3M-DeSyn: Design Synthesis for Multi-Layer 3D-Printed Microfluidics with Timing and Volumetric Control

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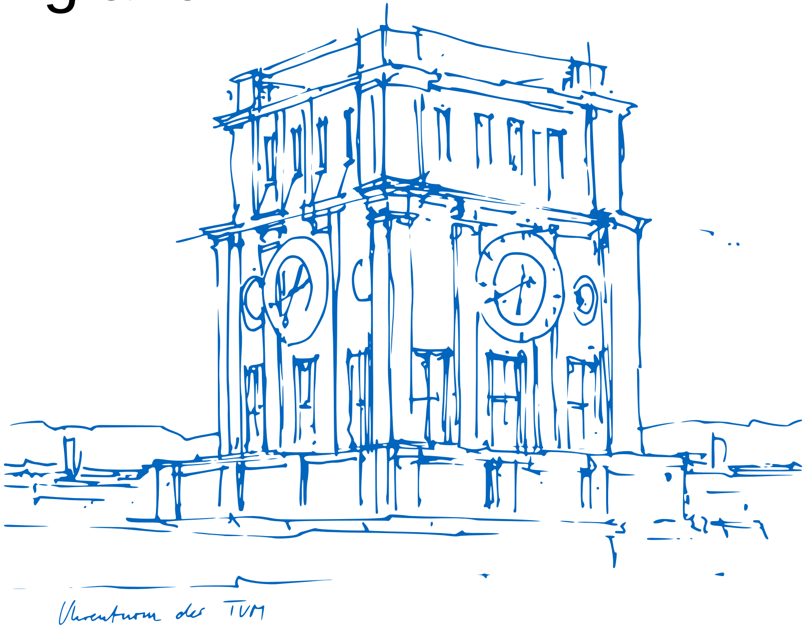

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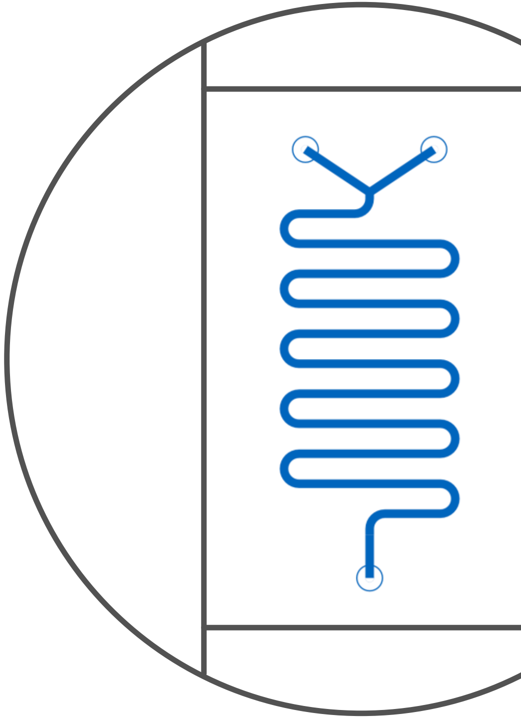
Microfluidics

In essence, microfluidics is:

- The manipulation and control of fluids at the **microscale**
- Typically, within channels that are **micrometer-sized**
- A technology that underpins a **wide array of applications** in fields such as biotechnology, chemistry, and medicine

