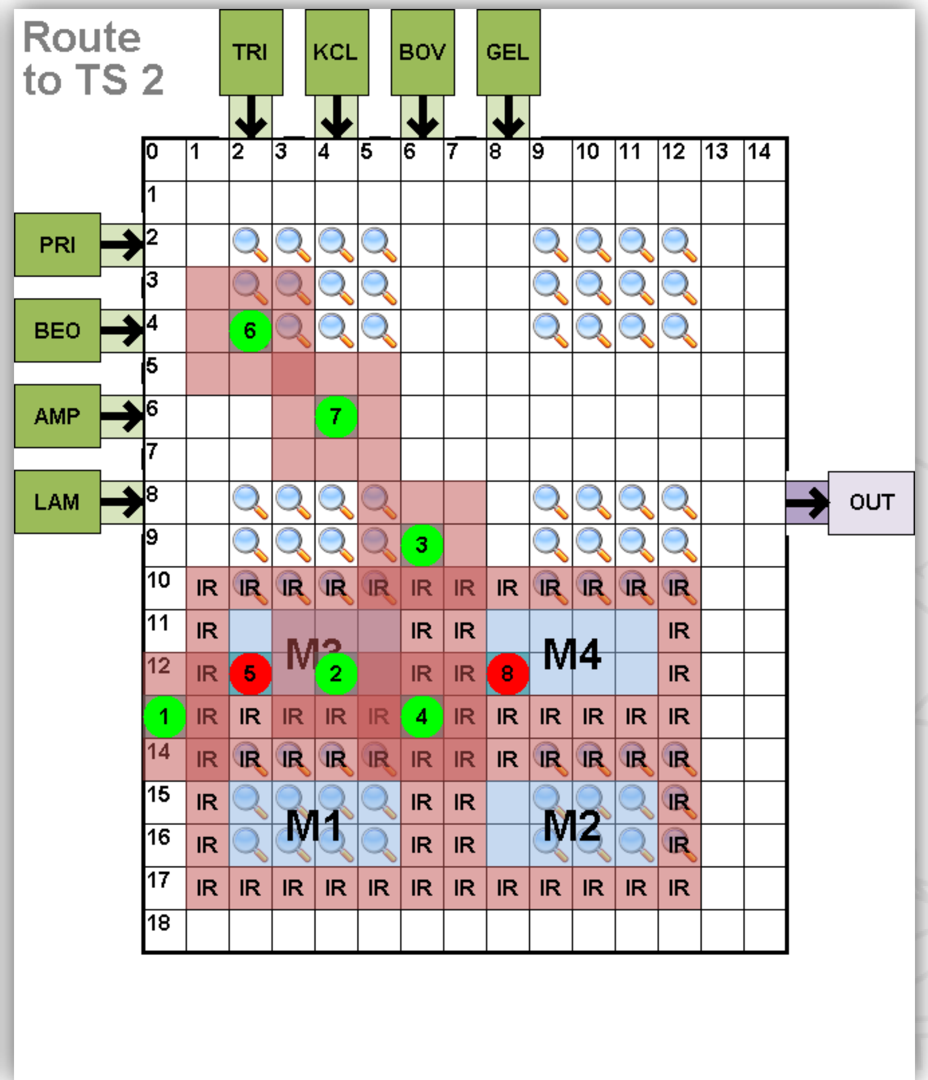

Corresponding Droplet Motion

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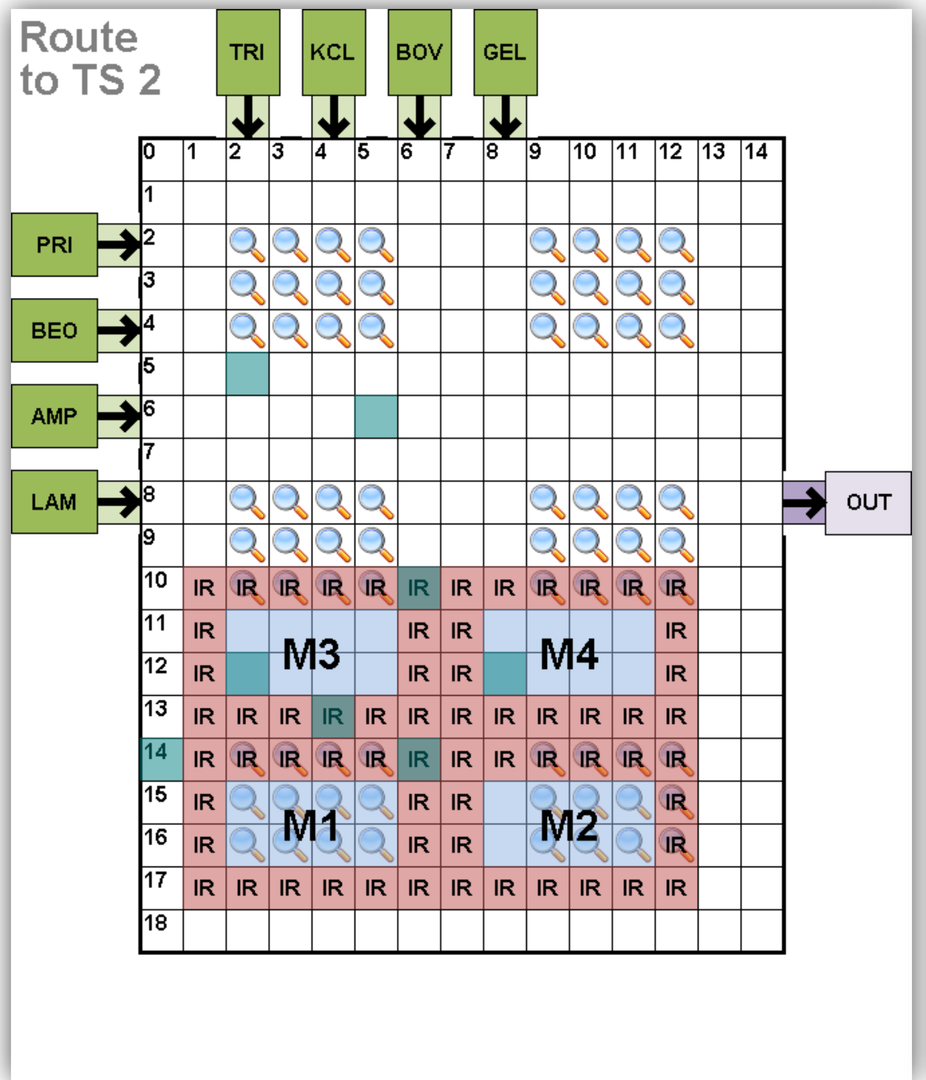

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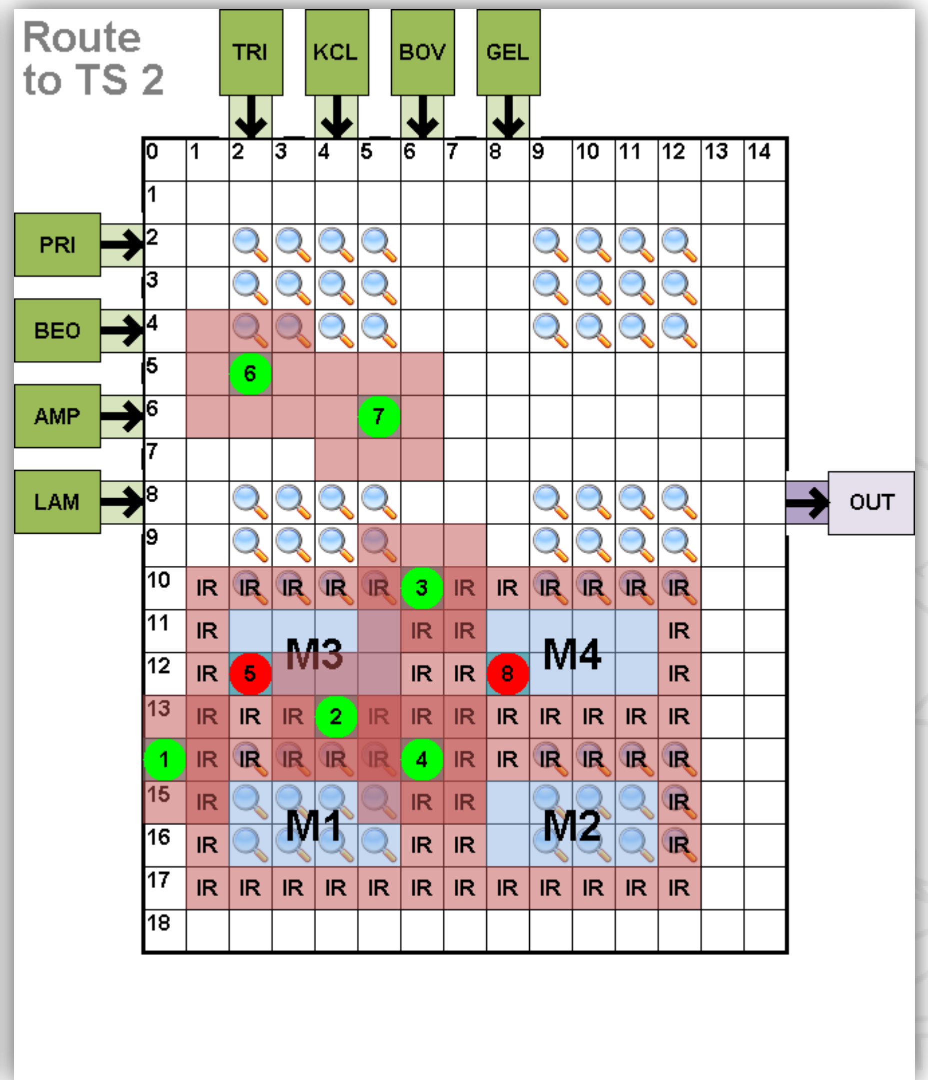

Corresponding Droplet Motion

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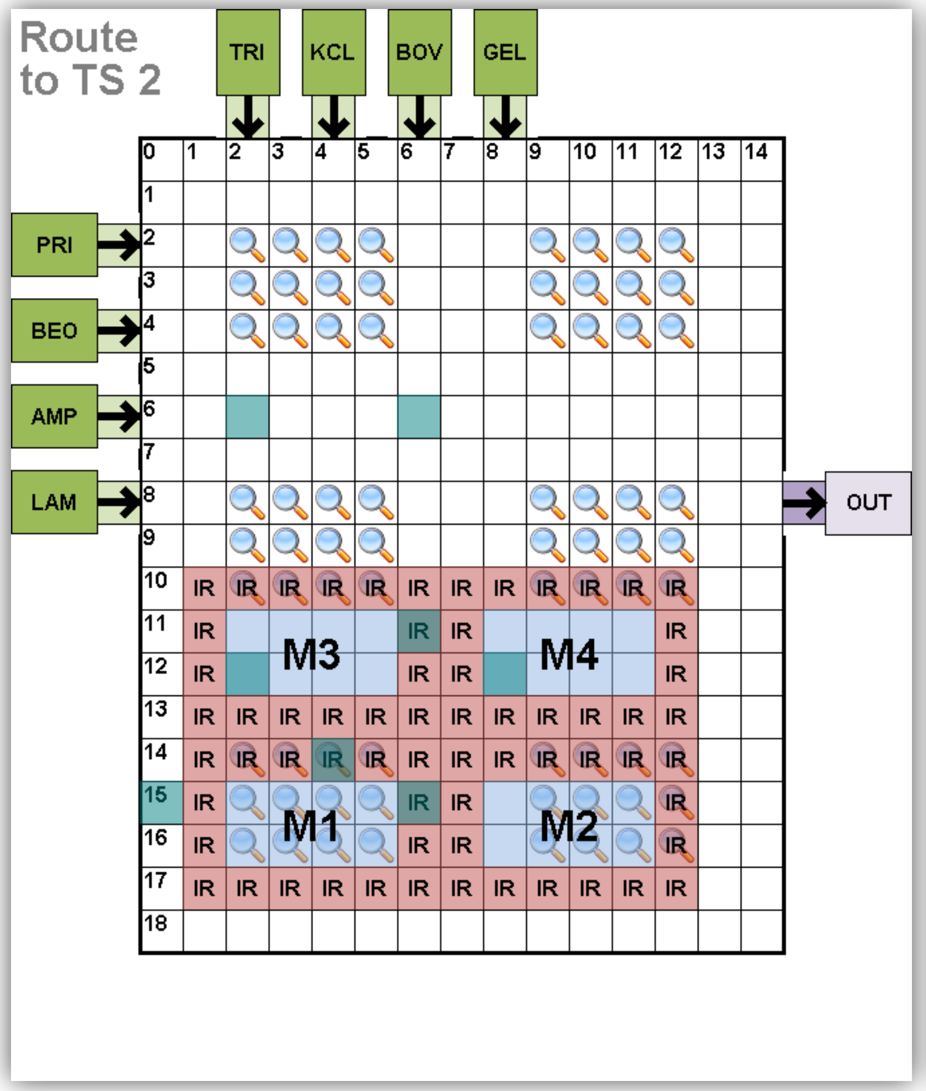

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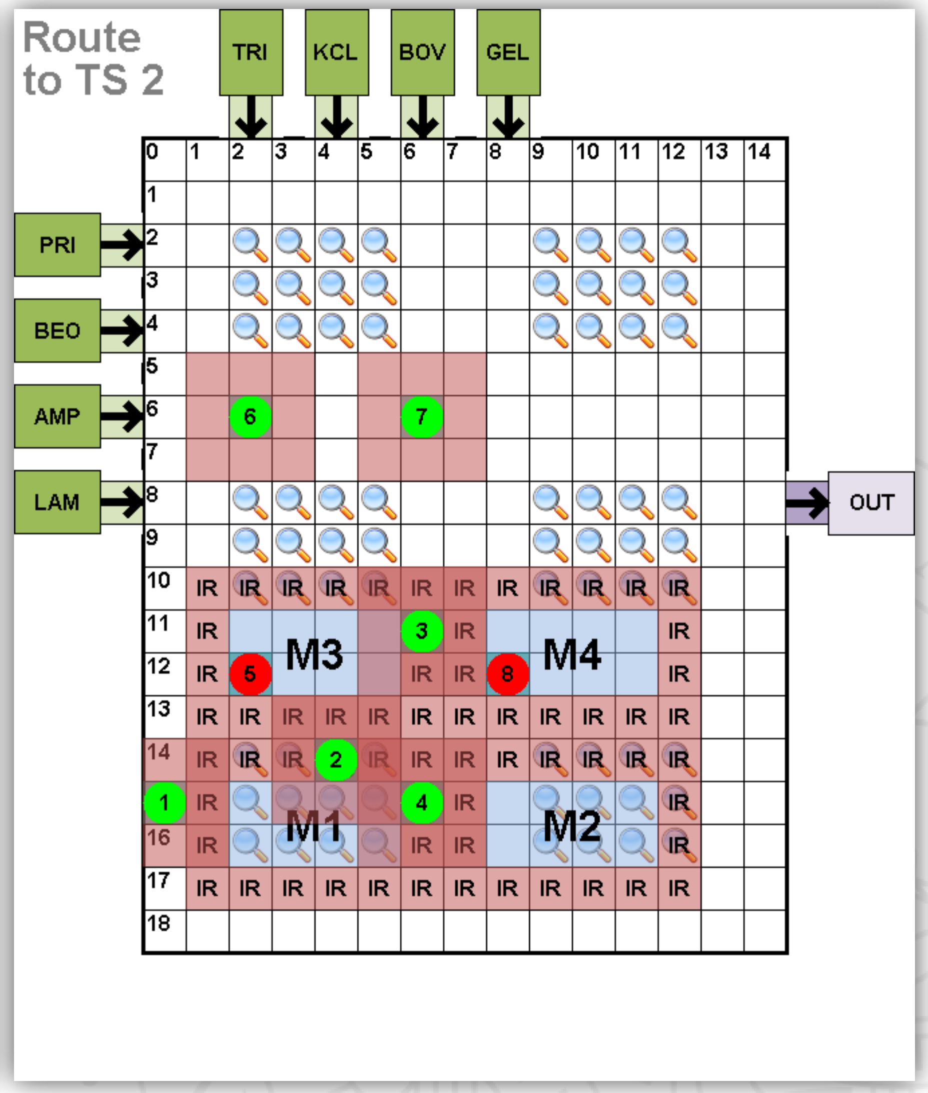

Corresponding Droplet Motion

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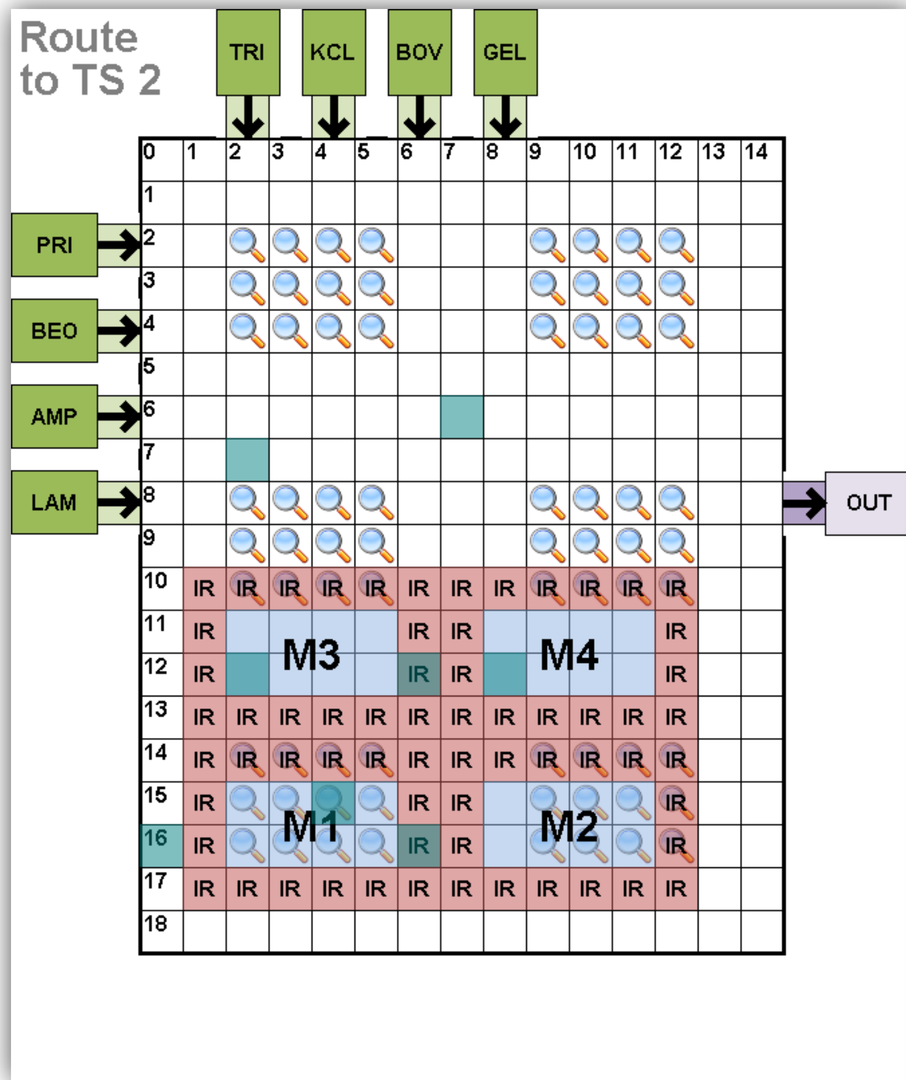

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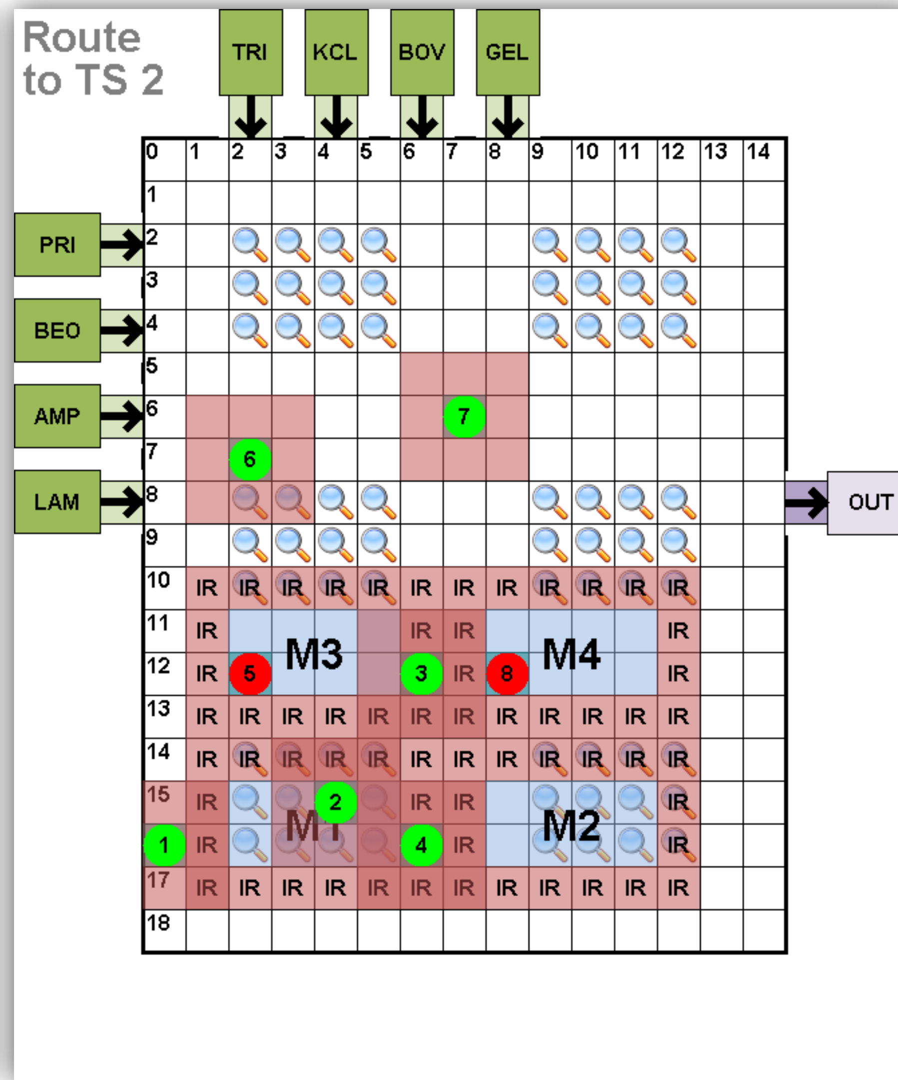

