Characterizing Coherent Errors Efficiently, Robustly, and Simply

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Middlebury College

Based on Arxiv:1502.02677, (joint with Ted Yoder, Guang Hao Low)
Arxiv:1702.01763 (joint with Kenny Rudinger + Sandia)

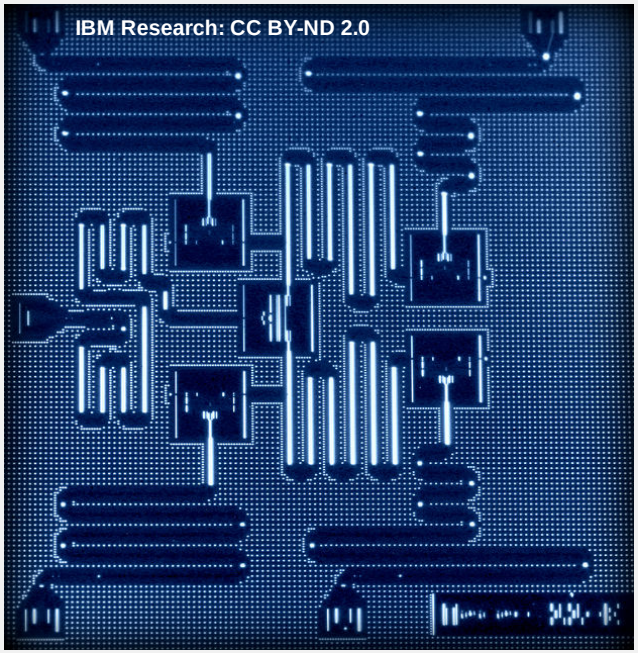
Middlebury

IBM,
December 6, 2017

Beyond Prototype Quantum Computers

IonQ

Microsoft



Google

Rigetti

IBM Quantum
Research Experience

Beyond Prototype Quantum Computers

What challenges do we face to move beyond prototypes?

Beyond Prototype Quantum Computers

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- Good calibration techniques

Beyond Prototype Quantum Computers

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- Good calibration techniques
  - Need to be able to quickly and easily tune up hundreds/thousands of qubit gates, potentially multiple times a day.
  - Tune up = detect and correct control errors

Beyond Prototype Quantum Computers

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  - Need to be able to quickly and easily tune up hundreds/thousands of qubit gates, potentially multiple times a day.
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Our focus

Characterization Protocol Desiderata

	EASY	FAST	ROBUST	USEFUL

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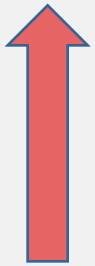

Can be run in the lab with minimal effort

Characterization Protocol Desiderata

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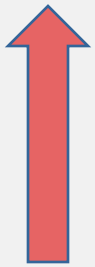

Time is (quantum) money

Characterization Protocol Desiderata

	EASY	FAST	ROBUST	USEFUL

Accurate even if don't have good characterization of other parts of the system.
Especially SPAM (state preparation and measurement errors)

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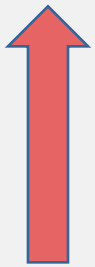

Useful for calibration: this information can be used to “fix” gate

Characterization Protocol Desiderata

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Characterization Protocols

	EASY	FAST	ROBUST	USEFUL
Ad-hoc	✓			✓

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Sexy adaptive machine learning strategy		✓	✓	✓

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Robust Phase Estimation	✓	✓	✓	✓

Characterization Protocols

	EASY	FAST	ROBUST	USEFUL
Robust Phase Estimation	✓	✓	✓	✓

- Experiments are identical to Rabi/Ramsey sequences the lab is probably already doing.
- Non adaptive
- Simple to analyze

Characterization Protocols

	EASY	FAST	ROBUST	USEFUL
Robust Phase Estimation	✓	✓	✓	✓

- Heisenberg scaling (optimally fast)

Characterization Protocols

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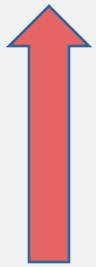

- Robust to (not too large) SPAM

Characterization Protocols

	EASY	FAST	ROBUST	USEFUL
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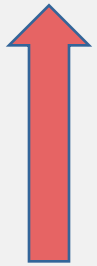
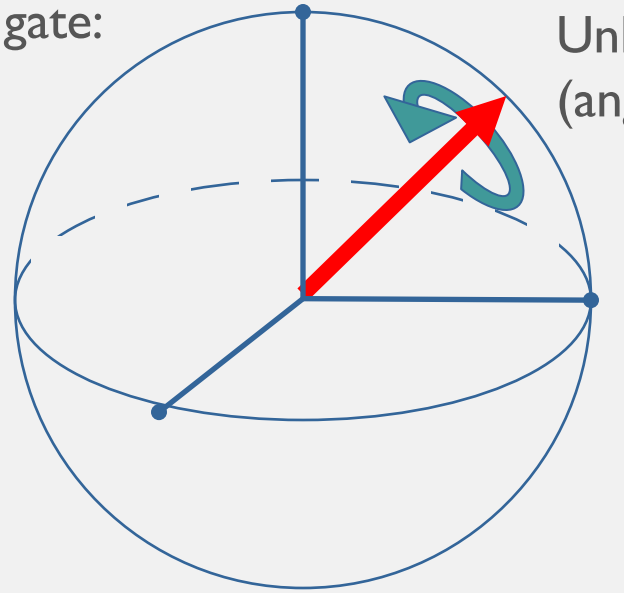


- Learns over/under rotation of unitary gates (plus other stuff).
- Can fix these errors

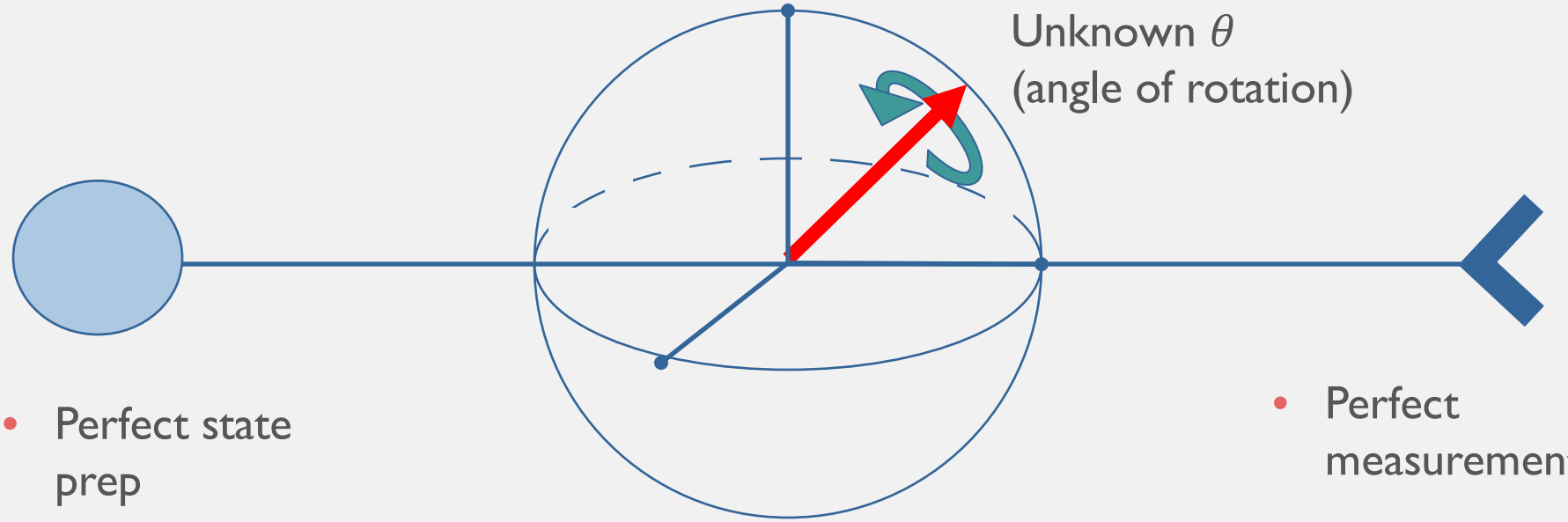
Simple enough to explain in 10 min…

Goal:
Characterize single qubit gate:



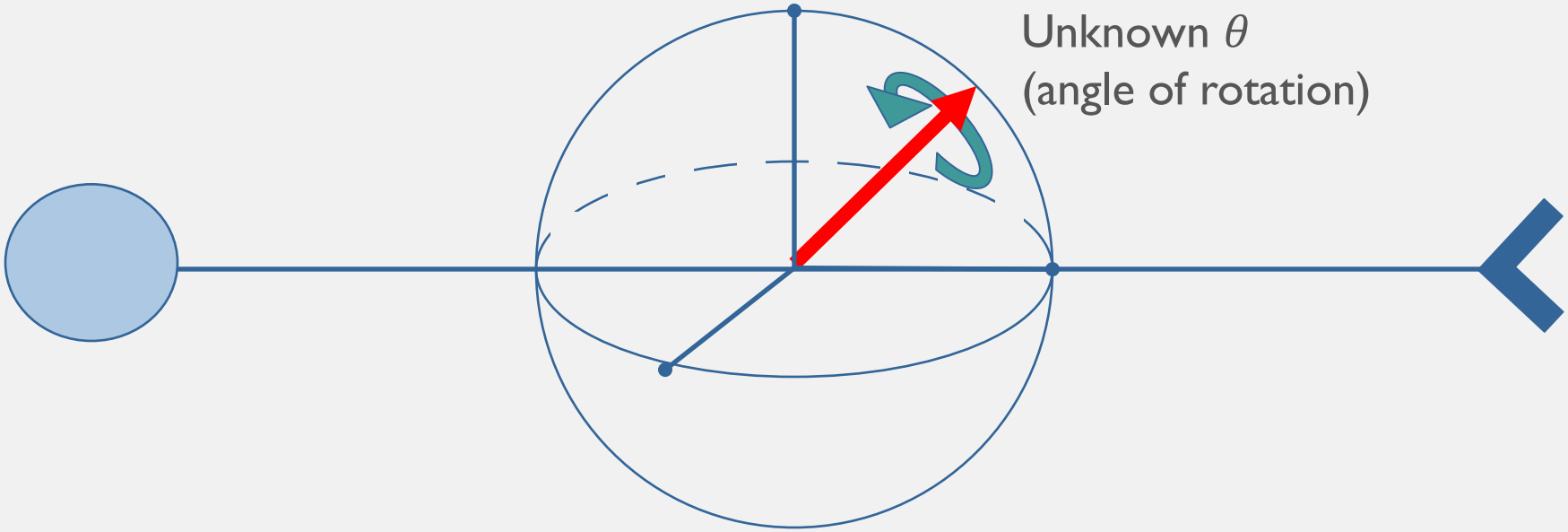
Unknown θ
(angle of rotation)

