Quantum Computing Hardware

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HBO-ICT Technical Computing

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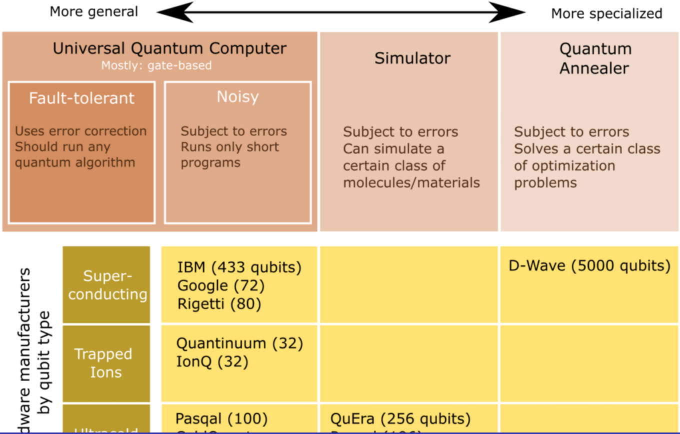
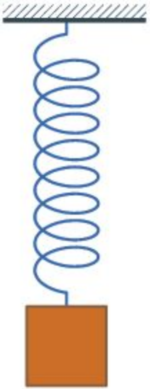
- The professional's guide to Quantum Technology
- The hardware part guide

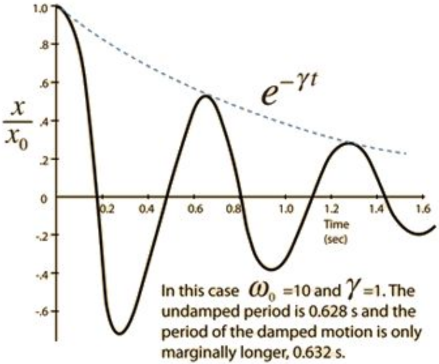


Quantum theory and simulation

- Quantum Mechanics simulation
- Scientific Python examples
- 1D-tutorial equation solution
- Solving Schrödinger equations numerically
- Elektromagnetism
- QuTiP.org, QuTIP github
- QuTIP github

Classic damped oscillator





Quantum Mechanics basics

the wave function conclusively describes the chance to detect the particle according to a probability distribution:

$$P(\boldsymbol{x}) = \psi^*(\boldsymbol{x}).\psi(\boldsymbol{x}) = \|\boldsymbol{x}\|^2$$

where the * denotes a complex conjugate, or negating the imaginary part of the number, and the whole operation is equivalent to getting the magnitude squared of the complex numbers. This probabilistic interpretation requires that the following be true:

$$\int \|\psi(\boldsymbol{x}\|^2 d\boldsymbol{x} = 1$$

meaning themeaning the total magnitude of the complex field is 1, conserving p

Time evolution Schrödinger equation

The purpose of quantum mechanics is to describe how wave functions change as a function of time, i.e. $\psi(\boldsymbol{x}.t)$. This is captured by the Schrödinger equation in its most general form:

$$i\hbar\frac{\psi(\boldsymbol{x},t)}{dt} = \mathcal{H}(\psi(\boldsymbol{x},t)$$

Here, $\mathcal{H}$is called the Hamiltonian operator and essentially measures, or specifies, the energy of a wave function. Namely, the energy of a wave function is the expectation value of the Hamiltonian, which physicists write as

$$E = \mathbb{E}(\mathcal{H}) = \int \psi^*(\boldsymbol{x})\mathcal{H}\psi(\boldsymbol{x})d\boldsymbol{x}$$

which can be thought of as a weighted average of the Hamiltonian applied to the wave function everywhere.

Solving Schrödinger equation

The Schrödinger equation says that the rate of change of the wave function is related to the energy of $\phi(\boldsymbol{x})$. Eigenstates satisfy the following relationship:

$$\mathcal{H}\phi = E\phi$$

meaning the result of the Hamiltonian operating on ϕ is the same wave function ϕ scaled by a fixed energy E constraints on what ϕ can be, which depends on exactly what the Hamiltonian is. Eigenstates of the Hamiltonian will satisfy

$$\frac{d\phi}{dt} = -iE\phi$$

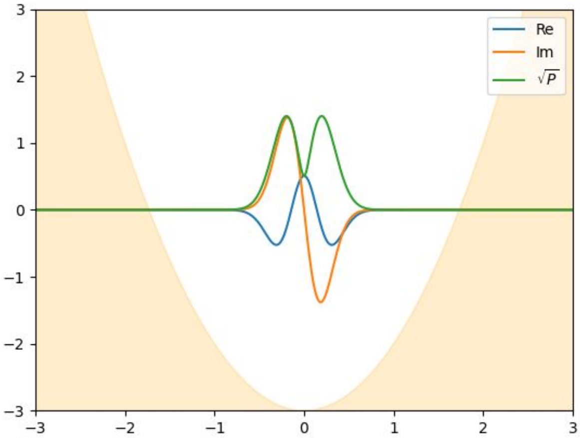
The solution to this is any function proportional e^{iEt}, which shows that

$$\phi(\boldsymbol{x}, t) = e^{iEt}\phi(\boldsymbol{x})$$

meaning only the complex phase of the eigenstates change with time, which is the

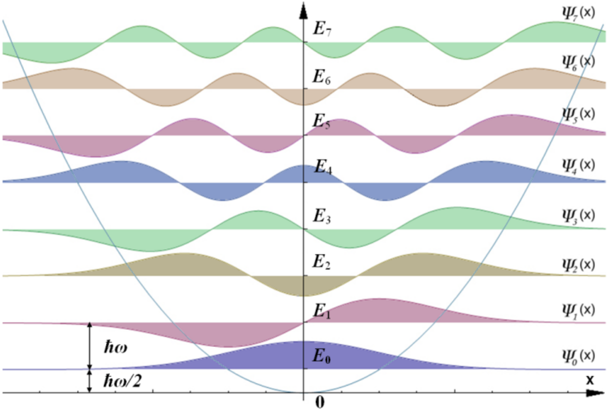
Quantum mechanics demo

See notebook extracted from: Quantum Mechanics simulation



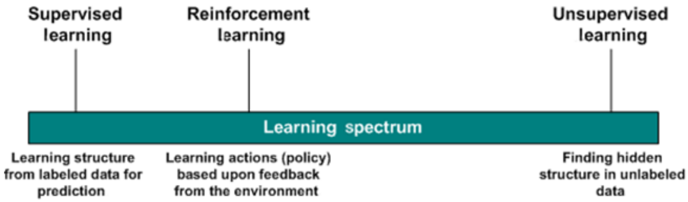
Quantum Harmonic Oscillator

$$H = \sum_k E_k \left|\psi_k\right\rangle \left\langle\psi_k\right|, \left\langle\psi_k\right| \left|\psi_k\right\rangle = \delta_j, k, \left|psi_k\right\rangle \mapsto \left|k\right\rangle$$



Quantum Machine Learning and stack

- ML Tutorials Qiskit)
- Pennylane.ai
- Recent package sqlearn [1]
- Qiskit and AI [2]
- Optimizatioin and Learnning ofview[3]
- Overviews: [4], [5], [6]



