Energy-efficient neuromorphic computing with magnetic tunnel junctions

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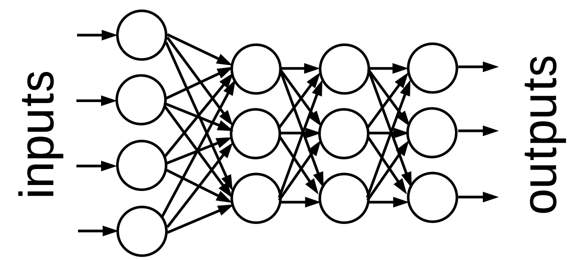
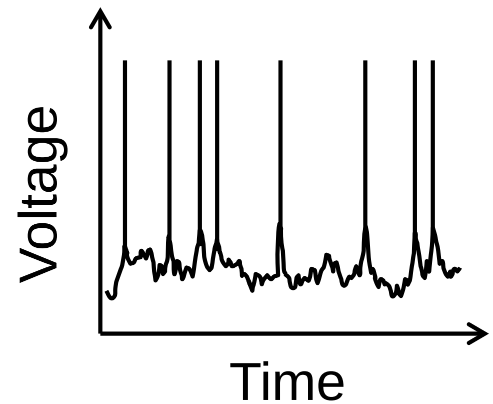
WHAT: Brain-inspired computing for cognitive tasks

- Neural networks.
  - Already in heavy commercial application.
  - Quasi-static.



- **Dynamic processing.**
  - **Make use of dynamical properties of devices.**

  → **Spikes, rates, oscillations, timing, …**



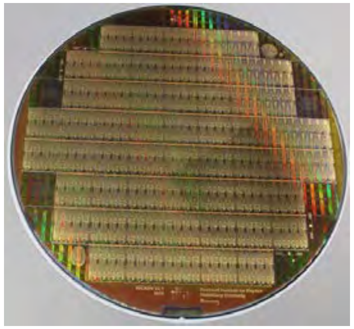
- Simulate brain function

Sophisticated CMOS-based neuromorphic chip development

Loihi (Intel)

TrueNorth (IBM)

BrainScales
(Human Brain Project)



- Brain-like features natural in CMOS
  - local energy source

    → Incoming signal does not power outgoing signal.
  - Connectivity

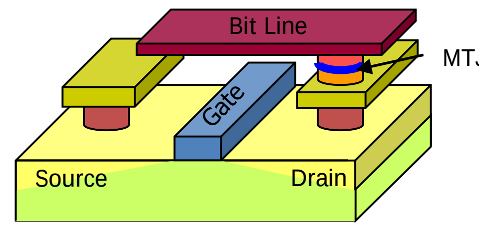
    → Digital spikes – shared communication channels

Energy efficiency and complexity is still far from the brain!

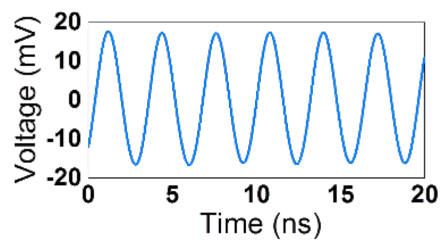
HOW: Augment CMOS with efficient neural devices (MTJs)

- Features for which CMOS may be inefficient (energy and/or device area)
  - Non-volatility
  - Plasticity (local learning)
  - Stochasticity
  - **Oscillators**

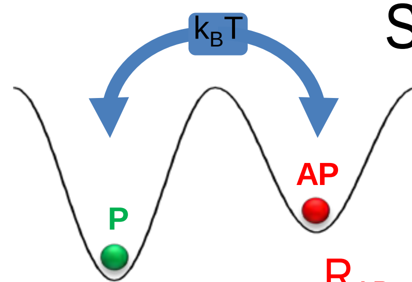
MRAM

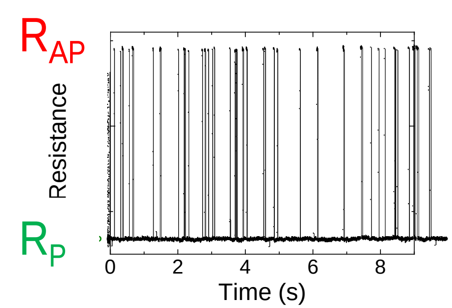


Nano-oscillators



Superparamagnetic tunnel junctions

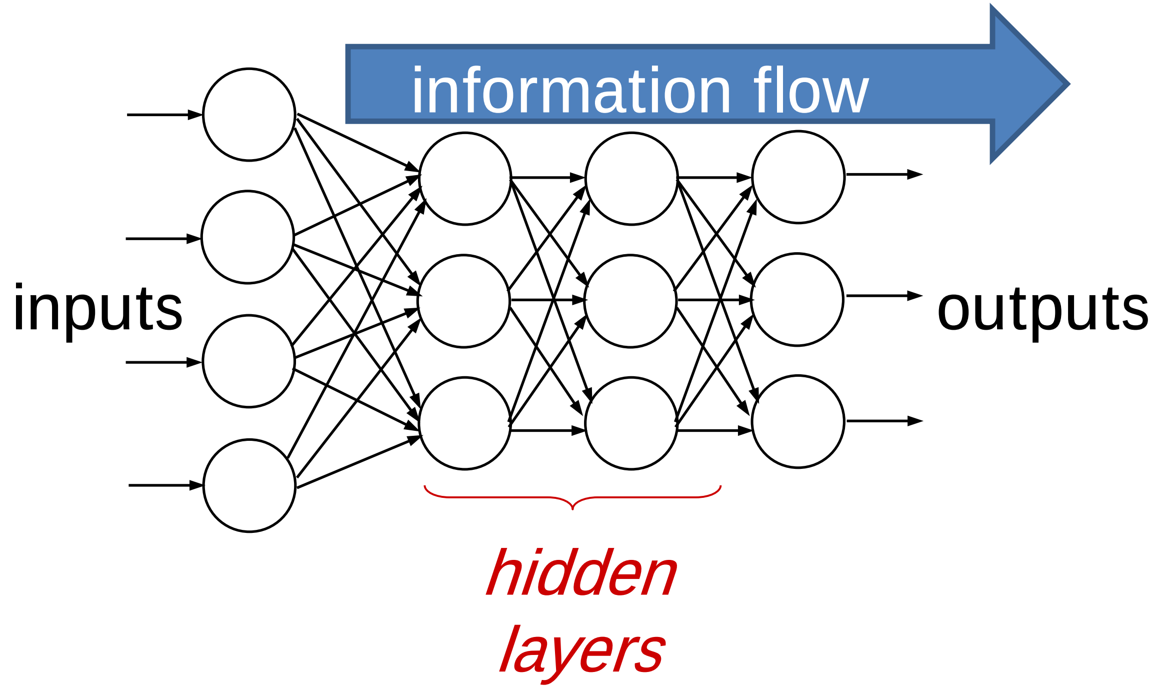




Single oscillator reservoir computing

- **Time multiplexed reservoir computing**
- Sine/Square Identification (Intrinsic memory)
- Spoken digit recognition (Non-linearity)
- Sine/Square Identification (Delayed feedback memory)

Feed-forward networks – one direction of information flow



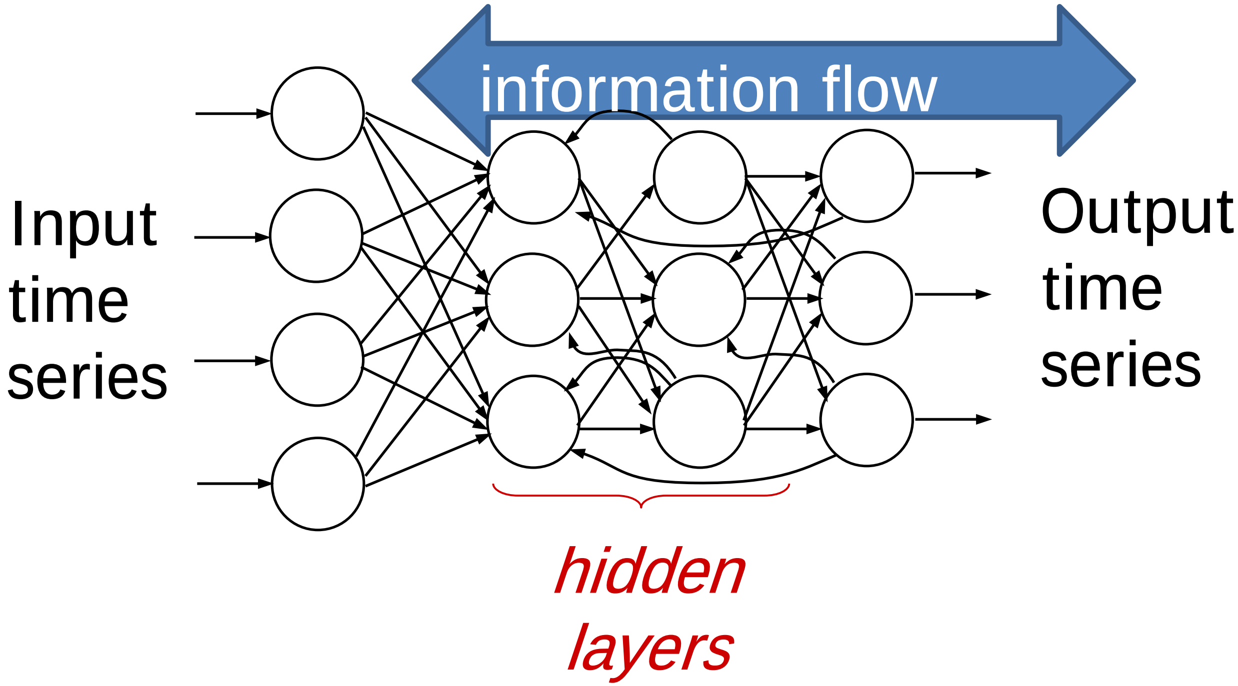
Non-linear nodes (neurons)