Perfect Experiment



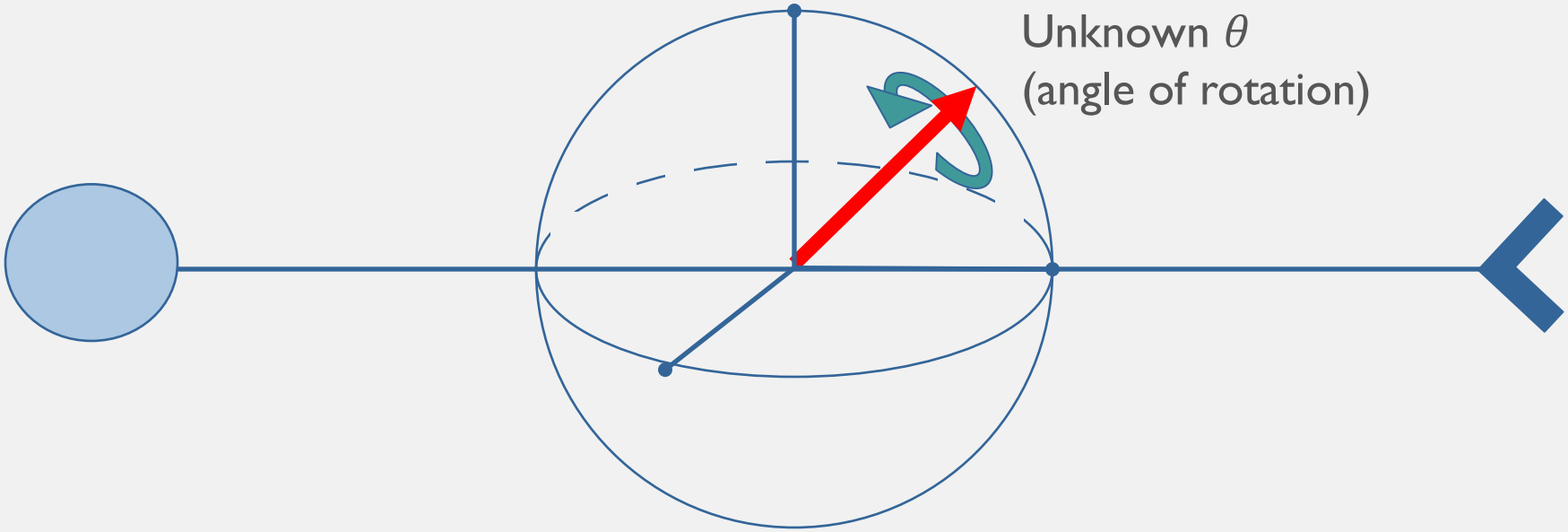
- Perfect state prep
- Perfect rotation
- Axis of rotation known
- Perfect measurement

Perfect Experiment



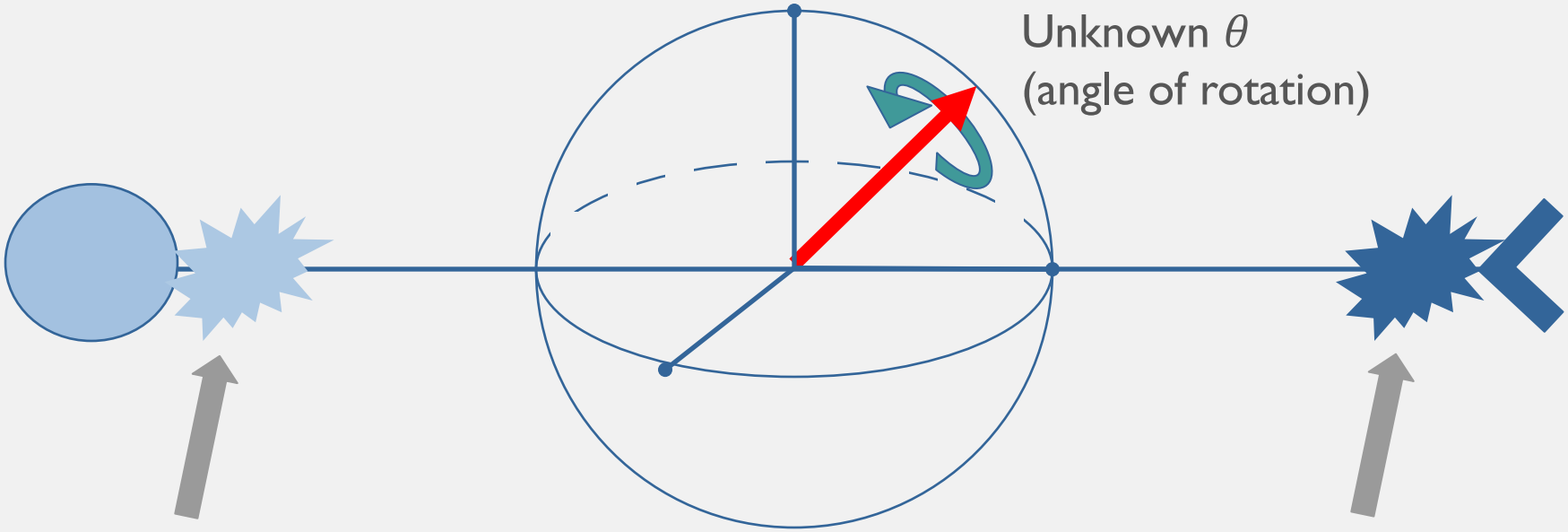
- Outcome is 0 with probability $\theta/2\pi$
- Outcome is 1 with probability $1-\theta/2\pi$.

Perfect Experiment



- Outcome is 0 with probability $(\theta \bmod 2\pi)/2\pi$
- Outcome is 1 with probability $1 - (\theta \bmod 2\pi)/2\pi$

Less Perfect Experiment

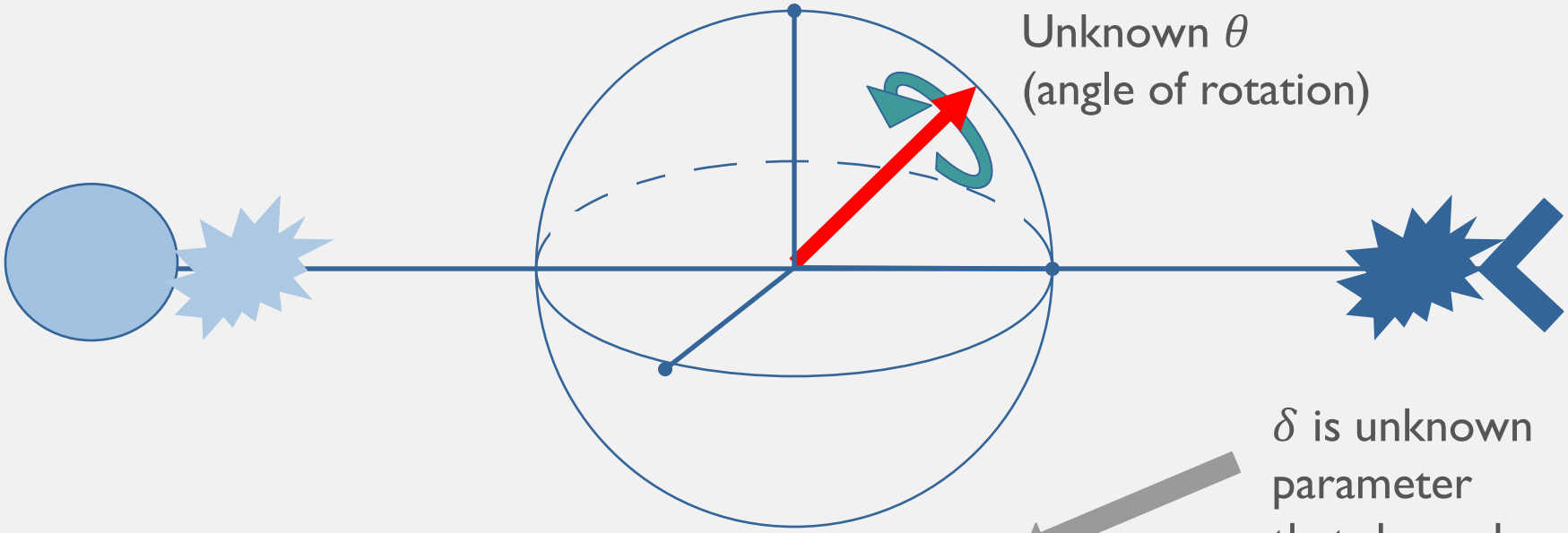


Unknown state preparation error

- Perfect rotation
- Axis of rotation known

Unknown measurement error

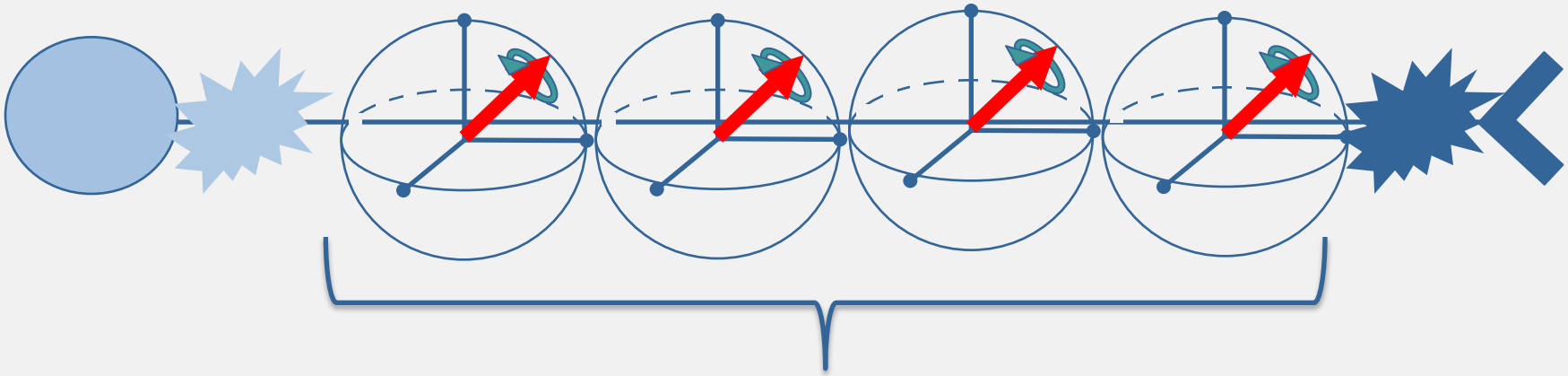
Less Perfect Experiment



δ is unknown parameter that depends on SPAM

- Outcome is 0 with probability $(\theta + \delta)/2\pi$
- Outcome is 1 with probability $1 - (\theta + \delta)/2\pi$.