Corresponding Droplet Motion

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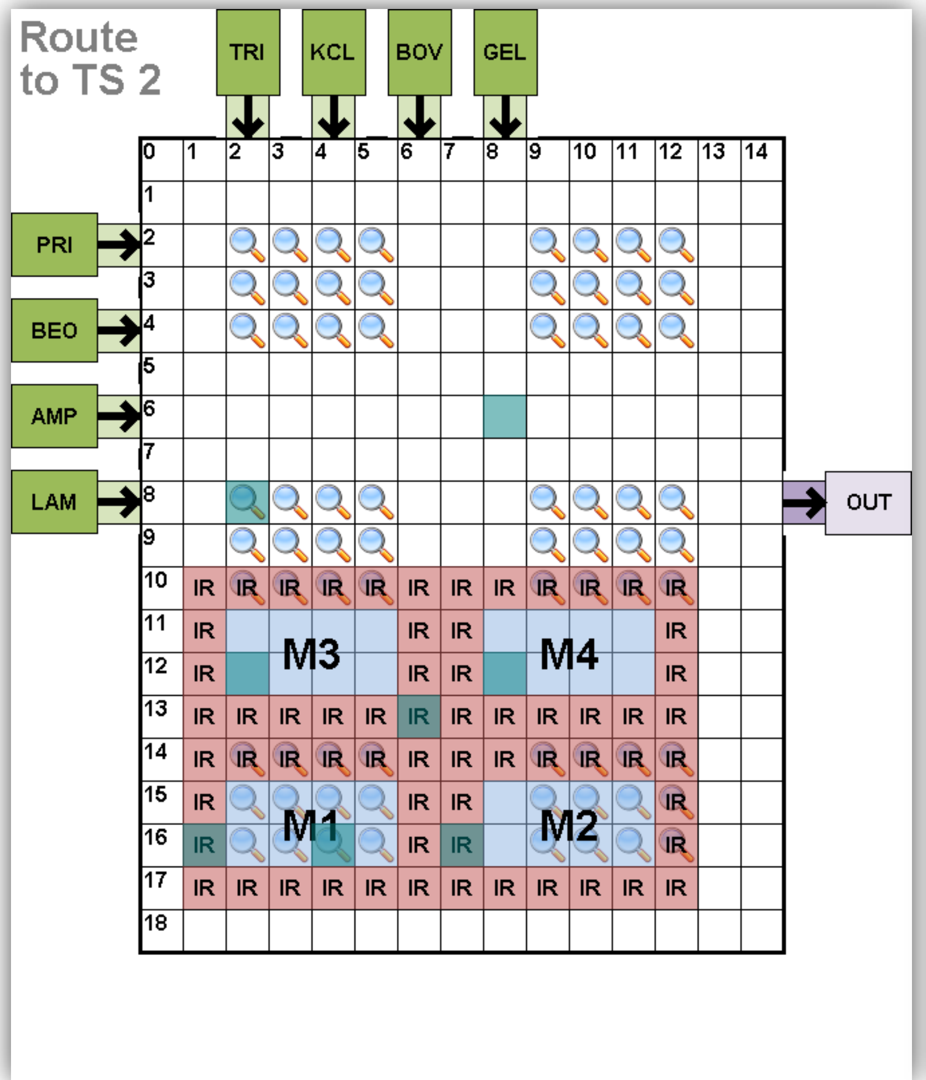

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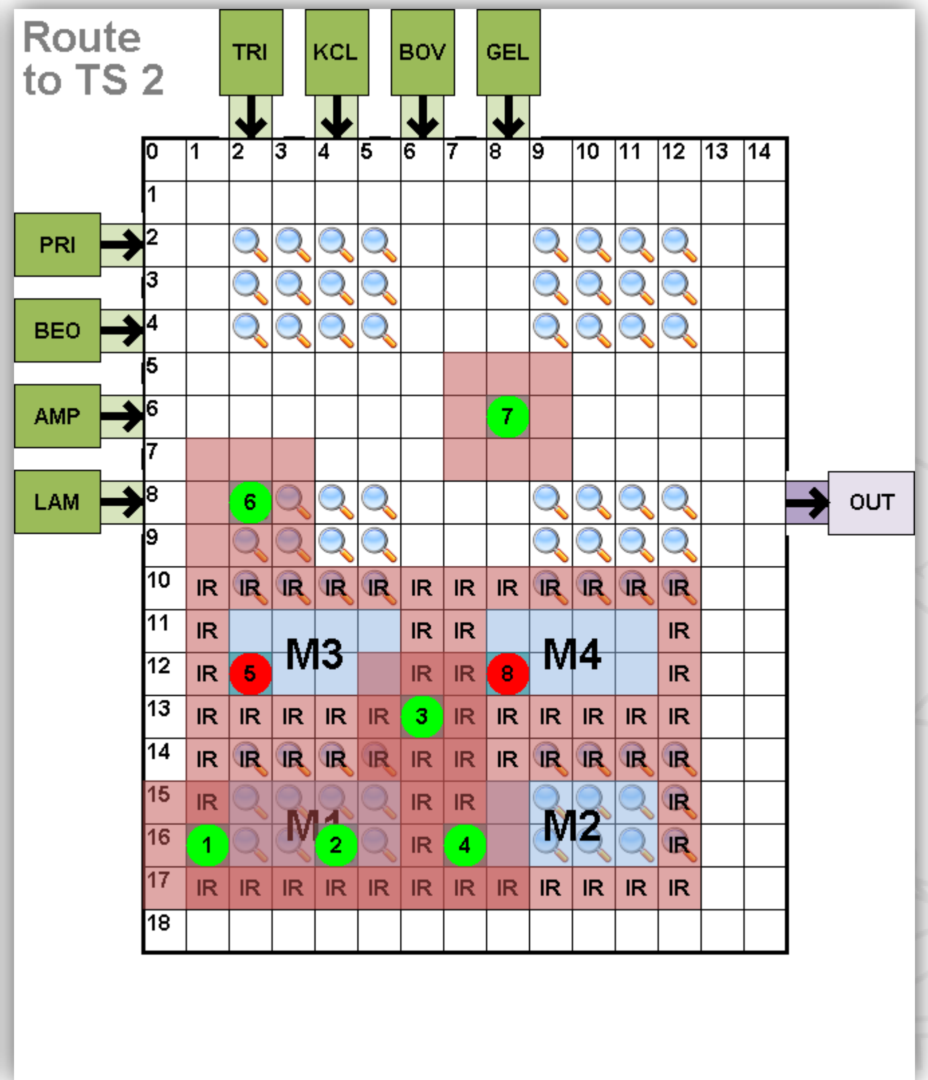

Corresponding Droplet Motion

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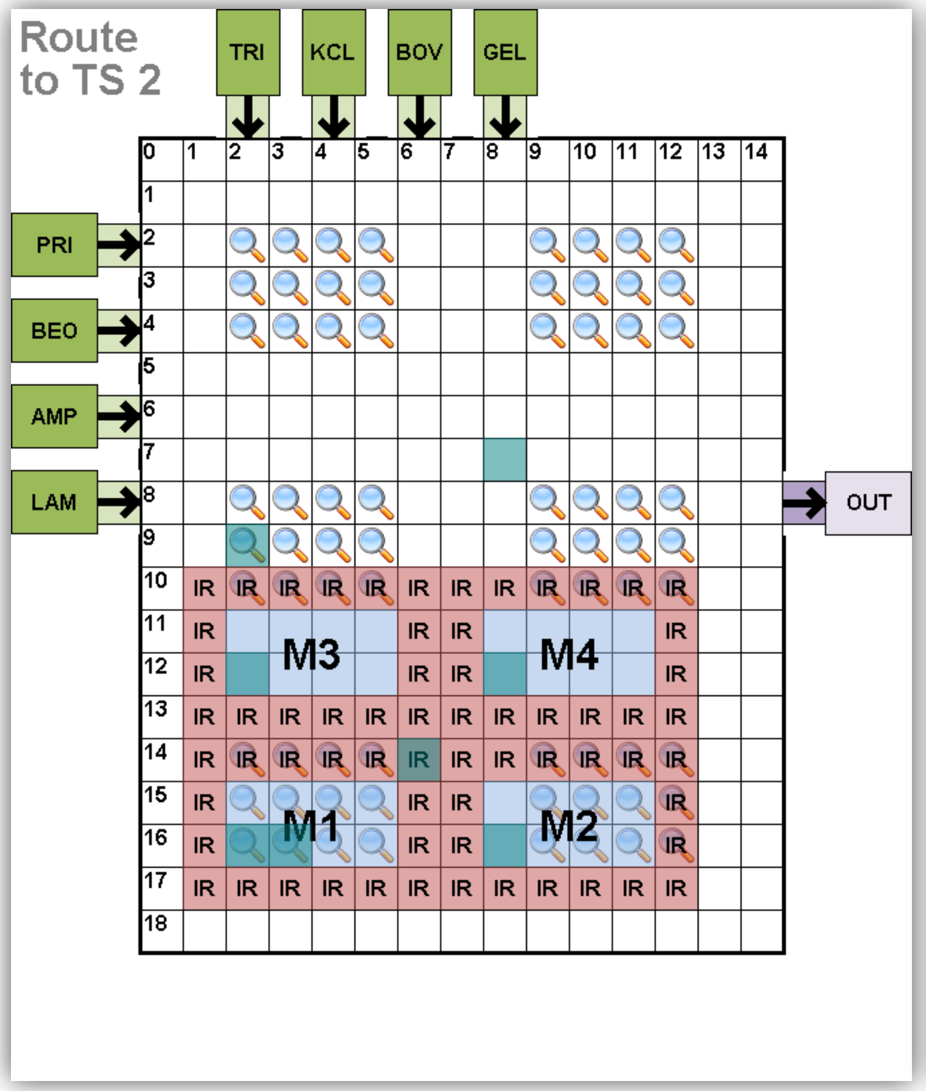

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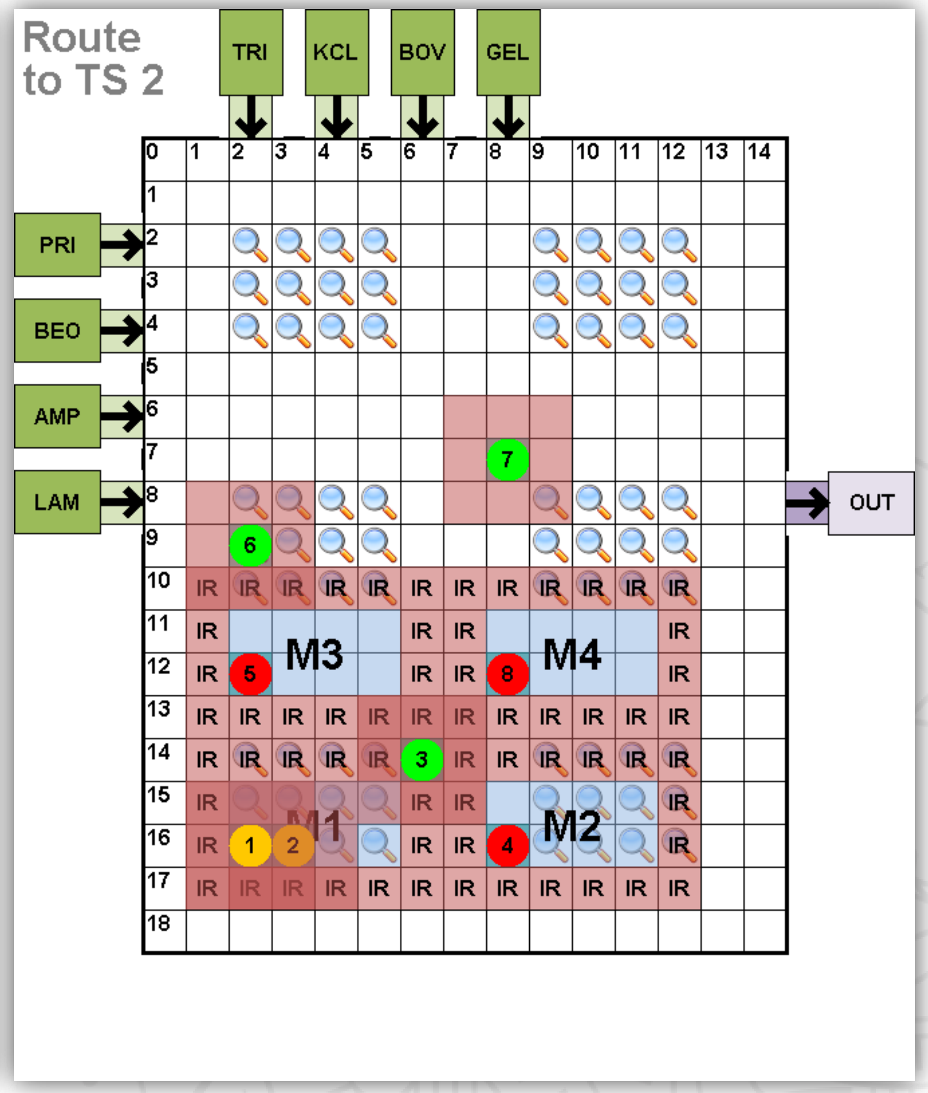

Corresponding Droplet Motion

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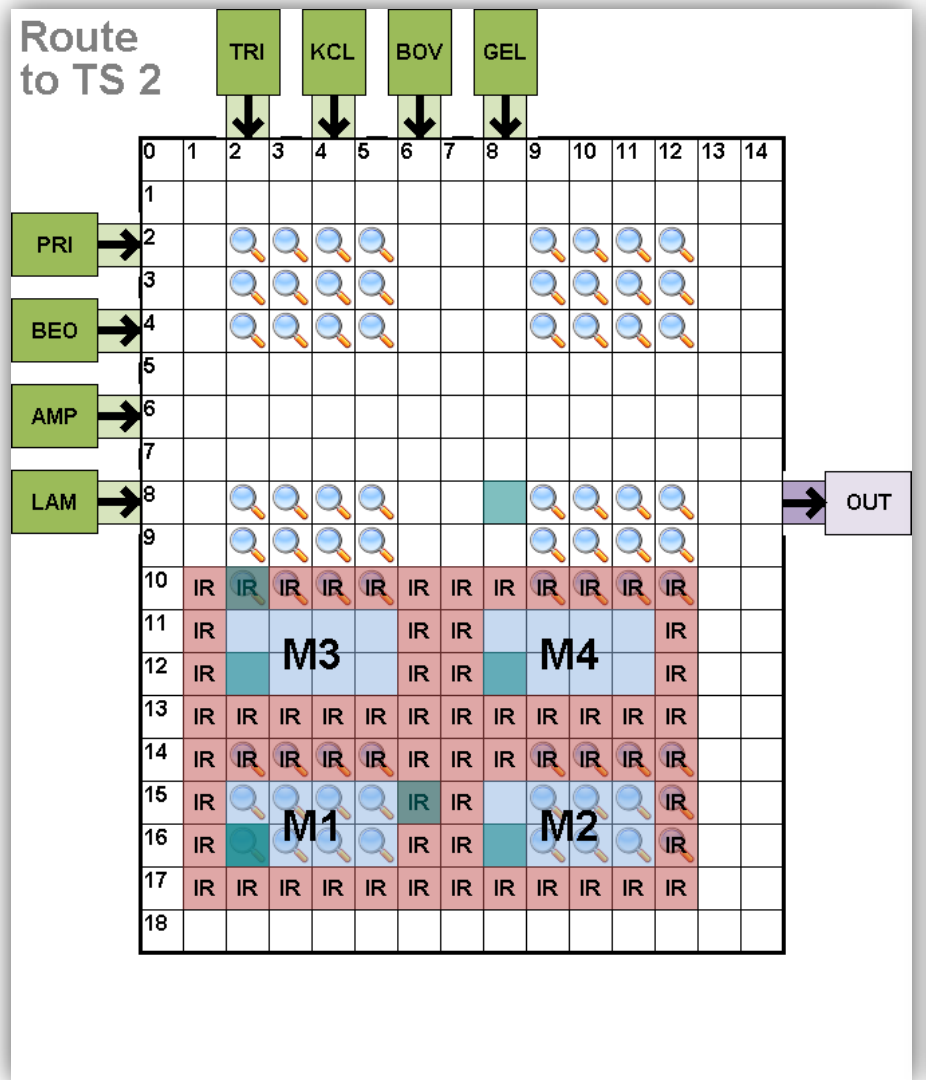

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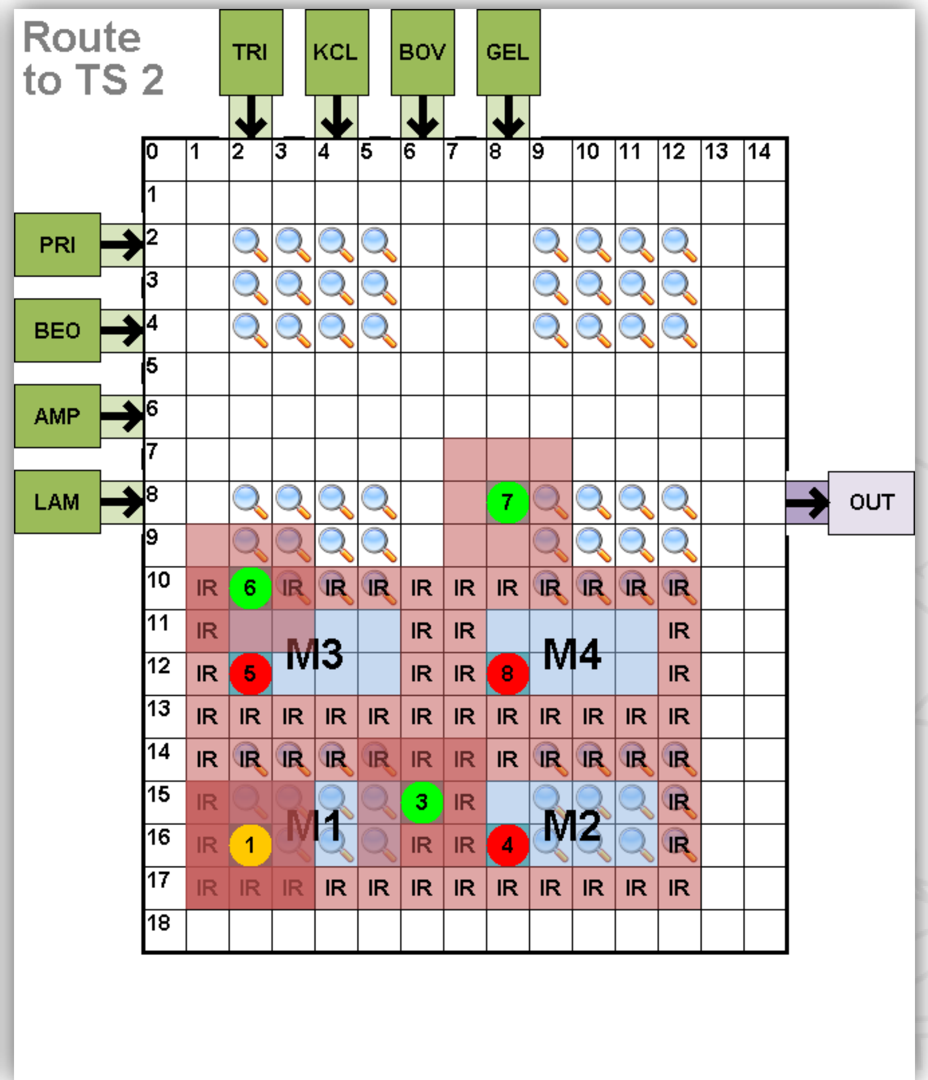

Corresponding Droplet Motion

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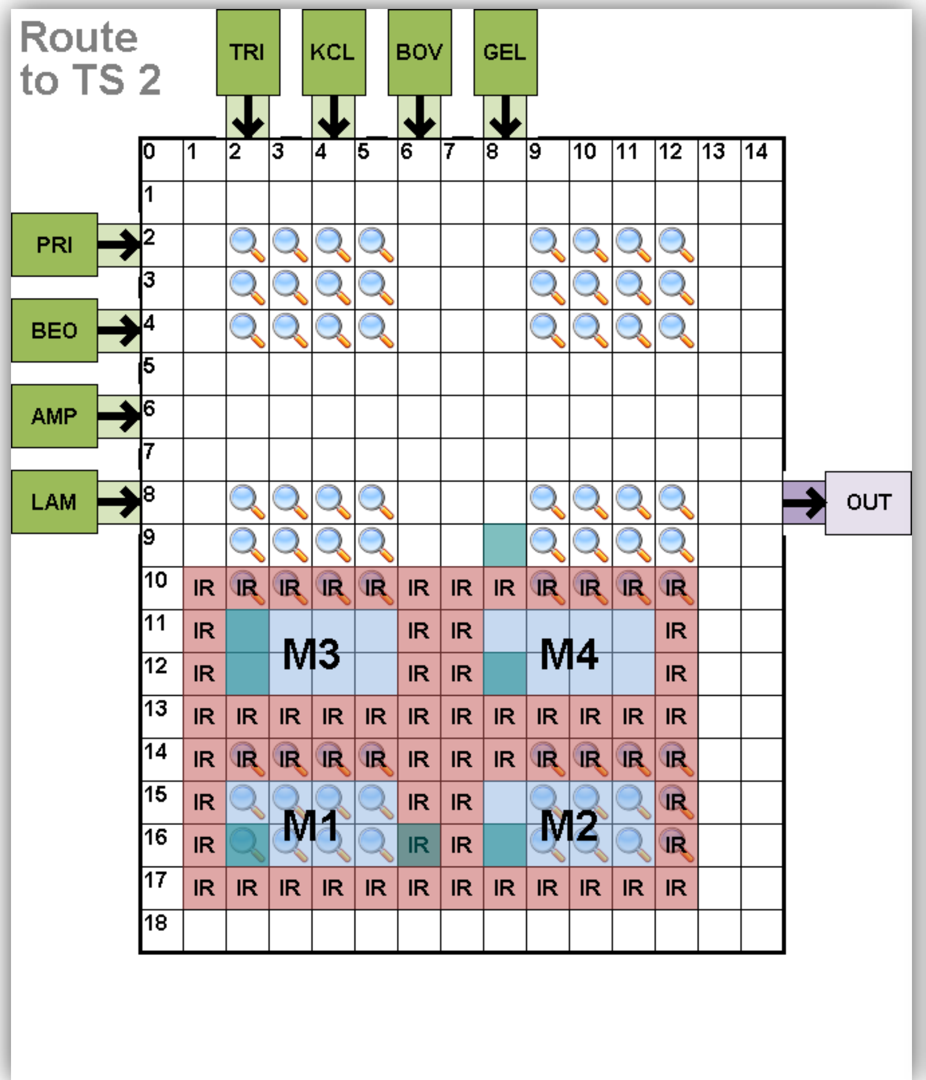

