Demonstration of Fidelity Improvement Using Dynamical Decoupling with Superconducting Qubits

Bibek Pokharel

University of Southern California

USC Viterbi School of Engineering

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GOAL

Suppress memory errors on open-access cloud based quantum computers (using Dynamical Decoupling)

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Outline

- Qubits!
- Dynamical decoupling (DD)?
- Experimental Setup - IBM and Rigetti
- What did we find?

Dynamical decoupling:

1. removes initial condition dependence of fidelity,
2. improves fidelity of single qubit states, and
3. slows decay of entanglement. <- ask me about this later!

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Qubits

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- Bits – 0 and 1
- Qubits – superposition of 0 and 1

  a <u>**0**</u> + b <u>**1**</u> where a & b are complex numbers

  and $|a|^2$ and $|b|^2$ are probabilities

- Example:
  - $\frac{1}{2}\underline{\mathbf{0}} + \frac{3}{2}\underline{\mathbf{1}}$ ==> ¼ probability of 0 and ¾ probability of 1
  - $\frac{1}{\sqrt{2}}\underline{\mathbf{0}} + \frac{i}{\sqrt{2}}\underline{\mathbf{1}}$ ==> ½ probability of 0 and ½ probability of 1

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Qubits on a sphere

- Bits – 0 and 1
- Qubits – superposition of 0 and 1 - $\frac{1}{2}\underline{\mathbf{0}} + \frac{3}{2}\underline{\mathbf{1}}$

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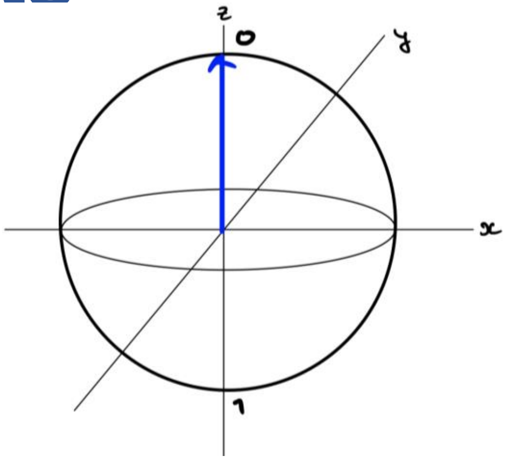
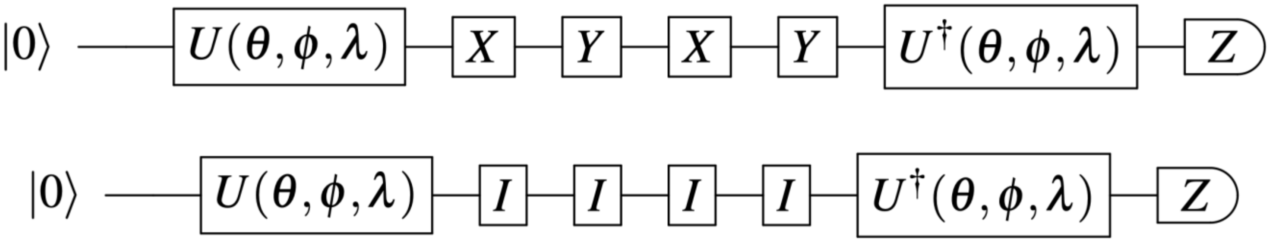
Quantum circuits

- Bits – 0 and 1
- Qubits – superposition of 0 and 1 - $\frac{1}{2}\underline{\mathbf{0}} + \frac{3}{2}\underline{\mathbf{1}}$