rearranges spaces to allow classification

Train off-line

adjust synaptic weights to optimize fit to test data

Recurrent networks – have intrinsic time scales

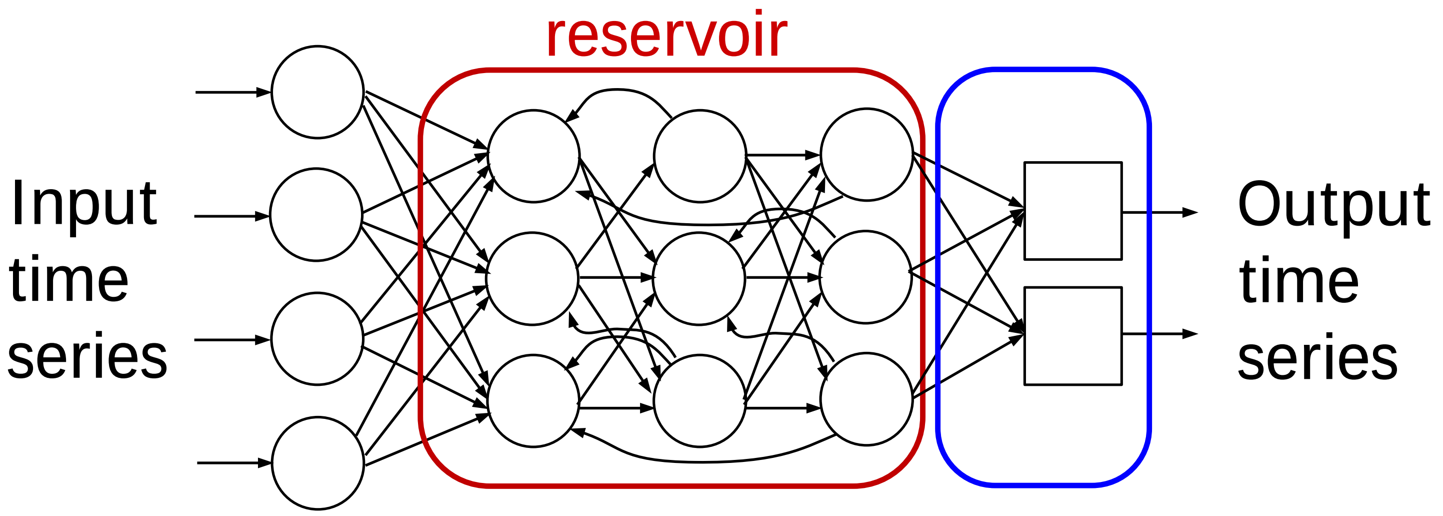


Output time dependent

input becomes time series

Training protocol not simple

Reservoir computing – a simply trainable recurrent network



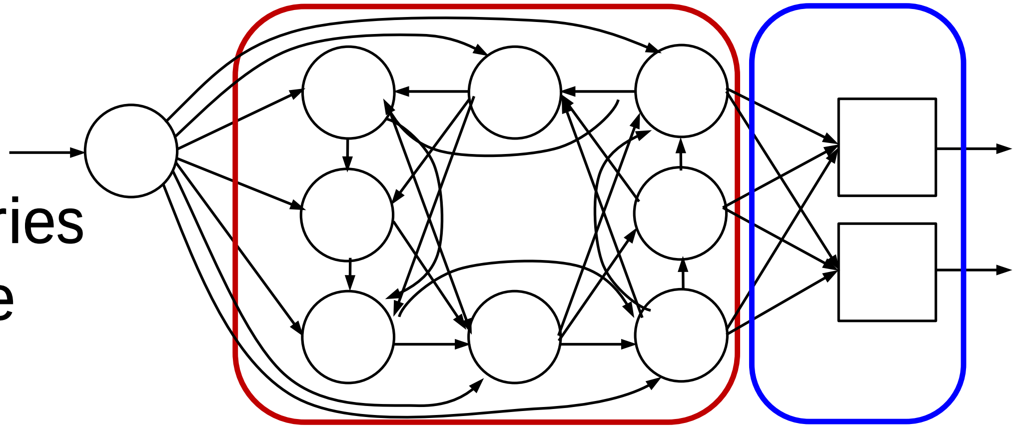
Non-linear,
Fixed synaptic
weights

Linear,
Trained synaptic
weights

Reservoir computing – ring geometry

reservoir

Input time series
to each device

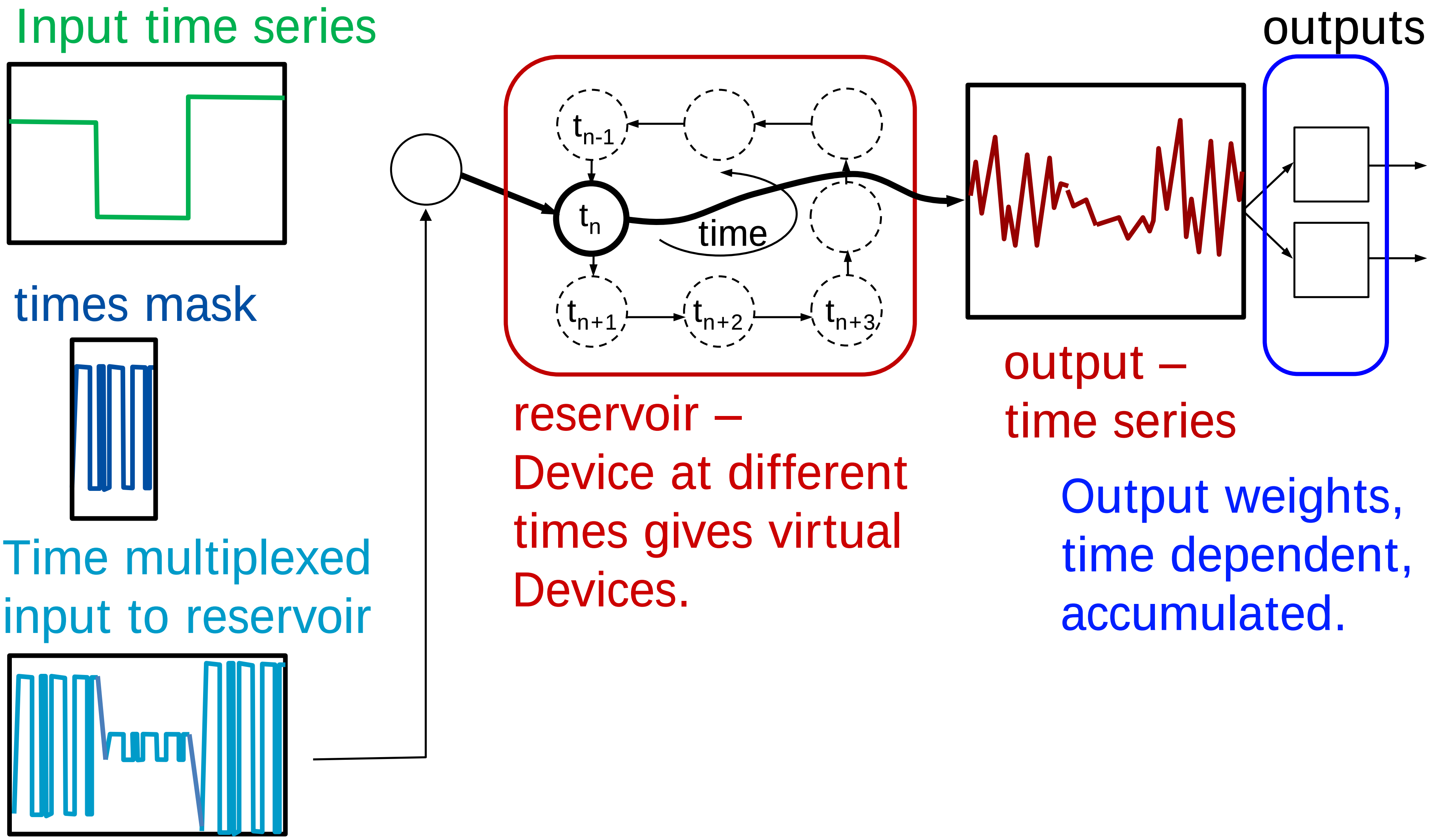


Output
time
series

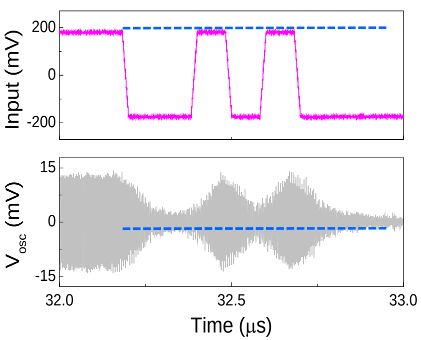
Non-linear,
Fixed synaptic
weights

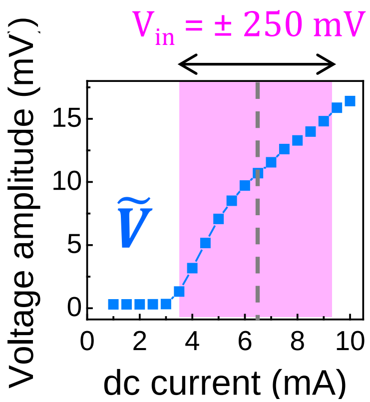
Linear,
Synaptic weights
trained off-line

Reservoir computing – time multiplexed single device



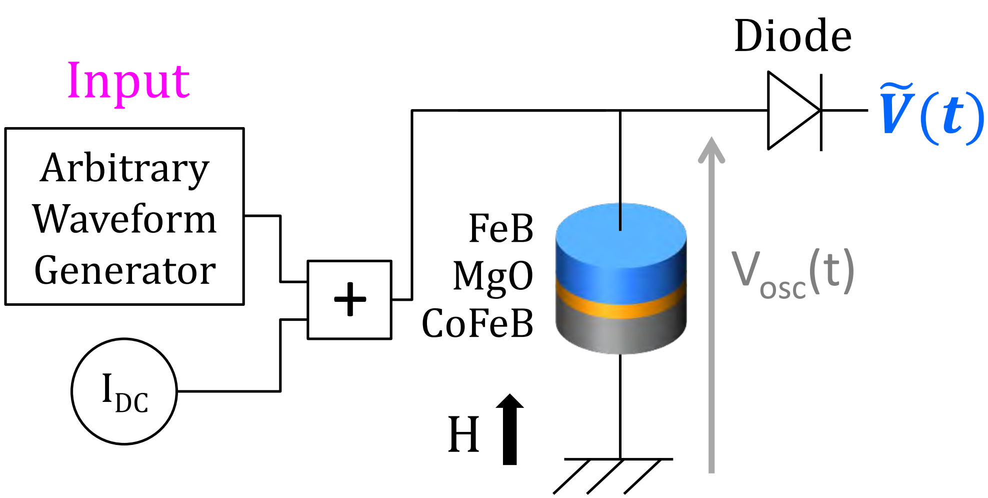
Spin-torque nano-oscillators: non-linear amplitude dynamics and memory

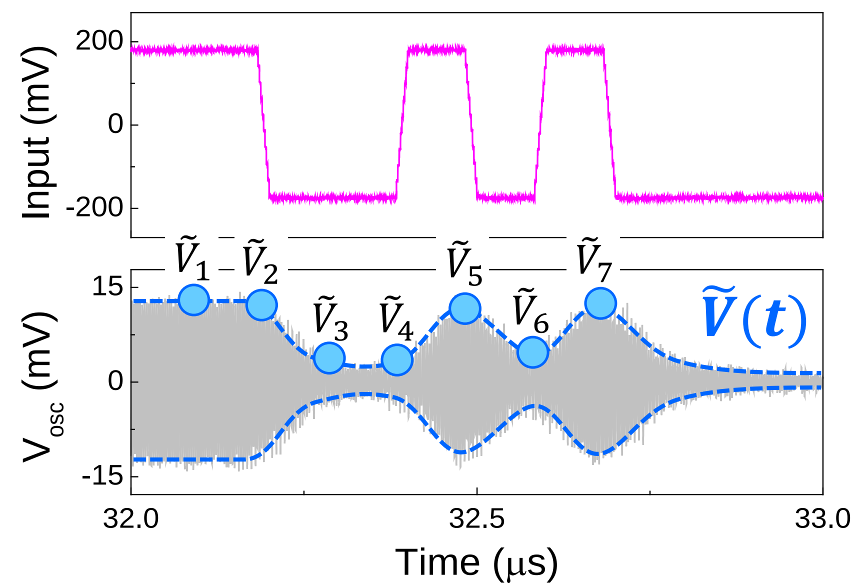




Torrejon *et al*., Nature 547, 428 (2017).

