자유와 활력이 넘치는
파워풀 대구

FIX All on AI

Future Innovation tech eXpo Conference 2025

자율주행차 시대 위한 뉴로모픽 반도체 기술

우지용/경북대

Outline

- Analog Synaptic Devices for Neuromorphic Computing
- Why Unconventional Computing?
- Oscillation Neuron for Oscillatory Neural Network
  - -NbO_x Threshold Switch Oscillator
  - -Dynamics of Coupled Oscillators
- Probabilistic Bit (p-Bit) for Probabilistic Computing
  - -Leveraging Instability of SiO_x Threshold Switch
  - -Complex Optimization Problems
  - -TRNG & Cryptography Accelerators for Security
- Outlook and Summary

Data Is Everywhere

✓ A minute on the internet in 2023

✓ Real-time data handling

✓ 2 zettabyte (ZB=10^{21}) in 2010 → 47 ZB in 2020 → 2,142 ZB in 2035

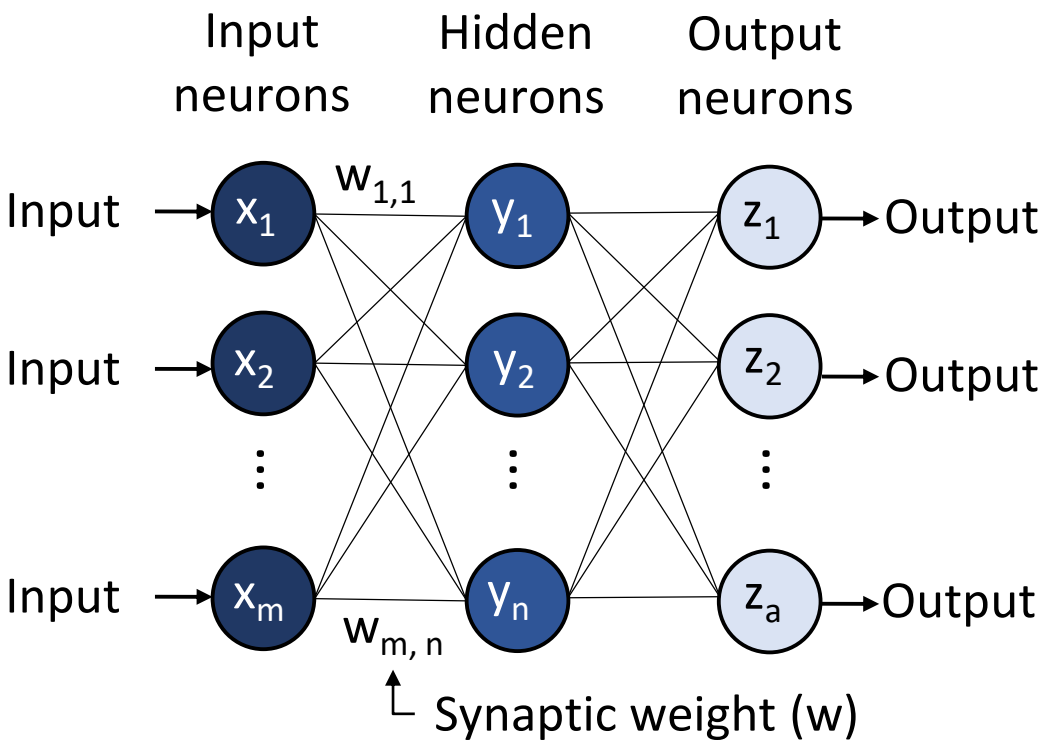
✓ Memory-centric computing systems

→ Data processing in an efficient manner from power and latency perspectives

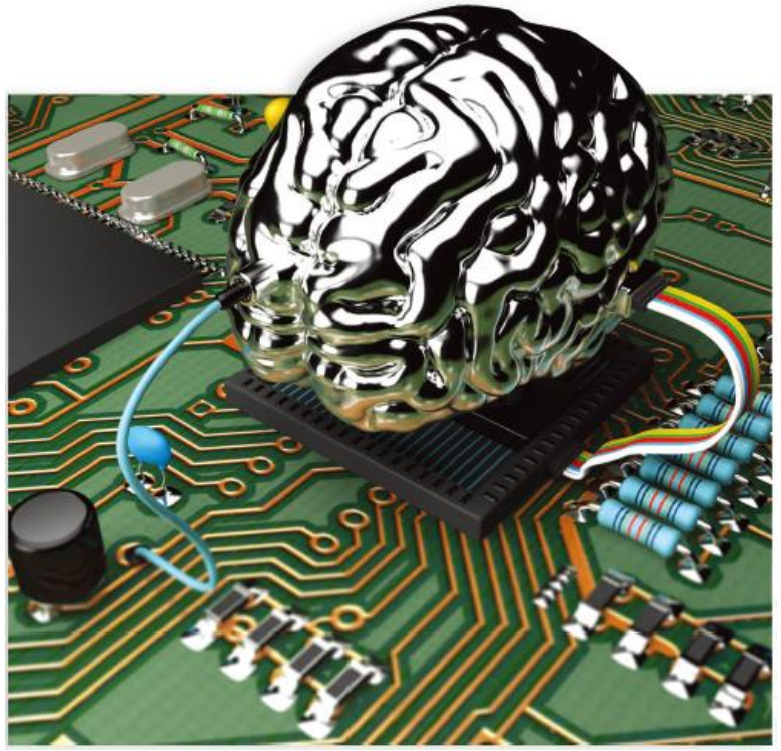
eDiscovery Today
Waymo

Brain Inspired Neuromorphic Technology

✓ Deep neural network



✓ Neuromorphic system



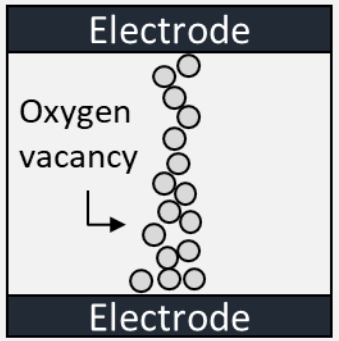
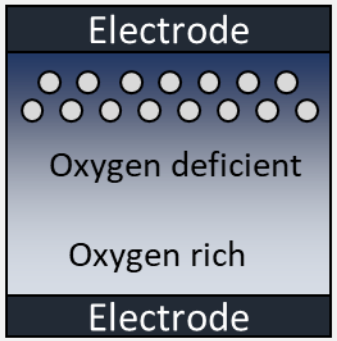
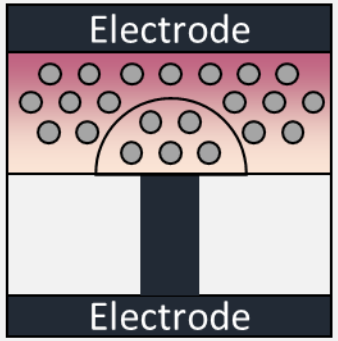
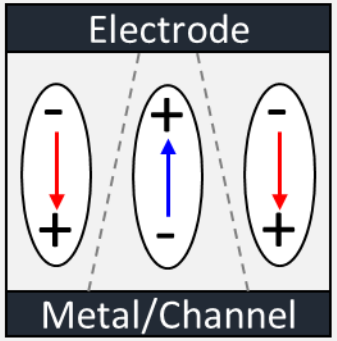
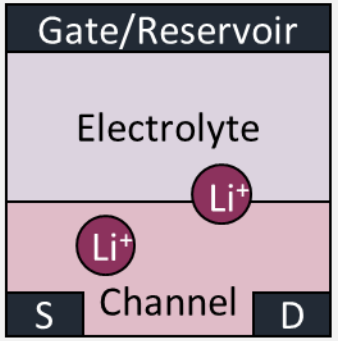
✓ Emulating the brain that processes data

-Transfer data from one neuron to the other through synapses in parallel

✓ Analog synaptic elements speed up the computation efficiency in hardware

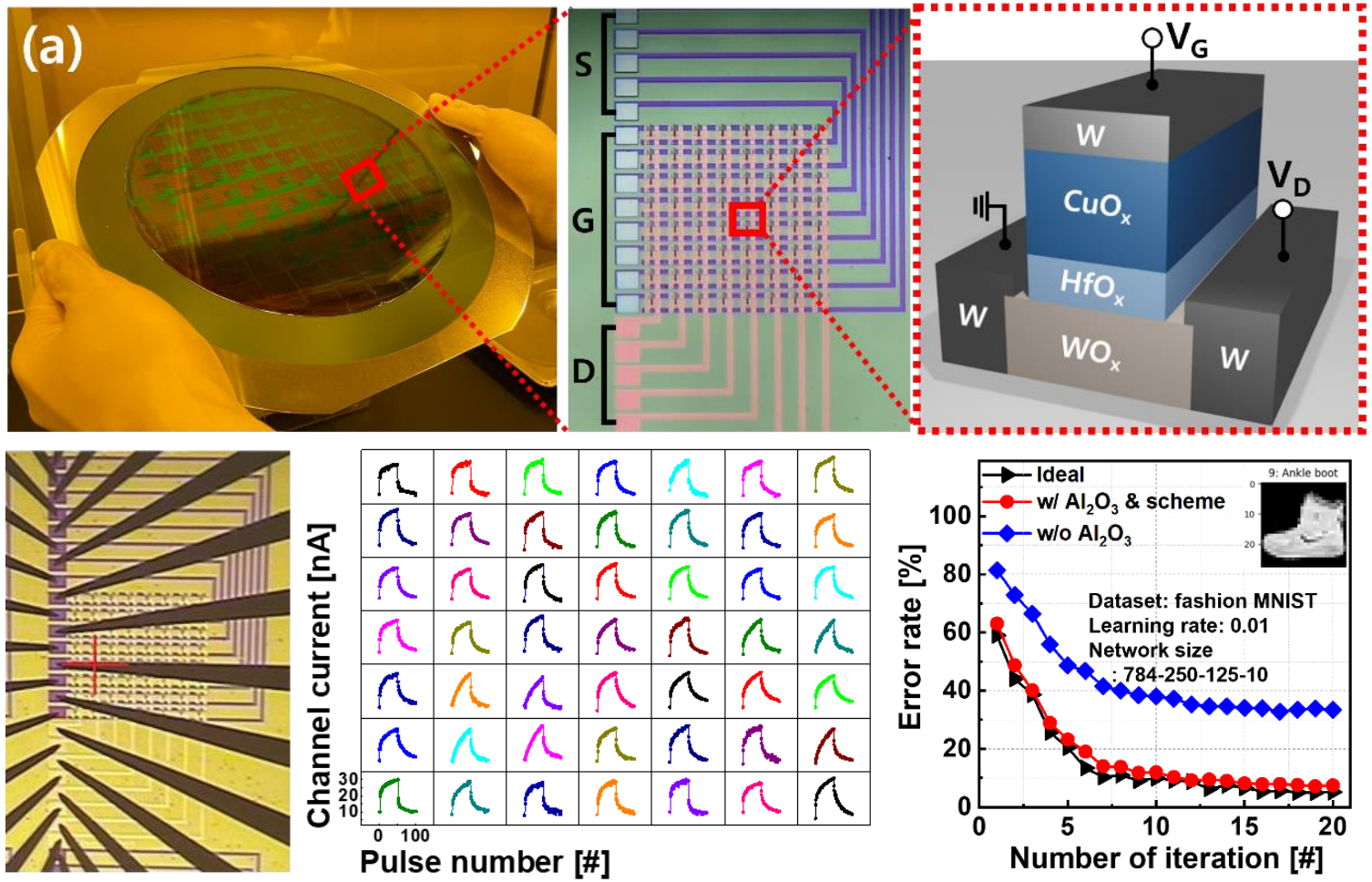
J. Woo et al., IEEE Nanotechnology Magazine, 2018