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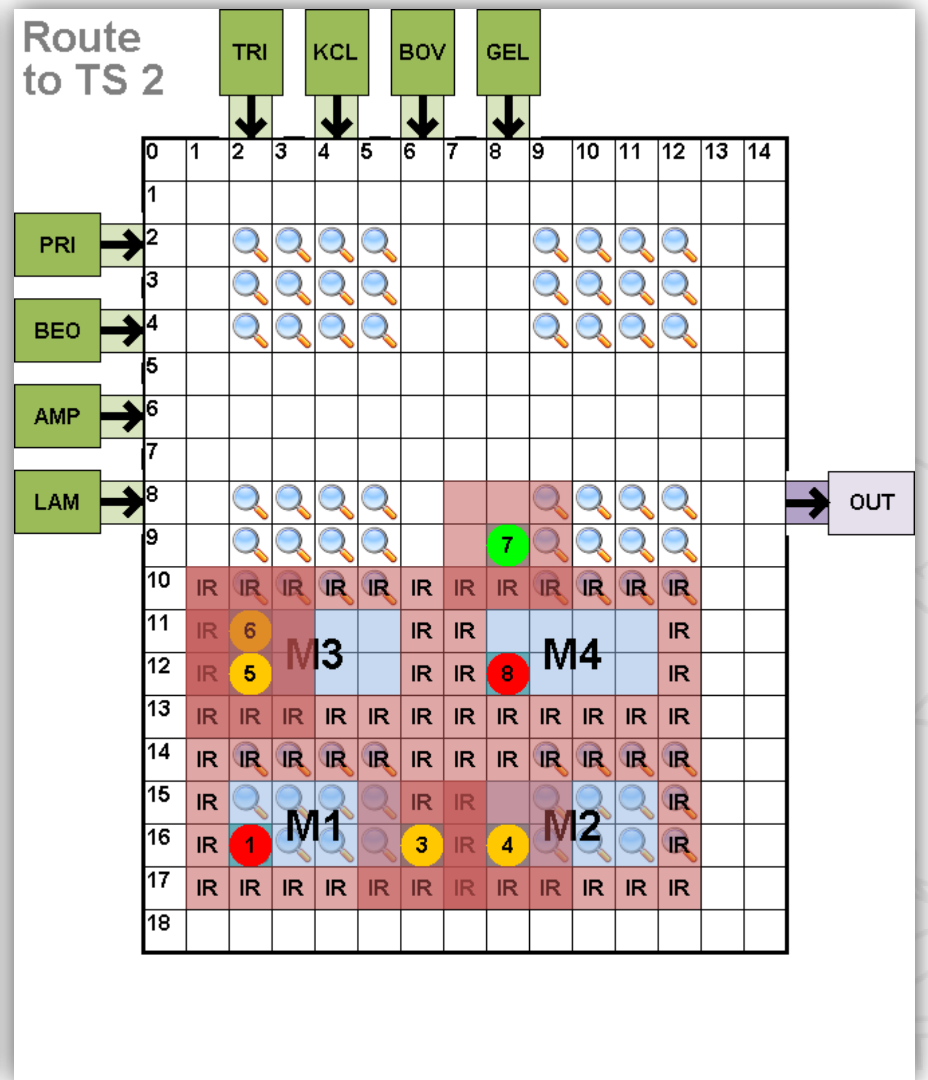

Corresponding Droplet Motion

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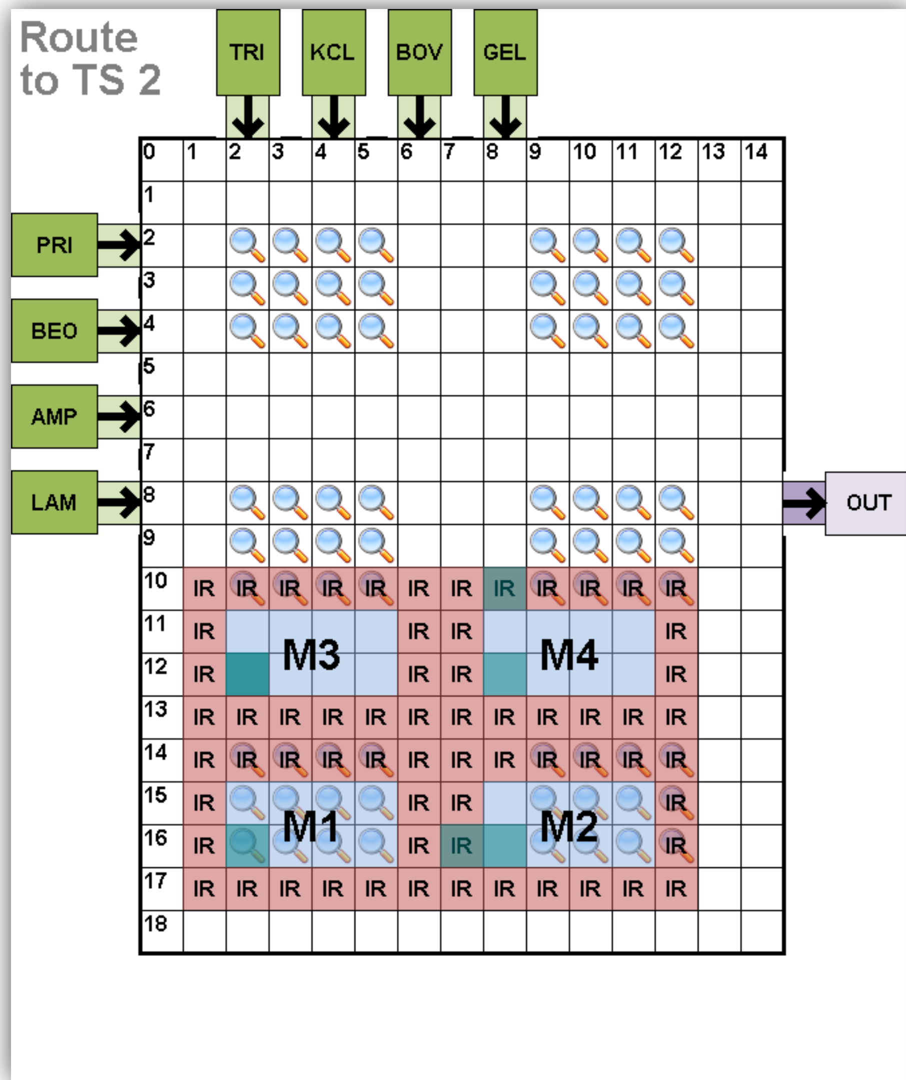

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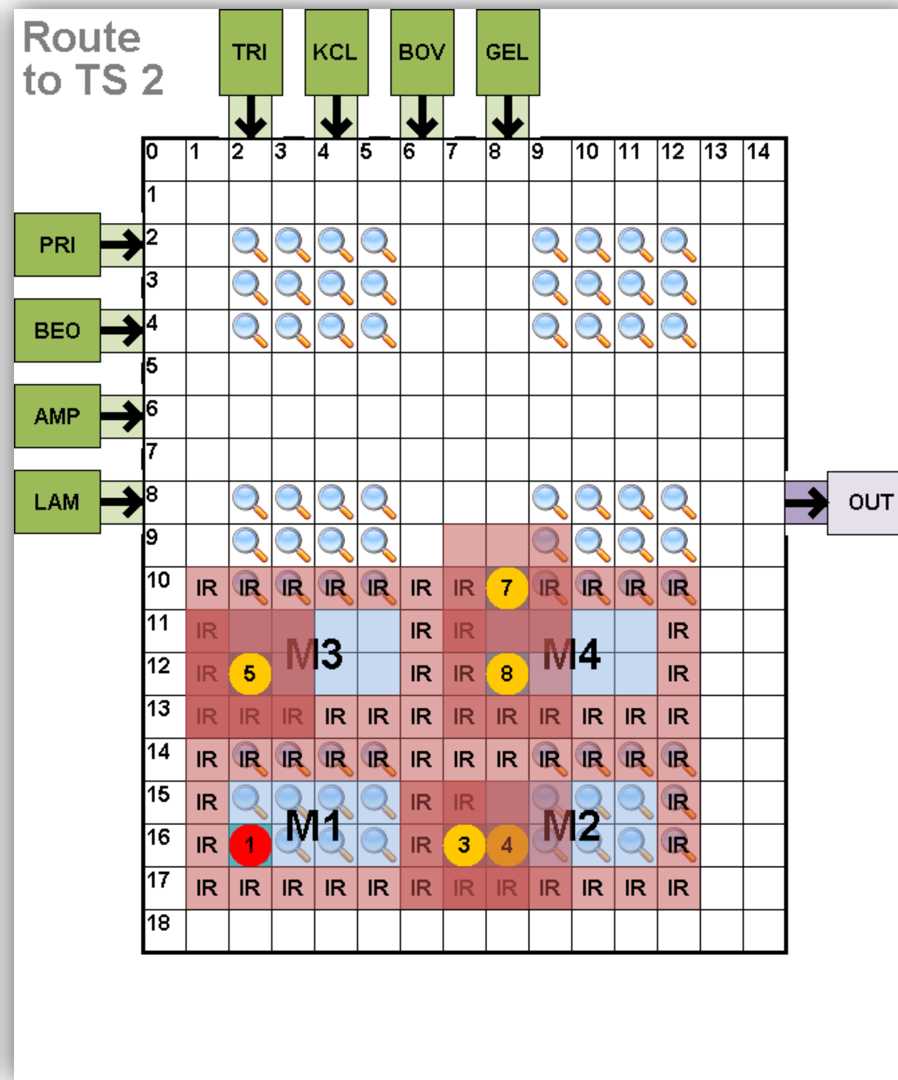

Corresponding Droplet Motion

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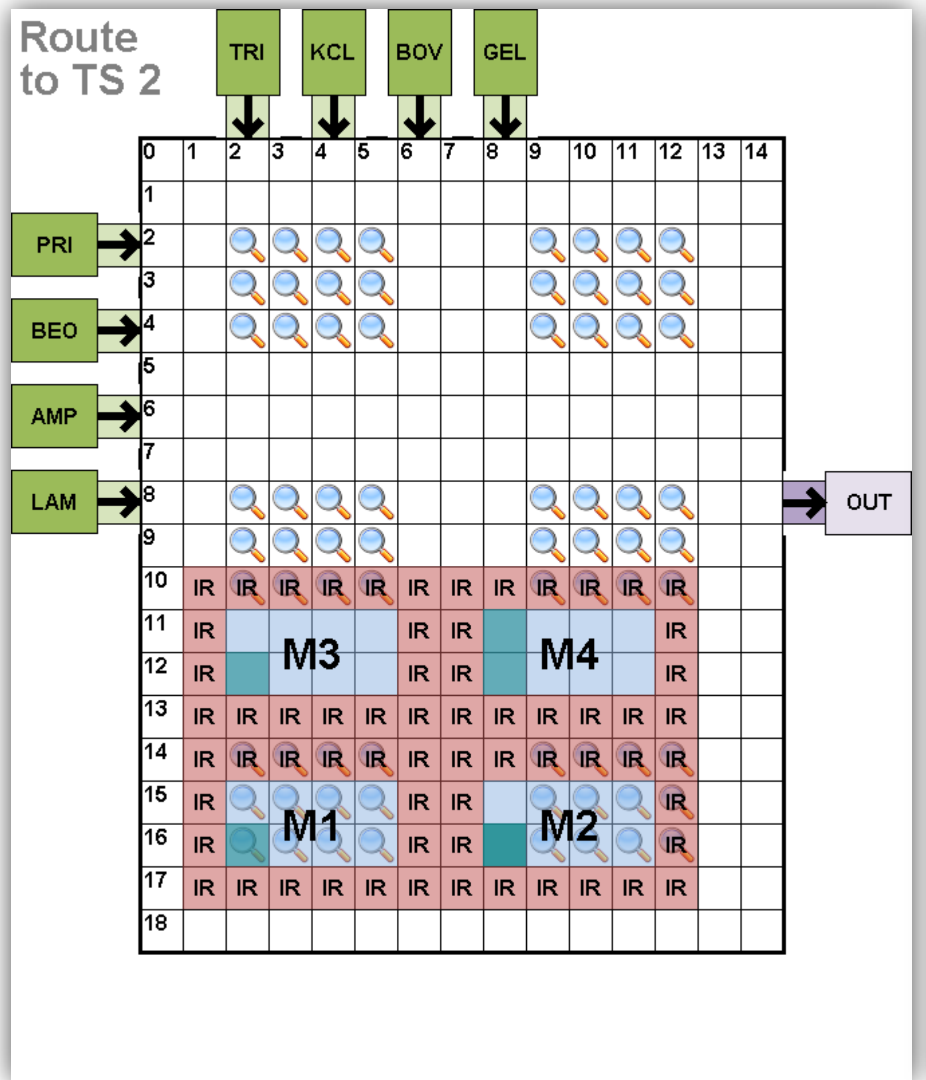

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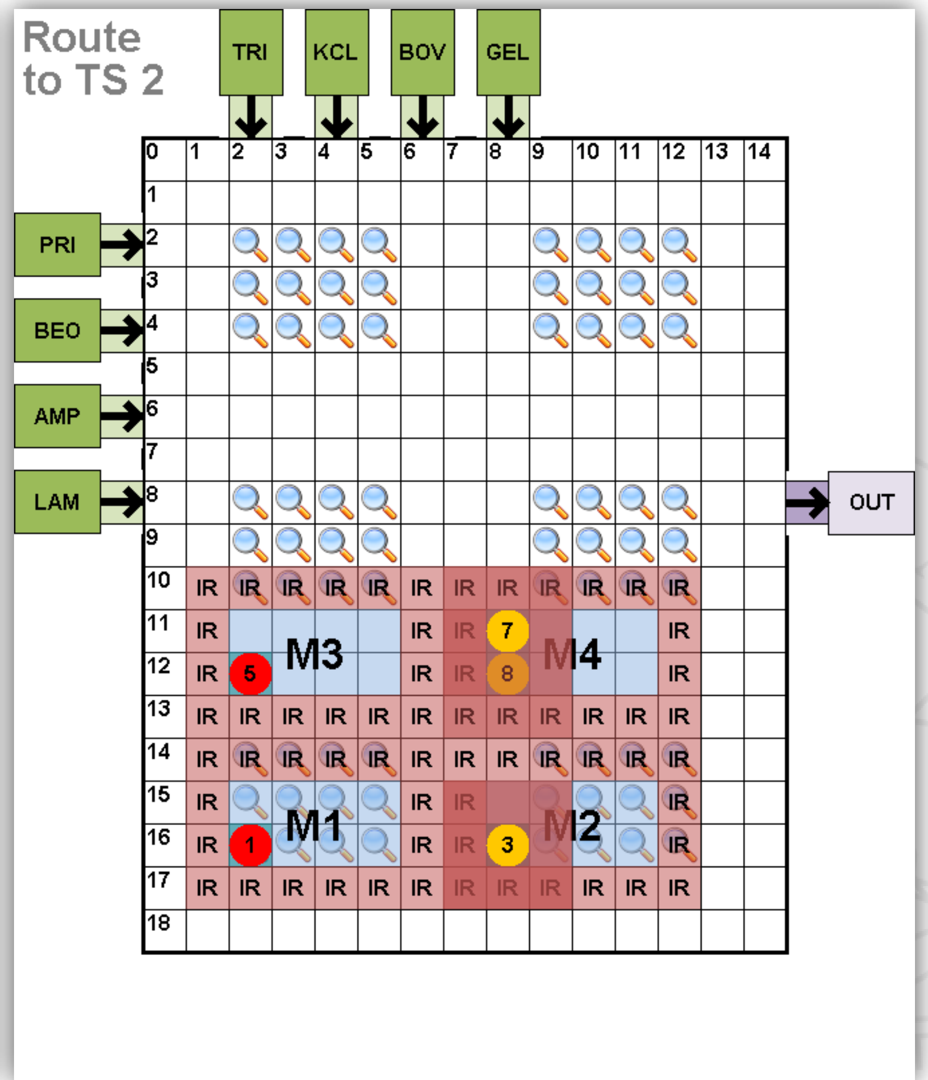

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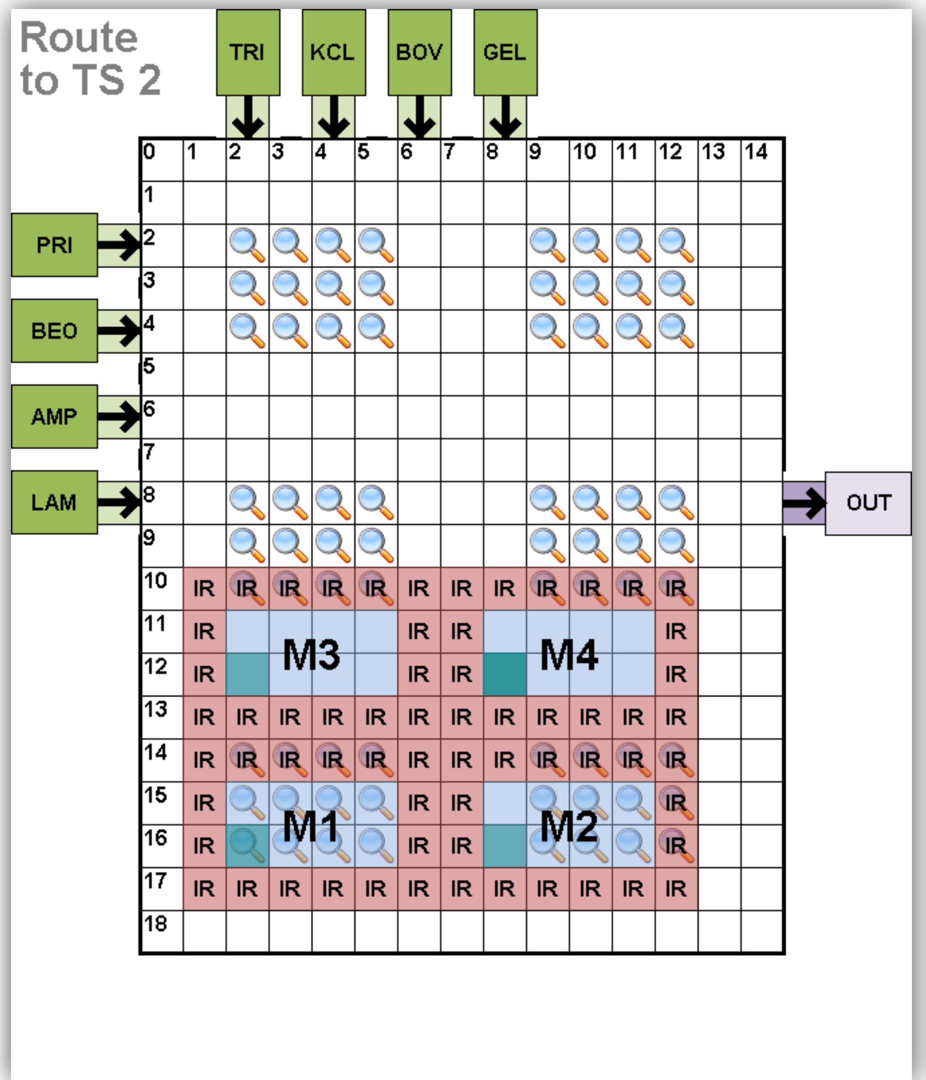

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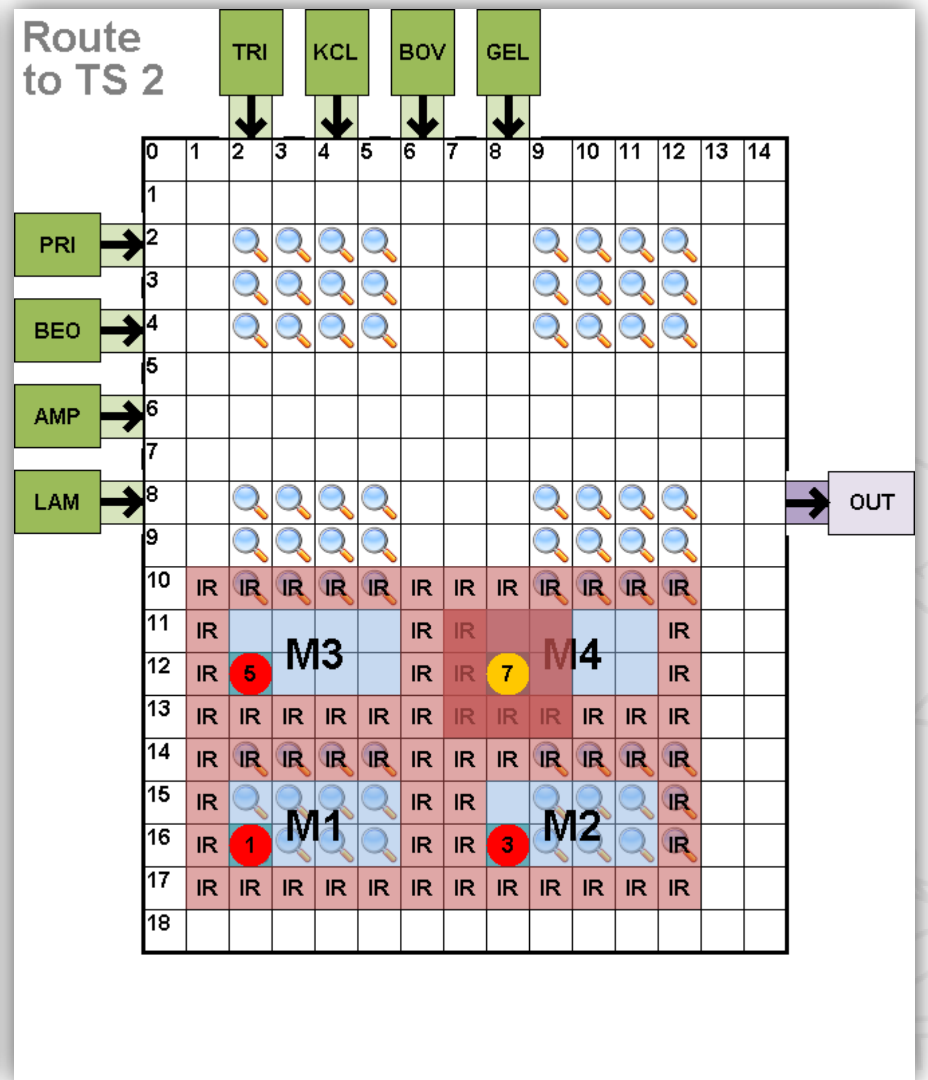