Input: current
Output: amplitude of the oscillator’s voltage





Single oscillator reservoir computing

- Time multiplexed reservoir computing
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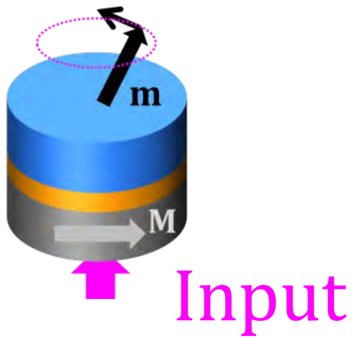
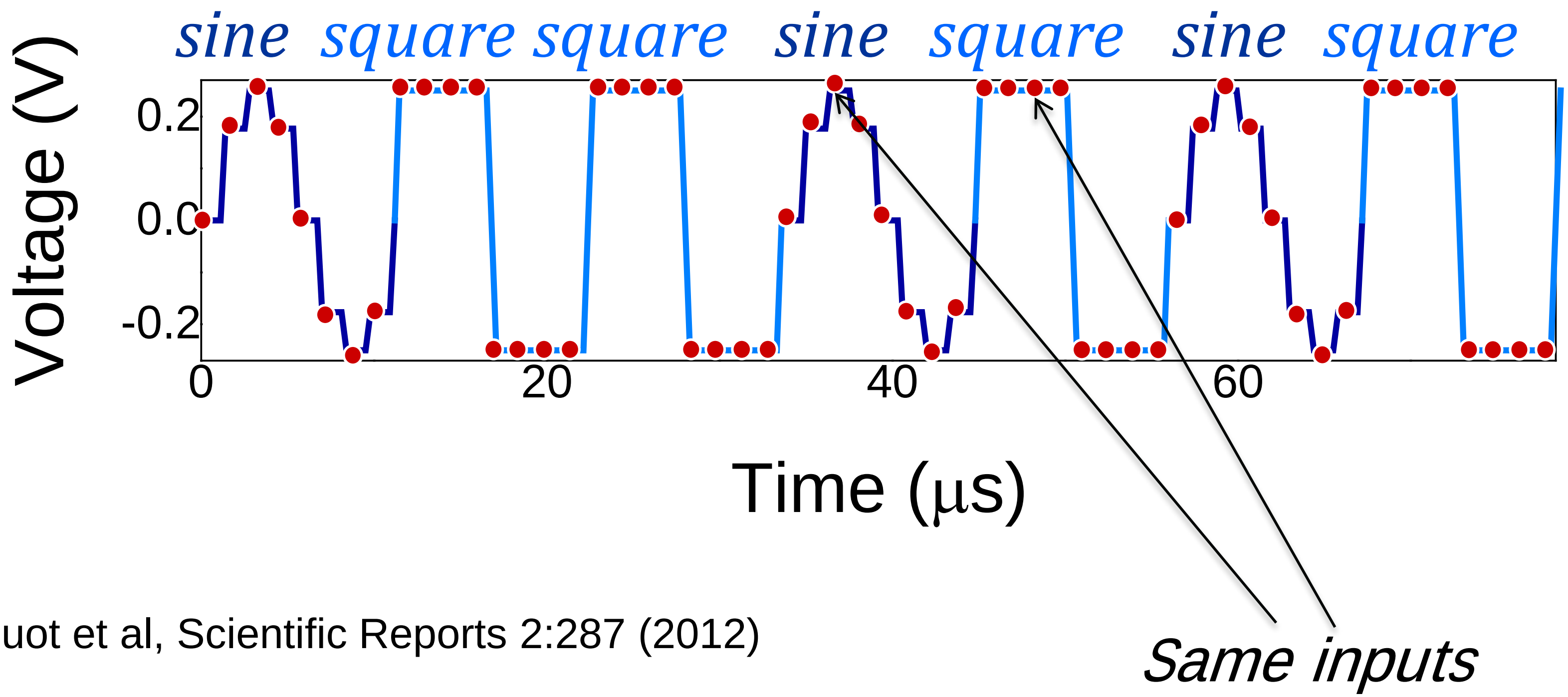
- Sine/Square Identification (Delayed feedback memory)

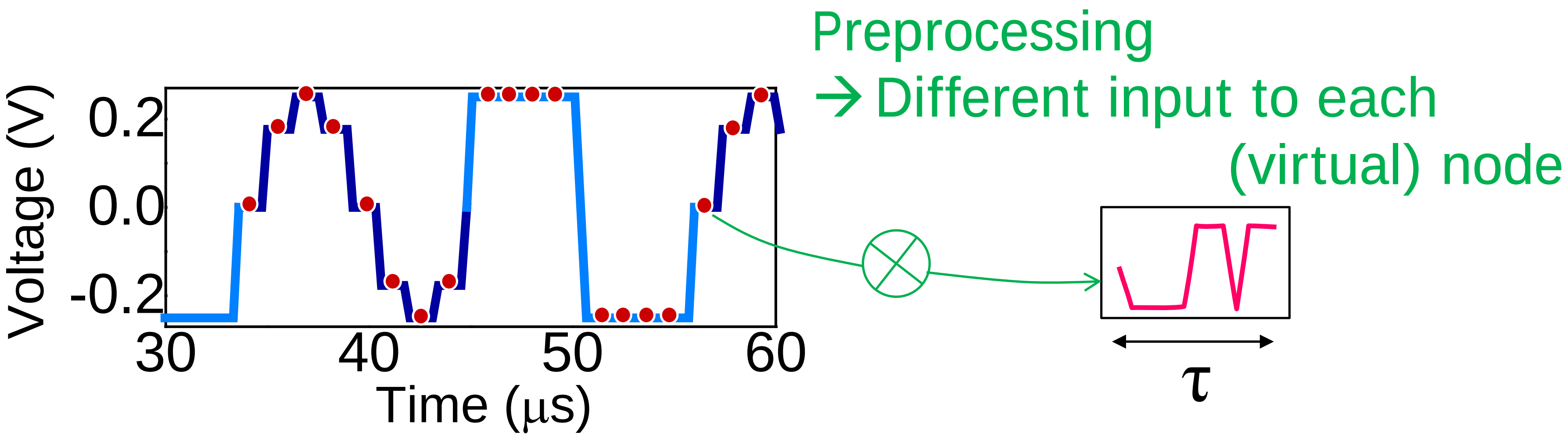
Task: recognizing sines from squares at each point in time with a single oscillator

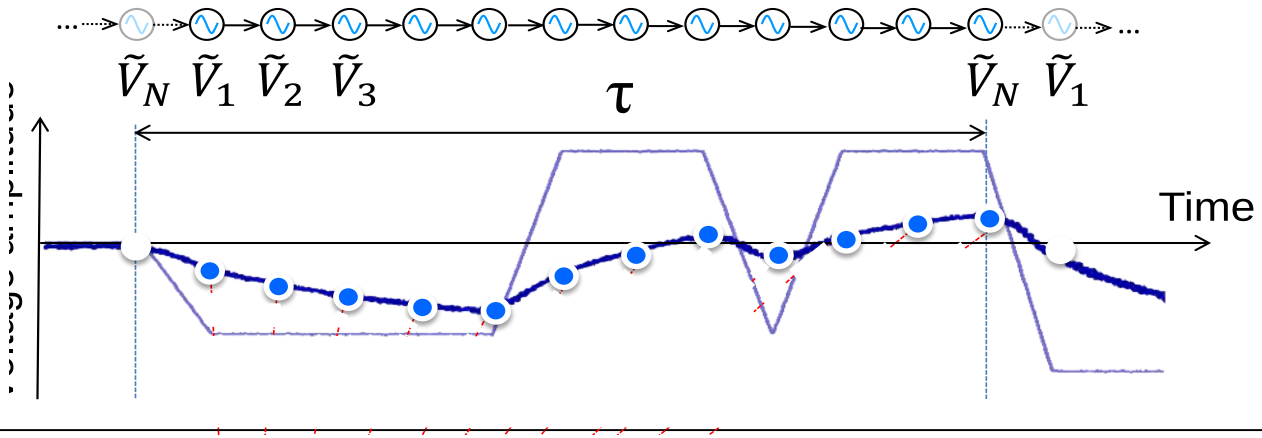




Paquot et al, Scientific Reports 2:287 (2012)

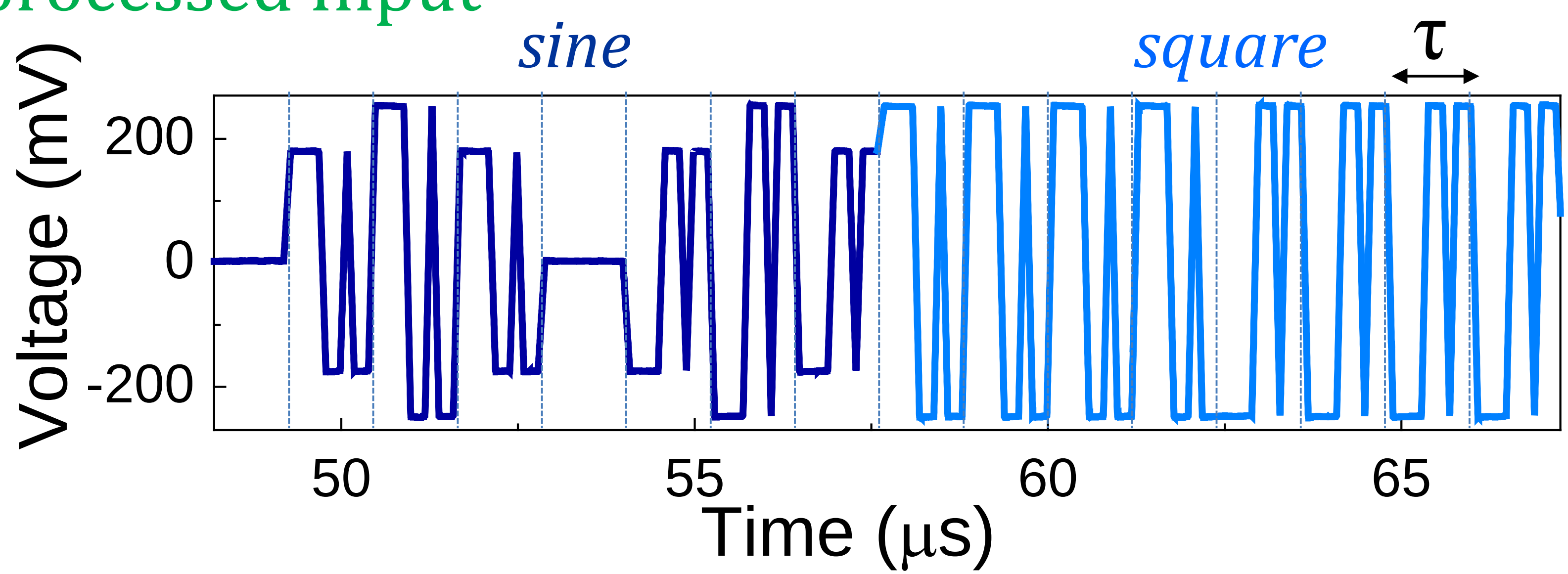
For extrinsic memory, each node should couple to a few other nodes.



