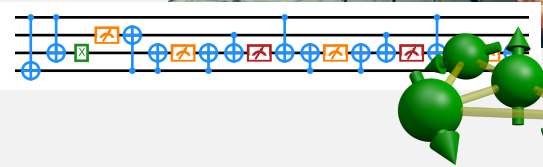
Reinforcement Learning for Quantum Memory

Thomas Fösel

Marquardt group
Max Planck Institute for the Science of Light
Erlangen, Germany

May 8th, 2019



MPL
Max Planck Institute
for the science of light

[T. Fösel, P. Tighineanu, T. Weiss & F. Marquardt, PRX 8, 031084 (2018)]

AlphaGo

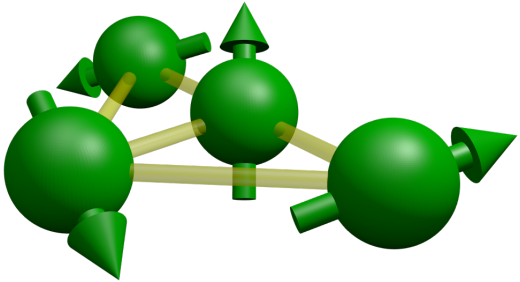
Oct 2015
Fan Hui
5:0

Mar 2016
Lee Sedol
4:1

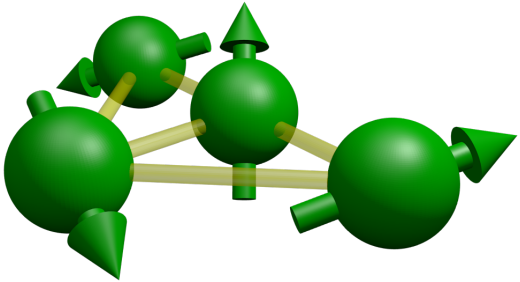
May 2017
Ke Jie
3:0

What are the “games” that we play in physics?

e. g.: manipulating quantum systems

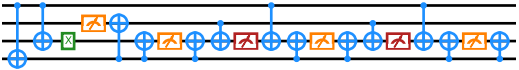


e. g.: manipulating quantum systems



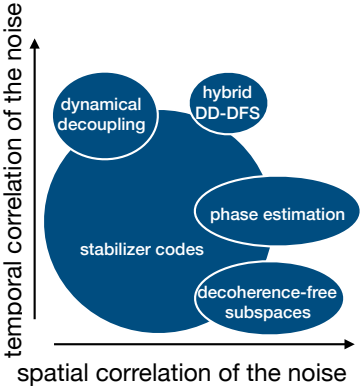
unexperienced (random)

reinforcement learning
(no human guidance!)

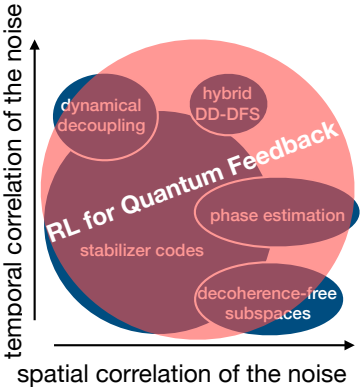


smart

Quantum error correction: the RL approach



Quantum error correction: the RL approach



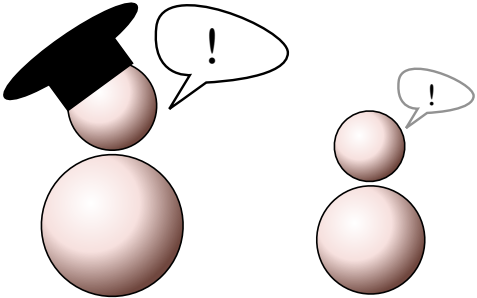
long-term vision: unified approach to quantum error correction

Reinforcement learning example: Go

[Silver et al., Nature 529, 484-489 (2016)] [Silver et al., Nature 550, 354-359 (2017)]