Resistive Memories for Analog Synapse

RRAM		PCM	FeRAM/FeFET	ECRAM
Filamentary	Interfacial barrier	Phase transition	Polarization	Electrochemical reaction
Binary oxides (HfO_2)	Metal/Ternary oxide ($Al/PrCaMnO_3$)	Chalcogenides ($Ge_2Sb_2Te_5$)	Doped HfO_2 ($HfZrO_2$)	Li-ternary oxide ($LiCoO_2$)
				
+ Scalability + Fast speed	+ Analogue	+ Maturity	+ Symmetry	+ Symmetry + Linearity
- Stochasticity	- Slow speed	- Asymmetry	- Domain wall controllability	- Slow speed - Scalability

J. Woo et al., Advanced Intelligence Systems, 2020

Wafer-level Resistive Memory Array



✓ Fully parallel weight update in 8-inch wafer-level synapse array

In collaboration with Prof. Seyoung Kim (POSTECH)
S. Jeon et al., Scientific Reports, 2023

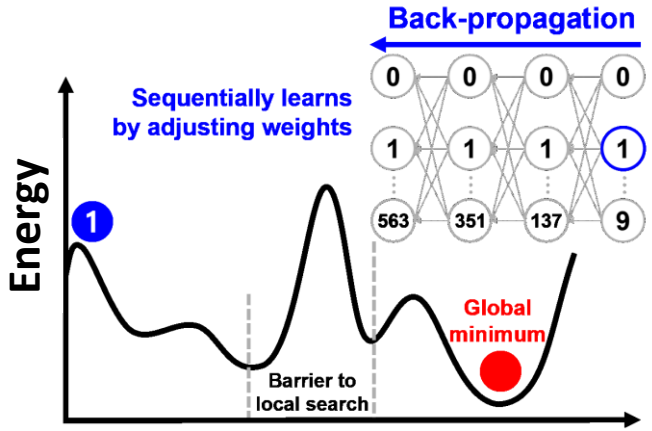
New Applications Beyond Classification

- ✓ AI technology plays an important role in future business
- ✓ Assign delivery order of vehicles more efficiently to reduce time/fuel consumption
- ✓ Demands for solving complex optimization problems (COPs)

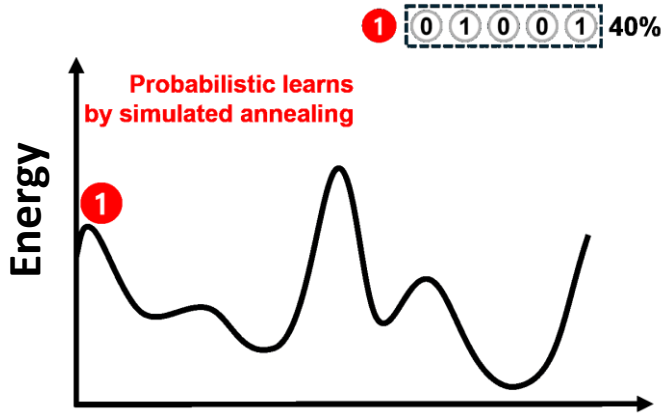
OptaPlanner
MathGifs

Unconventional Computing

✓ Neural network



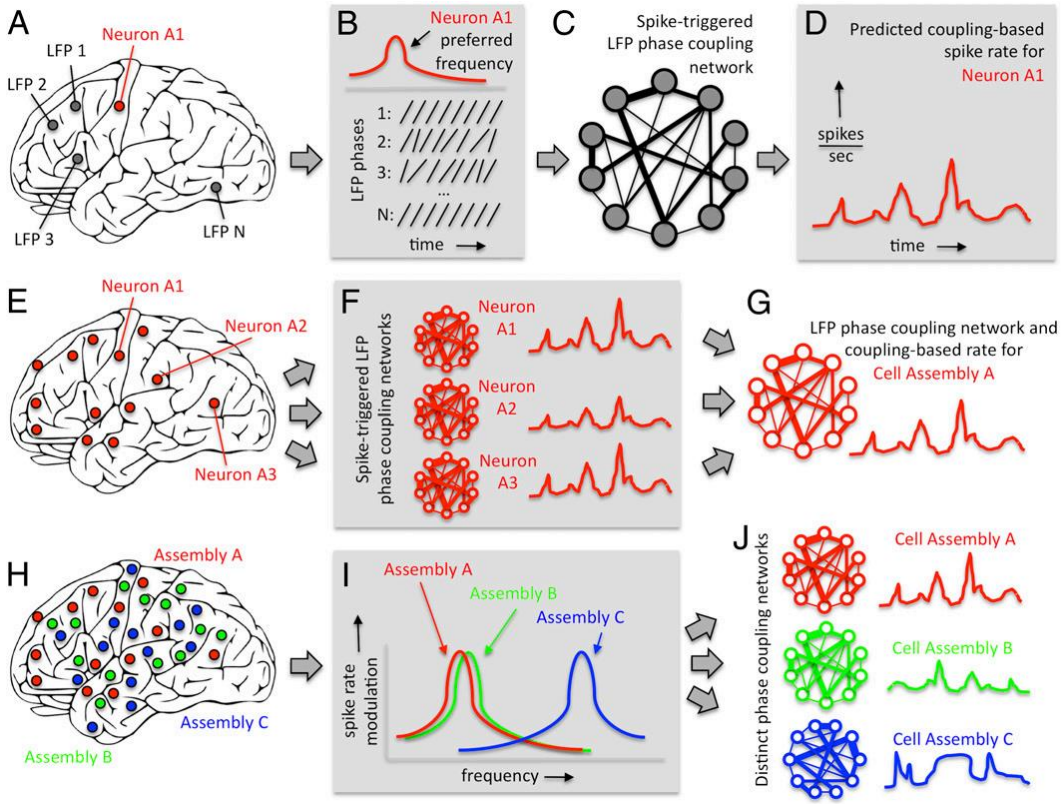
✓ Optimization algorithms

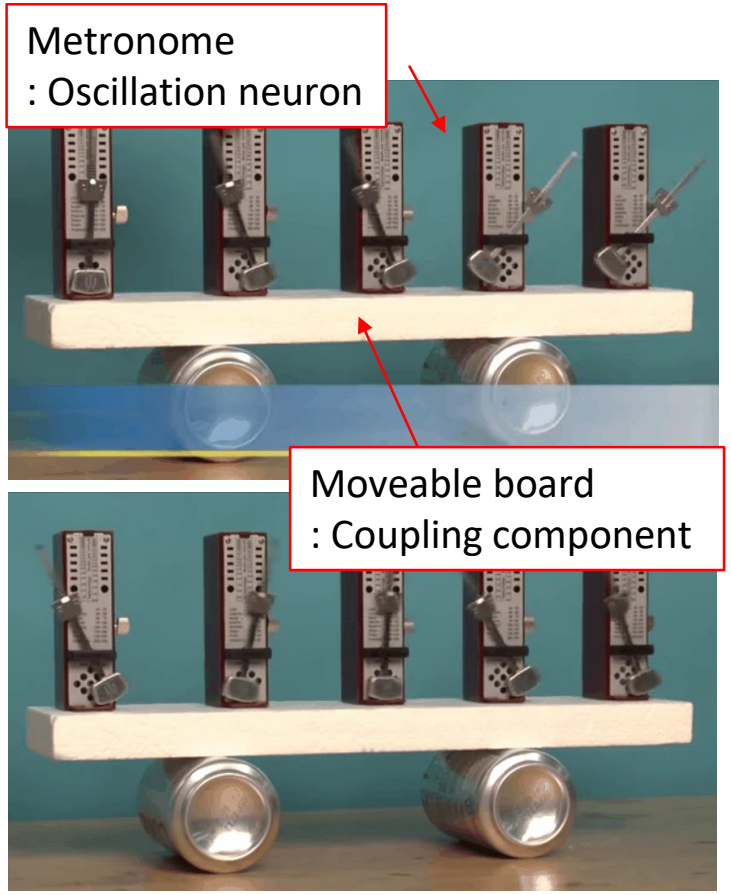


Back-propagation	Learning Algorithms	Simulated Annealing
Gradient Descent	Optimization Process	Energy Minimization
Stuck-at-local Minimum	Cost Landscape	Lack of Cost Stability
Pattern Recognition	Applications	Optimization Solver (COP)