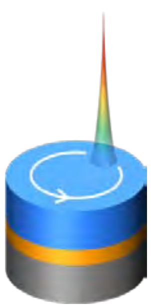


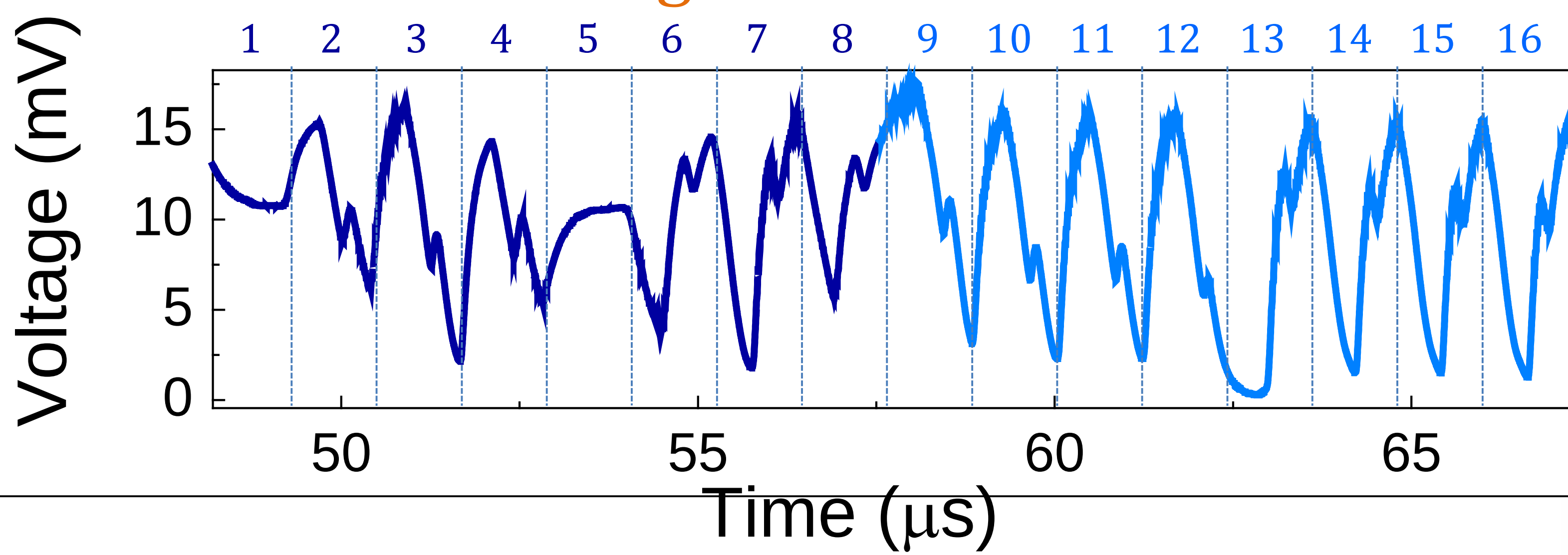
Experimental trajectories of oscillators' amplitude

Preprocessed Input



Oscillator's emitted voltage $\tilde{V}(t)$





Experimental trajectories of oscillators' amplitude

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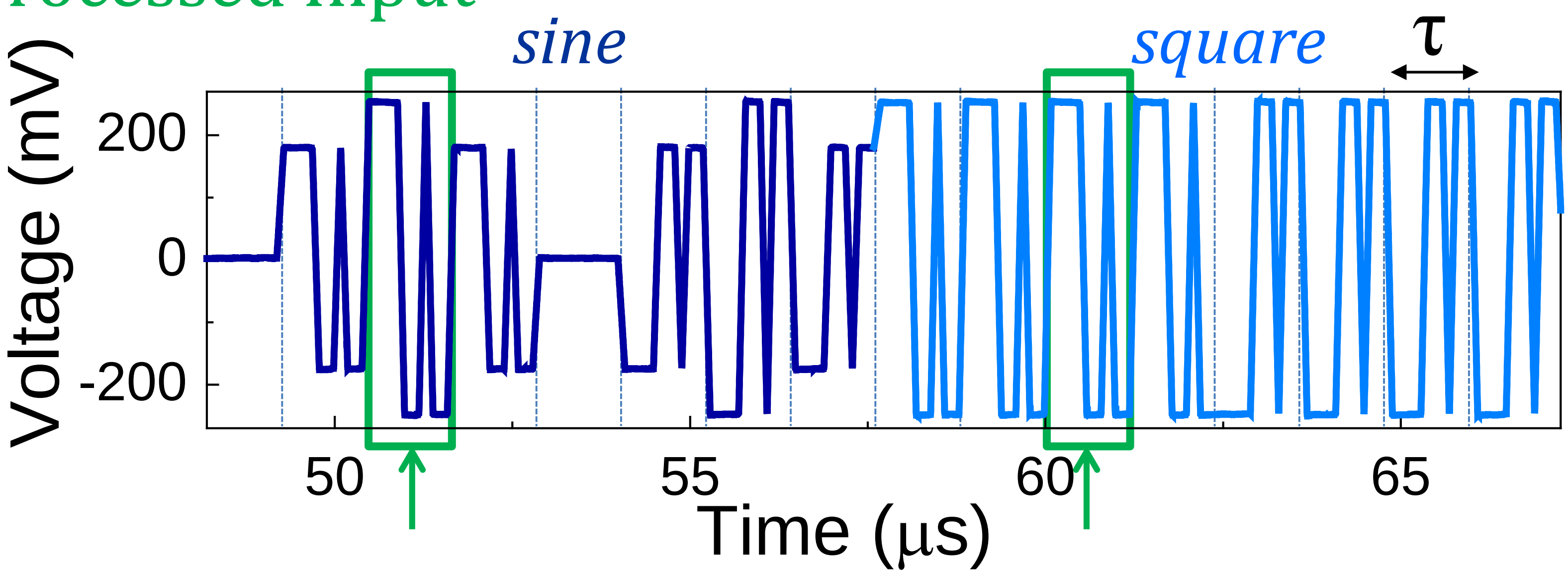

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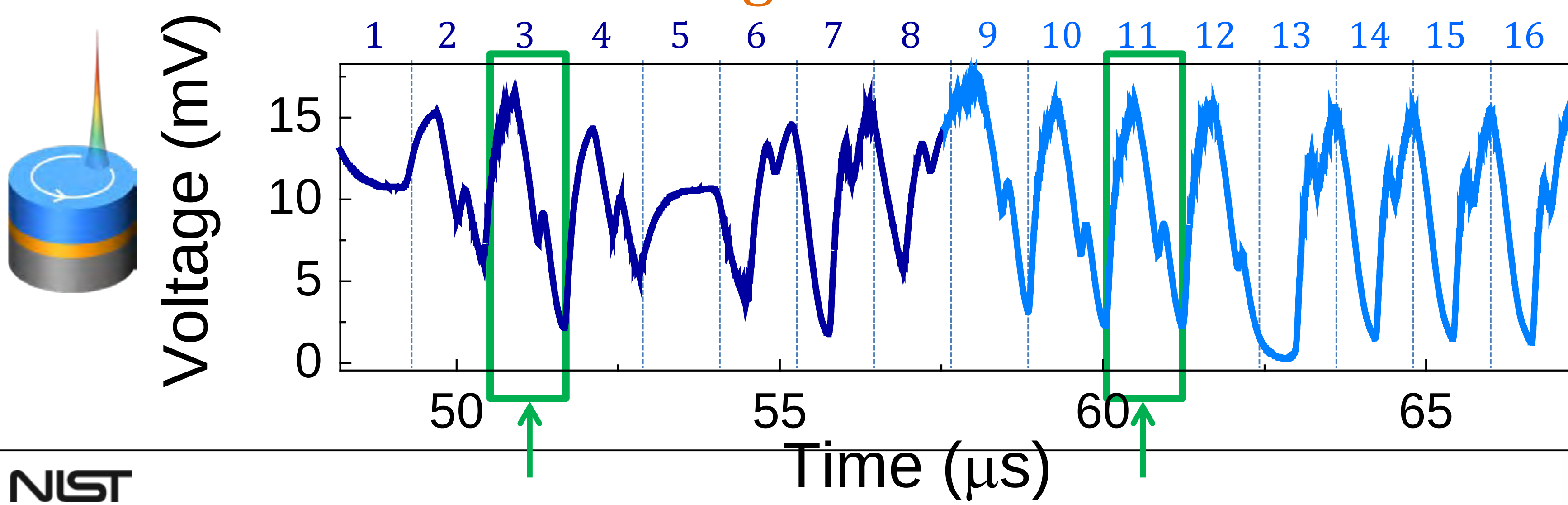
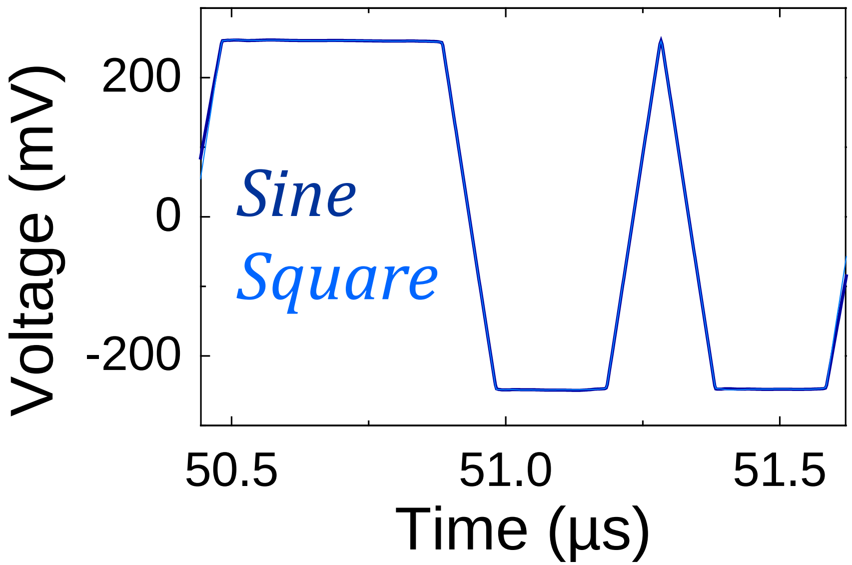
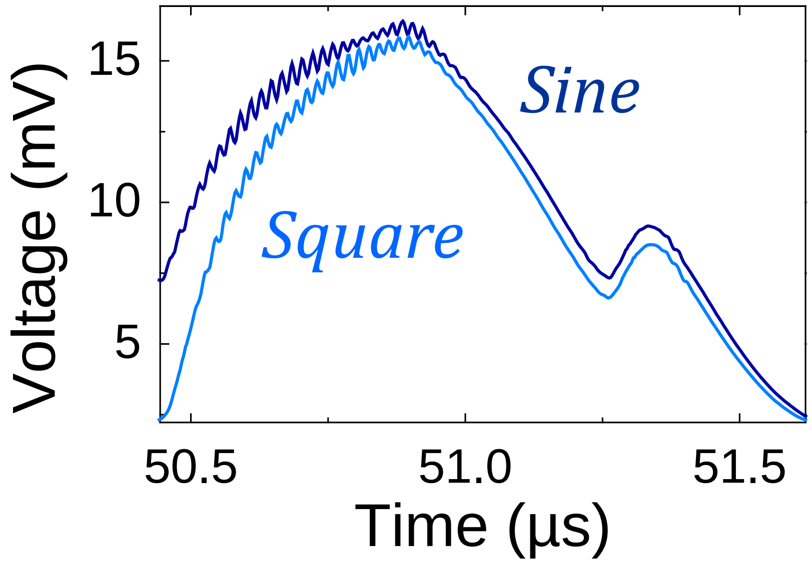


