Quantum reservoir computing

From basics to photonic schemes

Johannes Nokkala

Turku Collegium of Science, Medicine and Technology

Summer School on New Directions in Quantum and Quantum Reservoir Computing, Quantum Devices and Related Technologies

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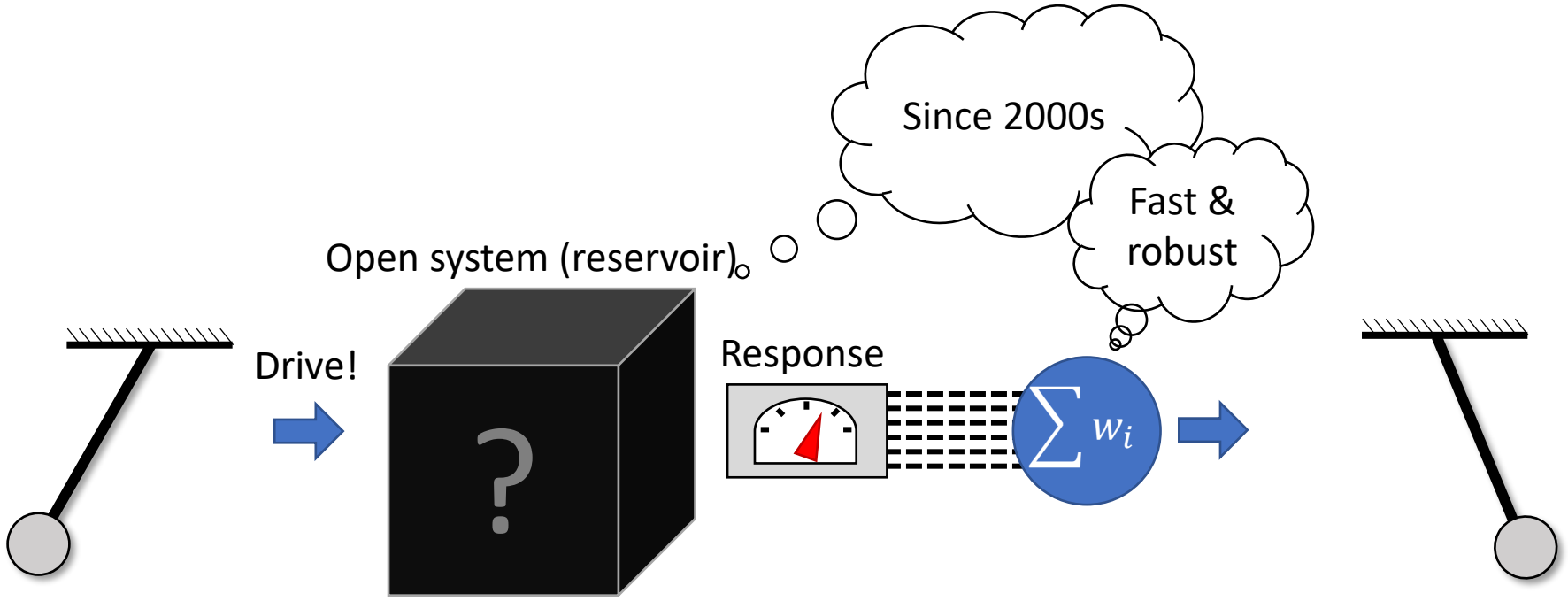
UNIVERSITY OF TURKU

Predict dynamics

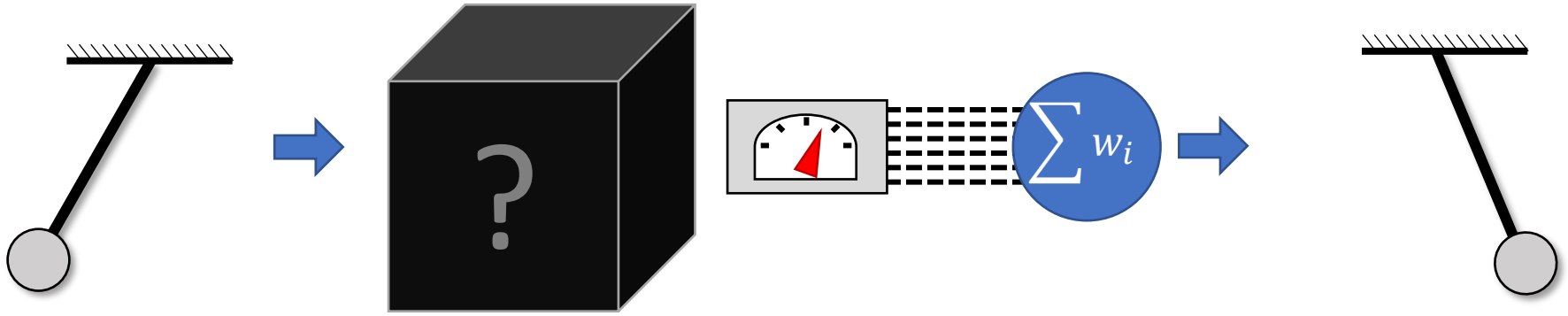
Unknown EOM, must
<u>generalize</u> from data

Say, position data



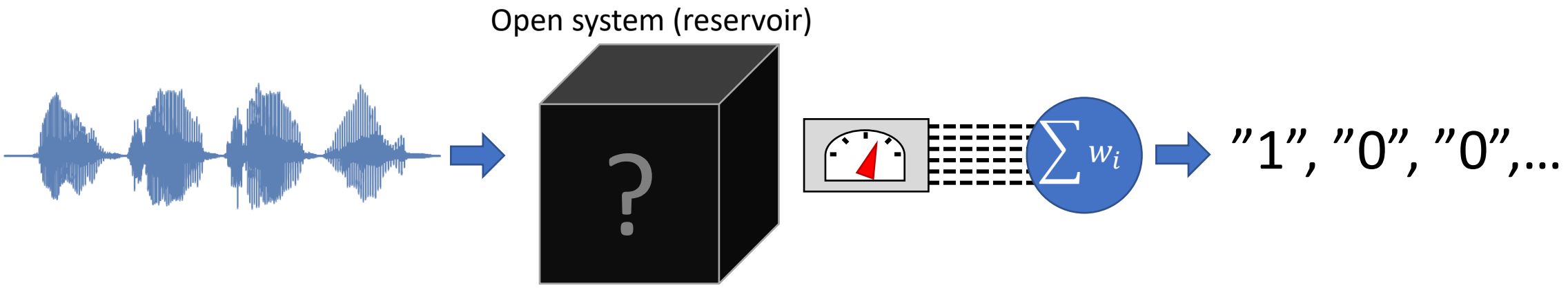
Predict dynamics

Open system (reservoir)

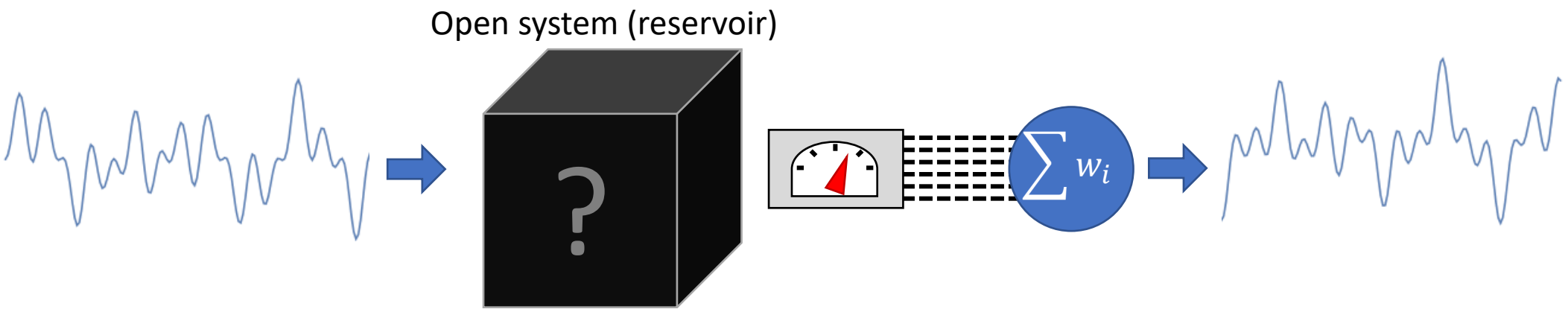


Predict dynamics

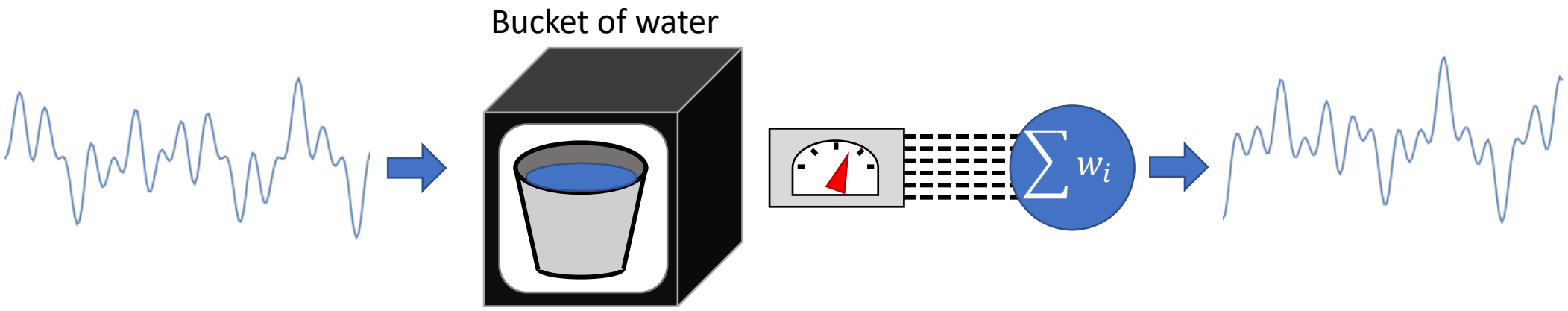
Impossible from current position alone:
coming or going? Need memory!



Speech recognition

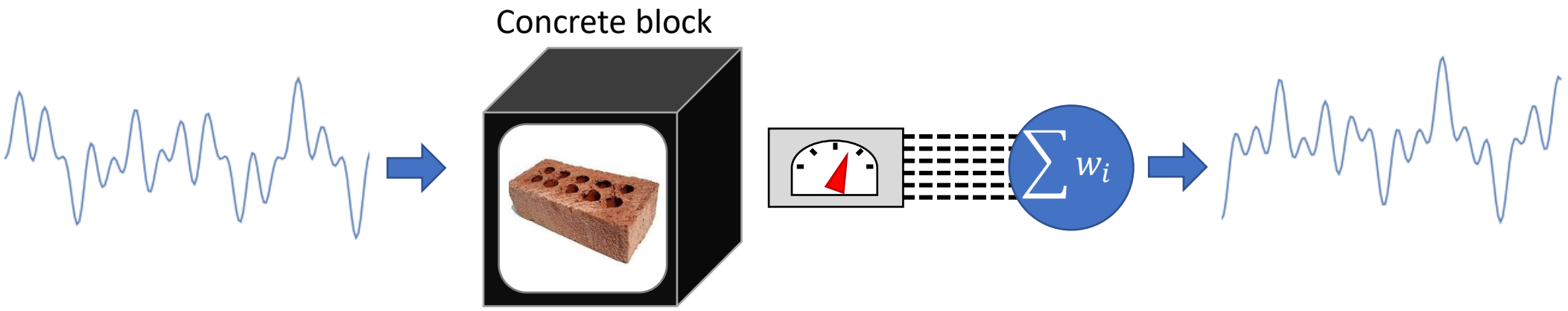


Chaotic time series forecasting



Chaotic time series forecasting

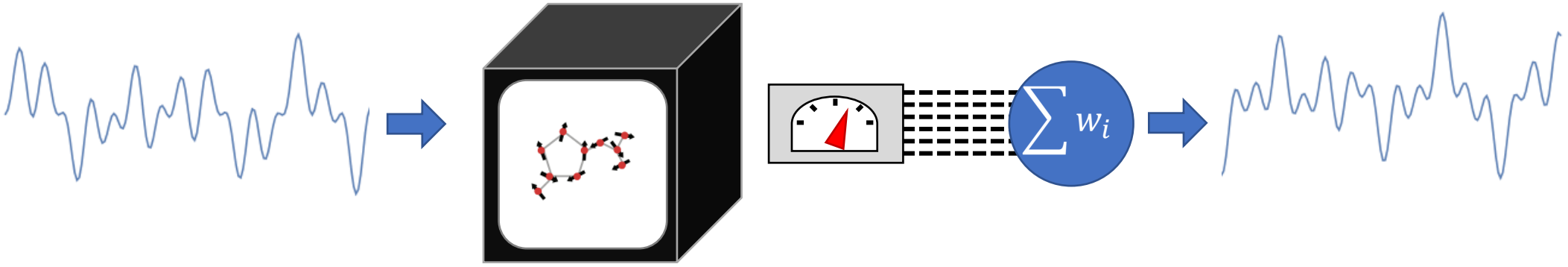
Chrisantha Fernando & Sampsa Sojakka.
European conference on artificial life
(2003).