J. Kim et al., IEEE IRPS 2025
J. Kim et al., IEEE Access, 2025

Neuronal Oscillations in Cerebral Cortex

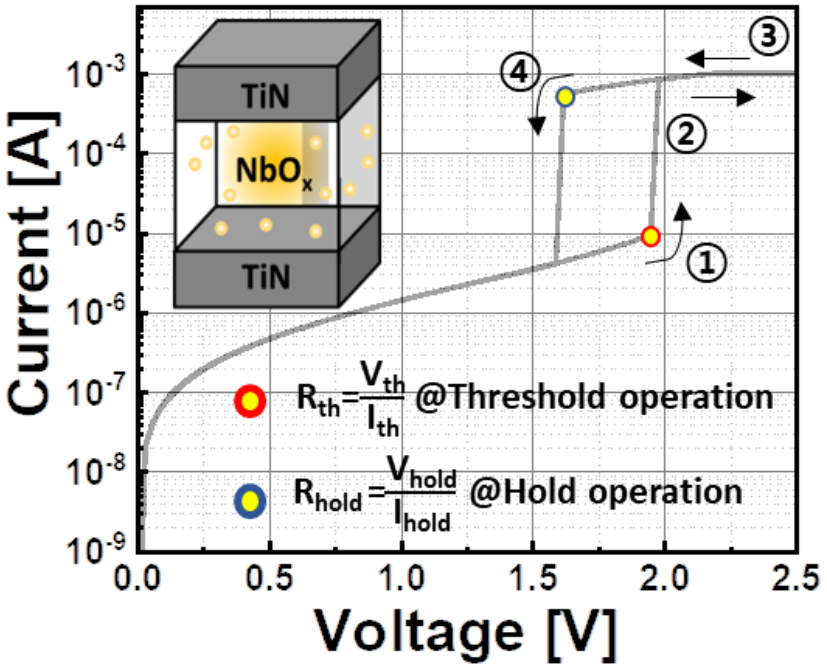


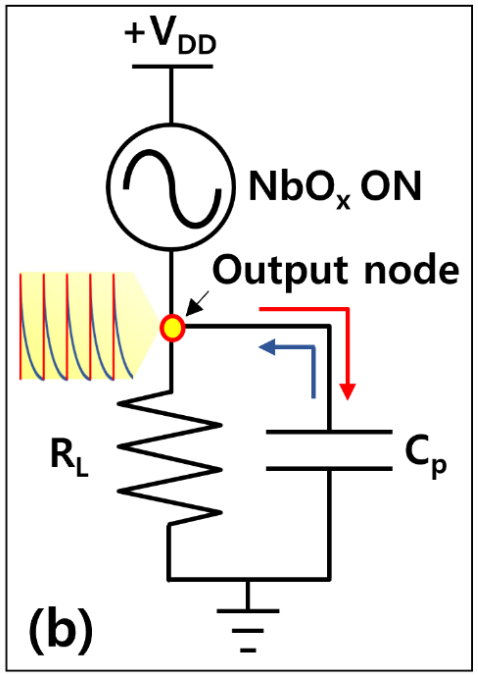


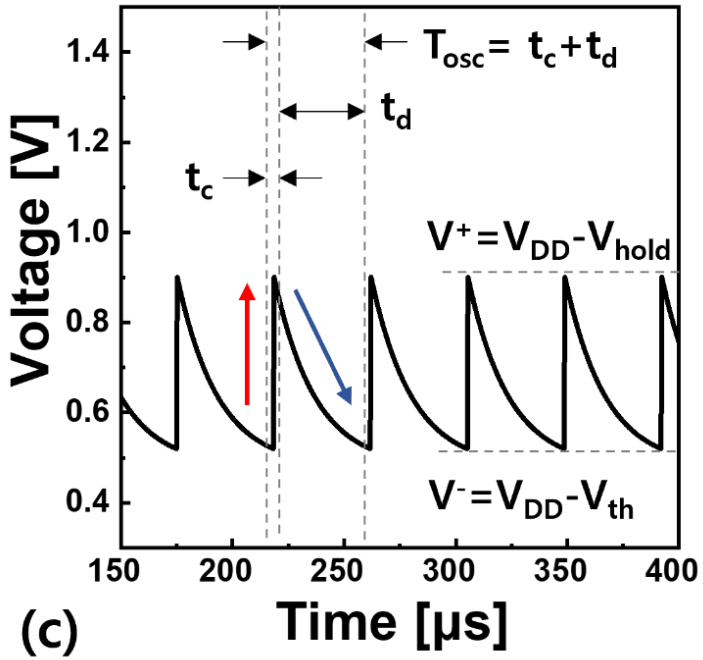
- ✓ Higher-level functions based on synchronization of these oscillations
- ✓ Brain networks mediated by oscillatory neural coupling

R. T. Canolty et al., PNAS, 2010
https://www.youtube.com/watch?v=T58lGKREubo

NbO_x Threshold Switch for Oscillation Neuron



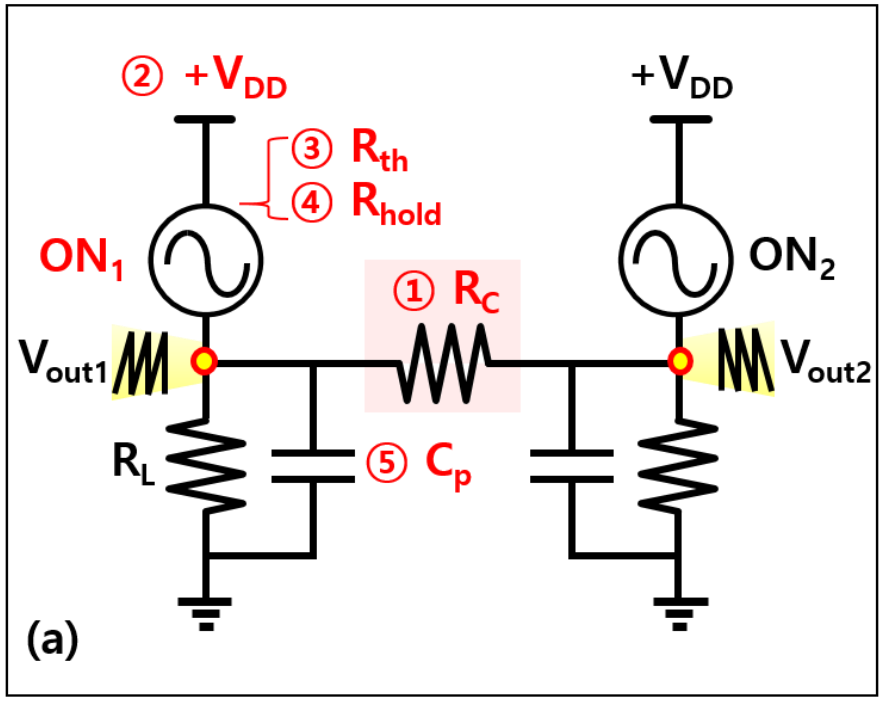


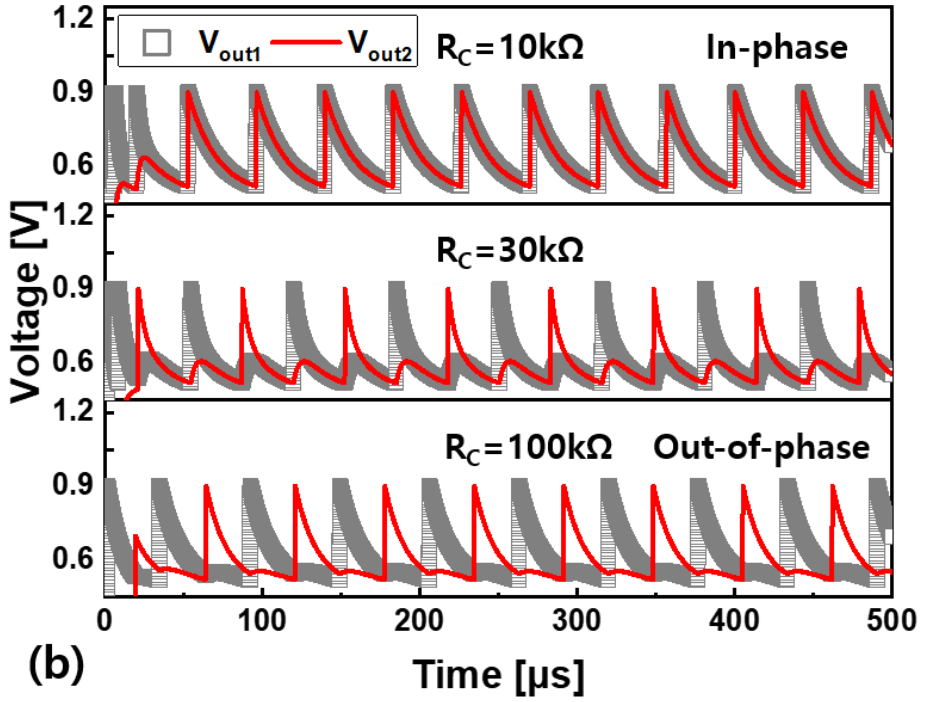


- ✓ Thermally driven Metal-Insulator transition (MIT) in VO_2 and NbO_2
- ✓ Voltage begins to be applied to the threshold switch → Charging
- ✓ Charged voltage at V_{th} discharges due to lowered R_{on} of threshold switch → Discharging
- ✓ Back and forth of the charging and discharging → Voltage oscillation

H. W. Kim et al., IEEE TED, 2023

Coupled Oscillator Dynamics in Simulation





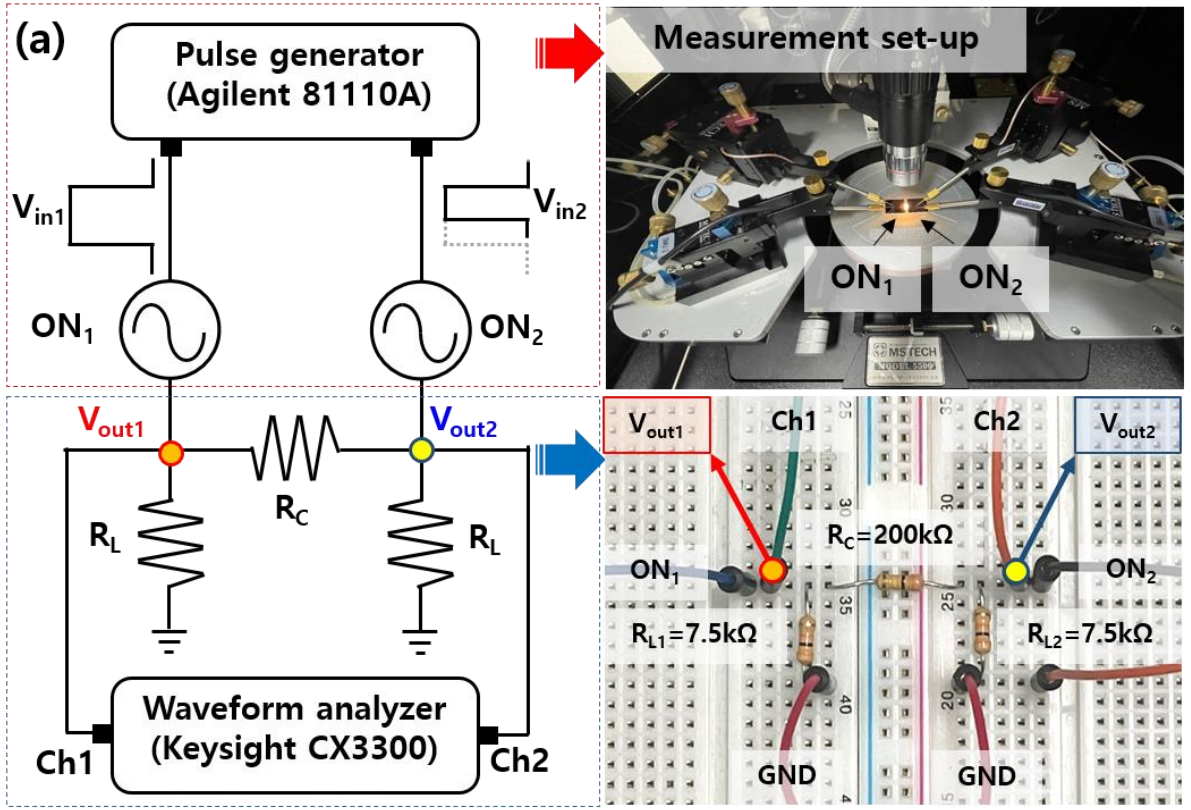
✓ Voltage oscillations begin to synchronize
  -Strong coupling (=lower R_C) → In-phase synchronization → White
  -Weak coupling (=higher R_C) → Out-of-phase synchronization → Black