News messages May 2024

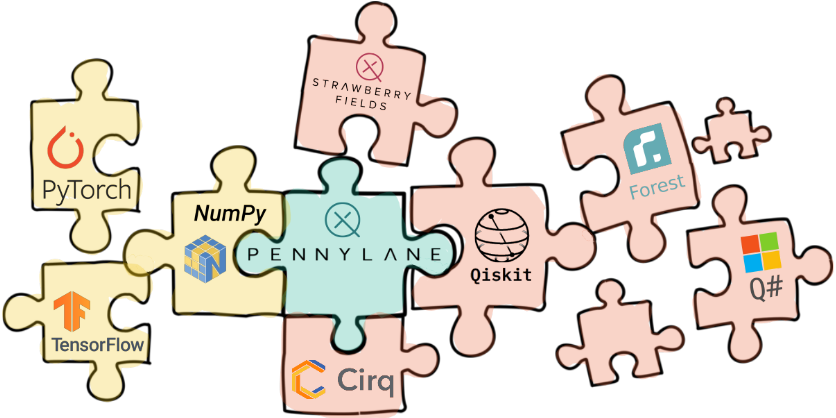
- Teleoperation Breakthrough
- Breakthrough high temperature sperconductors
- Rydberg quantum simulation
- QuEra
- NVida CUDA-Q
- new groundbreaking device
- Million Qubits?
- Fault-tolerant quantum memory
- Alternatives?
- Promissing?

Investigating electronics

- IBM Quantum learning
- Example in Transmon physics
- pennylane.ai

Pennylane overview

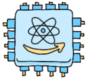
pennylane.ai



Pennylane demos HW 1

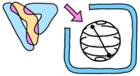
Demo

Efficient Simulation of Clifford Circuits



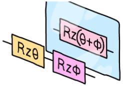
Demo

Getting started with the Amazon Braket Hybrid Jobs



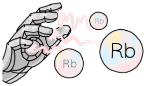
Demo

Using PennyLane with IBM's quantum devices and Qiskit



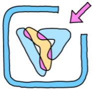
Demo

Compilation of quantum circuits



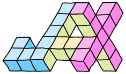
Demo

Pulse programming on Rydberg atom hardware



Demo

Using PennyLane with PySCF and OpenFermion



Demo

Using JAX with PennyLane

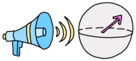
Demo

Computing gradients in parallel with Amazon Braket

Pennylane demos HW 2

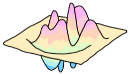
Demo
Turning quantum nodes into Torch Layers

Demo
Turning quantum nodes into Keras Layers

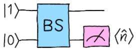


Demo
Optimizing noisy circuits with Cirq

Demo
PyTorch and noisy devices



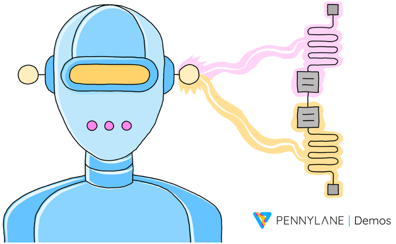
Demo
Training a quantum circuit with PyTorch



Demo
Plugins and hybrid computation

Pennylane demos HW 3

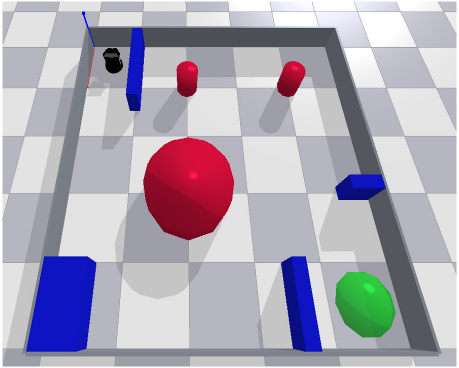
Gate calibration reinforcement Learning



Other approach [7]

Quantum, Reinforcement learning and robotic navigation

- Quantum Deep Reinforcement Learning for Robot Navigation Tasks [8]



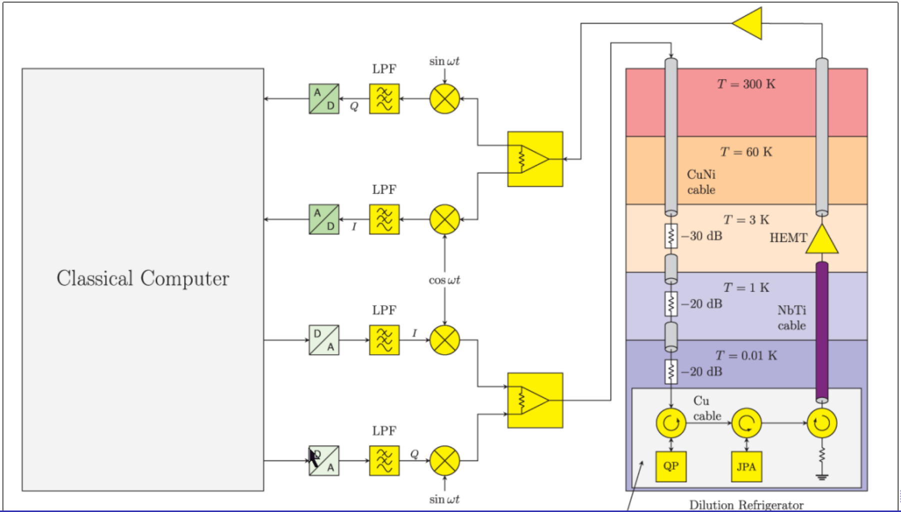
Pennylane hardware notebook tutorial

quantum_volume.ipynb tutorial_mbqc.ipynb tutorial_neutral_atoms.ipynb tutorial_odegen.ipynb tutorial_optimal_control.ipynb tutorial_pasqal.ipynb tutorial_photonics.ipynb tutorial_pulse_programming101.ipynb tutorial_rl_pulse.ipynb tutorial_sc_qubits.ipynb tutorial_trapped_ions.ipynb

Quantum hardware references

- Overivew ([9], [10])
- Diffferent qubits overview
- Google ([11])
- QC_CMU
- Course: the Hardware of a Quantum Computer
- Qubit dashboard Factbased Insight

Superconducting Quantum Computer example



Technologies

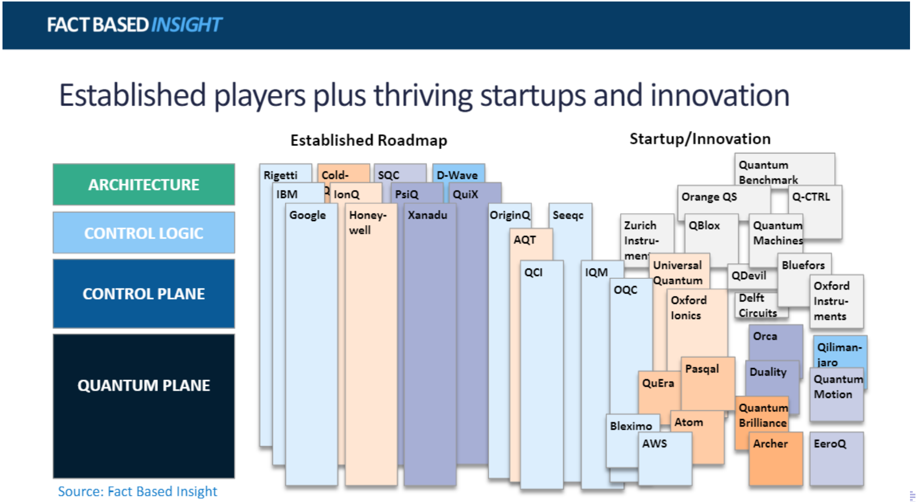
FACT BASED *INSIGHT*

Old high level comparison of qubit technologies

	Superconducting Circuits	Trapped Ion	Neutral Atom	NV Diamond	Silicon Spin	Photonic
ARCHITECTURE			Sensing	Sensing		
	Building	Building	Large	Q Network	Chip	Compact
Control Processor	Rack	Rack	Rack	Rack	*Integrated*	*Integrated*
	Cross talk?	Scaling?	?	?	?	?
Gate Control	Wire	Laser	Laser	Laser	Circuit	Electrical
	Fast gates	Long life	Long life	Long life	Fast gates	Fast Gates
Environment	Dilution	UHV	UHV	Ambient	Dilution	Ambient
				Deployable		Deployable
Connectivity	2D	All-to-all	2D/3D	Clusters	2D	Flexible
	Multi Q	Multi Q	Simulation		CMOS fab	CMOS fab
Substrate	Circuit	Trap	Trap	^{12}C	^{28}Si	Photonics
	99.4%	99.9%	97%	88%	98%	“98%”
Qubit	Current loop	Ion	Atom	NV defect	Electron	Photon

