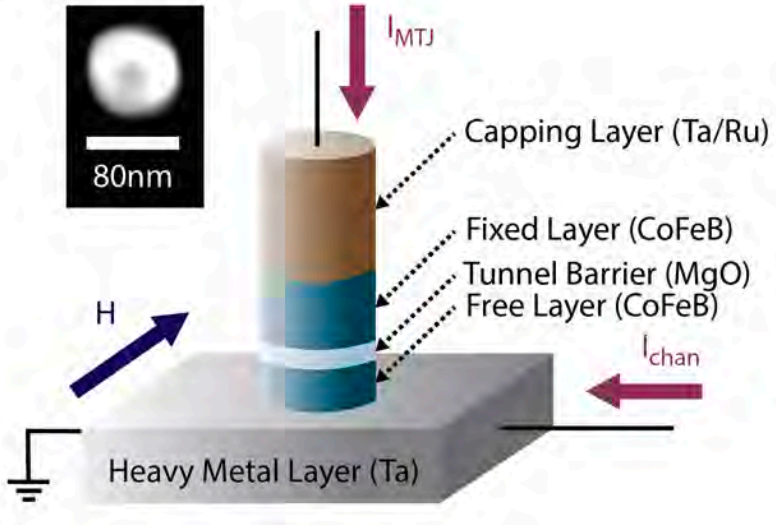
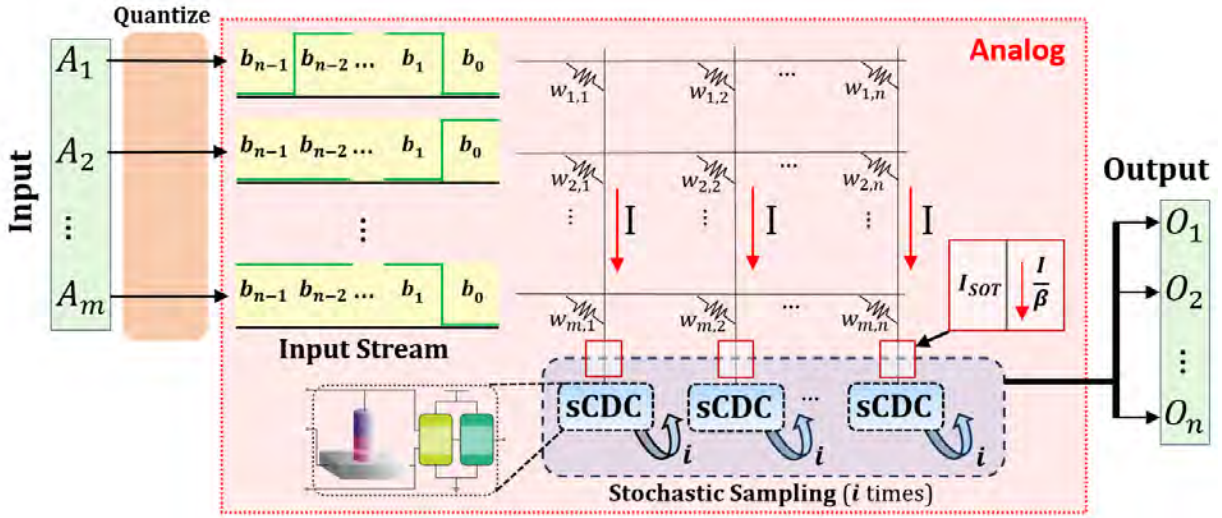
Magnetic tunnel junctions for stochastic neuromorphic computing