✓ Two distinguishable synchronizations can be used to encode binary information in the phase domain

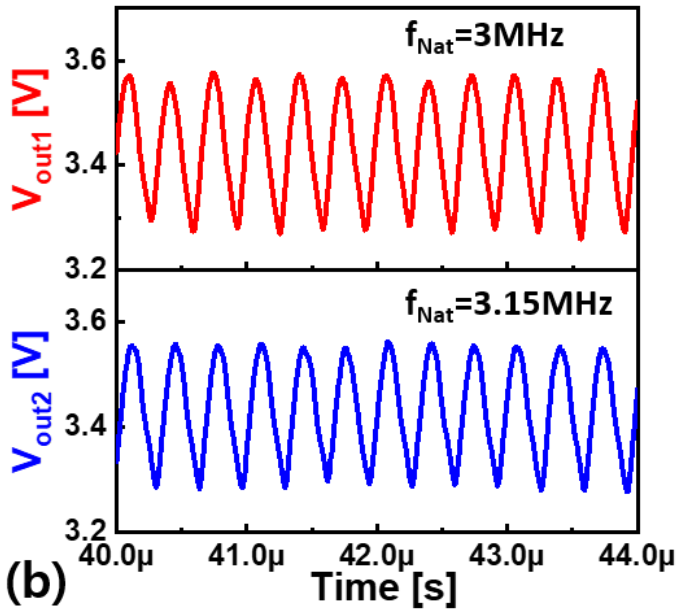
H. W. Kim et al., IEEE TED, 2023

Coupled Oscillator Dynamics in Experiment

✓ Experimental set-up



✓ Uncoupled system



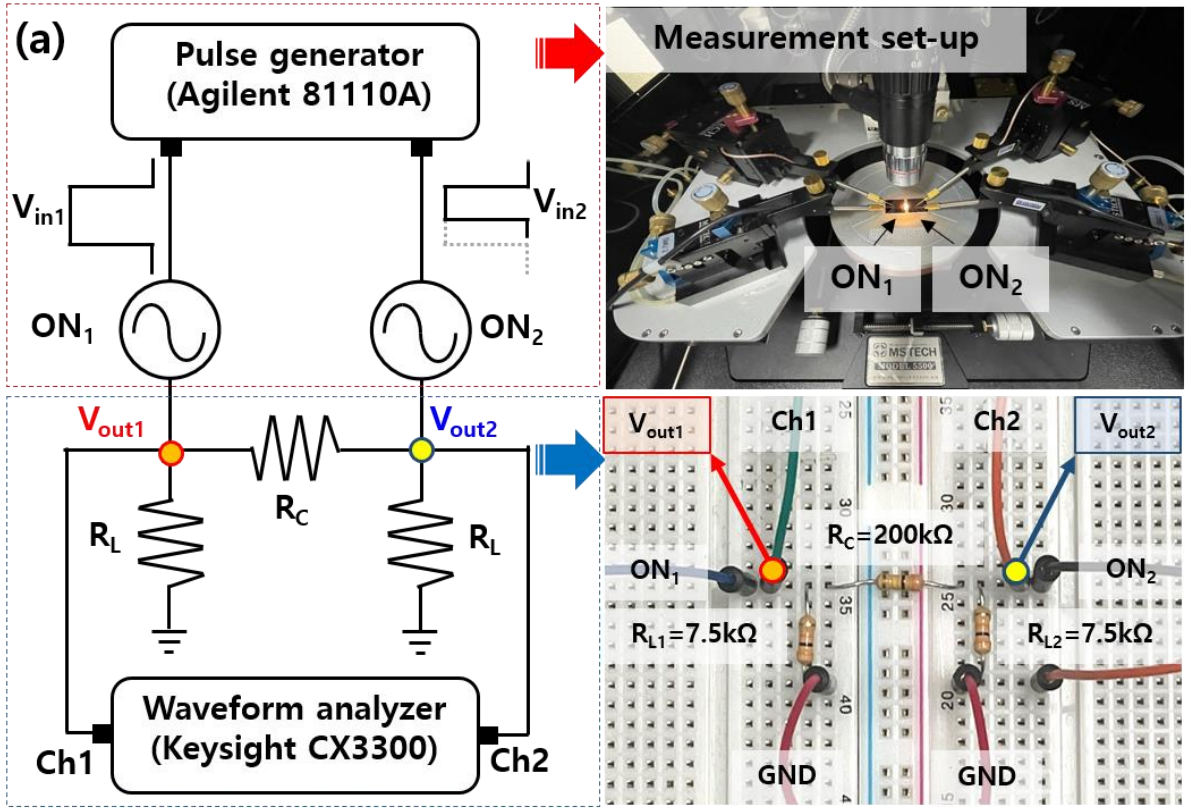
✓ Independent voltage oscillations observed at each node before coupling

In collaboration with ETRI

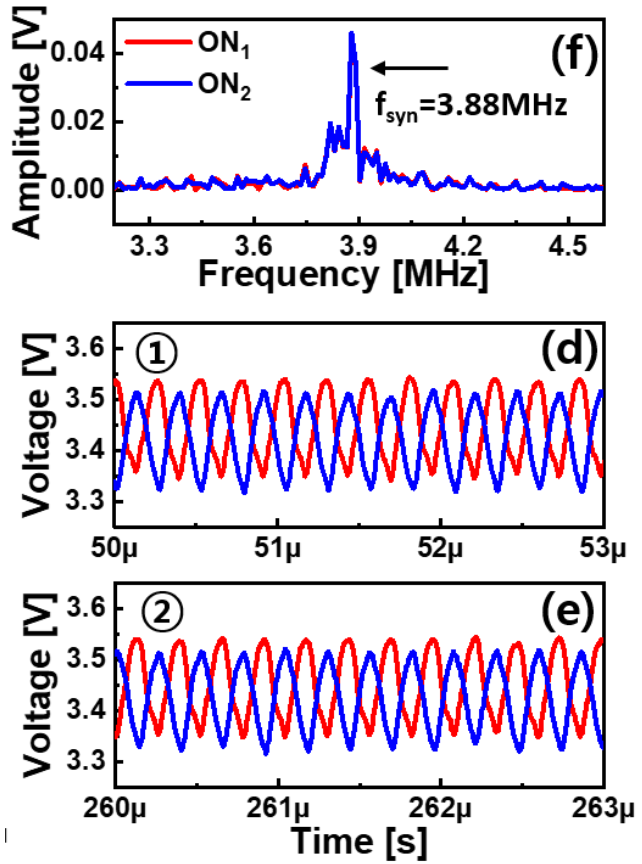
H. W. Kim et al., IEEE TED, 2023

Coupled Oscillator Dynamics in Experiment

✓ Experimental set-up



✓ Coupled system

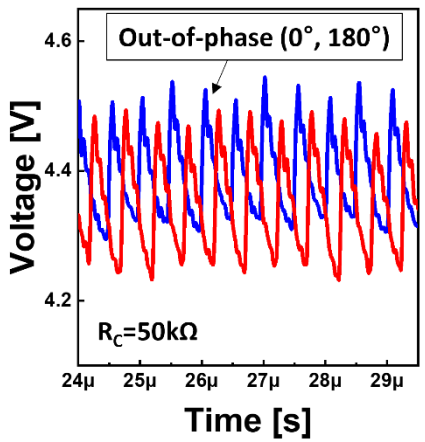


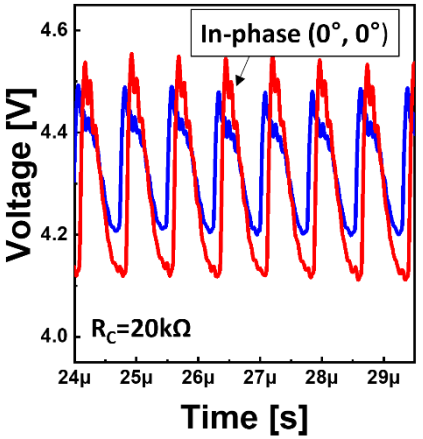
✓ Robust out-of-phase synchronization due to weak coupling