Different trajectories: data separation is achieved

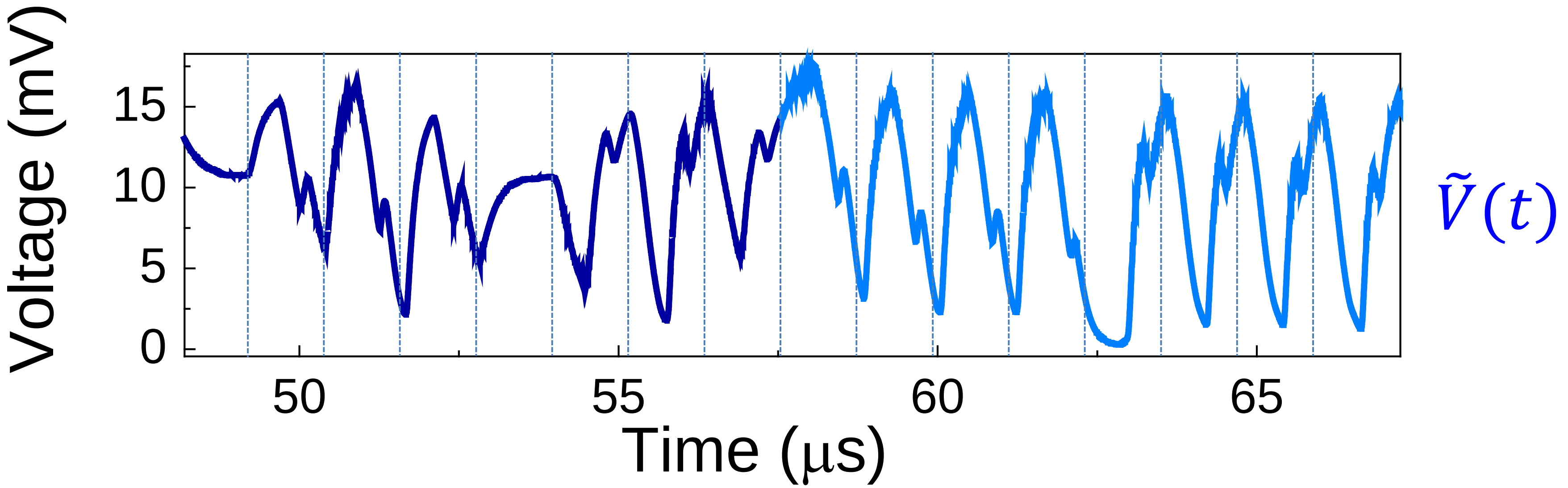
Same input for sine and square

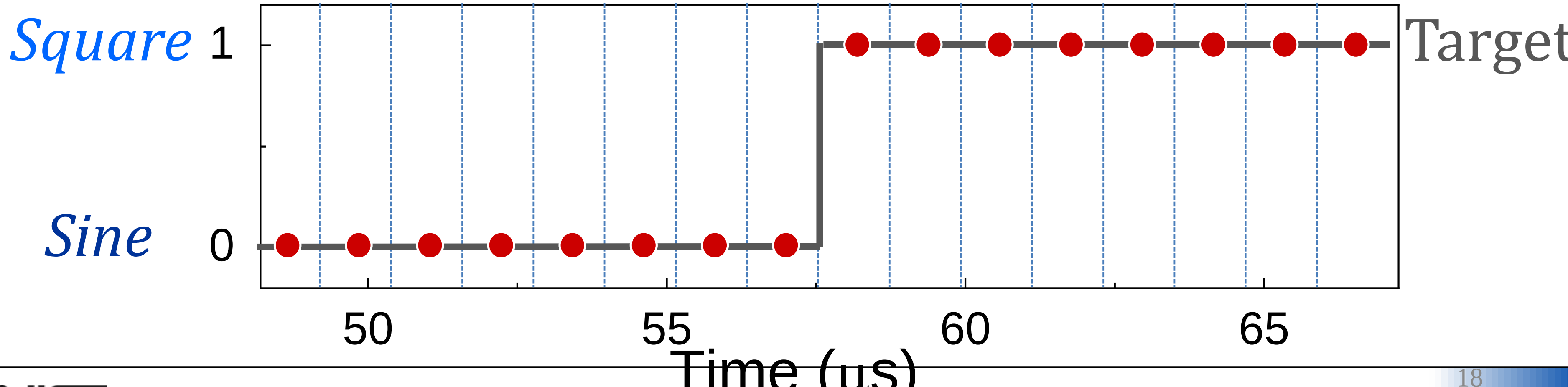


Different outputs $\tilde{V}(t)$



Trajectories need to be grouped to be classified in sines and squares





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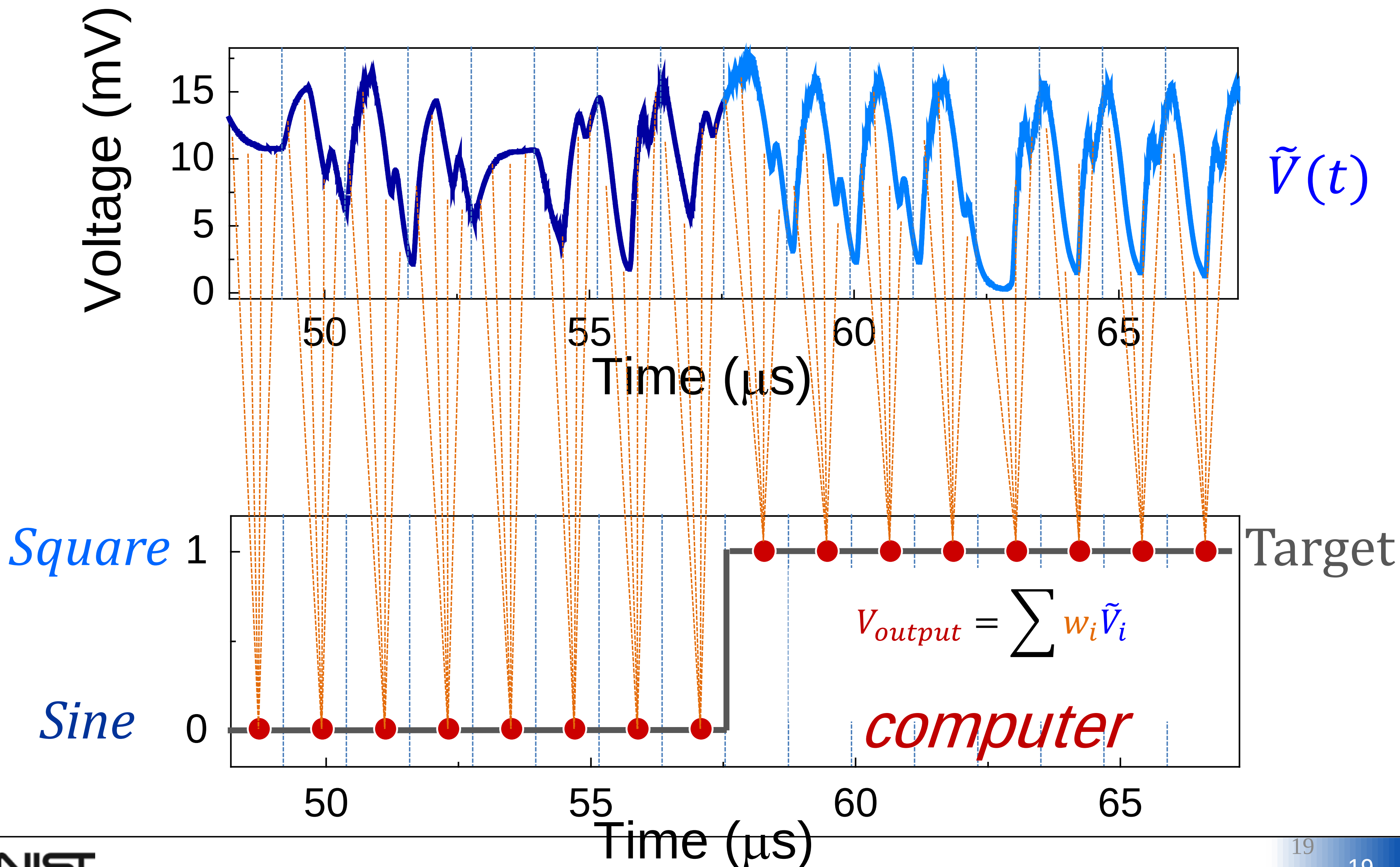
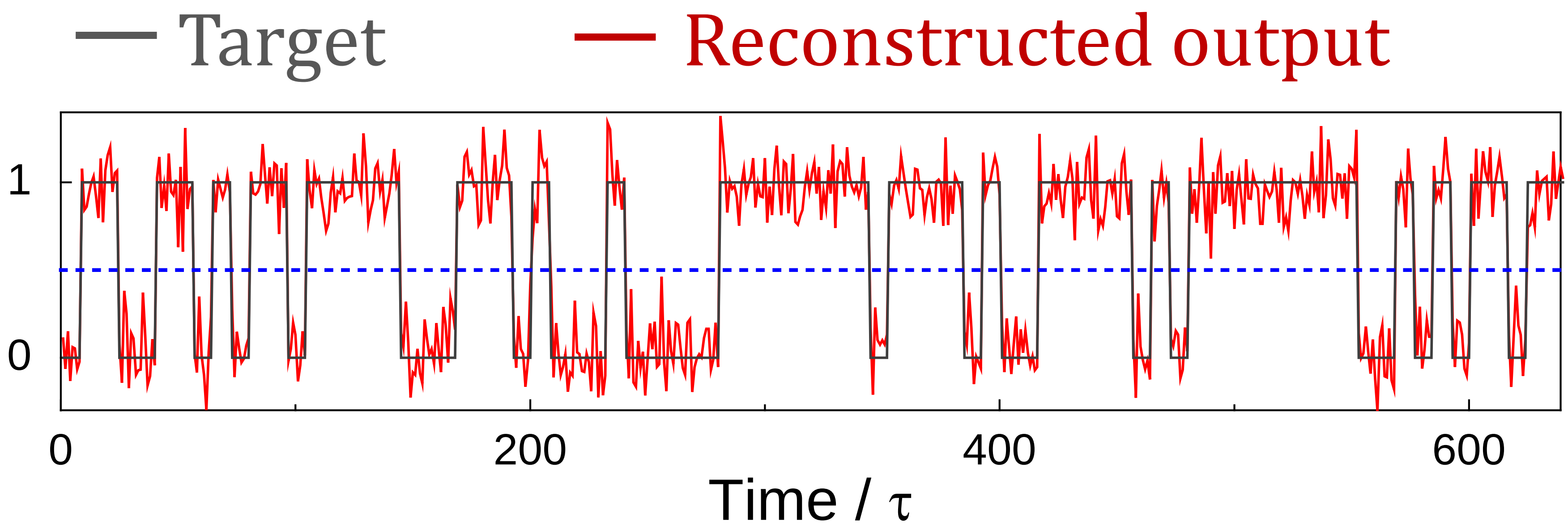
Classification: constructing the output
0 for sine, 1 for square