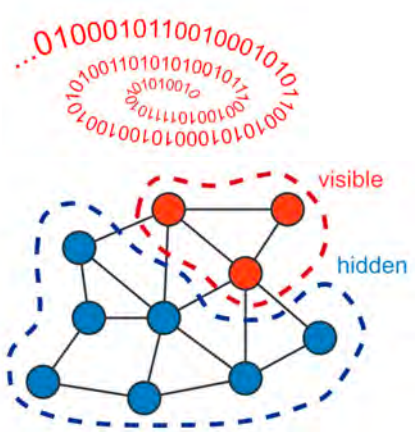
Luqiao Liu
Department of EECS

Mar 31st, 2025

Introduction

Applications Heavily Rely on Random Number Generators

Machine Learning

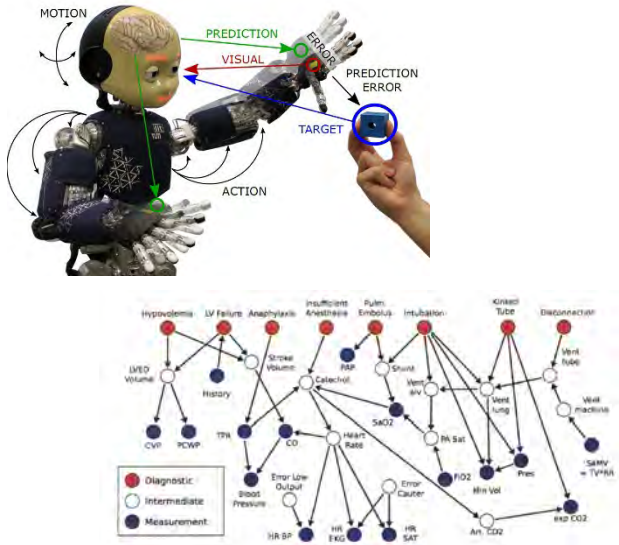


Chowdhury, S. *et al.,* JXCDC 9, 1 (2023)

Optimization problems

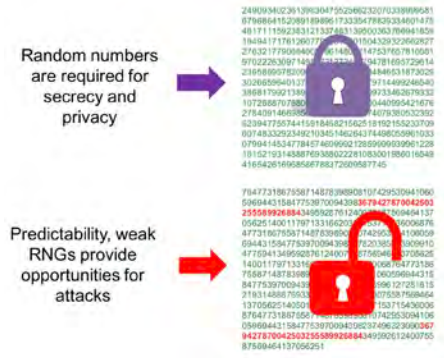
Mohseni, N. *et al.,* Nat. Rev. Phys. 4, pp. 363-379 (2022)
Lucas, A., Front. Phys. 2, 5 (2014)

Bayesian Inference



Oliver, G. *et al.,* ArXiv preprint, ArXiv: 1906.03022 (2020)
Jonas, E., Doctoral Dissertation, MIT (2014)

Cybersecurity

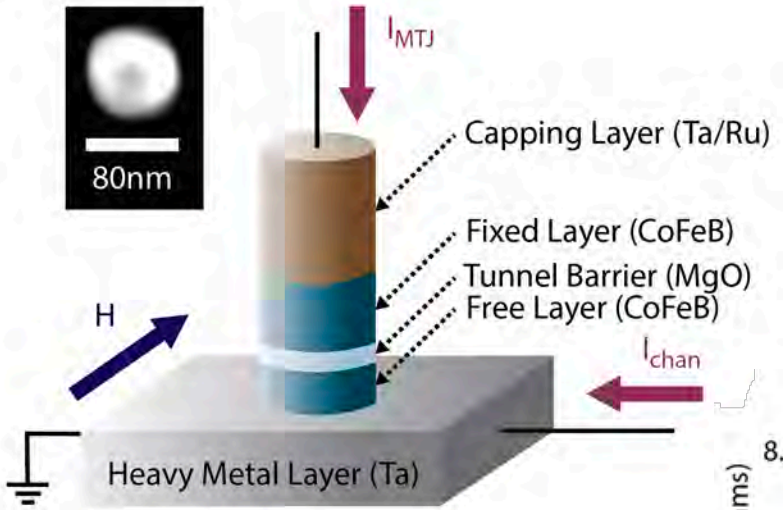


https://www.synopsys.com/designware-ip/technical-bulletin/true-random-number-generator-security-2019q3.html

