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Computing for a new era

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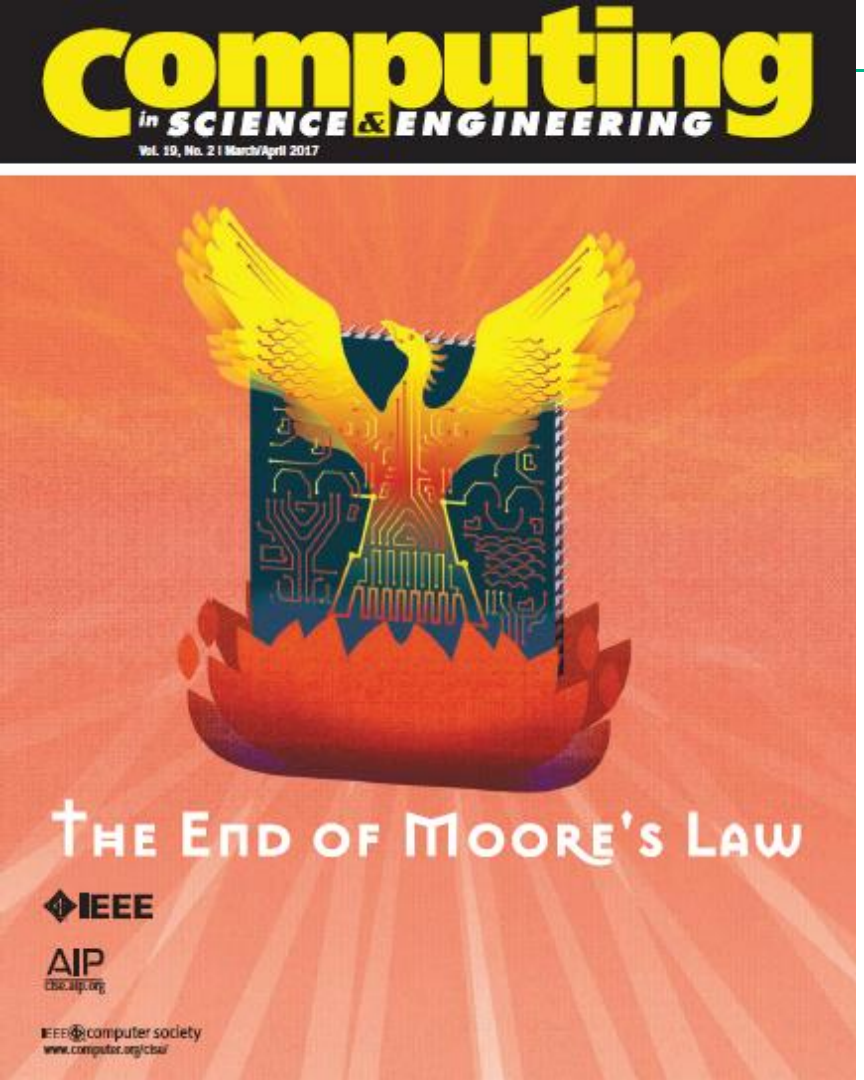
BESAC Meeting **July 13, 2017**



What's Next?

The end of Moore's law could be the best thing that has happened in computing since the beginning of Moore's law.

Future exponential increases in computer performance and efficiency will require multiple advances:

Systems and Architectures

- Memory-centric computing – no von Neumann bottleneck
- Gen-Z – high performance open fabric to democratize computing
  (http://genzconsortium.org/ - ~40 companies so far)
- Dot-product engine: memristor-based vector-matrix multiplication accelerator for neural nets and signal processing
- Chaos as a computing resource for constrained optimization problem solving (Hopfield network)