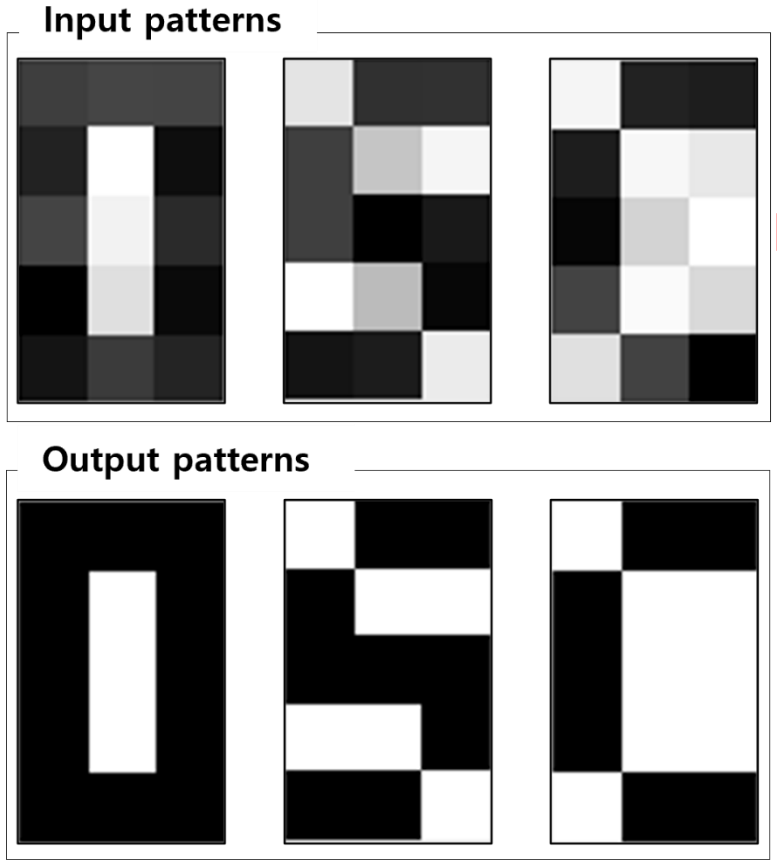
In collaboration with ETRI

H. W. Kim et al., IEEE TED, 2023

Pattern Retrieval in Coupled Oscillators







✓ Experimental demonstration of robust synchronization in two-coupled system
→ "Let physics compute"

In collaboration with ETRI
H. W. Kim et al., IEEE TED, 2023

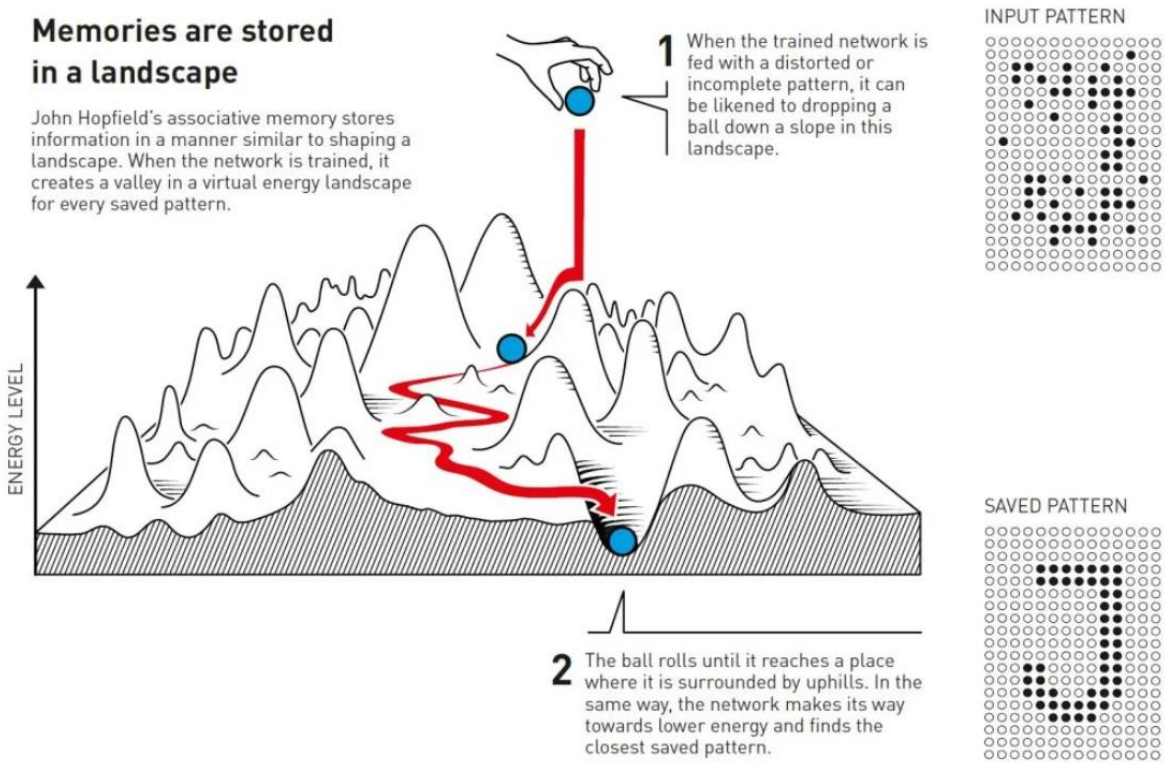
Hopfield Networks

The Nobel Prize in Physics 2024

John Hopfield

"for foundational discoveries and inventions that enable machine learning with artificial neural networks"

John Hopfield. Ill. Niklas Elmehed © Nobel Prize Outreach

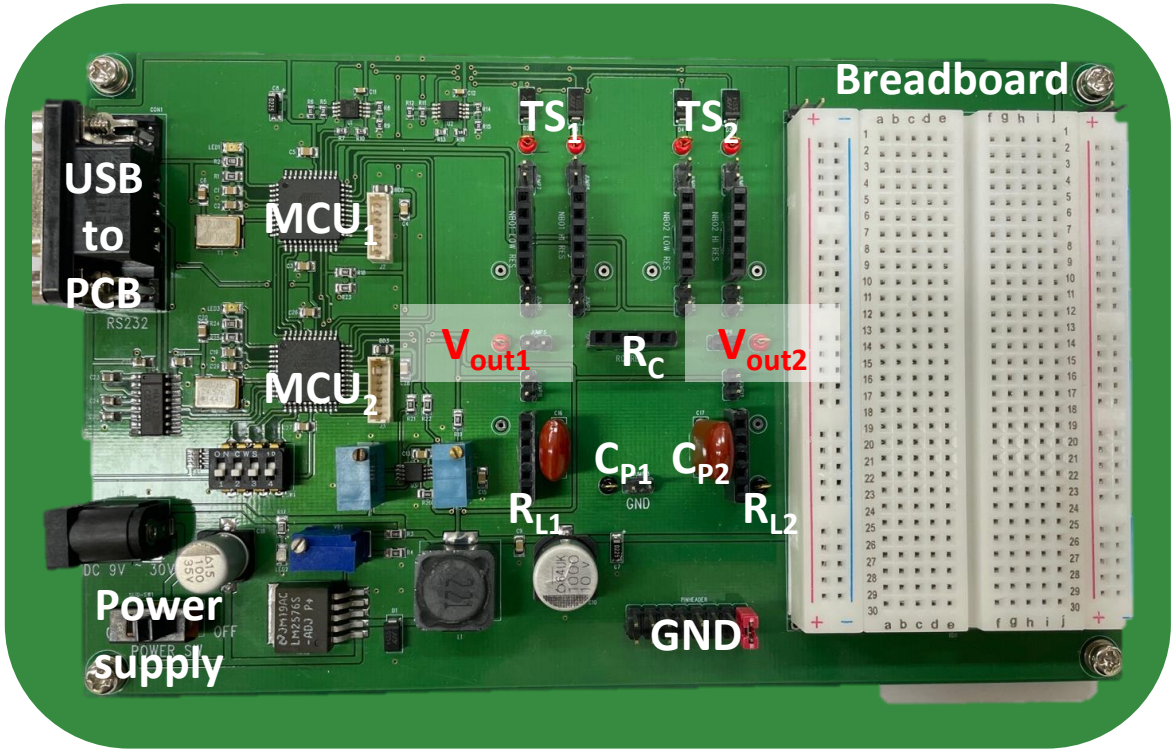


© Johan Jarnestad/The Royal Swedish Academy of Sciences

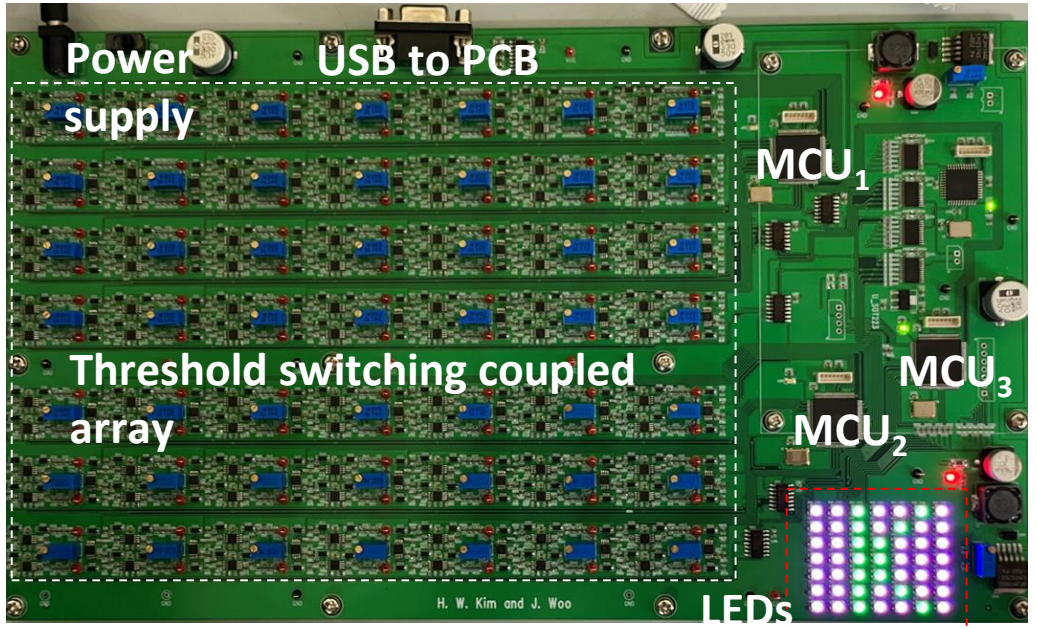
- ✓ Collection of interconnected neurons (Each neuron has +1 and -1)
- ✓ Hopfield network is energy function
  - → The network reaches a stable state corresponding to stored patterns