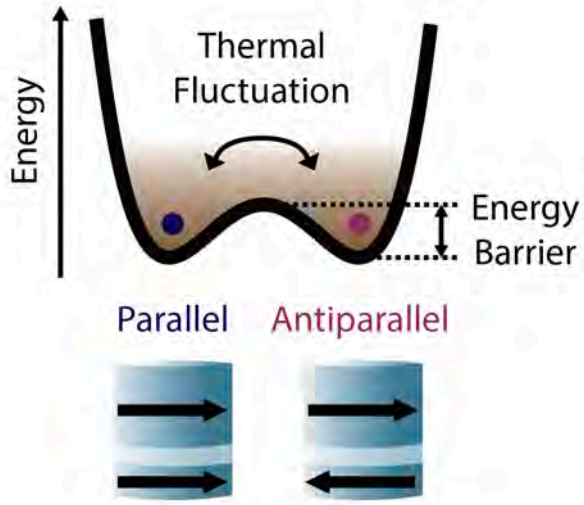
- Probabilistic models require source of randomness
- The cost to generate randomness and implement stochastic computing is high with standard hardware.
- Example: Conventional 32-bit LFSRs require >1000 transistors
- Pseudo randomness is usually what one gets

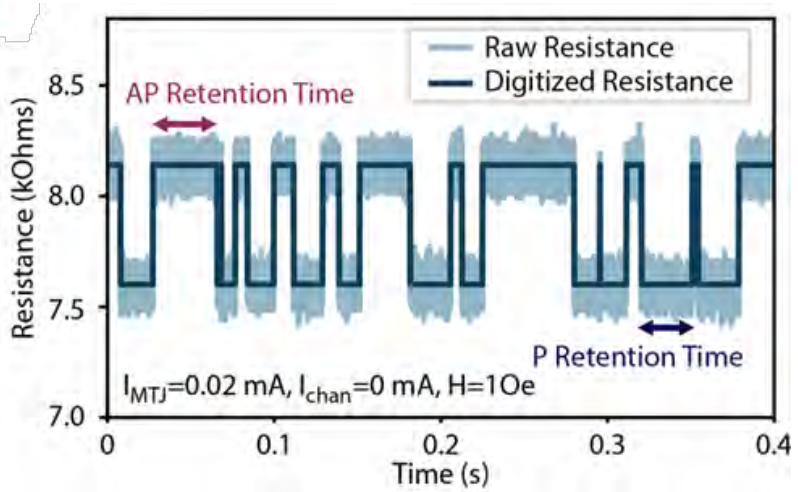
Stochastic Nanomagnets for True Randomness Generation