- Qubits are wires, boxes are gates / operations / transformations



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Gates as transformations

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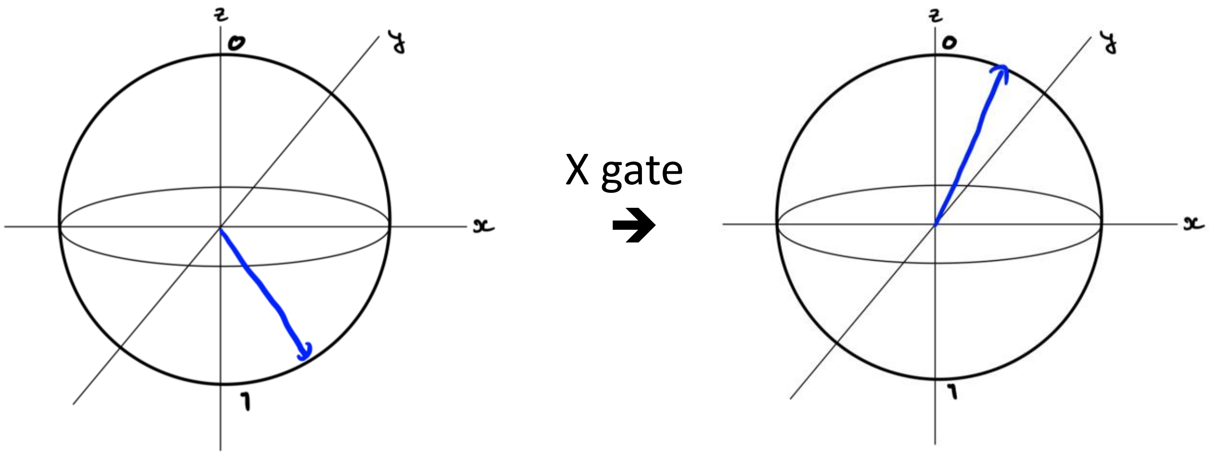
- Qubits are vectors, gates are matrices
- For single qubits, think of gates are rotations and reflections of the sphere
- Rotation i.e. choose an axis and an angle to rotate by



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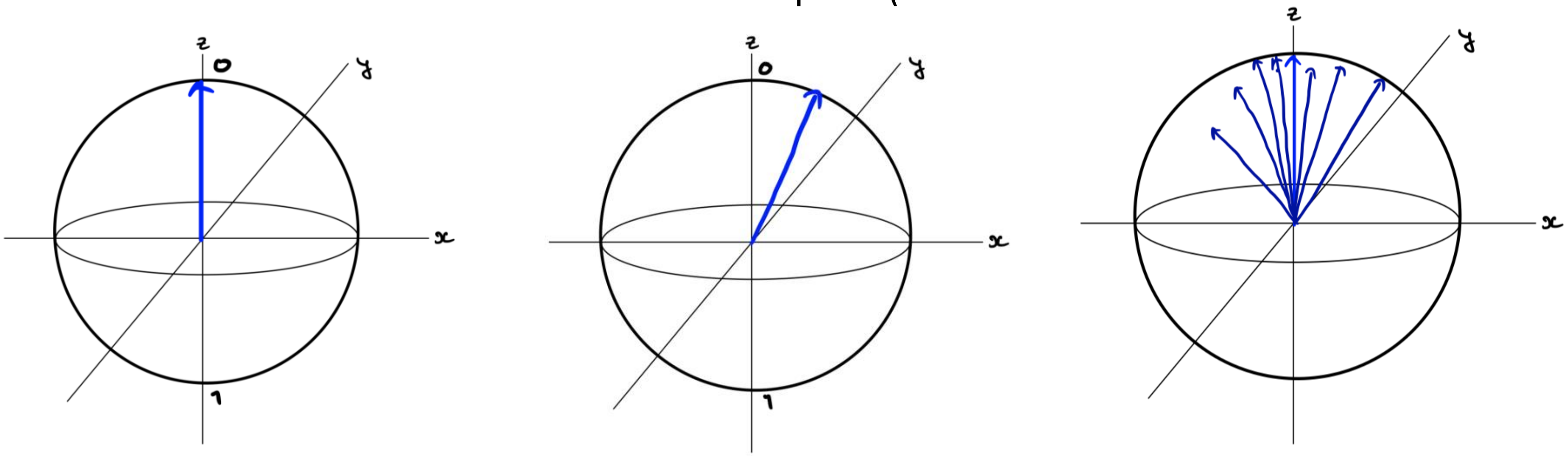
Noise as unknown rotation

- For single qubits, think of gates are rotations and reflections of the sphere
- Rotation i.e. choose an axis and an angle to rotate by
- Noise – rotates in a direction with some speed (both unknown)