Corresponding Droplet Motion

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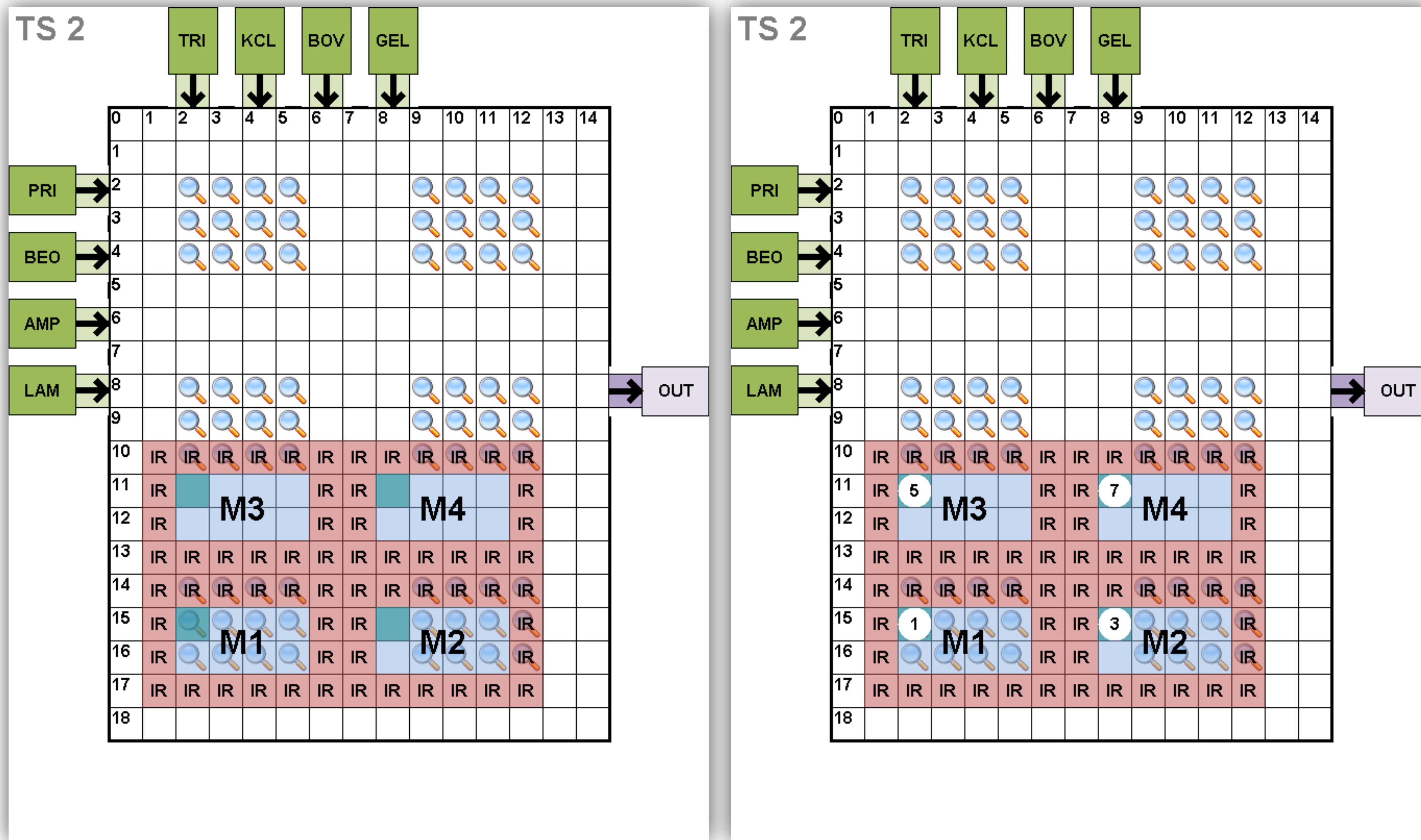

Electrode Activations

Corresponding Droplet Motion

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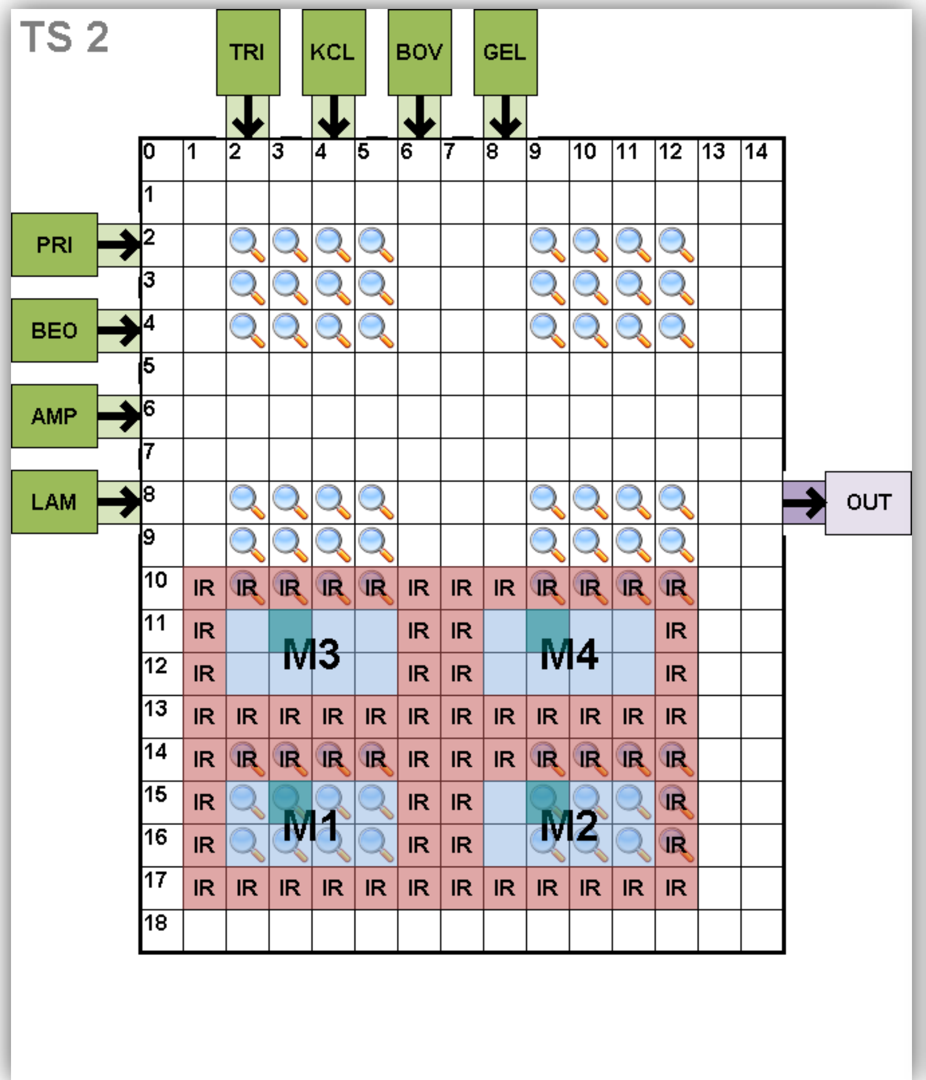

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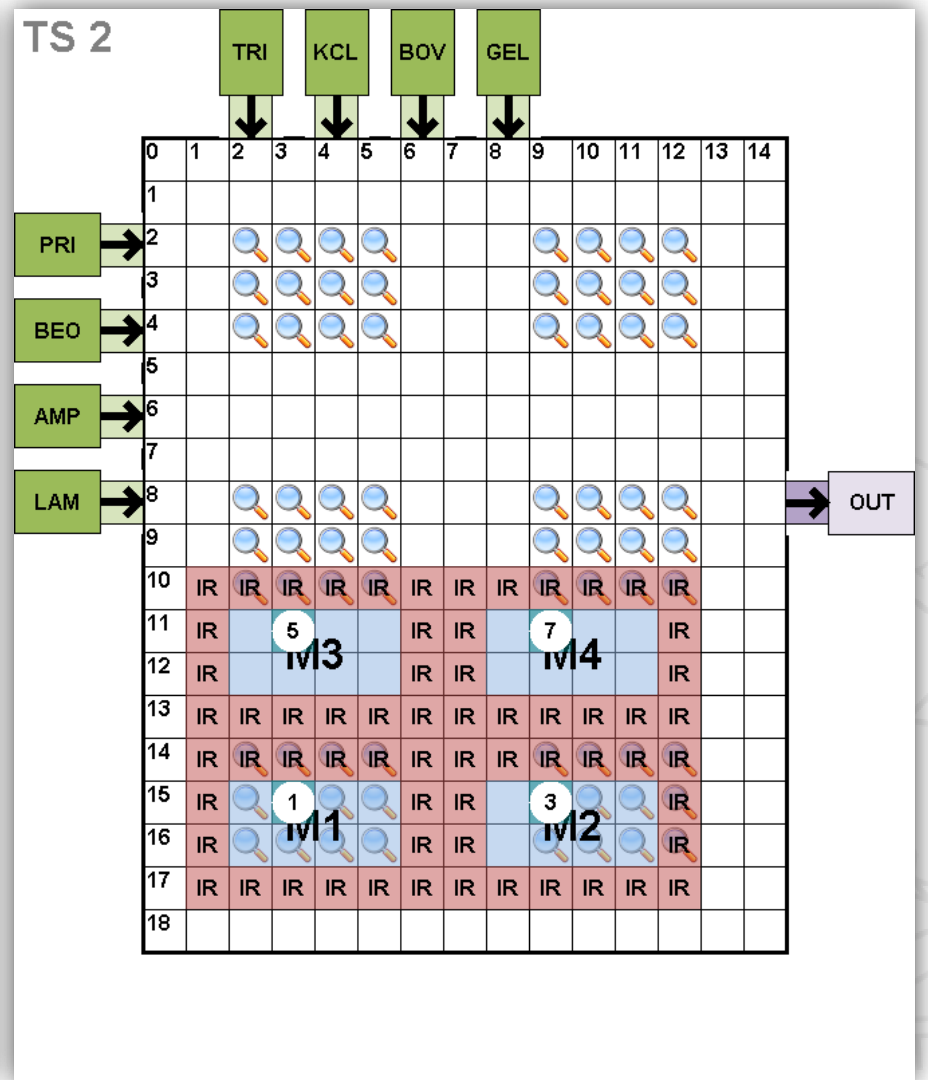

Corresponding Droplet Motion

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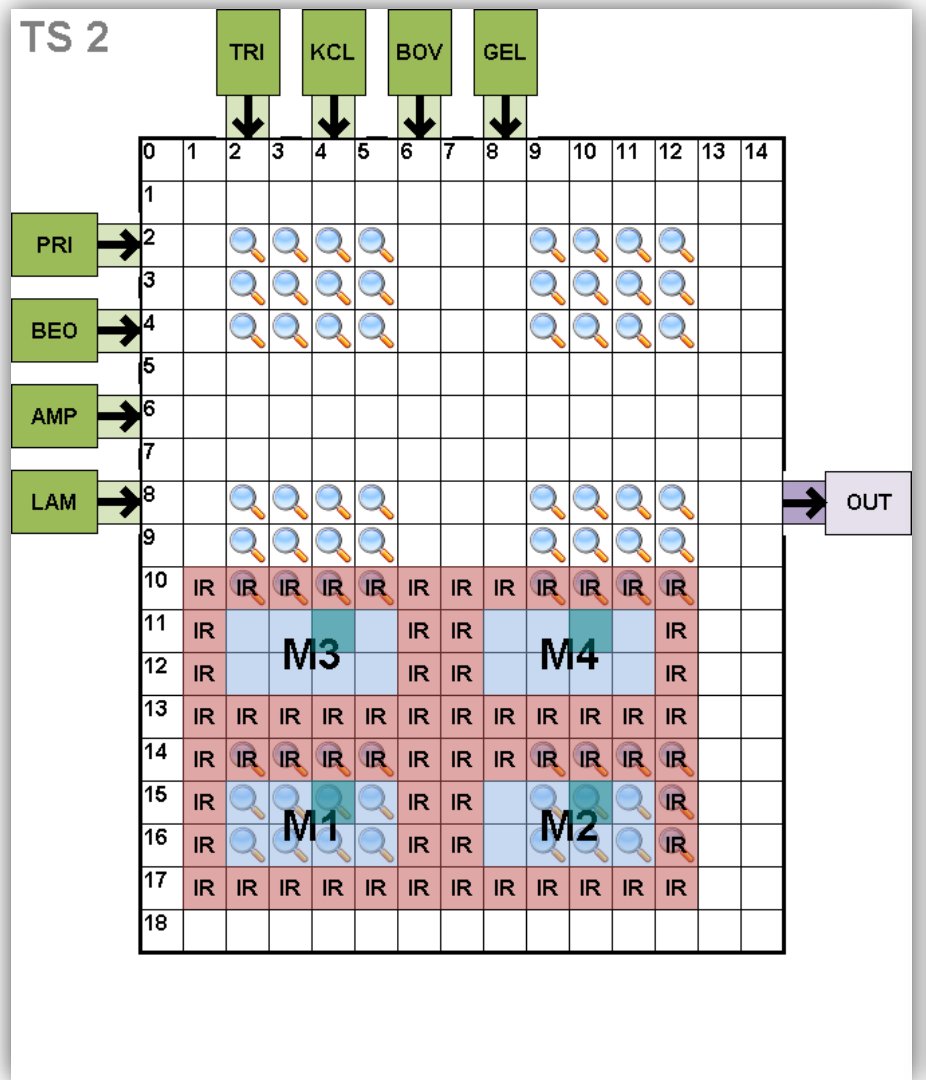

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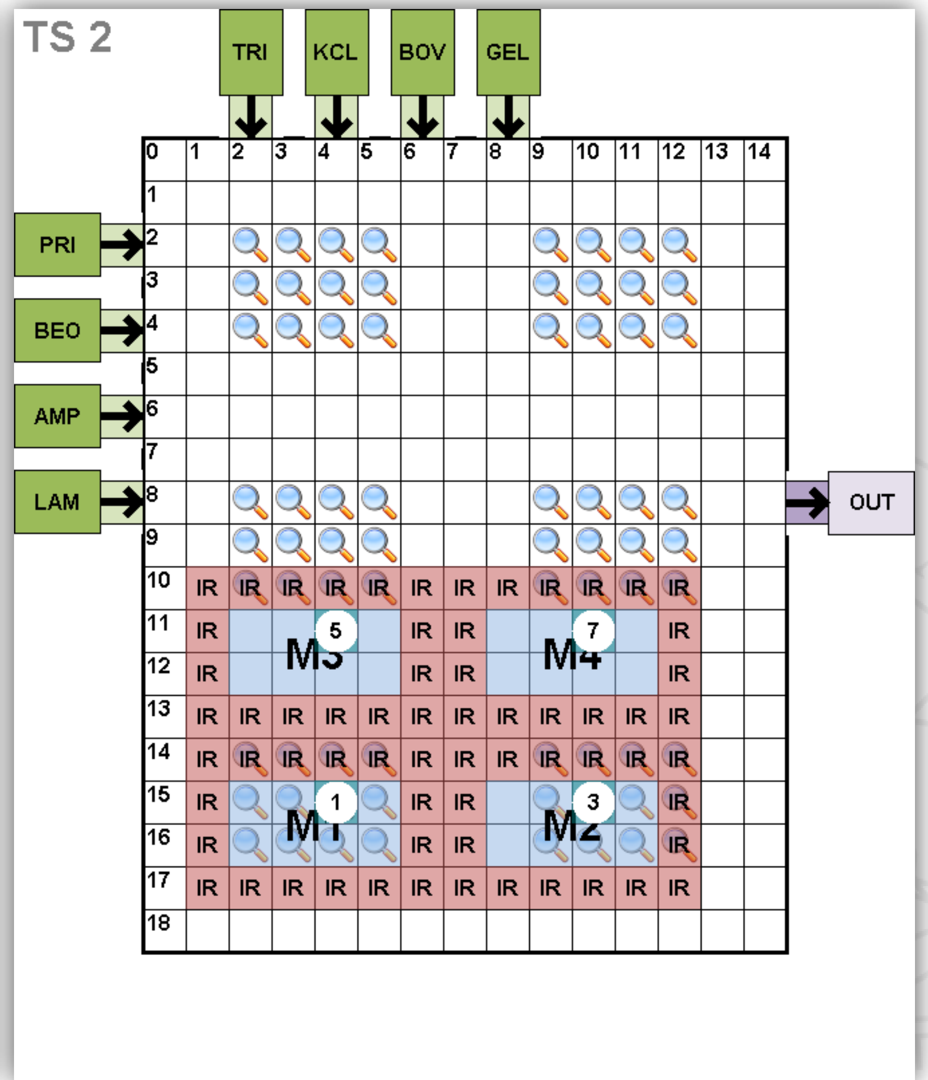

Corresponding Droplet Motion

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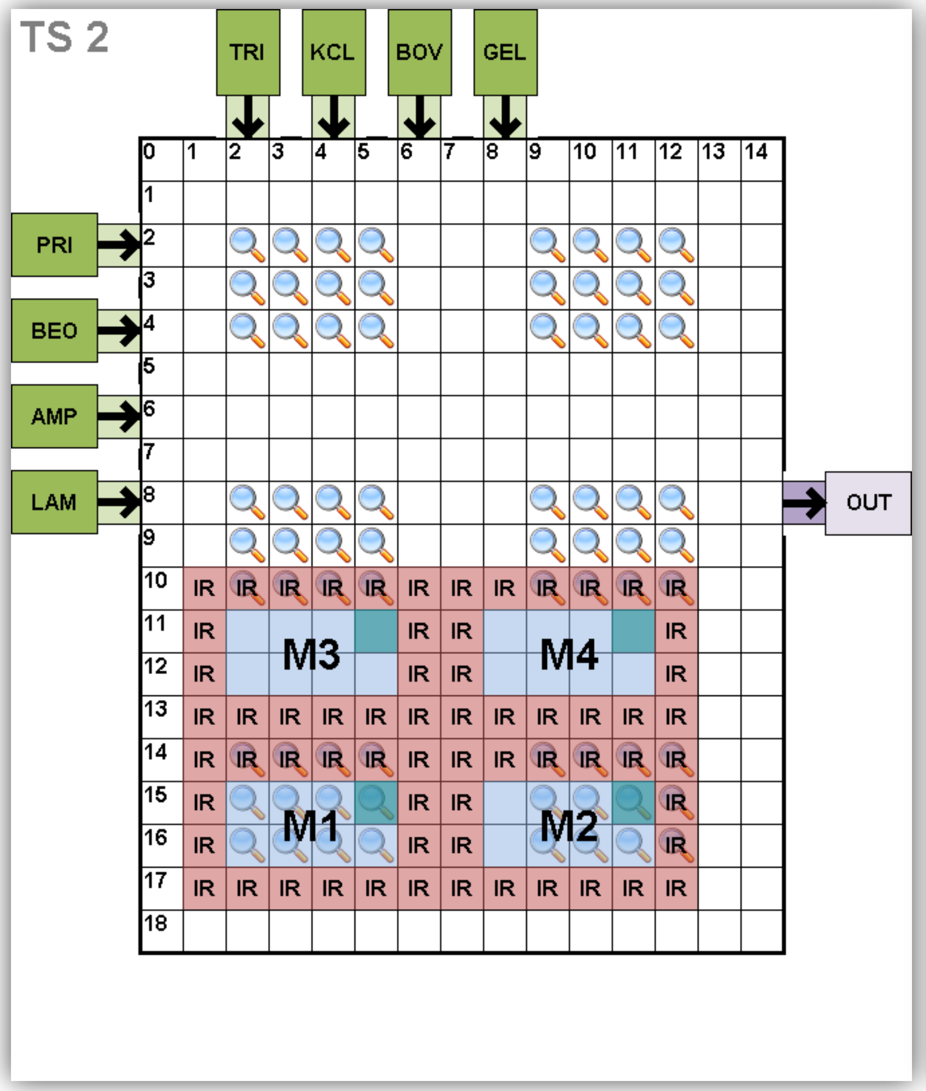

