Quantum gates and circuits on a quantum computer

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Self-Introduction

• BS Physics, Emory University 1998
• MS, PhD Electrical Engineering, Stanford University 2000, 2003
  • Liquid State NMR Quantum Computing
• Postdoc, NIST (Boulder, CO) and UCSB (Santa Barbara, CA) 2003-2006
  • Phase qubits
• RSM, IBM Yorktown Heights, NY 2006
• APS Fellow (2013), IEEE Senior Member (2015), IBM Fellow (2017)
The Quantum Bit

• Overview

• Gates
  • Quantum operations are analog – simply quoting a spec to work to may not be appropriate
  • Lengthy discussion and examples of errors and sources of errors

• Electronics
Extension of Moore’s Law??
One of the following must be true:

- Strong Church-Turing** thesis is false
- Factoring is easy
- Quantum mechanics is wrong

** Church-Turing thesis: anything that can be simulated efficiently can be simulated efficiently on existing digital computers

* Scott Aaronson’s PhD thesis
Applications of quantum computing

Easy problems

Hard problems for classical computers

Quantum possible

Quantum Advantage with Shallow Circuits IBM 2018

Factoring

Simulating quantum mechanics

Applications:
- Chemistry
- Materials
- Machine learning
- Optimization

Also check out: https://quantumalgorithmzoo.org
The Quantum Bit

The quantum Bit:
\[ \alpha |0\rangle + \beta |1\rangle \]

Entangled quantum Bit:
\[ \frac{|00\rangle + |11\rangle}{\sqrt{2}} \]
Unitary operations

- Qubit operations correspond to the qubit state rotating around the Bloch sphere
  - Example: Hadamard (creates equal superposition)
- Two-qubit operations correspond to rotations in a 4-dimensional space
- In general: A quantum operation is a rotation in the $2^n$-dimensional Hilbert space
- Some of the unitary operations have well-known names or classical analogs (NOT, CNOT, Hadamrad, Z, etc)
Quantum Computing: Extra power from interference

- Many computational paths from the initial state to each final state
- Each path accumulates a complex phase, e.g.
- Output probability is concentrated at the final states where (almost) all paths arrive with (approximately) the same phase.
- Unitary gates define the paths for the “correct” answer
A classical algorithm generates a description of a quantum circuit.
One needs a quantum hardware to actually run the quantum circuit.
What is a quantum gate

A quantum circuit translates into a sequence of physical operations (microwave pulses, voltage or current pulses, etc).

Sequence of microwave pulses

Sequence of microwave and bias pulses
Quantum Computing Technologies

What’s your favorite qubit?

Ions
Credit: S. Debnath and E. Edwards/JQI
Monroe Group, University of Maryland/JQI

Photons
Image from the Centre for Quantum Computation & Communication Technology, credit Matthew Broome

Nanowires
Image from Kouwenhoven Group, Delft

Neutral Atoms
Image from Cheng Group, University of Chicago

Solid-state defects
NV Centers, Phosphorous in Si, SiC defects, etc.
Image from Hanson Group, Delft

Quantum dots
Image from Univ. Basel

Superconducting Circuits
The Transmon

Superconducting Qubit:
Josephson Junction as a non-linear inductor

\[ tV_L dt = \delta \]

\[ I = I_0 \sin \delta \]

\[ V = (\Phi_0 / 2\pi) \dot{\delta} \]

\[ \Psi_1 = e^{i\phi_1} \]

\[ \Psi_2 = e^{i\phi_2} \]

\[ \delta = \phi_1 - \phi_2 \]

\[ H = q^2 + \cos(\Phi) \]

Josephson Relations

Non-linear inductor

\[ E_{01} \approx 5 \text{ GHz} \approx 240 \text{ mK} \]

\[ \text{~300MHz anharmonicity} \]

100 nm \( \times \) 100 nm

\( \Phi_0 \)

\( \Phi \)

\( I \)

\( I_0 \)

\( L \)

\( V \)

\( \delta \)

\( \dot{\delta} \)

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Types of Errors

**Gate errors**

- Gate rotates around incorrect axis, or rotates with incorrect angle of rotation. This can be single or multi-qubit errors.

**Spectator errors**

- Qubits not involved in a gate undergo a rotation, or they can impact qubits that are involved in a gate.

**Leakage**

- Transitions out of qubit manifold are allowed!

- Qubits leaves computational space (this is a really bad error)
Controlling the Qubit State

\[ |\Psi\rangle = \cos(\theta/2) \, |0\rangle + e^{i\phi} \sin(\theta/2) \, |1\rangle \]

Drive around the Bloch sphere using microwave pulses (typically 10-50ns @ 5GHz)

Shaped pulses for frequency selectivity!

\[ H_{\text{dr}} = \hbar \Omega(t)(b + b^\dagger) \]

\[ \rightarrow \frac{\hbar \Omega_x(t)}{2}(b + b^\dagger) + \frac{\hbar \Omega_y(t)}{2}(-ib + ib^\dagger) \]

Phase errors due to leakage terms are reduced by DRAG [1].

