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ParalESN: Enabling parallel information processing in Reservoir Computing

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Poster

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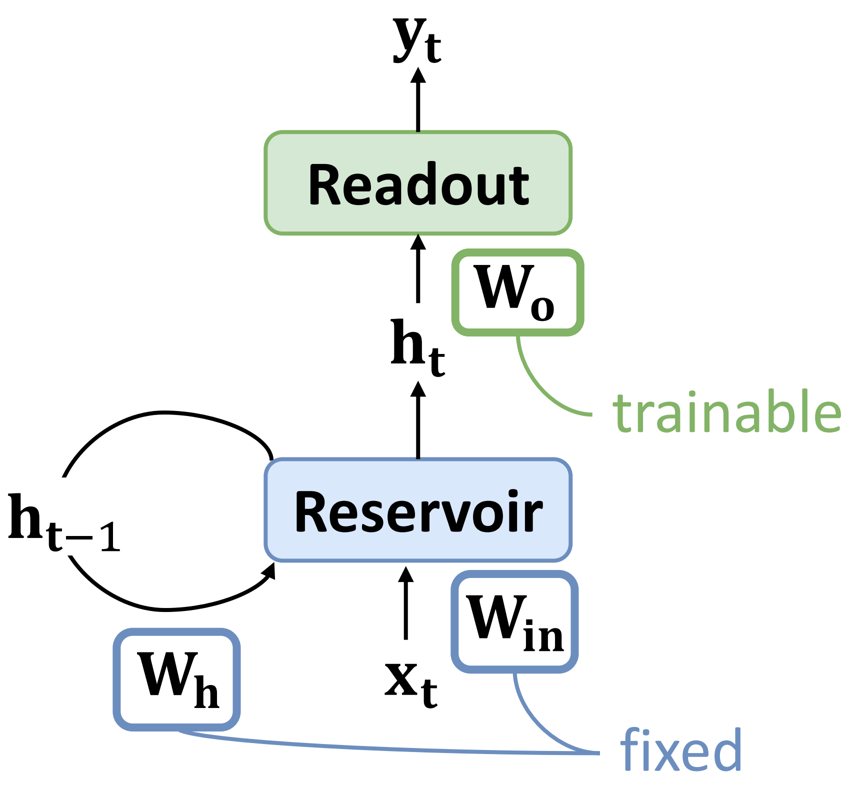
“Randomization is computationally cheaper than optimization”

Rahimi A. and Recht B., *NeurIPS* (2007, 2008)

Reservoir Computing: efficient, untrained RNNs

Untrained dynamics of a (stable) dynamical system

No backpropagation-through-time (BPTT)



$$\mathbf{y_t} = \mathbf{W_o h_t} + \mathbf{b_o}$$

$$\mathbf{h_t} = tanh(\mathbf{W_h h_{t-1}} + \mathbf{W_{in} x_t} + \mathbf{b_h})$$

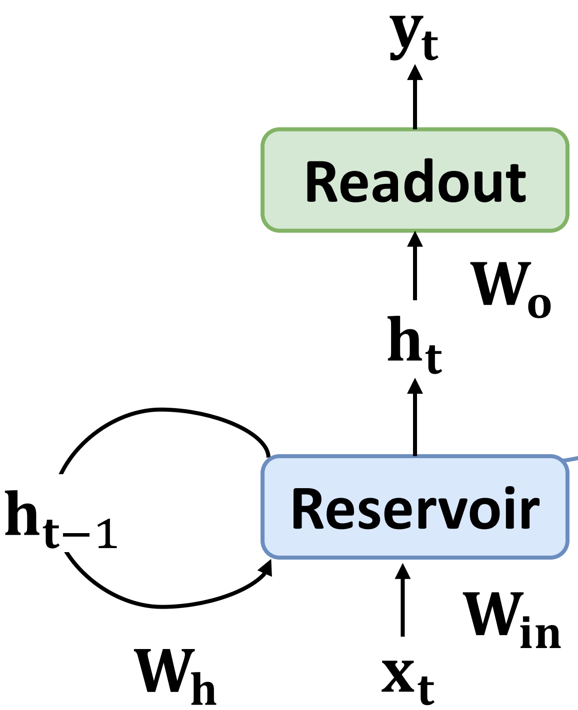
Verstraeten D. et al., *Neural networks* (2007)

Jaeger H. et al., *Neural networks* (2007)

Why does this work?