Chaotic time series forecasting

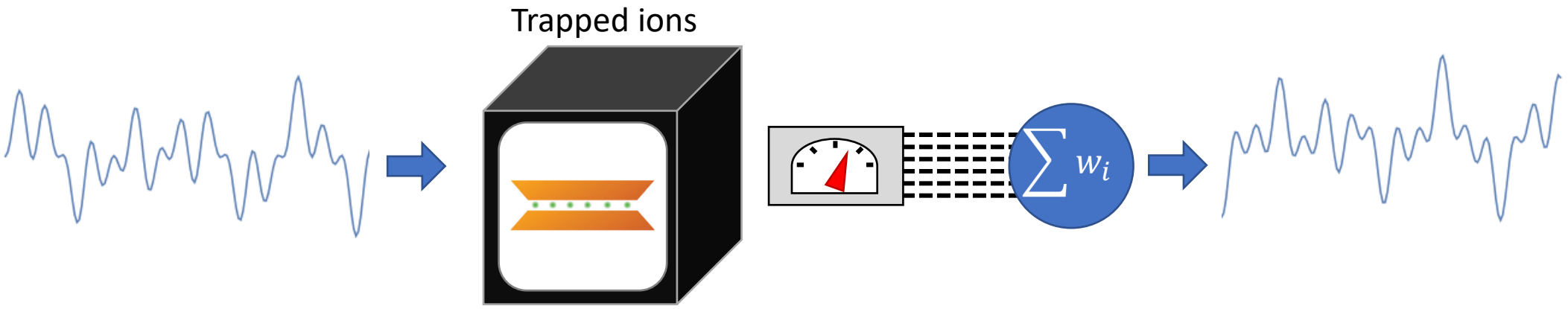
Przyczyna, Dawid, et al. *Materials* 14.7 (2021): 1724.

NMR in molecules



Chaotic time series forecasting

Mujal, Pere, et al. *Advanced Quantum Technologies* 4.8 (2021): 2100027.



Chaotic time series forecasting

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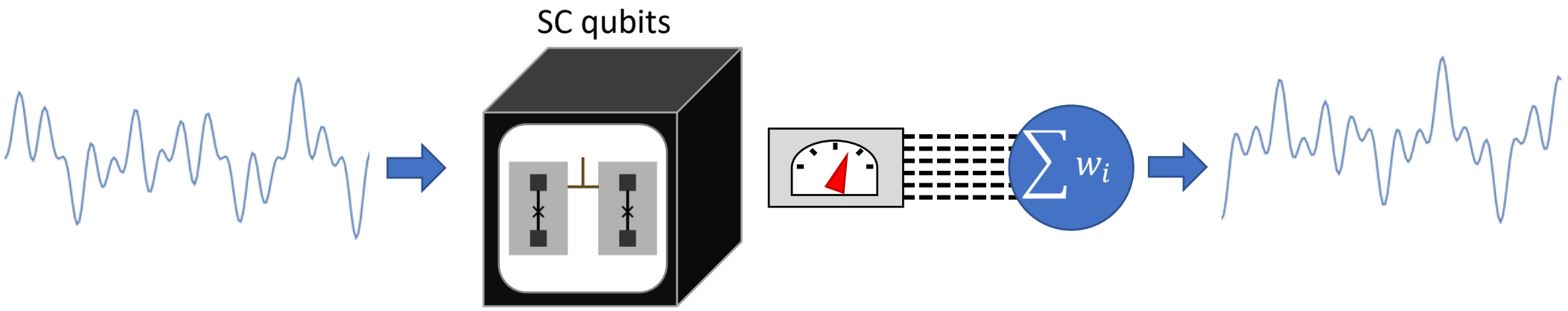
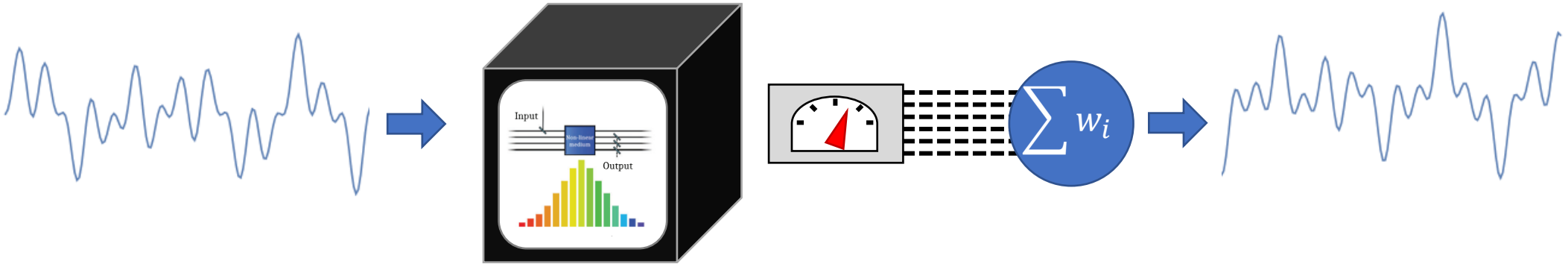


Chaotic time series forecasting

Mujal, Pere, et al. *Advanced Quantum Technologies* 4.8 (2021): 2100027.

Photonic platforms



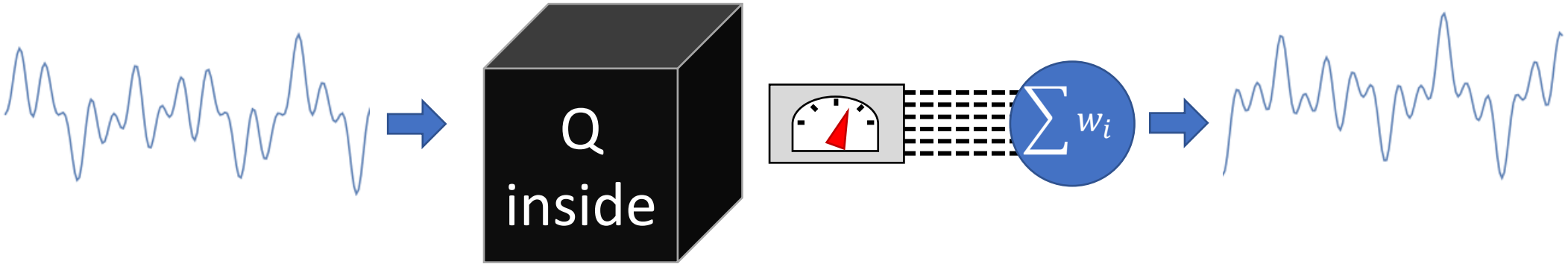
Chaotic time series forecasting

Mujal, Pere, et al. *Advanced Quantum Technologies* 4.8 (2021): 2100027.

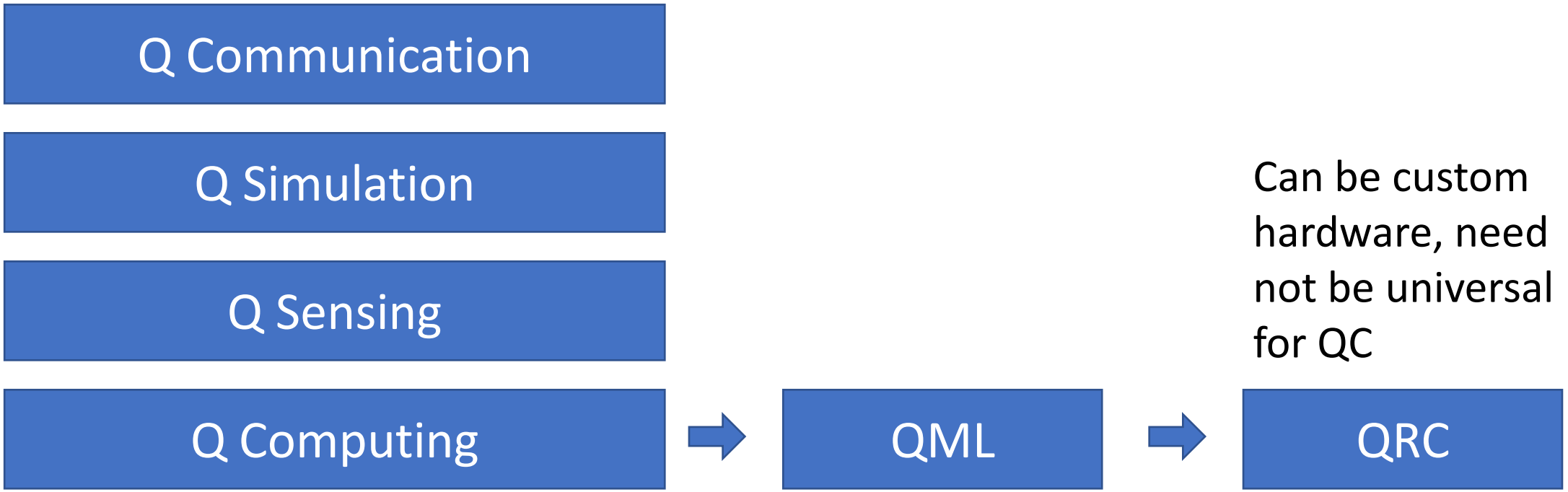
Plan for the talk

- What is QRC? What's it for?
- Why QRC instead of Q or C alternatives?
- Examples & challenges