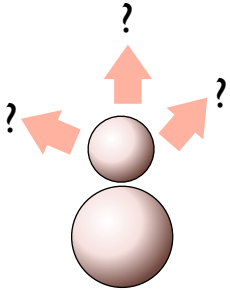
Supervised learning vs. reinforcement learning

supervised learning



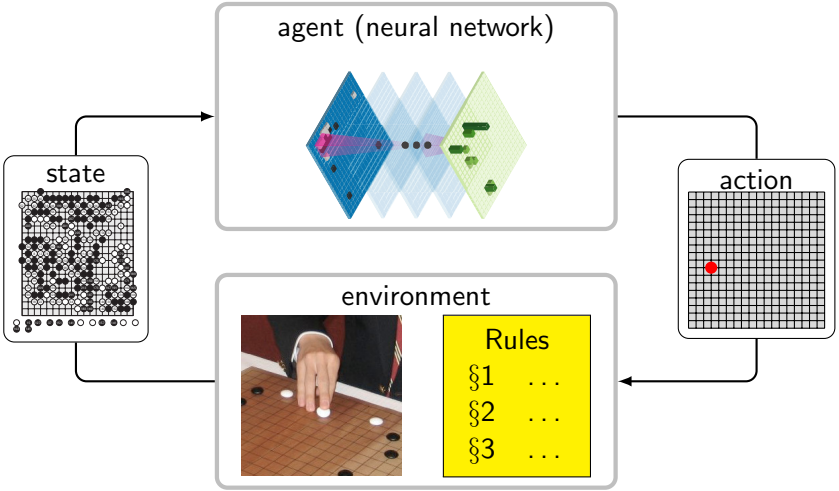
teacher student

reinforcement learning



develop own strategies
(no teacher)

(Model-free) reinforcement learning: basic setup



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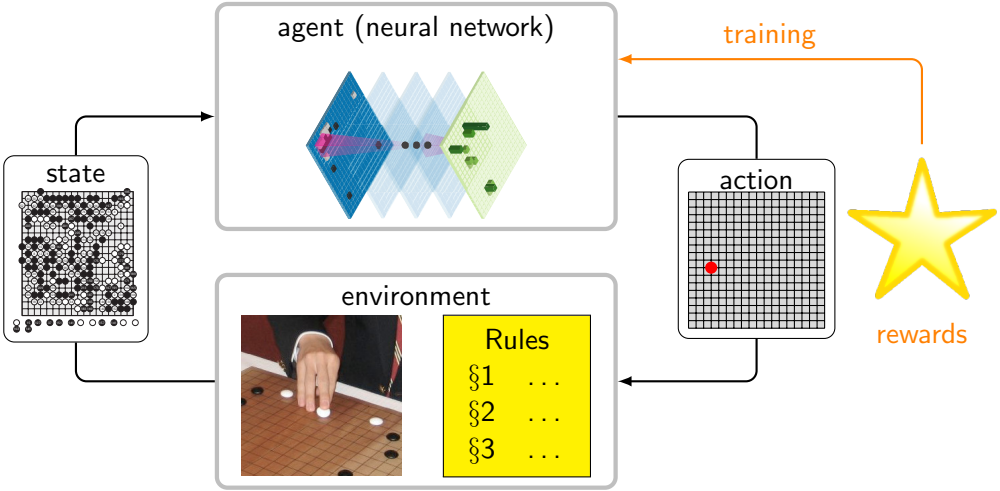
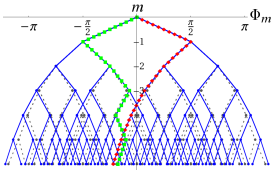


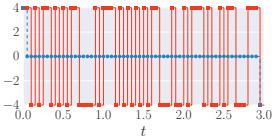
Prior applications of reinforcement learning in physics

quantum phase estimation



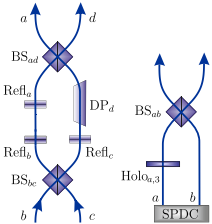
[Hentschel & Sanders, PRL 104, 063603 (2010)]

quantum control



[Bukov et al., PRX 8, 031086 (2018)]

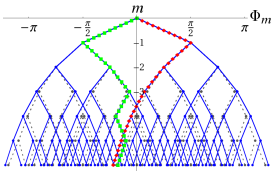
design quantum optics experiments



[Melnikov et al., PNAS, 201714936 (2017)]

