NANOARCH 2023

Towards Temporal Information Processing

Printed Neuromorphic Circuits with Learnable Filters

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OUTLINE

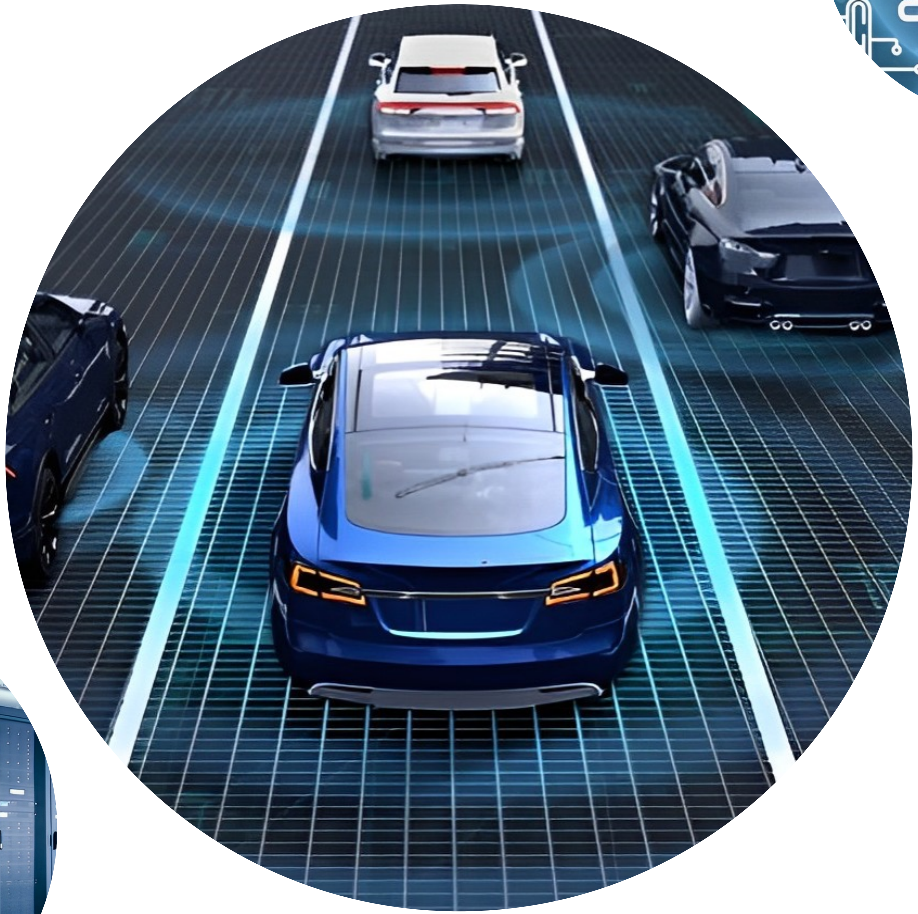
Printed Electronics

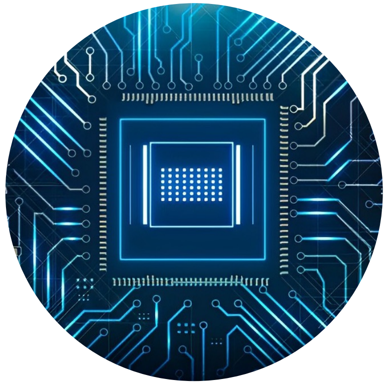
Printed Neuromorphic Circuits

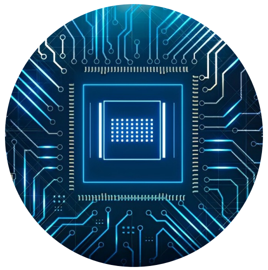
Printed Temporal Processing Block

Experiment

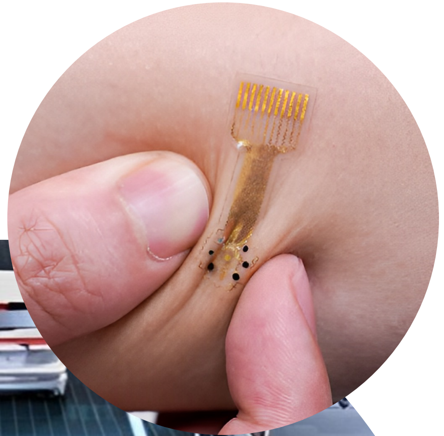
Conclusion







[E. Shirzaei 2023]