Sources of errors

- High frequency noise
- Low frequency noise (drift)
  - Shaped pulses and refocusing can help
- Accuracy (number of bits)
  - Shaped pulses and refocusing can help
- Cross talk (spectator errors)

- Sidebands overlap transitions (spectator and leakage errors)
- Noise away from intended microwave tone (spectator / leakage)
Two-qubit gates: Cross resonance


Sources of errors

- Phase noise
- Amplitude noise
- Mixer sidebands

- High frequency noise
- Low frequency noise (drift)
  - Shaped pulses and refocusing can help
- Accuracy (number of bits)
  - Shaped pulses and refocusing can help
- Cross talk (spectator errors)

- Sidebands overlap transitions (spectator and leakage errors)
- Noise away from intended microwave tone (spectator / leakage)

Rigetti and Devoret, PRB 81, 134507 (2010)
Two-qubit gates: Flux-tunable

- Fixed frequency qubits
- Floating qubits
- Modified bypass coupler

Contour: log10(ZZ)
Q1 at 5.1GHz

Gate length: 60ns total -- EPG less than 0.2%

Flux pulses (e.g. Gaussian shaped) implement the gate!
Sources of errors

- Amplitude noise
- Tails

Non-electronics: Flux noise, non-adiabatic effects
- Flux noise (low frequency)
  - Mitigation: Design, positive/negative pulses
- Non-adiabatic effects
  - Mitigation: Pulse shaping
- Temperature stability

- High frequency noise
- Low frequency noise (drift)
  - Can be mitigated with upper sweet spot
- Accuracy (number of bits)
  - Shaped pulses and refocusing can help
- Cross talk (spectator errors)
- History dependent errors
  - Positive/negative pulses can help [1]
  - (From skin loss in cables but can be other causes too)

Relation to Fidelity

What do we need? 1e-3 error or less [1]

Static error

- Error $\approx \theta^2/6$ (in radians)
- Qubit offset of 50kHz for 100ns results in 1.6e-4 error
- “Always-on” ZZ interaction of 100kHz for 100ns results in 1.6e-4 error (assuming qubit is in mid place)

Dynamic (phase) error

Filter function for Ramsey

$W(f, t) = \frac{\sin^2(\pi ft)}{(\pi ft)^2}$

Filter function for spin echo

$W(f, t) = \frac{\sin^4(\pi ft)}{(\pi ft/2)^2}$

$T_2^*$ from decay function

$\rho(t, \Phi_0) = \exp\left\{-(2\pi t \cdot \sigma_Q)^2\right\}$

$T_2^*$ is just the 1/e time of the decay function $\rho$

Inside a dilution refrigerator

10mK!!!
Cryogenic attenuation, filtering and thermalization

1. Small Signals

- Readout signal near -110dBm
- Qubit control near -95dBm
  - ~200pA of induced current gives Rabi drive of 100MHz for typical transmons
  - Or ~120 uV applied to a C=50aF induces the necessary current for a 100MHz Rabi drive
- Cross-resonance requires about 2-5x increase in amplitude
- Noise must be low relative to signal strength

Cryogenic attenuation, filtering and thermalization

2. Thermalization

- Do attenuators, filters, circulators, etc get “cold”?
  - Residual heat can cause errors (like reduced T2)
  - Evidence that custom components might help (heatsinks)
- Must attenuate noise sufficiently well or design electronics with low enough noise
Recap

- Qubit responds in analog fashion to input signals
- Errors scale quadratically

- Some pulses are narrow band (single qubit, cross-resonance); some are much more broad band (fast flux) and may require pre-distortion
- Amplitude and phase noise can cause errors
  - High and low frequency noise can be problematic
- Spurs can be problematic
  - In particular for anharmonic systems like transmon qubits where transitions out of the qubit manifold exist
- Thermalization crucial and needs to be understood
What are the limits

COTS

< ~20 qubits

Custom in-house electronics

< ~1,000 – 2,000 qubits

C. Menolfi et al., 2018 IEEE International Solid-State Circuits Conference - (ISSCC)
What is the state of the art in cryo-electronics

S.J. Pauka et al, arxiv:1912.01299 [Microsoft]

Bardin et al., IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 54, NO. 11, NOVEMBER 2019

B. Patra et al., 2020 IEEE International Solid-State Circuits Conference - (ISSCC), San Francisco, CA, USA, 2020

E. Charbon, ESSCIRC 2019 [EPFL]
Wishlist for cryo-electronics

• Arbitrary waveform generators
  • For amplitude modulation on RF pulses
  • For voltage pulses (that become flux pulses for example)
    • Skin-loss should be mitigated with 4K signal generation!
• High enough output voltage with high enough SNR
• Low power dissipation / heating
• Manufacturable (vendors)
• How much of this can be standardized between different approaches? For example, is there an agreeable operating temperature?
Cryogenic Testing