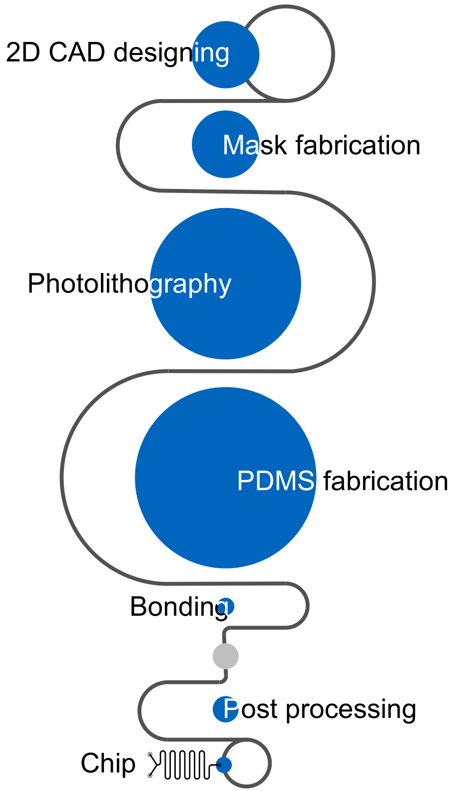


Conventional Fabrication

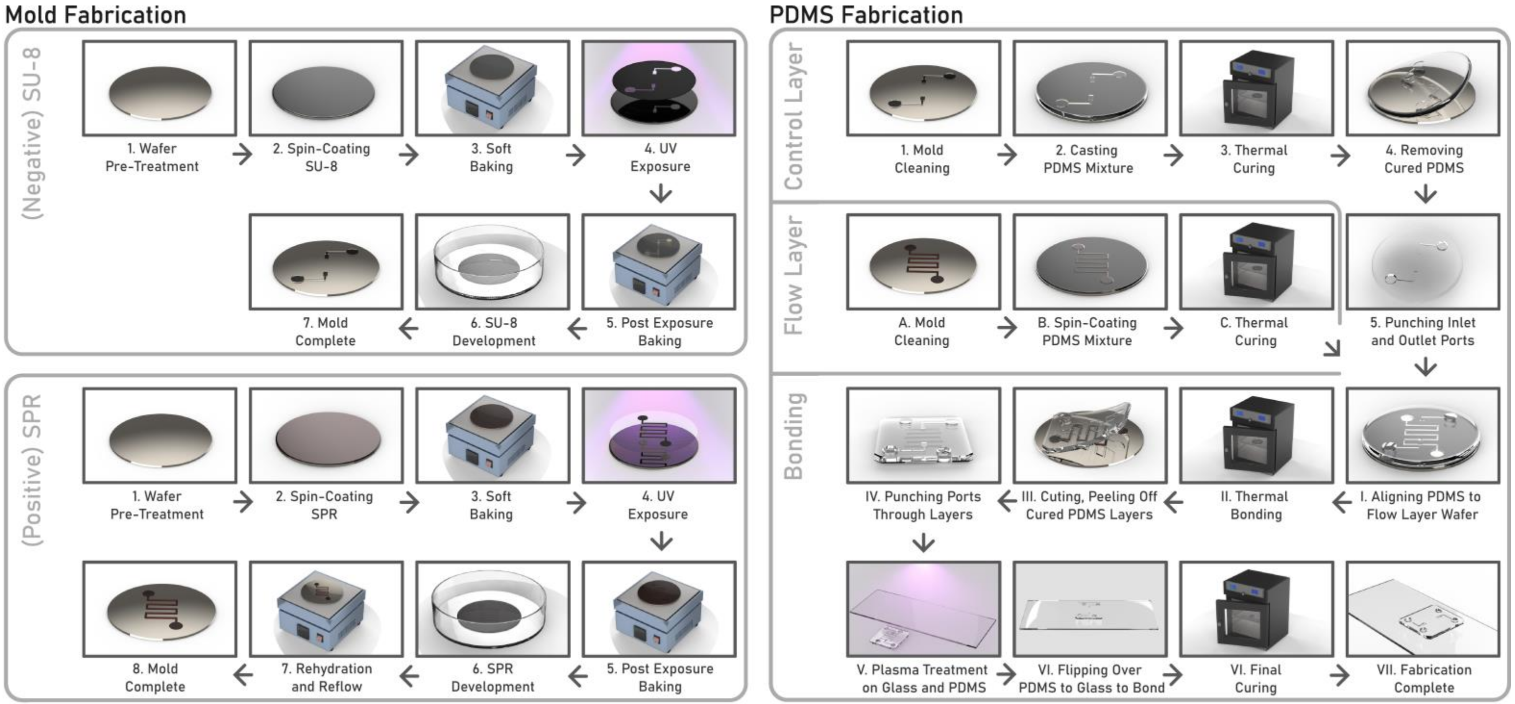
Soft lithography is a widely utilized technique in microfluidic fabrication:

- **Photolithography** to pattern microchannel designs on silicon wafers. **Requires cleanroom** facility and **specialized equipment** like mask aligner
- **PDMS fabrication** to cast the microchannel in a mixture of Polydimethylsiloxane base and curing agent. **Requires separate lab** facility and **specialized equipment** like oxygen plasma

Conventional fabrication methods are precise but can be **time-consuming and expensive**, especially for prototyping.