Less Perfect, Repeated Experiment

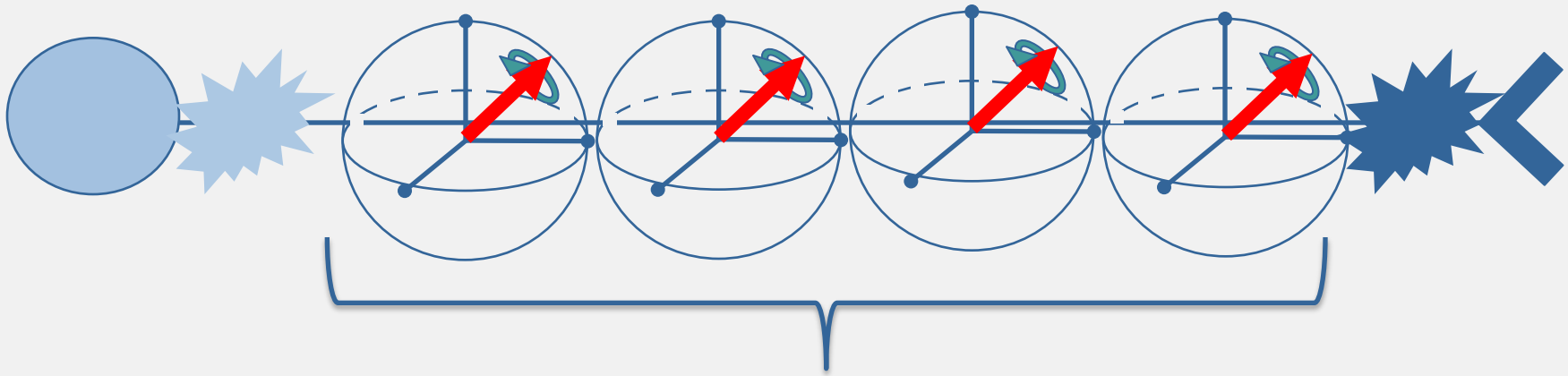


Apply gate k times

- Perfect rotation
- Axis of rotation known
- Unknown θ

Less Perfect, Repeated Experiment

- Outcome is 0 with probability $(k\theta + \delta_k)/2\pi$
- Outcome is 1 with probability $1 - (k\theta + \delta_k)/2\pi$.



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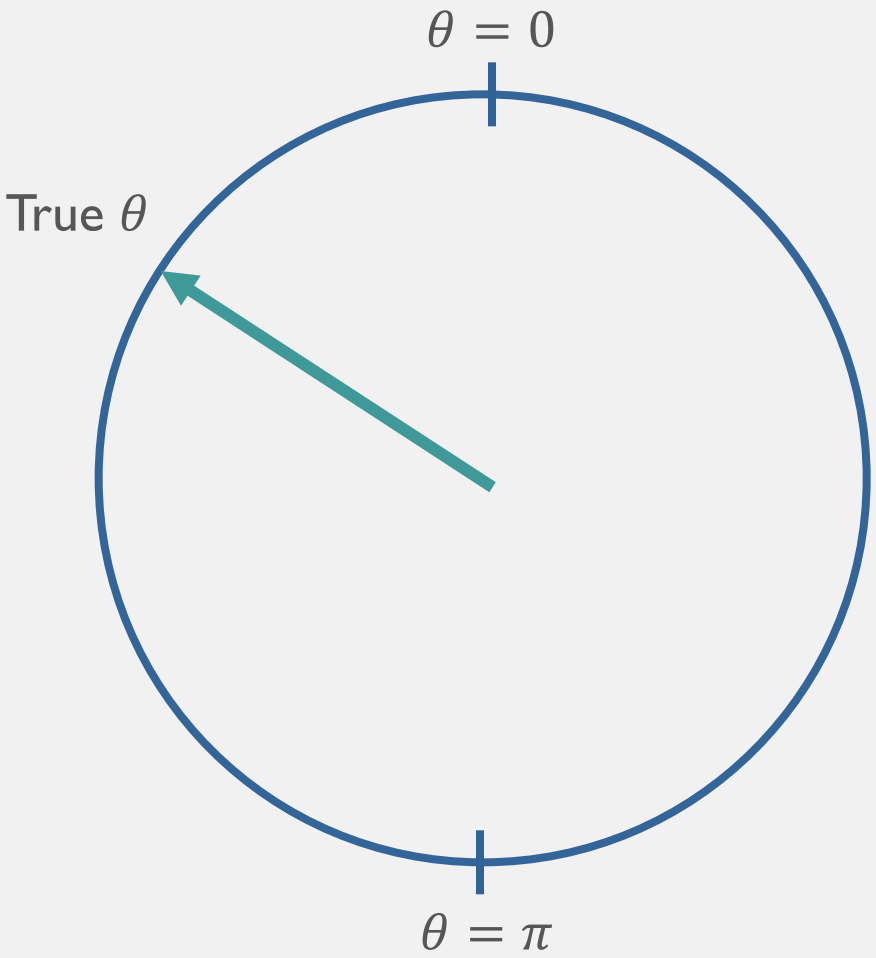
Robust Phase Estimation Strategy



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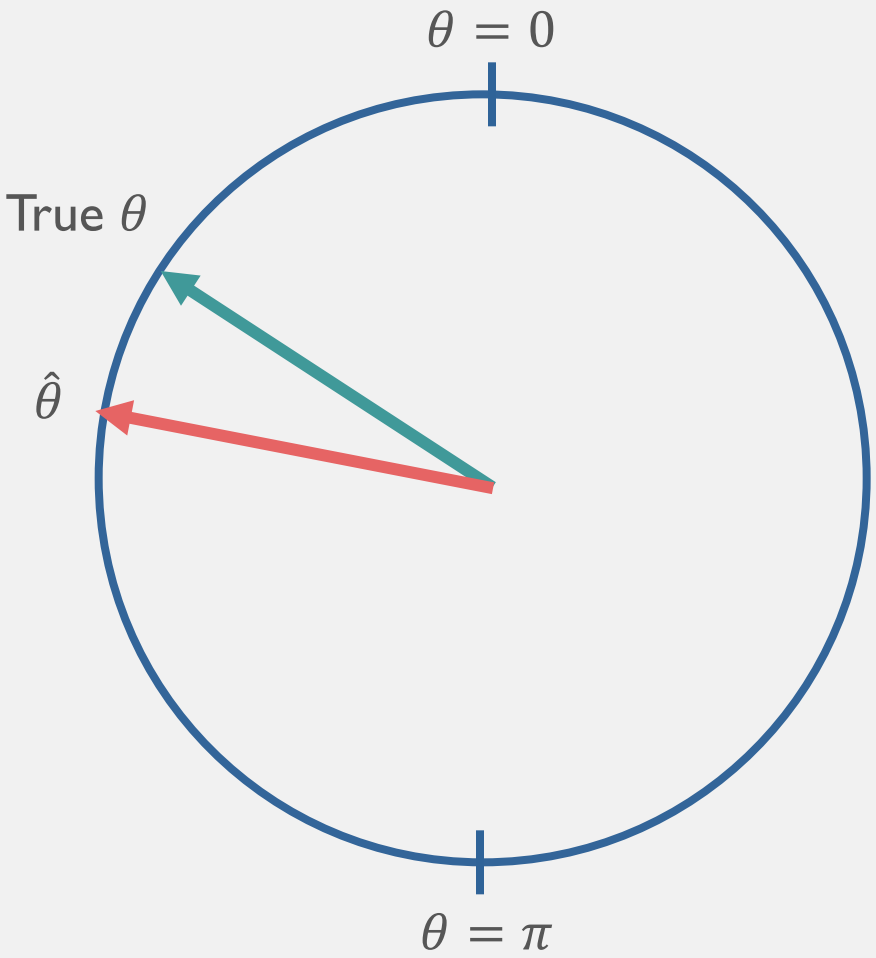

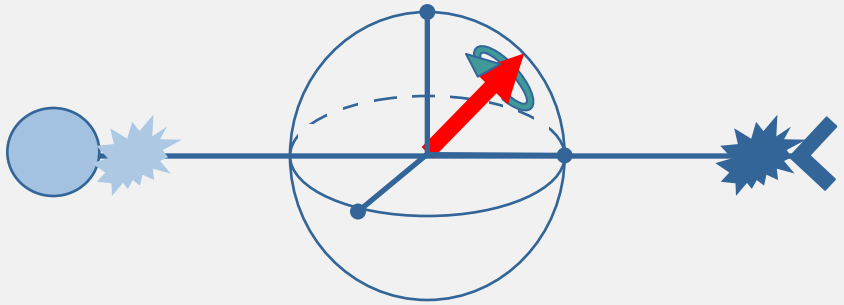

- Get estimate of $\theta + \delta_1$

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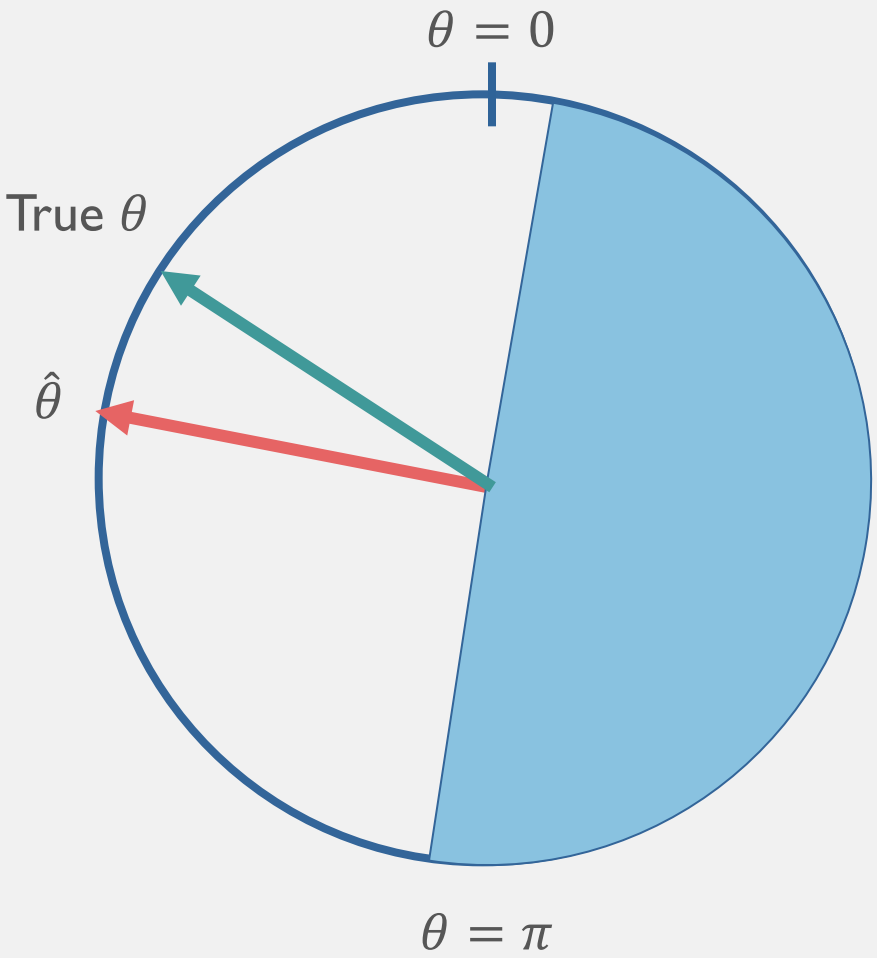