Untrained dynamics… but stable

High-dimensional random projection



initialized under the **Echo State Property (ESP)**

Necessary Condition

$$\rho(\mathbf{W_h}) < 1$$

Sufficient Condition

$$|||\mathbf{W_h}||| < 1$$

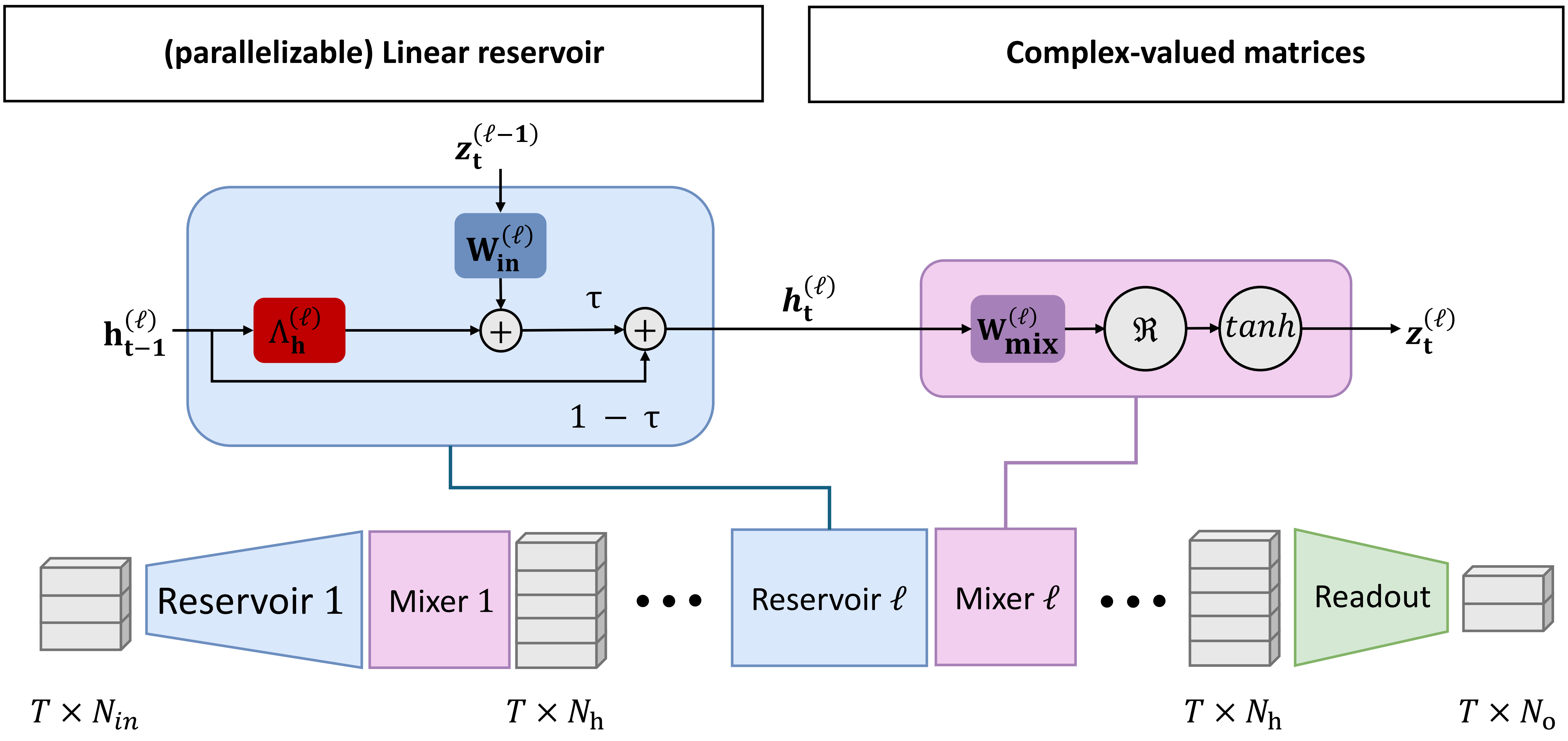
Yildiz I. B. et al., Neural networks (2012)