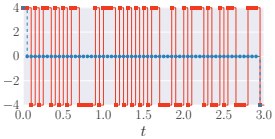
Prior applications of reinforcement learning in physics

quantum phase estimation



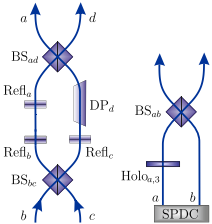
[Hentschel & Sanders, PRL 104, 063603 (2010)]

quantum control



[Bukov et al., PRX 8, 031086 (2018)]

design quantum optics experiments



[Melnikov et al., PNAS, 201714936 (2017)]

we:

- address new problem: build complete QEC protocol
- introduce model-free RL with neural networks in physics

Overview: machine learning for quantum error correction

QEC decoding problem

- surface/toric code
  [Torlai & Melko, PRL 119, 030501 (2017)]
  [Baireuther et al., Quantum 2, 48 (2018)]
  [Krastanov & Jiang, Sci. Rep. 7, 11003 (2017)]
  [Sweke et al., arXiv:1810.07207]
- color code
  [Baireuther et al., NJP 21.1, 013003 (2019)]

QEC protocol optimization

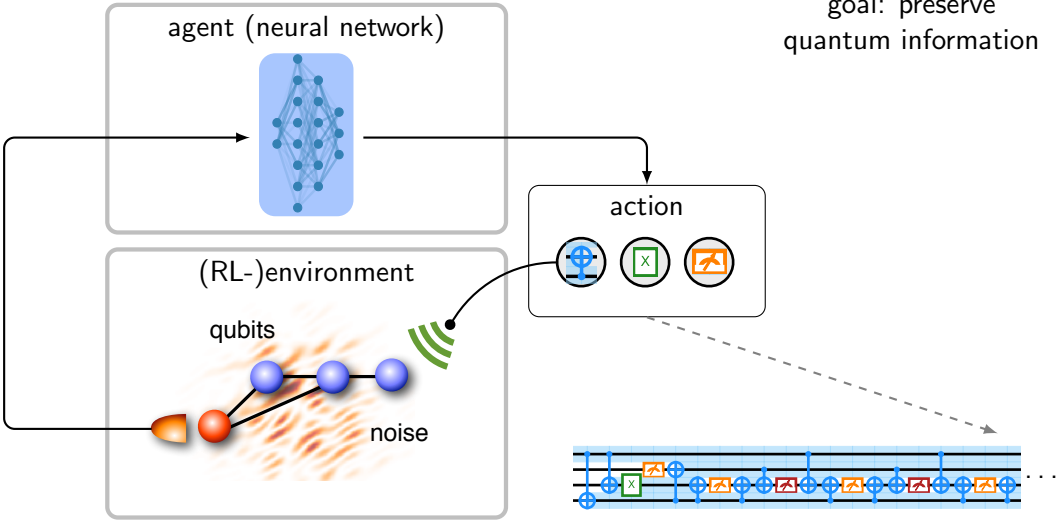
- bang-bang protocols
  [Bukov et al., PRX 8, 031086 (2018)]
- QVECTOR [Johnson et al., arXiv:1711.02249]
- (model-free) RL approach
  [August & Hernández-Lobato, arXiv:1802.04063]
  [Fösel et al., PRX 8, 031084 (2018)]

related problems:

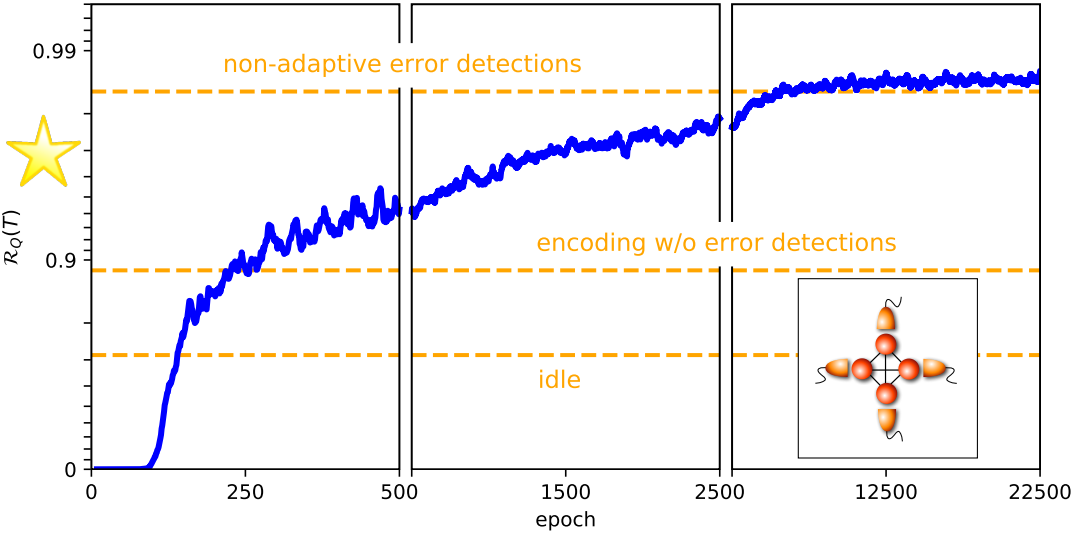
- quantum phase estimation [Hentschel & Sanders, PRL 104, 063603 (2010)] [Hentschel & Sanders, PRL 107, 233601 (2011)] [Palittapongarnpim et al., Neurocomputing 268, 116-126 (2017)]
- design quantum optics experiments [Melnikov et al., PNAS, 201714936 (2017)]
- quantum control [Niu et al., arXiv:1803.01857] [Porotti et al., arXiv:1901.06603]
- search QEC codes [Nautrup et al., arXiv:1812.08451]

