DESIGN, AUTOMATION & TEST IN EUROPE
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Split Additive Manufacturing for Printed Neuromorphic Circuits

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Outline

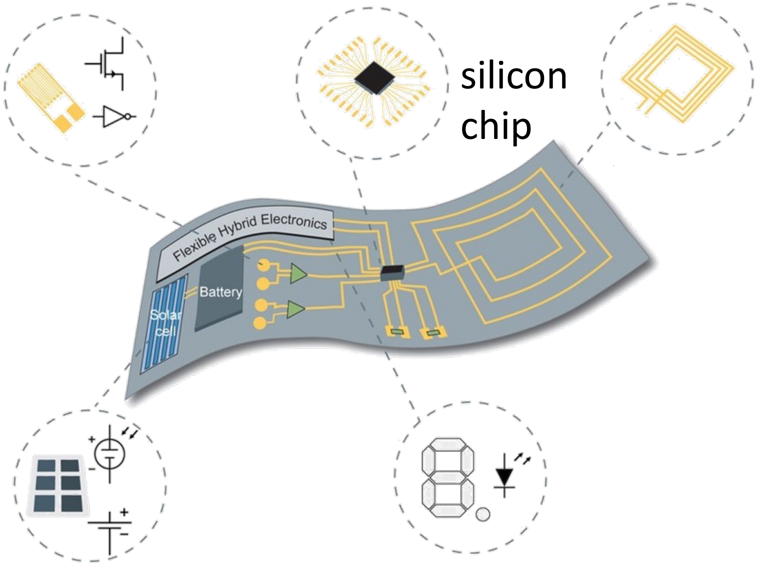
- Printed Electronics
- Printed Neuromorphic Circuits
- Split Additive Manufacturing
- Experiment
- Conclusion

Printed Electronics – Overview

printed sensors

printed antennas

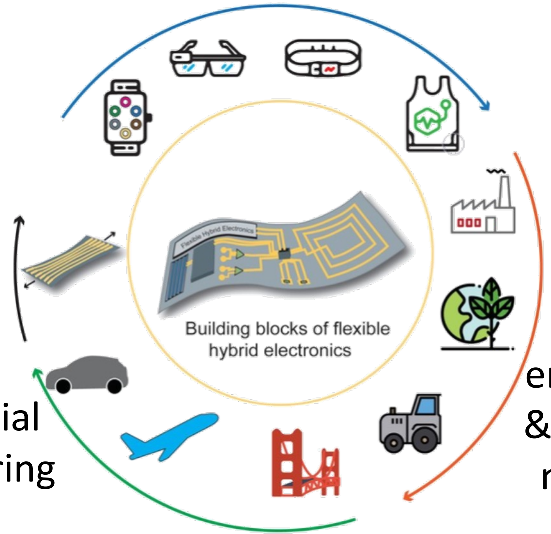
silicon chip



printed energy storage & harvester

printed displays

wearable devices



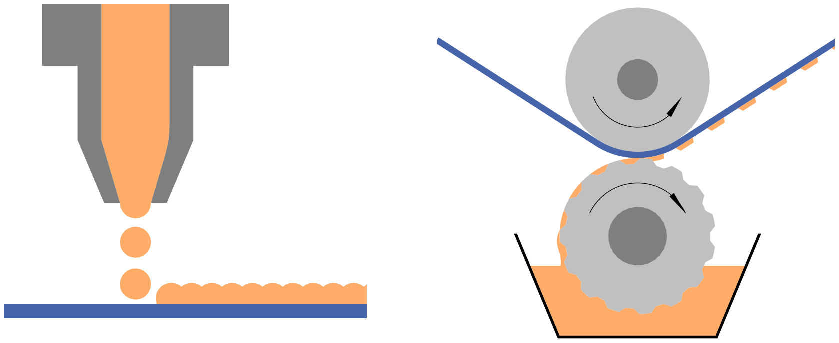
industrial monitoring

environment & agriculture monitoring

Source: Khan Y, *et al*. “A New Frontier of Printed Electronics: Flexible Hybrid Electronics”. *Advanced Materials,* 2020