Revisiting the Reservoir Computing paradigm to enable:

(i) Parallel recurrence

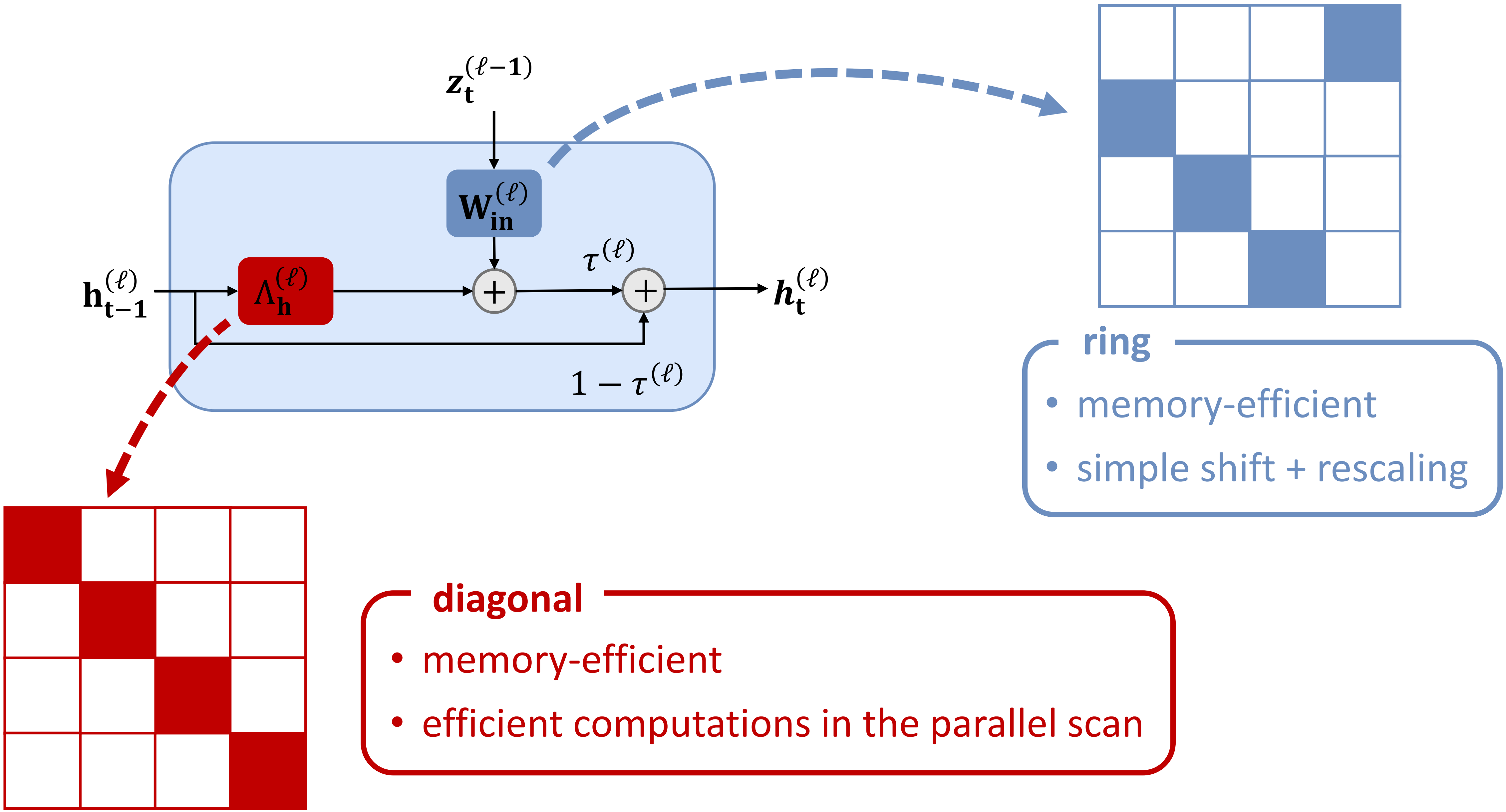