Source: Fact Based Insight

Innovation


FACT BASED INSIGHT
Established players plus thriving startups and innovation
Established Roadmap
Startup/Innovation
ARCHITECTURE
CONTROL LOGIC
CONTROL PLANE
QUANTUM PLANE
Rigetti
Cold-
SQC
D-Wave
IBM
IonQ
PsiQ
QuiX
Google
Honey-well
Xanadu
OriginQ
Seeqc
AQT
QCI
IQM
OQC
Bleximo
AWS
Zurich Instru-
Universal Quantum
Oxford Ionics
QuEra
Pasqal
Atom
Quantum Benchmark
Orange QS
Q-CTRL
QBlox
Quantum Machines
QDevil
Bluefors
Delft Circuits
Oxford Instru-ments
Orca
Qiliman-jaro
Duality
Quantum Motion
Quantum Brilliance
Archer
EeroQ
Source: Fact Based Insight

Overview

FACT BASED *INSIGHT*

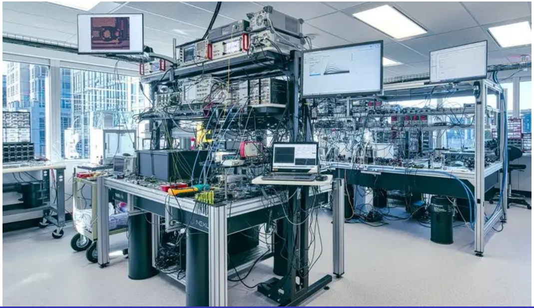
	Superconducting Circuits	Trapped Ions	Neutral Atoms	NV Diamond	Silicon Spin	Photonic
Important Variants	Tunable, Fixed Freq., Parametric	Hyperfine, Optical, NF Microwave, GF Microwave	Hyperfine, Optical	Nitrogen Vacancy, Silicon Vacancy	Quantum Dots, Imp. Donor, STM-Fab. Door	MBQC, CVQC
Qubit T2 Lifetimes	Short 15-120μs	Long 0.2-50s	Long 0.2-50s	Long 10s	Mixed 1μs-0.5s	Short 150μs
2Q Gate Fidelity	High 99%-99.85%	High 99%-99.9%	Promising 97%	Interesting 99% (88%)	Promising 98%	Promising 98%
Gate Speeds	Fast 12-200ns	Mixed 1μs-3ms	Intermediate 1μs	Slow 100μs	Fast 0.8-80ns	Very Fast 1ns
Lifetime/ Speed	1250-100	1000000-500	1000000-100000	c.100000	10-50	c.150000
Environment	20mK	Ultra High Vacuum	Ultra High Vacuum	Ambient	20mK - 1K	1K - 10K (detectors)
Current Devices	65Q	20Q	51Q	10Q	2Q	12Q
Announced Devices for 2021	100Q 128Q	32Q 50Q	100Q	10Q	6Q	24Q 40Q-80Q
FTQC Footprint	Building	Building	Large	Network	Chip	Compact

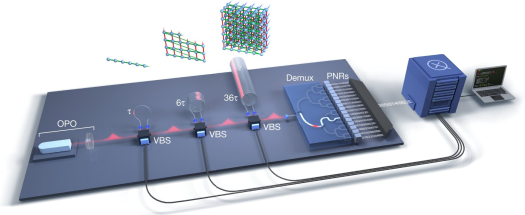
Source: Fact Based Insight

1s = 1000ms = 1000,000μs = 1000,000,000ns

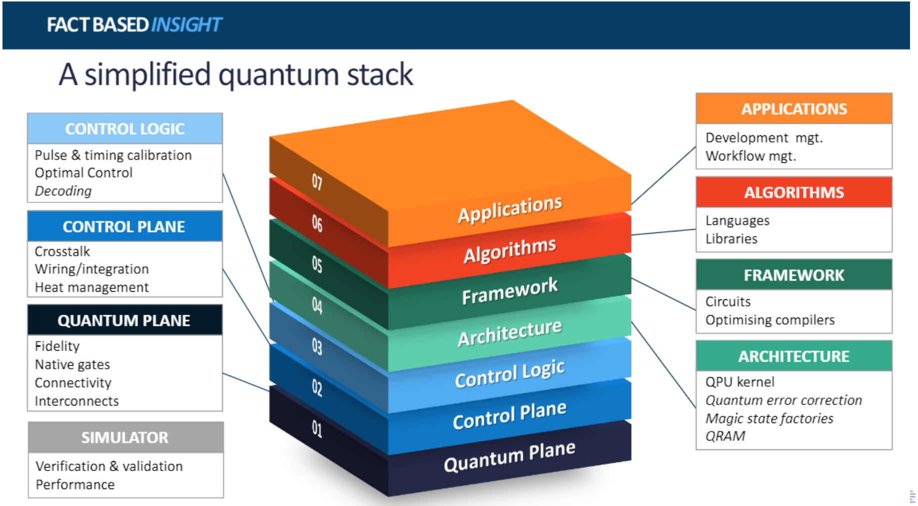
Optical quantum computer progress

- New Scientist announcement 1 June 2022: Advanced quantum computer made available to the public for first time (219 photons)
- Quantum computational advantage with a programmable photonic processor
- Jiuzhang 3.0 255 photons detected





Quantum stack



Quantum HW roadmap

FACT BASED INSIGHT

Quantum hardware roadmaps are hard to directly compare

Platform	Player	2020	2021	2022	2023	2024	2025 to 2030
Superconducting	Google	**53Q**	100Q		10^3Q		10^4Q - 10^4Q - 1MQ
Superconducting	IBM	**65Q**	127Q	433Q	1121Q		path to 1MQ
Superconducting	Rigetti	**32Q**	4x32Q				
Trapped Ion	Honeywell	**H1**		H2		H3	H4 H5
Trapped Ion	IonQ	22AQ		29AQ		256AQ	1024AQ
Neutral Atom	ColdQuanta		100Q	300Q		1000Q	
Silicon	CEA Leti		6Q		100Q		
Silicon	SQC			10Q			100Q
Photonic	QuiX		12Qm	50Qm			
Photonic	PsiQ						1MQ
Photonic	Xanadu	X24	X40	X80	XD80		1MQ