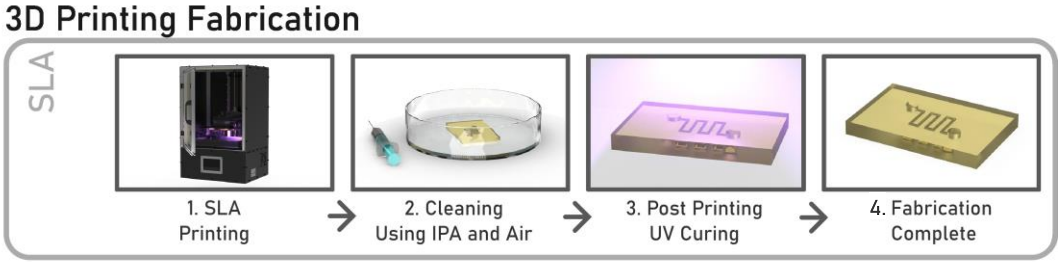
Conventional Fabrication



3D Printing Fabrication

Advancements in **3D printing** have opened new avenues for the fabrication of microfluidics by:

- Allowing **rapid** prototyping
- The creation of **intricate** designs
- **Reducing costs**



Microfluidic Design Automation Tools

…are few and mainly focus on 2D conventional fabrication method:

- **3Dμf**[1], **Micado**[2], **Fluigi**[3] – design tools for the creation of planar (2D) continuous-flow microfluidic chips
- **Cloud Columba**[4] – design synthesis tool for continuous-flow microfluidics, again, in 2D

[1] Sanka, R., Lippai, J., Samarasekera, D. *et al.* 3DμF - Interactive Design Environment for Continuous Flow Microfluidic Devices. *Sci Rep* **9**, 9166 (2019).

[2] Amin, N. Computer-Aided Design for Multilayer Microfluidic Chips. PhD thesis, Massachusetts Institute of Technology, (2008).

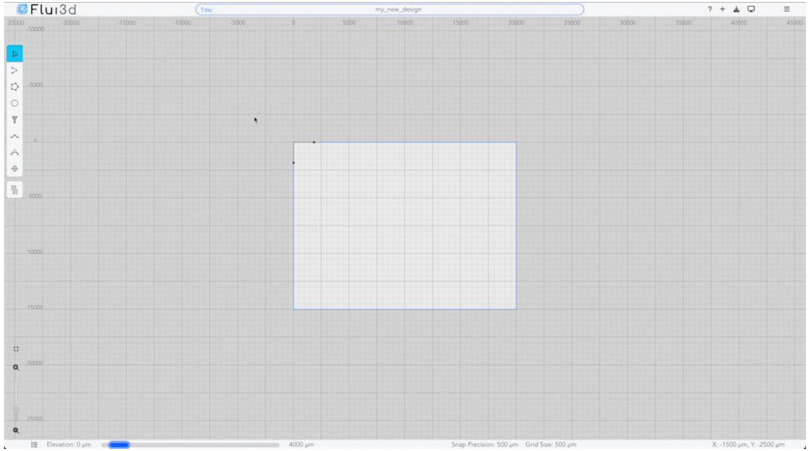
[3] Huang, H. and Densmore, D. Fluigi: Microfluidic Device Synthesis for Synthetic Biology. *J. Emerg. Technol. Comput. Syst.* **11**(3) (2015).

[4] Tseng, TM, Li, M., Zhang, Y. *et al*. Cloud Columba: Accessible Design Automation Platform for Production and Inspiration. *ICCAD*, 1–6 (2019).