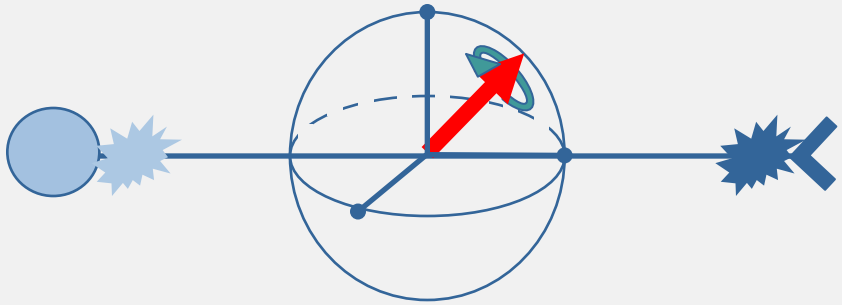

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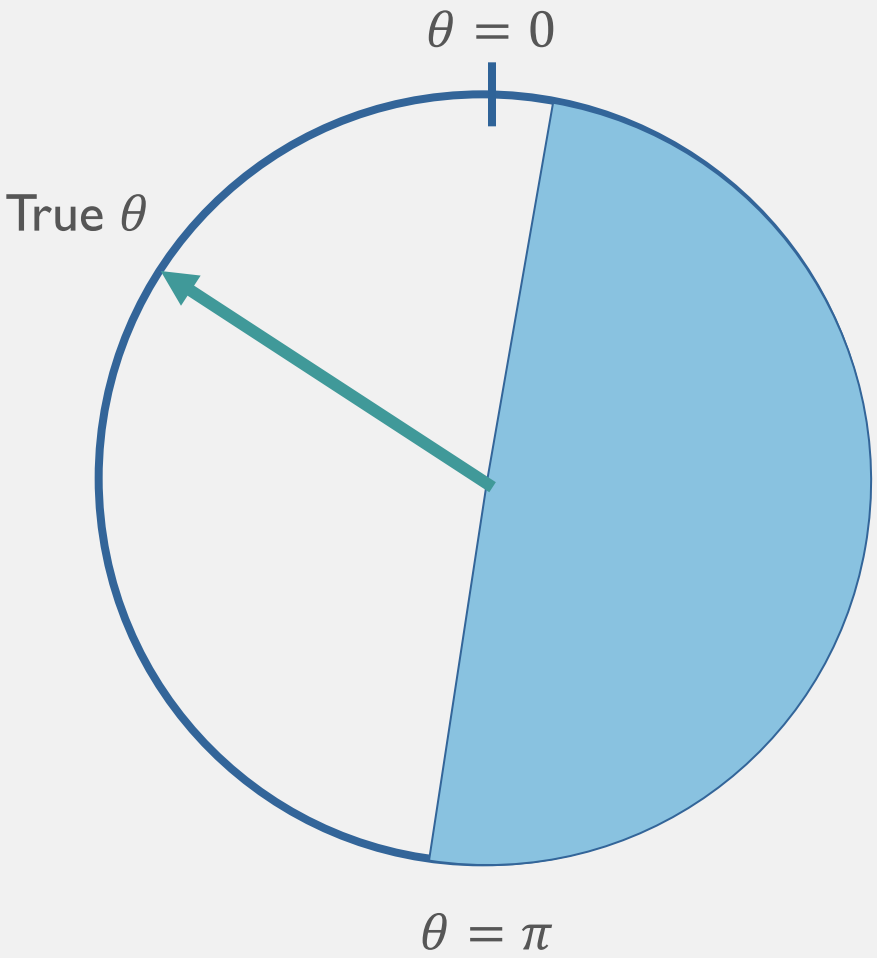

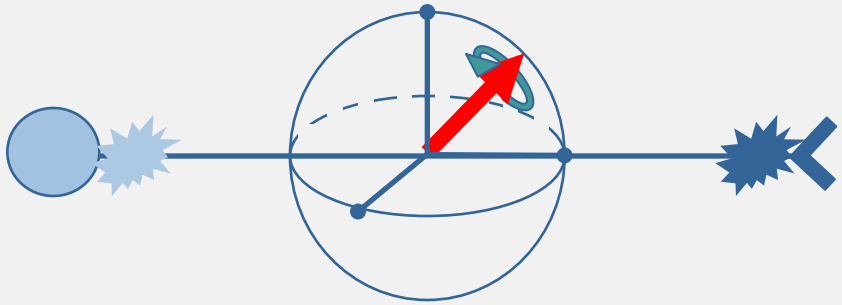

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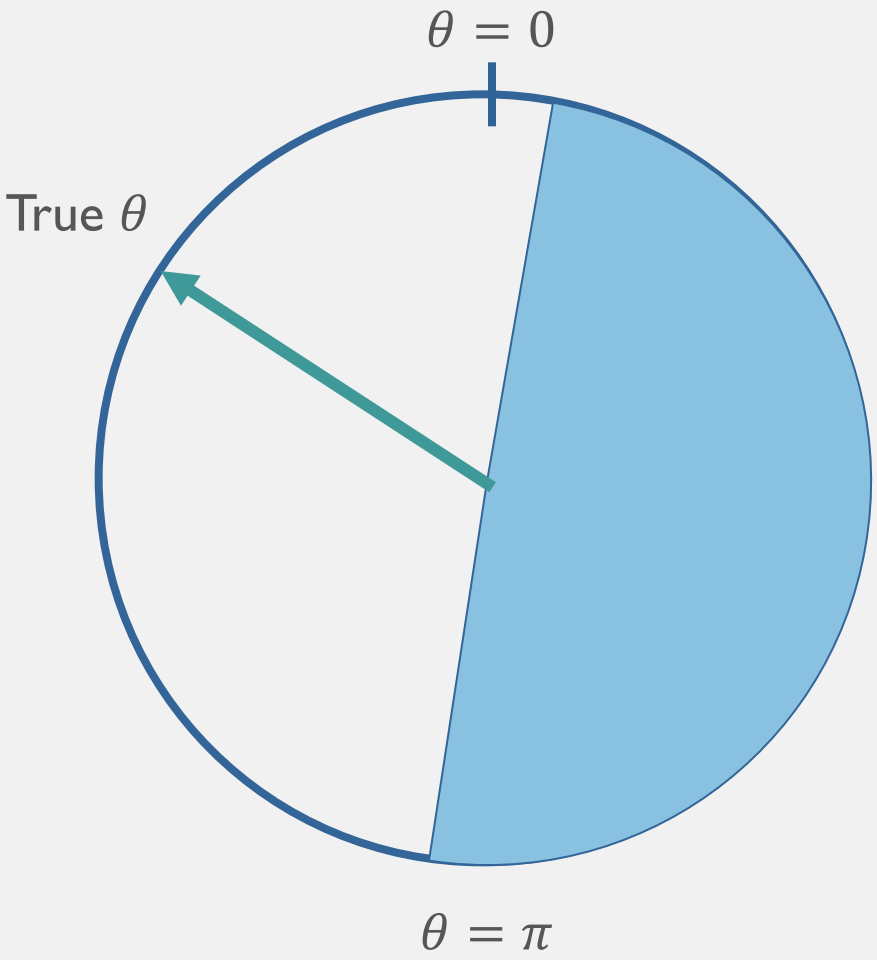
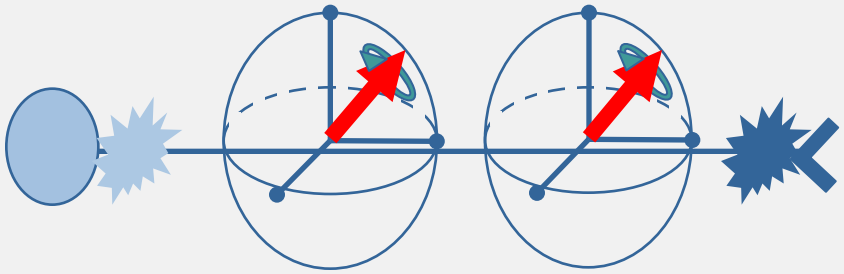
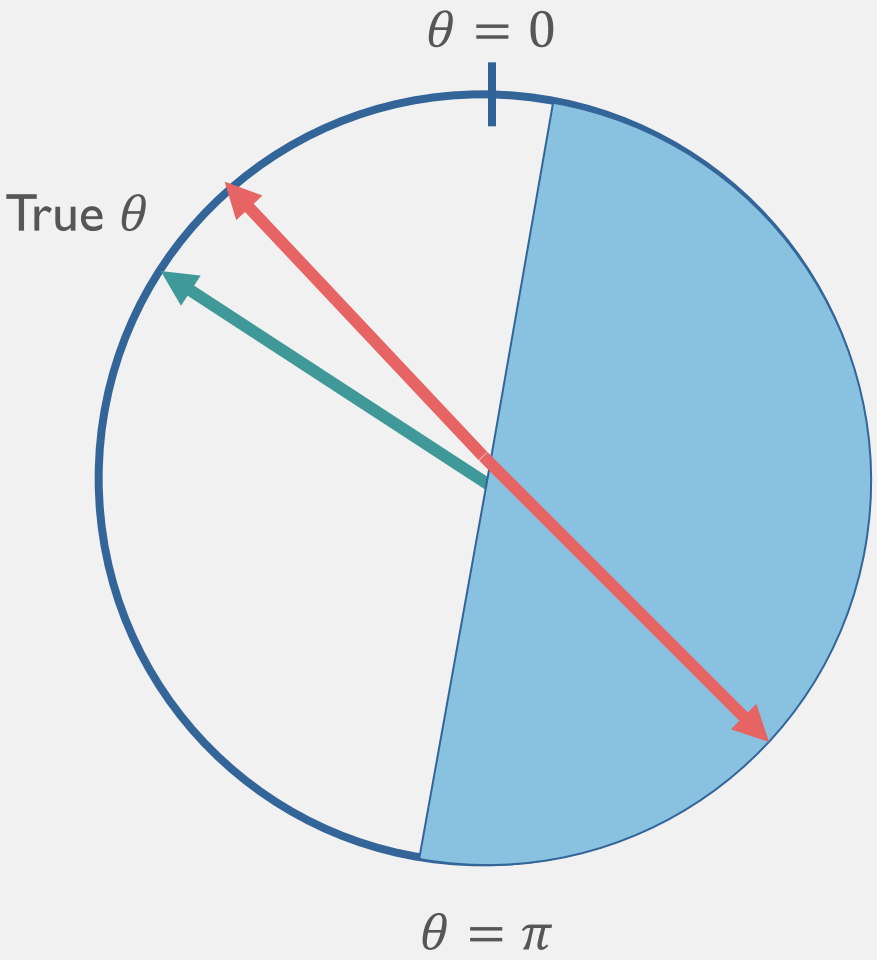
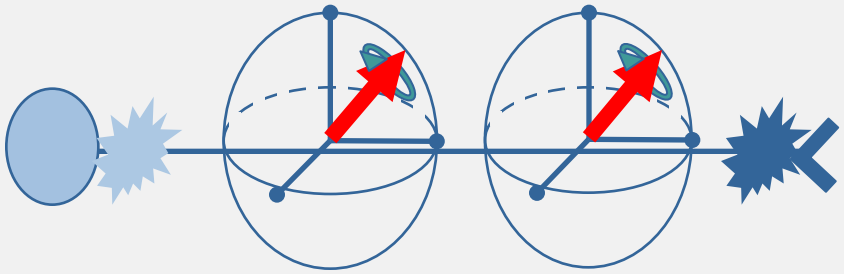