Reinforcement learning setup for quantum memory

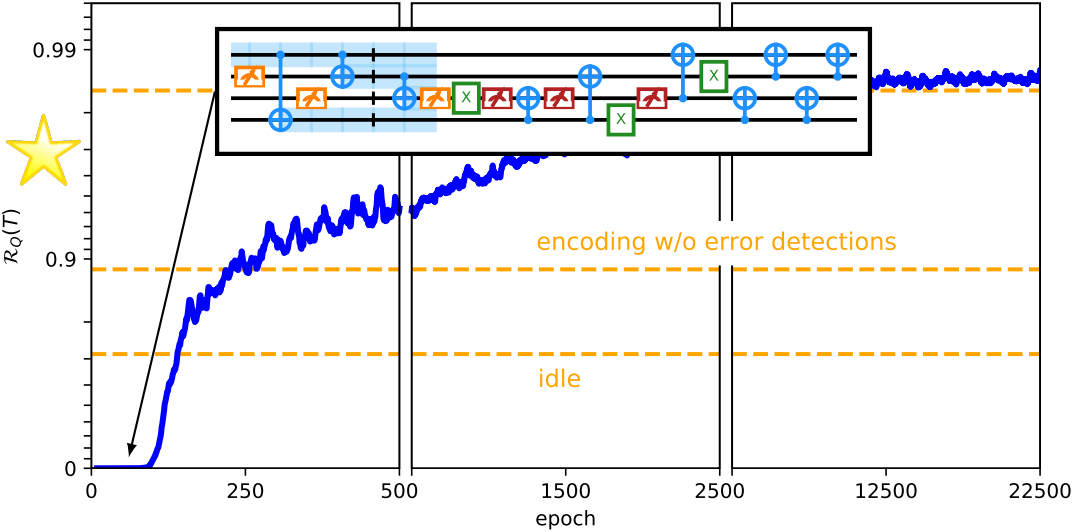
goal: preserve quantum information



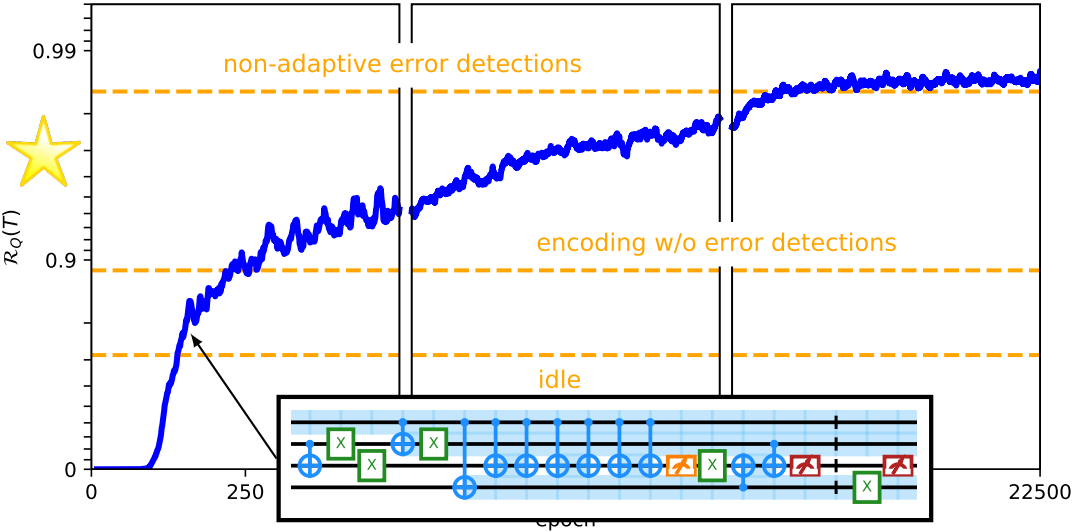
Training progress



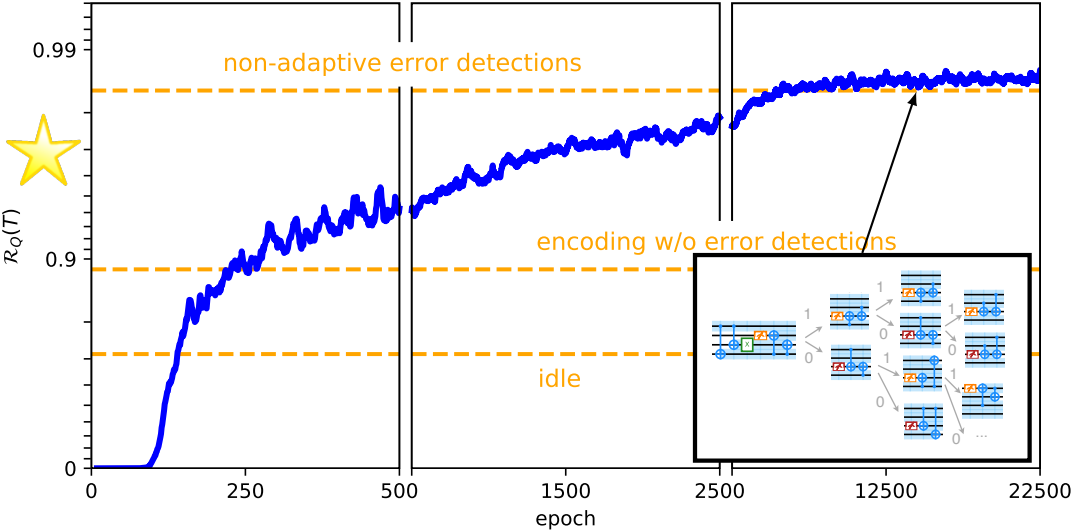
Training progress



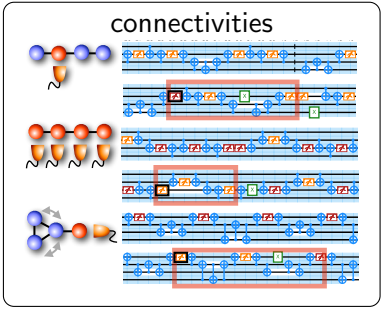
Training progress