Microfluidic Design Automation Tools

Last year, we introduced

- **Flui3d**[1] – the first design automation tool for multi-layer 3D-printed microfluidics



[1] Zhang, Y., Li, M., Tseng, TM. *et al.* Open-source interactive design platform for 3D-printed microfluidic devices. *Commun Eng* **3**, 71 (2024).

Still Necessitate Manual Effort

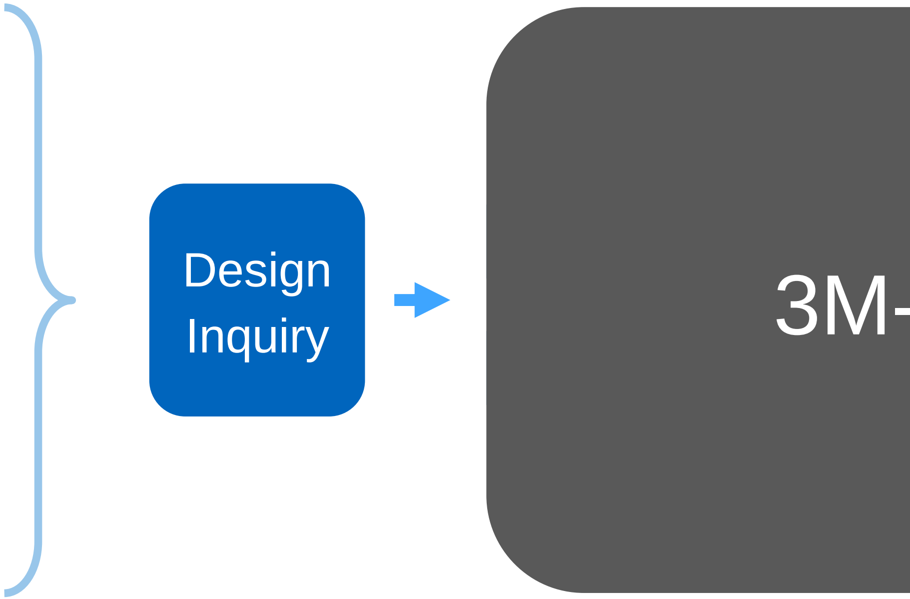
No design synthesis exists for 3D-printed microfluidics:

- Manual **architectural research**
- Manual **placement consideration**
- Manual **channel routing**
- **Timing** and **volumetric** constraints are **crucial for various applications**, such as drug delivery and chemical synthesis
- 3D-printed microfluidic chips primarily **rely on the exact design** of internal geometries and fluidic pathways