Devices

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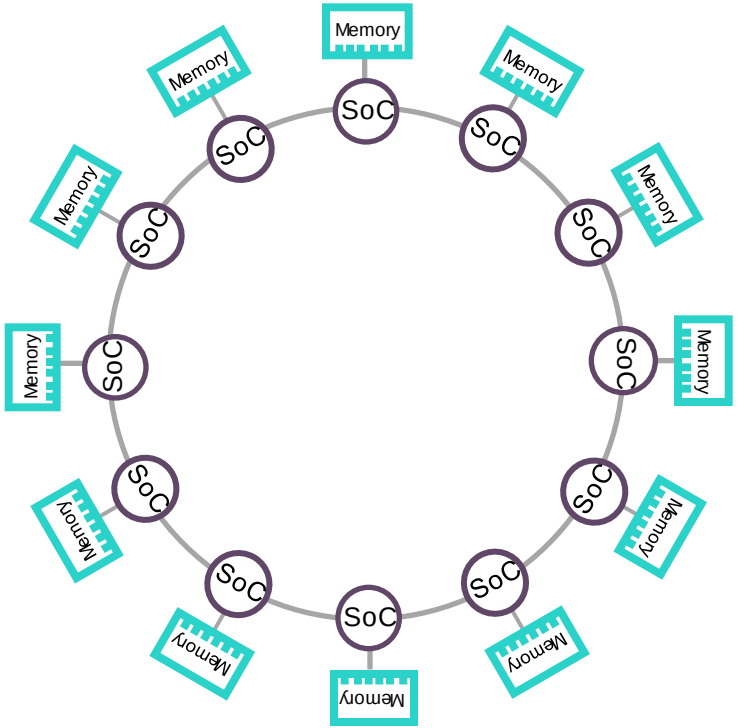
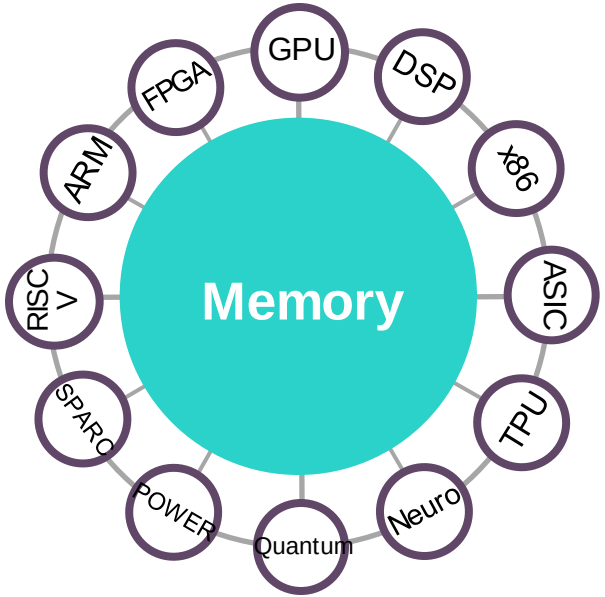


From processor-centric computing…

the traditional von Neumann architecture



…to Memory-Driven Computing

with Gen-Z open (nonproprietary) fabric, computing is plug and play

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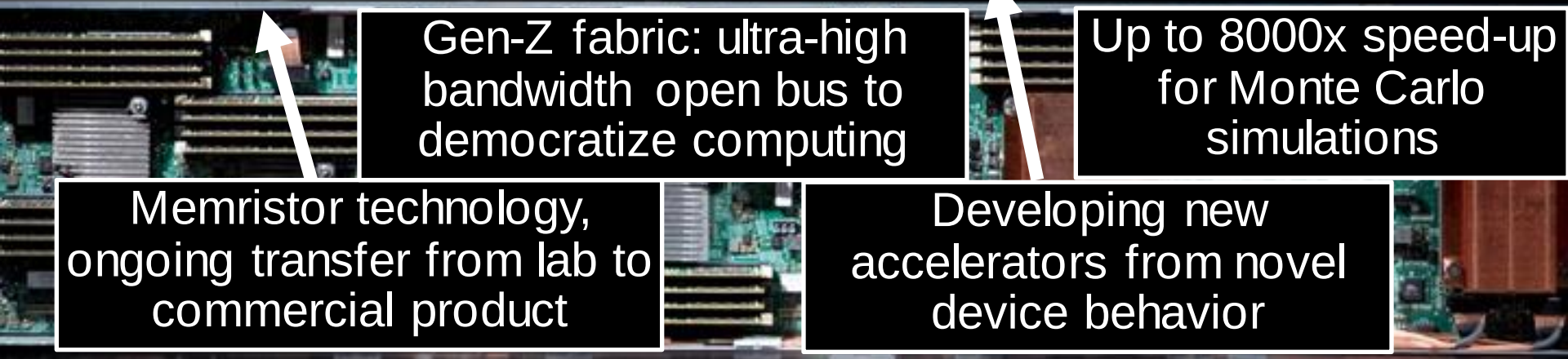
Memory-Driven Computing (MDC) is a reality: The Machine