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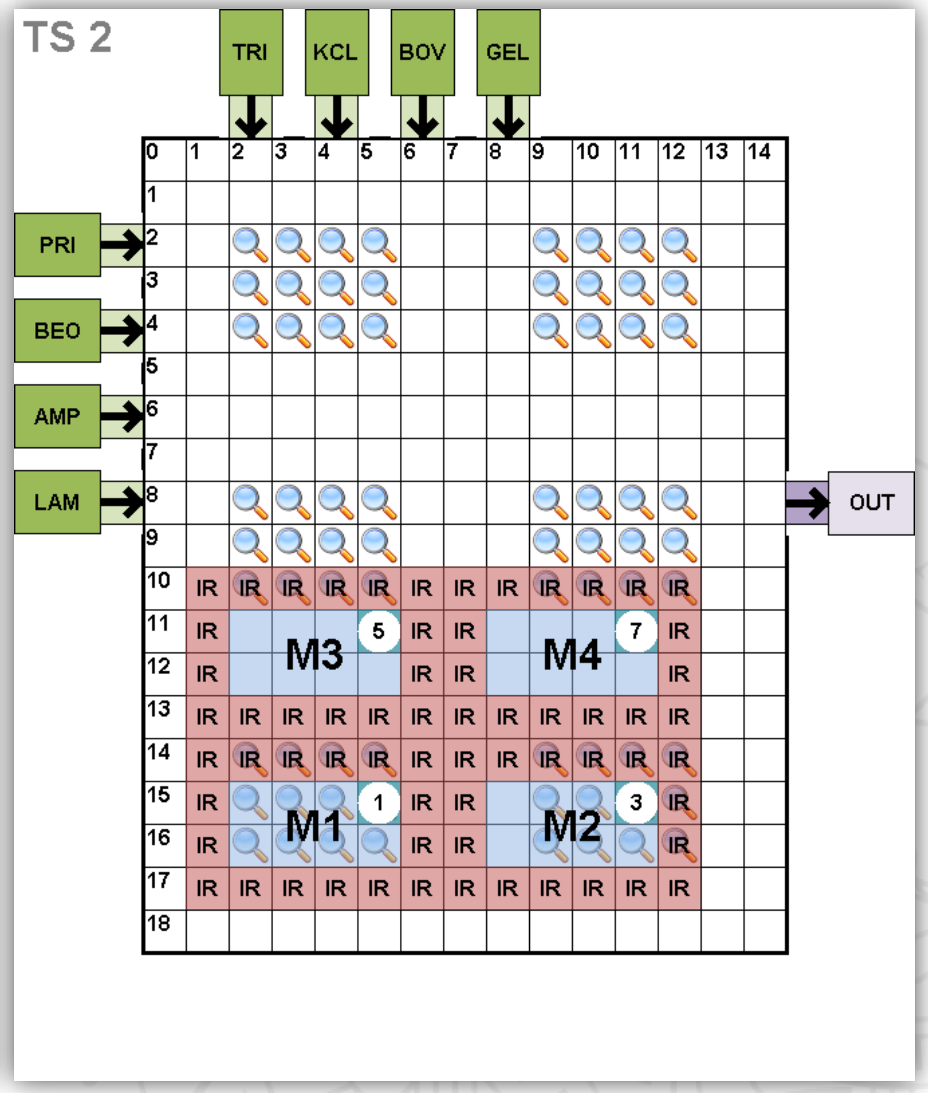
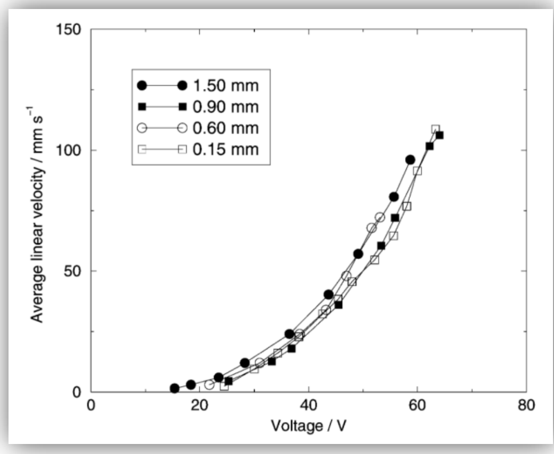
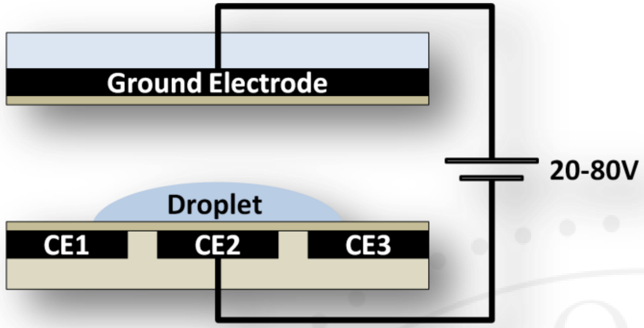


Corresponding Droplet Motion

Discrete Perspective

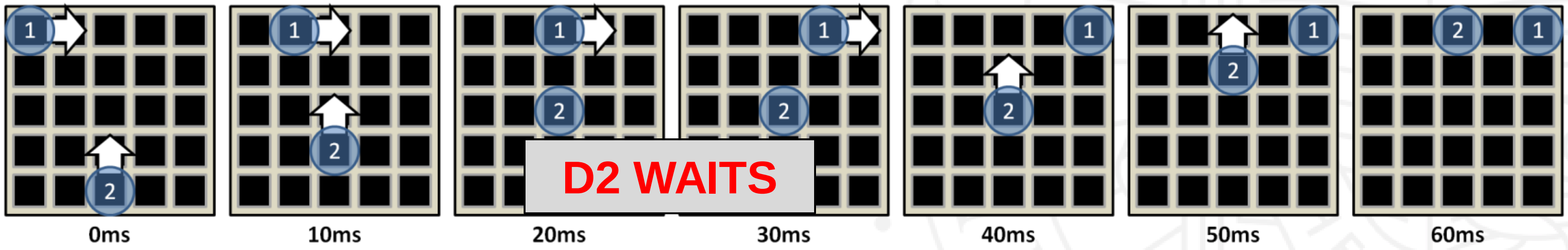
- Increase Voltage → Increase Velocity





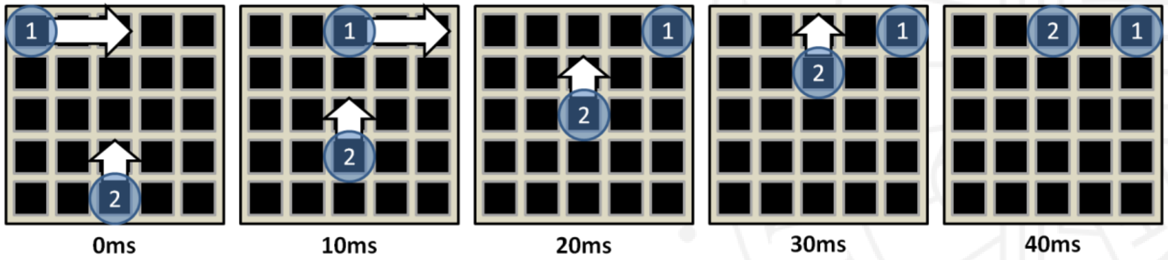
Pollack, M. G., Shenderov, A. D., and Fair, R. B. 2002. Electrowetting-based actuation of droplets for integrated microfluidics. *Lab-on-a-Chip 2, 2 (Mar. 2002), 96-101.*

- Compaction treated as discrete problem
  - Single voltage used for all droplet movements
  - All droplets move at same speed (requires halts)



Continuous-Time Perspective

- Voltages can be changed
  - Abandons synchronous droplet movement
- Reduce energy usage; maintain timing
- Compaction treated as continuous problem
  - Multiple voltages used for droplet movements
  - Droplets move at different speeds (avoid halts)



Formal Problem Formation

$$E_{i,j} = \frac{{V_{i,j}}^2}{1G\Omega} \times \Delta T_{i,j}$$

$$Z(d_i) = \sum_{j=1}^{N} z_{i,j}$$

$$T(d_i) = \sum_{j=1}^{N} \left(t_{i,j} + u_{i,(j,j+1)}\right)$$

$$U(d_i, p_{i,j}) = \sum_{k=0}^{j-1} \left(t_{i,k} + u_{i,(k,k+1)}\right)$$

$$I(d_i, p_{i,j}) = \left[U(d_i, p_{i,j}), U(d_i, p_{i,j}) + t_{i,j}\right]$$

$$J(d_i, p_{i,j}, p_{i,j+1}) = \left(U(d_i, p_{i,j}) + t_{i,j}, U(d_i, p_{i,j+1})\right)$$

$$O(d_i) = \langle I(d_i, p_{i,1}), J(d_i, p_{i,1}, p_{i,2}), \ldots, I(d_i, p_{i,N}), J(d_i, p_{i,N-1}, p_{i,N})\rangle$$

$$C = (K-1)\sum_{i=1}^{K} |O(d_i)|$$

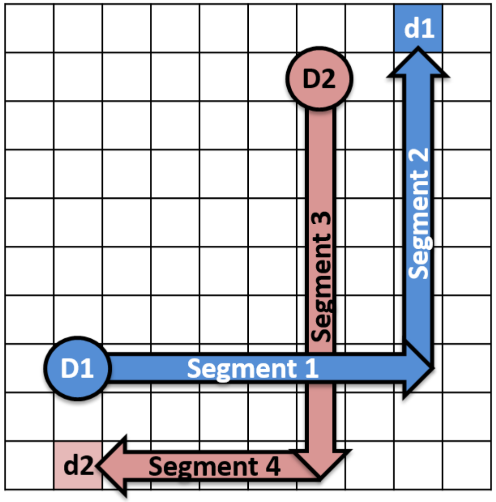
$Velocity =$ 0.0[illegible]35 $\times Voltage^2 + 0.0358 \times Voltage - 0.9103$

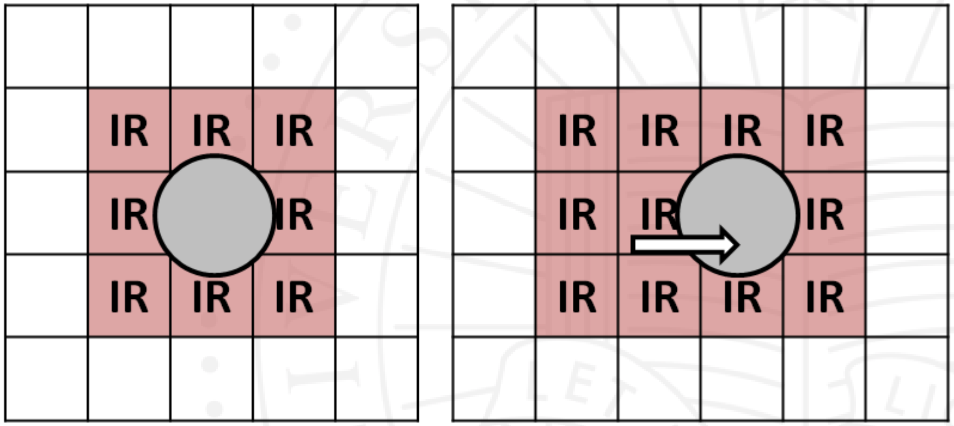
$$Energy = Power \times Time = \frac{Voltage^2}{Resistance} \times Time$$

Details In Paper

General Problem Formation

- Droplet paths broken into segments
  - Max-length contiguous subsequence in one direction
- Droplet motion:
  - Constant velocity/voltage along entire segment
  - Only stops at beginning/end of segments
  - Interference constraints at continuous-time positions



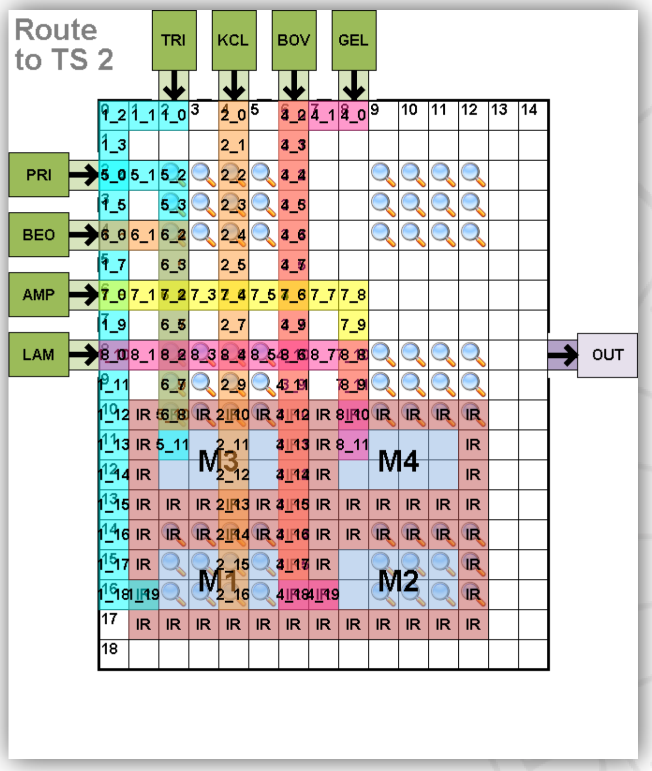


Static Constraints Dynamic Constraints

Interference Regions (IR) Prevent Droplet Collisions

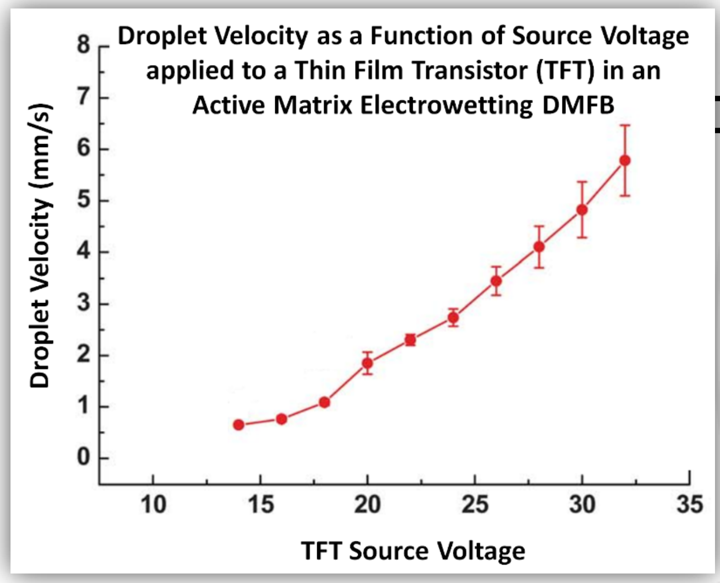
Algorithmic Description

- Step 1: Route computation
  - Roy's maze-based droplet router (greedy)
    - Computes routes that could overlap
  - Never re-visit/re-compute routes



Algorithmic Description

- Step 2: Time-constrained, energy-aware compaction
  - Given timing constraint T_c
  - For each droplet path:
    - Compute initial path velocity $vel = \frac{pathLength}{Tc}$
      - Minimum Voltage for velocity derived from graph



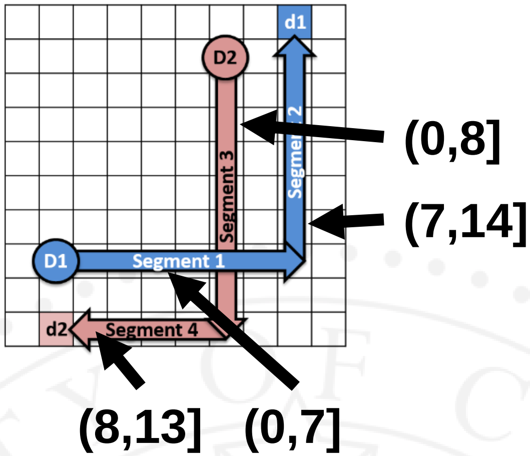
$$Velocity = 0.005 \times Voltage^2 + 0.0358 \times Voltage - 0.9103$$

Least-squares-fit equation

Noh, J. H., Noh, J., Kreit, E., Heikenfeld, J., and Rack, P. D. 2012. Toward active-matrix lab-on-a-chip: programmable electrofluidic control enabled by arrayed oxide thin film transistors. *Lab-on-a-Chip* 12, 2 (Jan. 2012), 353-360.

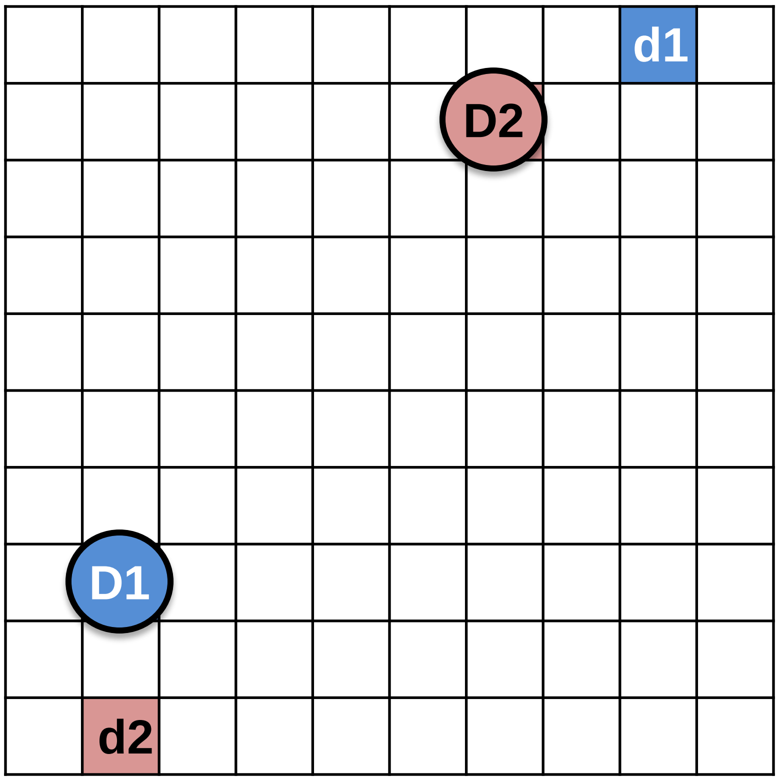
Algorithmic Description

- Step 2: Compaction (continued)
  - Compute all segment timings from initial velocities
  - For each droplet path P_d
    - For each electrode position e_{di} in P_d
      - Compare against each previously compacted path
        - If no interference along segment:
          - Accept segment
        - If interference along segment:
          - Speedup current droplet along its segment
          - Adjust remaining segments to conserve energy
          - Re-compute path timings for that droplet

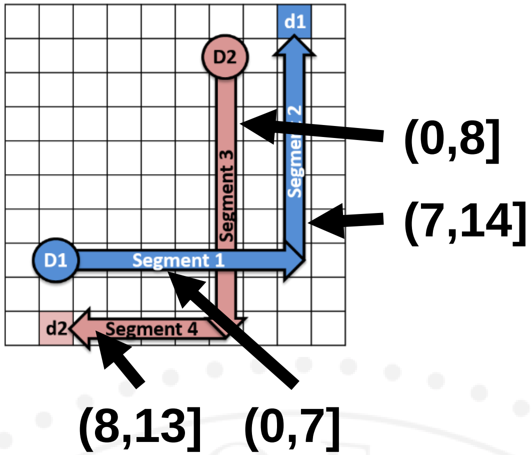


Example Coming!

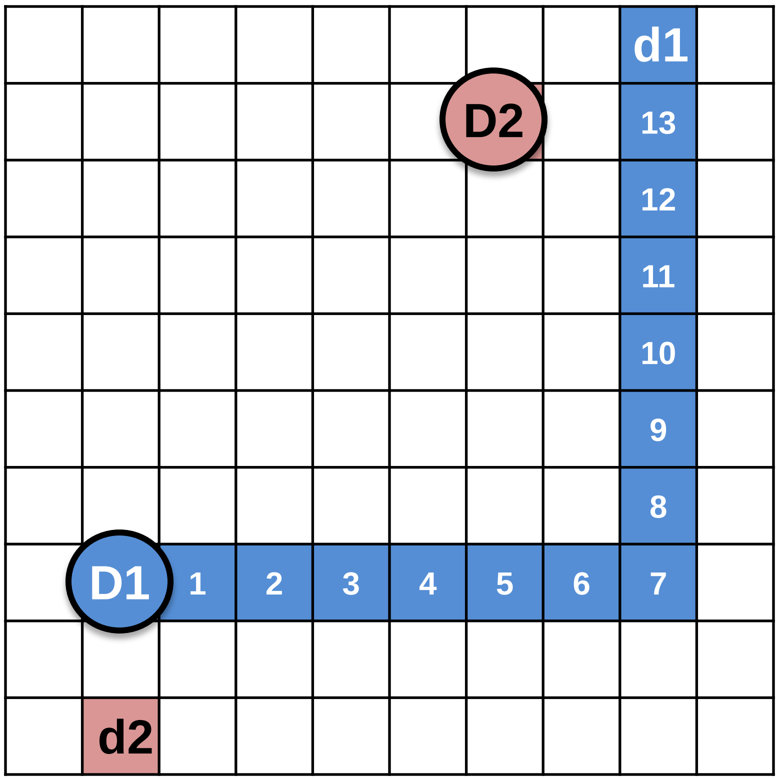
Simple Example



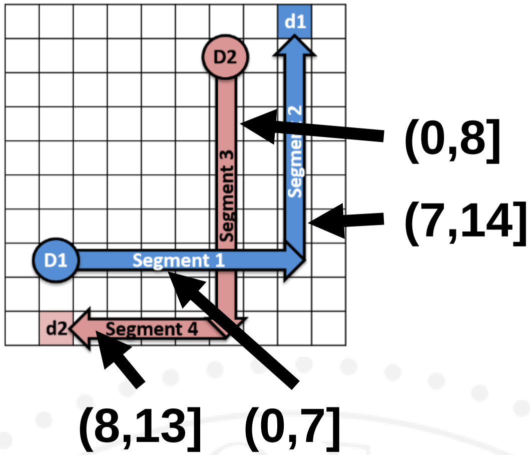
Compact D1.



Simple Example



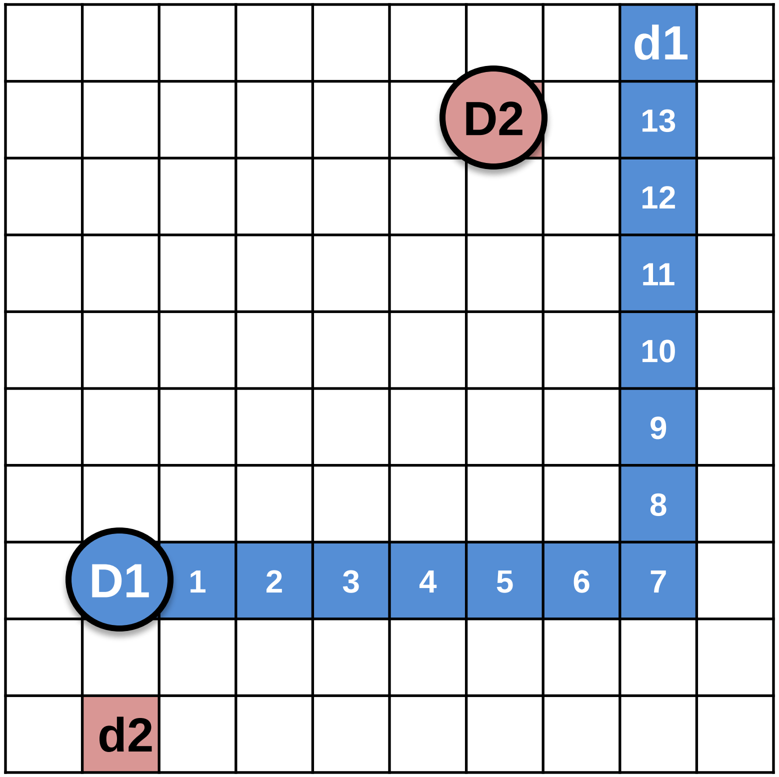
No previous paths; D1 routes with no problems.