Source: Fact Based Insight

Atoms and spectra

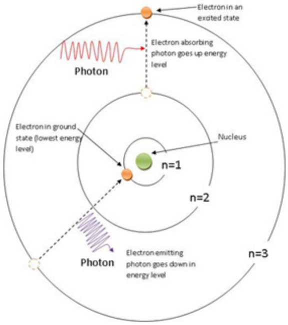


Figure 3

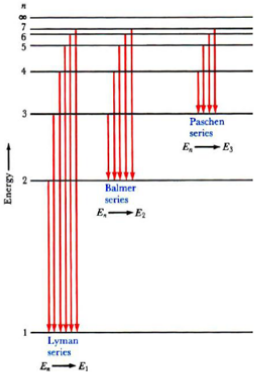
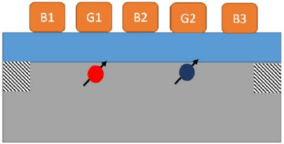


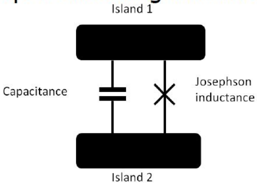
Figure 4

Quantum qubits

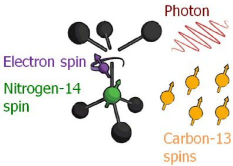
Quantum dot

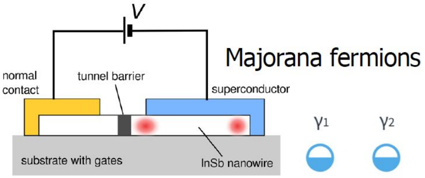


Superconducting transmon



The NV center in diamond





Quantum sensing

	Qubit(s)	Measured quantity(ies)	Typical frequency
Neutral atoms			
Atomic vapor	Atomic spin	Magnetic field, Rotation, Time/Frequency	DC–10 GHz
Cold clouds	Atomic spin	Magnetic field, Acceleration, Time/Frequency	DC–10 GHz
Trapped ion(s)			
	Long-lived electronic state	Time/Frequency Rotation	THz
	Vibrational mode	Electric field, Force	MHz
Rydberg atoms			
	Rydberg states	Electric field	DC, GHz
Solid state spins (ensembles)			
NMR sensors	Nuclear spins	Magnetic field	DC
NV center ensembles	Electron spins	Magnetic field, Electric field, Temperature, Pressure, Rotation	DC–GHz
Solid state spins (single spins)			
P donor in Si	Electron spin	Magnetic field	DC–GHz
Semiconductor quantum dots	Electron spin	Magnetic field, Electric field	DC–GHz
Single NV center	Electron spin	Magnetic field, Electric field, Temperature, Pressure, Rotation	DC–GHz

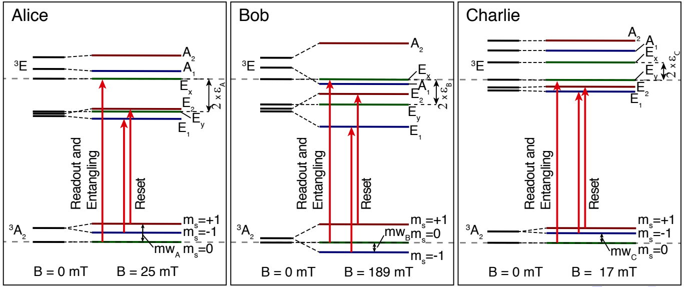
Quantum sensing 2

Superconducting circuits				
SQUID	Supercurrent	Magnetic field	DC–10 GHz	
Flux qubit	Circulating currents	Magnetic field	DC–10 GHz	
Charge qubit	Charge eigenstates	Electric field	DC–10 GHz	
Elementary particles				
Muon	Muonic spin	Magnetic field	DC	R
Neutron	Nuclear spin	Magnetic field, Phonon density, Gravity	DC	I
Other sensors				
SET	Charge eigenstates	Electric field	DC–100 MHz	
Optomechanics	Phonons	Force, Acceleration, Mass, Magnetic field, Voltage	kHz–GHz	
Interferometer	Photons, (Atoms, Molecules)	Displacement, Refractive Index	–	

Table: Experimental implementations of quantum sensors. SET: single electron transistor, NV: nitrogen-vacancy, status 2017 ([12])

Quantum technology hardware for distributed operations

- Technology of quantum clocks to synchronize integrated quantum clock consortium. Prof. Florian Schleck from the University of Amsterdam is involved.
- In the quantum internet experiments in Delft spectra used ([13]) with a demo ([14])



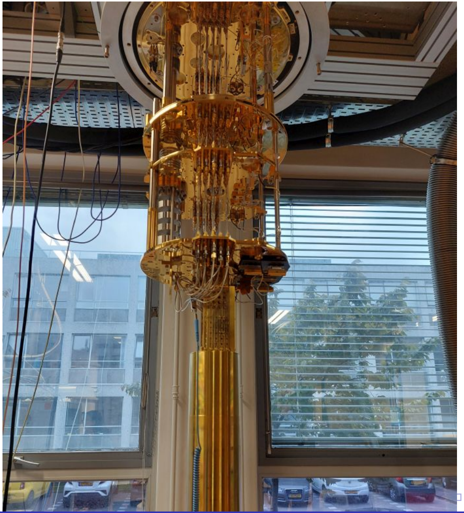
Quantum technologies for space applications

Cooperation between ESA and EU (see e.g. Policy papers)

- Secure Quantum Communication (QKD via satelite)
- Quantum technology for accurate time and Frequency Transfer (e.g. Navigation)
- Earth Sensing and Observation(e.g. measuring gravity field Earth)
- Fundamental Physics (e.g. Bose-Einstein Condensates)

Webreference of related projects in vandersypenlab

Inside when opened



Neutral atoms

Four laser beams around atom ensemble to realise Magnetic-Optical-Trap

FACT BASED *INSIGHT*

Trapped ions – very different approaches

Notable variations	USP	Key Challenge	Notable Players	Leading device 2020	Announced For 2021
Hyperfine qubits with laser gates	99.9% Highest fidelity	Scaling-up laser control system	IonQ, Honeywell	QV 10Q (QV 128)	? 32Q (QV 4millon)
Optical qubits with laser gates	99.6% Easier optical integration	Mitigating shorter qubit lifetime	AQT, NextGenQ	20Q	50Q
Hyperfine qubits with near-field microwave gates	99.7% High fidelity without lasers	Demonstrate multi-qubit device	Oxford Ionics	2Q	
Dressed states with global-field microwave gates	Very modular and scalable	2Q gate fidelities	Universal, NextGenQ	2Q	

Trapped Ions

FACT BASED *INSIGHT*

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Source: Fact Based Insight

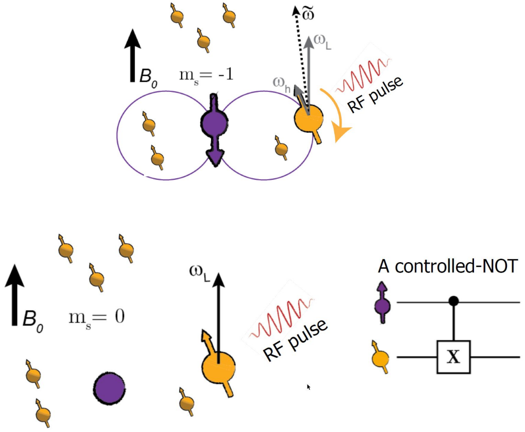
FACT BASED *INSIGHT*

Superconducting circuits – a challenge of fidelity and scaling

Notable variations	USP	Key Challenge	Notable Players	Leading device 2020	Announced For 2021
Tunable qubits 99.7%	Fast gates	Scaling-up	Google, OriginQ, QuTech, IQM, Seeqc,	53Q QS	100Q
Fixed-frequency 99.85%	Longer qubit lifetime	Integrating tunable couplers	IBM, OQC	27Q (QV 128) QV	128Q
Parametric gates 99%	Hybrid benefits	2Q gate fidelities	Rigetti, Bleximo,	32Q	4x32Q
Flux qubits	Rapid scale-up for quantum annealing	Demonstrating quantum advantage	D-Wave, Qilimanjaro	5000Q	