Magnetic Tunnel Junction



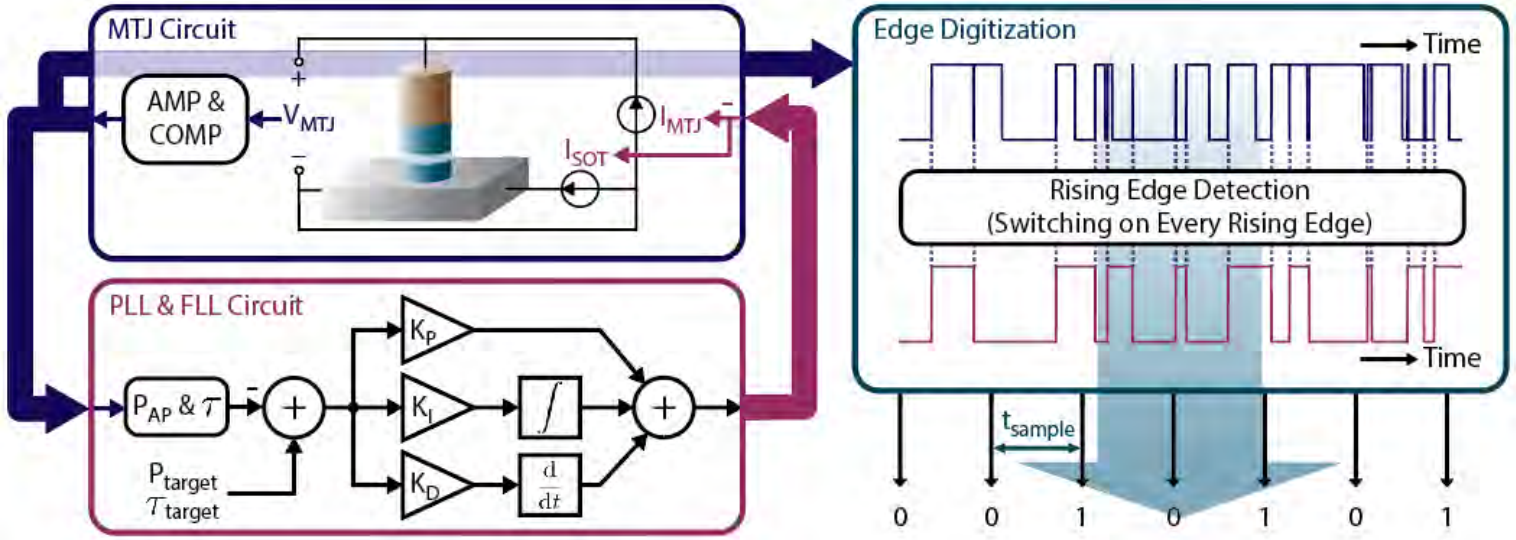
Thermally Activated Bipolar Fluctuation

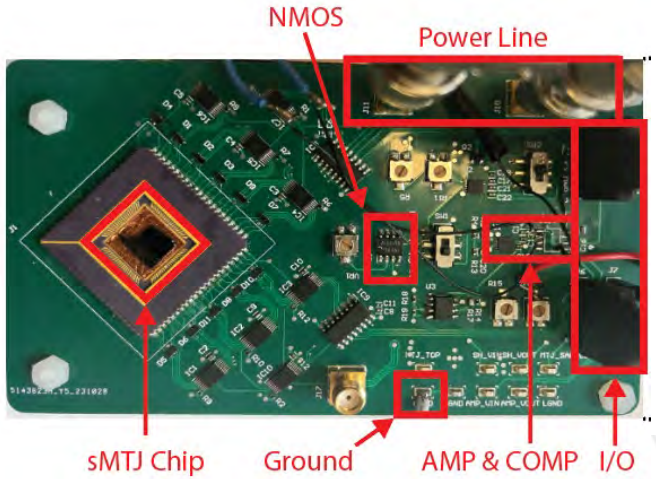




- low thermal stability magnetic tunnel junction device with spontaneous fluctuation
- Resistance fluctuate under room temperature without input energy requirement
- The bottom channel current provides a mechanism for feedback control or current-to-voltage conversion.

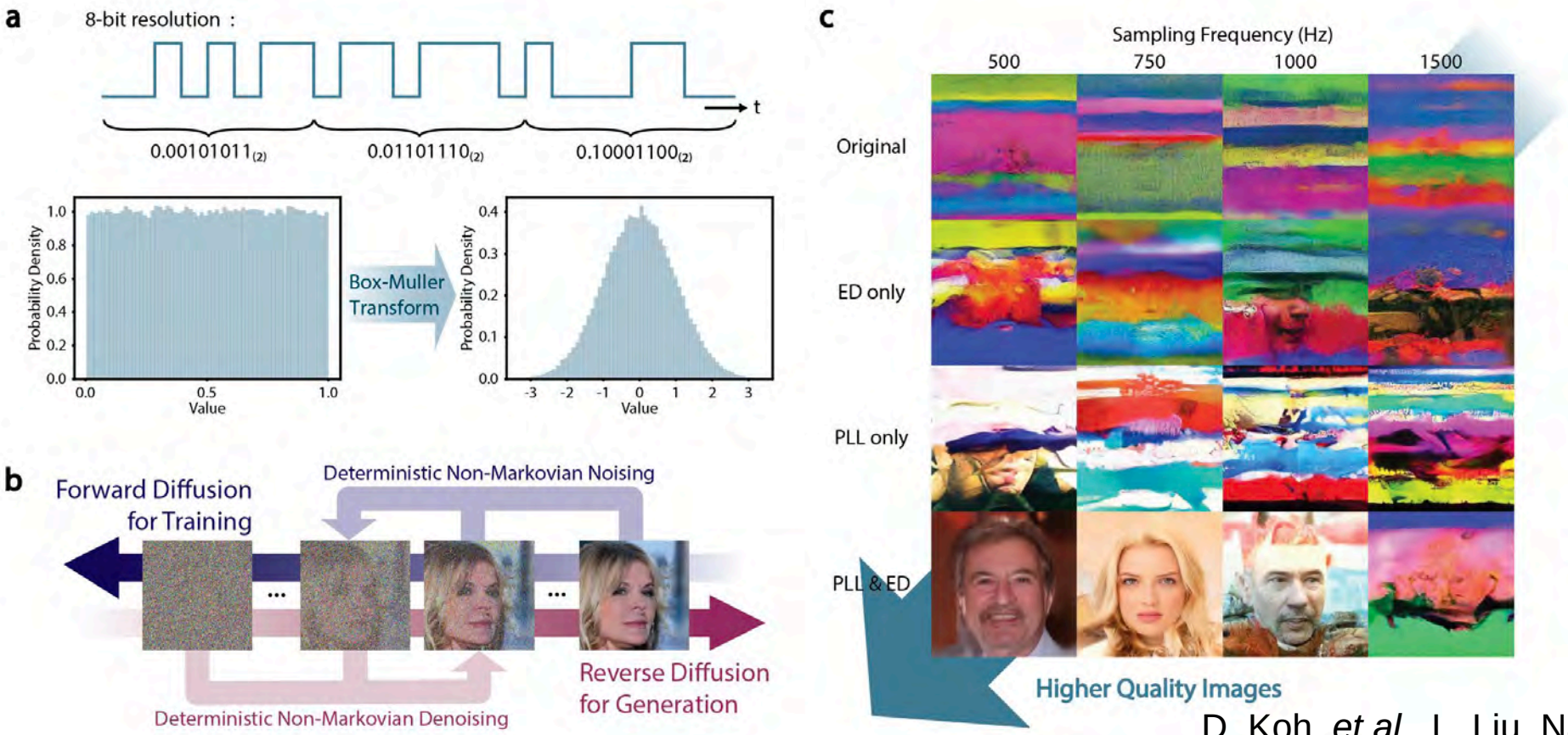
Reliable True Randomness Generation with Probability Locked Loop (PLL)