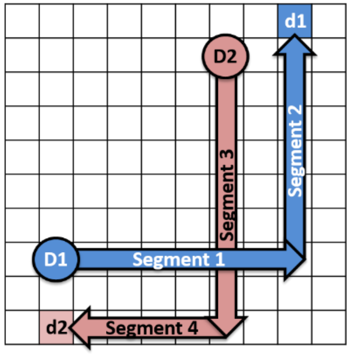


Numbers on electrodes indicate the time the droplet arrives at the electrode.

Segment 1: 1 electrode/s
Segment 2: 1 electrode/s

Simple Example





Numbers on electrodes indicate the time the droplet arrives at the electrode.

Segment 1: 1 electrode/s
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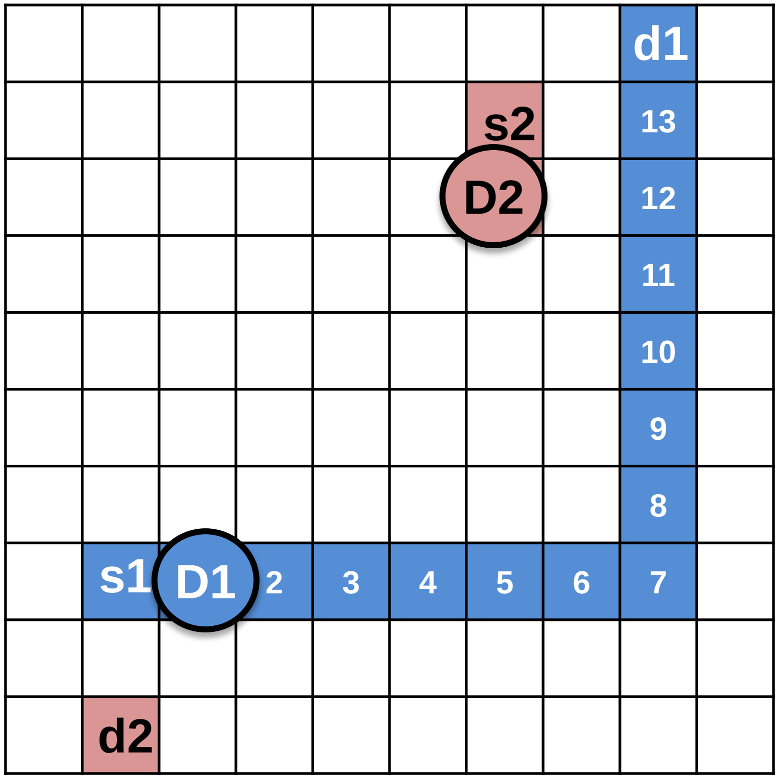
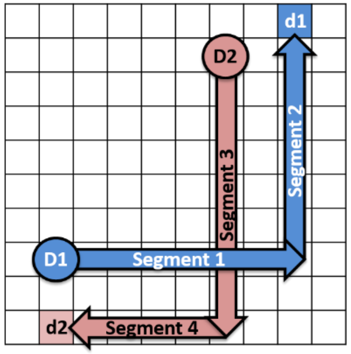
Segment 3: 1 electrodes/s

Now compact D2 against all previous droplet paths (D1).

Simple Example





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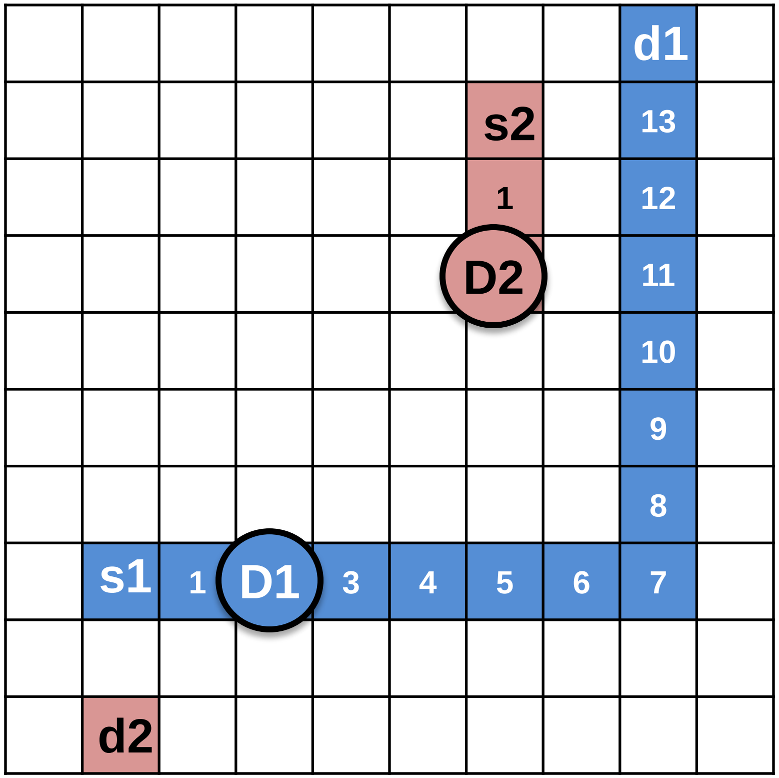

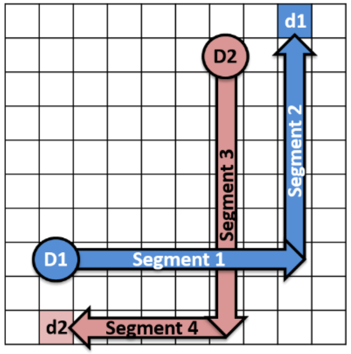

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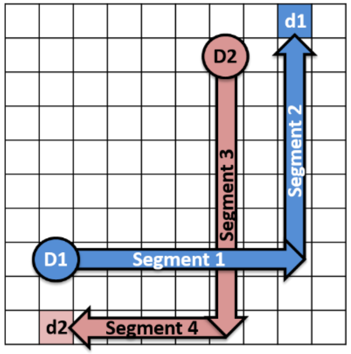

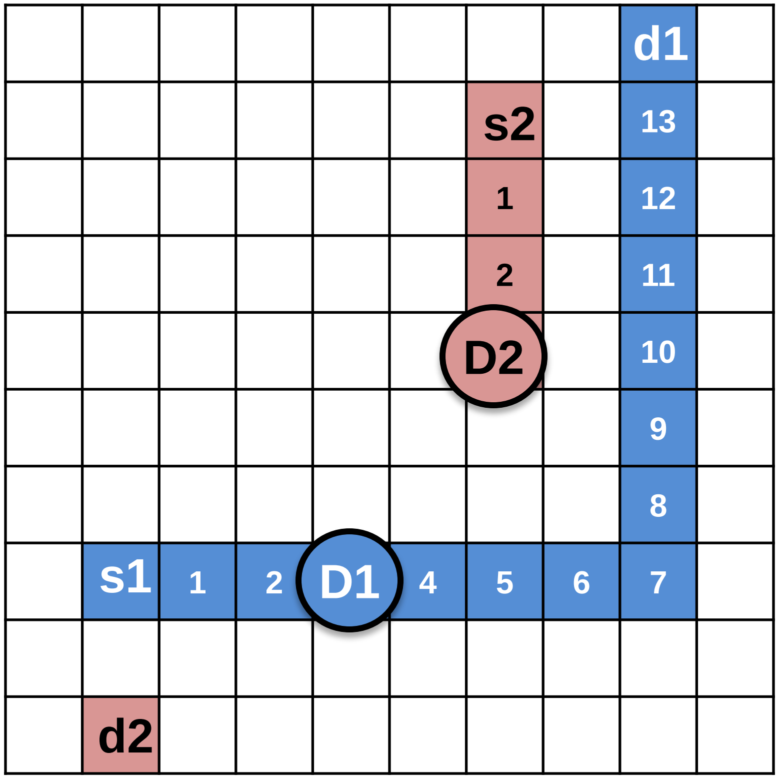

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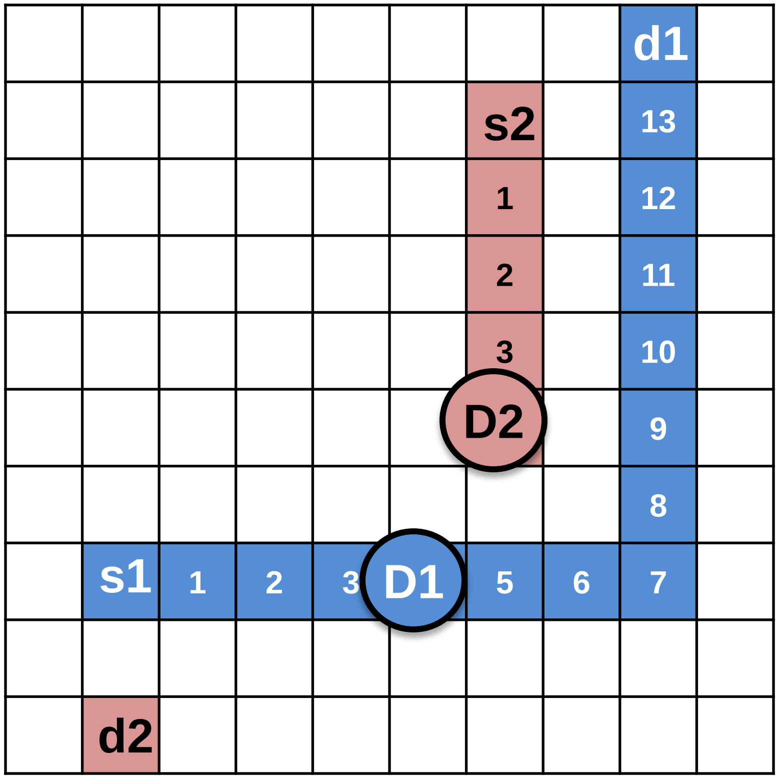

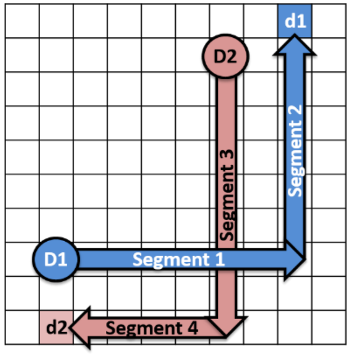

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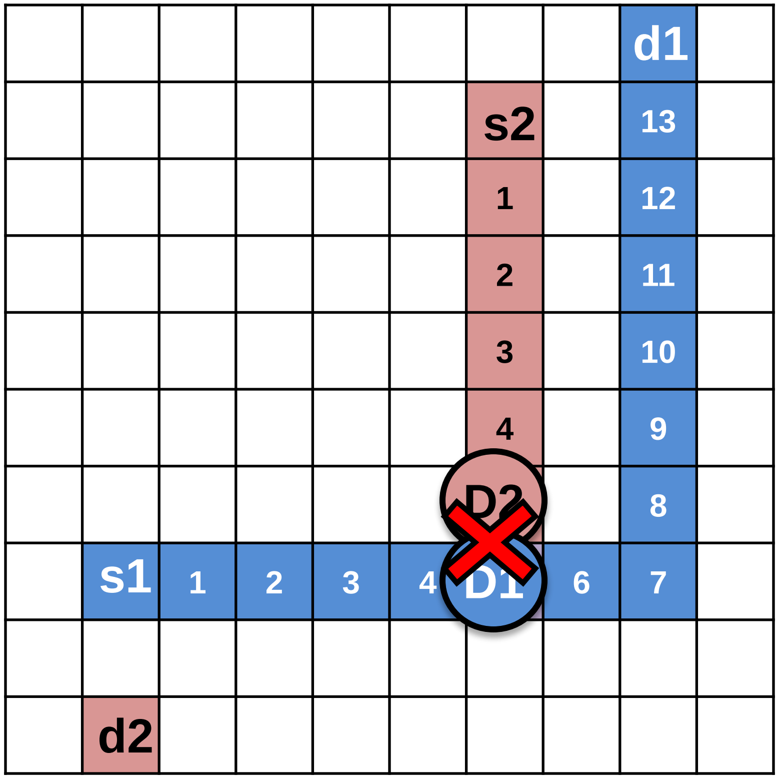

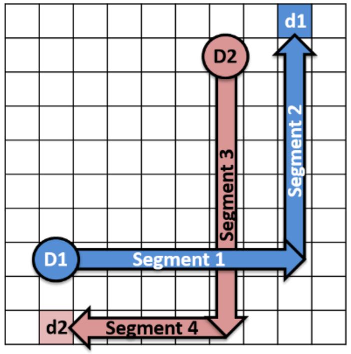

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Segment 2: 1 electrode/s
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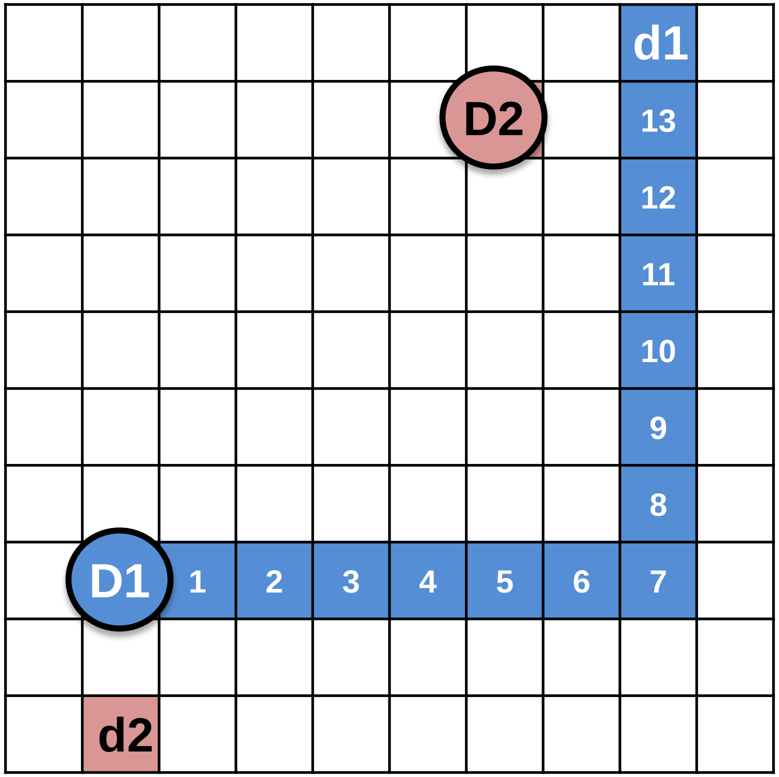
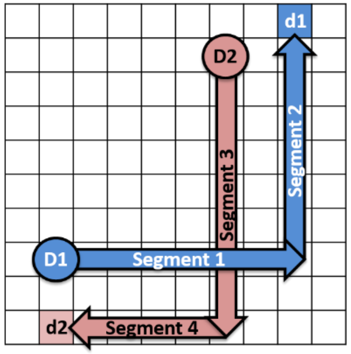
While compacting D2, detected interference at time 5 between D1 and D2.

Simple Example



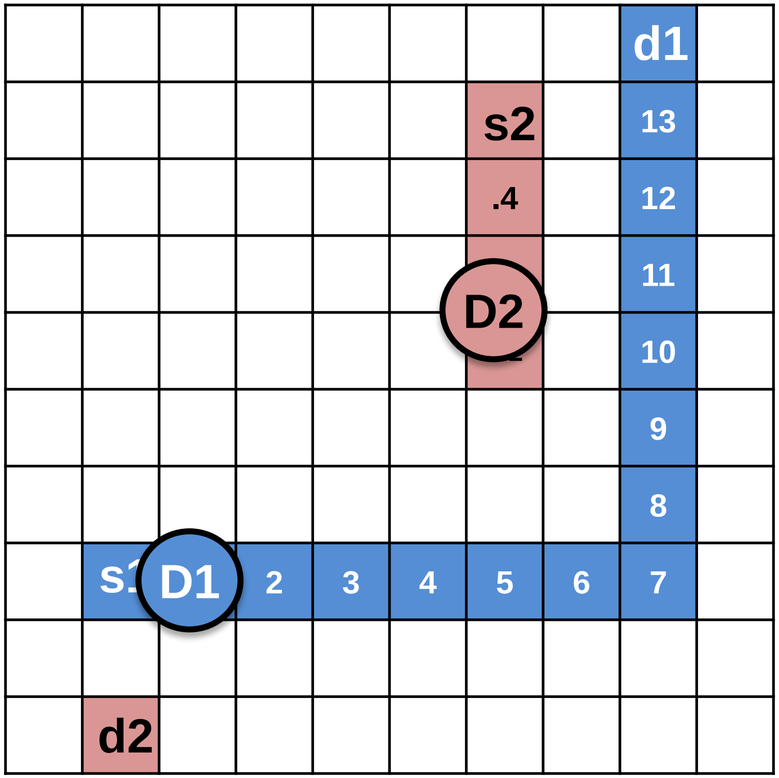


Numbers on electrodes indicate the time the droplet arrives at the electrode.

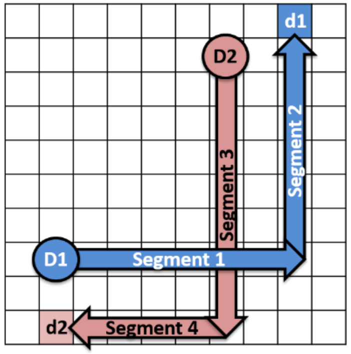
Segment 1: 1 electrode/s
Segment 2: 1 electrode/s
Segment 3: 2.5 electrodes/s

Increases D2’s velocity/voltage (2.5x) and restart compaction for D2.

Simple Example



Re-compact D2 at 2.5x speed against all previous droplet paths (D1).



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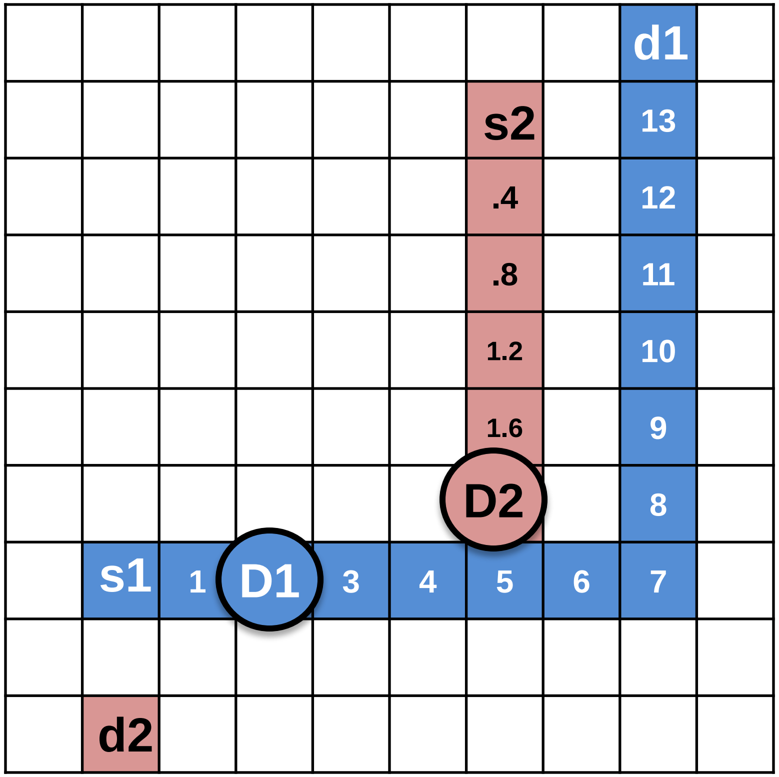

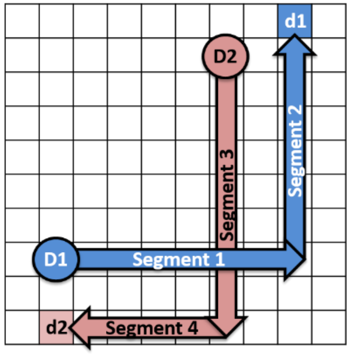

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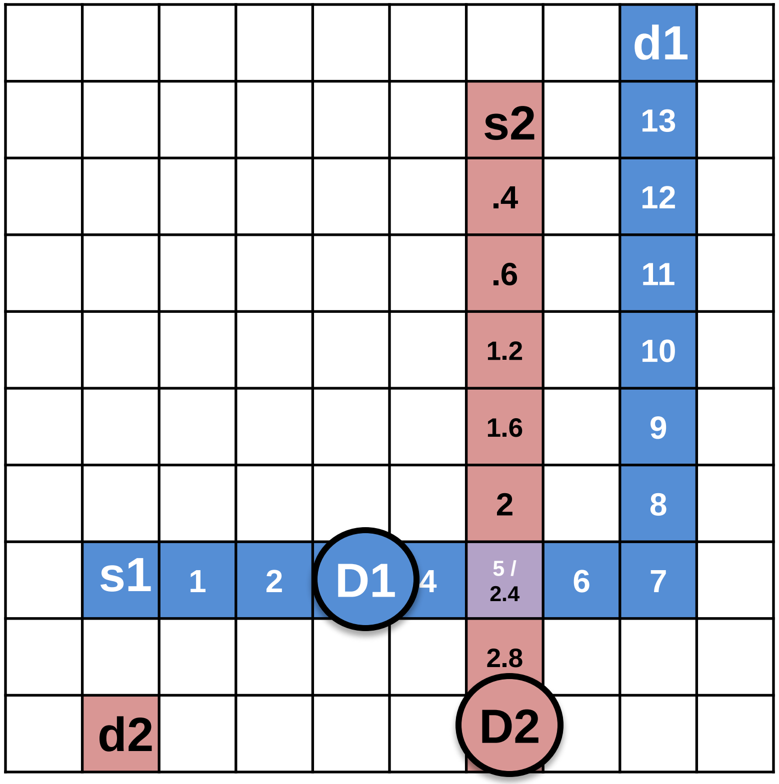

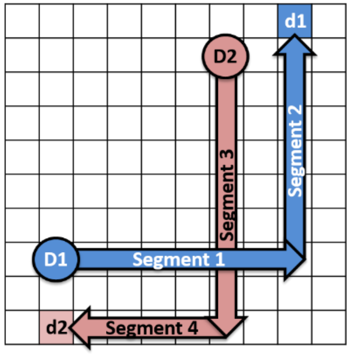

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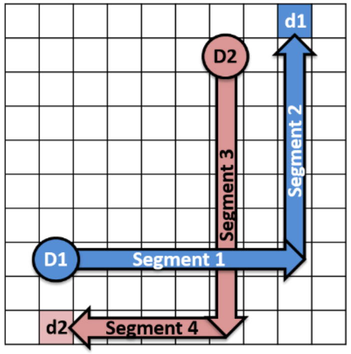
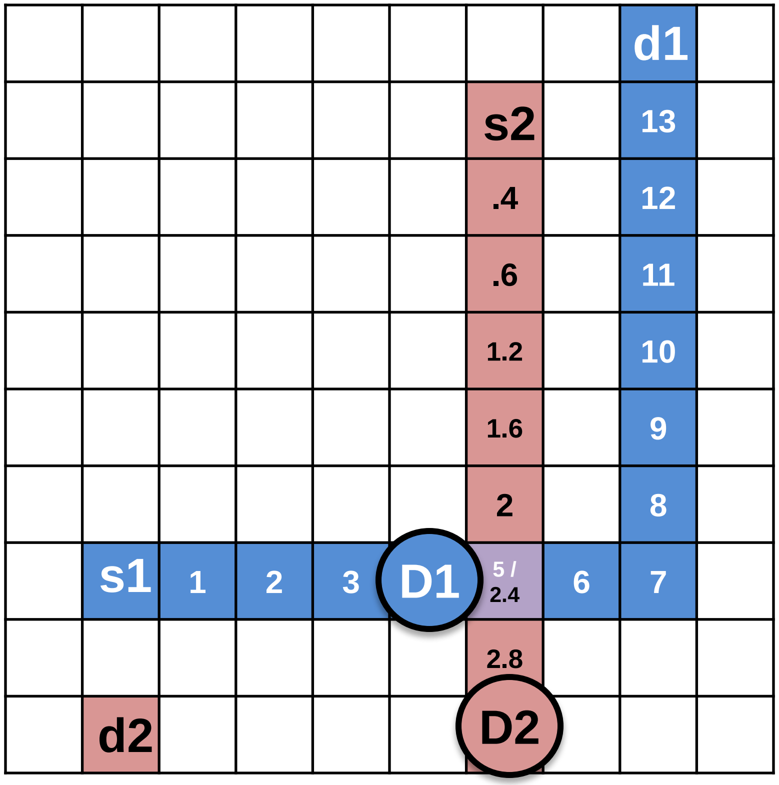
D2 reached end of segment.