(ii) Higher-dimensional reservoir

Parallel Echo State Networks (ParalESN)



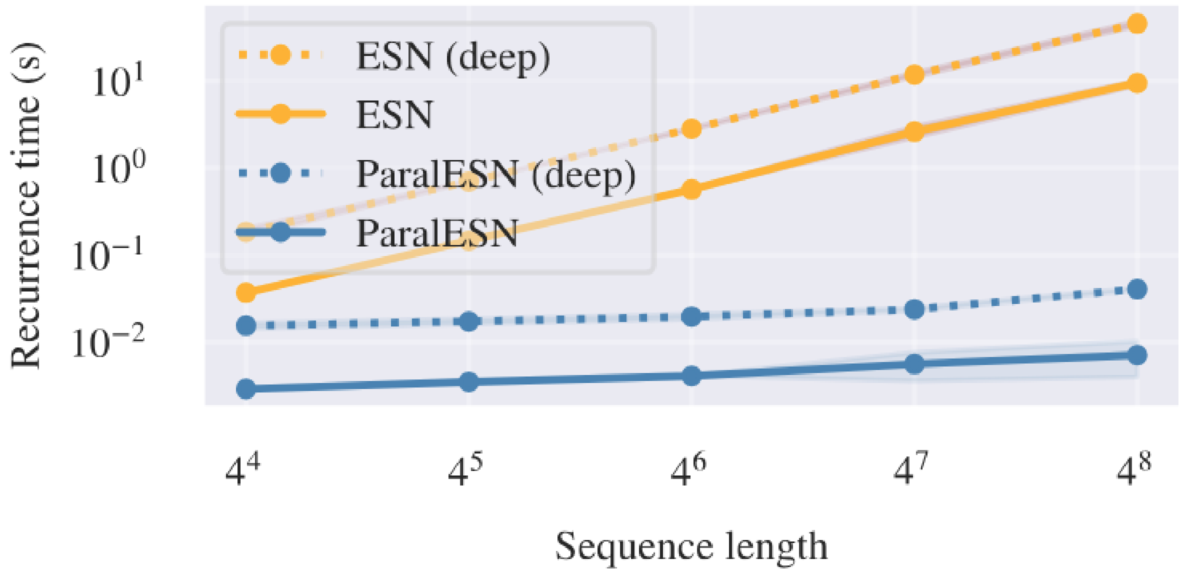
Orvieto A. et al., *PMLR* (2023)