- Get estimate of $2\theta + \delta_2$
- Divide estimate by 2 to get estimate of $\theta + \delta_2/2$

Robust Phase Estimation Strategy





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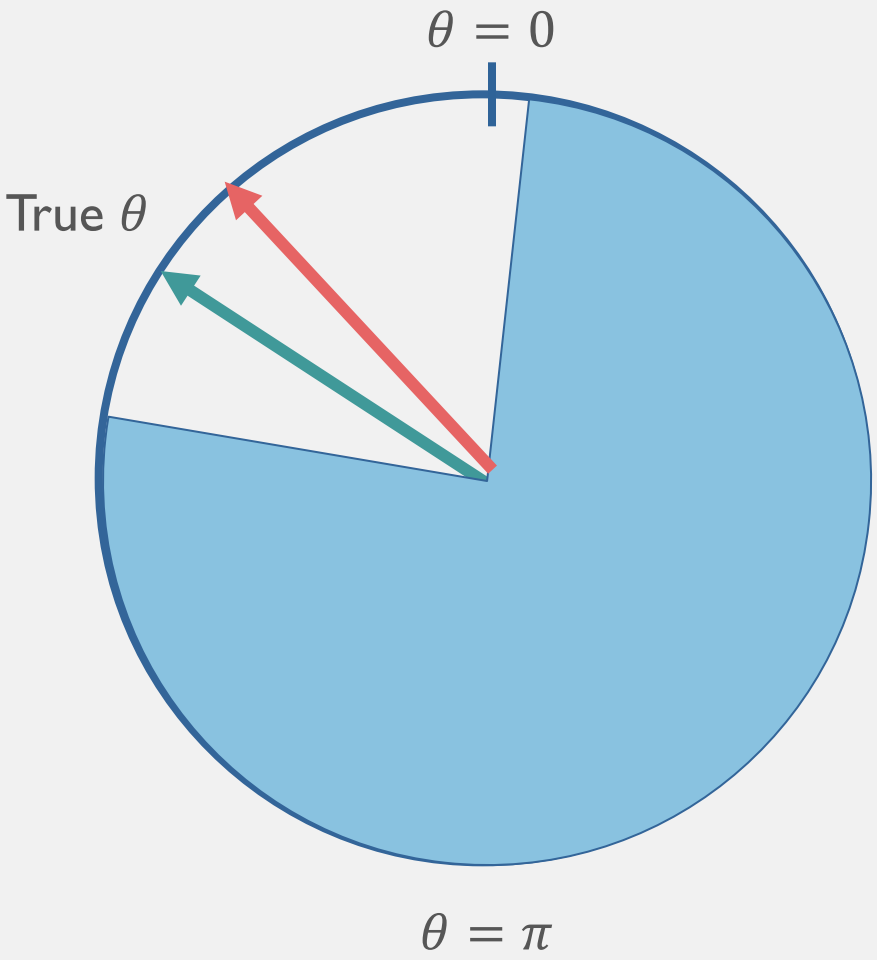

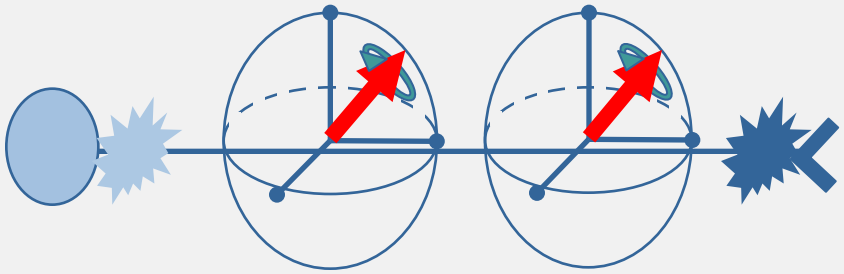

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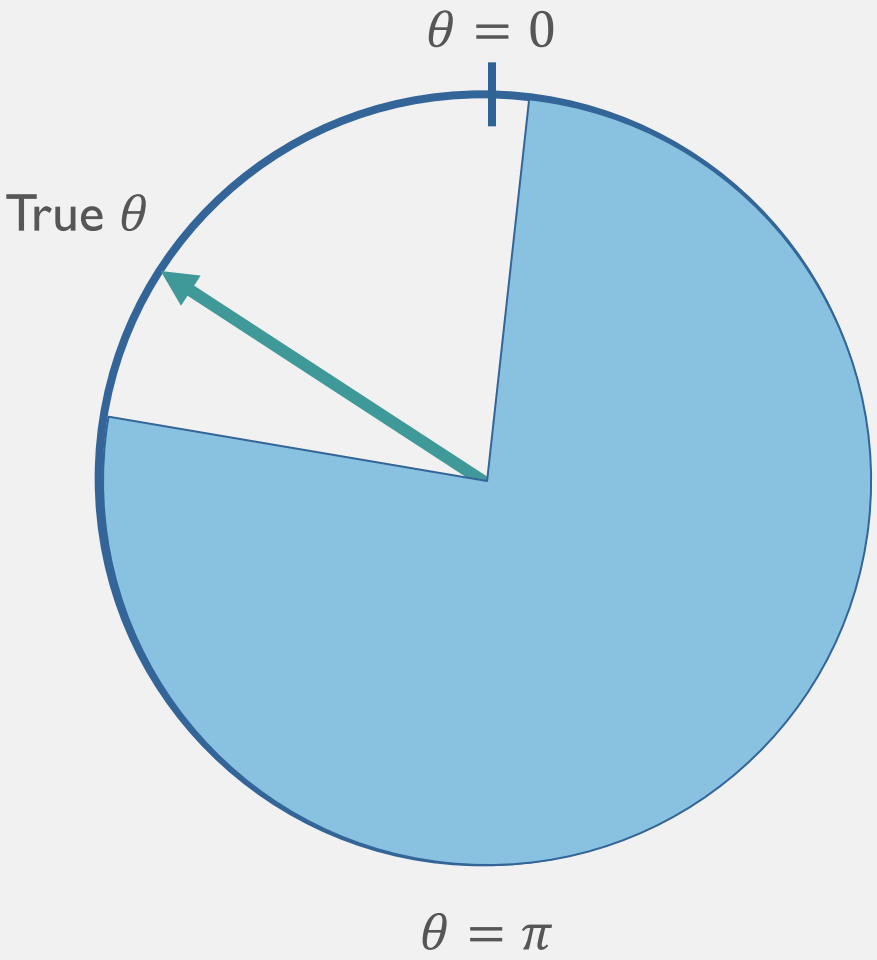