- Using PID control to reliably control both probability and fluctuation frequency
- Passed the NIST Randomness test

Application Example 1: Generative Artificial Intelligence

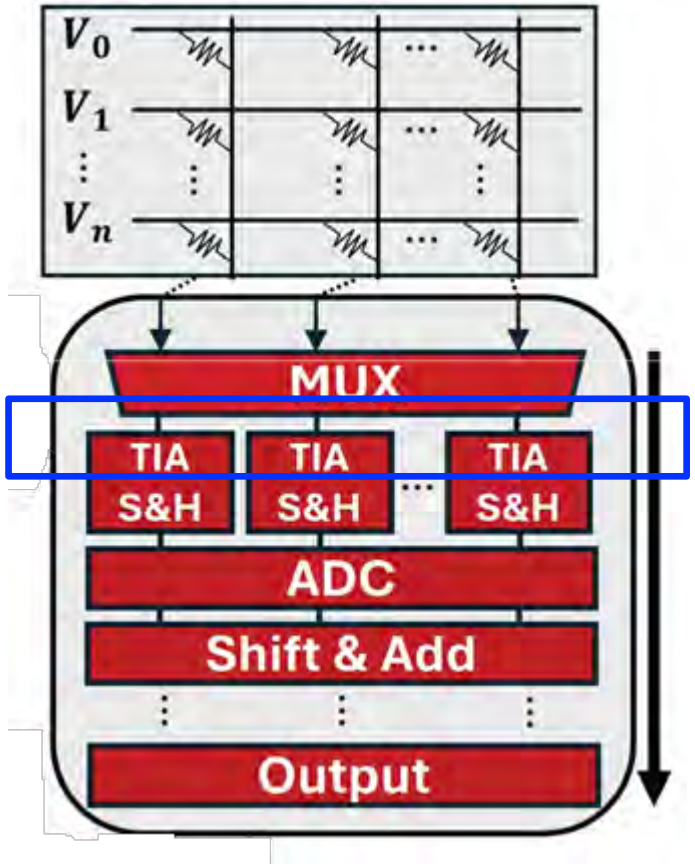


D. Koh, *et al.*, L. Liu, Nano Lett. 25, 10, pp. 3799-3806 (2025)

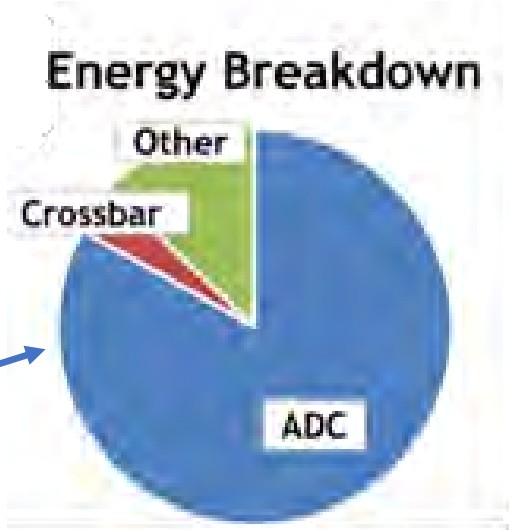
- Box-Muller Transform to convert to normal distribution
- Diffusion model to generate high quality images