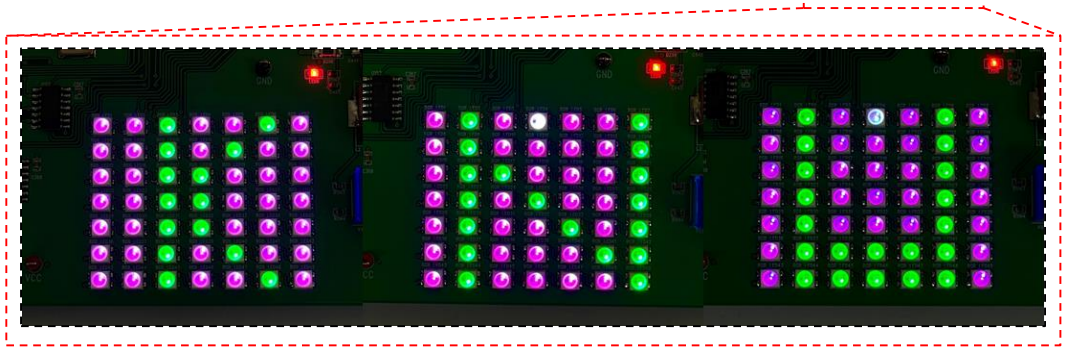
Oscillatory Neural Network Hardware

✓ Ver. 1



✓ Ver. 2

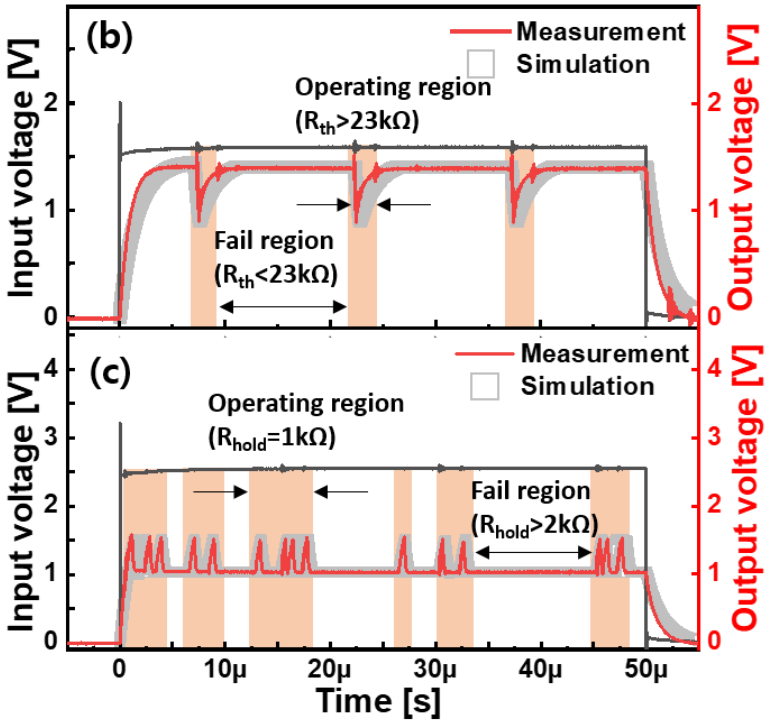




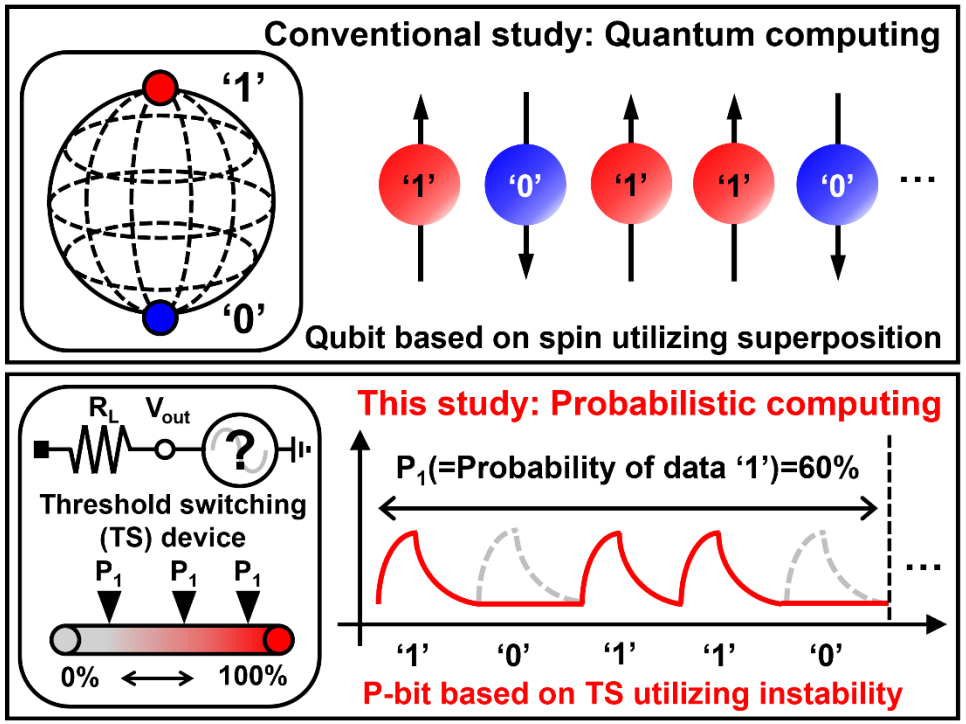
✓ Demonstration of pattern recognition using 98 oscillation neurons

p-Bit for Probabilistic Computing

✓ Oscillation failures



✓ p-Bit vs. qubit

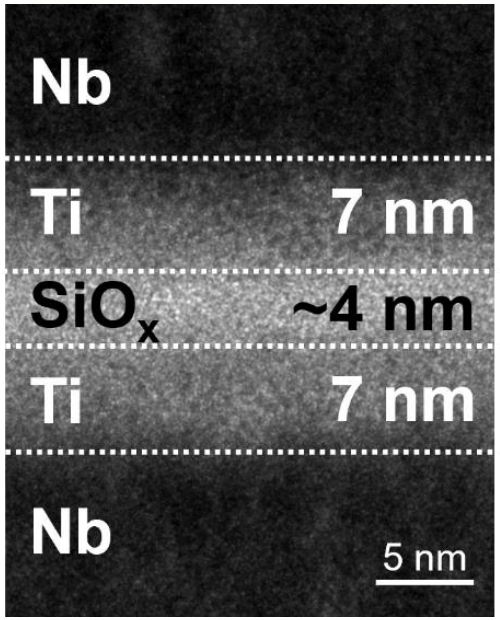


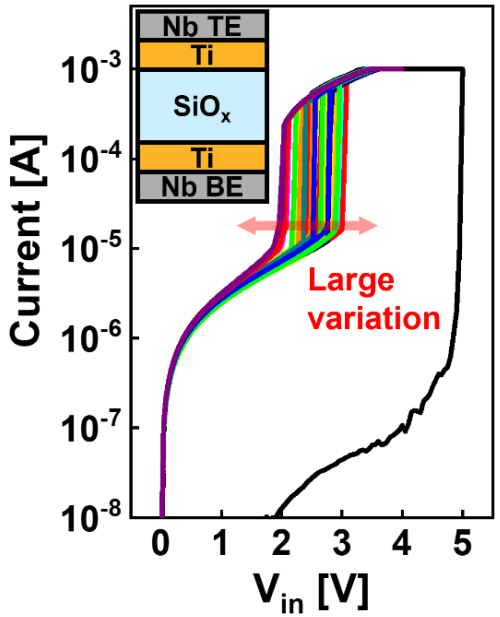
✓ In previous work, the challenge was unstable oscillations due to device variability

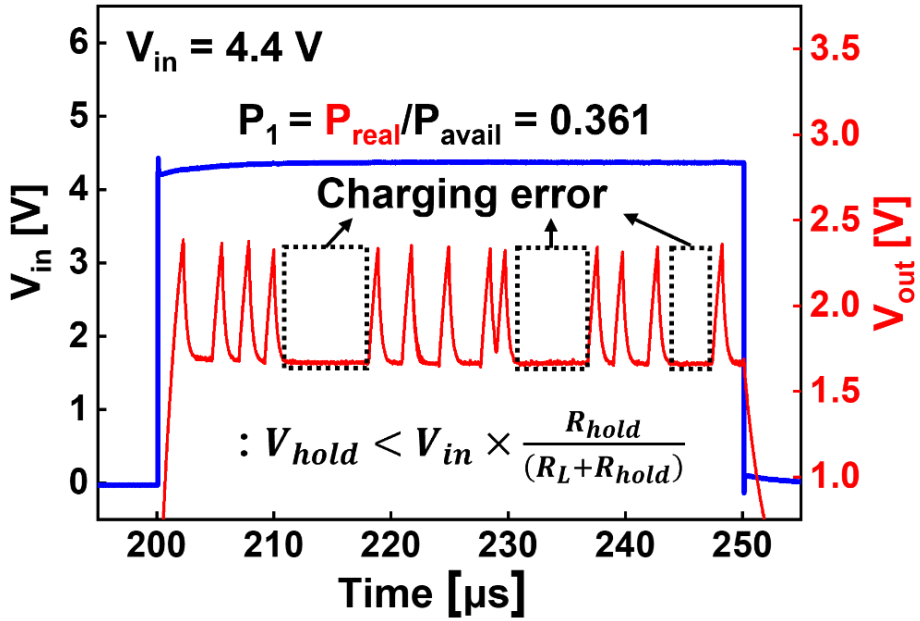
✓ How about leveraging device instability for probabilistic bit (p-Bit)?