ultra-low cost
bio-compatible
degradable
stretchable
…

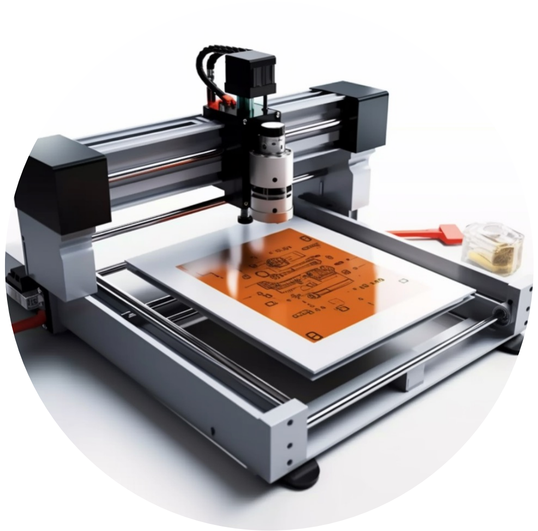
RipeSense®

To-Genkyo®

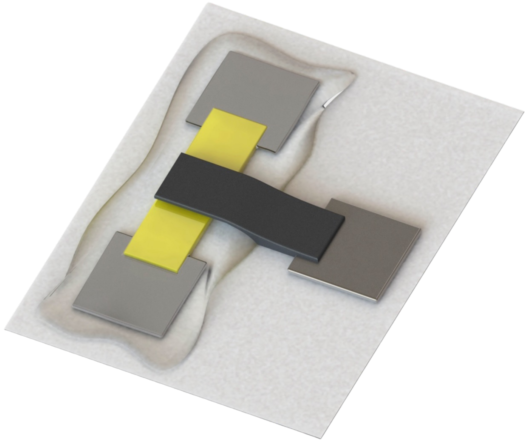
Printed Electronics

enabler of the next-generation electronics

Gravure Printing



Inkjet Printing



Printed Transistor

Printed Circuit

Additive process
- avoid photo-lithography
- ultra-low cost

Various technologies
- high- and low- throughput

Functional inks
- semiconductors
- non-toxicity, degradability, …

Substrate materials
- flexibility, porosity, …

Printed Electronics

enabler of the next-generation electronics

- Thin-film transistor
  - Signal routing: indium tin oxide (ITO)
  - Semiconductor: indium oxide (In_2O_3)
  - Gate insulator: composite solid polymer electrolyte
  - Top gate: PEDOT:PSS
- Voltage levels: ≤ 1.5 V, ≈ 100 µA – 1 mA
- Frequency range: 100 Hz – 1 kHz