Revisiting reservoir structure through structured operators

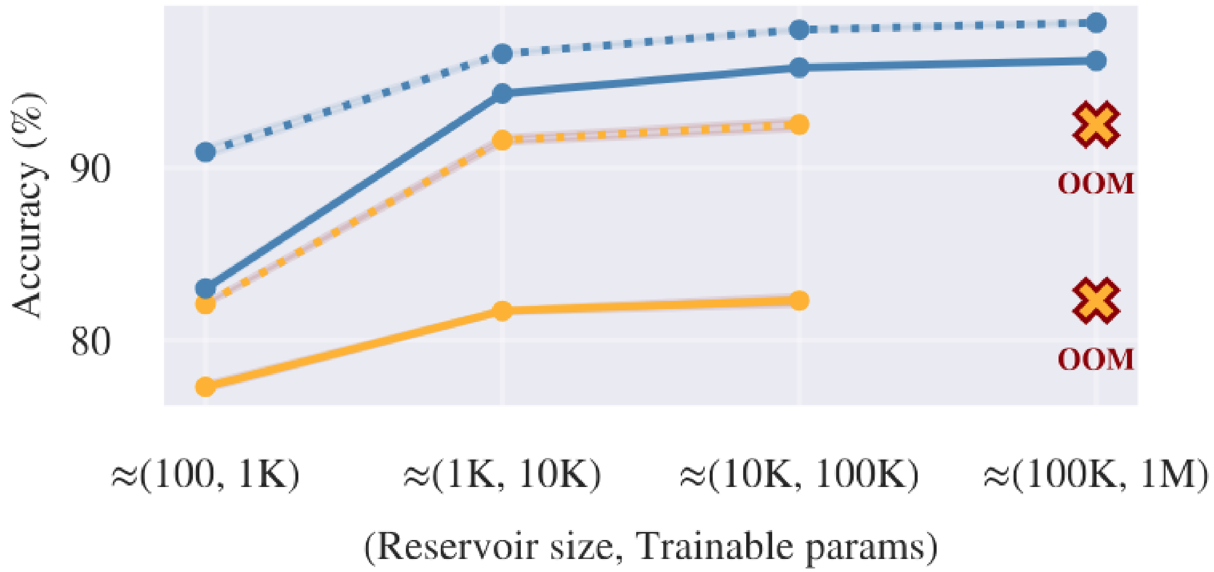


ParalESN is faster and more scalable than traditional reservoirs