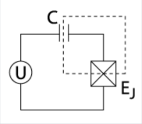
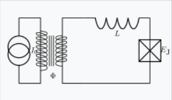
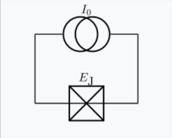
Source: Fact Based Insight

Example NOT-gate



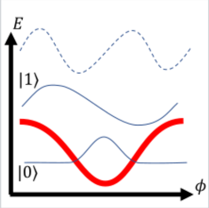
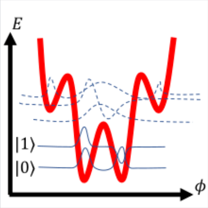
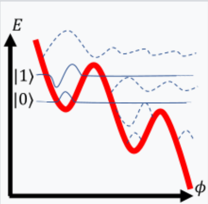
Different Superconducting Qubit types

Overview wikipedia

Aspect \ Type	Charge qubit	RF-SQUID qubit (prototype of the Flux Qubit)	Phase qubit
Circuit	 Charge qubit circuit. A superconducting island (encircled with a dashed line) is defined between the leads of a capacitor with capacitance C and a Josephson junction with energy E_J biased by voltage U.	 Flux qubit circuit. A superconducting loop with inductance L is interrupted by a junction with Josephson energy E_J. Bias flux Φ is induced by a flux line with current I_0.	 Phase qubit circuit. A Josephson junction with energy parameter E_J is biased by current I_0.
Hamiltonian	$H = E_C(N - N_g)^2 - E_J \cos\phi$ In this case N is the number of Cooper pairs to tunnel through the junction, $N_g = CV_0/2e$ is the charge on the capacitor in units of Cooper pairs number, $E_C = (2e)^2/2(C_J + C)$ is the charging energy associated with both capacitance C and Josephson	$H = \frac{q^2}{2C_J} + \left(\frac{\Phi_0}{2\pi}\right)^2 \frac{\phi^2}{2L} - E_J \cos\left[\phi - \Phi\frac{2\pi}{\Phi_0}\right]$ Note that ϕ is only allowed to take values greater than 2π and is alternatively defined as the time integral of voltage along inductance L.	$H = \frac{(2e)^2}{2C_J} q^2 - I_0 \frac{\Phi_0}{2\pi}\phi - E_J \cos\phi$ Here Φ_0 is magnetic flux quantum.

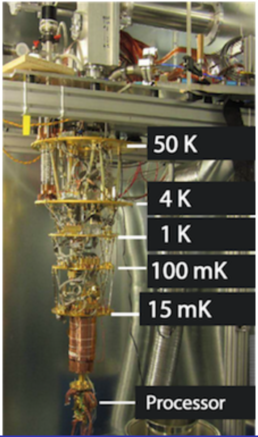
Different potentials Qubit

Overview wikipedia

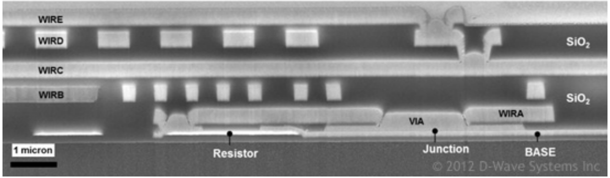
Potential	 $U = -E_J \cos\phi$. Bias voltage is set such that $N_g = \frac{1}{2}$, minimizing the energy gap between $\lvert 0\rangle$ and $\lvert 1\rangle$, consequently distinguishing the gap from other energy gaps (e.g. gap between $\lvert 1\rangle$ and $\lvert 2\rangle$). The difference in gaps allows addressing transitions from $\lvert 0\rangle$ to $\lvert 1\rangle$ and vice versa only, without populating other states.	 $U = \left(\frac{\Phi_0}{2\pi}\right)^2 \frac{\phi^2}{2L} - E_J \cos\left[\phi - \Phi\frac{2\pi}{\Phi_0}\right]$ Bias flux is $\Phi = \Phi_0/2$. Different wells correspond to a distinct number of flux quanta trapped in the superconducting loops. The two lower states correspond to a symmetrical and anti-symmetrical superposition of zero or single trapped flux quanta, sometimes denoted as clockwise and counterclockwise loop current states: $\lvert 0\rangle = [\lvert\circlearrowleft\rangle + \lvert\circlearrowright\rangle]/\sqrt{2}$ and $\lvert 1\rangle = [\lvert\circlearrowleft\rangle - \lvert\circlearrowright\rangle]/\sqrt{2}$.	 $U = -I_0 \frac{\Phi_0}{2\pi}\phi - E_J \cos\phi$, also known as "washboard" potential. Bias current is adjusted to allow wells shallow enough to contain exactly two localized wave functions. A slight increase in bias current causes a selective "spill" of higher energy state ($\lvert 1\rangle$), expressed with a measurable voltage spike (a mechanism commonly used for phase qubit measurement).

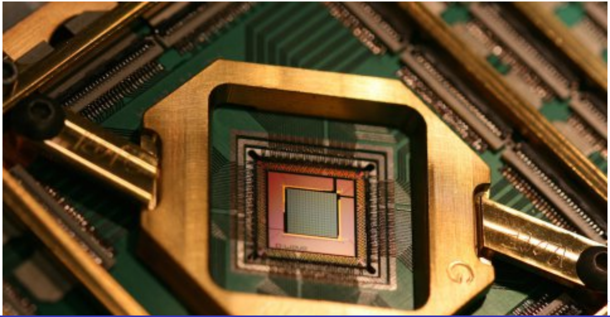
D-wave SQUID

How annealing Works in D-Wave QPUs D-wave hardware references, D-Wave Quantum hardware

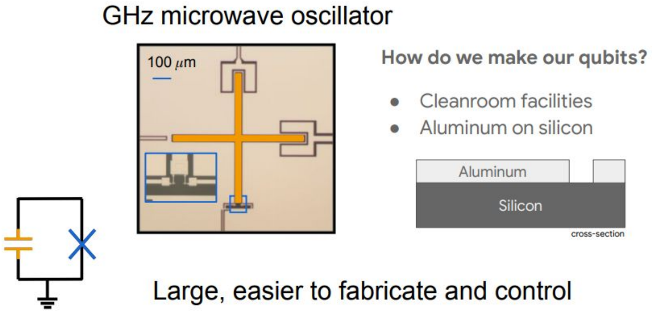


D-Wave hardware cross-section

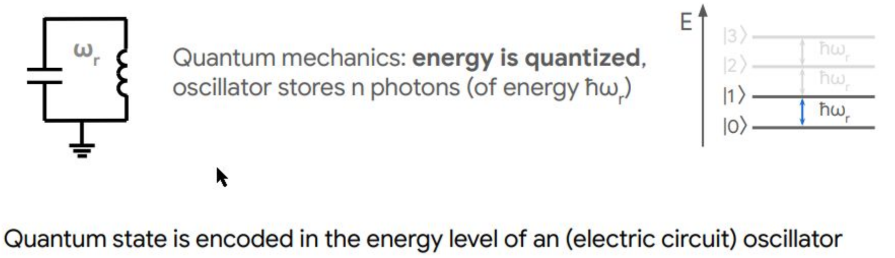




Transmon


GHz microwave oscillator
100 μm
How do we make our qubits?
Cleanroom facilities
Aluminum on silicon
Aluminum
Silicon
cross-section
Large, easier to fabricate and control