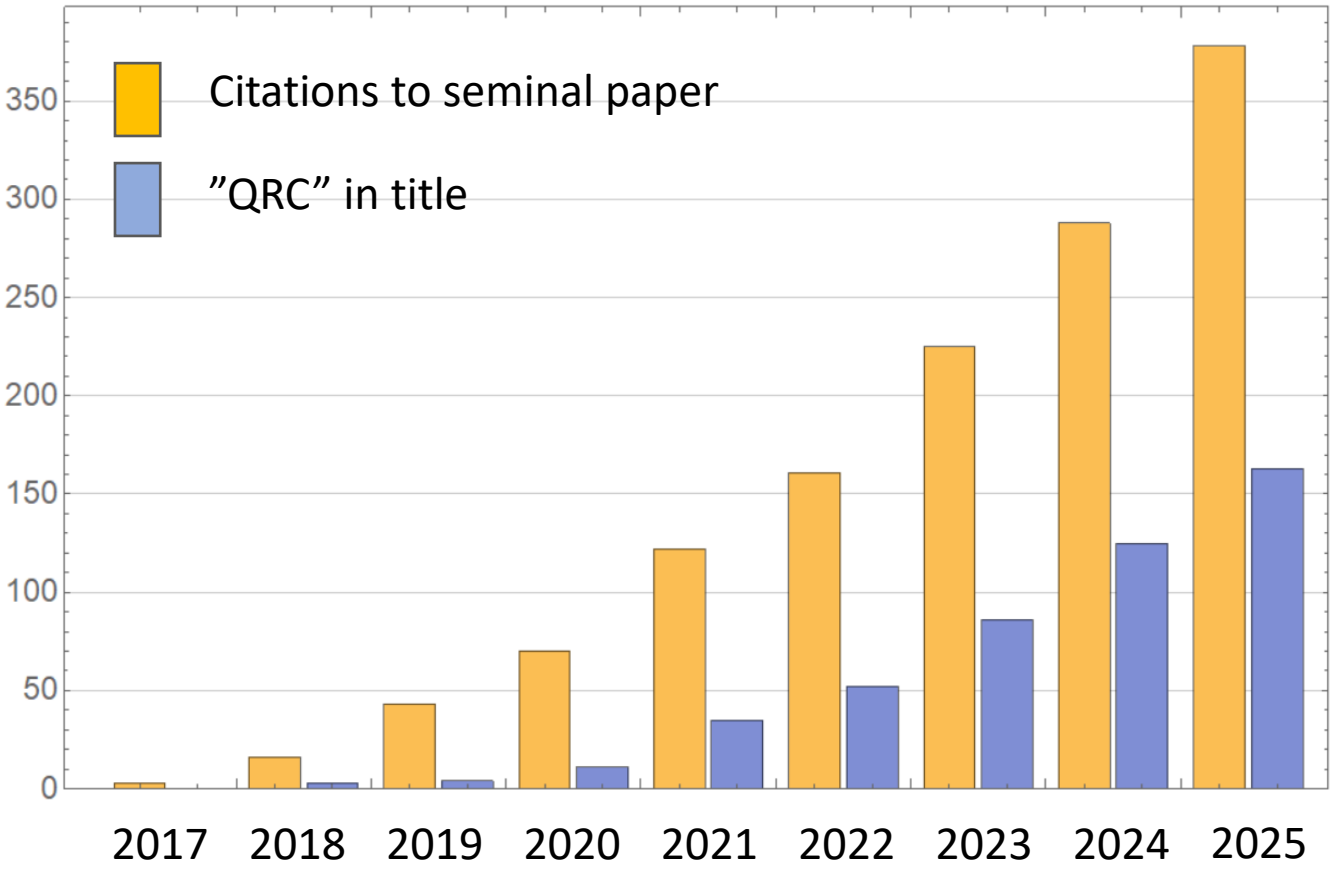
What QRC? What is it for?



Harness Q dynamics by driving with the signal of interest and post-processing the response


Q Communication
Q Simulation
Q Sensing
Q Computing
QML
QRC
Can be custom hardware, need not be universal for QC

Rough proxies of interest



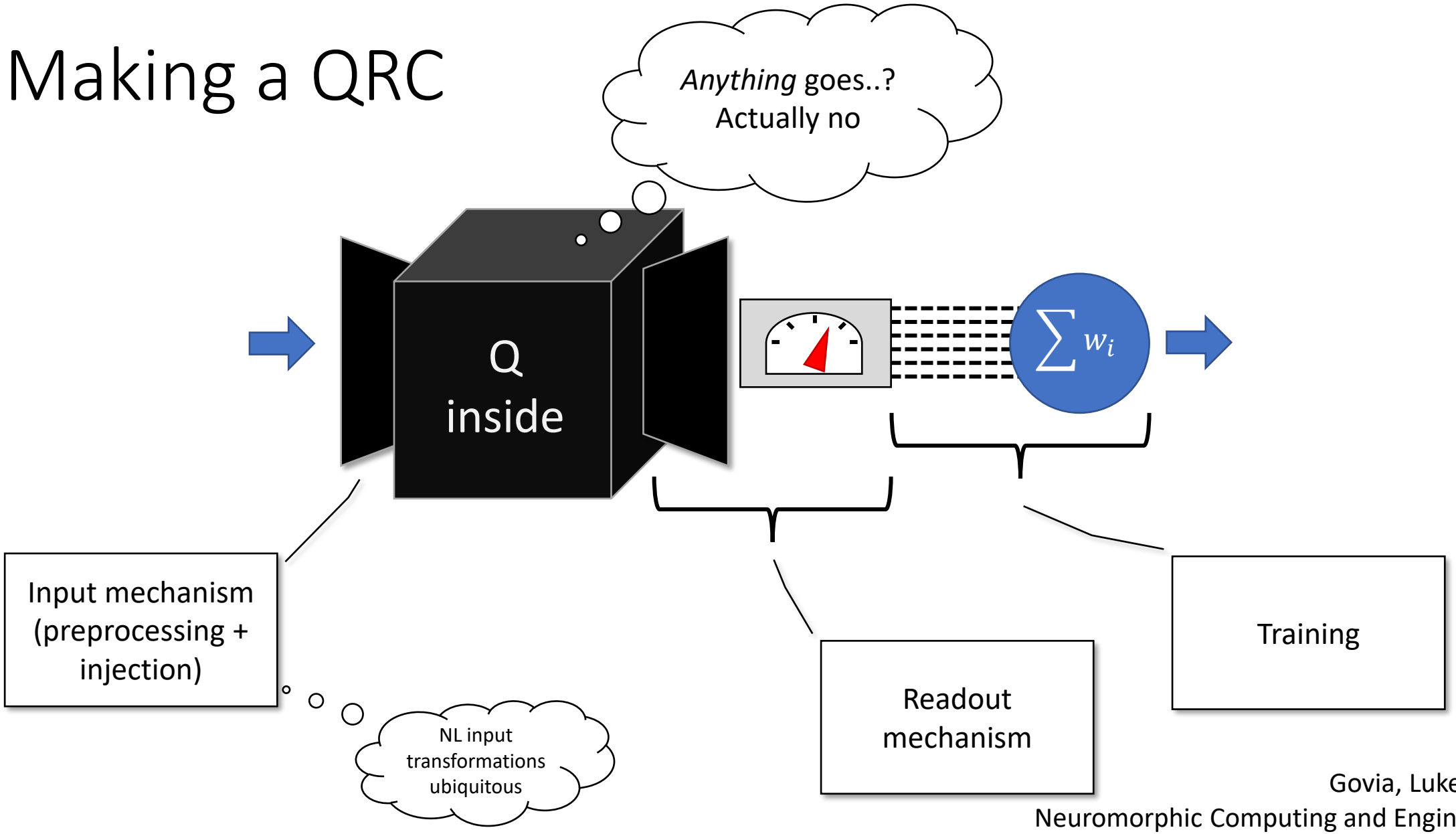
≲ talk about it

≲ work done

Stage 1: can it be done on paper?

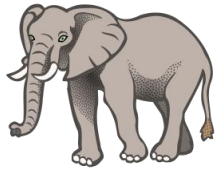
Stage 2: can it be done in a lab?

Making a QRC



Govia, Luke CG, et al.
Neuromorphic Computing and Engineering 2.1
(2022): 014008.

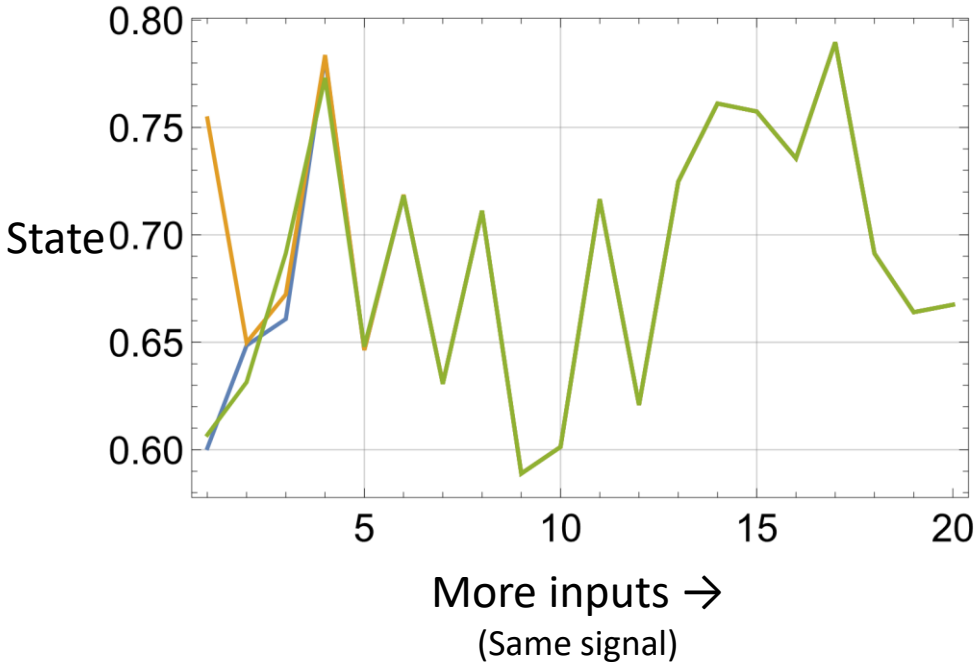
Need fading memory!

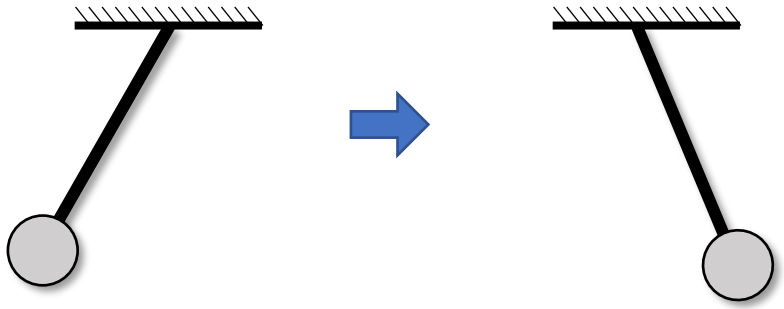


- State ≈ cont. function of recent input history

→Initial state irrelevant, tiny changes in recent input = tiny changes in state
  - Self correcting!