Fast, persistent memory	Fast memory fabric	Task-specific processing	New and Adapted software
Combining memory and storage in a stable environment to increase processing speed and improve energy efficiency	Using photonics where necessary to eliminate distance and create otherwise impossible topologies	Optimizing processing from general to specific tasks	Radically simplifying programming and enabling new applications that we can't even begin to build today



Gen-Z fabric: ultra-high bandwidth open bus to democratize computing

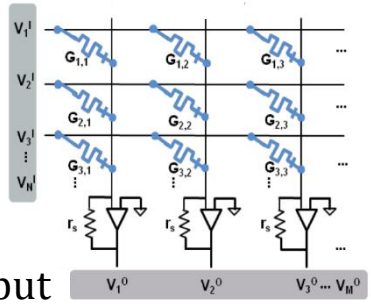
Up to 8000x speed-up for Monte Carlo simulations

Memristor technology, ongoing transfer from lab to commercial product

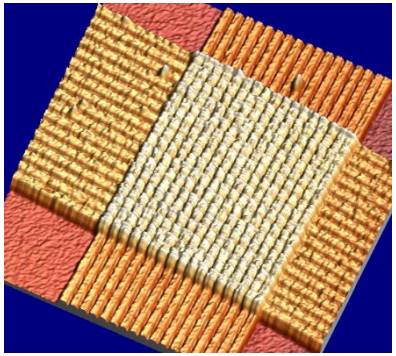
Developing new accelerators from novel device behavior

Dot Product Engine: memristor arrays accelerate vector-matrix multiplication

Input Voltage vector



Output current $I_j^O = \sum_i G_{ij} \cdot V_i^I$



- **Parallel multiply & add through Kirchoff's and Ohm's laws**

  1961, K. Steinbuch "*Die Lernmatrix*" – suggests using "ferromagnetic toroids"

- **Memristors as highly scalable, tunable analog resistors**

  High ON/OFF ratio (~10^5), supporting multiple levels

- **Well suited for streaming workloads like neural nets**

- **Many ways to scale up**

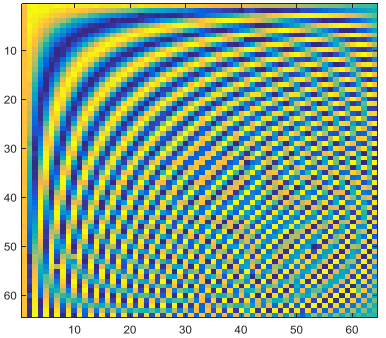
  Memristor levels, array size, wire pitch, 3D layer, DAC/ADC speed & width etc.

- **Performance (execution time) improvements >1000x and**

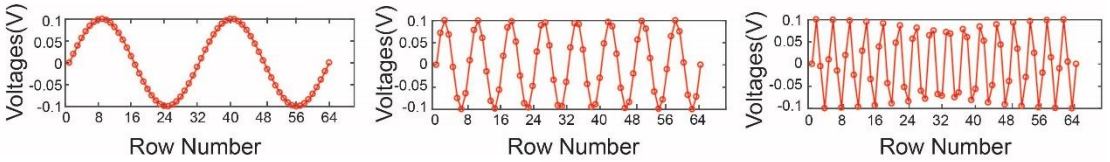
  energy efficiency >100x over GPUs for <u>particular applications</u>

Experimental Demo - Signal processing on DPE system

(UMass collaboration) – instantaneous cosine transform

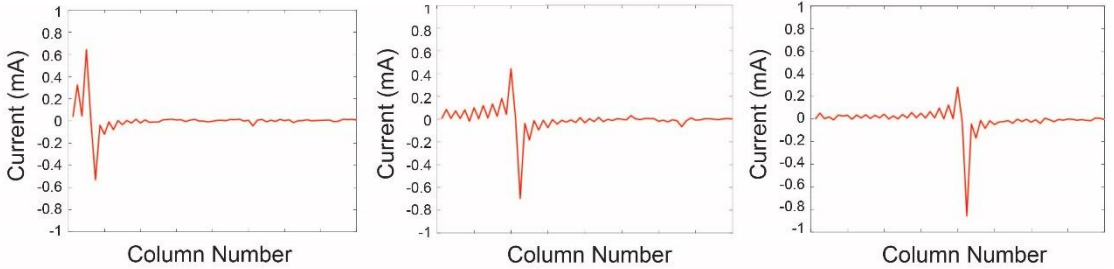


Time-domain inputs (applied to rows)