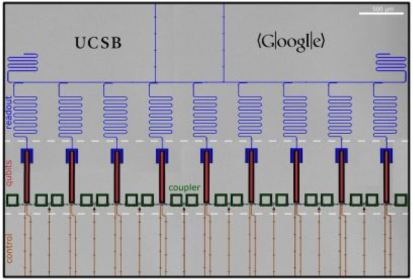
Harmonic Oscillator



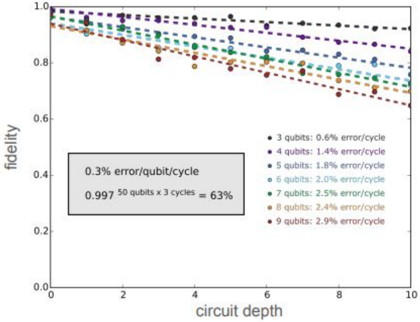
Details computation: Qiskit intro Transmon Physics

9 Qubits

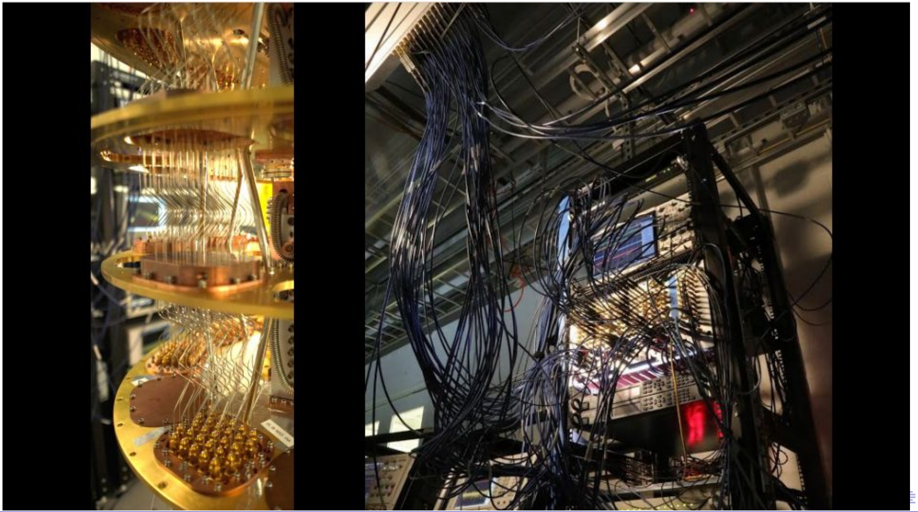
9 qubit device



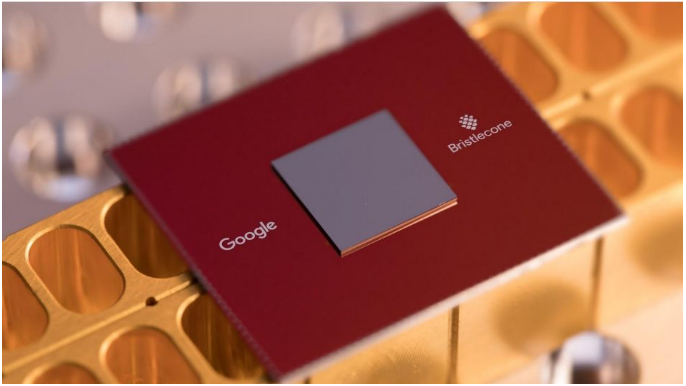
benchmarking data



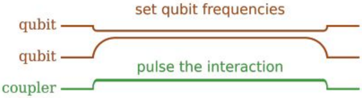
QPU



Britlecone

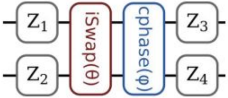


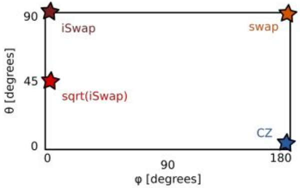
Gate implementation



$$\begin{array}{c} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i\alpha}\cos\theta & e^{i\beta}\sin\theta & 0 \\ 0 & e^{i\gamma}\sin\theta & e^{i\delta}\cos\theta & 0 \\ 0 & 0 & 0 & e^{i\varphi} \end{pmatrix} \\ \begin{array}{cccc} 00 & 01 & 10 & 11 \end{array} \end{array}$$

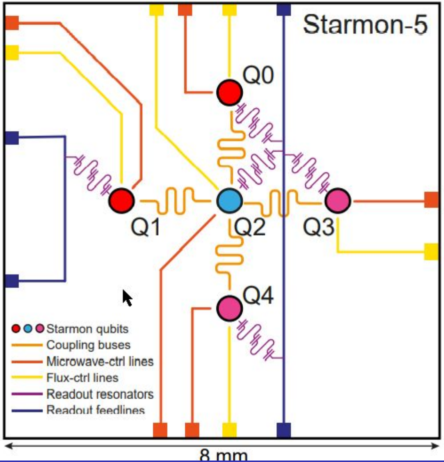
Model for arbitrary photon-conserving gate