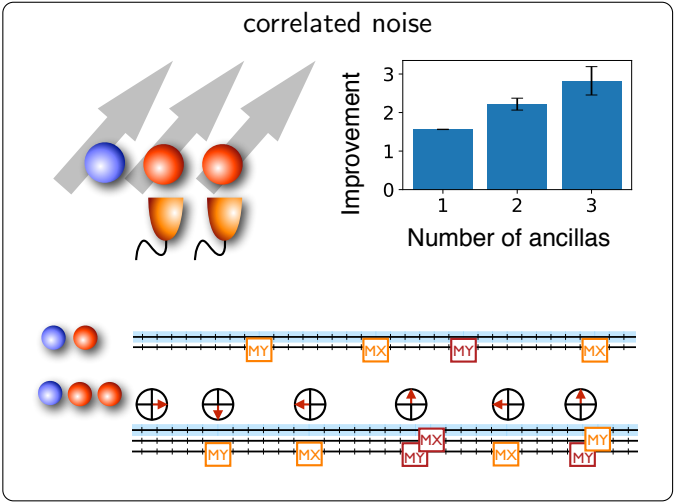


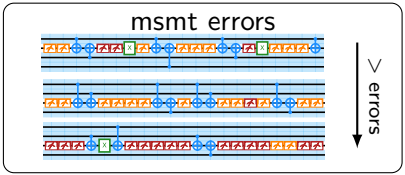
Training progress



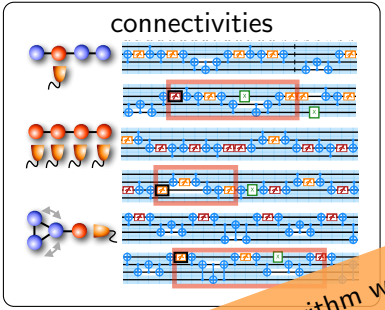
Flexibility

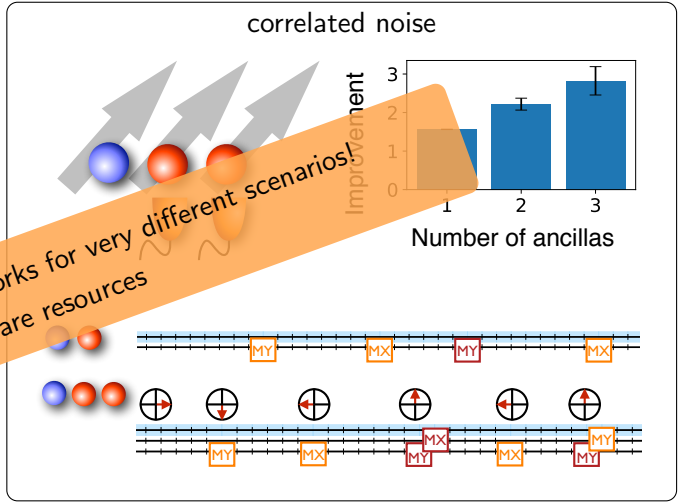






Flexibility



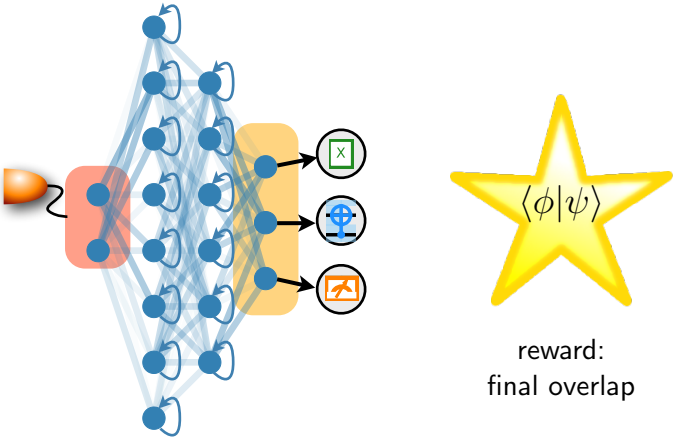


same algorithm works for very different scenarios!