Simple Example



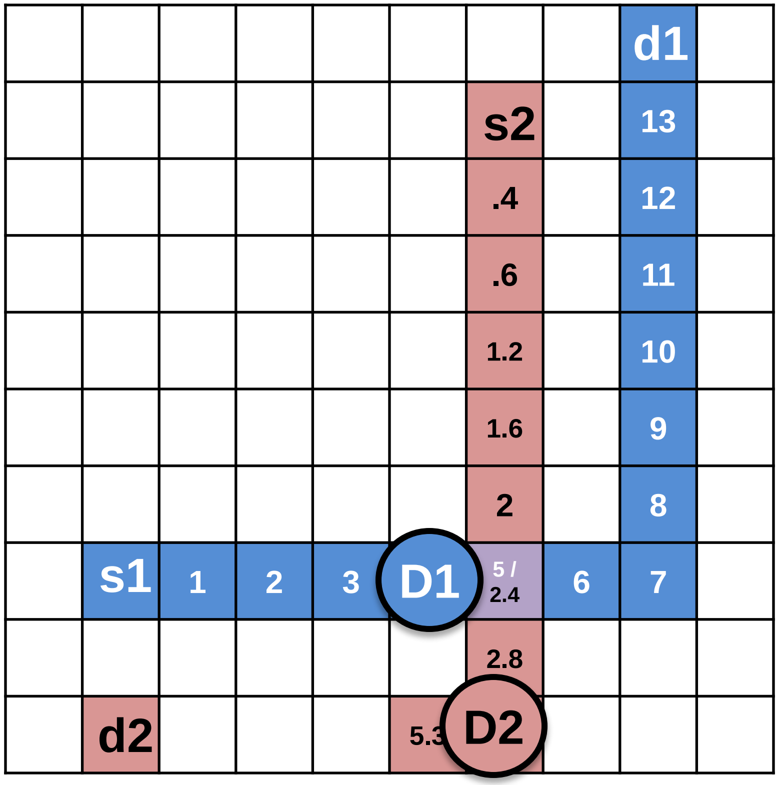


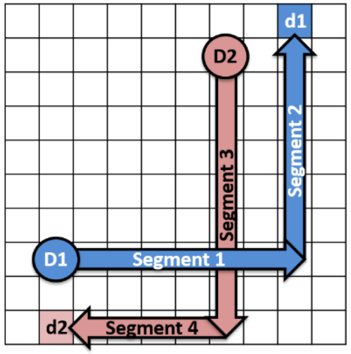
Numbers on electrodes indicate the time the droplet arrives at the electrode.

Segment 1: 1 electrode/s
Segment 2: 1 electrode/s
Segment 3: 2.5 electrodes/s
Segment 4: 0.46 electrodes/s

D2 does not need to get there before D1; save energy and slow D2 down to 0.46 electrodes/sec.

Simple Example





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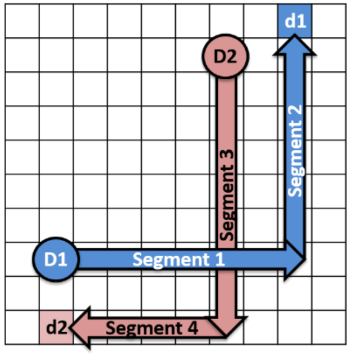

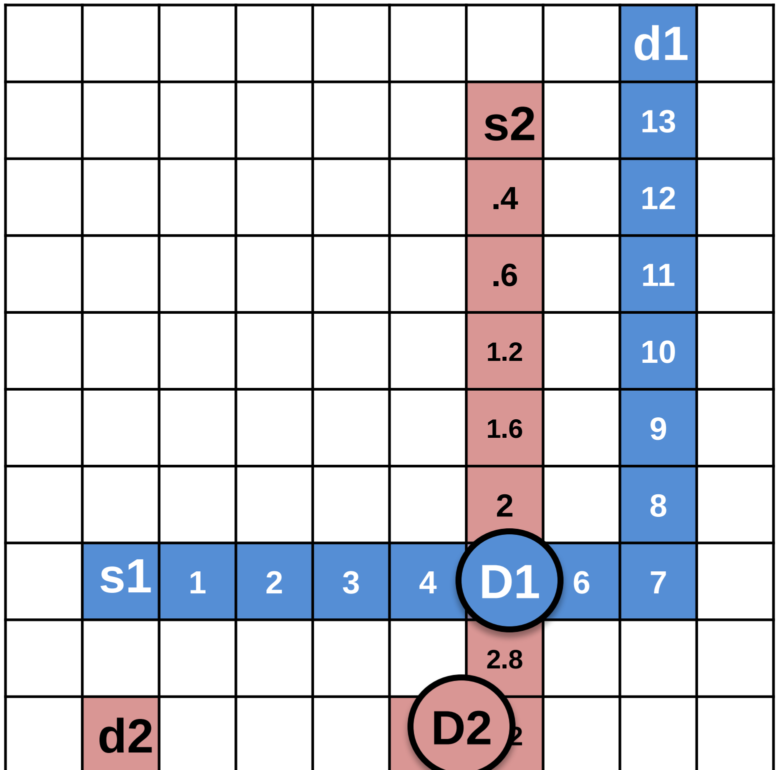

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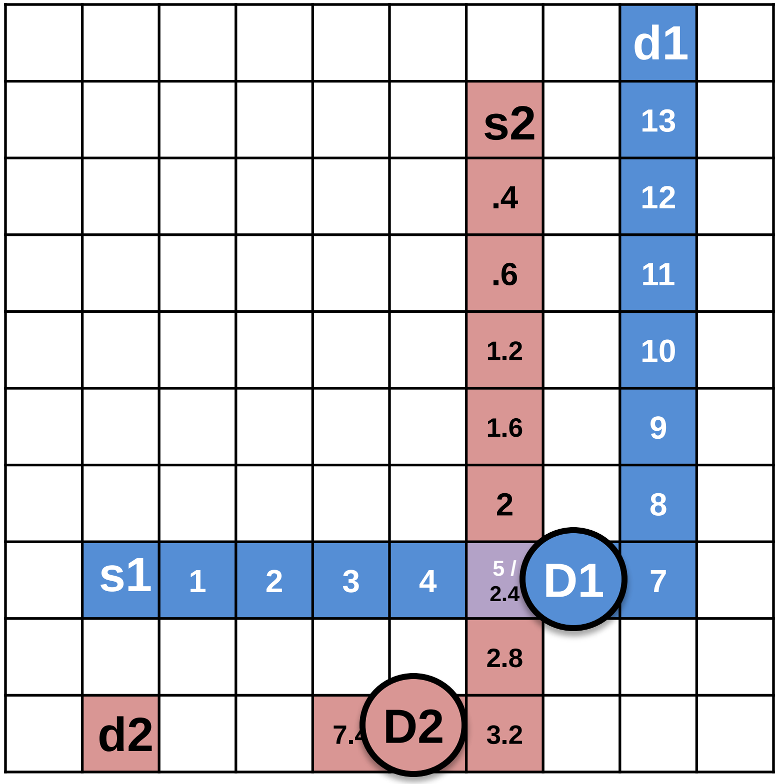

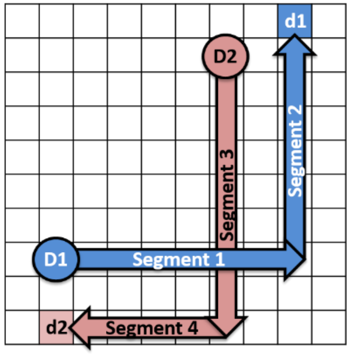

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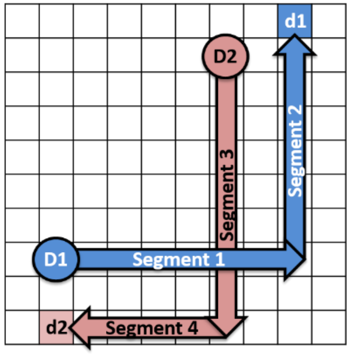

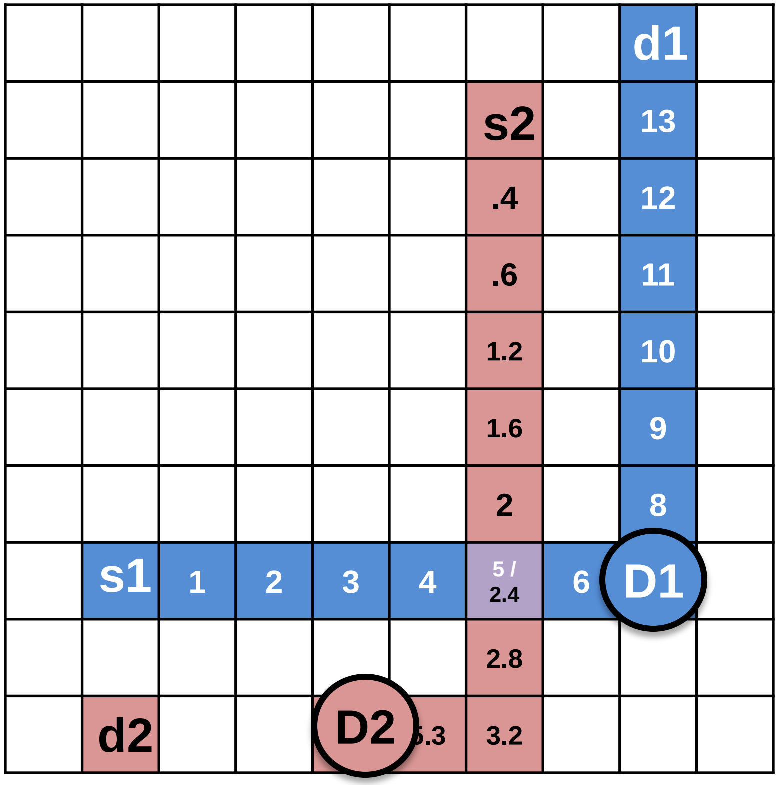

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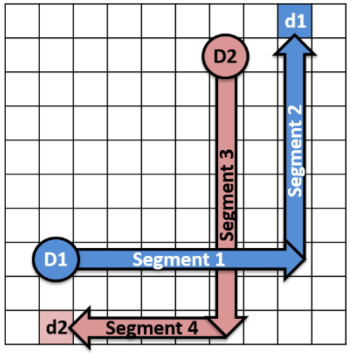

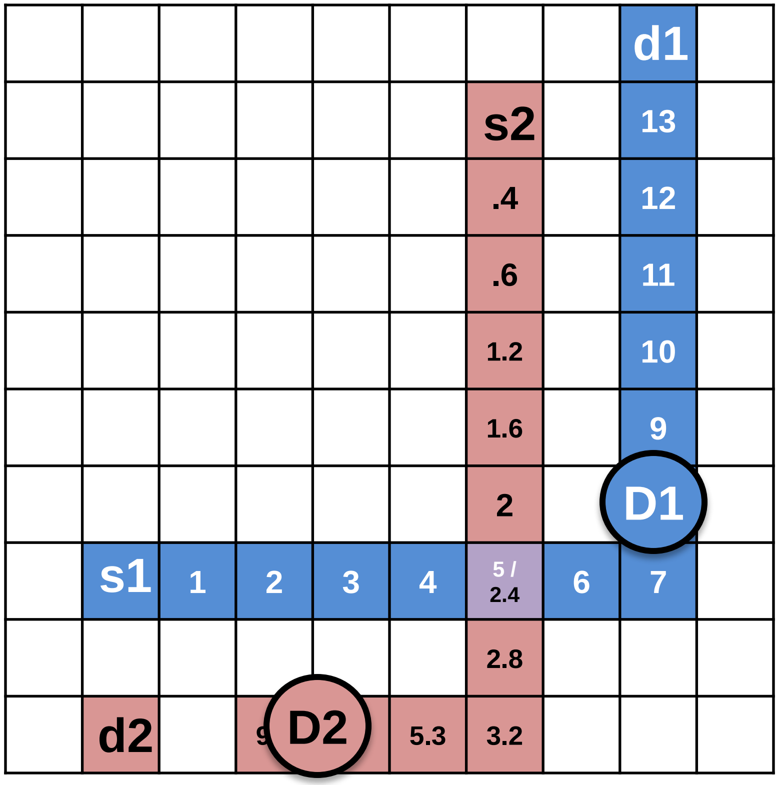

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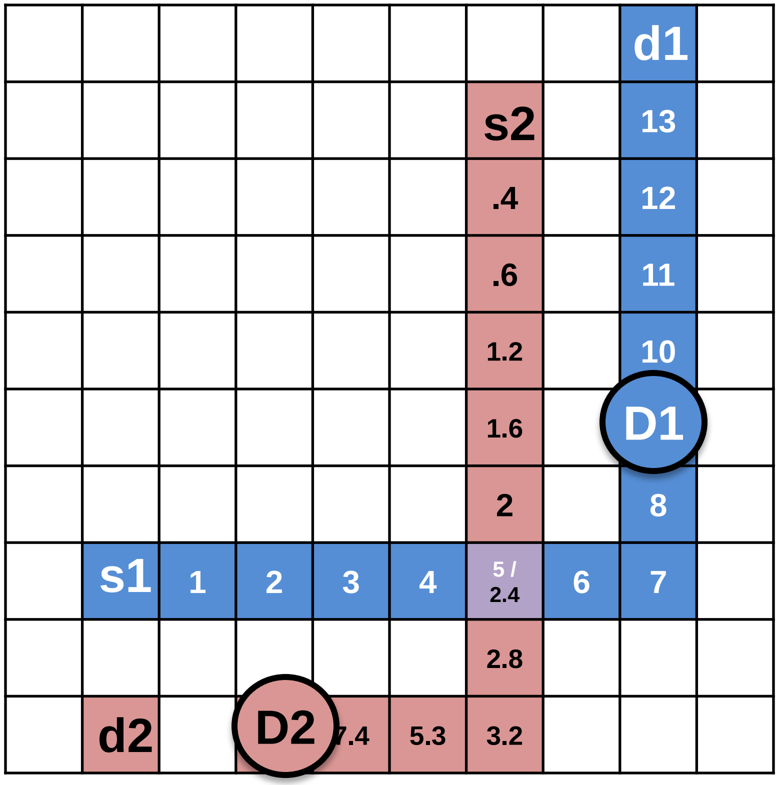

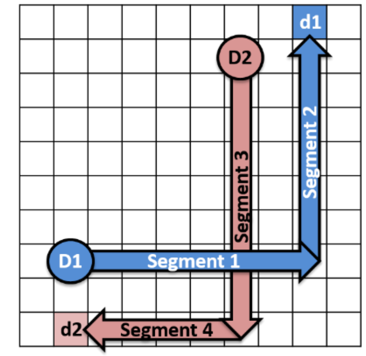

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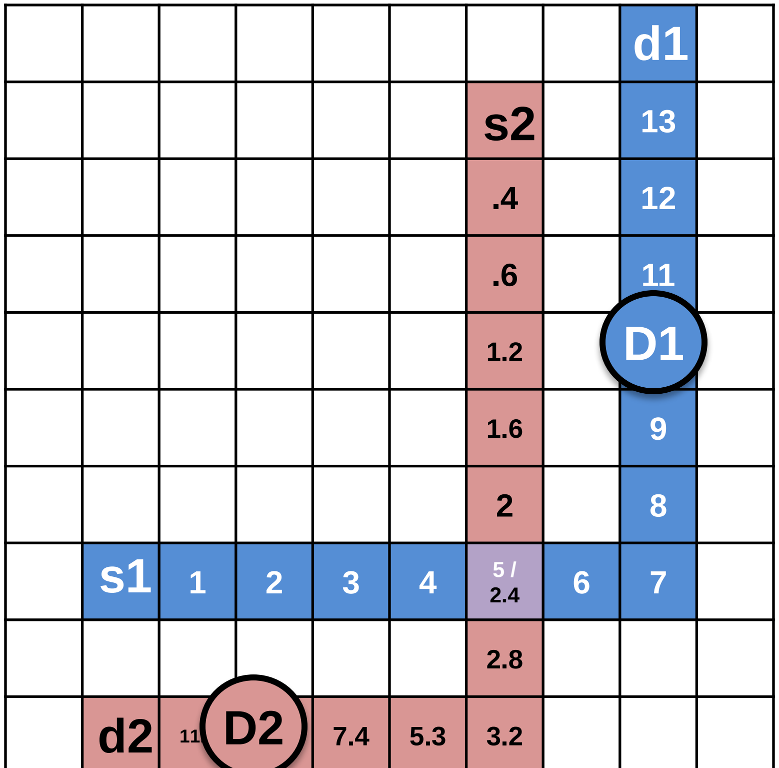

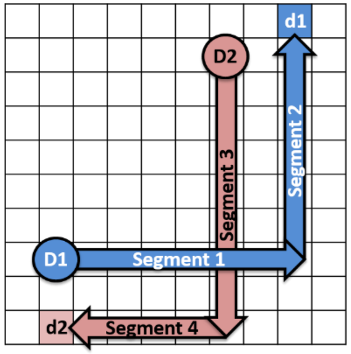

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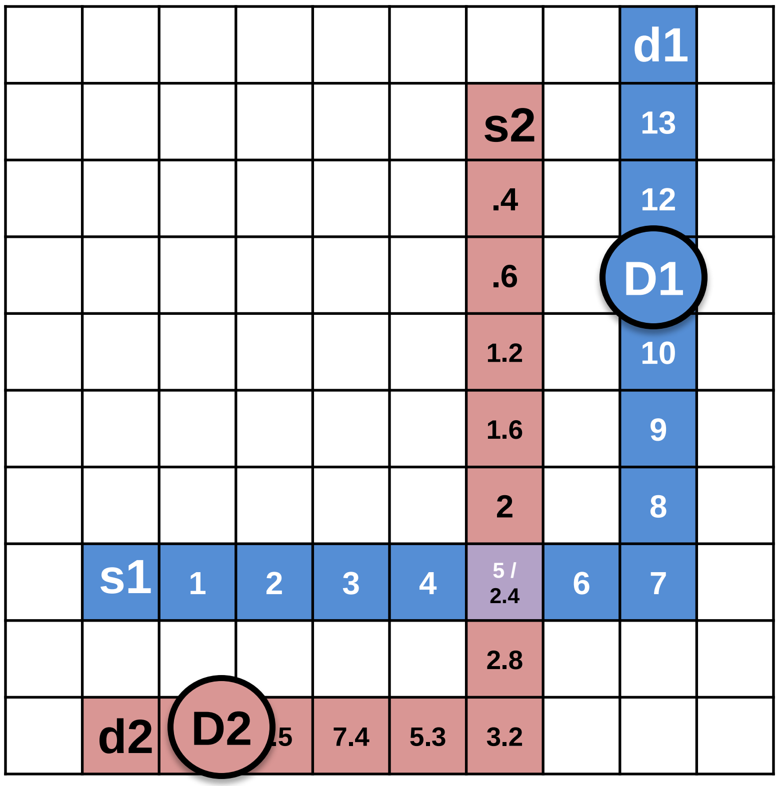