Application Example 2: stochastic Analog to Digital Converter

Large, Energy-Inefficient ADCs in Analog In-Memory Crossbars



70%~80% in energy, area

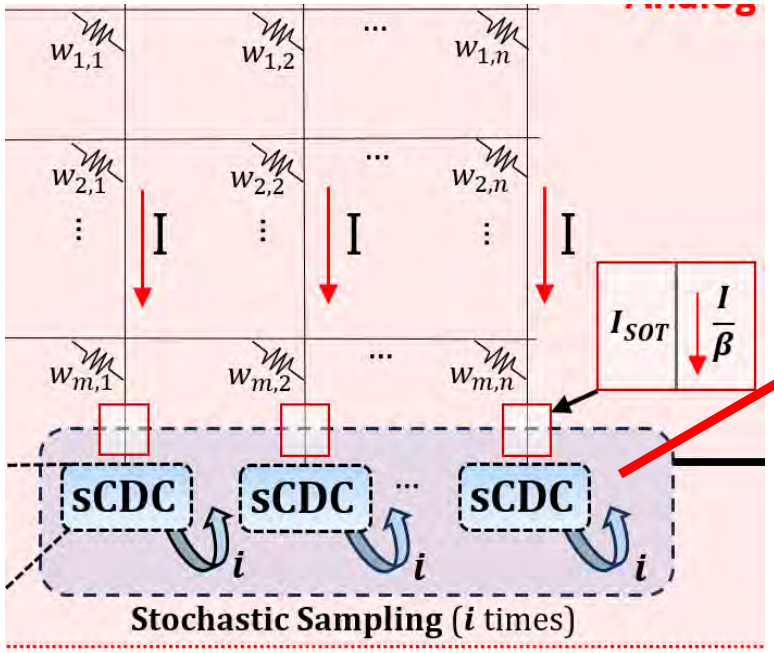


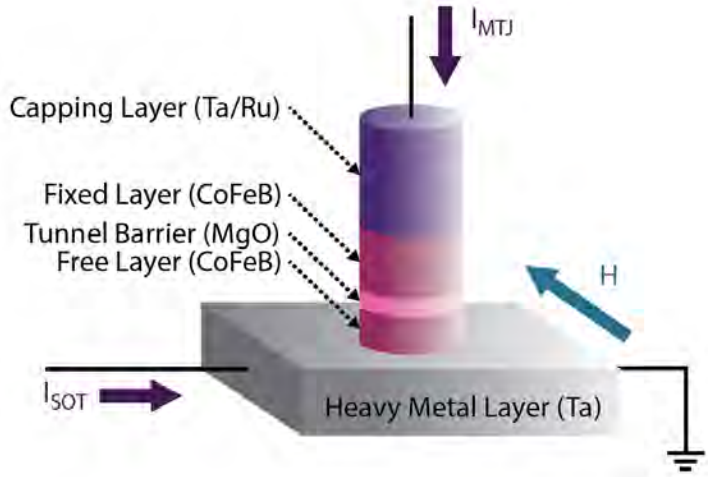
Rogers, E. G. *et al.*, ArXiv: 2407.12378 (2024)
Andrulis, T. *et al.*, ISCA 2023.