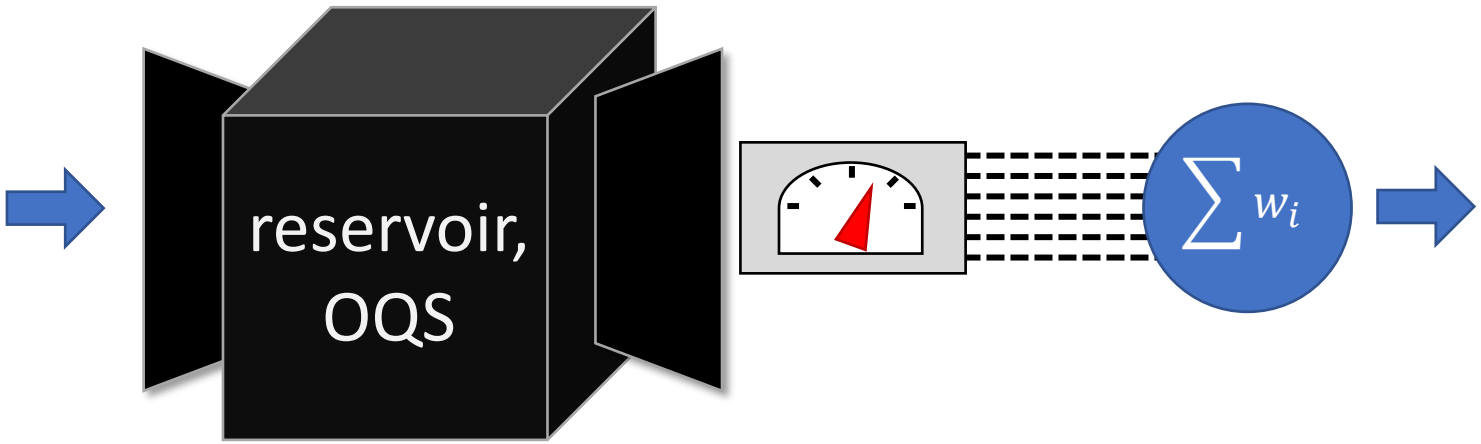
- Tasks typically such functions

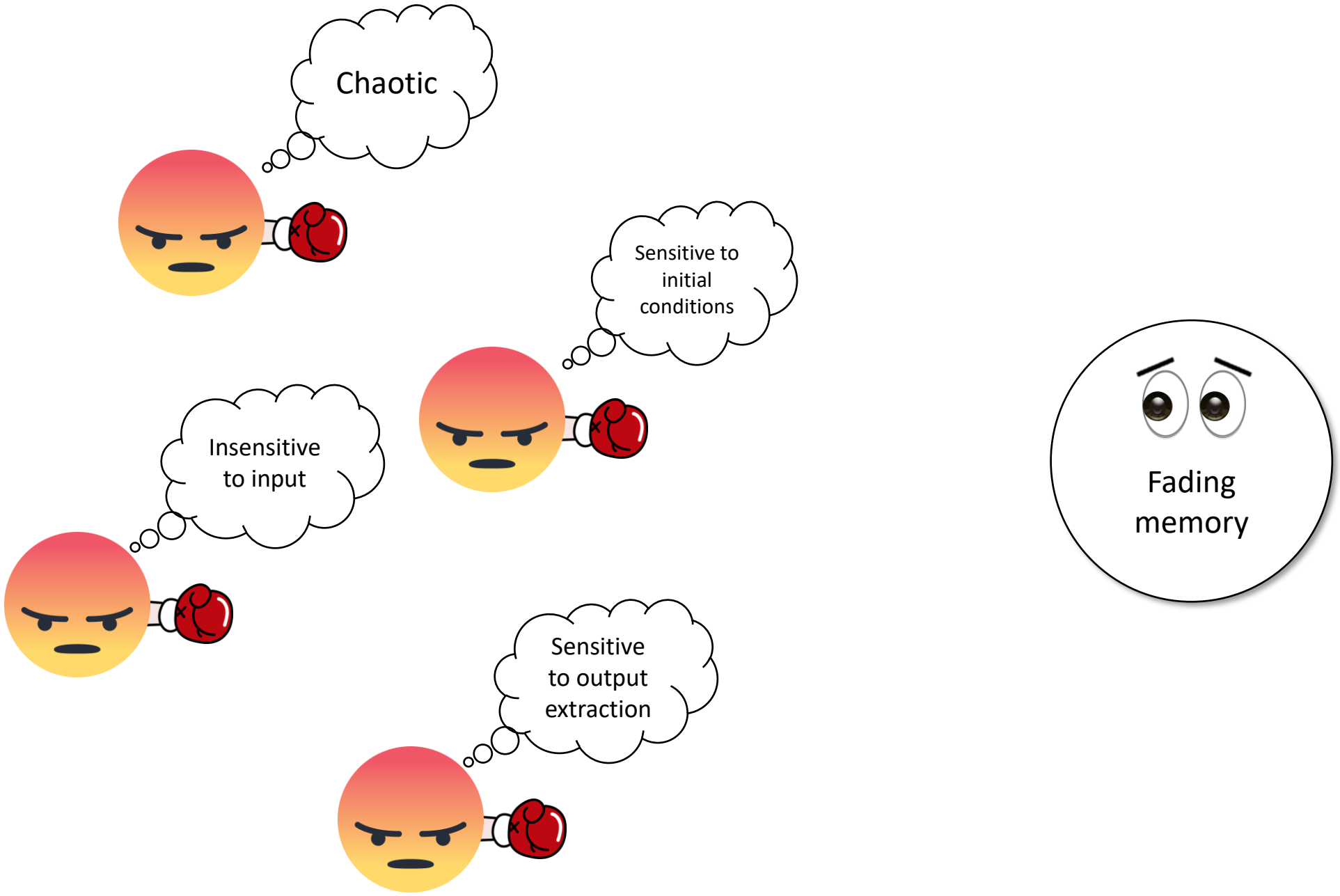




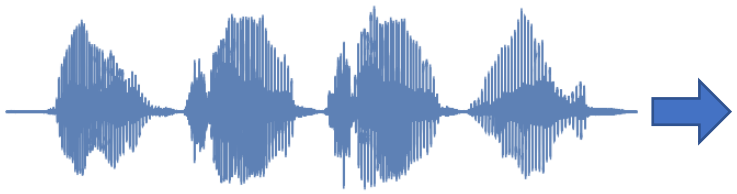
Fading memory? OQS!

- Necessary, not sufficient
  - *U dynamics reversible*
- Some mechanisms
  - Partial state reset
  - Continuous dissipation
  - Beam splitter

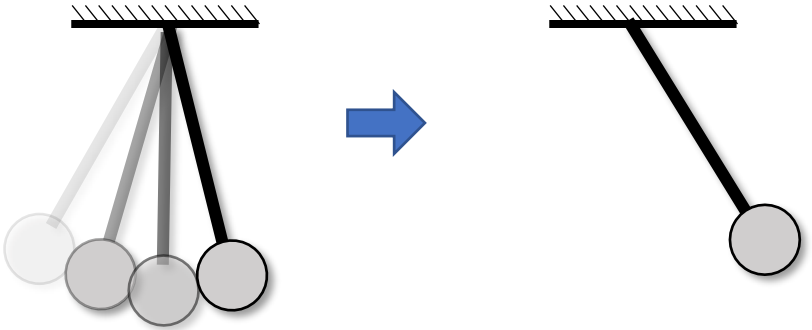



Chaotic
Sensitive to initial conditions
Insensitive to input
Sensitive to output extraction
Fading memory

Ideally suited for?



”1”, ”0”, ”0”,…

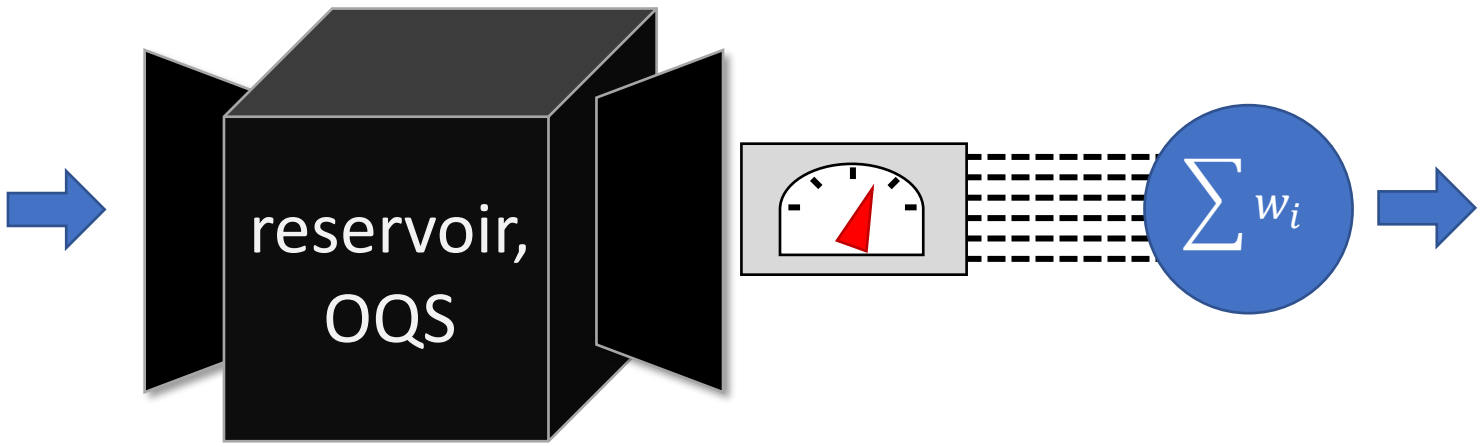


- Time series processing! FM transformations
- But also, e.g., procedural generation (see poster by H. Pettugani)

Why QRC?

Comparison with some Q and C alternatives

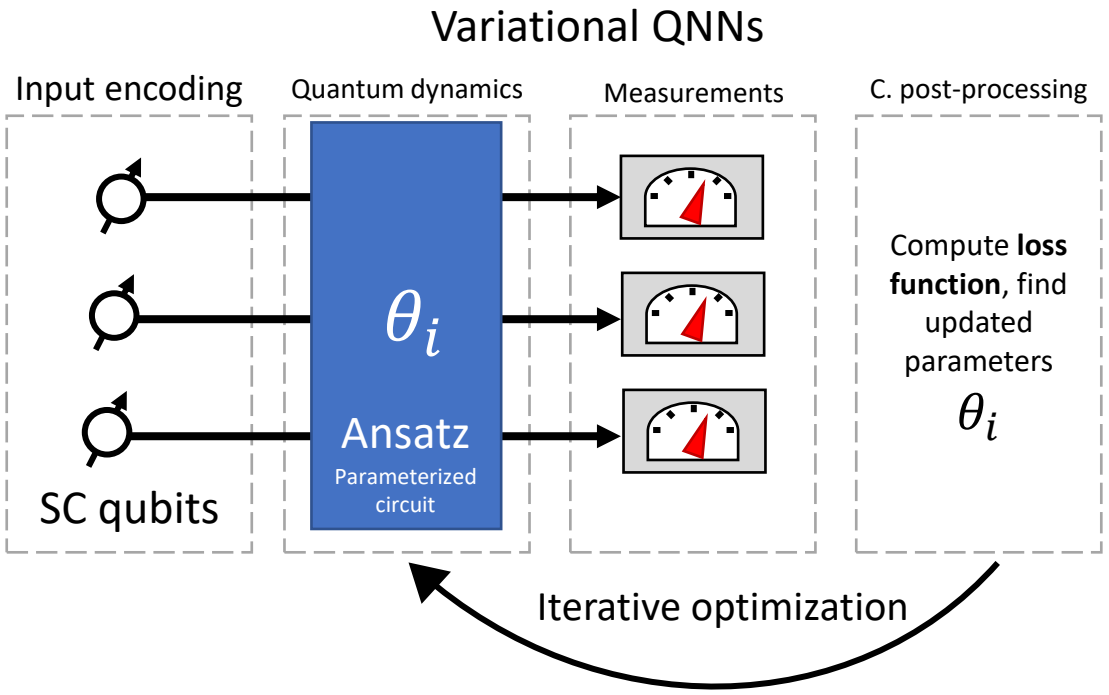
How good can it be?



Compare with Q alternatives

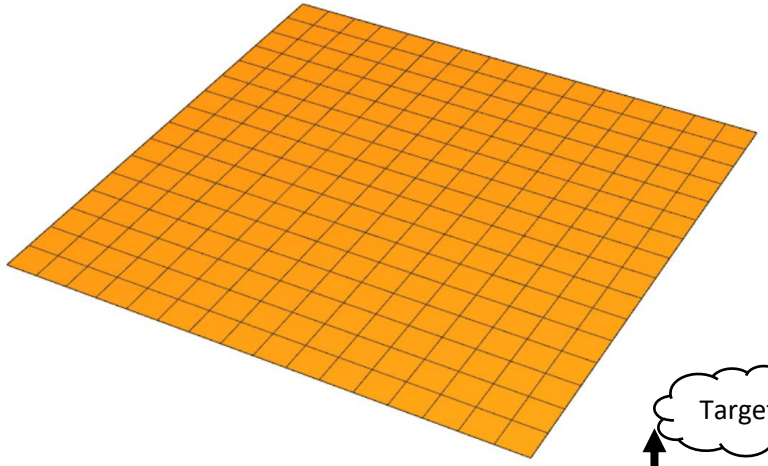
- Any task QRC can solve a QNN can solve too

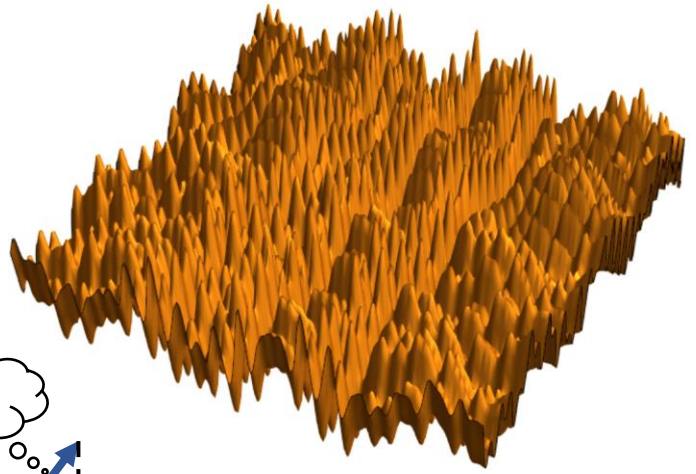
- 1st advantage of QRC: engineering freedom
  - Don’t need QC
  - Don’t need specific gates
  - Don’t need qubits!