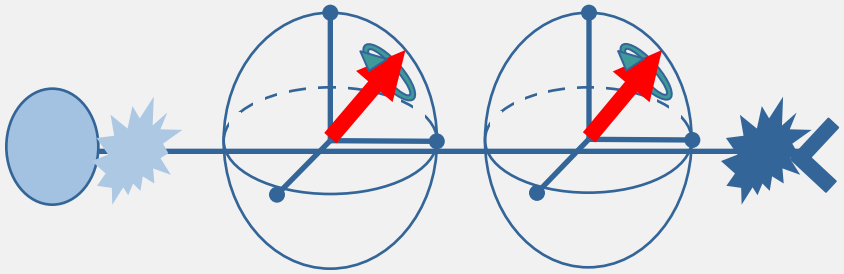

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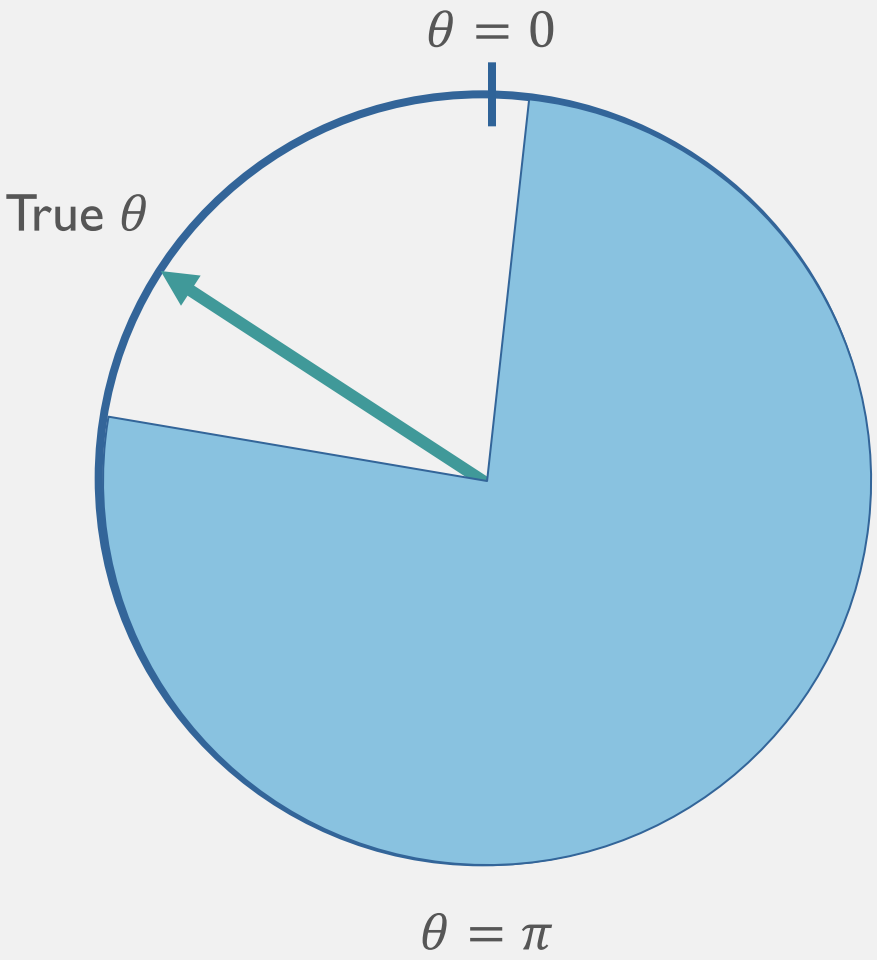

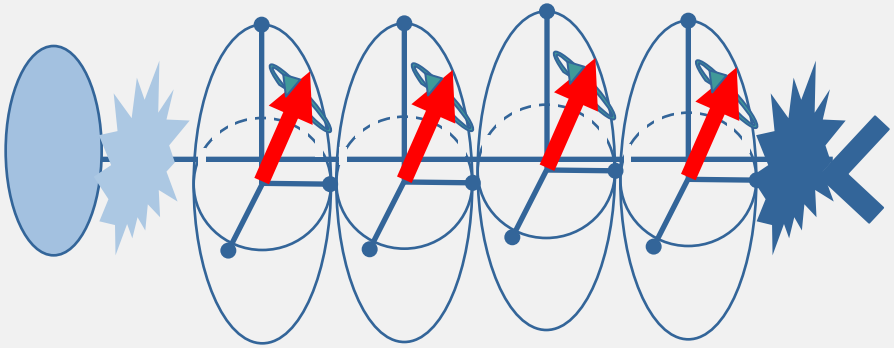

- Get estimate of $4\theta + \delta_4$
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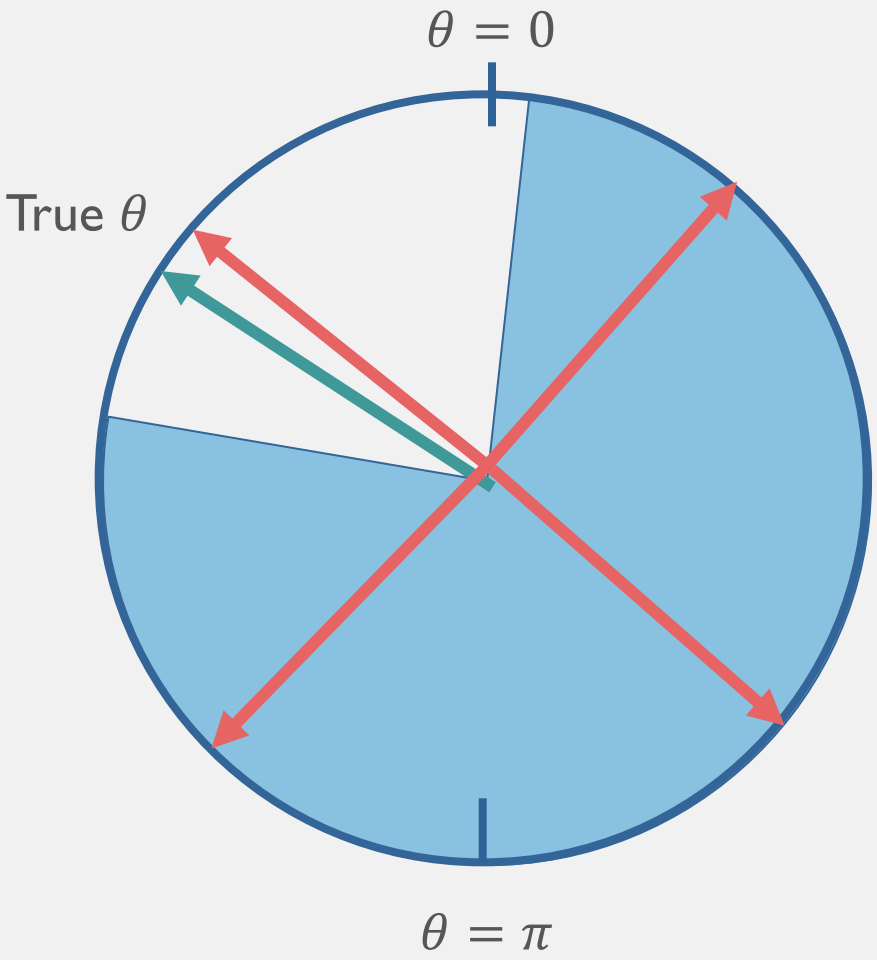
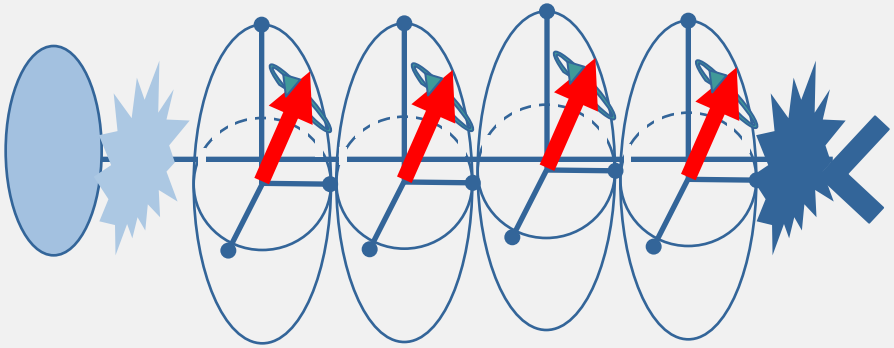
Robust Phase Estimation Strategy





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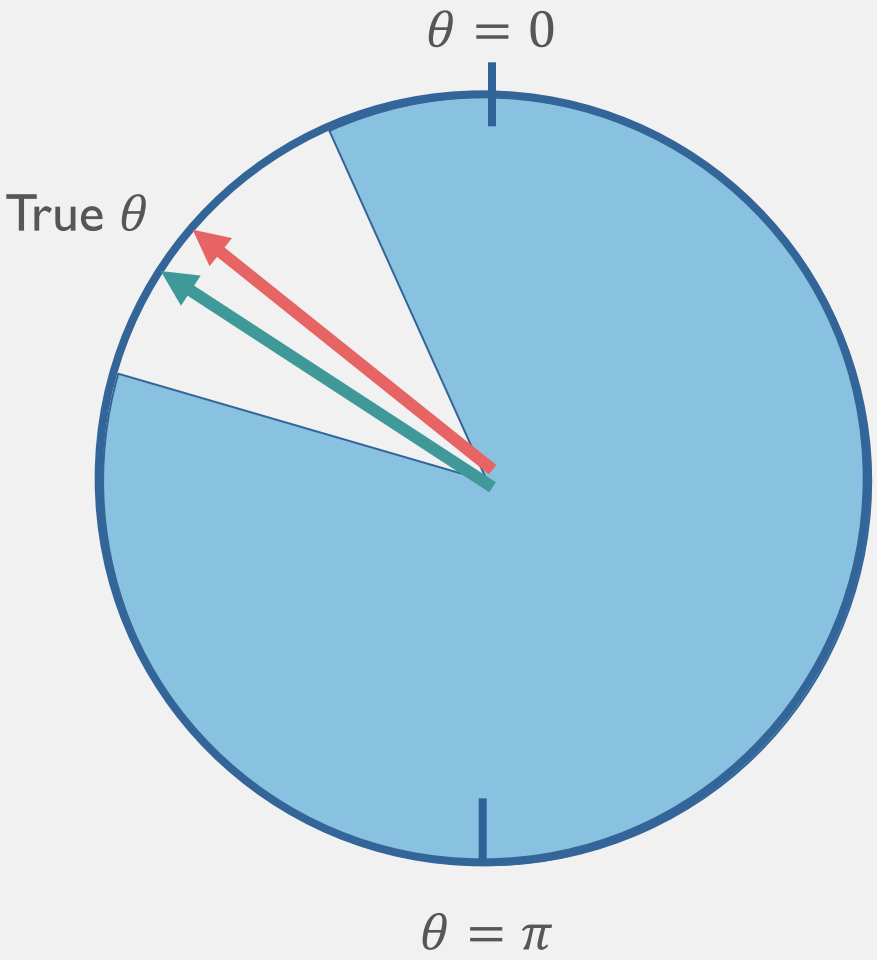

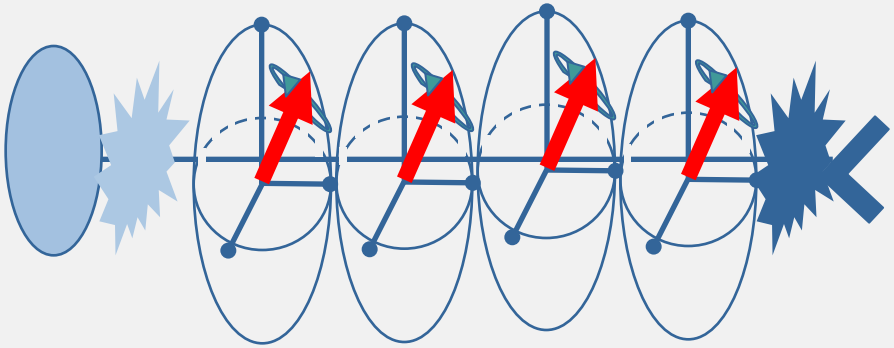

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Robust Phase Estimation Strategy

- Run experiments with applications $k = 1,2,4,8,16, \ldots, 2^n$
- End up with an estimate with error $1/2^n$.
- Need to repeat experiment enough times for each k so don't end up in the wrong regime.