Experimental result : RMS = 10%
perfect classification of sines and squares

waveform with 80 randomly arranged sines and squares



H = 3800 Oe, I_{DC} = 6.4 mA
8 τ per period, 24 nodes, θ = 100 ns
640 first τ for training, 640 next τ for classification

Single oscillator reservoir computing

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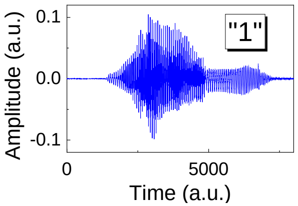
- **Spoken digit recognition (Non-linearity)**
- Sine/Square Identification (Delayed feedback memory)

Spoken digit recognition (NIST TI-46 corpus)

Oscillator

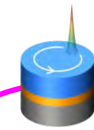
Input: audio file

Output



Spectrogram or Cochlear

Pre-processed input



Recorded trace

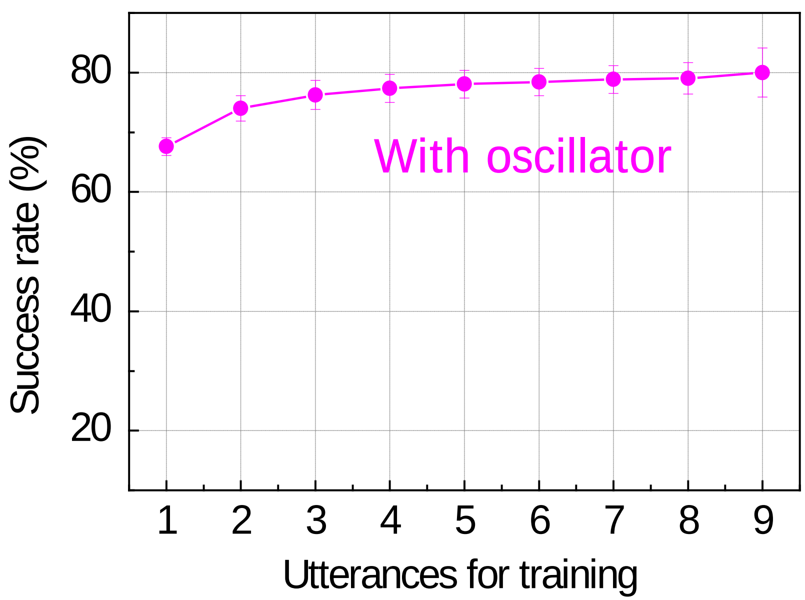
"1"

Acoustic features

Pre-processing

Computer

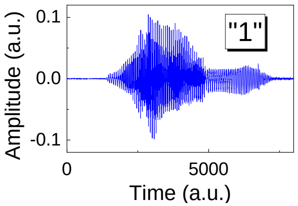
Spectrogram



Spoken digit recognition (NIST TI-46 corpus)

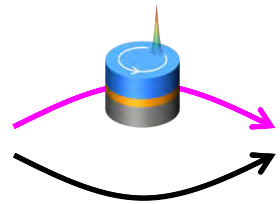
Oscillator

Input: audio file



Spectrogram or Cochlear

Pre-processed input



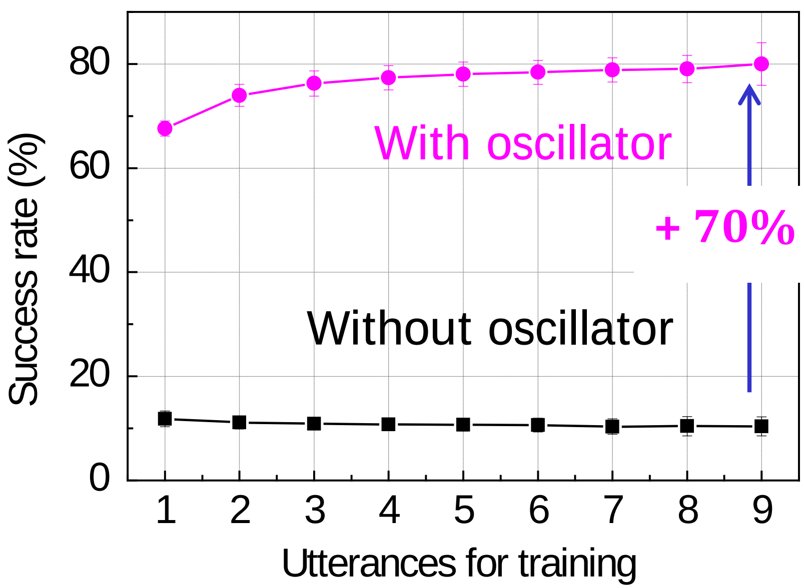
Recorded trace

Output

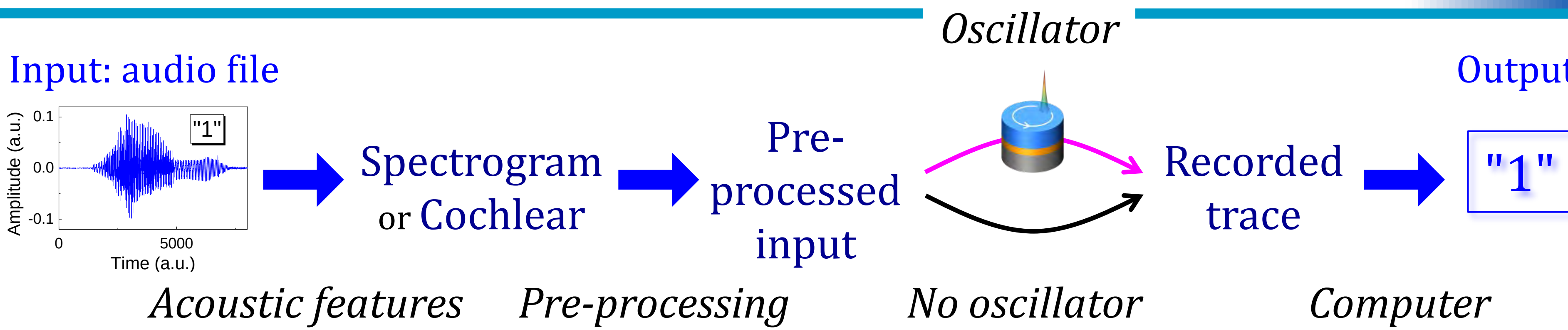
"1"

Acoustic features *Pre-processing* *No oscillator* *Computer*

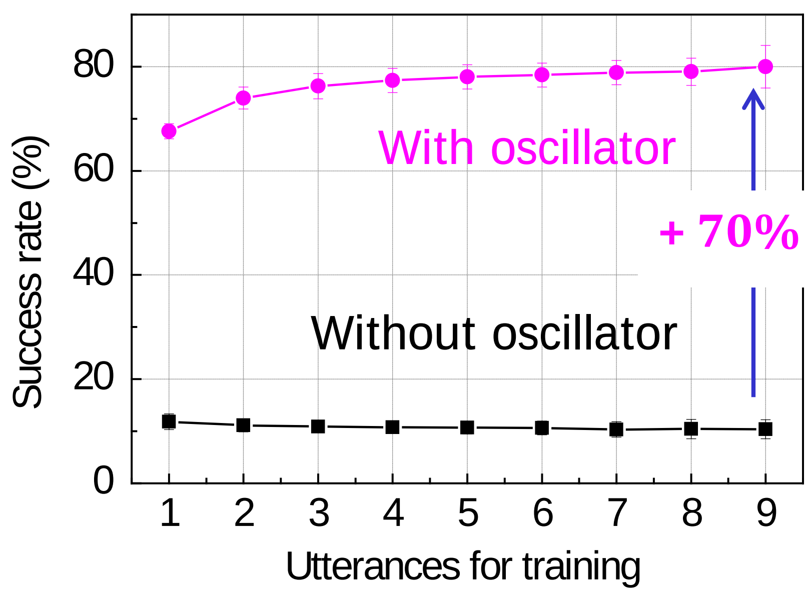
Spectrogram



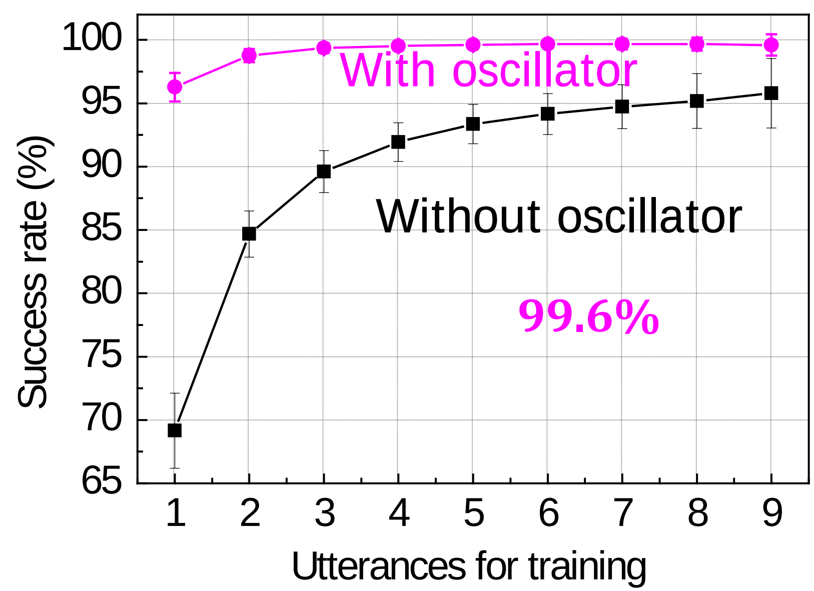
Spoken digit recognition (NIST TI-46 corpus)