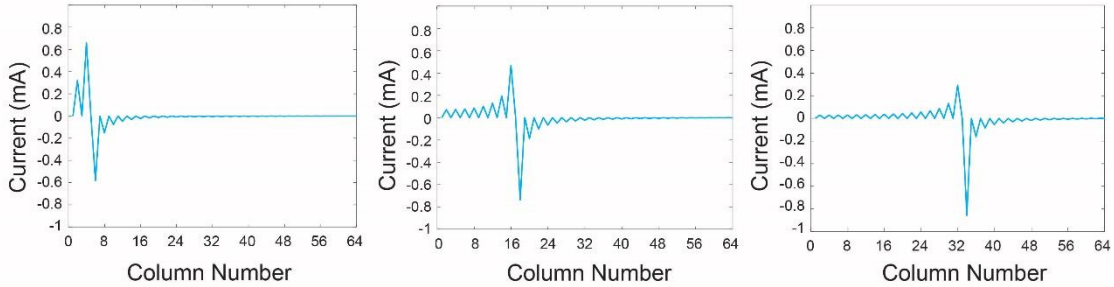


Freq-domain (DCT) outputs (read from columns)

Real-time experimental data from DPE

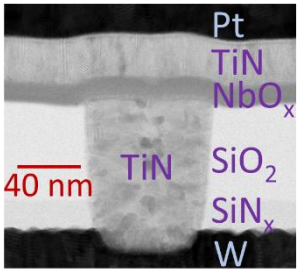


Software cosine transform



C. Li, et. al, *manuscipt under review*

NbO_2 memristor: computing with nonlinear dynamics and chaos



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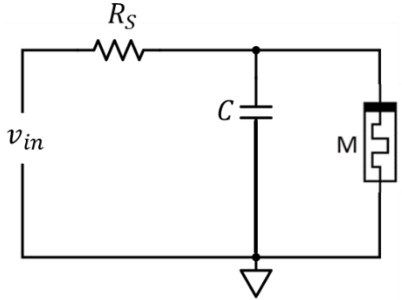
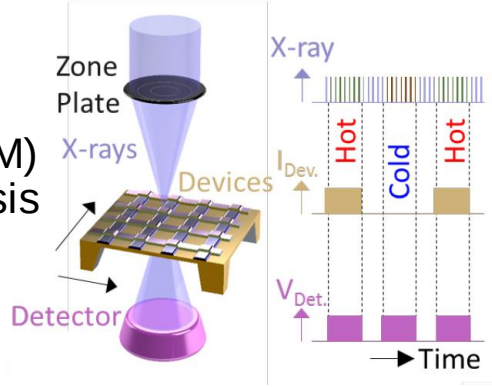
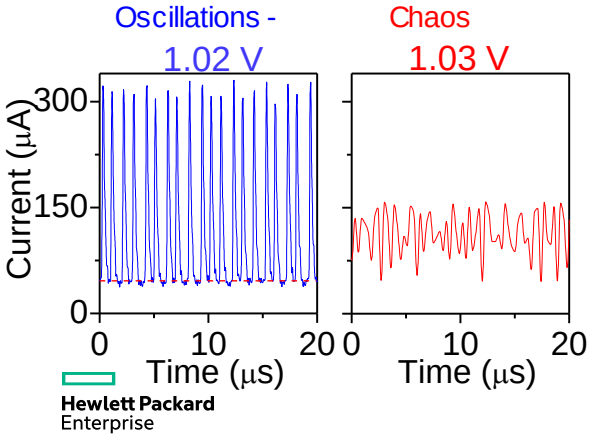
nanoscale oscillator



in situ and *in operando* scanning transmission x-ray microscopy (STXM) at ALS critical for analysis of memristor operation