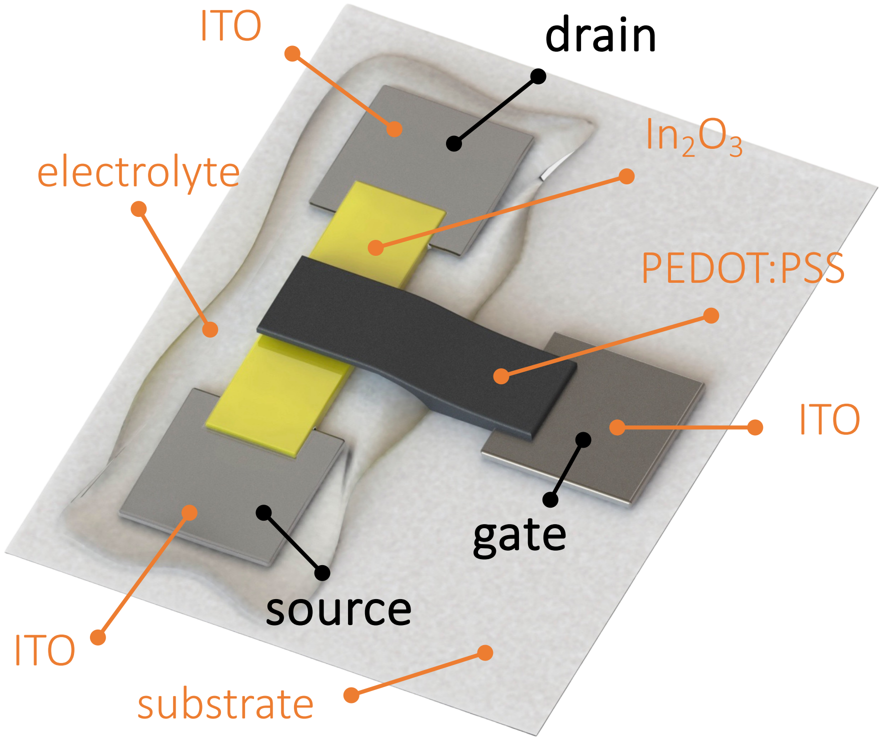
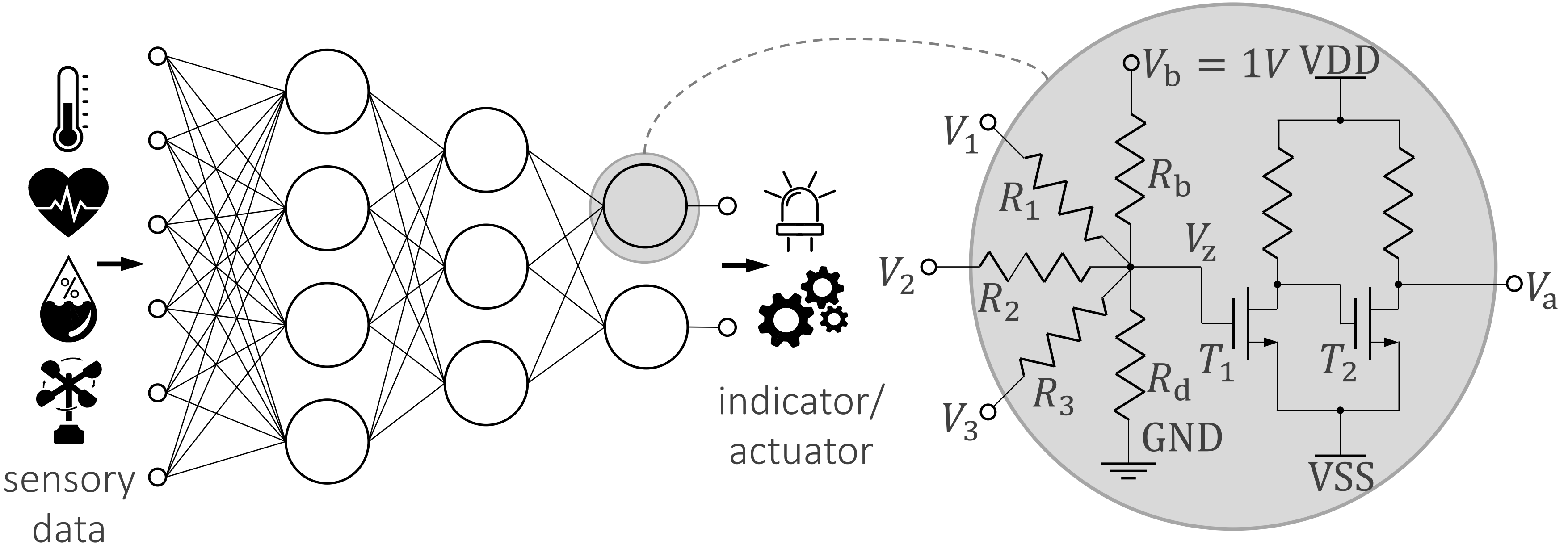


Figure: Structure of Electrolyte-Gated Transistor (EGT).

Printed Analog Neuromorphic Circuit

hardware implementation of artificial neural networks



Artificial neuron:

weighted-sum

nonlinear activation

Component	#Transistor	
	4-bit digital	analog
Input ADC	185	–
Weighted-sum	265	≤ 4
Activation	10	2

Neuromorphic circuit:

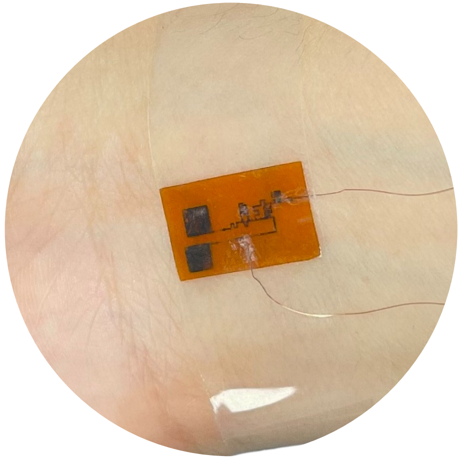
resistor crossbar

inverter-based nonlinear circuit

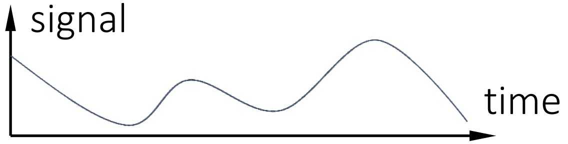
Motivation

temporal signal processing envisioned in the target applications of PE

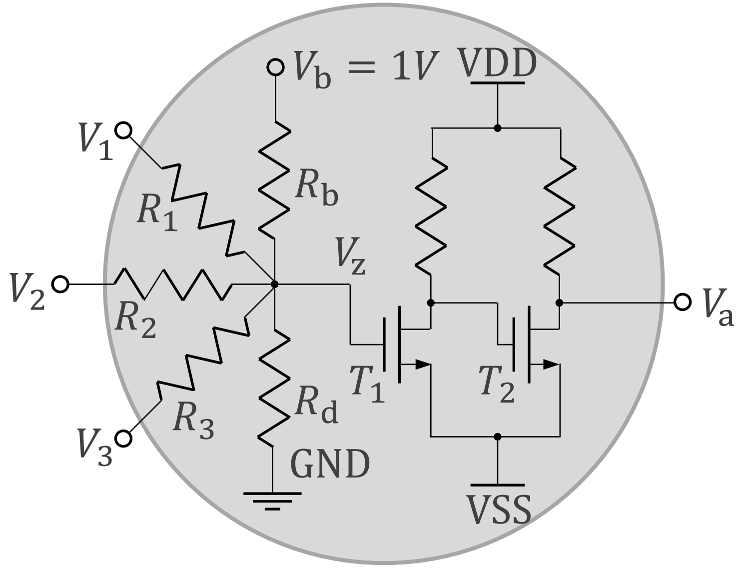
wounder healing
[E. Shirzaei 2023]



stress detection
[H. Zhao 2022]



specific signal value -> less informative
changes of the signal over time -> important
temporal information (time series data) processing required



lack of components with
time dependencies

introducing printed capacitors
into the neuromorphic circuits

Printed Temporal Processing Block

printed neuromorphic circuit with learnable low-pass filters

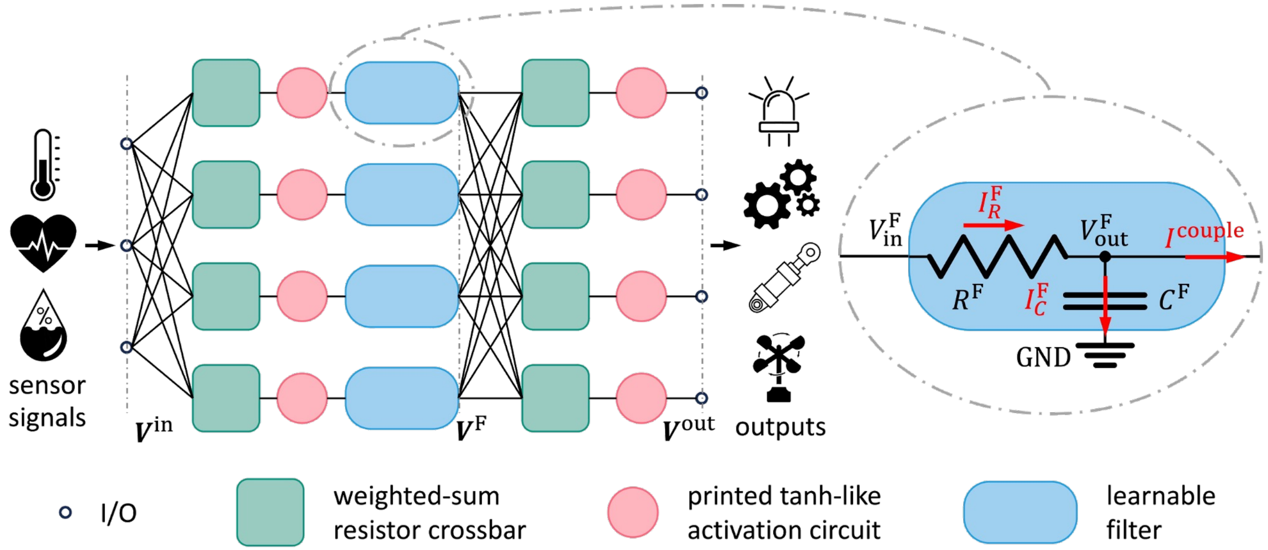
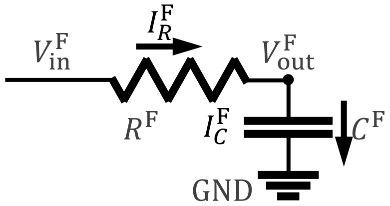
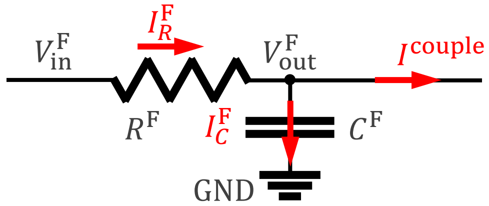