H. W. Kim et al., IEEE TED, 2023
H. Choi et al., IEEE ESSERC 2024

Probabilistic Oscillation in Ti/SiO_x/Ti TS



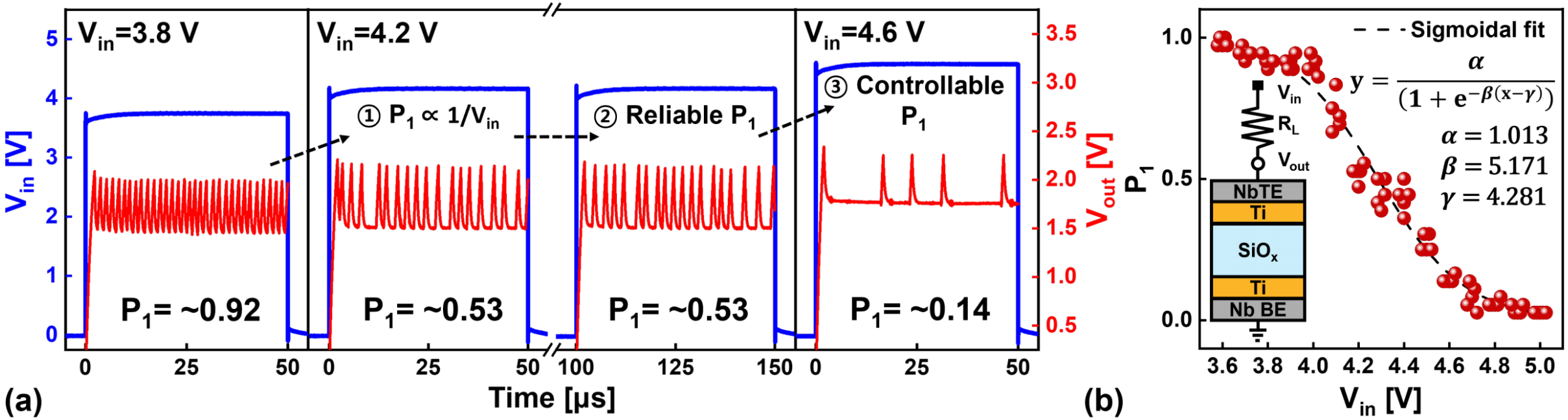




- ✓ Ti scavenging layer induces variations in the TS distribution
- ✓ Charging error generate random oscillatory behavior
- ✓ The number of spikes: probability (P_1)

J. Kim et al., IEEE IRPS 2025

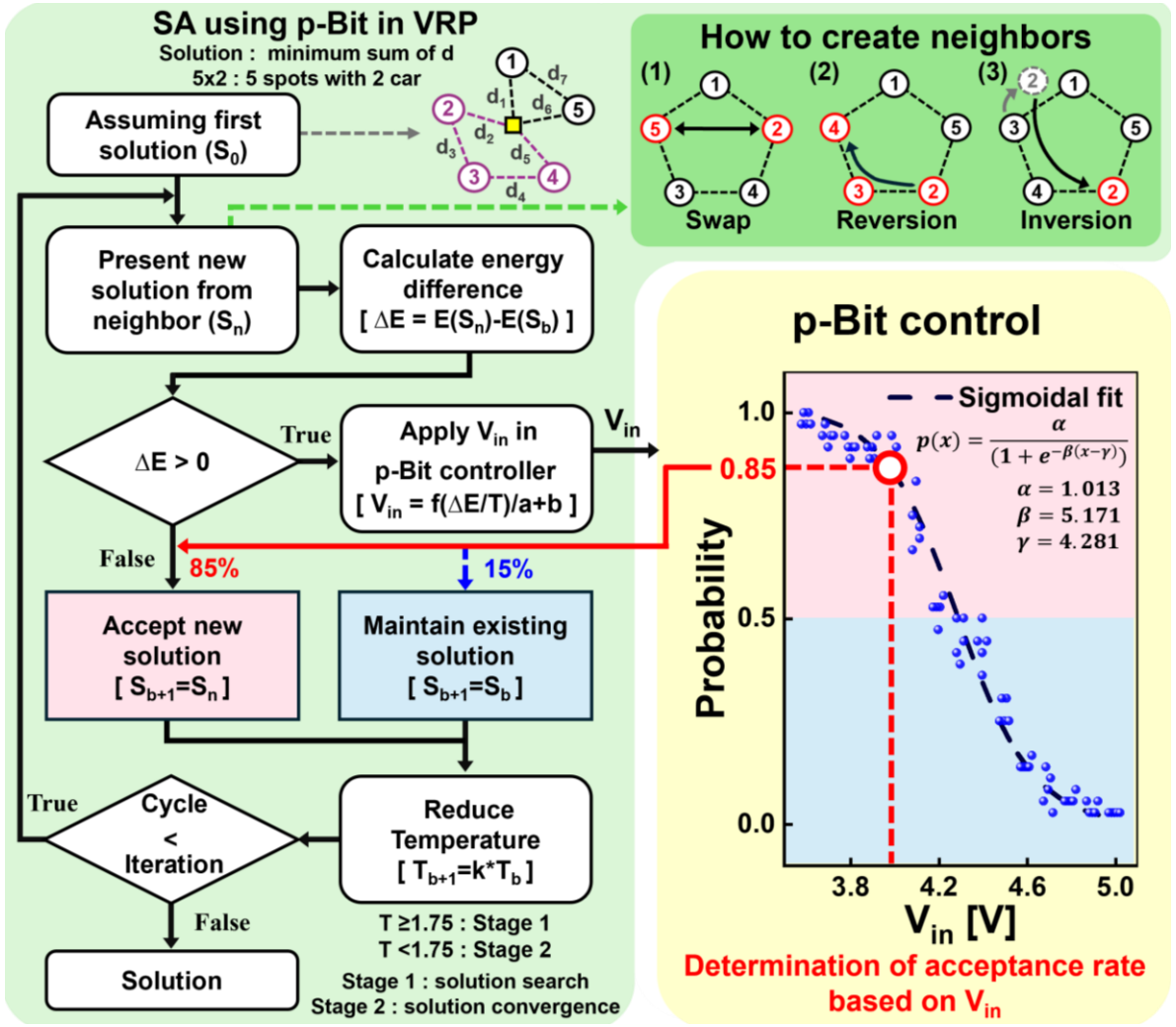
Highly Controllable Ti/SiO_x/Ti p-bit

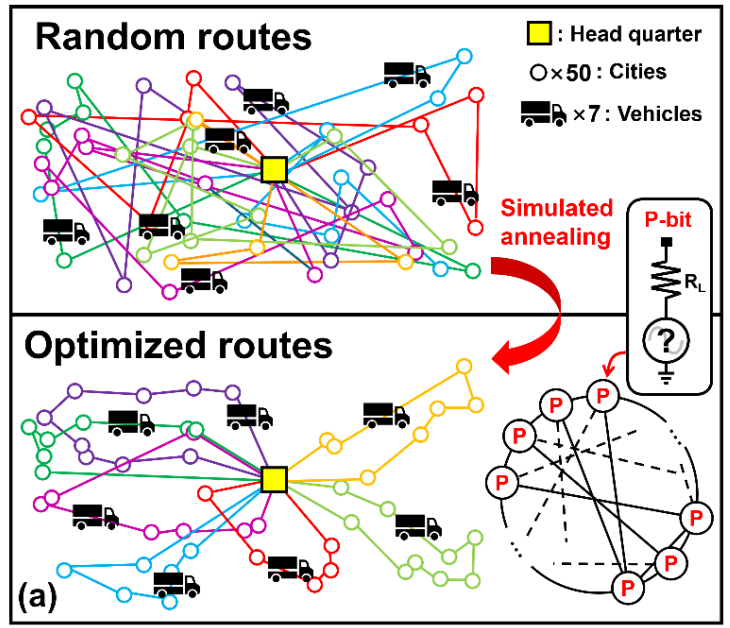


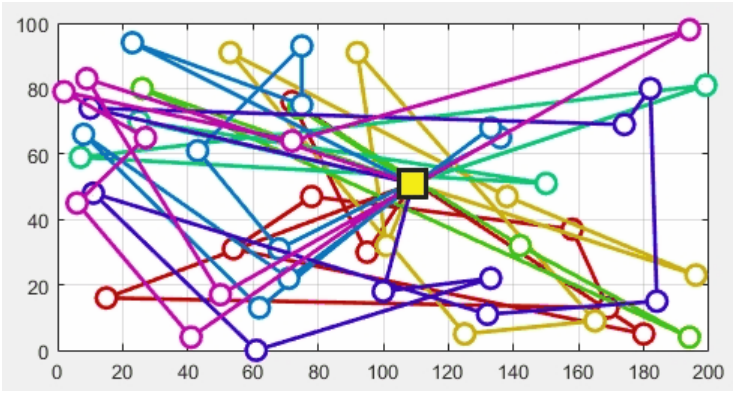
- ✓ Probability inversely proportional to V_{in}
- ✓ Sigmoid probabilistic behavior within the V_{in} range of 3.6 V to 5 V

H. Choi et al., IEEE ESSERC 2024
H. Choi et al., IEEE TED, 2025

Vehicle Routing Problems







✓ Accelerate simulated annealing algorithm for finding the optimal path

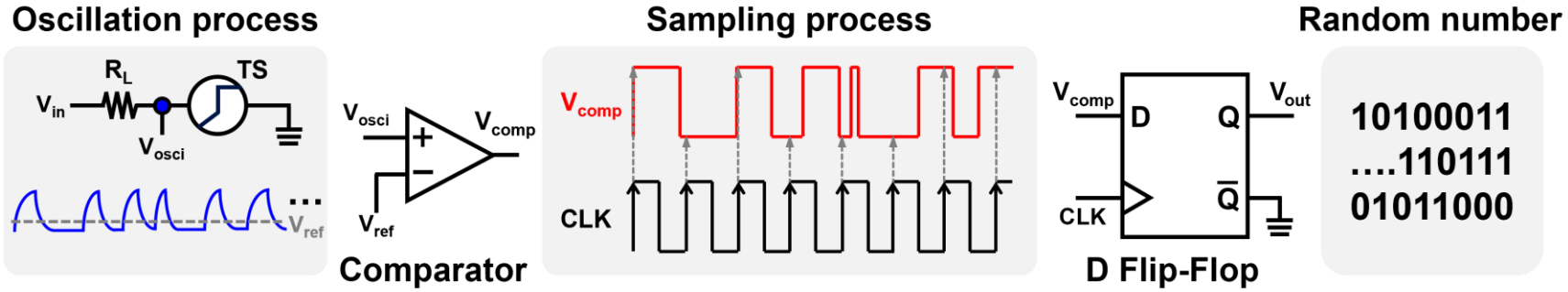
J. Kim et al., IEEE IRPS 2025

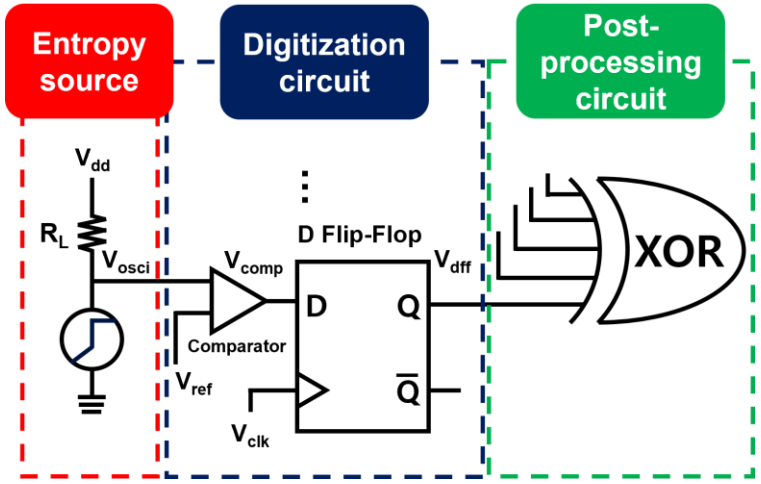
Hardware Security Applications

Telsa
Wireless car

✓ Connected/wireless cars and shared mobility
✓ Real-time actionable intelligence
→ Increased vehicle utilization
① Device randomness for TRNG in encryption
② Invertible logic gates for accurate decryption