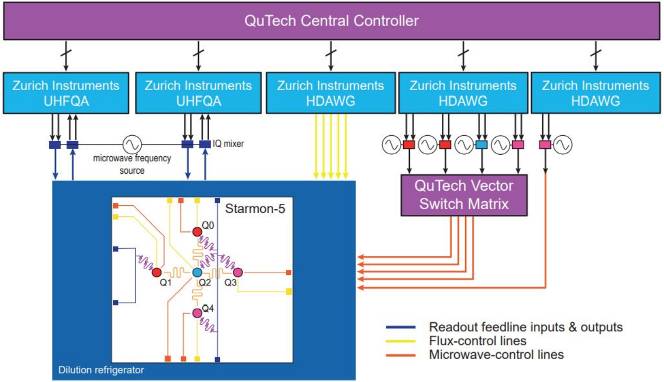


Transmon-5 factsheet

Reference to factsheet

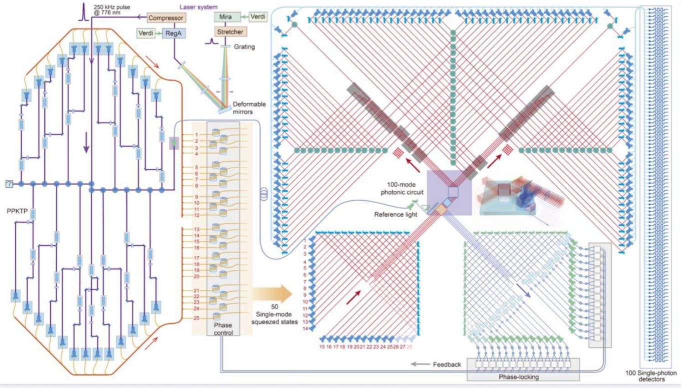


Transmon-5 equipment

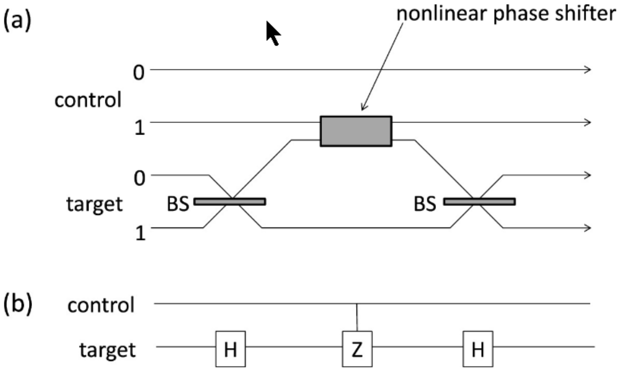


Optical approaches

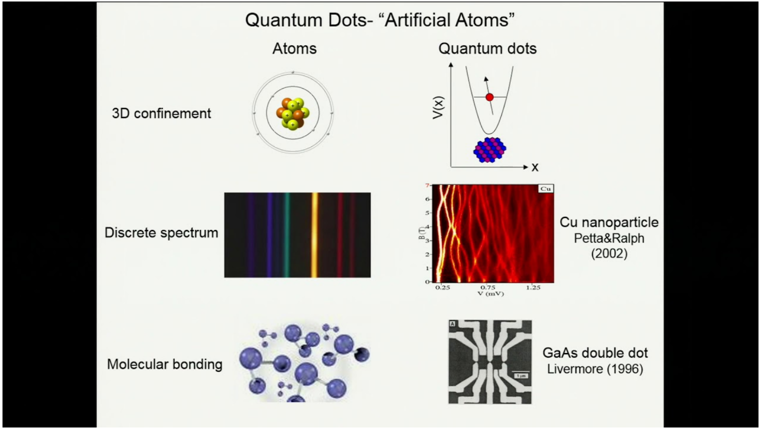
Chinese computer with 62 qubits based on optical principles([15])


250 kHz pulse @ 776 nm
Laser system
Compressor
Mira
Verdi
Verdi
RegA
Stretcher
Grating
Deformable mirrors
PPKTP
Phase control
50 Single-mode squeezed states
100-mode photonic circuit
Reference light
Feedback
Phase-locking
100 Single-photon detectors

Optical components



Quantum dot


Quantum Dots- "Artificial Atoms"
Atoms
Quantum dots
3D confinement
V(x)
x
Discrete spectrum
Cu
B (T)
V (mV)
Cu nanoparticle
Petta&Ralph
(2002)
Molecular bonding
GaAs double dot
Livermore (1996)

Variations

FACT BASED *INSIGHT*

Increasingly, variations of qubit technology are important

	Superconducting Circuits	Trapped Ion	Neutral Atom	NV Diamond	Silicon Spin	Photonic
Error Correction	*Surface code* *Colour code*	*Bacon-Shor co* ! *Surface code*	*Surface code*		*Surface code*	*Beyond foliat* ! *GKP code*
Control Processor	*CryoCMOS* ! *SFQ*	Rack	Rack	*Mounted*	*Monolithic*	*Flipchip*
Gate Control	Freq. tuning M 99.85% e Tunable couplers	Laser QV NF Microwave ! GF Microwave	Laser	Laser	CMOS fab STM fab 1K	Electrical
Environment	20mK	UHV	UHV	Ambient	200mK?	2K (detector)
Connectivity	Square grid Hex grid	All-to-all Shuttling	2D+ 1000Q?	Clusters 99%	2D	Flexible
Substrate	Circuit	RF trap	MOT trap	^{12}C	^{28}Si	Photonics
Qubit	Tunable Fr QS Fixed Freq.	Hyperfine Optical	Hyperfine Optical	NV SiV	Qdot Donor	Single Photon QS Squeezed Light

Source: Fact Based Insight

Simplyfing circuits

- Use of Transpiler
- Manual simplification
- Use of dedicated libraries
- Classical for Boolean algebra, e.g. Karnaugh Maps, simplification rules

Example PyZX library

PyZX (pronounce as Pisics) is a Python tool implementing the theory of ZX-calculus for the creation, visualisation, and automated rewriting of large-scale quantum circuits (Github library, [16])

- `Circuit` - The name of the circuit
- `qubits` - Amount of qubits in the circuit
- `G-count` - Gate count of original circuit
- `2-count` - Amount of 2-qubit gates in original circuit
- `G/2-NRSCM` - Total amount and 2-qubit gate amount from optimized circuit of [1]
- `G/2-Tpar` - Total amount and 2-qubit gate amount from optimized circuit of [2]
- `G/2-PyZX` - Total amount and 2-qubit gate amount from optimized circuit made by PyZX
- `Time-Simp` - The time taken for running the simplification routine on the circuit
- `Time-Extract` - The time taken for extracting the circuit after the simplification

Examples PyZX library

```
In [4]: print("Circuit".ljust(20), "qubits", "G-count", "2-count", "G-NRSCM", "2-NRSCM", " G-Tpar", "2-Tpar", '
        for c in fast_circuits:
            print(c.get_output())
```

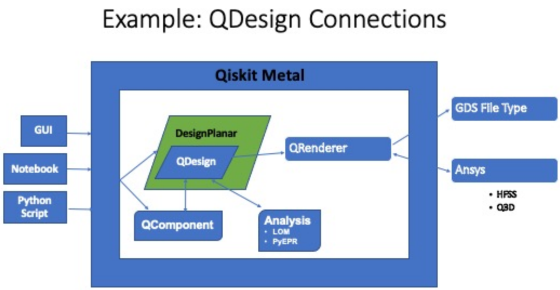
```
Circuit              qubits G-count 2-count G-NRSCM 2-NRSCM  G-Tpar 2-Tpar G-PyZX 2-PyZX Time-Simp Ti
me-Opt
Adder8                   23 |    637    243 |    190      94 |      -      - |    362    199      1.06
0.13
adder_8                  24 |    900    409 |    606     291 |   1280    885 |    677    337      2.03
0.21
barenco_tof_10           19 |    450    192 |    264     130 |    517    328 |    365    176      0.62
0.44
```

```
hwb8.qc                  12 | 14856   7129 |      -       - |      -      - |  12491   6234    174.24
13.42
mod_adder_1024           28 |  4285   1720 |   2736    1278 |   5183   3540 |   3136   1430     12.82
1.80
nth_prime8.tfc           12 | 16968   8235 |      -       - |      -      - |  14511   7229    136.90
18.58
QFT32                    32 |  1562    612 |   1012     612 |      -      - |   1012    612      1.71
0.34
QFTAdd16                 32 |  1822    716 |   1168     716 |      -      - |   1186    716      2.90
0.51
QFTAdd32                 64 |  4814   1900 |   3040    1900 |      -      - |   3077   1900     10.31
1.44
```

Designing with Qiskit metal

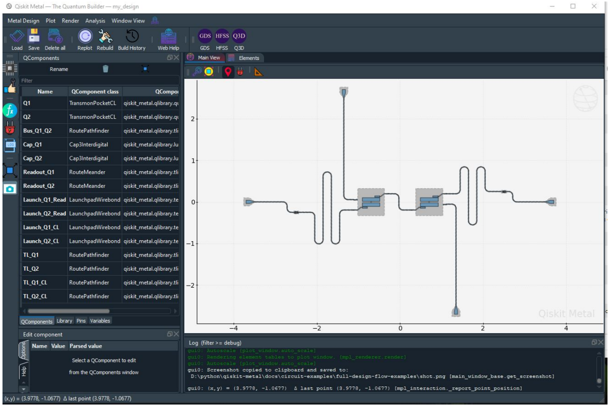
- Qiskit Metal
- Qiskit metal documentation
- Quantum Device Design (QDesign): QDesign
- Quantum Device Components (QComponent): Core Classes
- Quantum Renderer (QRenderer): Renderer Base
- Quantum Analysis (QAnalysis): Analysis Core