Initial condition | After some time | Multiple realizations

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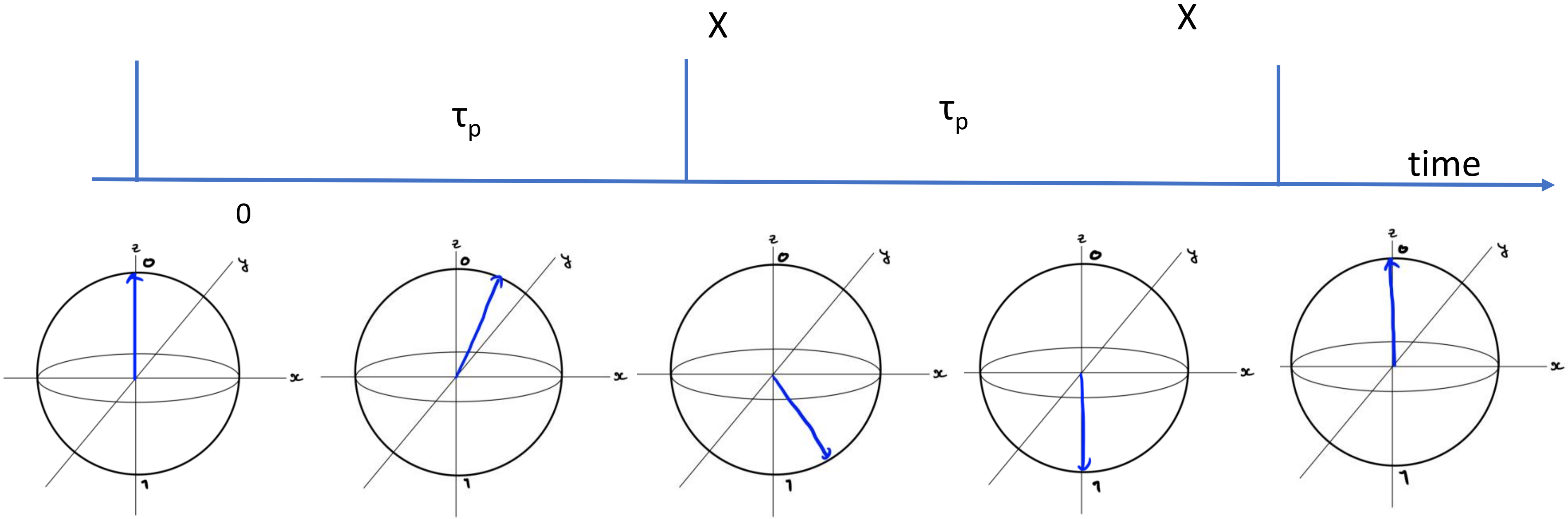
Single axis rotation



- Assume noise only on the XZ plane

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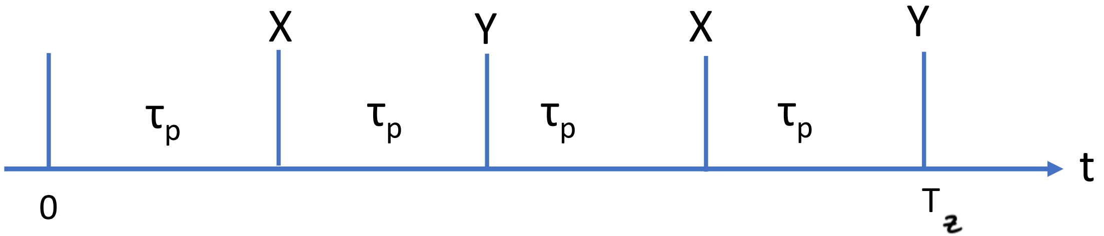
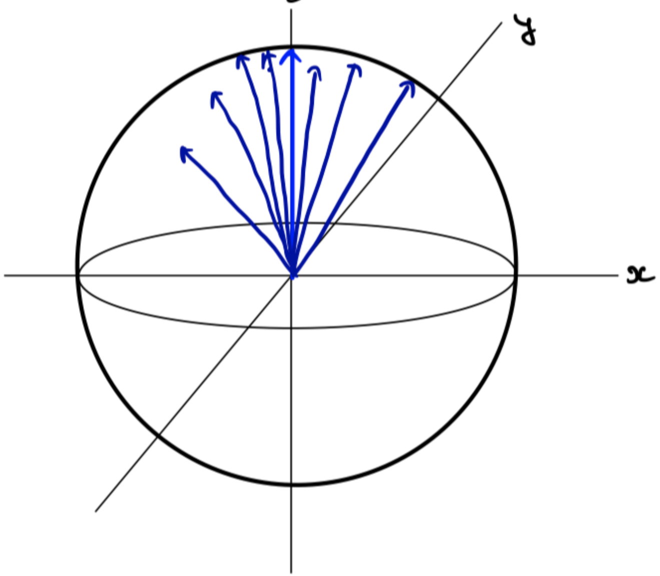
XYXY Sequence