Spectrogram



Cochlear

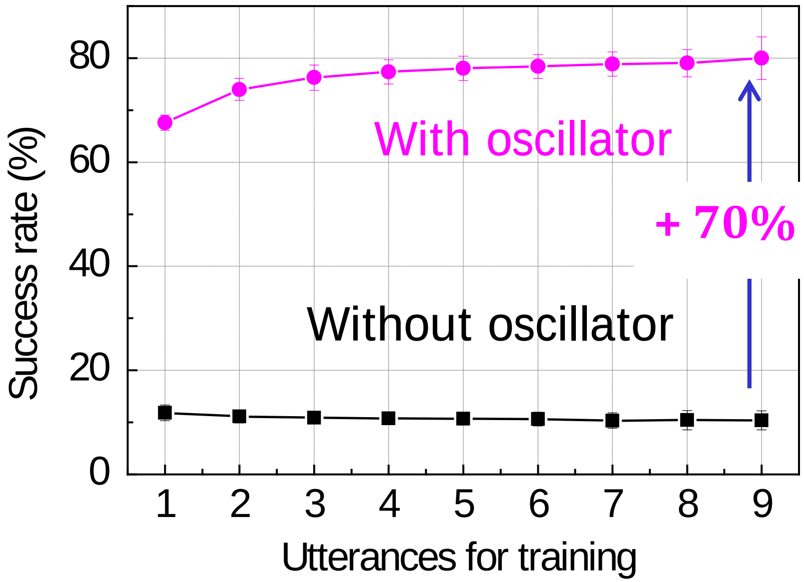


Spoken digit recognition (NIST TI-46 corpus)

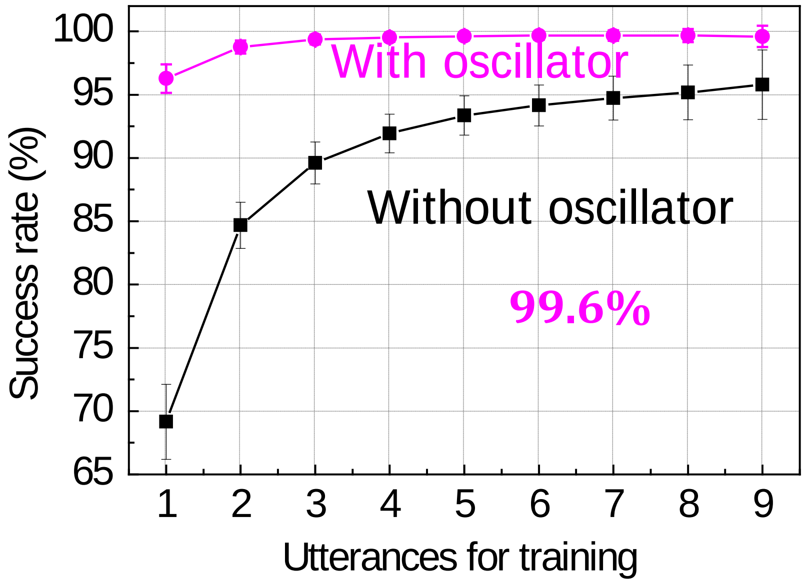
Jacob Torrejon-Diaz, Mathieu Riou, Flavio Abreu-Araujo, et al, Nature 547, 428-431 (2017)

State of the art: 96 to 99.8 %

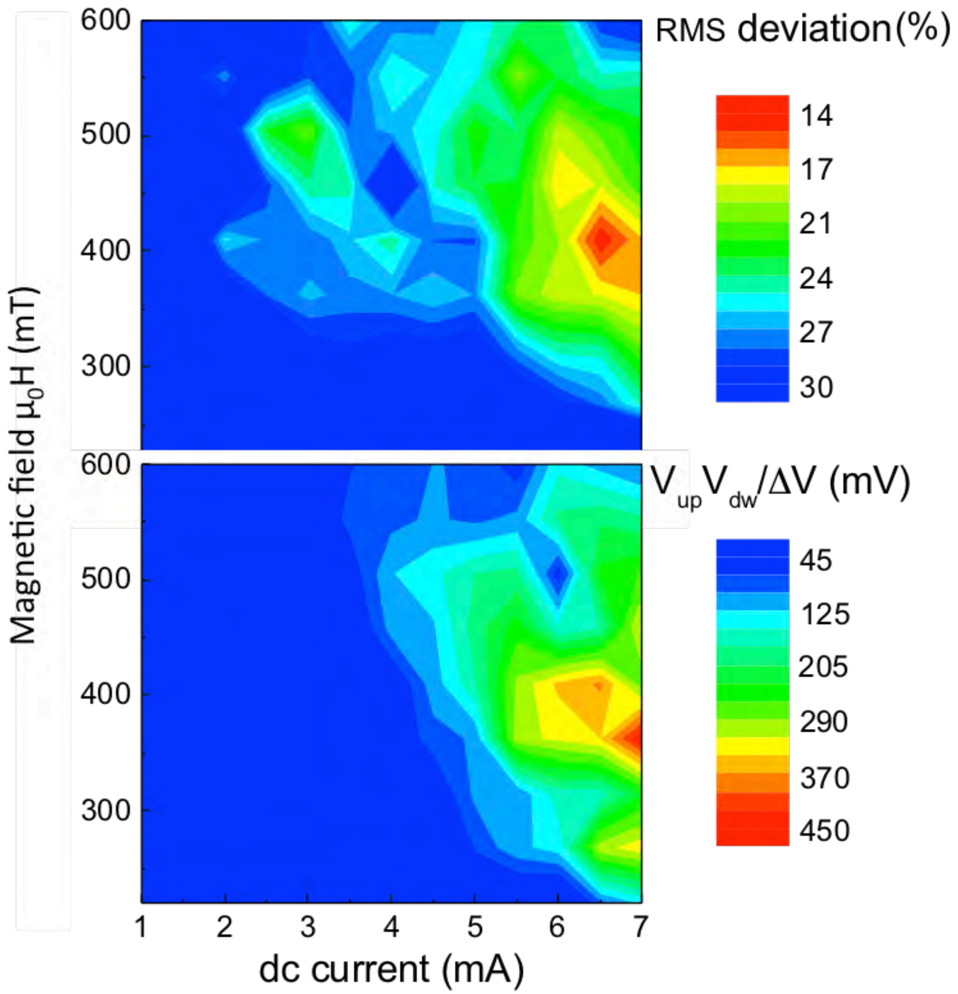
Spectrogram

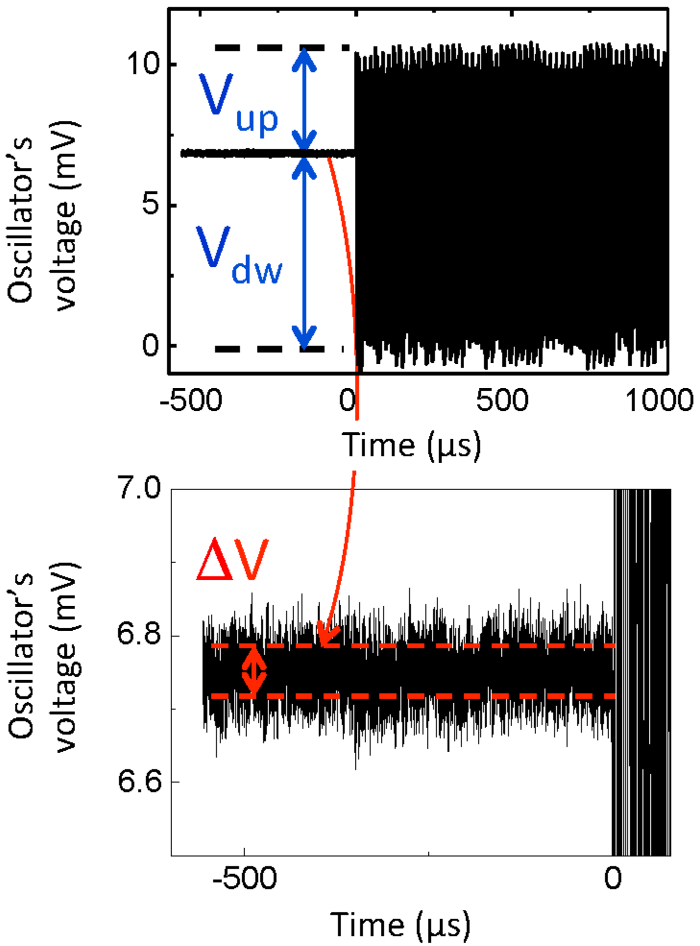


Cochlear



Recognition results are sensitive to the noise, an optimal bias area is found





Single oscillator reservoir computing

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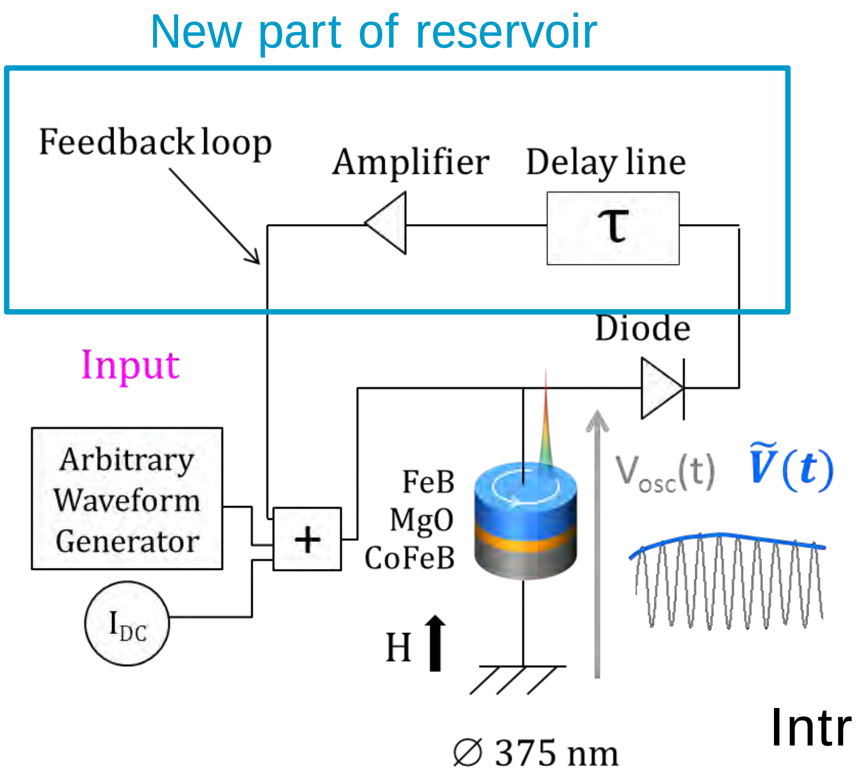
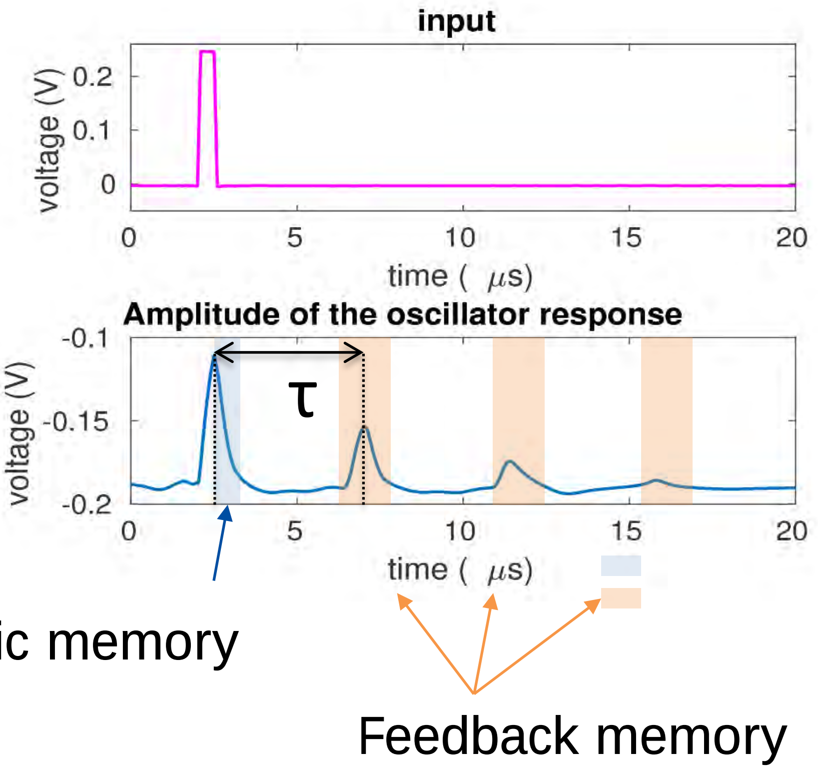
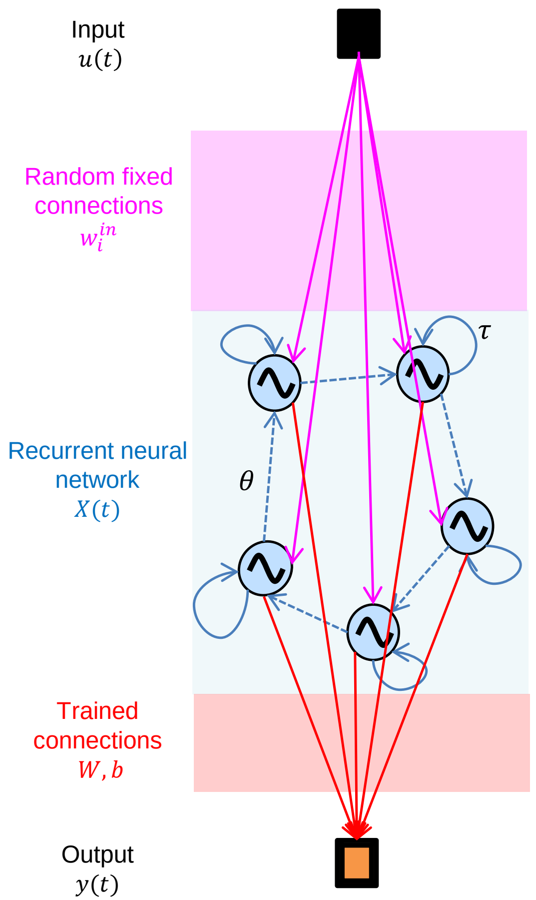
- **Sine/Square Identification (Delayed feedback memory)**