Dynamical Behavior:



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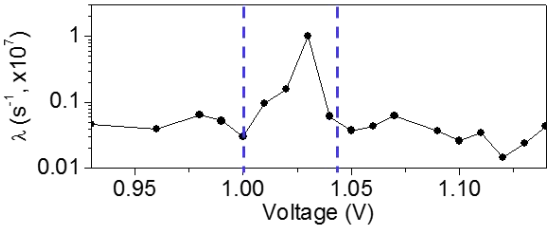
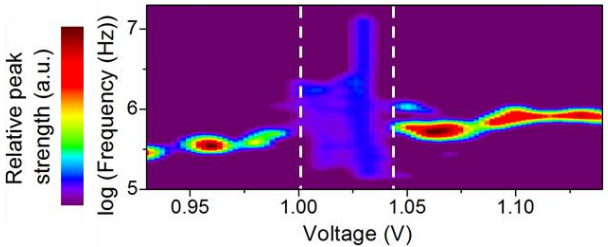
Lyapunov exponent

$$\lambda = \lim_{t\to\infty} \lim_{\delta \mathbf{Z}_0 \to 0} \frac{1}{t} \ln \frac{|\delta \mathbf{Z}(t)|}{|\delta \mathbf{Z}_0|}$$



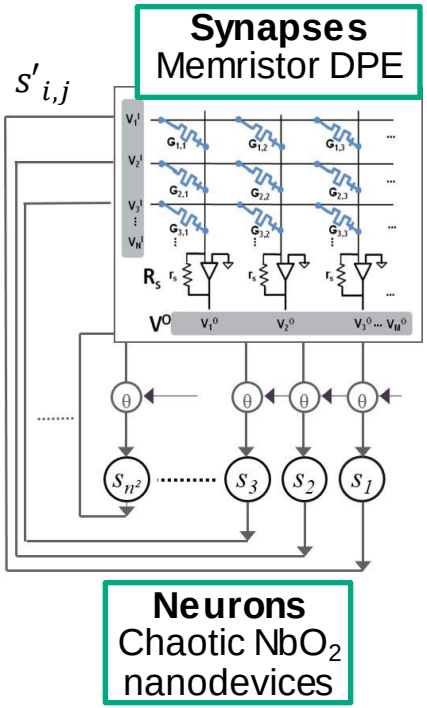
Frequency analysis



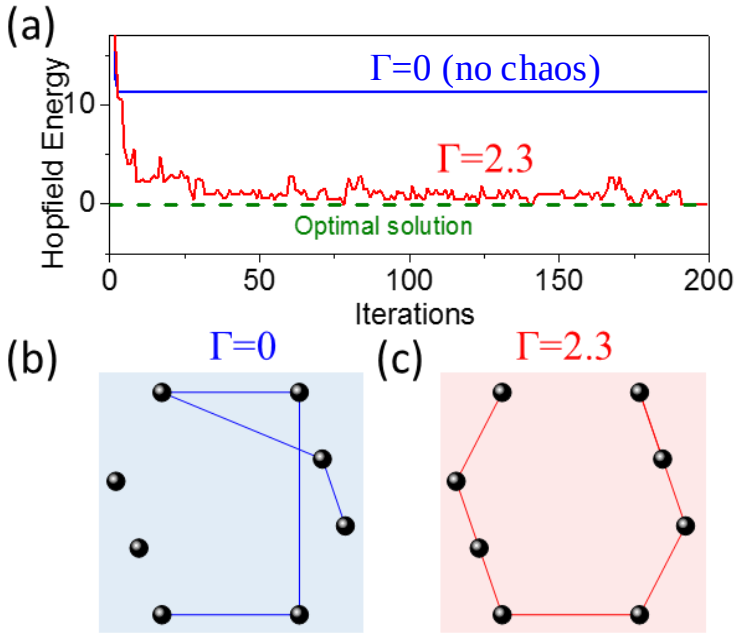
Chaos enabled Hopfield network for optimization problems

Traveling Salesman problem:

Find shortest route visiting all cities



Example solutions w/ and w/o chaos



S Kumar, et al. Nature, in press

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To study the very small, we had to use the very large

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