- Noise can be more general
- Apply X, Y alternatingly

  i.e. two axis rotations of the sphere
- There are more sophisticated DD sequences

  but XYXY is the sequence we used.



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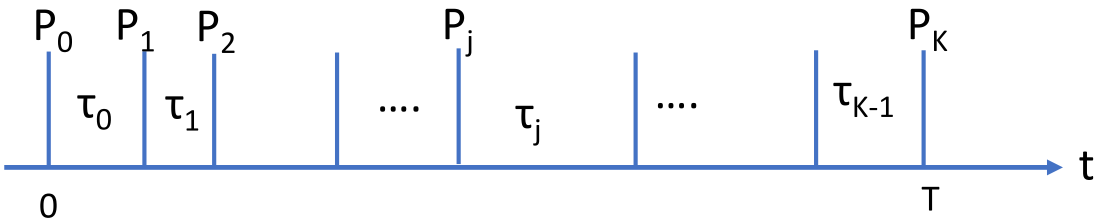
Dynamical Decoupling



- DD : applying a sequence of pulses (rotations) with the goal of suppressing errors.
- Pulse intervals do not need to be uniform
- Pulses are not restricted to X and Y.
- DD = open-loop, passive; QEC = closed-loop, active, feedback-based

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Why use DD?

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There is work on using quantum error correction (QEC) on cloud-based QCs.

Previous QEC experiments have not conclusively shown improvement in fidelity over no error correction, while applying standard initialization, gates, and readout operations.

[13] S. J. Devitt, Phys. Rev. A **94**, 032329 (2016).
[14] J. R. Wootton and D. Loss, Phys. Rev. A **97**, 052313 (2018).
[15] C. Vuillot, Quantum Inf. Comput. **18**, 0949 (2018).
[16] J. Roffe, D. Headley, N. Chancellor, D. Horsman, and V. Kendon, Quantum Sci. Technol. **3**, 035010 (2018).
[17] I. K. Sohn, S. Tarucha,, and B.-S. Choi, Phys. Rev. A **95**, 012306 (2017).
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[19] R. Harper and S. Flammia, arXiv:1806.02359.

DD is

- simpler,
- capable of suppressing general decoherence (in principle), and
- compatible with Quantum error correction [Ng, Lidar, Preskill, Phys. Rev. A (2011)].

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Why DD might not work?

- DD evolution must deal with preparation and measurement errors, free evolution errors AND gate errors.
- Pulses are not perfect:
  - Pulses (X, Y gates) are not instantaneous
  - Rotation angle (θ) errors
  - Axis errors

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Access Date:
06/19/2018 (IBM)
04/13/2018 (Rigetti)

Hardware

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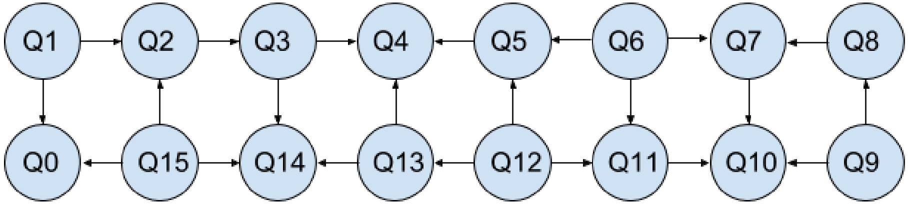
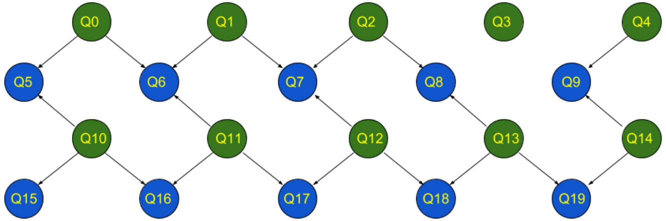
	IBMQX5	Rigetti - ACORN
		