Figure: printed temporal processing block (pTPB).

single low-pass filter model



single low-pass filter with **circuit interference**



Printed Temporal Processing Block

bespoke training objective

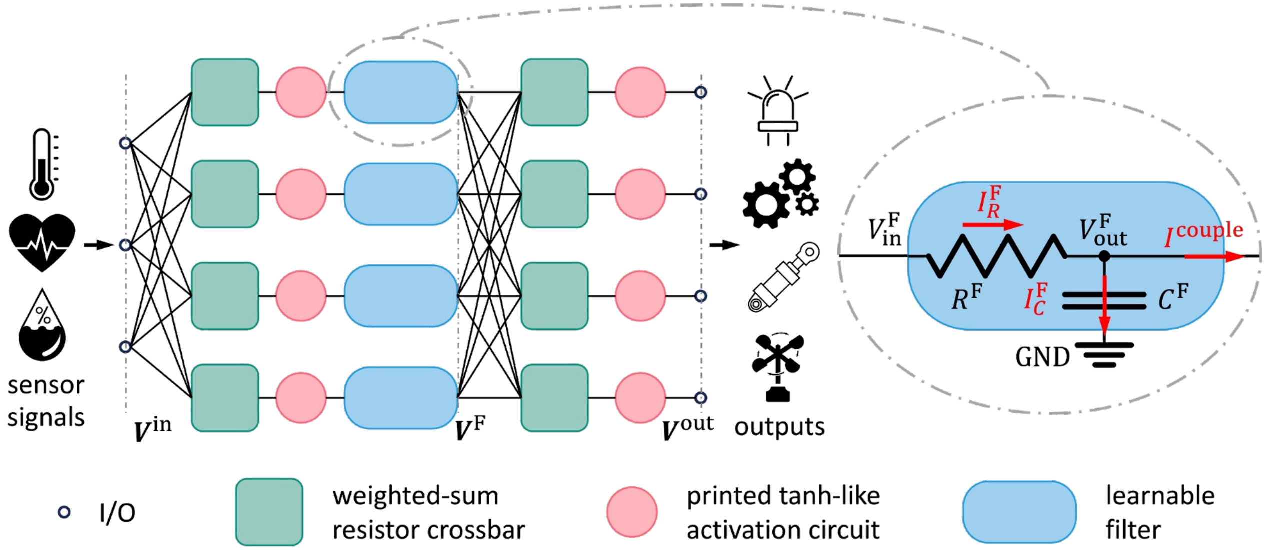


Figure: printed temporal processing block (pTPB).

$$V_k^{\mathrm{F}} = \beta' \odot V_{k-1}^{\mathrm{F}} + (1-\beta') \odot \mathrm{ptanh}\left(W_1 V_k^{\mathrm{in}} + b_1\right)$$
$$V_k^{\mathrm{out}} = \mathrm{ptanh}\left(W_2 V_k^{\mathrm{F}} + b_2\right)$$