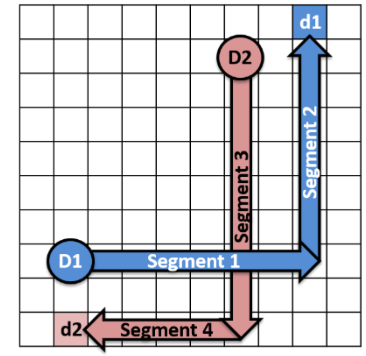

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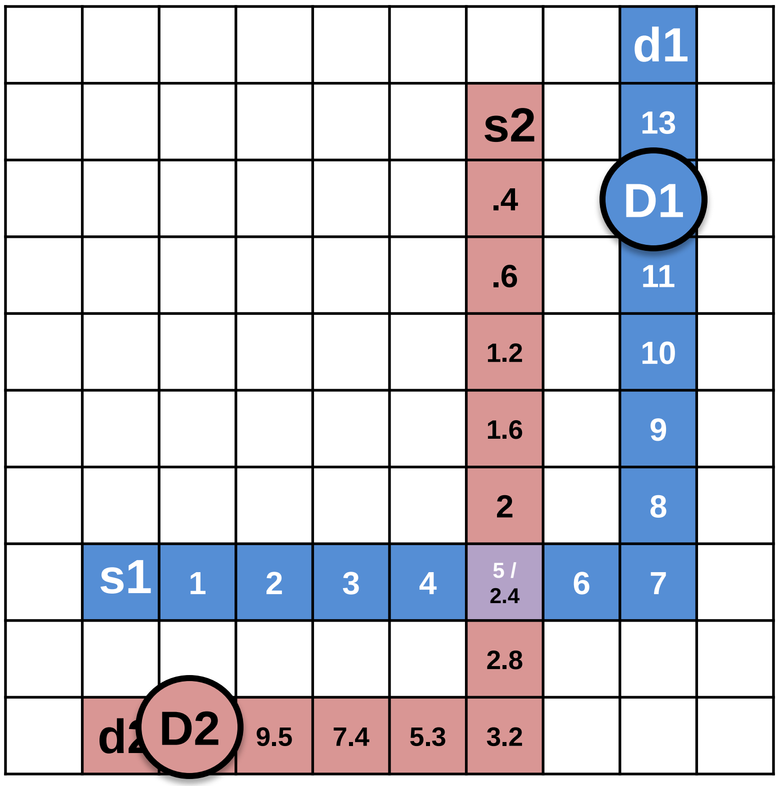

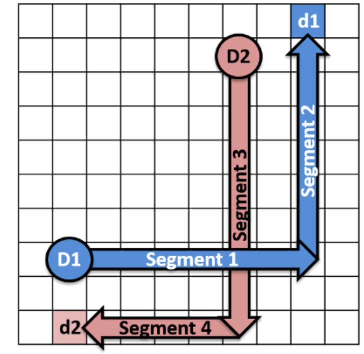

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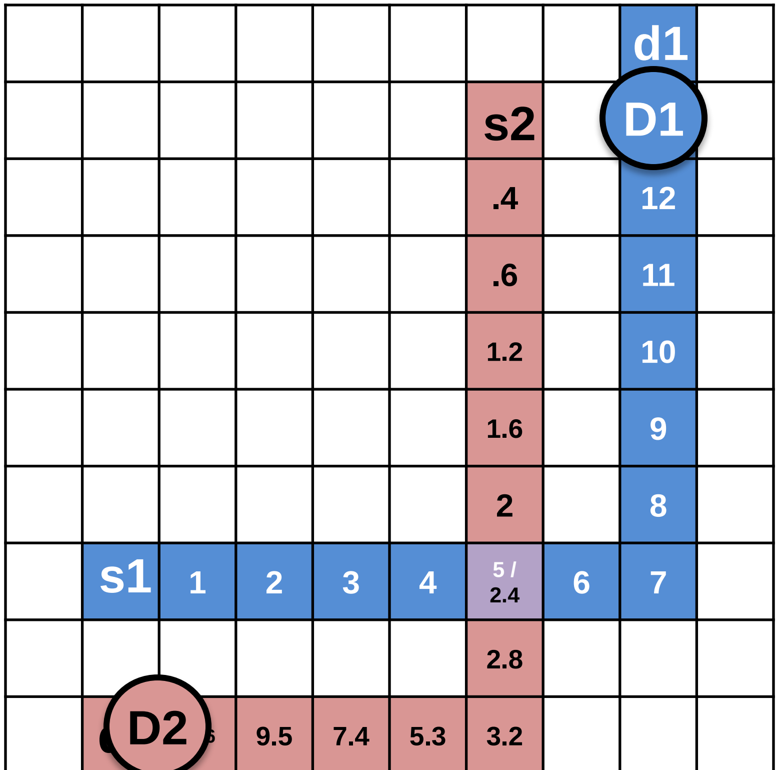
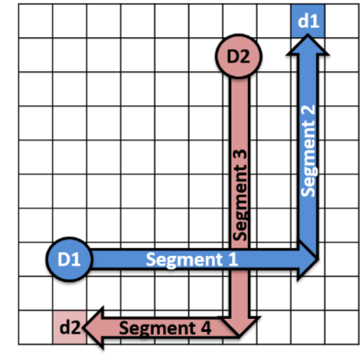
Segment 4: 0.46 electrodes/s

D2 does not need to get there before D1; save energy and slow D2 down to 0.46 electrodes/sec.

Simple Example



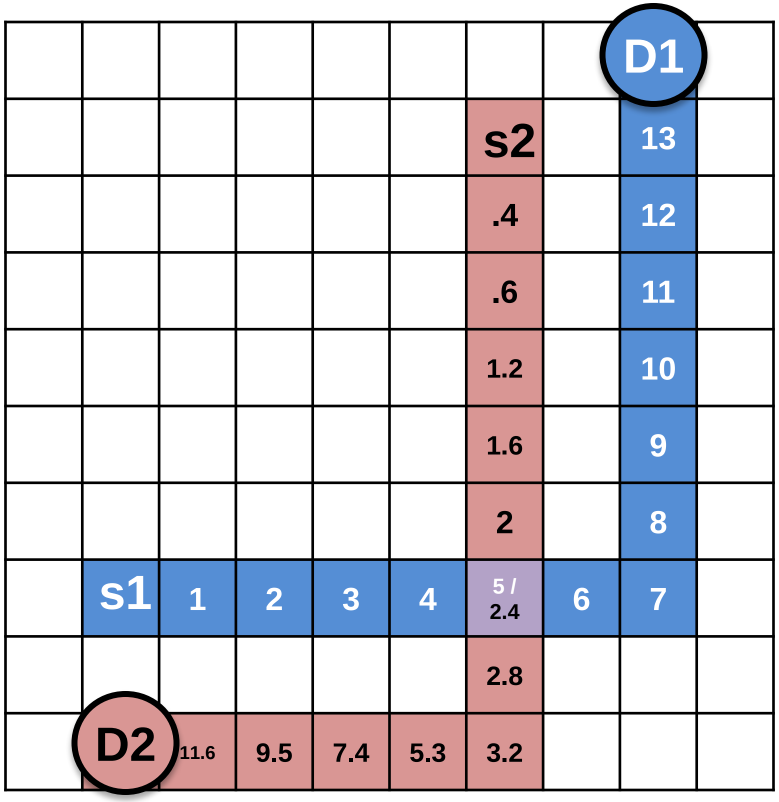


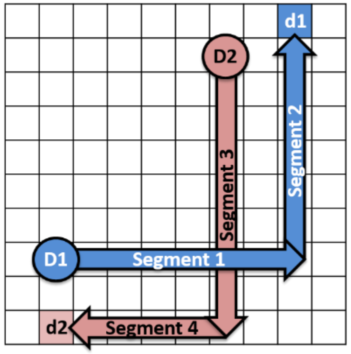
Numbers on electrodes indicate the time the droplet arrives at the electrode.

Segment 1: 1 electrode/s
Segment 2: 1 electrode/s
Segment 3: 2.5 electrodes/s
Segment 4: 0.46 electrodes/s

D2 does not need to get there before D1; save energy and slow D2 down to 0.46 electrodes/sec.

Simple Example





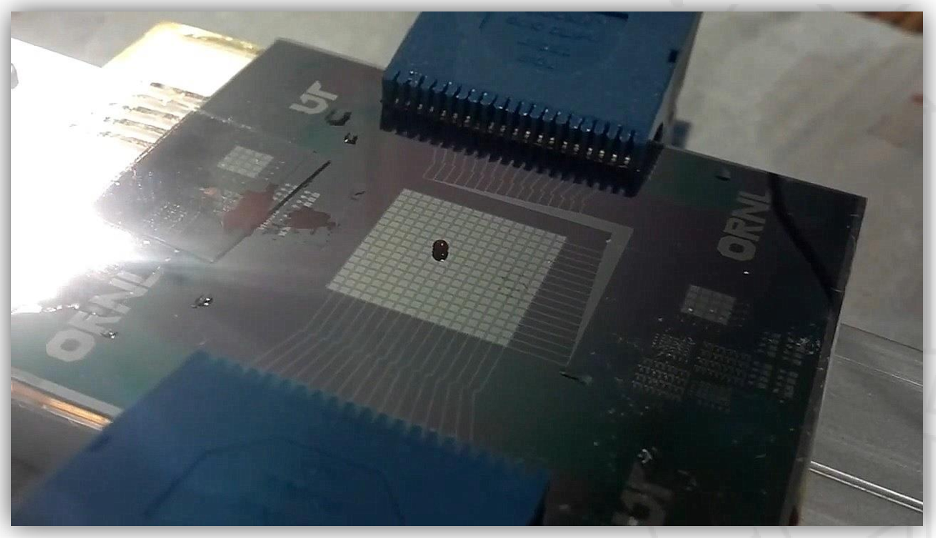
Numbers on electrodes indicate the time the droplet arrives at the electrode.

Segment 1: 1 electrode/s
Segment 2: 1 electrode/s
Segment 3: 2.5 electrodes/s
Segment 4: 0.46 electrodes/s

D2 compacted against D2 with no interference.

Simulation Details

- DMFB modeled after University of Tennessee's active matrix design[1]
  - Electrode resistance = 1GΩ
  - Electrode pitch (dimension) = 2.54mm
  - $Voltage_{min}$ = 13V, $Voltage_{max}$ = 70V
  - Voltage/velocity relationship: $$Velocity = 0.005 \times Voltage^2 + 0.0358 \times Voltage - 0.9103$$



[1] Noh, J. H., Noh, J., Kreit, E., Heikenfeld, J., and Rack, P. D. 2012. Toward active-matrix lab-on-a-chip: programmable electrofluidic control enabled by arrayed oxide thin film transistors. *Lab-on-a-Chip* 12, 2 (Jan. 2012), 353-360.

Simulation Details

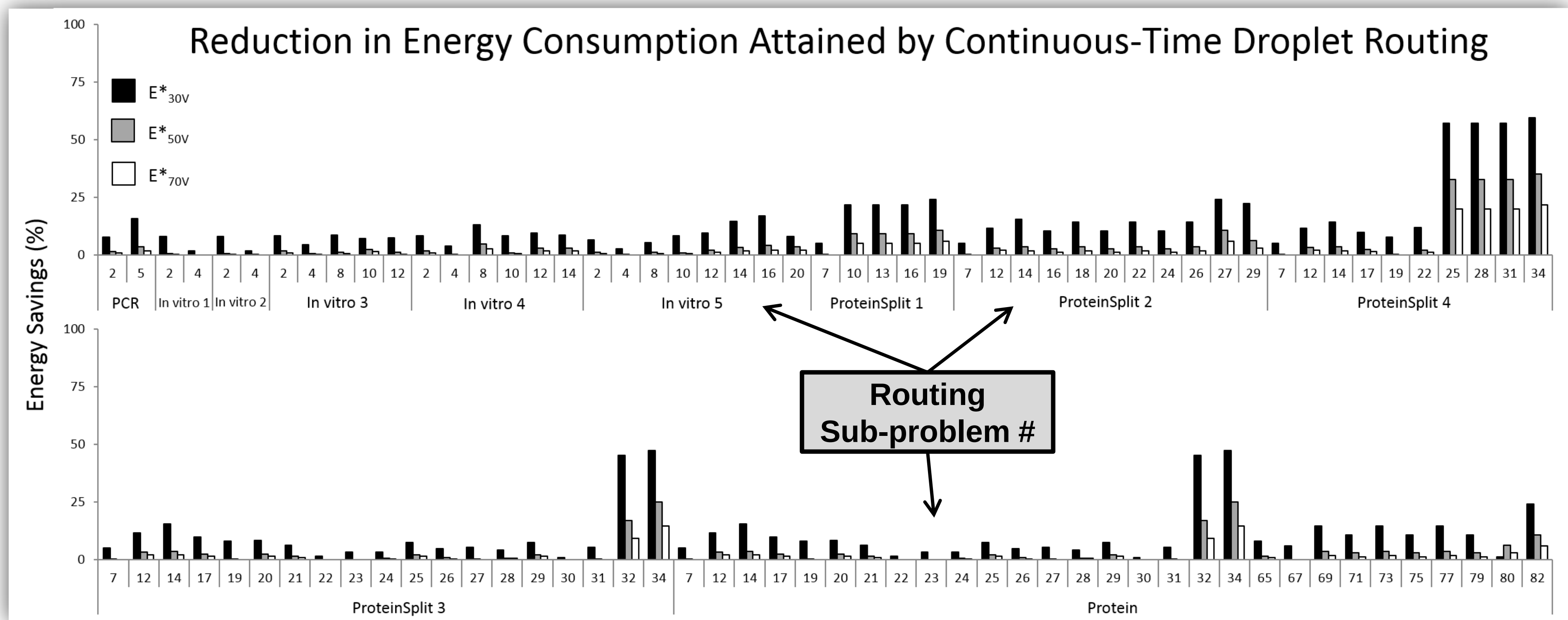
- Benchmarks
  - PCR, In-Vitro Diagnostics, Protein, ProteinSplit assays (common benchmarks)

- Base Routing Flow[2]
  - Step 1: Roy maze router (same as proposed)
  - Step 2: Constant voltage
    - Add stalls at beginning of routes to avoid interference

- Setup
  - Schedules and placements same for both route compactors

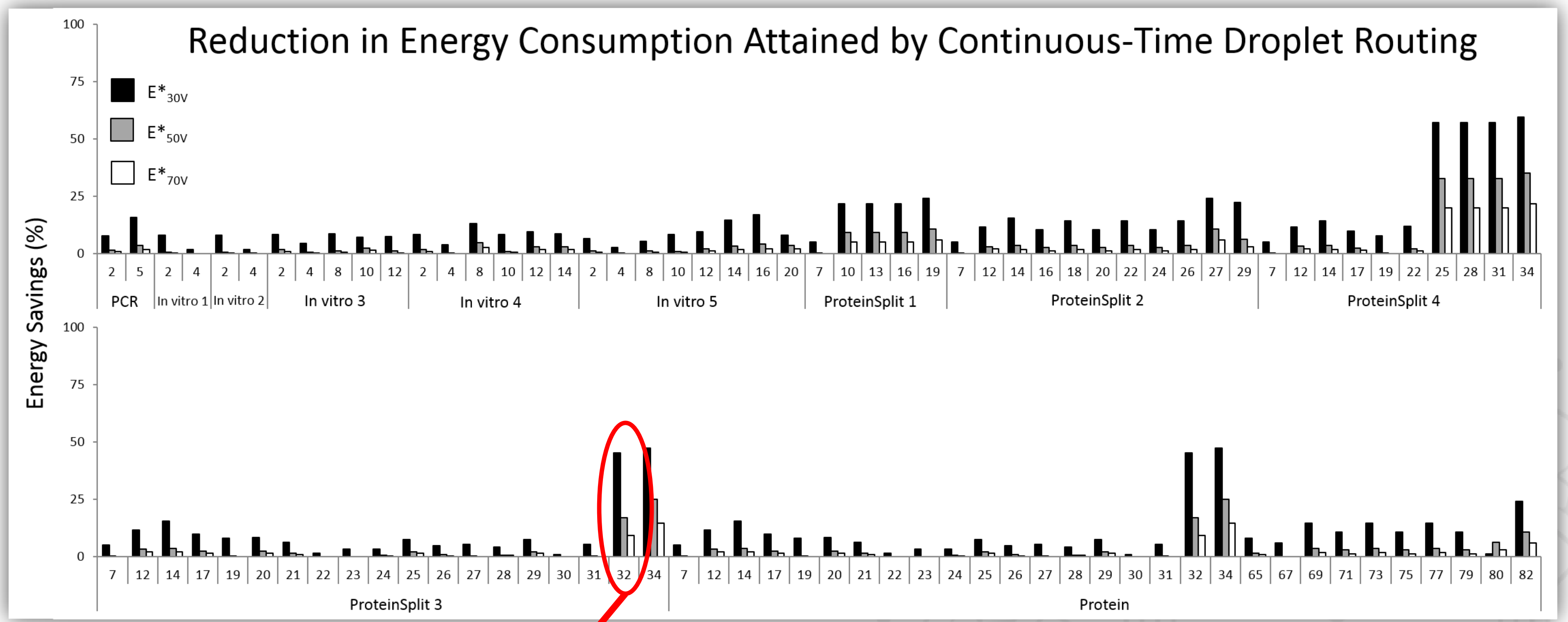
[2] Grissom, D., and Brisk, P. Fast online synthesis of generally programmable digital microfluidic biochips. In *Proceedings of the ACM/IEEE International Conference on Hardware Software Codesign and System Synthesis* (Tampere, Finland, October 07 - 12, 2012). CODES-ISSS '12, 413-422.

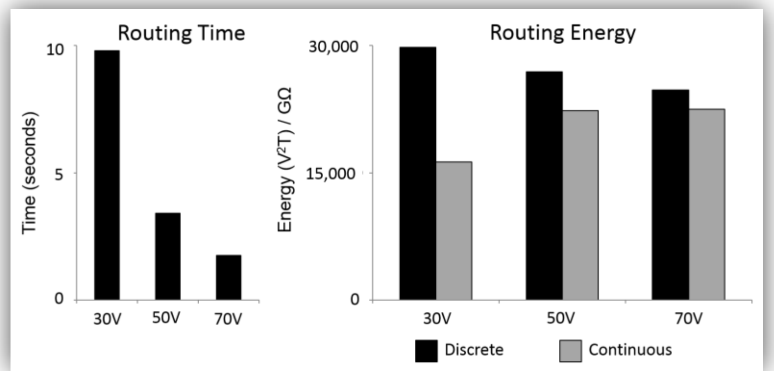
Results: Energy Savings



- Base flow performed at 30V, 50V and 70V
  - Time constraints for continuous-time compaction derived from these runs
- Energy savings vary greatly between sub-problems
  - Due to amount and complexity of droplets being routed

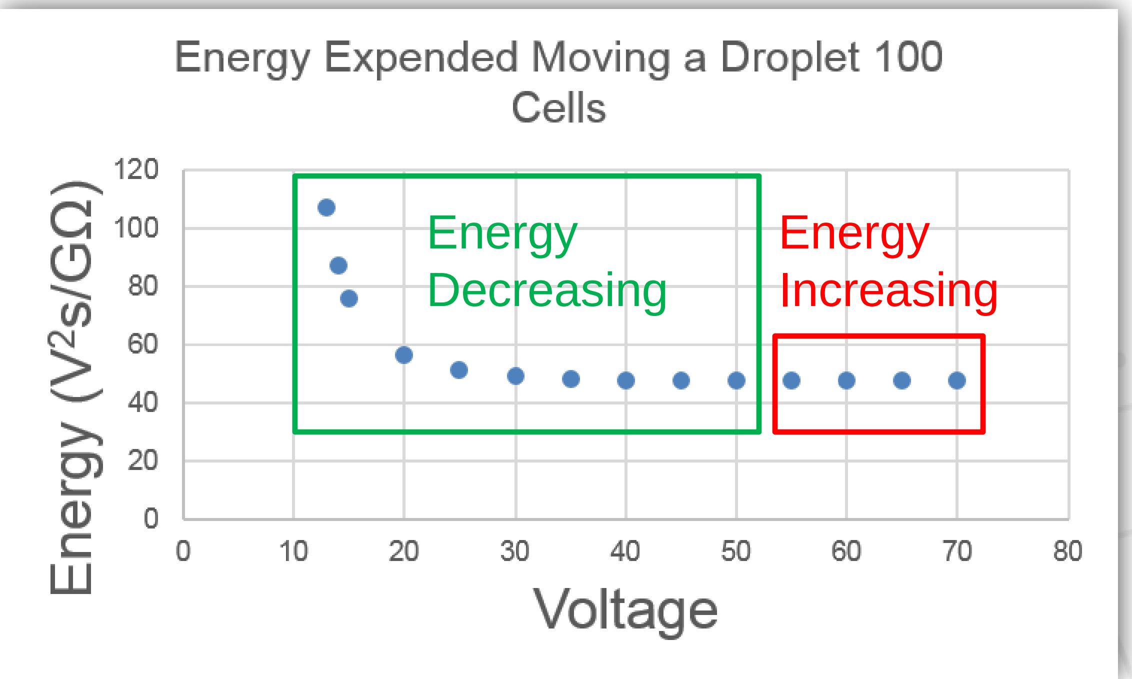
Results: Energy Savings





- Higher voltages ➔ Better energy usage across platforms
- More V for less time can lead to energy savings
- 30V sees greatest savings because slower paths provide more opportunities for route speedups

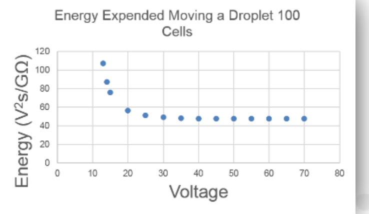
Results: Energy Savings



- Threshold exists where *Increasing Voltage* ➔ *Decreases Energy* becomes not true
- Threshold depends on device characteristics
- Large savings can be incurred by decreasing voltage on halts
  - Wait for 0.5s:
    - @ 30V ➔ 450 $V^2s/G\Omega$
    - @ 70V ➔ 2450 $V^2s/G\Omega$

Conclusion

- First model for continuous-time domain droplet routing (compaction)
  - Varying voltage ➔ varying velocity



- Multiple speeds allow for energy savings
  - Higher voltages can have better energy usage
  - Continuous-time domain droplet compaction can achieve energy savings across range of voltage

- Tradeoffs may vary based on characteristics of DMFB

Thank You

http://microfluidics.cs.ucr.edu/