Qubits used	16	16 (19 total)
1 Qubit gate errors	0.24 %	1.78 %
Readout errors	7.0 %	9.35 %
Multiqubit gate errors	6.65 %	13.5 %
Single qubit gate time	90 ns	50 ns

Not shown here: IBMQX4,
IBM_16_MELBOURNE,
Rigetti 8Q-Agave

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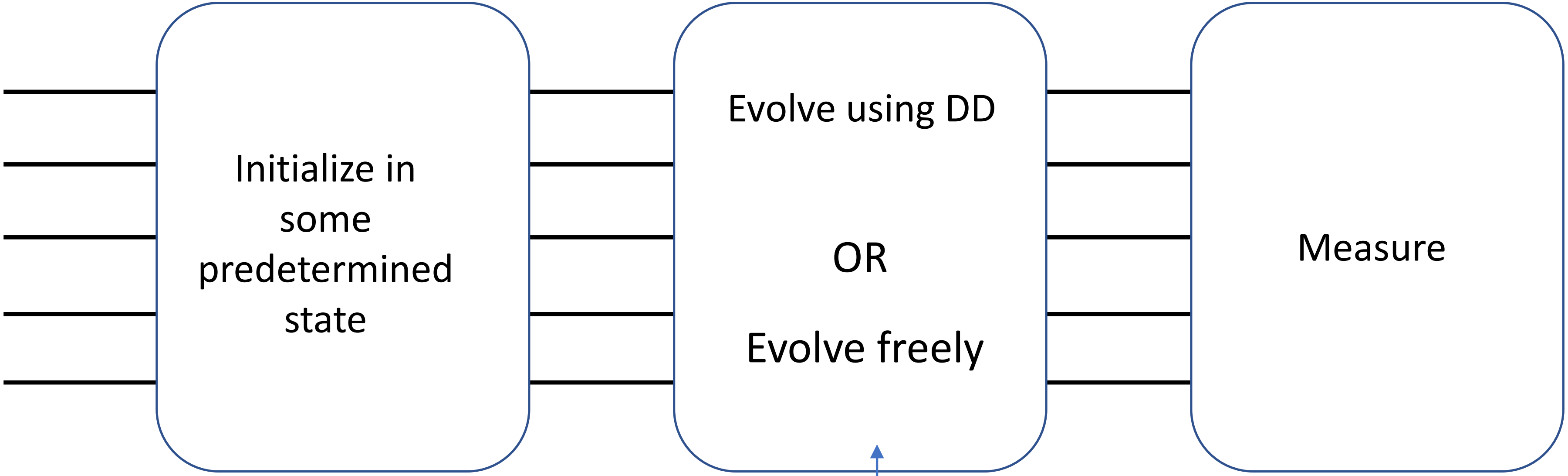
Experimental Setup



Free evolution must account for finite pulse duration

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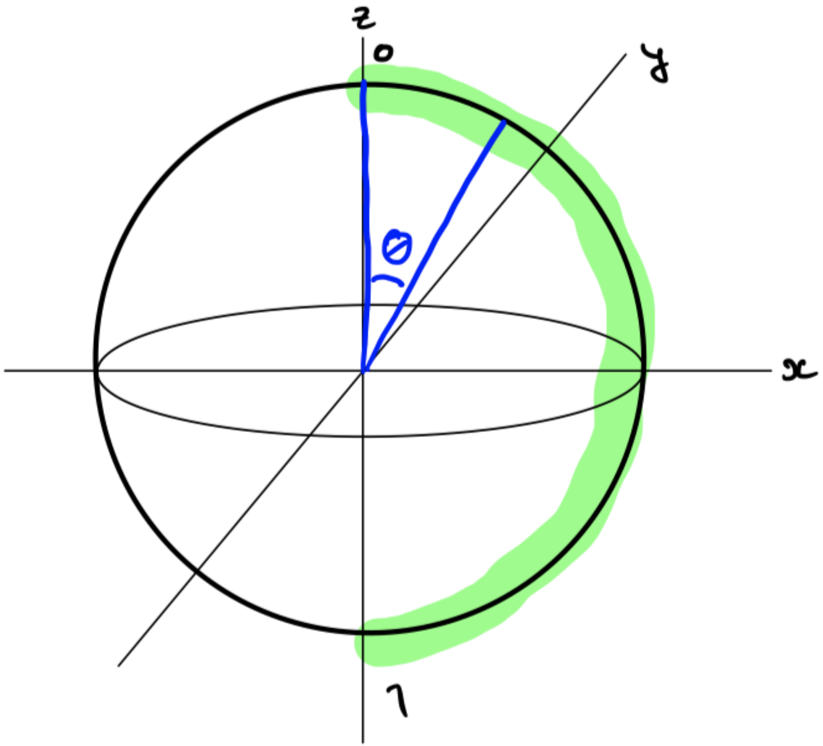
Experimental Setup 1