tailored to hardware resources

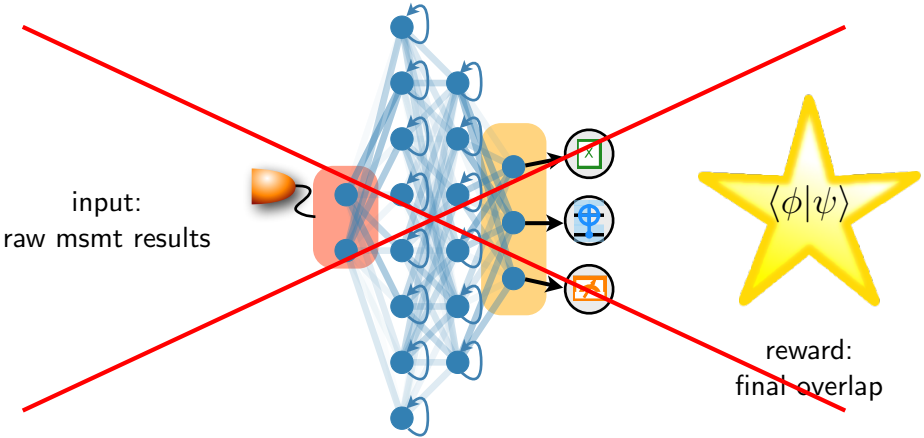
Naive approach

input:
raw msmt results



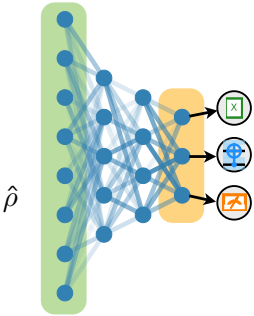
reward:
final overlap

Naive approach

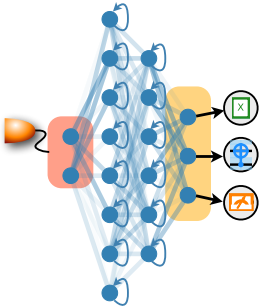


does not work!!! (at least with present-day RL techniques)

Two-stage learning

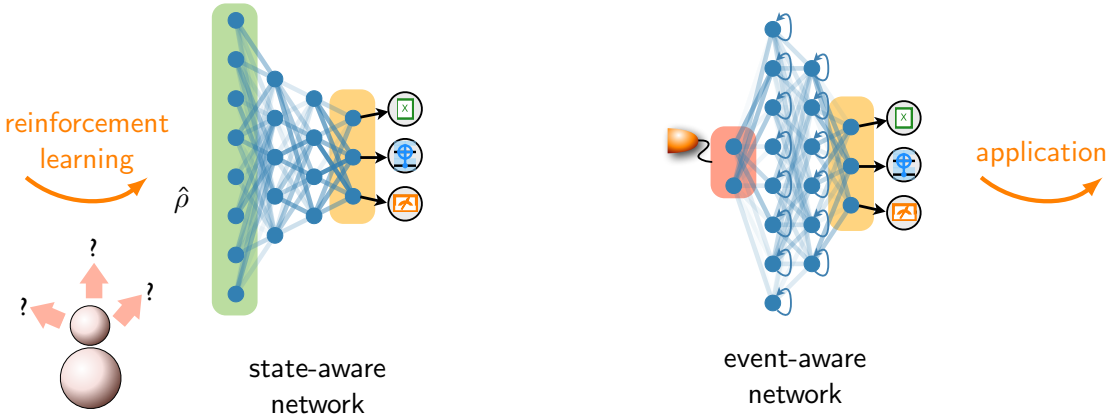


state-aware network

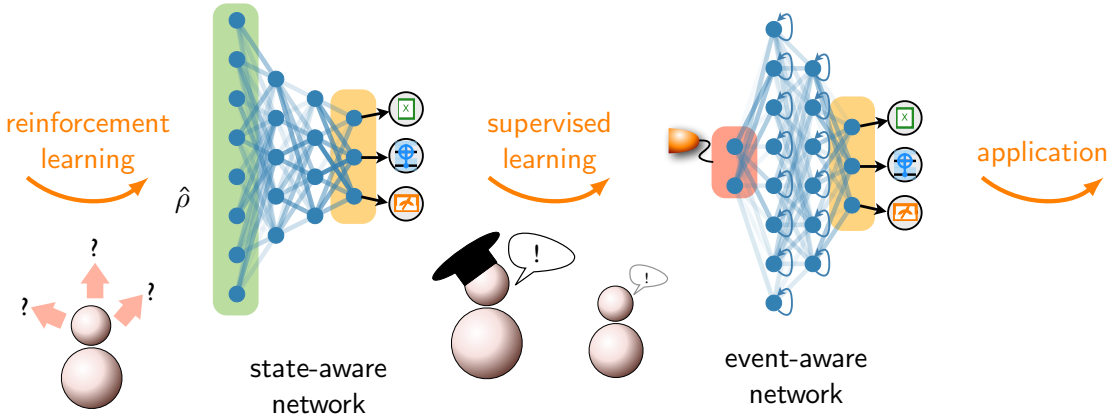


event-aware network

Two-stage learning



Two-stage learning



What about the reward?

problem with reward $\sim |\langle\phi|\psi\rangle|$: sequence must be **completely correct**

- include encoding, error detection, error correction, and decoding
- in particular: don't collapse superposition state with a msmt!