Printed Electronics – Manufacturing

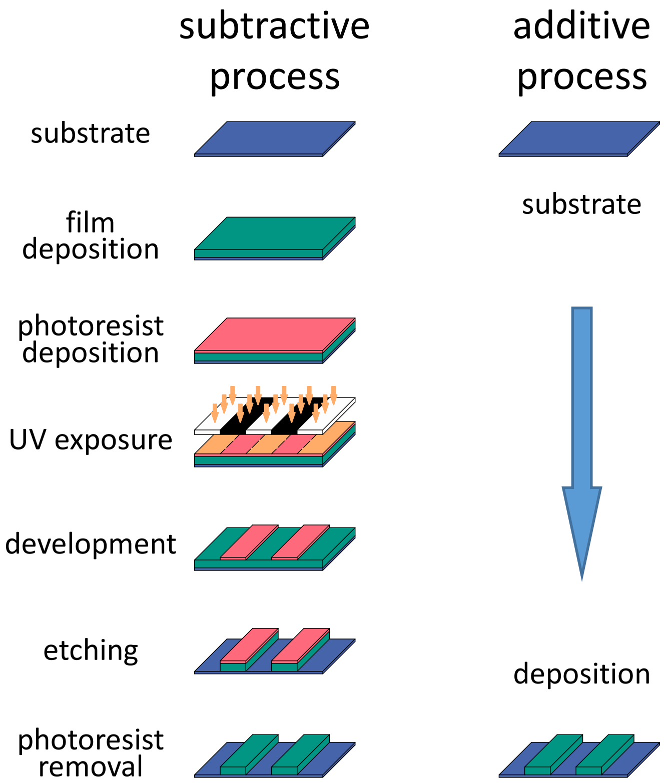
- **Additive Manufacturing**



Inkjet printing

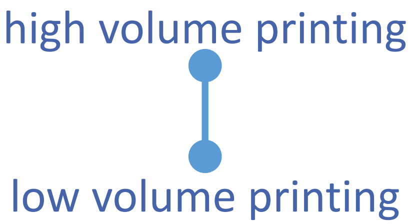
Gravure printing

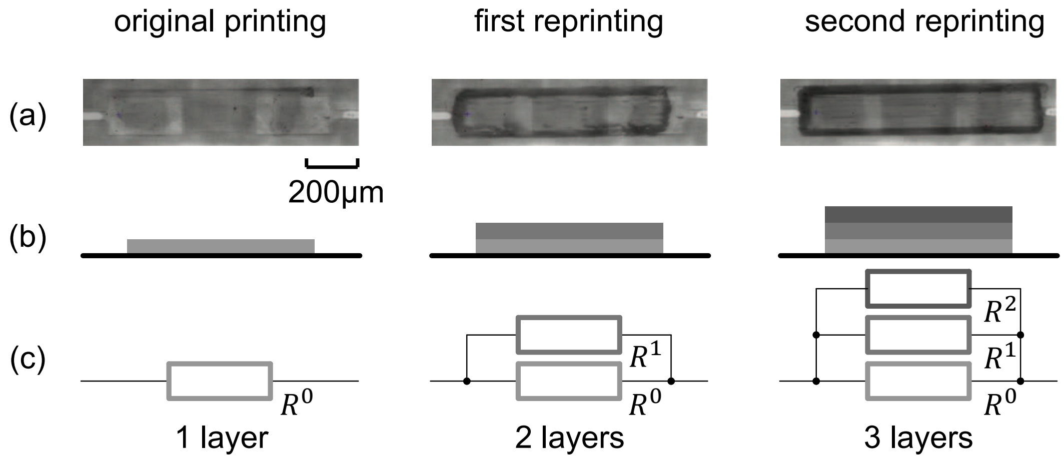
	Low volume process	High volume process
printing speed	-	+
customization	+	-