Does the fidelity depend on initial condition (with evolution time fixed)?

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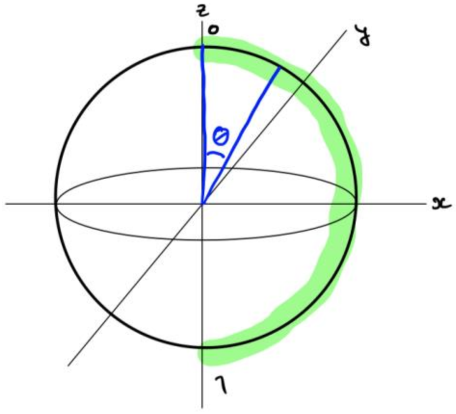
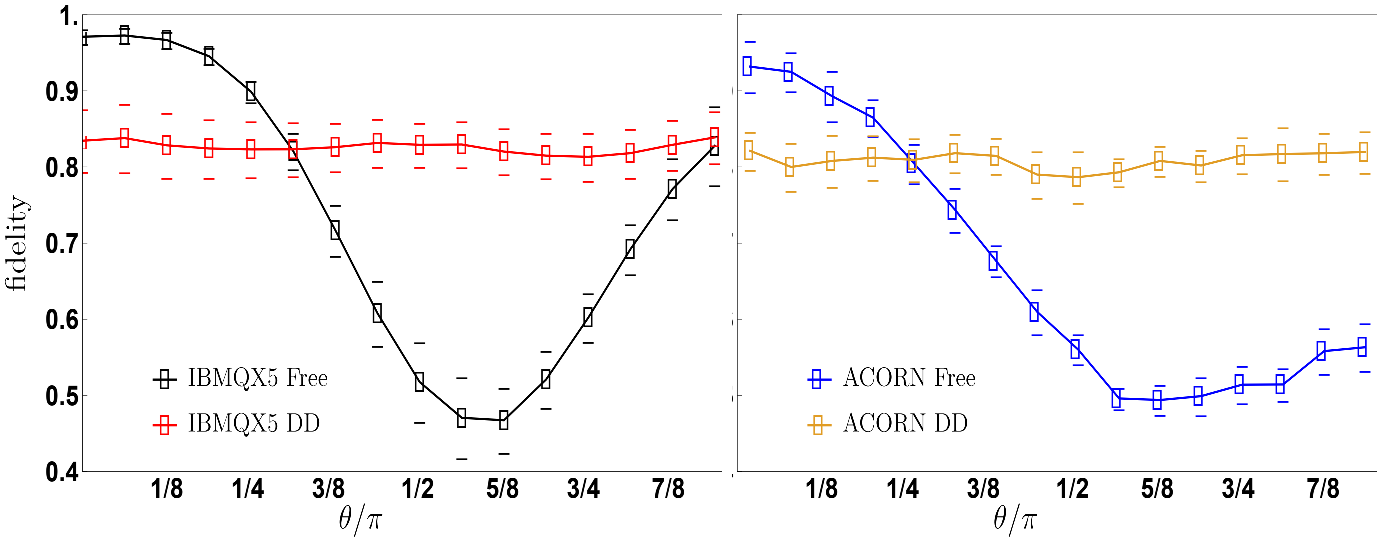
Initial state dependence

- DD removes initial state dependence.
- DD reduces fidelity for states close to the ground states, but improves fidelity on average.



Fidelity as a function of θ after 10 XYXY (IBMQX5) and 48 XYXY (ACORN).