p-Bit Entropy Source for TRNG





NIST SP 800-22 test results

Before and after XOR post processing

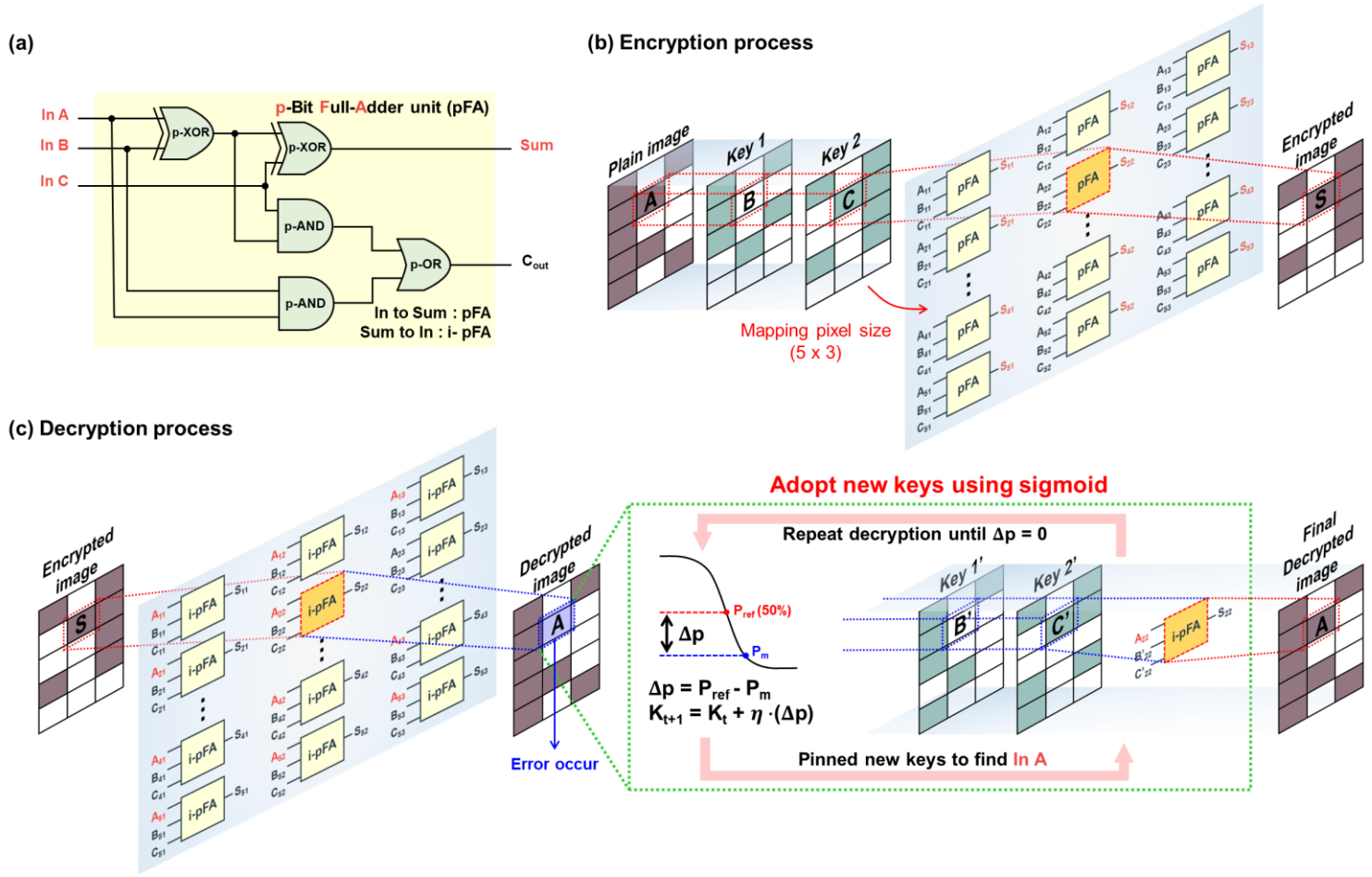
Statistical test	p-value	Test result	Result
1) Frequency	0.904483	1/1	Pass
2) Block Frequency	0.977287	1/1	Pass
3) Cumulative Sums	0.444425*	1/1	Pass
4) Runs	0.000000	0/1	Fail
5) Longest Run	0.000116	0/1	Fail
6) Rank	0.157494	1/1	Pass
7) FFT	0.000000	0/1	Fail
8) Non-Overlapping Template	-	129/148 87.16%	Fail
9) Overlapping Template	0.156657	1/1	Pass
10) Universal	-	-	-
11) Approximate Entropy	0.000000	0/1	Fail
12) Random Excursions	-	-	-
13) Random Excursions Variant	-	-	-
14) Serial	0.000000	0/1	Fail
15) Linear Complexity	0.543677	1/1	Pass

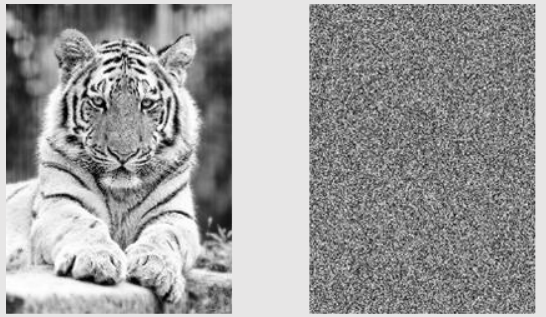
Statistical test	p-value	Test result	Result
1) Frequency	0.883171	98/100	P
2) Block Frequency	0.514124	99/100	P
3) Cumulative Sums	0.066882*	98/100	P
4) Runs	0.798139	96/100	P
5) Longest Run	0.678686	98/100	P
6) Rank	0.213309	100/100	P
7) FFT	0.236810	97/100	P
8) Non-Overlapping Template	0.016717*	14646/14800 98.95%	P
9) Overlapping Template	0.699313	98/100	P
10) Universal	0.181557	97/100	P
11) Approximate Entropy	0.171867	100/100	P
12) Random Excursions	0.289667*	529/536 98.69%	P
13) Random Excursions Variant	0.002758*	1187/1206 98.42%	P
14) Serial	0.798139*	99/100	P
15) Linear Complexity	0.102526	99/100	P

- ✓ Intrinsic device instability for physical entropy source
- ✓ NIST SP 800-22 test (15/15) pass

In preparation

p-Bit for Cryptography Accelerator





Plain image

Encrypted image

Decrypted image

Final decrypted image

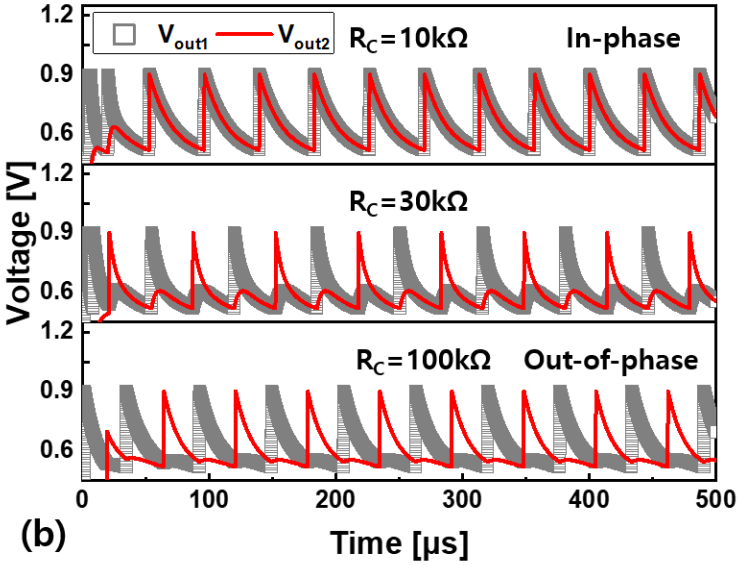
- ✓ Newly designed full-adder unit using p-Bit gates for encryption/decryption
- ✓ 99.7% accurate decryption of 8-bit image

In preparation

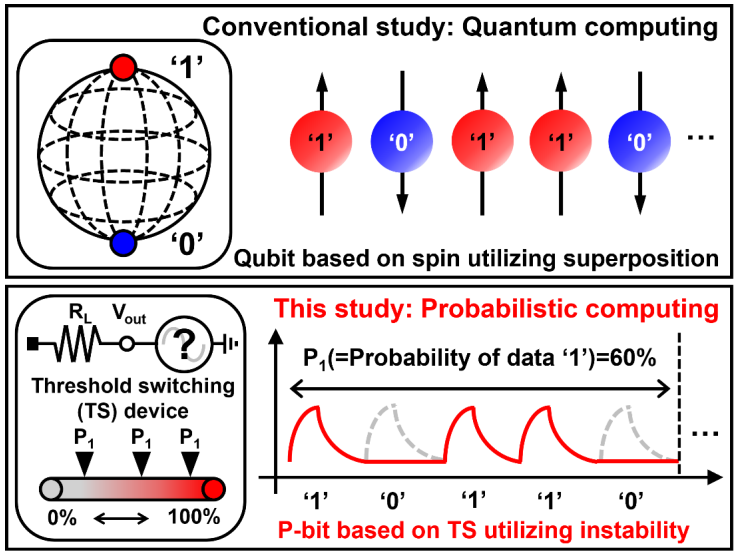
Outlook and Summary

- ✓ **Today**: Neuromorphic computing for energy-efficient real-time pattern recognition
- ✓ **The next phase**: In-cryostat neural processing for quantum computing or complex optimization problems solvers for logistics and delivery applications
- ✓ **Long-term vision**: Security in mainstream autonomous vehicles

Interaction of two oscillators



Leveraging instability of oscillator



Acknowledgement

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