RNN

with signal decay in β' each filter

$$\beta' = \frac{\mu R^{\mathrm{F}} C^{\mathrm{F}}}{\mu R^{\mathrm{F}} C^{\mathrm{F}} + \Delta t}$$

R^{F} and C^{F}: learnable parameters
Δt: temporal discretization
μ : coupling between filter and crossbar

Temporal classification result w.r.t. time

$$\max \mathbb{E}_t\{\text{accuracy}\}$$

expected accuracy w.r.t. time

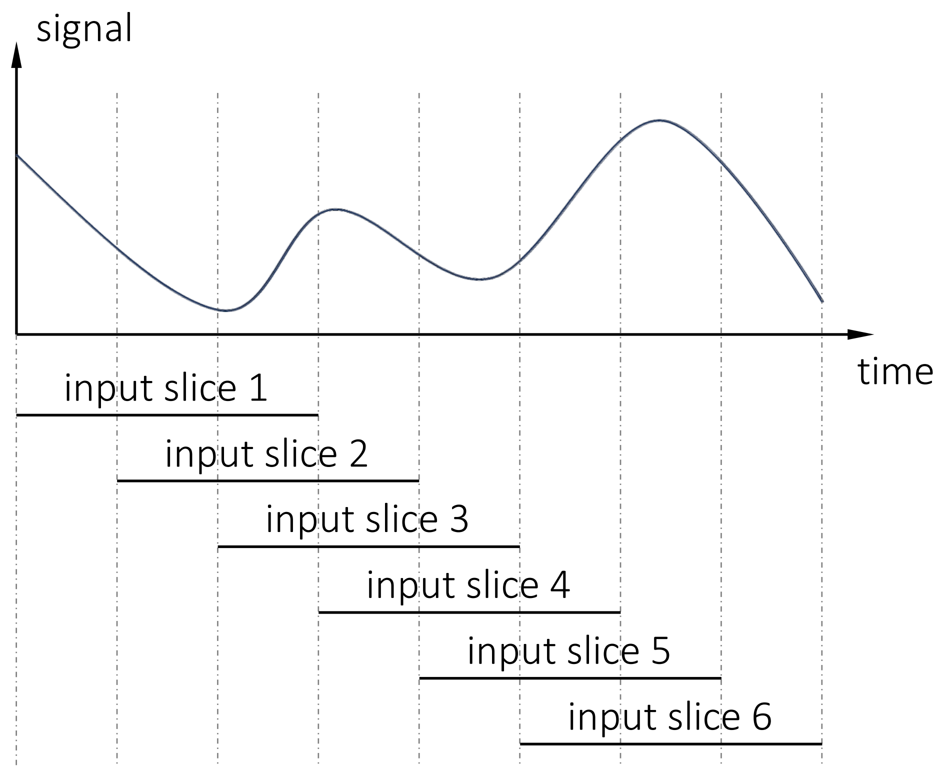
Robustness against circuit interference μ