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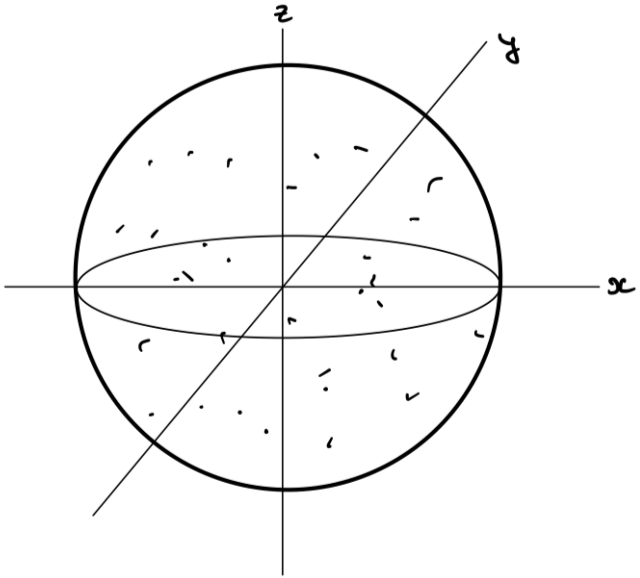
Experimental Setup 2



We report fidelity averaged over 36 initial conditions and all qubits as a function of time.

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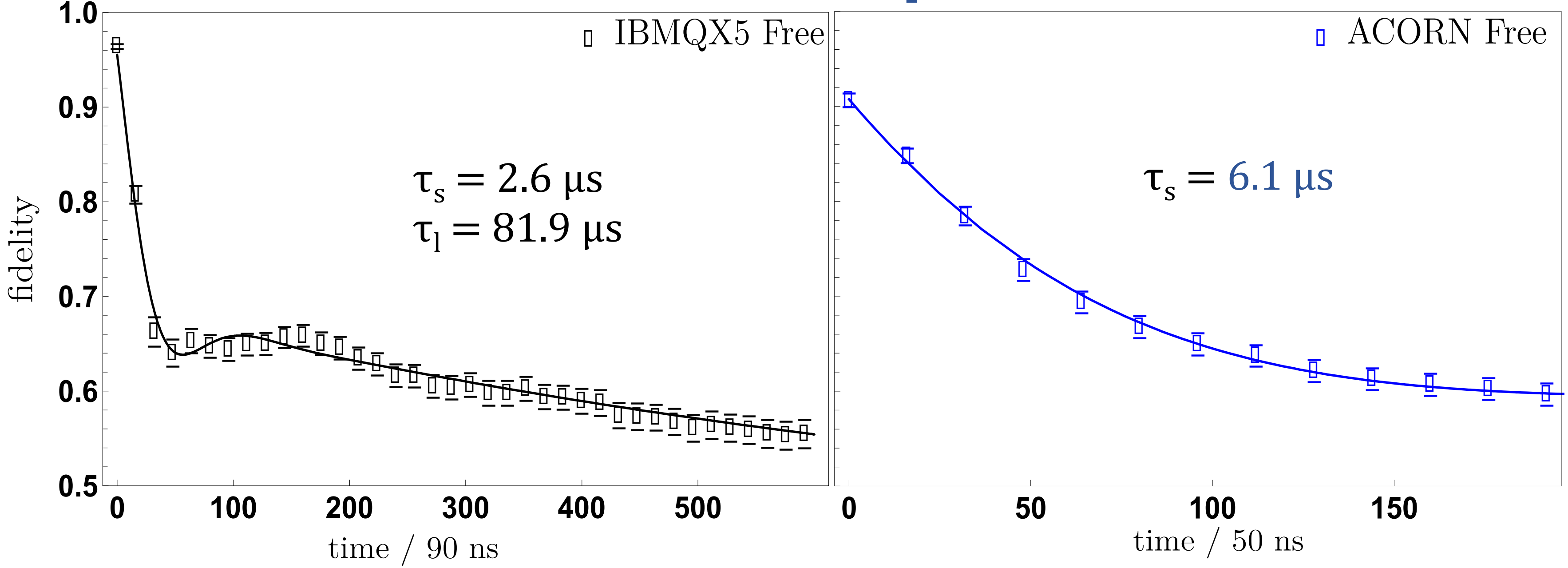
Measures of improvement



$$f(T) = e^{-T/\tau_s}\cos(\omega\, T) + e^{-T/\tau_l}$$

$$F(T) = \left[\frac{F(T_{\max}) - F(0)}{f\,(T_{\max}) - f(0)}\right] f(T) + \left[F(0) - \frac{F(T_{\max}) - F(0)}{f\,(T_{\max}) - f(0)}\right]$$