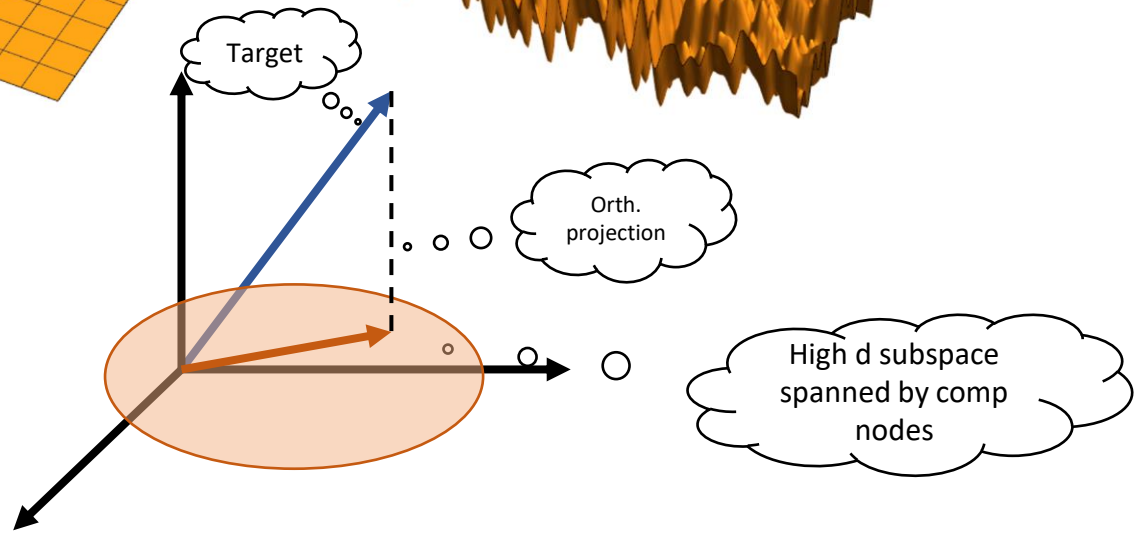


Compare with Q alternatives

- 2nd advantage of QRC: trainability
- QNN loss landscapes awful
- QRC? Gather data *once*, compute pseudoinverse







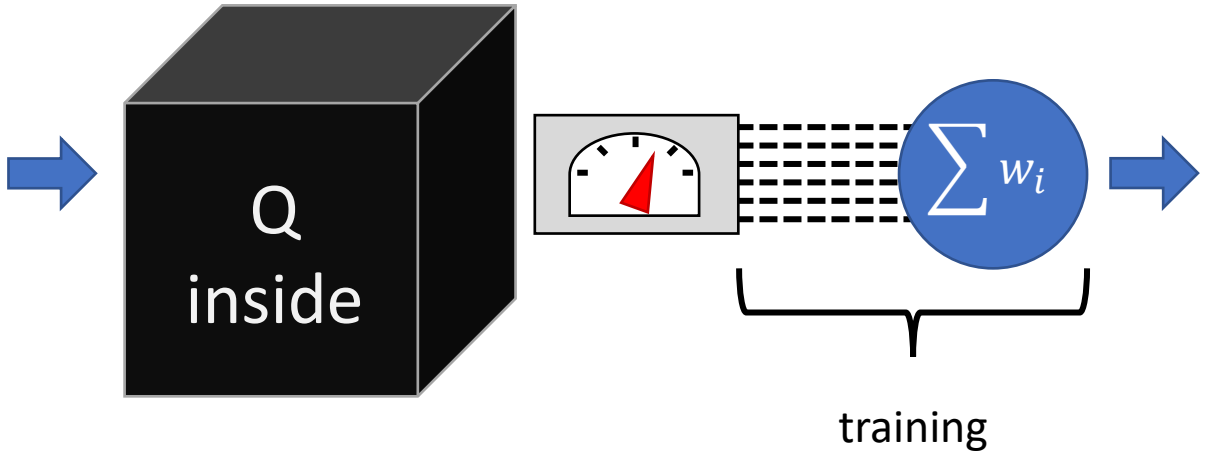
"Barren plateaus in quantum neural network training landscapes." *Nature communications* 9.1 (2018): 4812.

"Quantum variational algorithms are swamped with traps." *Nature Communications* 13.1 (2022): 7760.

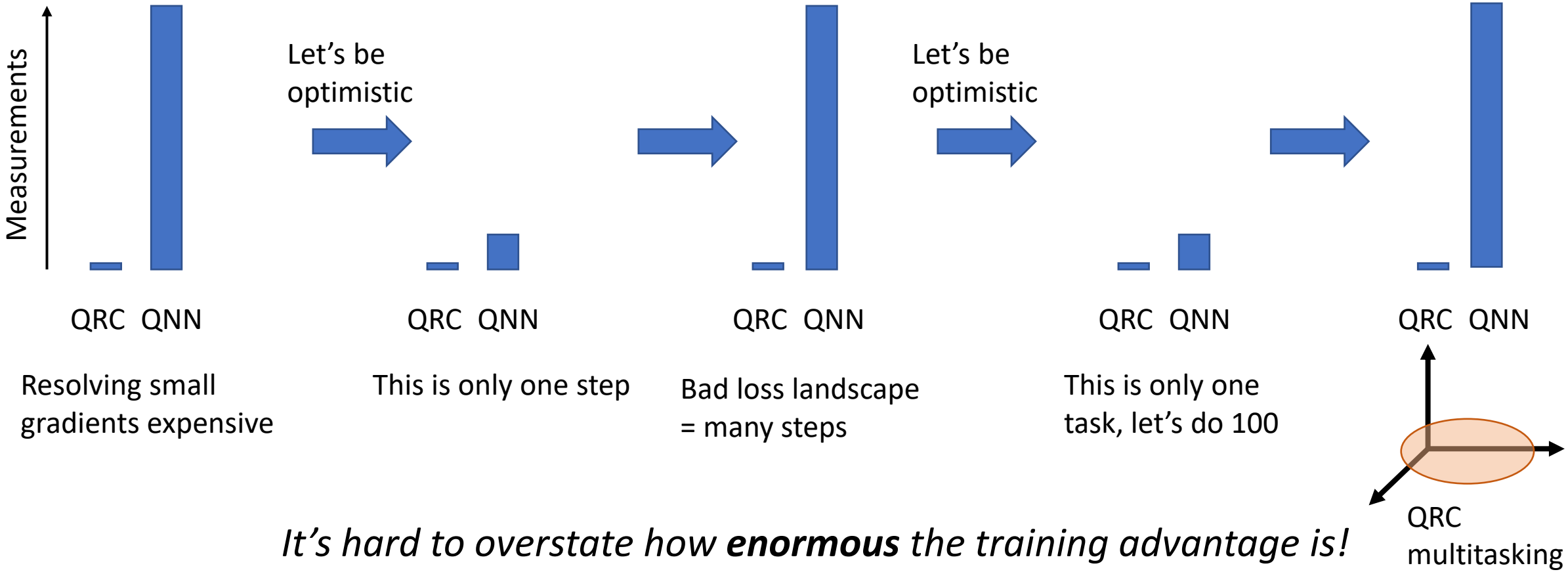
QRC multitasking

- Training = C post-processing of measurement results

- Train for different task = different post-processing of same results!

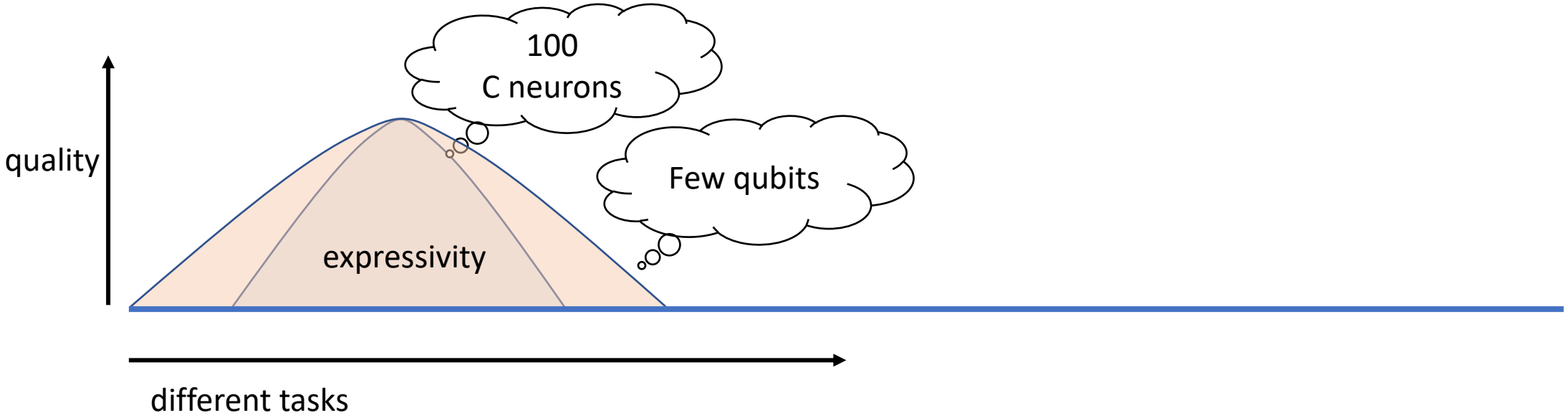


Compare with Q alternatives



*It's hard to overstate how **enormous** the training advantage is!*

Compare with C alternatives



The chief motivation since the beginning

- sporadic appearances of others

This *alone* enough?

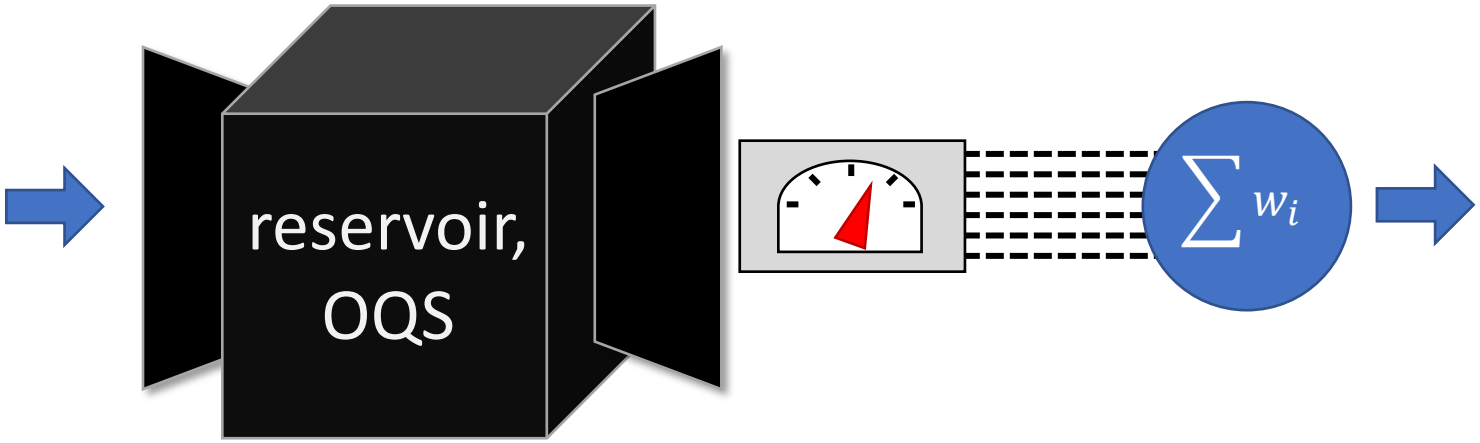
- Not yet, C approaches scalable to millions+ neurons
- Perhaps never, don't use QC to send email

	Classical NN	QNN	QRC
Scalability	★ ★ ★ ★ ★	★	★ – ★ ★
Expressivity	★ ★ ★	★ ★ ★ ★ ★	★ ★ ★
Trainability	★ ★ ★	★	★ ★ ★ ★ ★
Status	Commercialized	Proof-of-principle	Proof-of-principle

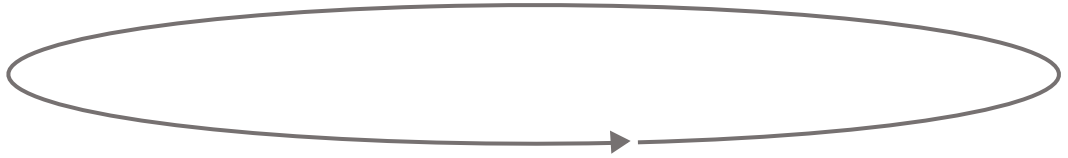
Examples & challenges

Making a Photonic QRC

- Reservoir?
- Input mechanism?
- Readout mechanism?