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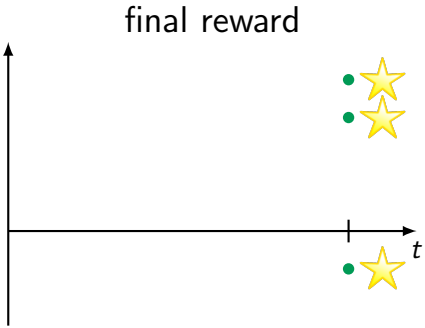
problem with reward $\sim |\langle\phi|\psi\rangle|$: sequence must be **completely correct**

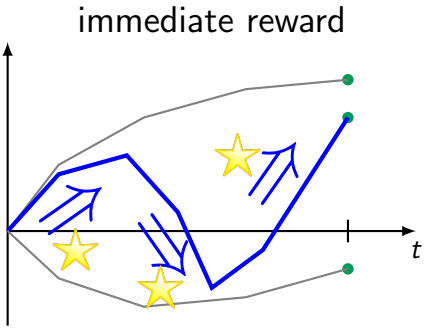
- include encoding, error detection, error correction, and decoding
- in particular: don't collapse superposition state with a msmt!

probability to randomly find good sequence:

$$\ll 10^{-20}$$

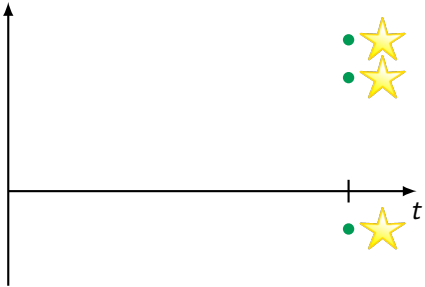
Final vs. immediate reward scheme



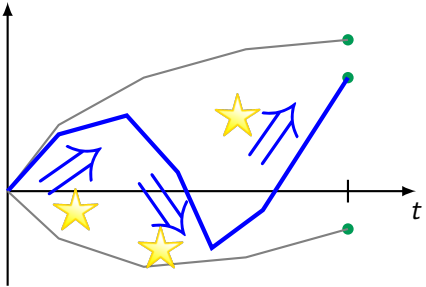


Final vs. immediate reward scheme

final reward



immediate reward



↓

for QEC: requires quantity which tells
"How much qu. info is still left?"

Recoverable quantum information

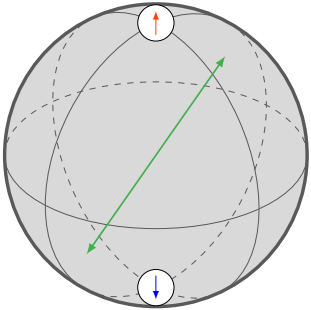
question: "How much quantum information is still left?"

$$\Updownarrow$$

eq. (under a few conditions): How well can antipodal logical states be distinguished?

$$\mathcal{R}_{\mathrm{Q}} = \min_{\vec{n}} \frac{1}{2} \left\| \hat{\rho}_{\vec{n}} - \hat{\rho}_{-\vec{n}} \right\|_1$$

recoverable
quantum information



Conclusion and Outlook

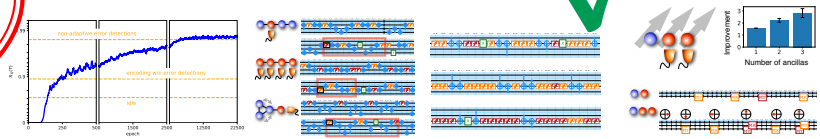
more difficult problems (higher qubit numbers, . . .)

better learning algorithms

more efficient physics engine

PRX 2018

last year: proof of concept



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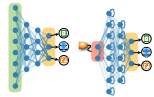

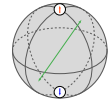

recoverable quantum information