• Need to develop low temperature models
  • Most models will not work at the temperature of interest
• From these models, design relevant test circuits (e.g. switches, receivers, etc)
  • Noise as applicable to fidelity-reducing mechanisms as discussed
  • Reproducibility, thermal cycling

• Power dissipation
  • Just because the fridge thermometer says something is cold does not make all components cold electrically
Quantum Hardware Challenges

Room temp electronics (stable, low-noise, cost)

Inside the Cryo Dilution Fridge

Cryo-CMOS controls

Cryo flex lines

Harris et al., Review of Scientific Instruments 83, 086105 (2012)

Amplifiers, Attenuators, Isolators, Packaging

Processor, device development

Coherence, junctions, materials

Better two-qubit gates

Packaging

Rosenberg et al., npj Quantum Information volume 3, Article number: 42 (2017)
4 Years After Becoming the First in the Cloud

Since 2016, 32 quantum computers to date have deployed on the IBM Cloud.

Over +280,000 registered users have run...

Over 589 Billion quantum circuits, and ran...

Over 1 Billion quantum circuits run each day

300+ contributors to Qiskit

400+ scientific papers using IBM Quantum.

132 Members of the IBM Q Network.
Writing quantum circuits: the “quantum score”

- “Textbook” way of showing quantum circuits
- Conducive to user-friendly drag-and-drop interface
- Useful for beginners studying simple circuits
- Becomes unmanageable for large/complex circuits (we have OpenQASM for text based circuit representation)
IBM Quantum Platform + Full Qiskit Stack

Applications
- Chemistry, AI, Optimization, Finance

Algorithms
- QPE, Grover, HHL, QSVM, VQE, QAOA, ...

Noise, V&V, Error Correction
- Benchmarking, Volume, Mitigation

3rd Party Plugins
- Transpilers, Visualizers, Circuit Constructors

Open Network Interface/API
- arXiv:1809.03452

Queueing Job Control

Authentication User/Group Management

3rd Party Plugins
- Languages, Toolkits

Hardware

Simulators (Aer)
- statevector, unitary, stabilizer, t-gate, tensor network

Third Party
- QuTech-Delft (cloud)
- JKK DD Simulator
- QCGPU Statevector Simulator
- Alpine Quantum Technologies (ions)

Backends
- ibmqx4
- ibmqx2
- melbourne
- tokyo
- poughkeepsie
- system1
- +8 more

https://qiskit.org
Performing Quantum Computing Experiments in the Cloud
Simon J. Devitt
Center for Emergent Matter Science, RIKEN, Wako, Saitama 351-0198, Japan.
(Dated: September 2, 2016)
Quantum computing technology has reached a second quantum is the next five years. Improved
Quantum computing interest from both
peripheral providers anticipated by n
cloud, with users released the Qua
paper, we take
paper informa
chip to realise pr
try and Faulk
While the results
Experimental Comparison of Two Quantum Computing Architectures
N. M. Linke,1 D. Maaslo,2,3 J. I. Latorre,4,5 and B. Kraus1
1Institute for Theoretical Physics, University of Innsbruck,
2Dept. Física Quântica e Astrofísica, Universitat de Barcelona, Diagon
3Institut de Ciències del Cosmos, Universitat de Barcelona, Diagonal
4The notion of automated quantum computation is introduced to the
ProjectQ: An Open Source Software Framework for Quantum Computing
Damian S. Steiger1, Thomas Hänsler1 and Matthias Troyer1
1Institute for Theoretical Physics, ETH Zurich, 8093 Zurich, Switzerland
(Dated: December 28, 2016)
We introduce ProjectQ, an open-source compiler framework for simulating quantum computers.
We introduce our Pylt package, which provides example implementations of quantum algorithms through
simulated and real backends. It allows users to develop, test, and optimize quantum circuits.
Quantum Computing: A New Perspective
Christine Corbett Moran1,2
1NSF AAPP California Institute of Technology, TAPIR, 1200 E California Blvd, Pasadena, CA 91125
2University of Chicago, 3616 SPT Wenteinveister Scientific, Anvendont-Scott South Pole Station, Antarctica 99606
From calculating the probability of 450+ Papers and Counting...
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Get started...

pip install qiskit
quantum-computing.ibm.com

Qiskit
An open-source quantum computing framework for leveraging today's quantum processors in research, education, and business

Qiskit Terra
A solid foundation for quantum computing

Qiskit Aqua
Algorithms for near-term quantum applications

Qiskit Aer
A high performance simulator framework for quantum circuits

Qiskit Ignis
Understanding and mitigating noise in quantum device
Conclusions

- Quantum computing (think of waves that also include entanglement)
- The machine language of quantum computers are a sequence of physical operations (e.g. microwave and/or flux pulses, or voltage pulses)
- Noise and imperfections can cause errors
- These noise sources and errors need to be considered when designing cryo-electronics
- Cryo-electronics and wishlist
- A full stack quantum computer requires many more hardware components
- Today’s systems are excellent enabler for remote research
- Try Qiskit!