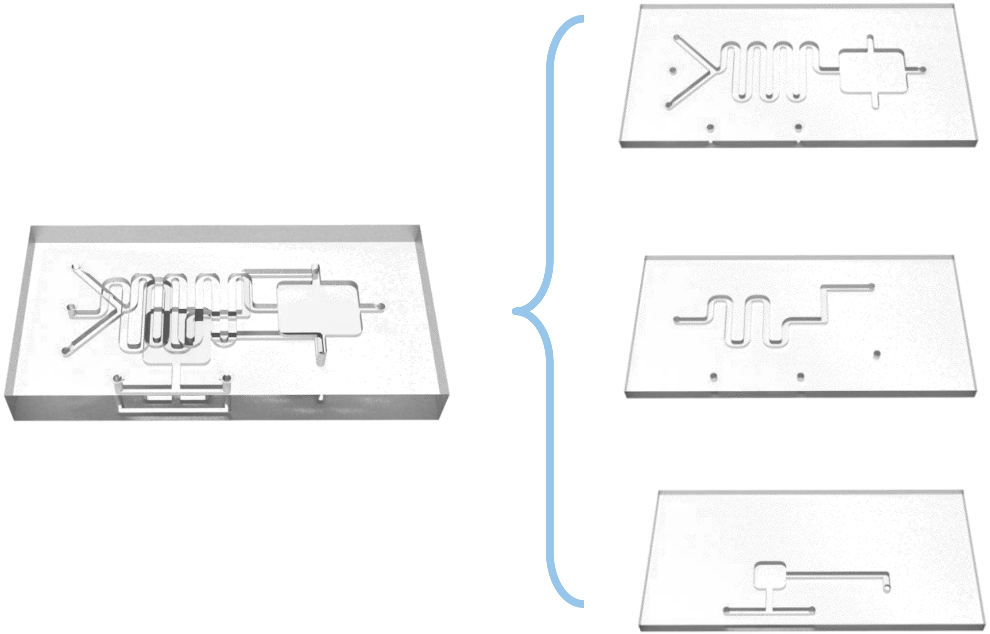
Design Synthesis

Design Synthesis

- Schematics
  - Component definitions
  - Inter-relationships
- Optional dimensional requirements
  - Margins
  - Min. distances
  - # of layers, etc.
- Optional timing and volumetric requirements
- Etc.

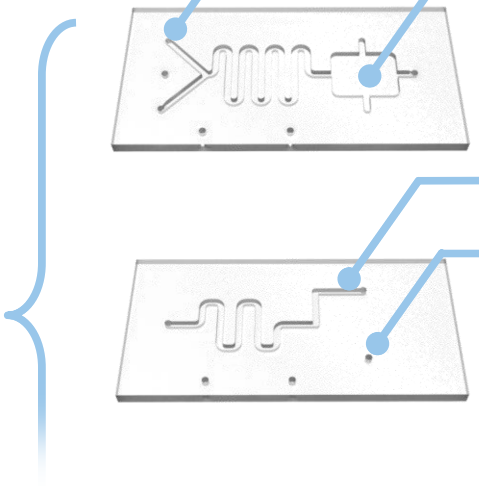


Chip Modeling



A chip comprises multiple layers.

Chip Modeling



Port (radius, layers[], x, y)

Component (length, width, height, layer, x, y, orientation …)

Channel (width, height, segments[]…)

Via (a cross-layer segment)

(layer, x_1, x_2, y_1, y_2, orientation,…)

Constraint Optimization Programming

To automatically synthesize the multi-layer design, we define the following constraints:

- Component:
  - Must be placed **inside the chip's boundary** with a margin
  - Must be placed **on a layer**
  - Has **an orientation** (0°, 90°, 180°, 270°)
  - Must **not overlap** with other features (components, channel segments)
- Channel:
  - Comprises **multiple segments**
  - Each segment must be placed **on a layer** and **inside the chip's boundary** with a margin
  - Each segment has **an orientation** (0°, 45°, 90°, cross-layer)
  - Must **not overlap** with other features (components, channel segments)
  - The first and the last segment **connect to the desired components**

Timing and Volumetric Requirements

Governing Equation:

$$T = \frac{V}{Q}$$

Timing and volumetric constraint:

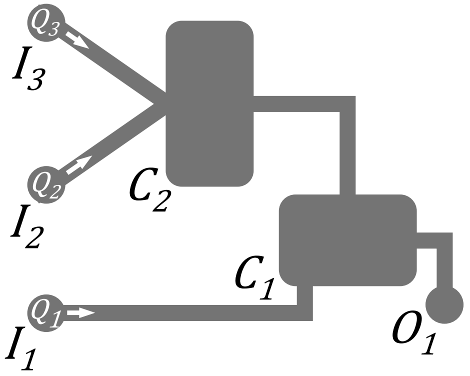
- **Equality of volumes** of different flow paths:

$$\left| \frac{\sum_{a \in A} v_a}{Q_A} - \frac{\sum_{b \in B} v_b}{Q_B} \right| < \varepsilon$$

Timing and Volumetric Requirements

Flow path finding:

- Construct a **graph** based on the schematic
- Traverse the graph to **find flow paths** taken by different fluids from their inlets to the shared destination
- **Calculate components' volumes**
- **Create the constraints**



Optimization

A key objective in 3D-printed microfluidic chip design is minimizing chip volume.