Printed Electronics – Reprinting

- **Additive Manufacturing**
  - **Reprinting**
    - **Post processing**
    - **Repair**
    - **Split manufacturing**





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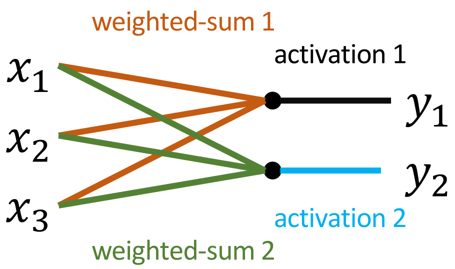
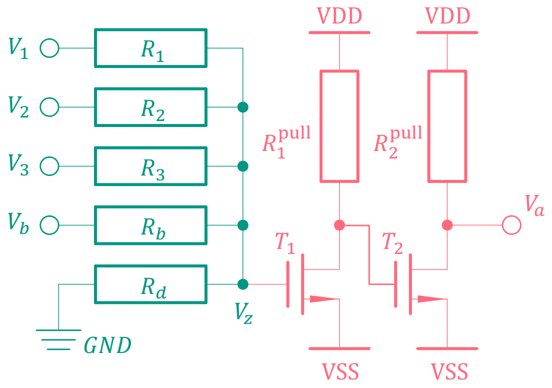
Printed Neuromorphic Circuit – Motivation

- **Conventional digital NNs are infeasible for PE**
  - **Large feature size**
  - **Low integration density**
  - **Low device count**



Components	Number of transistors	
	4-bit digital NN	Analog NN
Input converter	185	-
Weighted-sum	265	≤ 4
Activation	10	2



- **Analog neuromorphic circuits were developed**

Printed Neuromorphic Circuit – Primitives

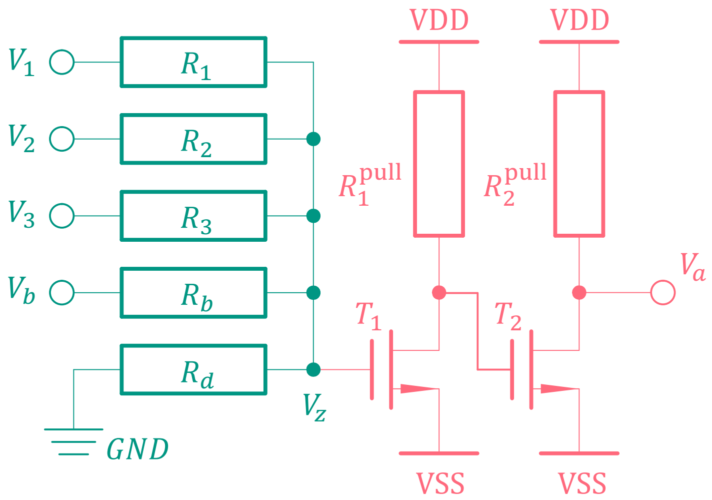
- **Resistor crossbar for weighted-sum**

$$V_z = \frac{g_1}{G}V_1 + \frac{g_2}{G}V_2 + \frac{g_3}{G}V_3 + \frac{g_b}{G}V_b$$

where $g_i = \frac{1}{R_i}$, G is the sum of g_i, $V_b \equiv 1V$.