Scaling *logarithmically* w.r.t. sequence length

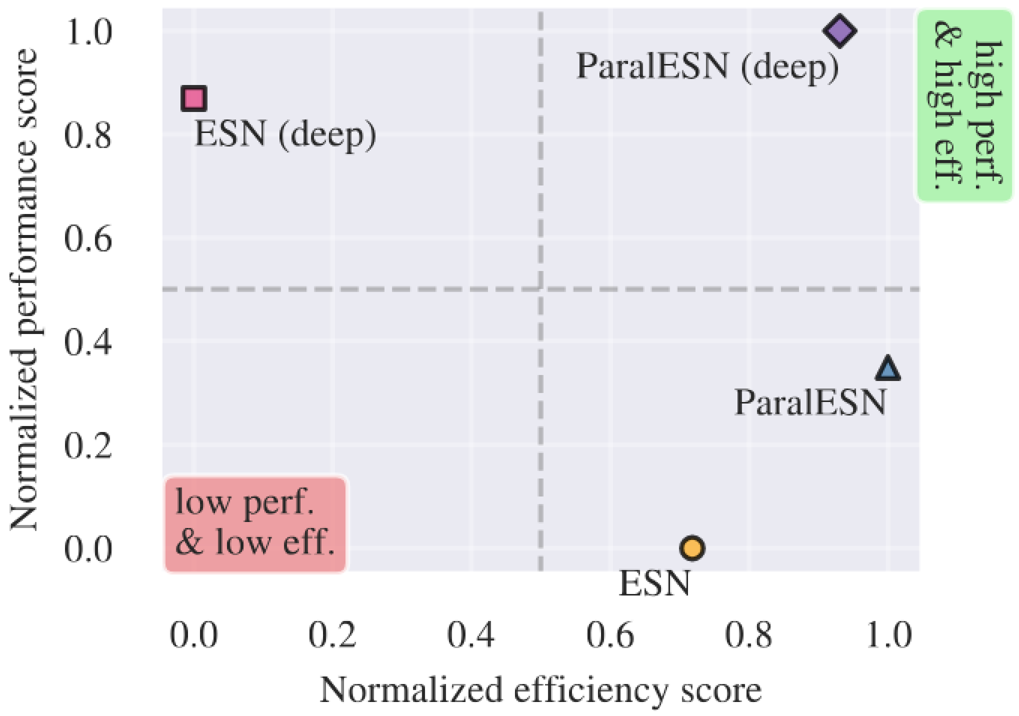


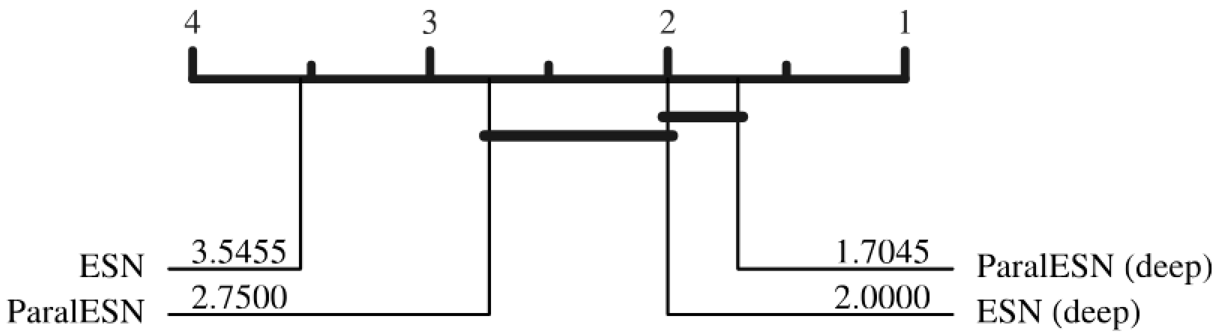
Scaling *linearly* w.r.t. hidden size



(sequential MNIST)