In essence, we **minimize the dimension of the chip** and the **total length of all channels**:

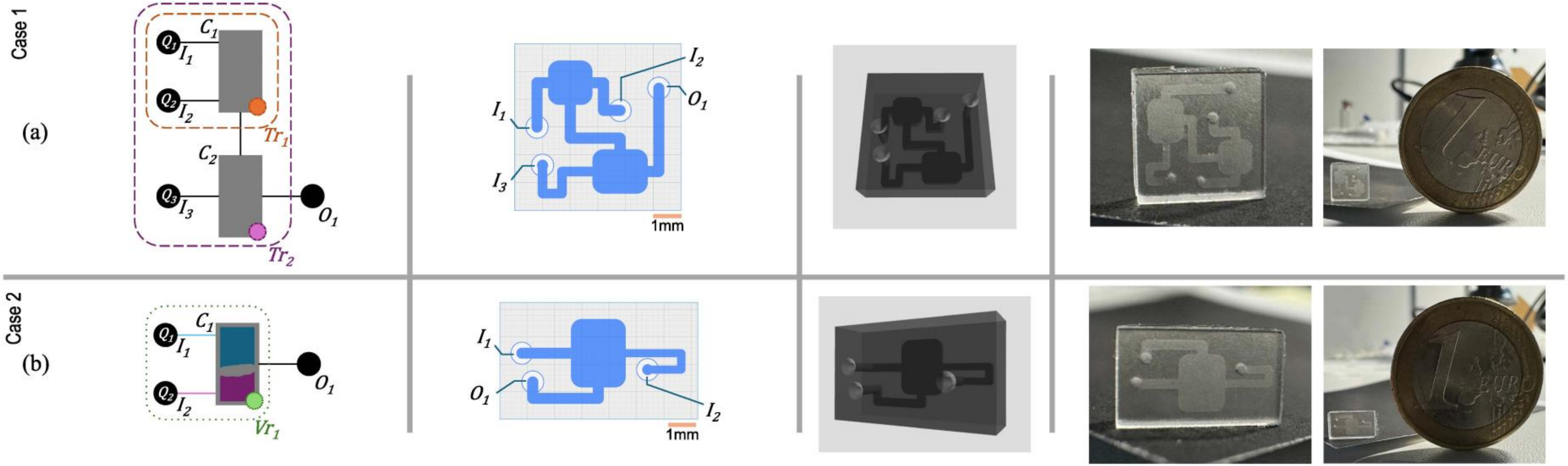
$$Minimize\colon w_{chip} \cdot l_{chip} \cdot \#layer_{chip} + \sum l_{seg}$$