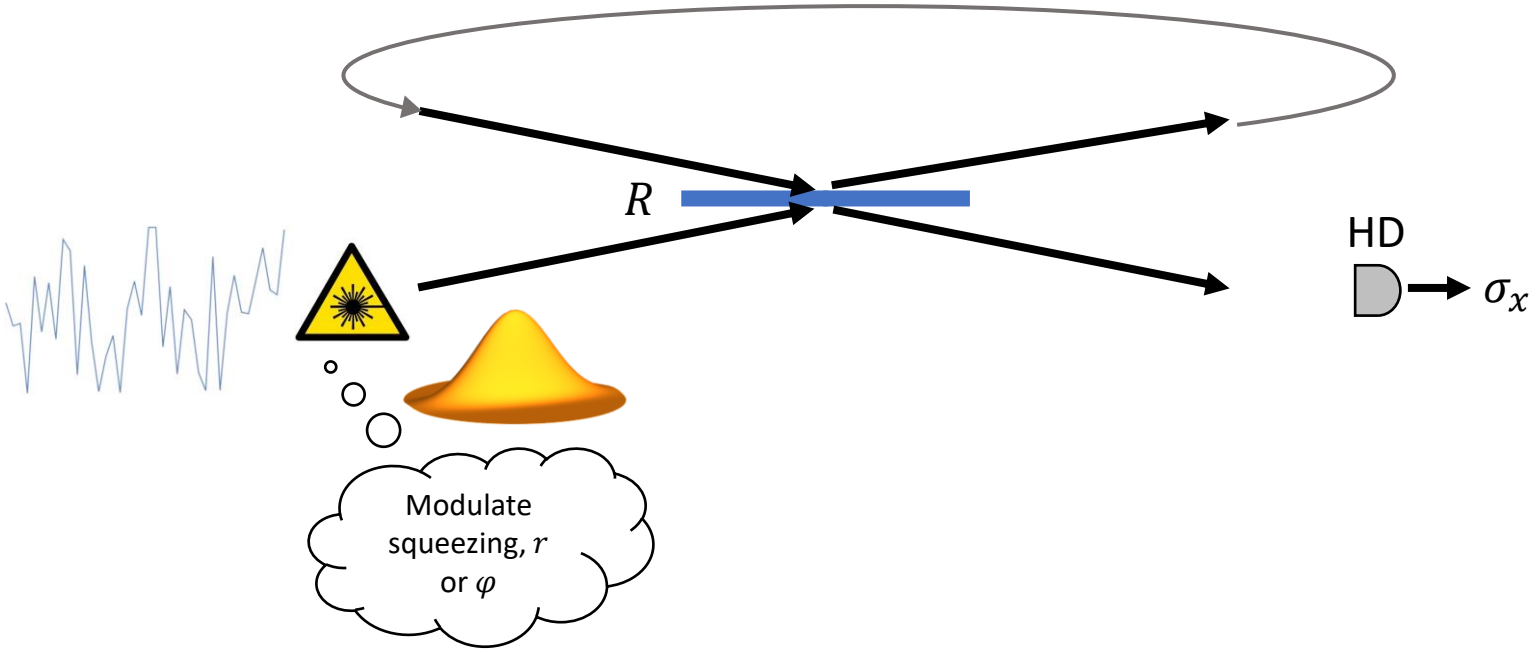
Simple reservoir: modes in fiber loop



For simplicity:
lossless

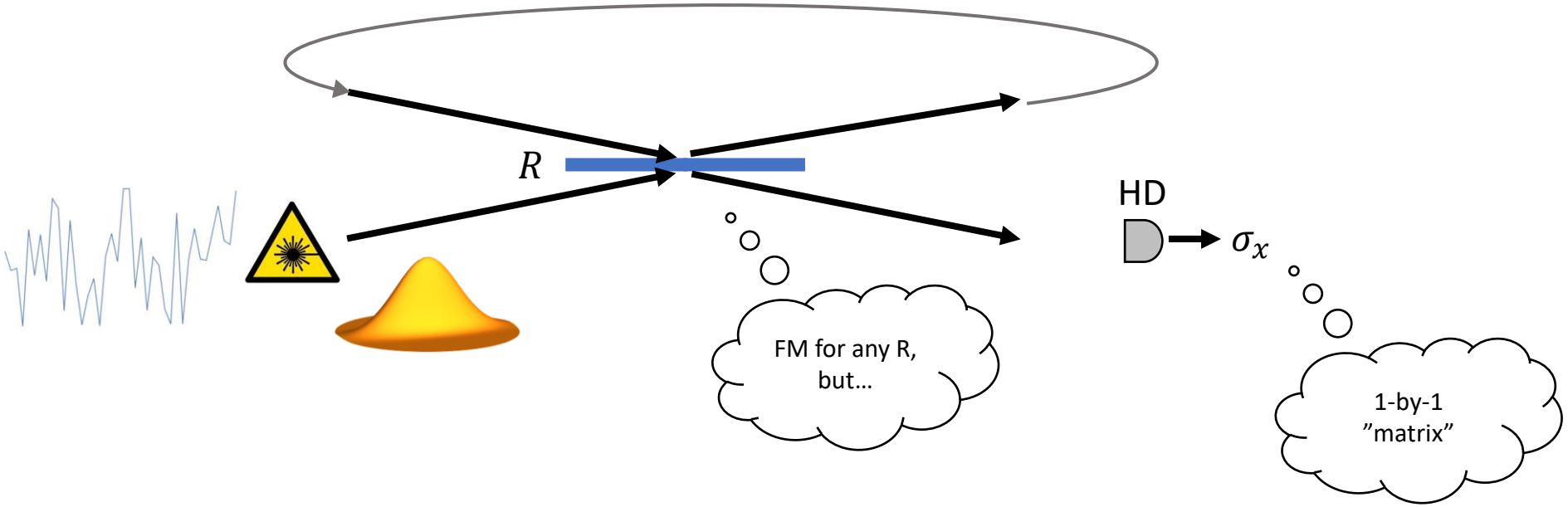
García-Beni, Jorge, et al.
Physical Review Applied 20.1
(2023): 014051.

Simple I/O mechanism: must be open!



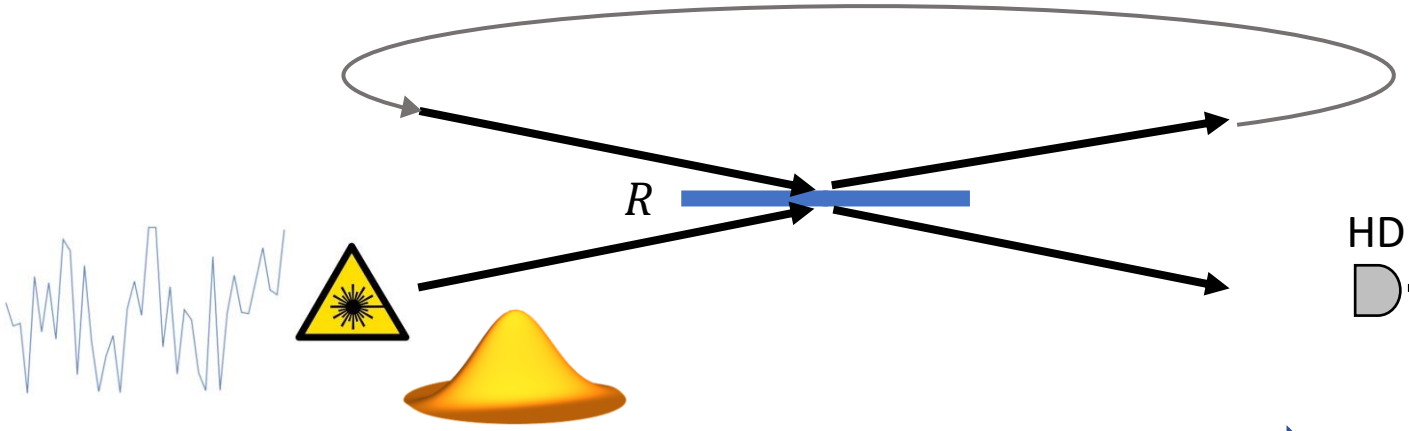
García-Beni, Jorge, et al.
Physical Review Applied 20.1
(2023): 014051.

Just one mode?



García-Beni, Jorge, et al.
Physical Review Applied 20.1
(2023): 014051.

Simple training



HD → σ_x ---------- $\sum w_i$

Bias
(Degree
0 term)

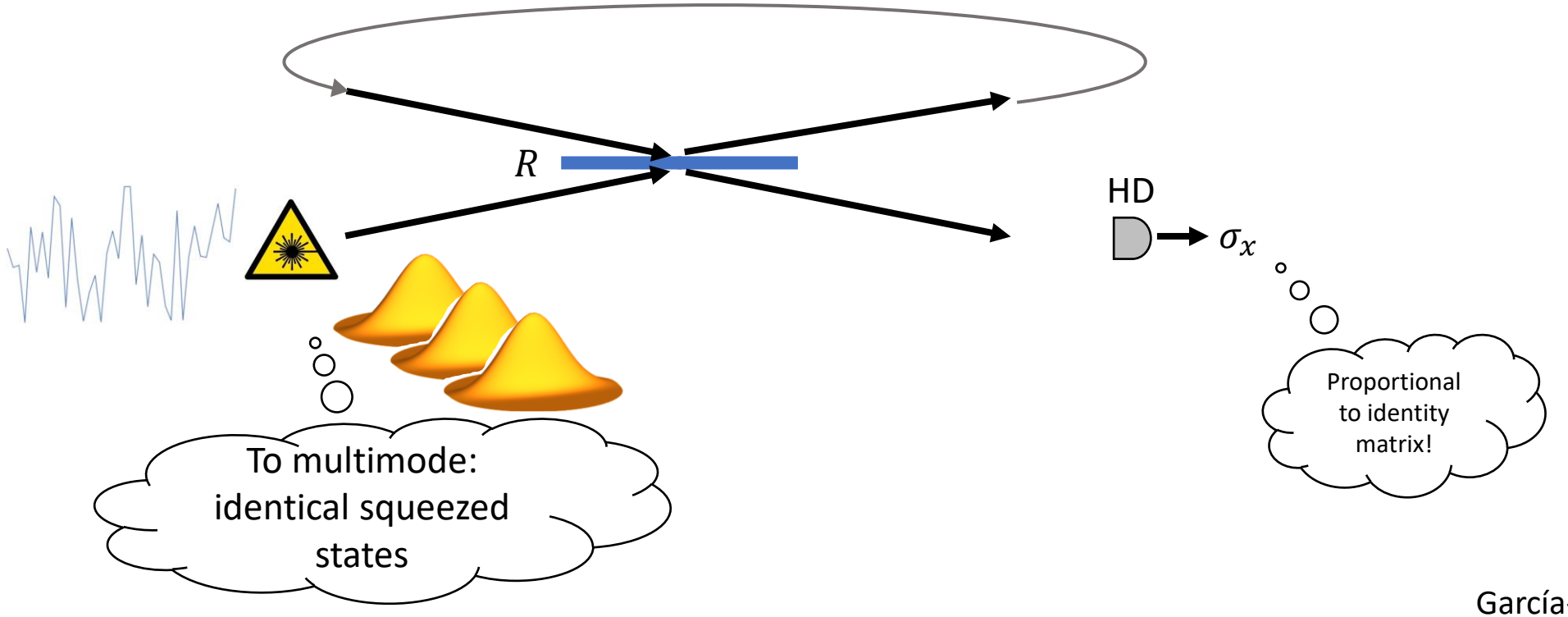
Fixed!

$$f(t) = w_1 F[s_t, s_{t-1}, s_{t-2}, \dots] + w_0$$

At least nonlinear

García-Beni, Jorge, et al.
Physical Review Applied 20.1
(2023): 014051.