$$\max \mathbb{E}_{\mu,t}\{\text{accuracy}\}$$

expected accuracy w.r.t. interference factor

Printed Temporal Processing Block

bespoke training objective



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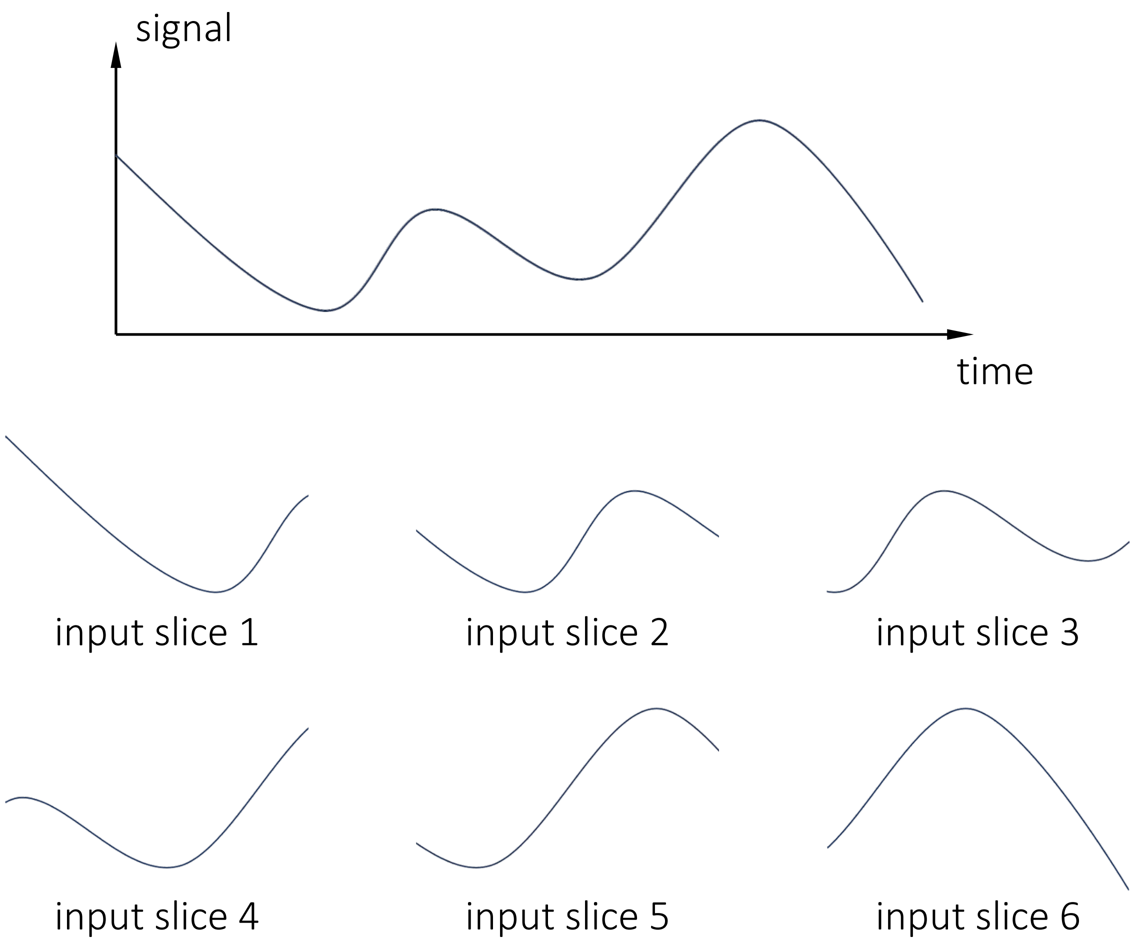

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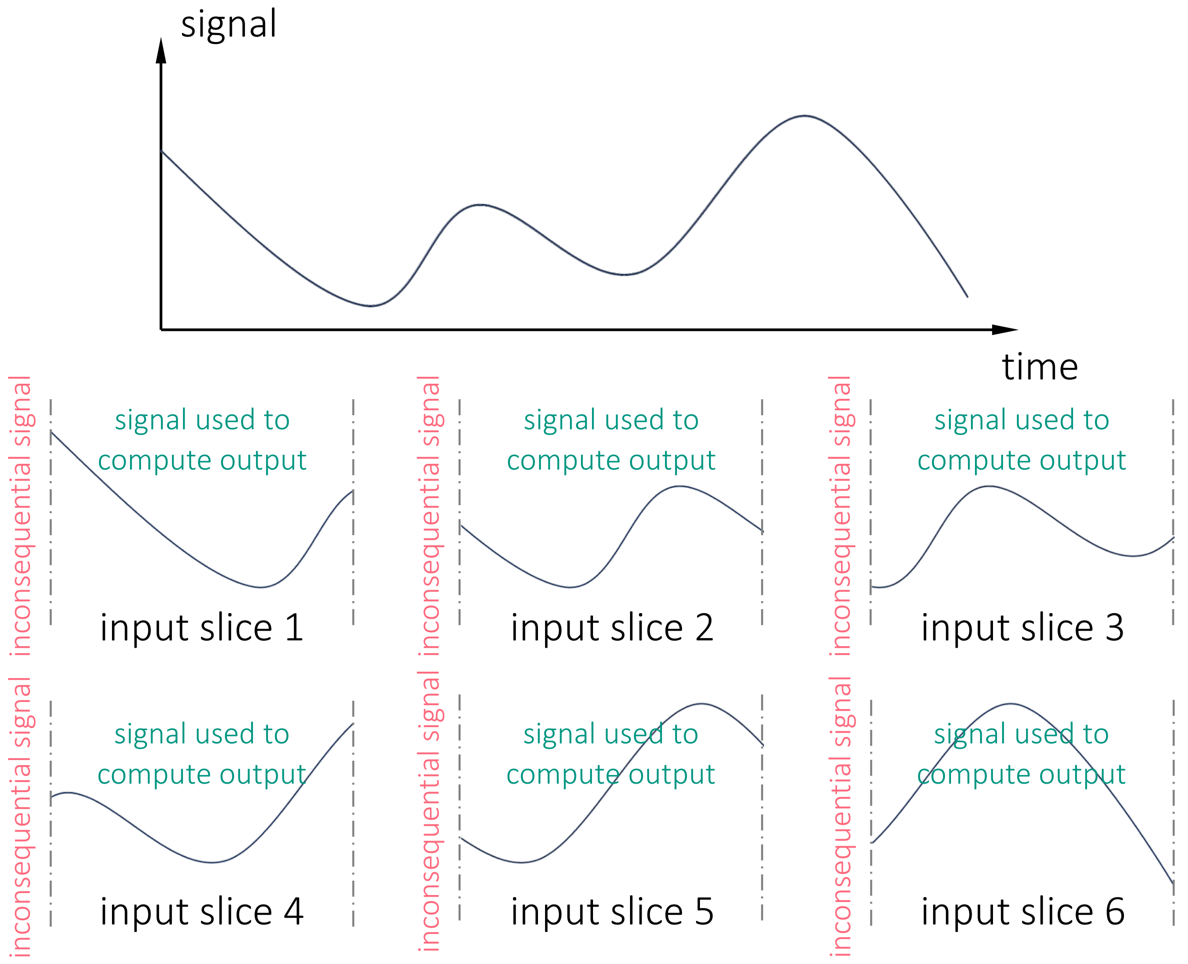