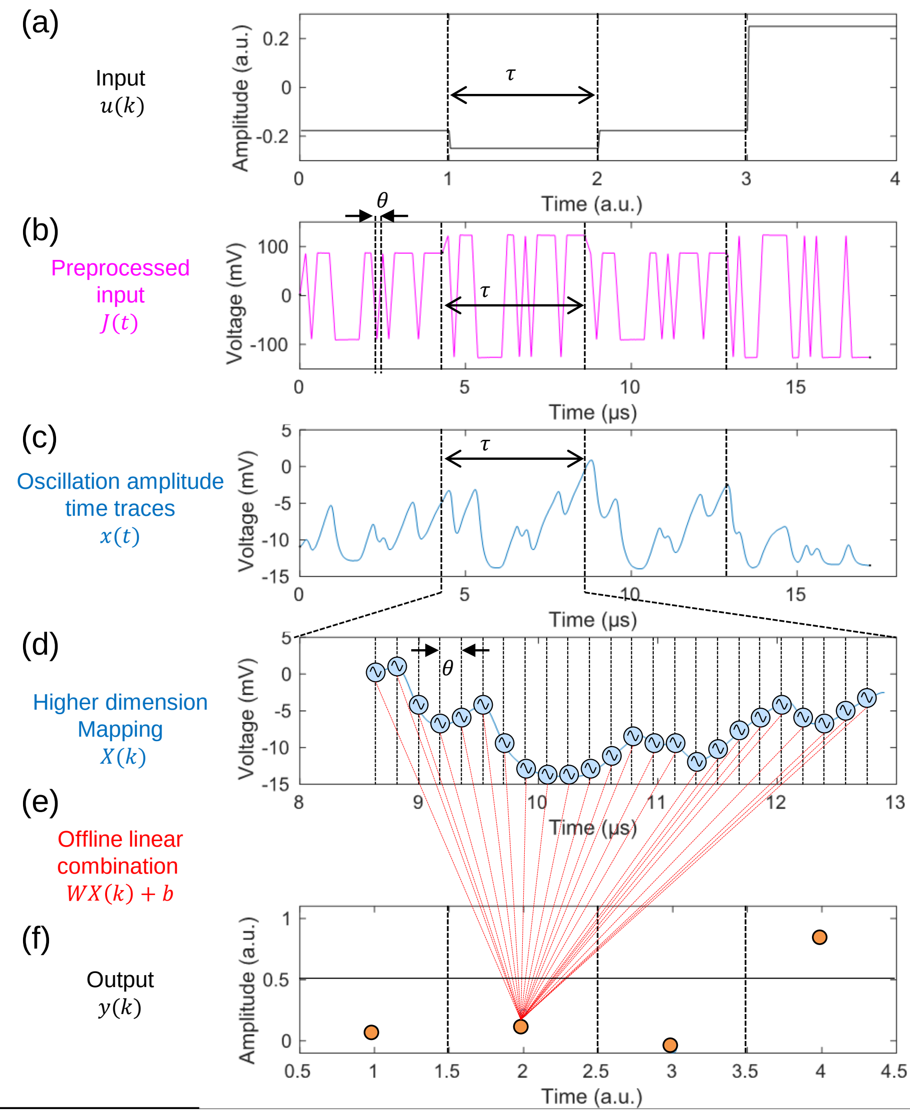
Replace intrinsic memory with delayed feedback



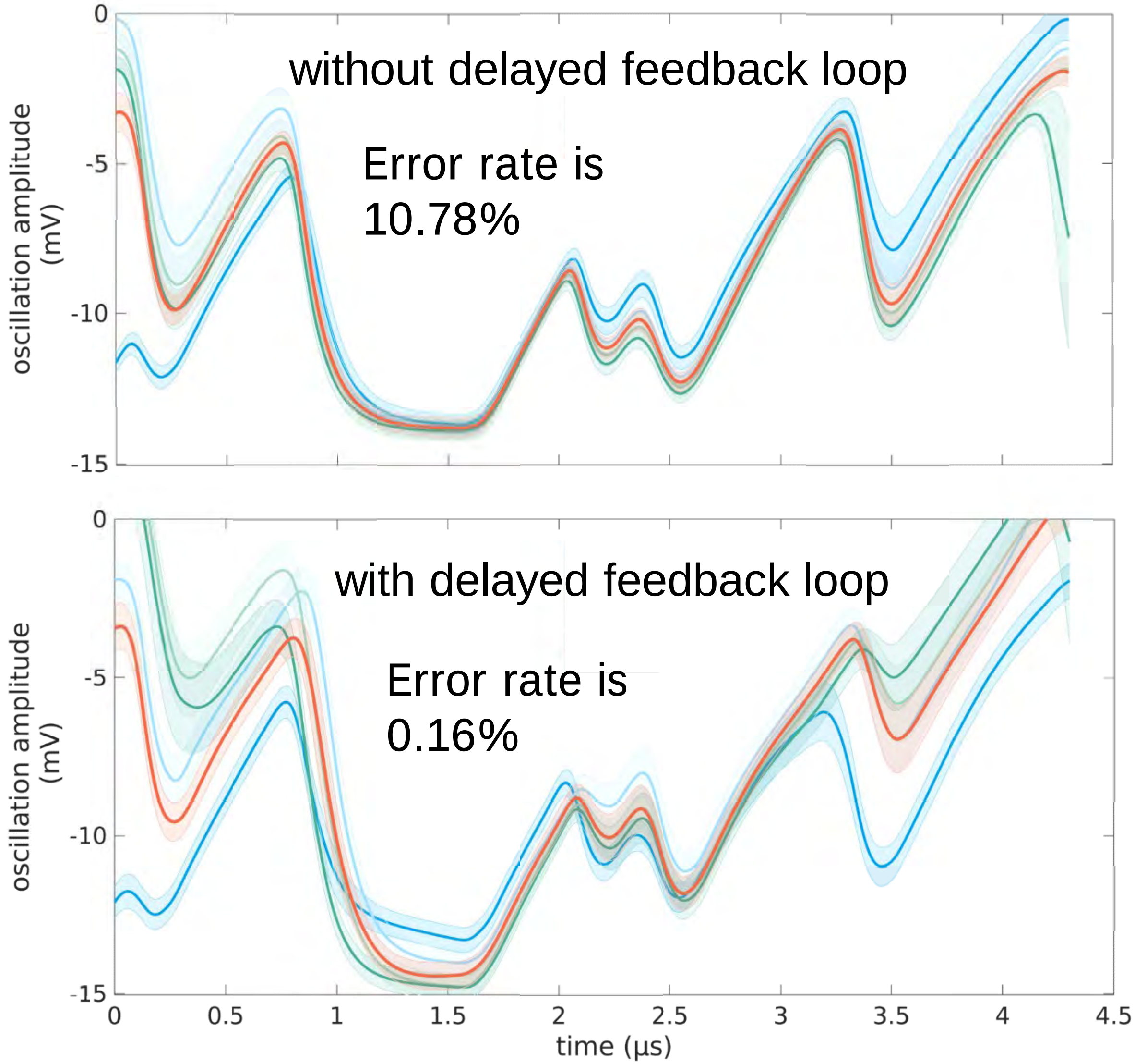


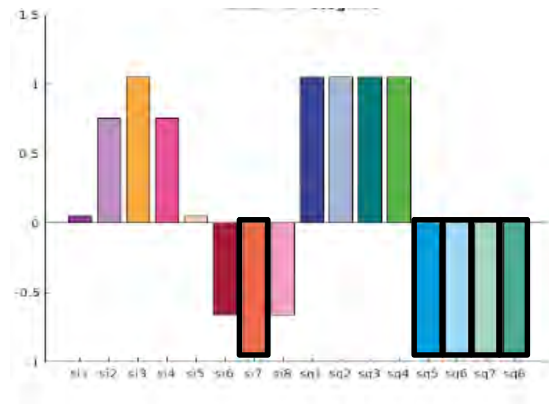
To focus on feedback, nodes only couple to past states of themselves





Feedback allows separation of similar inputs





Single oscillator reservoir computing

- Augmenting CMOS based neuromorphic circuits with energy-efficient spintronic devices.
  - MTJs already accessible in stat-of-the-art BEOL CMOS
- Time multiplexed reservoir computing.
  - Memory (intrinsic or delayed feedback) allows context dependent discrimination.
  - Single oscillator achieves state of the art at spoken digit recognition – non-linearity.
- Where to?
  - Small low power oscillators.
  - Efficient coupling.
  - Appropriate algorithms