Qiskit metal interfaces



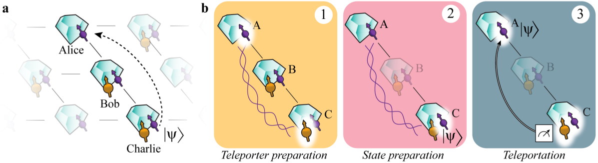
Qiskit metal tutorials

Qiskit-metal including tutorials



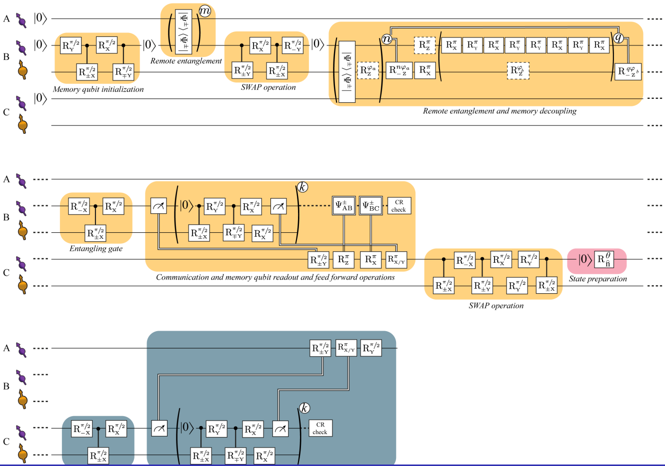
Recent developments

- Science daily news quantum computers
- Overview tools
- Qubit teleportation between non-neighbouring nodes in a quantum network, (arxiv) [14]



Quantum repeater protocol using quantum memory

[14]



Quantum Computer Quality

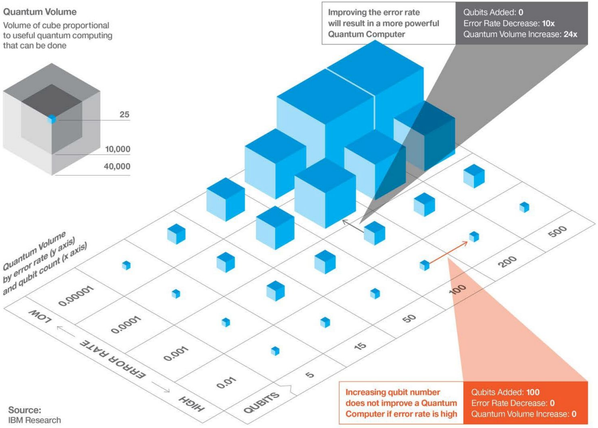
- number of Qubits
- error rates
- error mitigation
- noise
- decoherence
- topology

Quantum Volume protocol

Ref: Qiskit Measurering Quantum Volume

- Generate QV sequences
- Simulate the ideal QV circuits
- Calculate the heavy outputs
- Define the noise model
- Calculate the average gate fidelity
- Calculate the achievable depth
- Calculate the Quantum Volume

Quantum Volume



Investigating Hardware

Investigating Quantum Hardware in Qiskit, Quantum measurement lab Qiskit

- Quantum Error Correction using Repetition Codes
- Measurement Error Mitigation
- Randomized Benchmarking ([17])
- Measuring Quantum Volume
- The Density Matrix & Mixed States

Calibration and measurements

- During initialization a quantum computer needs to be calibrated before using quantum computer for calculations
- Quantum measurement lab Qiskit
- Calibrating Qubits with Qiskit Pulse

Conclusion

- Different hardware technologies are competing
- Hardware underlying software design quite complicated
- Hardware design tools are being developed
- interface to hardware requires interfacing to electronics
- Quantum commputinng requires time consuming calibration
- Criterai needed to evaluate quantum hardware

Exercises: and ideas for Quantum Stack

- Exercise fundamental Schrödinger equation solution examples and links with Quantum hardware
- Report on Quantum Hardware in Qiskit or Pennylane
- Explore design options in Qiskit metal: Qiskit Metal tutorial examples
- Qiskit notebook on quantum volume

References I

[1] David A. Kreplin, Moritz Willmann, Jan Schnabel, et al. *sQUlearn – A Python Library for Quantum Machine Learning*. 2024. arXiv: 2311.08990 [quant-ph].

[2] A. Wichert. *Quantum Artificial Intelligence with Qiskit*. CRC Press LLC, 2024. ISBN: 9781032448985. URL: https://books.google.nl/books?id=74AP0AEACAAJ.

[3] E.F. Combarro and S. González-Castillo. *A Practical Guide to Quantum Machine Learning and Quantum Optimization: Hands-on Approach to Modern Quantum Algorithms*. Packt Publishing, 2023. URL: https://books.google.nl/books?id=L_0WzwEACAAJ.

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[5] R. LaPierre. *Introduction to Quantum Computing*. The Materials Research Society Series. Springer International Publishing, 2021. ISBN: 9783030693183. URL: https://books.google.nl/books?id=C99EEAAAQBAJ.

[6] V. Kasirajan. *Fundamentals of Quantum Computing: Theory and Practice*. Springer International Publishing, 2021. ISBN: 9783030636906. URL: https://books.google.nl/books?id=yR0BzwEACAAJ.

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[9] Jack D. Hidary. *Quantum Computing: An Applied Approach*. Springer, 2019.

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[12] C. L. Degen, F. Reinhard, and P. Cappellaro. "Quantum sensing". In: *Reviews of Modern Physics* 89.3 (July 2017). ISSN: 1539-0756. DOI: 10.1103/revmodphys.89.035002. URL: https://dspace.mit.edu/handle/1721.1/124553.

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[13] M. Pompili, S. L. N. Hermans, S. Baier, et al. "Realization of a multinode quantum network of remote solid-state qubits". In: *Science* 372.6539 (2021), pp. 259–264. DOI: 10.1126/science.abg1919. eprint: https://www.science.org/doi/pdf/10.1126/science.abg1919. URL: https://www.science.org/doi/abs/10.1126/science.abg1919.

[14] S. L. N. Hermans, M. Pompili, H. K. C. Beukers, et al. *Qubit teleportation between non-neighboring nodes in a quantum network*. 2021. DOI: 10.48550/ARXIV.2110.11373. URL: https://arxiv.org/abs/2110.11373.

[15] Ming Gong, Shiyu Wang, Chen Zha, et al. *Quantum walks on a programmable two-dimensional 62-qubit superconducting processor*. 2021. arXiv: 2102.02573 [quant-ph].

References VI

[16] Aleks Kissinger and John van de Wetering. "PyZX: Large Scale Automated Diagrammatic Reasoning". In: *Electronic Proceedings in Theoretical Computer Science* 318 (May 2020), pp. 229–241. ISSN: 2075-2180. DOI: 10.4204/eptcs.318.14. URL: http://dx.doi.org/10.4204/EPTCS.318.14.

[17] Andrew W. Cross, Lev S. Bishop, Sarah Sheldon, et al. "Validating quantum computers using randomized model circuits". In: *Physical Review A* 100.3 (Sept. 2019). ISSN: 2469-9934. DOI: 10.1103/physreva.100.032328. URL: http://dx.doi.org/10.1103/PhysRevA.100.032328.