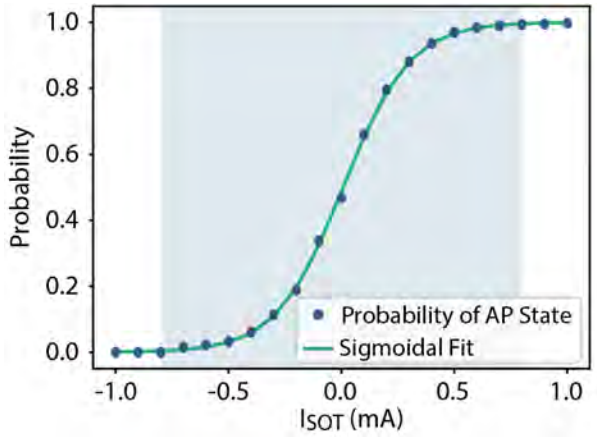
- Very expansive ADC to convert analog currents to digital voltages
- Mitigate strategies include time-multiplexing of ADCs and using low-bit-precision ADCs

Stochastic MTJ as ADC-Replacements in Crossbars

One step conversion from accumulated current to output voltage



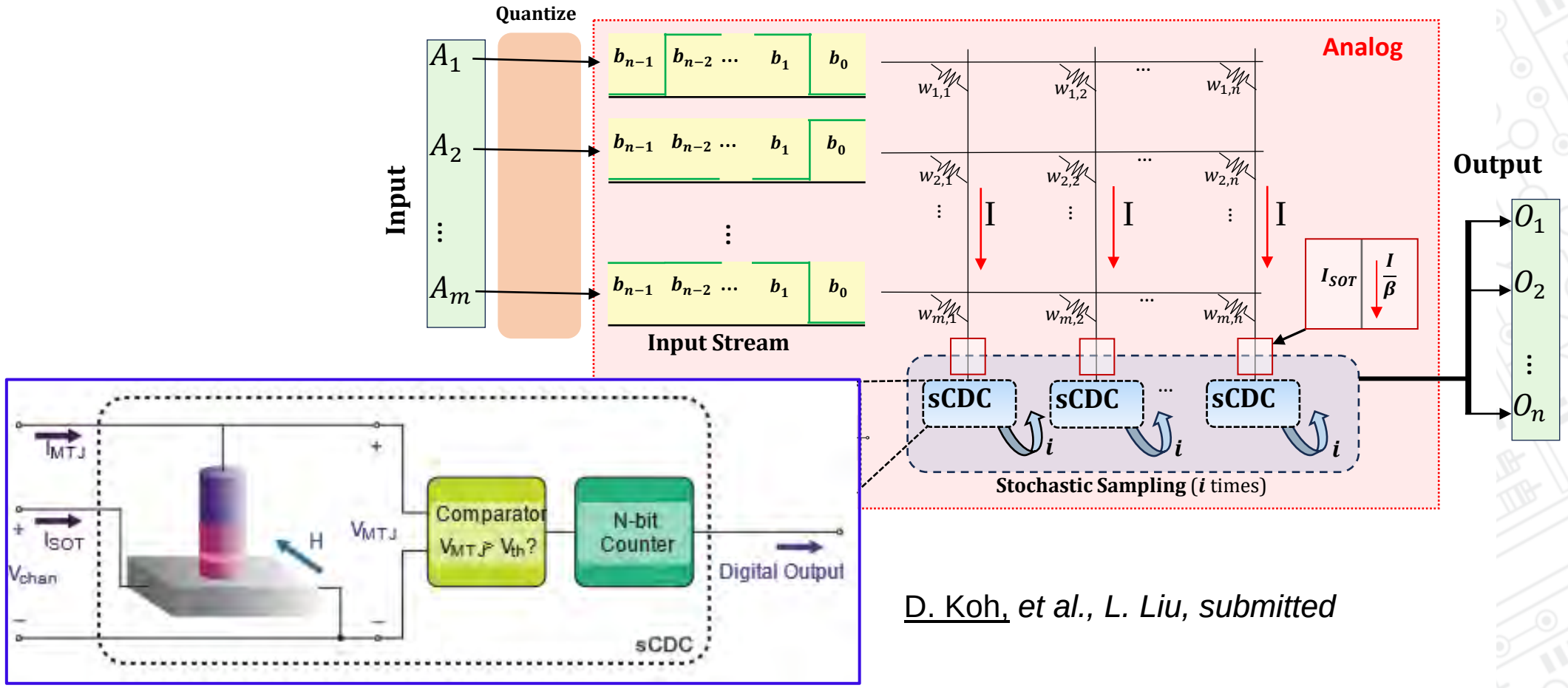




- sCDC: stochastic current to digital voltage converter
- The accumulated column current influences the switching probability through spin orbit torque
- Input: accumulated current in each column
- Output: stochastic digital voltages whose average represent the true multiplication value