Performance:

- Cost: C applications of the gate
- Error is proportional to: $1/C$

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Heisenberg Scaling, but

- No entanglement
- No adaptive measurements
- No Bayesian updates

Exceedingly Robust

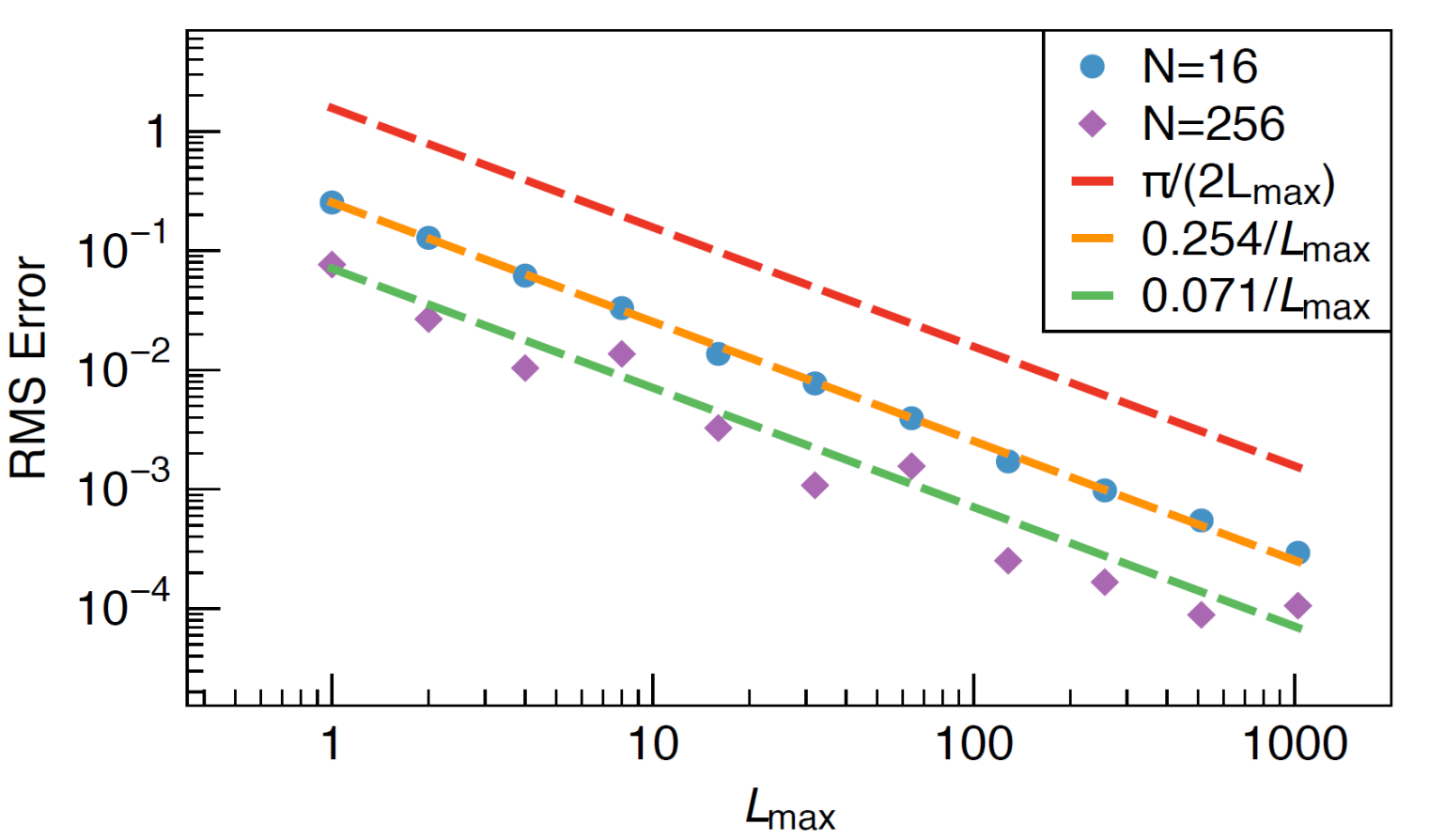
- Imperfect SPAM -> δ error
- Gate errors (e.g. depolarizing, dephasing, non-Markovian, time varying error) -> δ error

Can tolerate a lot of unknown effects! As long as…

Limitations

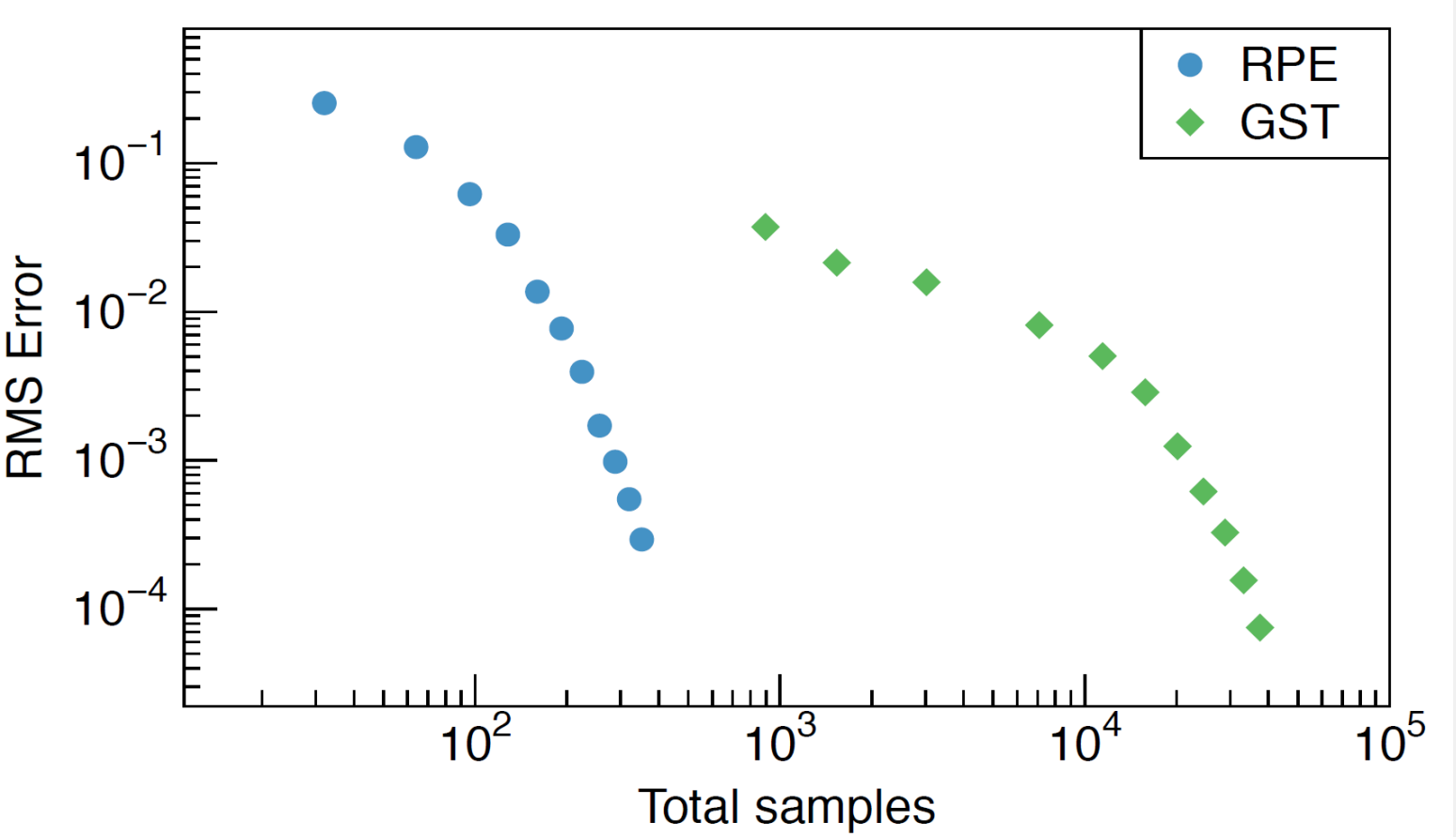
- Bias δ must be less than $\pi/4$.
- Reasonable for SPAM
- For large k, gate errors build up, and overwhelm $\pi/4$ bound.
- As bias approaches $\pi/4$ need to take more and more measurements to ensure true θ value is not excluded.

Implementation (with Sandia NL arxiv:1702.01763)



L_{max} is the longest sequence. It is closely related to "cost"

Implementation (with Sandia NL arxiv:1702.01763)