$F(T)$ = average fidelity (16 qubits, 36 ic)

τ_s= short decay time, τ_l = long decay time

ω = oscillation frequency

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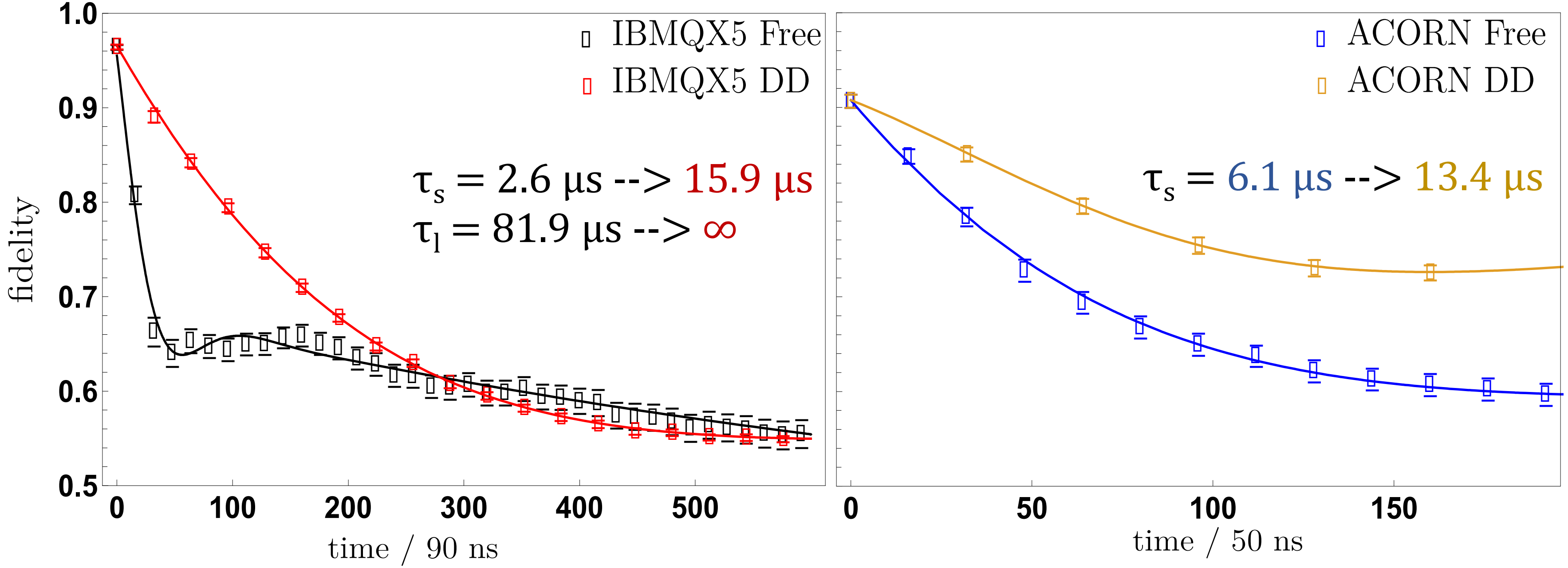
Free vs DD



Decay time increases × 6: 2.6 μs → 15.9 μs
Oscillatiions removed

Decay time increases × 2: 6.1 μs → 13.4 μs
Fidelity saturates at a higher value under DD

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Conclusion

We have shown that Dynamical Decoupling

1. removes variation due to initial conditions
2. increases fidelity decay time by X 6 (IBMQX5), X 2 (ACORN)

We plan to implement

- DD in the context of quantum algorithms or alongside QEC
- similar error suppression on other quantum computing platforms – such as trapped ions
- higher order and more robust DD sequences

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Bibek Pokharel,[1,*] Namit Anand,[2] Benjamin Fortman,[3] and Daniel A. Lidar[1,2,3,4]