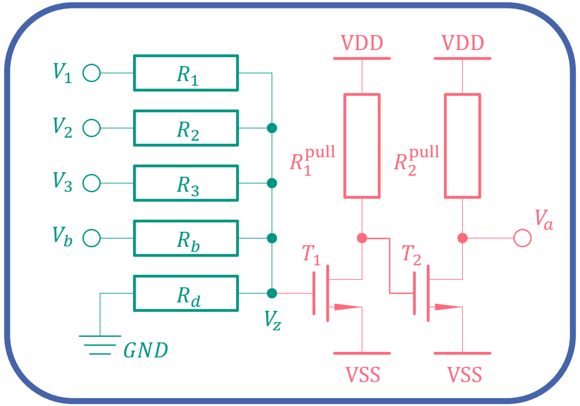
- **Tanh-like activation circuit**

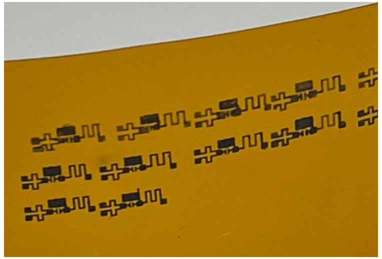
$$\begin{aligned} V_{\mathrm{out}} &= \mathrm{ptanh}(V_{\mathrm{in}}) \\ &= \eta_1 + \eta_2 \cdot \tanh\big((V_{\mathrm{in}} - \eta_3) \cdot \eta_4\big) \end{aligned}$$



Printed Neuromorphic Circuit – Design

Printed Neuromorphic Circuit





machine learning

model

fabrication

Printed Neural Network

learnable g_i

$$\boxed{w_i = \frac{g_i}{G}}$$

$$V_z = w_1 V_1 + w_2 V_2 + w_3 V_3 + b$$

activation

$$V_a = \mathrm{ptanh}(V_z)$$

well-trained g_i

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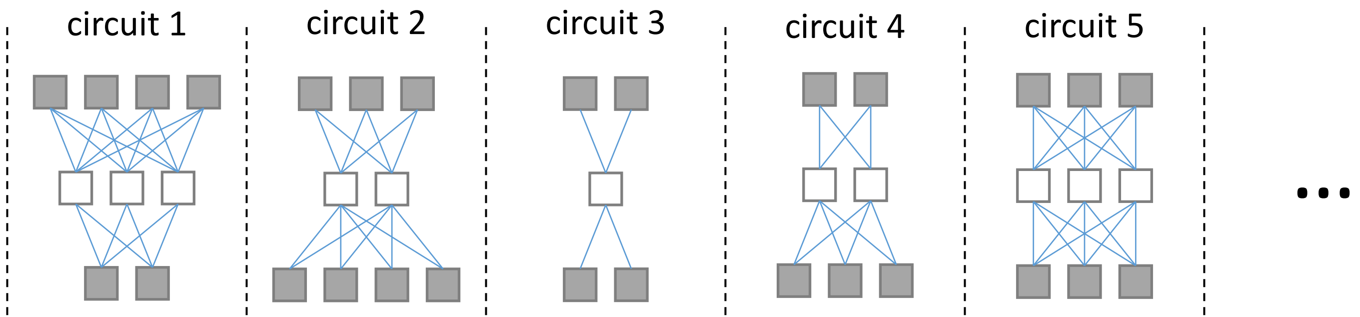
Split Additive Manufacturing – Motivation

- **Scenario**
  - **Numerous different circuits for different tasks**

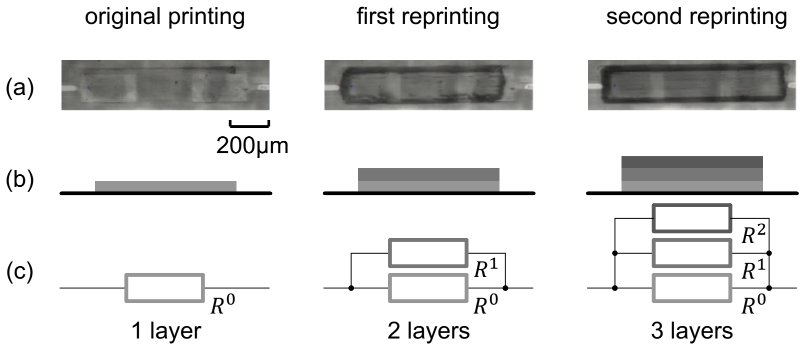


  - **Problem: despite the large printing batch, only low volume printing technologies can be adopted -> time consuming**
  - **Idea: combine high and low volume manufacturing**
    - **High volume – common part of circuits**
    - **Low volume – point-of-use correction**