Total samples is the number of experiments run

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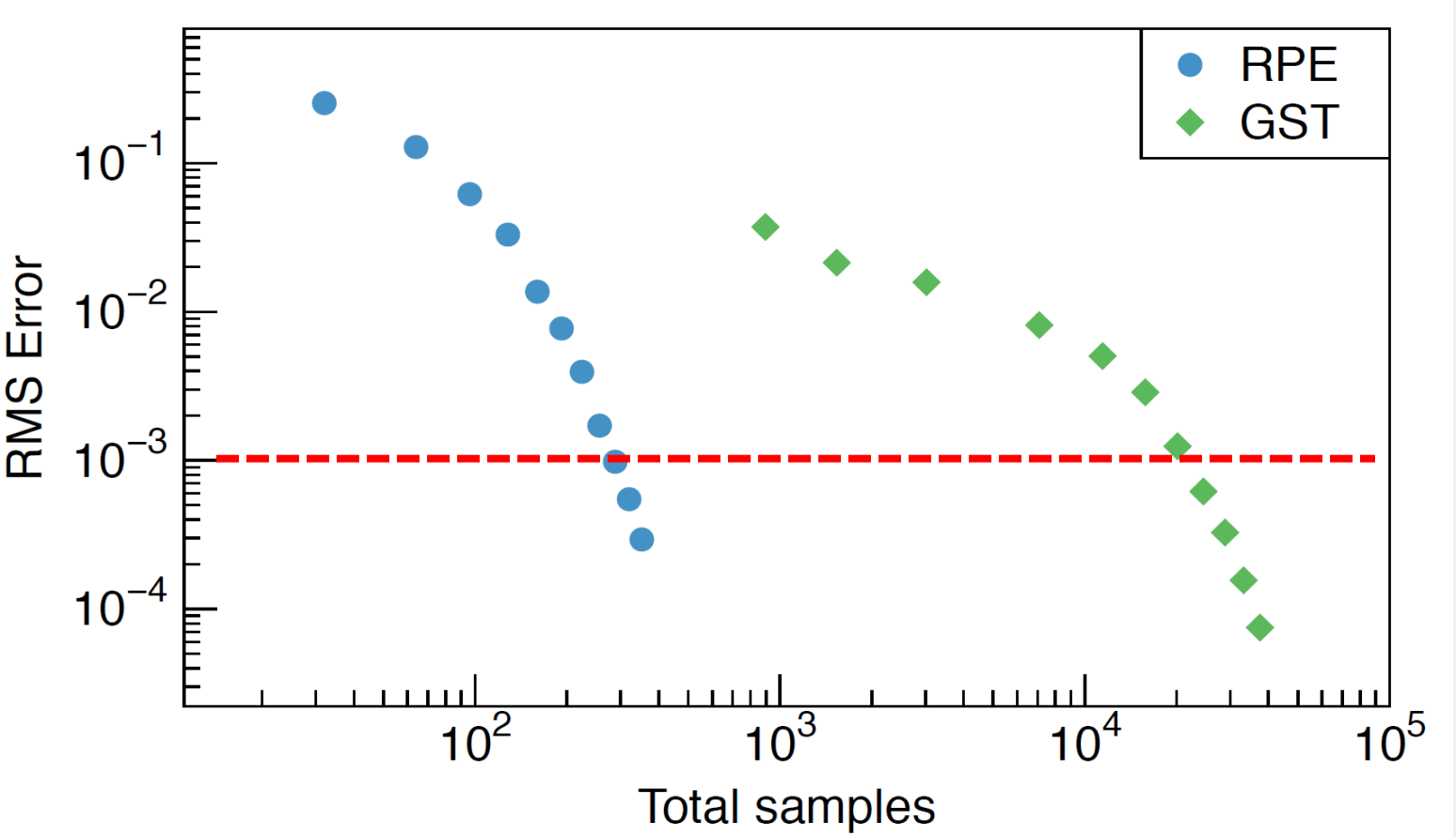
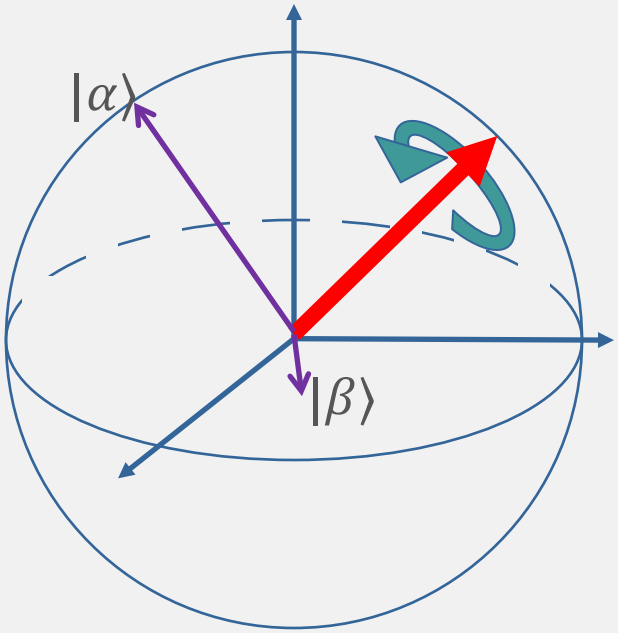


Total samples is the number of experiments run

Experimental Implementation

What should state preparation and measurement ideally be?

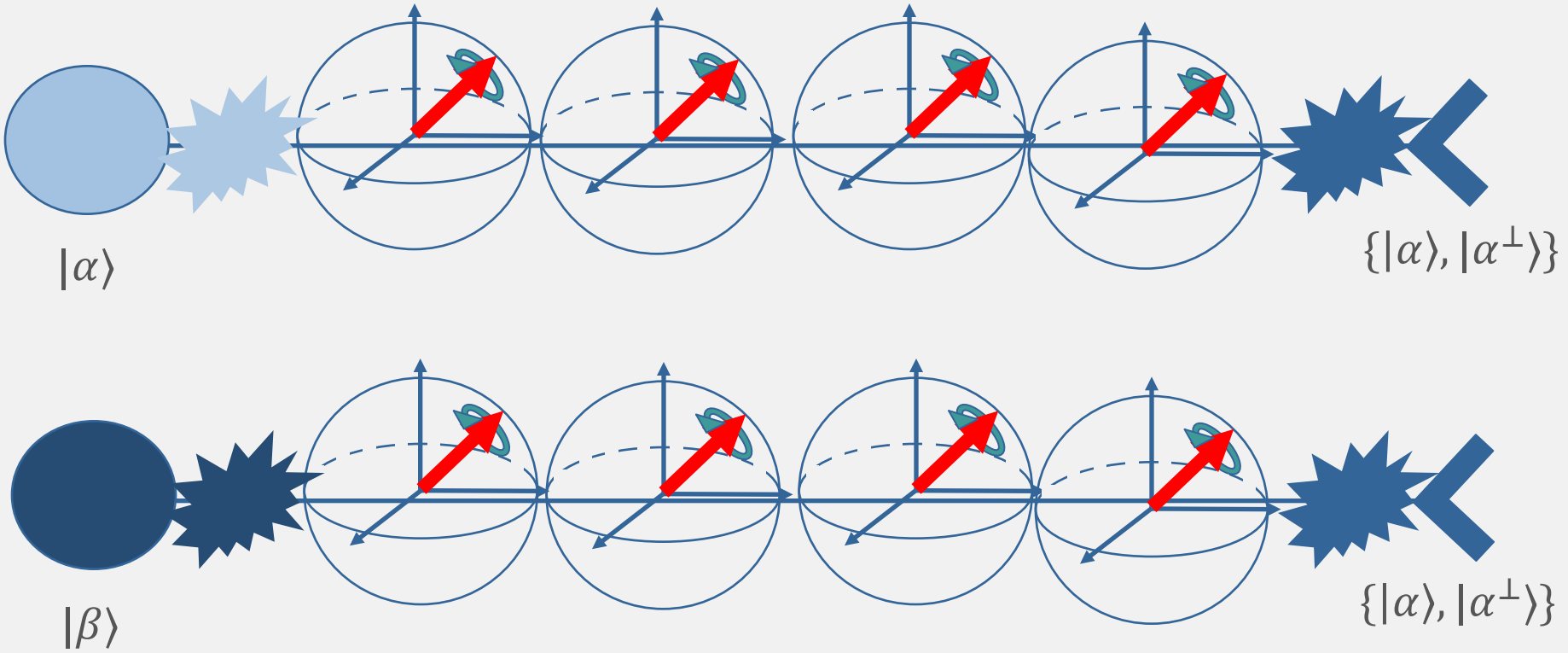


Axis of rotation

Angle of rotation

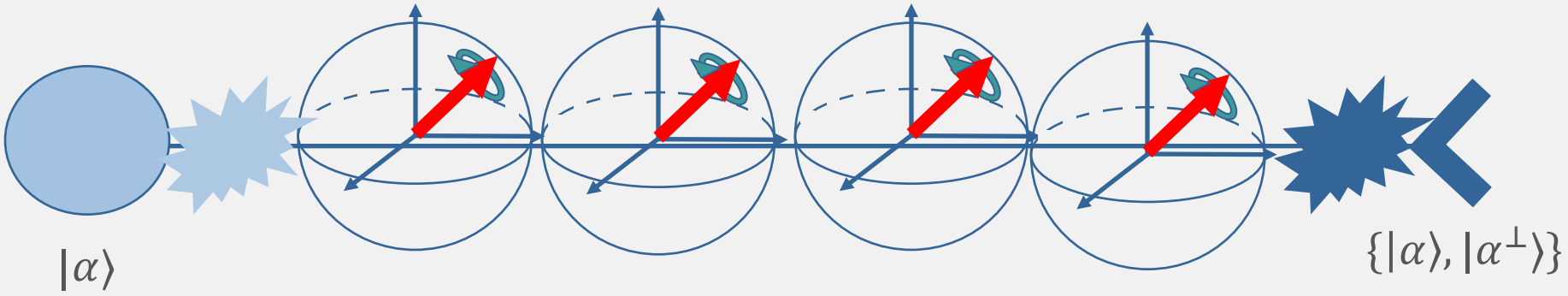
θ

Experimental Implementation

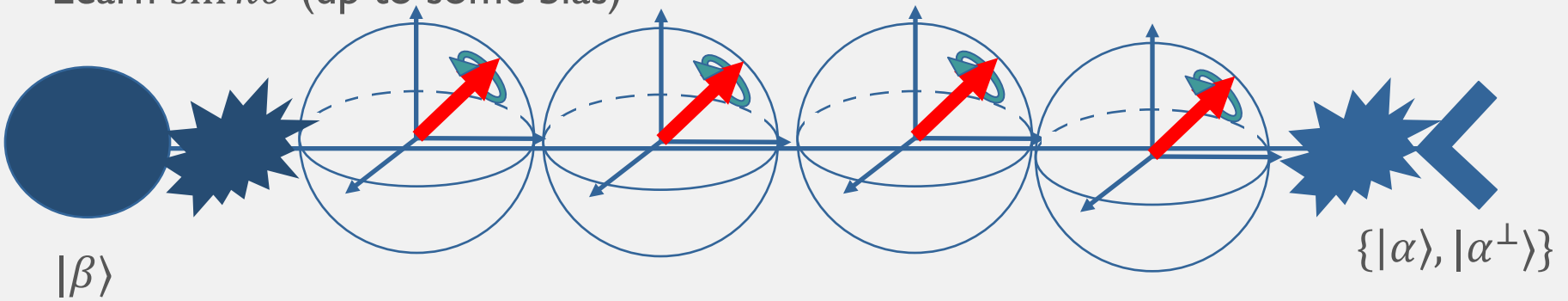


Experimental Implementation

- Learn $\cos k\theta$ (up to some bias)



- Learn $\sin k\theta$ (up to some bias)



- Combine to learn $\mathrm{k}\theta$ (up to some bias)

Future Directions

- Expanding to multi-qubit gates.
- Target parameters beyond coherent errors.
- Characterizing SPAM errors