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

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19th Asia & South Pacific Design Automation Conference
Singapore, January 21, 2014
Microfluidics will replace traditional bench-top 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

- Top Plate
- Ground Electrode
- Hydrophobic Layer
- Bottom Plate
- Control Electrodes (CE1, CE2, CE3)

Droplet

http://microfluidics.ee.duke.edu/
Droplet Actuation on a Prototype DMFB at the University of Tennessee
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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Route to TS 2

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Electrode Activations

Corresponding Droplet Motion
### Compaction Example

**Electrode Activations**

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**Corresponding Droplet Motion**

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**Legend:**
- **PRI**
- **BEO**
- **AMP**
- **LAM**

**Compaction Process:**
- **M1**, **M2**, **M3**, **M4** represent different stages of compaction.
## Compaction Example

### Electrode Activations

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### Corresponding Droplet Motion

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Compaction Example

Electrode Activations

Corresponding Droplet Motion
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Electrode Activations

Corresponding Droplet Motion
Discrete Perspective

- Increase Voltage ➔ Increase Velocity

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

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

\[ T(d_i) = \sum_{j=1}^{N} (t_{i,j} + u_{i,(j,j+1)}) \]

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

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

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

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

\[ C = (K - 1) \sum_{i=1}^{K} \left| \vec{v}_i \right|^2 \]

Velocity = \text{Current} \times \text{Voltage}^2 \]

\[ \text{Energy} = \text{Power} \times \text{Time} = \frac{\text{Voltage}^2}{\text{Resistance}} \times \text{Time} \]
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

---

![Diagram showing droplet paths and interference regions](image-url)
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 $vel = \frac{\text{pathLength}}{T_c}$
    - Minimum Voltage for velocity derived from graph

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

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

Segment 1: 1 electrode/s
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Now compact D2 against all previous droplet paths (D1).

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

Segment 1: 1 electrode/s
Segment 2: 1 electrode/s
Segment 3: 1 electrodes/s
While compacting D2, detected interference at time 5 between D1 and D2.

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

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

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<th>D1</th>
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While compacting D2, detected interference at time 5 between D1 and D2.
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

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

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

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
Simple Example

D2 reached end of segment.

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

D2 reached end of segment.
### Simple Example

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

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

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 |
Simple Example

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

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.

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

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| 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.

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

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

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

Segment 1: 1 electrode/s
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### Simple Example

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

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

- **Segment 1:** 1 electrode/s
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- **Segment 3:** 2.5 electrodes/s
- **Segment 4:** 0.46 electrodes/s

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<td>13</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The image shows a grid with electrodes labeled s1, s2, d1, and D1, and numbers indicating the time the droplet arrives at each electrode.
Simple Example

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

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.

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
Simple Example

<table>
<thead>
<tr>
<th>Segment 1:</th>
<th>1 electrode/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segment 2:</td>
<td>1 electrode/s</td>
</tr>
<tr>
<td>Segment 3:</td>
<td>2.5 electrodes/s</td>
</tr>
<tr>
<td>Segment 4:</td>
<td>0.46 electrodes/s</td>
</tr>
</tbody>
</table>

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

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

<table>
<thead>
<tr>
<th>s1</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5/2.4</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>s2</td>
<td>.4</td>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>.6</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5/2.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

D2 compacted against D2 with no interference.

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
Simulation Details

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

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

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 V²s/GΩ
    - @ 70V → 2450 V²s/GΩ
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/