Split Additive Manufacturing – Idea

- **Combination of high and low volume printing**
  - **Recall – resistor reprinting**

$$\frac{1}{R} = \sum_{l} \frac{1}{R_l} \rightarrow g = \sum_{l} g_l$$



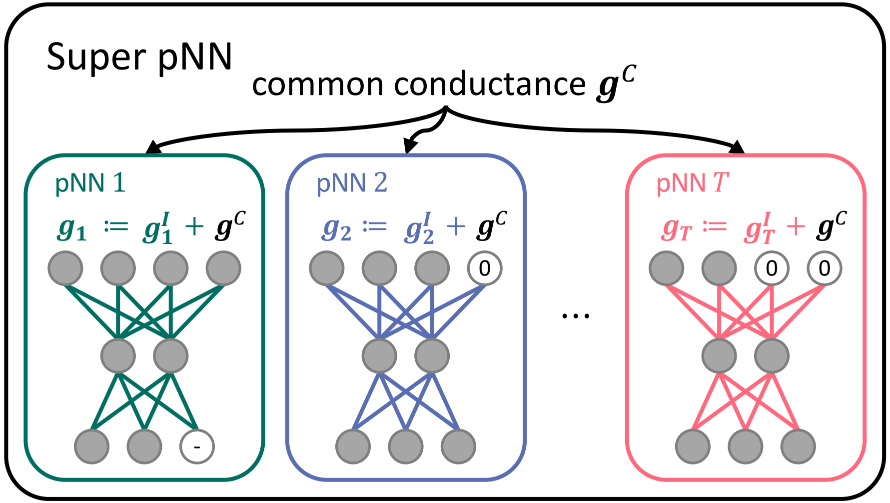
  - **Split each learnable conductance g into**

$$g = g^C + g^I$$

    - g^C **: common part shared across all circuits – high volume process**
    - g^I **: point-of-use individual part for each circuit – low volume process**

Split Additive Manufacturing – Idea

- **Super pNN**
  - **A model contains multiple pNNs for different tasks with**
    - **One learnable parameter g^C - high volume printing**
    - **Multiple independent learnable parameters g_t^I for each task**
    - **Resulted conductance $g = g^I + g^C$**



Split Additive Manufacturing – Idea

- **Training objective of the super pNN**

$$\mathcal{L} = \text{loss} + \alpha \cdot \text{cost}$$

  - **loss : cross entropy loss (classification accuracy)**
  - α **: trade-off between accuracy and cost**

- **Estimated cost:** $C = \|\boldsymbol{g}^I\|_1 = \sum_i |g_i^I|$
  - **Template cost can be ignored due to large number of circuits**
  - **Material cost stay constant regardless of printing technology**
  - **Production efficiency**