Design Synthesis

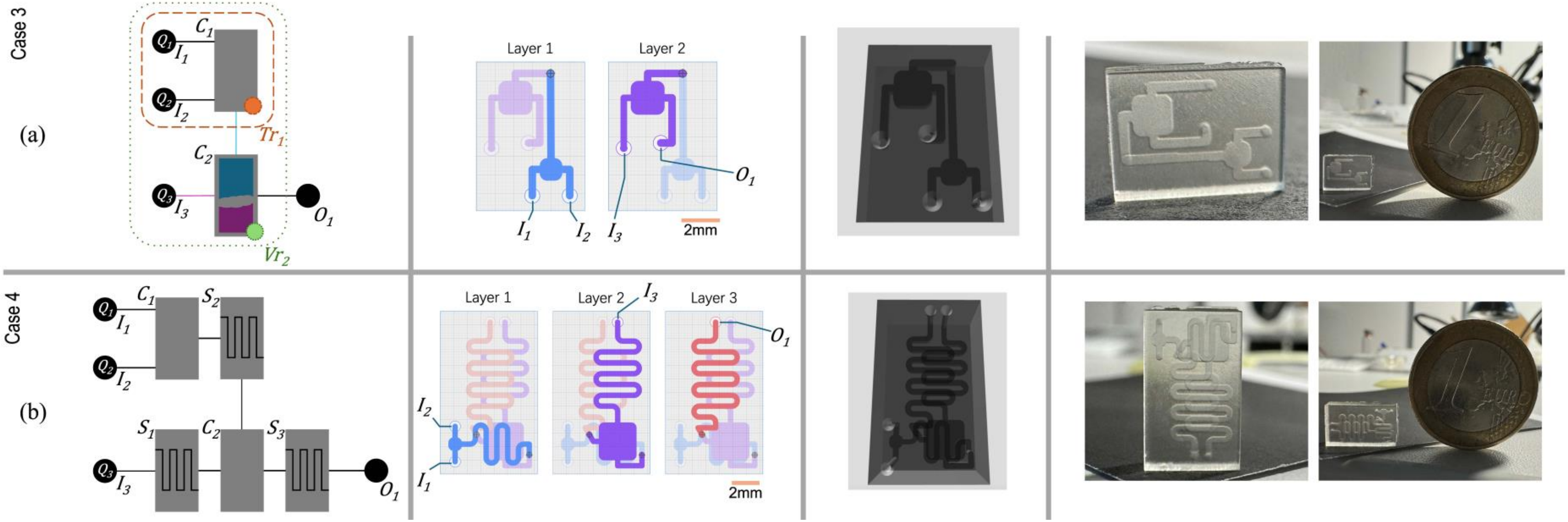
Design Inquiry → 3M-DeSyn → 3D Chip

Experimental Results

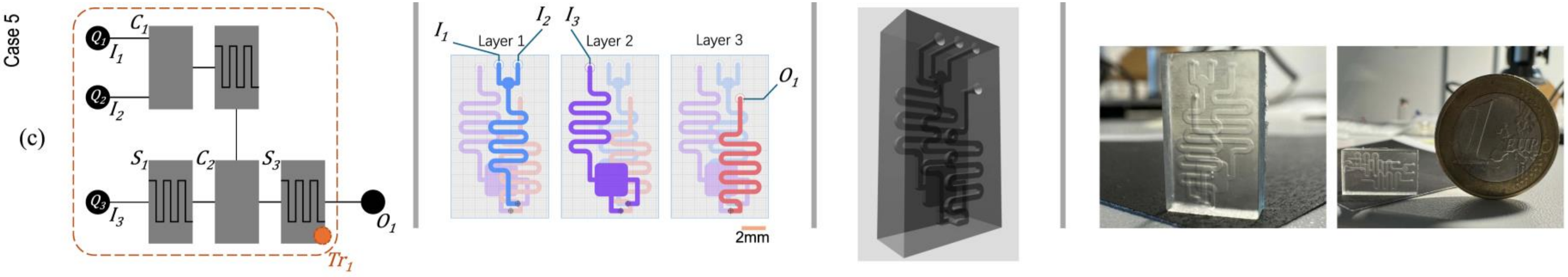
We implemented the model using Java utilizing Gurobi Optimizer and ran the program on a MacBook Pro with M1/16GB.



Experimental Results



Experimental Results



Result Comparison

We compared our synthesis method with our baseline (manual design):

$$T_{mandesign} = T_{schem} + T_{timing\&volume} + T_{architecture} + 3(T_{pre-placement} + T_{pre-routing} + T_{dimcalc} + T_{p\&r})$$

Case	$\#_{comp}$	$\#_{interrel}$	$\#_{layer}$	Area	$\#_{treq}$	$\#_{vreq}$	$\#_{chbnd}$	L_{ch}	$T_{mandesign}$	$T_{3M\text{-}DeSyn}$
1	7	5	1	6000 µm × 6000 µm	2	0	9	14413 µm	13h46m00s	00h00m13s
2	4	3	1	4250 µm × 7232 µm	0	1	4	9063 µm	05h07m30s	00h00m02s
3	7	5	2	5775 µm × 7900 µm	1	1	8	17023 µm	20h54m00s	00h00m35s
4	9	8	3	7200 µm × 12000 µm	0	0	10	12466 µm	08h07m00s	00h02m16s
5	9	8	3	8200 µm × 13653 µm	1	1	12	22108 µm	13h51m30s	00h03m40s

Conclusion

- Microfluidics has become a **star in many fields and applications**
- **3D printing** is an **alternative fabrication** method
- Designing 3D-printed microfluidics **still necessitate manual effort**
- **Timing and volumetric requirements are essential** for many applications
- We introduce **3M-DeSyn**, **a design synthesis method** for 3D-printed microfluidics
- Based on **constraint optimization programming**
- Producing **printable output**
- Results show **huge design time different** compared to manual design

Thank you!

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