Many modes

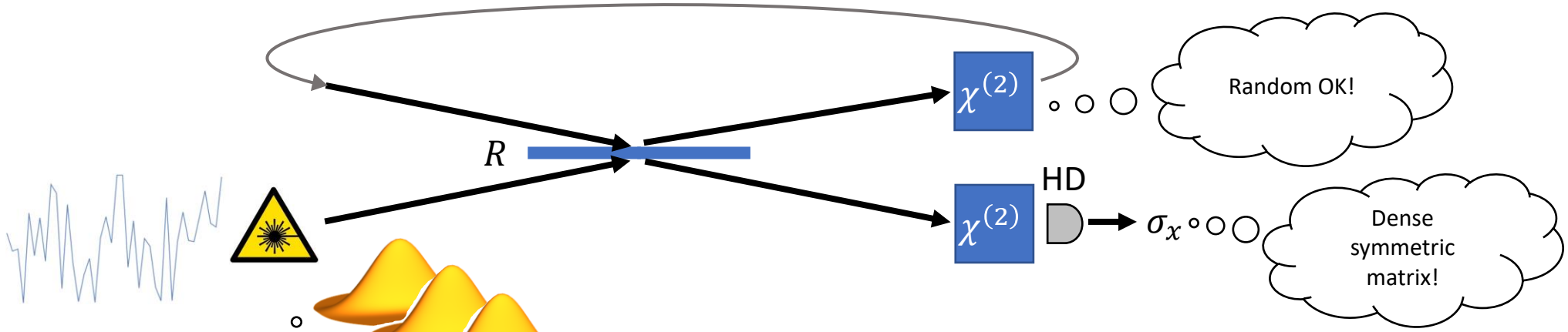


García-Beni, Jorge, et al. Physical Review Applied 20.1 (2023): 014051.

Many modes

$$H_{\chi^{(2)}} = \sum_{j=1}^{N} \omega_j \left(a_j^\dagger a_j + {}^1/_2 \right)$$

$$+ \sum_{l>j} \left(g_{jl} a_j^\dagger a_l + \mathrm{i} h_{jl} a_j^\dagger a_l^\dagger + \mathrm{h.c.} \right)$$



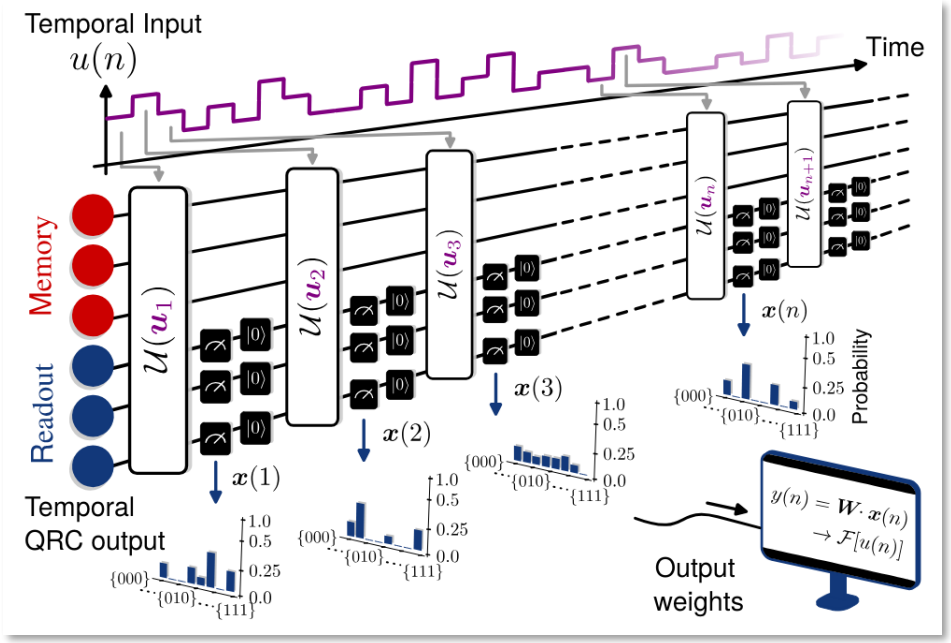
$N(N+1)/2$ computational nodes!

Lin. independence enough

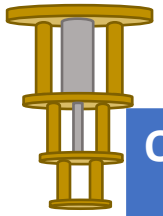
García-Beni, Jorge, et al. Physical Review Applied 20.1 (2023): 014051.

Qubit example: IBM platforms

- Mid circuit measurements & reset, separation of memory & readout qubits
- Fading memory that tolerates readout & erases even decoherence!



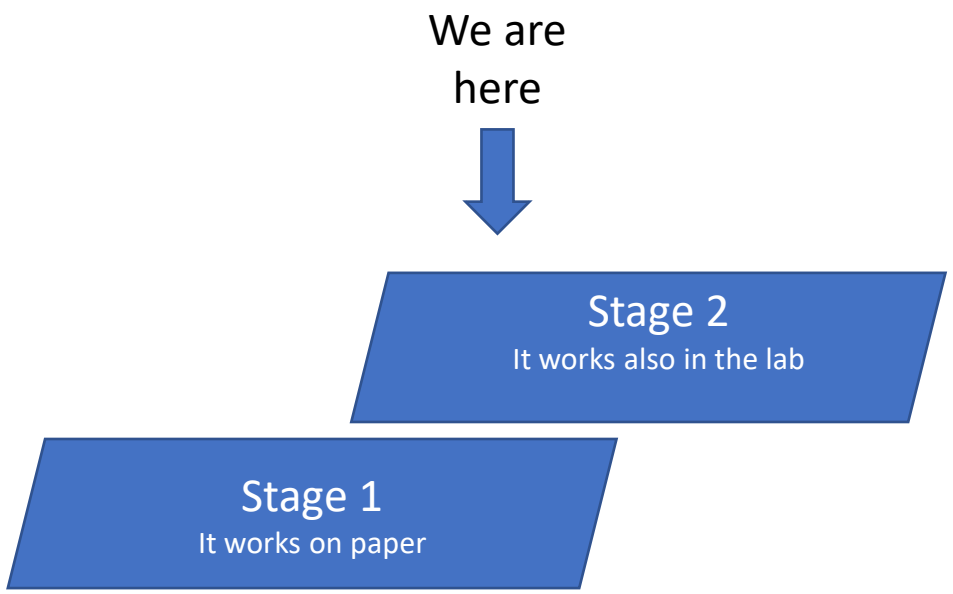
Hu, Fangjun, et al.
arXiv preprint arXiv:2312.16165 (2023)



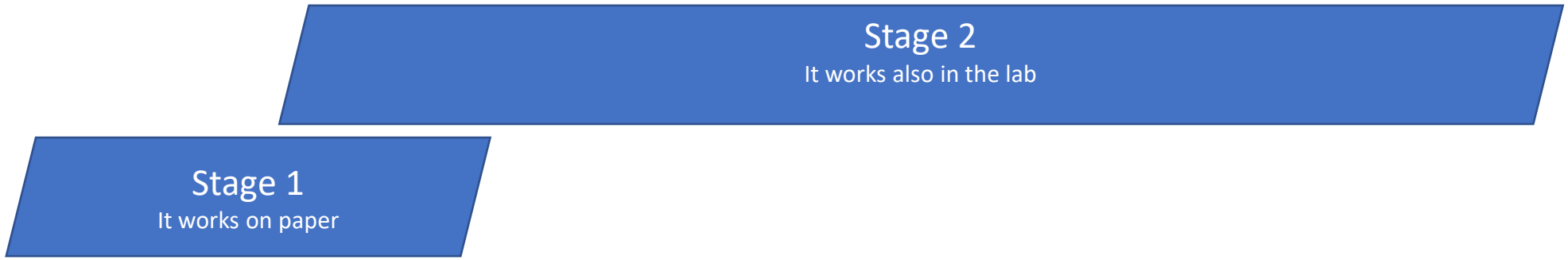
HD

Qubit QRC	Photonic QRC
Tends to be QC platform esp. experimental demos	Analog quantum optical device