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Experiment – Setup

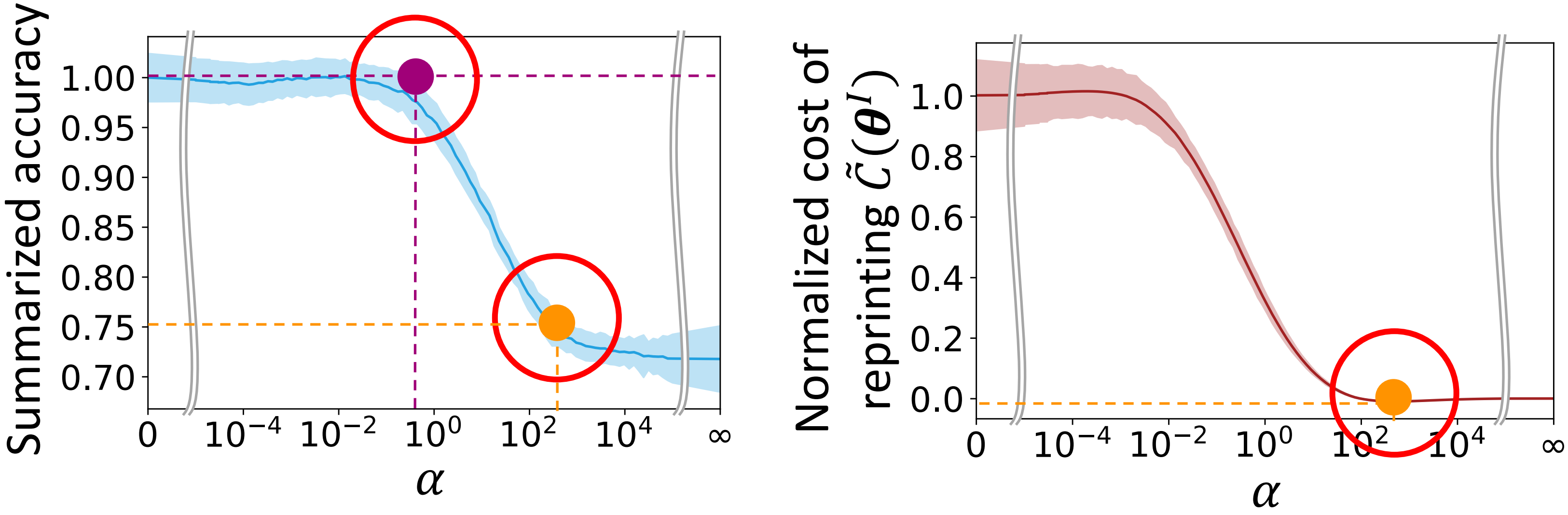
- Super pNN contains 30 benchmark datasets
- $\alpha \in [10^{-5}, 10^{5}]$ (trade-off between accuracy and cost)
- Baseline
  - Baseline1: $\alpha = 0$ (independent learning of all pNNs)
  - Baseline2: $\alpha \to \infty$ (same pNN for all tasks)

$$\mathcal{L} = \text{loss} + \alpha \cdot \text{cost}$$

- Evaluation metric
  - Accuracy
    - Normalized accuracy (by baseline1)
    - Summarized accuracy
  - Cost: normalized cost (by baseline1)