ParalESN consistently outperforms its traditional counterpart…

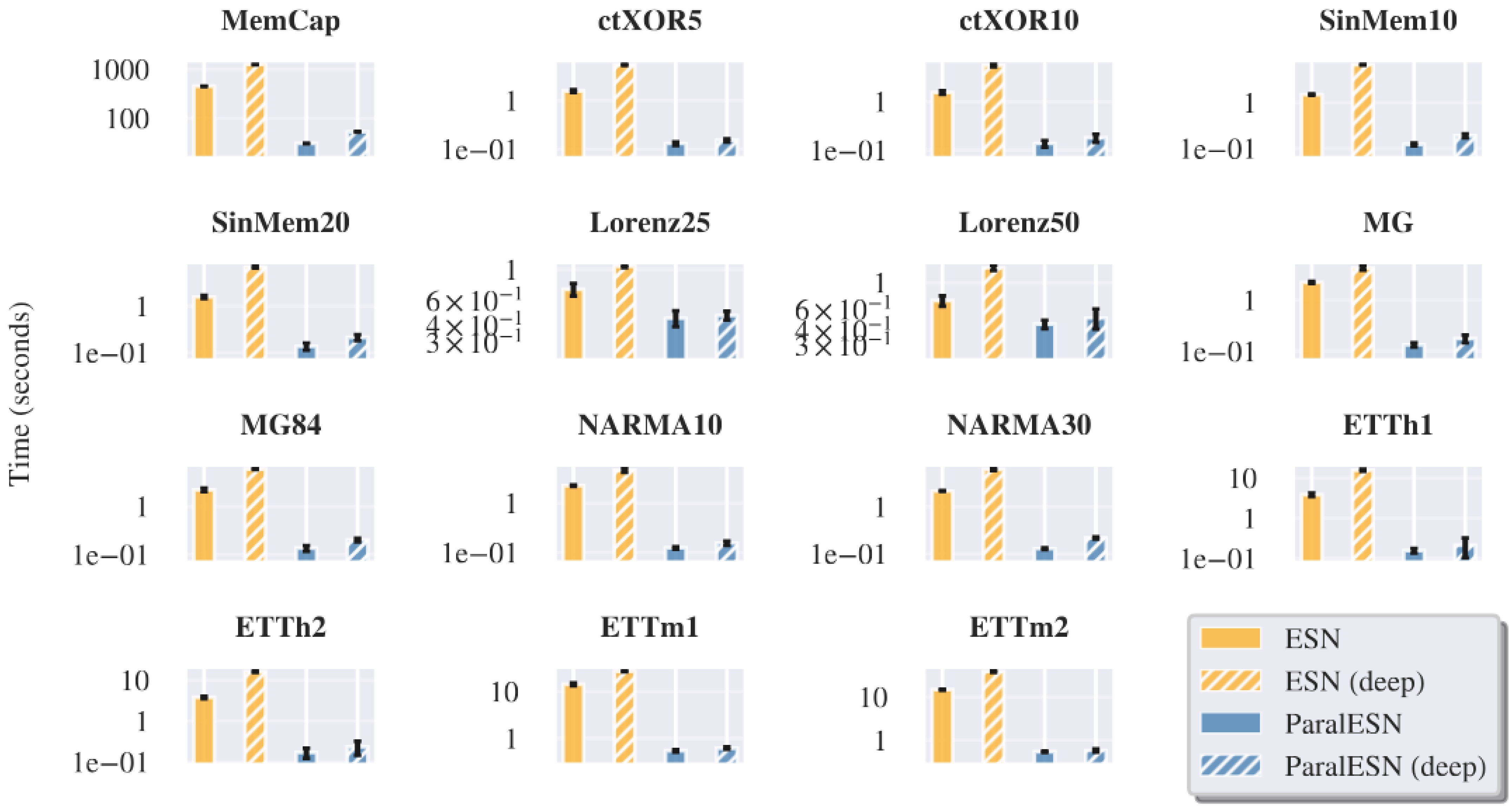




Results for benchmarks on time series

- ***(left)* Trade-off between predictive performance and efficiency**
- ***(right)* Critical difference diagram**

…while being more efficient by orders of magnitude



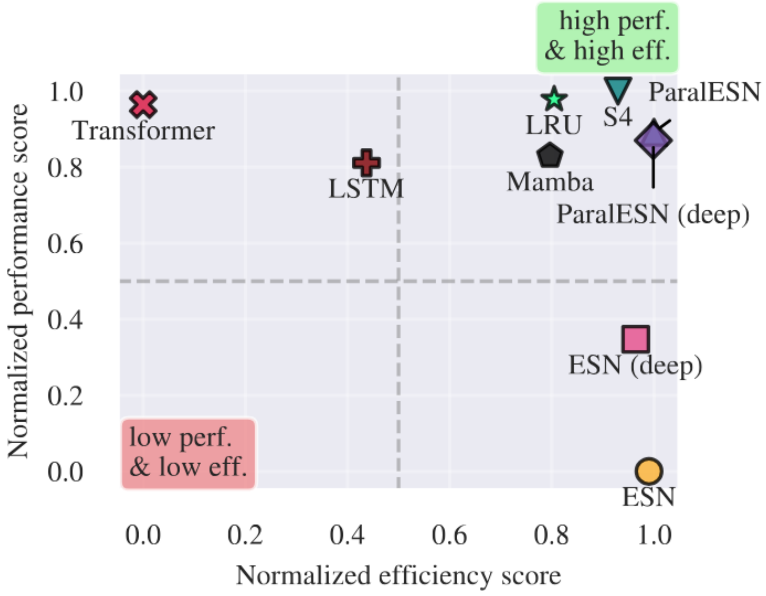
ParalESN is competitive with fully-trainable sequence models