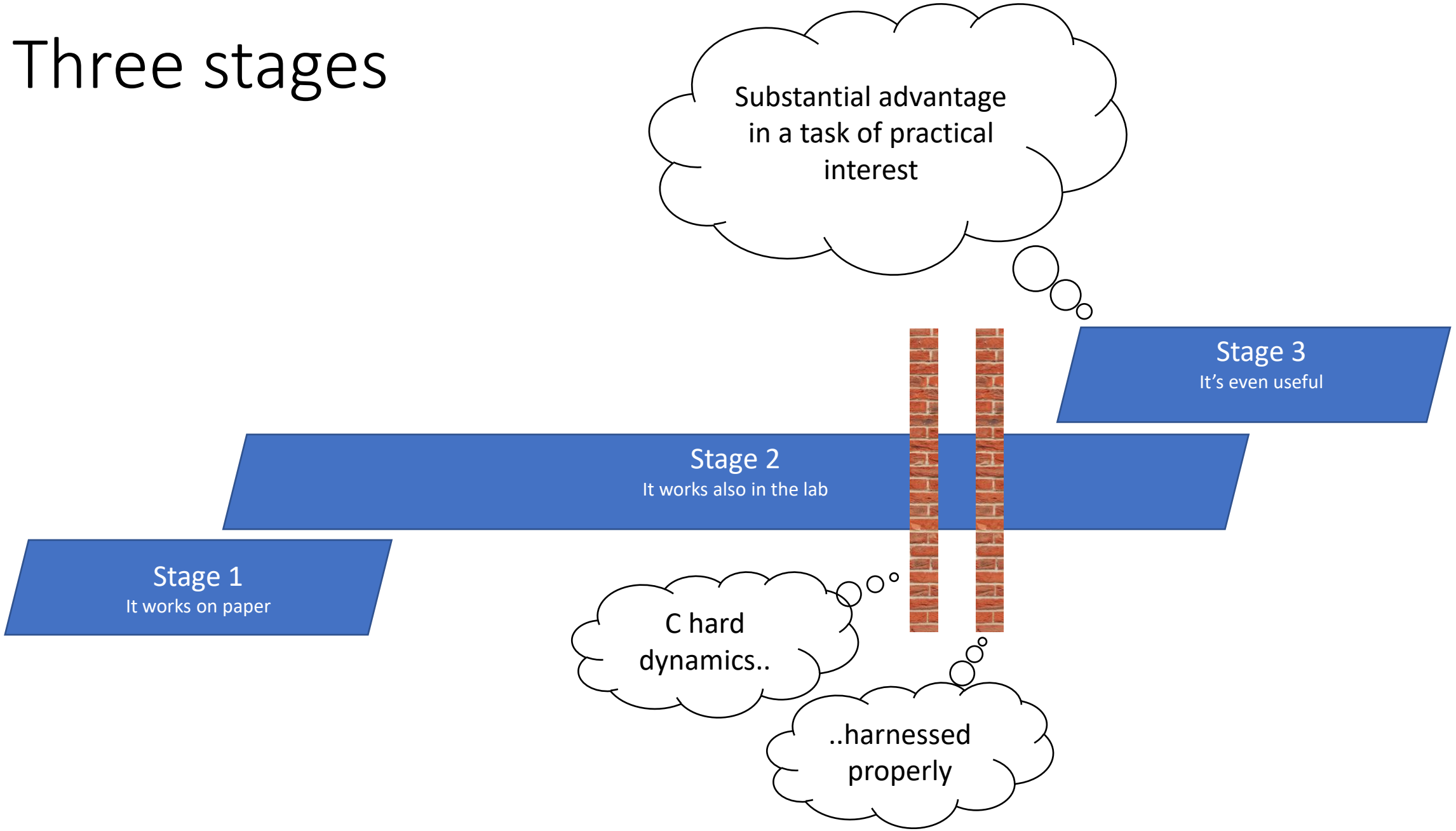
Three stages



Three stages

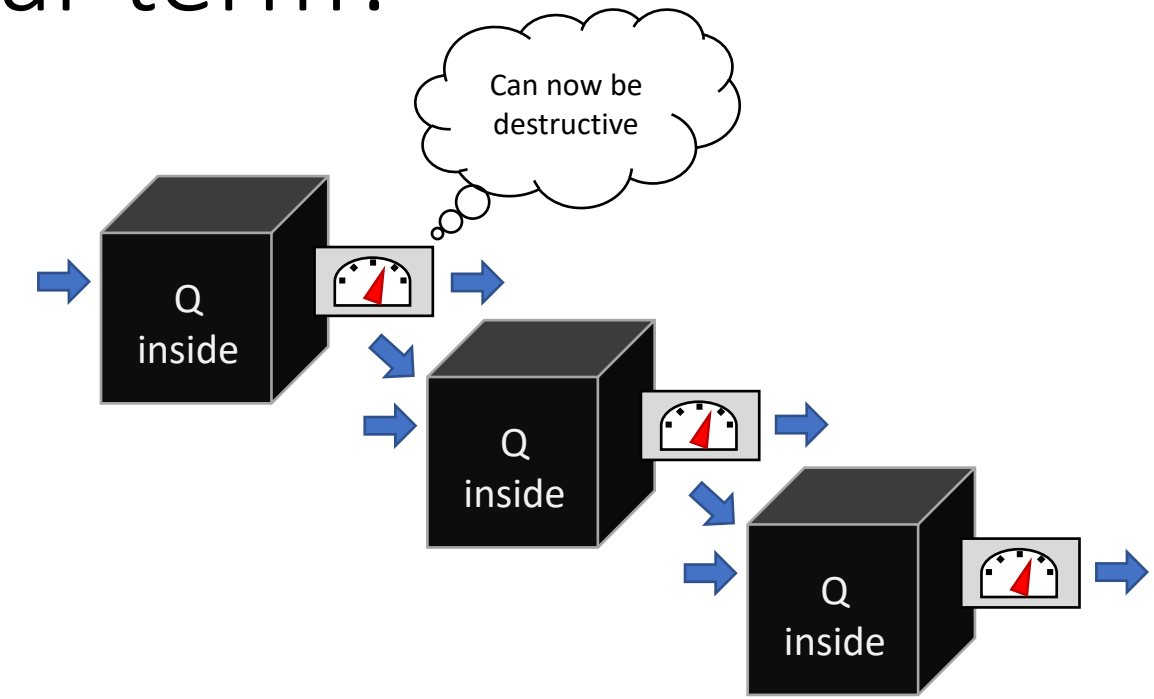


Three stages



Schemes optimal in near term?

- Recent trend: C feedback
  - Helps with decoherence, output extraction
- Scalability??
  - noisy qubits??
  - Photonic side: GBS (others) + CV & de-Gaussification (me)



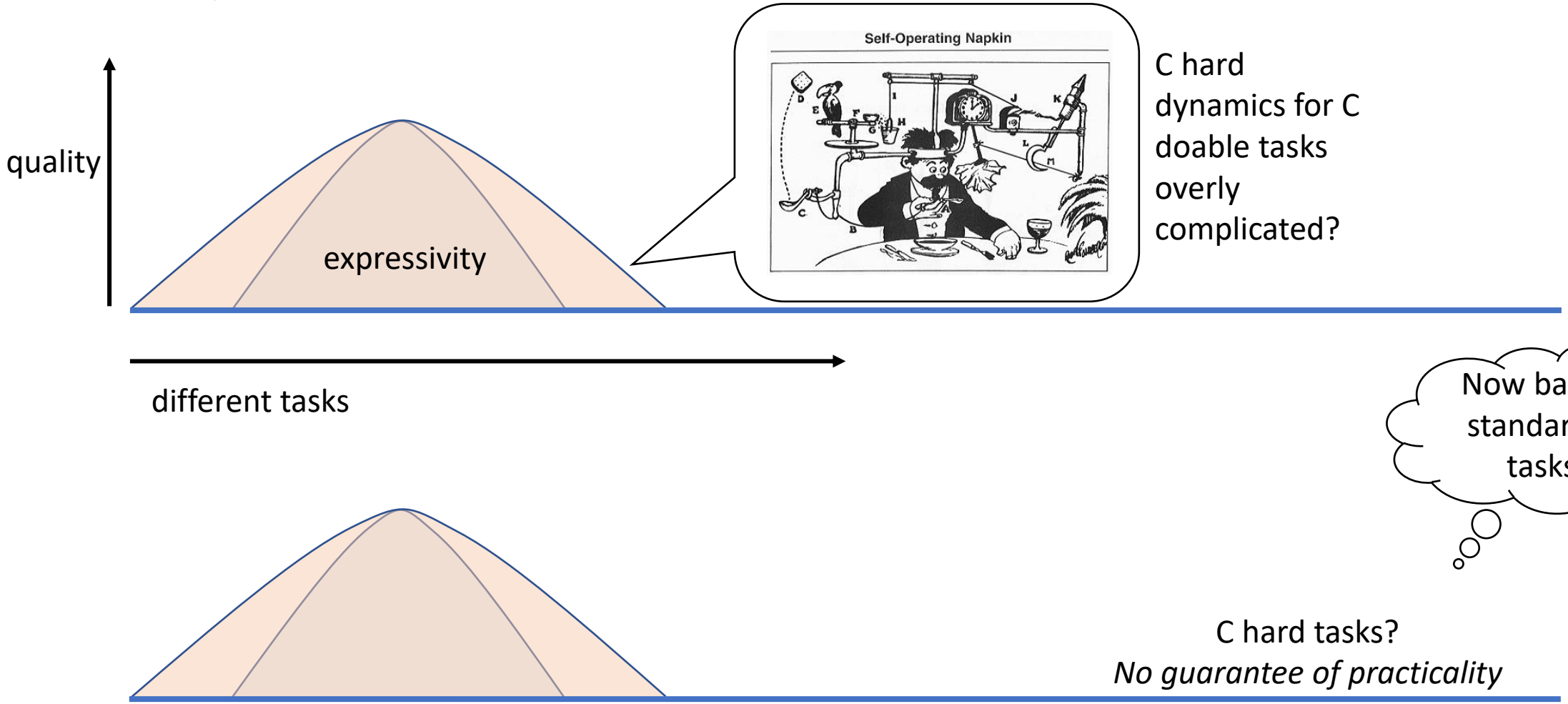
"Quantum optical reservoir computing powered by boson sampling." *Optica Quantum* 3.3 (2025): 238-245.

"Large-scale quantum reservoir computing using a Gaussian Boson Sampler." *arXiv preprint arXiv:2505.13695* (2025).

The problem with ML tasks

Conventional algorithm	ML

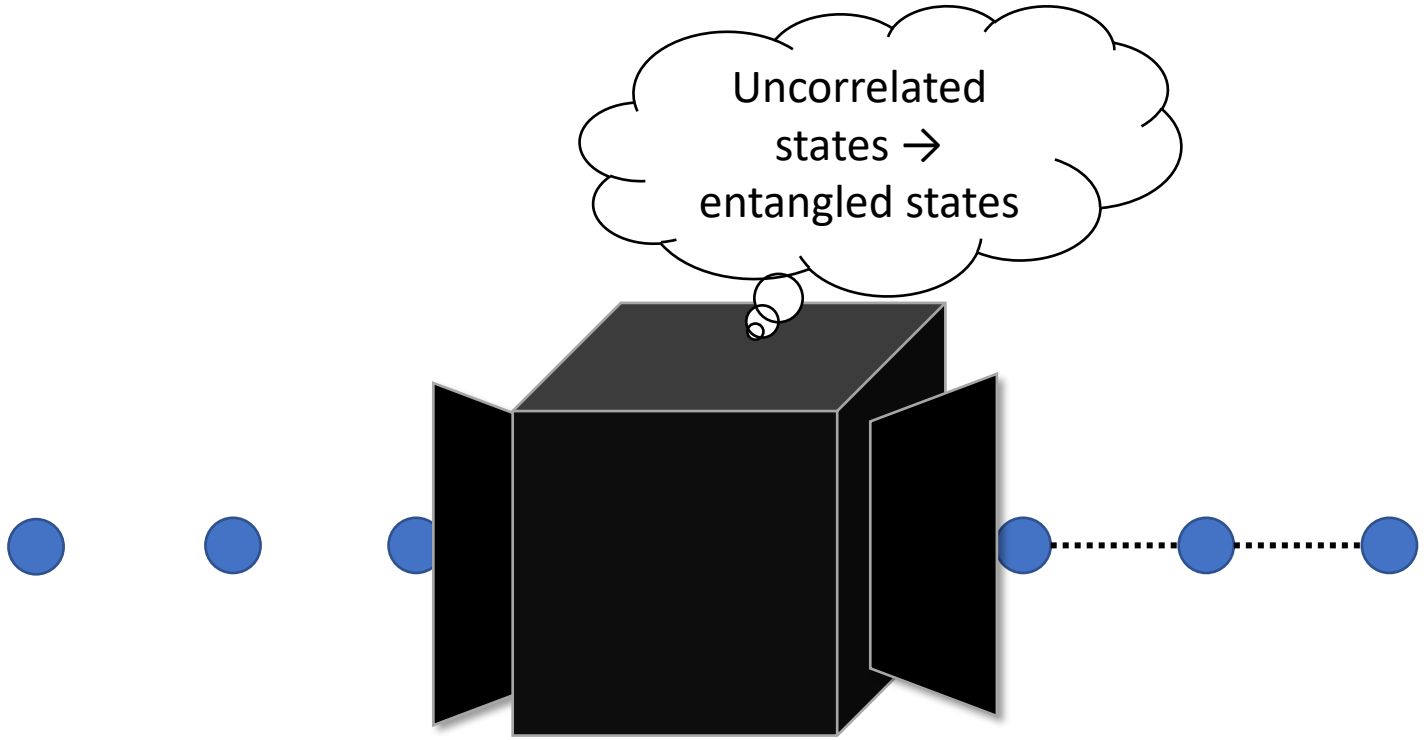
The problem with tasks from C literature



By Rube Goldberg - Originally published in Collier's, September 26 1931, Public Domain

Alternative: tasks without C counterpart

- State preparation
- Gate synthesis
- Entangler ☞



Nokkala, Johannes. Scientific Reports 13.1 (2023): 7694.

QRC: potential for near term QML tech

- Engineering freedom, training advantage, multitasking
- Field is moving to experimental demonstrations & expanding to Q tasks
- Important challenge: reach C hard regime, harness it for a substantial advantage in a task of practical interest