Temporal classification result w.r.t. time

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expected accuracy w.r.t. time

Robustness against circuit interference μ

$$\max \mathbb{E}_{\mu,t}\{\text{accuracy}\}$$

expected accuracy w.r.t. interference factor

Remove dependency on preceding signal

$$\max \mathbb{E}_{V_0,\mu,t}\{\text{accuracy}\}$$

expected accuracy w.r.t. initial voltage

Experiment

setup

Dataset preparation

- datasets from UCR time-series archive
- input and output less than 10
- top 15 datasets w.r.t. Elman RNN accuracy (most common RNN in ML)

Baseline

- random guess
- previous pNC (without filter)
- Elman RNN (most common RNN in ML)

Neural architecture: 2-layer network (N_{in} – N_{out} – N_{out})

Evaluation metric

- mean accuracy over time

Experiment

Averaged accuracy on benchmark datasets

Models	Baselines			Our
	RG	pNC	Elman RNN	pTPNC
Accuracy	0.437	0.501 ± 0.025	0.779 ± 0.033	0.764 ± 0.062

* RG=random guess, pNC=printed neuromorphic circuit, RNN=recurrent neural network, pTPNC=printed temporal processing neuromorphic circuit

Previous pNCs are **unable** to process temporal information

Proposed **pTPNCs** are **able** to process temporal information

pTPNCs achieve **comparable** classification accuracy as the hardware-agnostic Elman **RNN**

Experiment

Averaged device count on benchmark datasets

Dataset	#Transistor		#Resistor		#Capacitor		**#Total Device**		**Power (mW)**	
	pNC	pTPNC	pNC	pTPNC	pNC	pTPNC	**pNC**	**pTPNC**	**pNC**	**pTPNC**
Values	18	23	60	88	-	6	78	118	0.463	0.634

* pNC=printed neuromorphic circuit, pTPNC=printed temporal processing neuromorphic circuit

50% more devices

30% more power

Conclusion

Printed electronics

- flexibility, bio-degradability, high customization, ultra-low cost, …

Printed analog neuromorphic circuits (pNCs)

- hardware ANN, simple-structured, strong computing power
- unable to handle temporal sensory (time series) data

Printed temporal processing neuromorphic circuit (pTPNC)

- pTPNC with learnable filters
- training objective for bespoke design
- comparable accuracy to RNN
- only 50% more devices and 30% more power (compared to pNC)

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Thank you for your attention

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