Stochastic MTJ as ADC-Replacements in Crossbars

Stochastic Current-to-Digital Converters (sCDCs) at the End of Columns in Crossbars

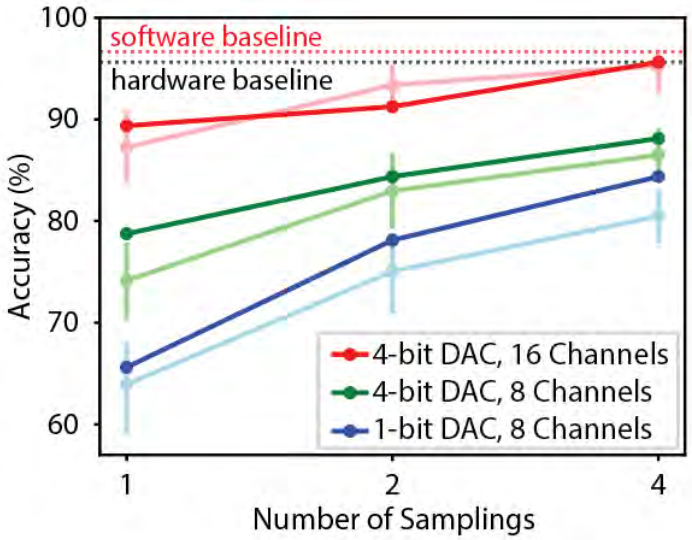


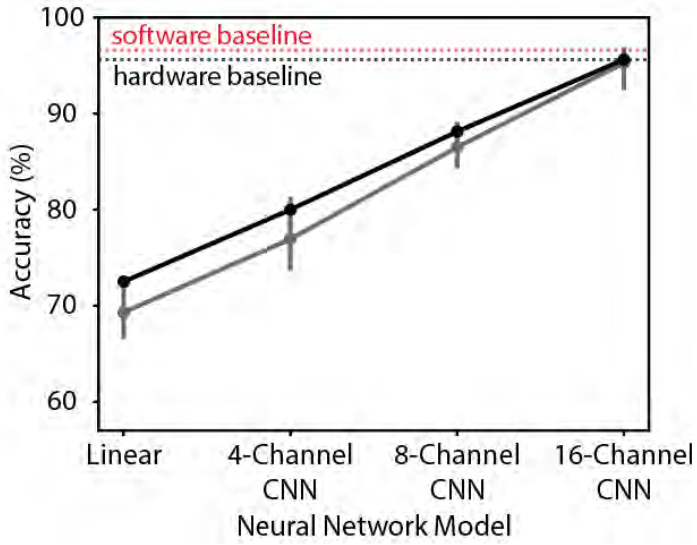
D. Koh, *et al., L. Liu, submitted*

- sCDCs convert output currents from the crossbar to digital signal, which further can be processed by the peripheral digital circuits
- Saves not only standard high precision ADC, but also transimpedance amplifier to convert current to voltage.

Stochastic MTJ as ADC-Replacements in Crossbars

Accuracy Preserved while Area, Energy, and Latency Improved





	ADC-based CDC[c]		sMTJ-based sCDC
	6-bit[a]	2-bit[b]	
Area (μm^2)	911244.6	59244.6	7352.2
Energy (pJ)	12064.0	1388.2	455.2
Latency (ns)	480.0	480.0	335.0

D. Koh, *et al.*, *L. Liu, submitted*

- MNIST dataset trained with 3-layer, binary-weight neural networks
- Achieved 95.63% accuracy with real sMTJ devices (software baseline: 96.63%)
- All of area, energy, and latency improved compared to conventional ADC architecture

Conclusion

- Nanoscale magnetic tunnel junction provides a very economic way to generate random numbers in terms of footprint and energy consumption
- Feedback control mechanism has been introduced to stabilize the probability of 0 and 1 generation, passing NIST test and used for generative AI
- Stochastic MTJ is also useful to replace standard ADC, where accumulated current is converted into stochastic voltage signals.
- Large improvement in energy efficiency, area and latency compared with traditional ADC while maintaining accuracy.