sMNIST

Model	Params.	↑ Accuracy	↓ Time (min.)	↓ Emissions (kg)	↓ Energy (kWh)
LSTM	≈ 160k	$97.5_{\pm 1.4}$	$80.8_{\pm 6.8}$	$0.34_{\pm 0.14}$	$1.02_{\pm 0.42}$
Transformer	≈ 160k	$98.4_{\pm 0.1}$	$141.0_{\pm 14.1}$	$0.60_{\pm 0.28}$	$1.81_{\pm 0.86}$
S4*	≈ 160k	$\mathbf{99.2}_{\pm \mathbf{0.0}}$	$16.1_{\pm 0.0}$	$0.53_{\pm 0.0}$	$1.61_{\pm 0.0}$
LRU	≈ 160k	$\underline{98.5_{\pm 0.2}}$	$29.1_{\pm 1.85}$	$0.18_{\pm 0.02}$	$0.57_{\pm 0.05}$
Mamba	≈ 200k	$98.4_{\pm 0.1}$	$22.87_{\pm 4.48}$	$0.19_{\pm 0.02}$	$0.57_{\pm 0.06}$
ESN	≈ 160k	$82.5_{\pm 7}$	$4.3_{\pm 0.1}$	$\underline{0.02_{\pm 0.00}}$	$0.07_{\pm 0.00}$
ESN (deep)	≈ 160k	$91.4_{\pm 1.1}$	$8.8_{\pm 0.1}$	$0.04_{\pm 0.00}$	$0.13_{\pm 0.00}$
ParalESN	≈ 160k	$96.2_{\pm 1.3}$	$\mathbf{2.7}_{\pm \mathbf{0.7}}$	$\mathbf{0.01}_{\pm \mathbf{0.00}}$	$\mathbf{0.04}_{\pm \mathbf{0.10}}$
ParalESN (deep)	≈ 160k	$97.2_{\pm 0.2}$	$\underline{3.3_{\pm 0.5}}$	$\underline{0.02_{\pm 0.00}}$	$\underline{0.05_{\pm 0.00}}$

psMNIST

Model	Params.	↑ Accuracy	↓ Time (min.)	↓ Emissions (kg)	↓ Energy (kWh)
LSTM	≈ 160k	$92.8_{\pm 0.5}$	$89.3_{\pm 4.2}$	$0.47_{\pm 0.04}$	$1.41_{\pm 0.11}$
Transformer	≈ 160k	$97.4_{\pm 0.2}$	$156.8_{\pm 2.7}$	$0.65_{\pm 0.24}$	$1.98_{\pm 0.73}$
S4*	≈ 160k	$\mathbf{97.9}_{\pm \mathbf{0.0}}$	$9.87_{\pm 0.0}$	$0.35_{\pm 0.0}$	$1.07_{\pm 0.0}$
LRU	≈ 160k	$\underline{97.8_{\pm 0.1}}$	$33.8_{\pm 3.42}$	$0.21_{\pm 0.03}$	$0.63_{\pm 0.09}$
Mamba	≈ 200k	$92.6_{\pm 0.1}$	$43.25_{\pm 5.02}$	$0.24_{\pm 0.03}$	$0.73_{\pm 0.08}$
ESN	≈ 160k	$78.2_{\pm 1.6}$	$4.3_{\pm 0.1}$	$\underline{0.02_{\pm 0.00}}$	$0.06_{\pm 0.00}$
ESN (deep)	≈ 160k	$82.1_{\pm 3.7}$	$7.3_{\pm 0.1}$	$0.04_{\pm 0.00}$	$0.11_{\pm 0.00}$
ParalESN	≈ 160k	$96.9_{\pm 0.1}$	$\mathbf{2.8}_{\pm \mathbf{0.3}}$	$\mathbf{0.01}_{\pm \mathbf{0.00}}$	$\mathbf{0.04}_{\pm \mathbf{0.00}}$
ParalESN (deep)	≈ 160k	$95.2_{\pm 0.1}$	$\underline{3.1_{\pm 0.2}}$	$\underline{0.02_{\pm 0.00}}$	$\underline{0.05_{\pm 0.00}}$



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paper

code