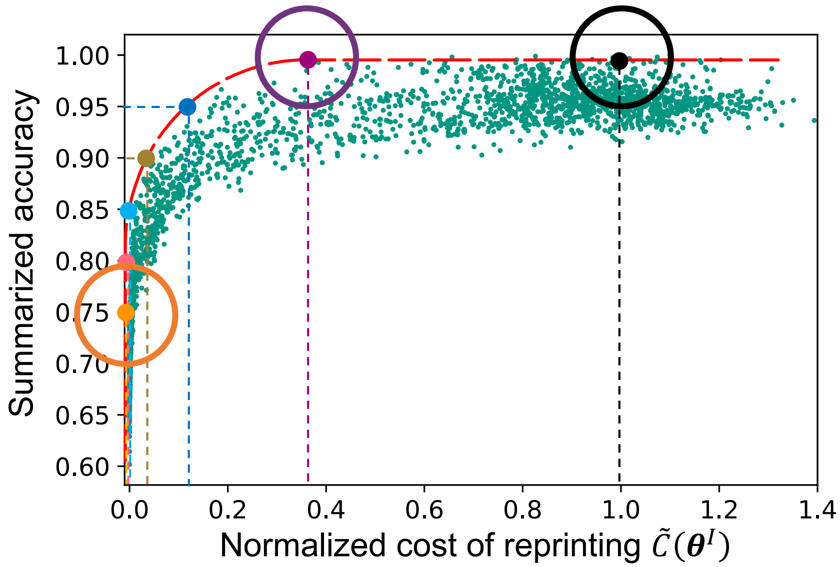
Experiment – Result

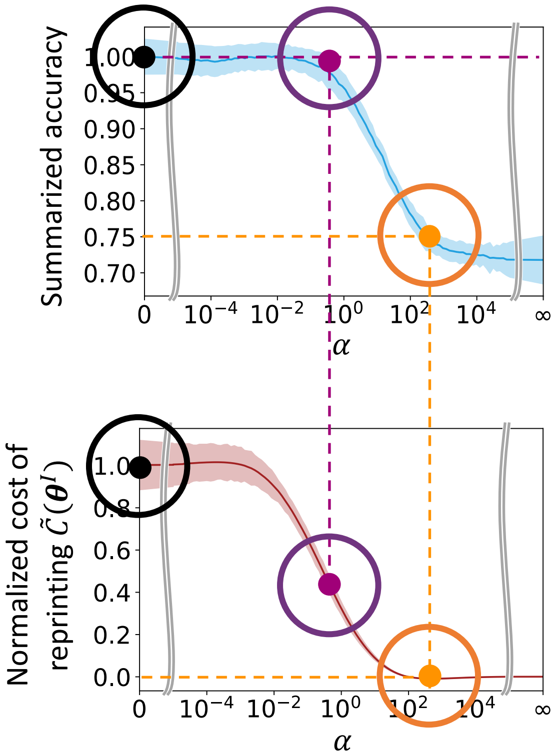
- α **vs. accuracy**
- α **vs. cost**



Experiment – Result

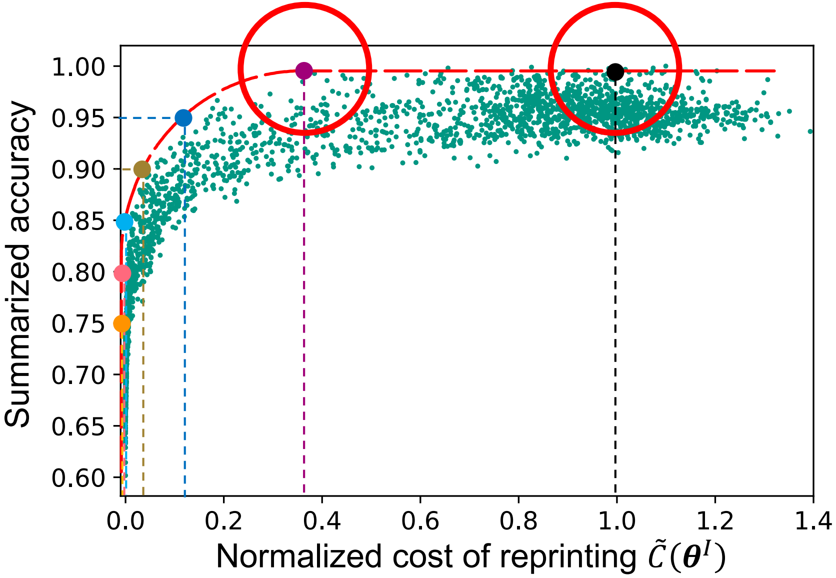
- **Pareto front - cost vs. accuracy**





Experiment – Result

- **Pareto front - cost vs. accuracy**



	Accuracy	Cost
independent	100%	100%
split additive manufacturing	100%	38.6%
	95%	15.7%
	90%	5.7%
	85%	2.9%
	80%	1.4%
common	75%	0%

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Conclusion

- **Printed electronics provides complementary advantages**
  - **Compared to traditional silicon-based VLSI technologies**
- **Low device count, large feature sizes, large latencies**
  - **Constraints for printed circuits**
- **Printed analog neuromorphic circuits**
  - **Analog computing to reduce device count**
- **Split additive manufacturing**
  - **Combining**
    - **High volume printing -> reduces cost**
    - **Low volume printing -> guarantees accuracy**
  - **Even suitable for**
    - **Different circuits**
    - **Small batch for each circuit**
  - **Bridges the gap between high and low volume processes**

Thank you for your attention

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