Everything You Need for Experimental Quantum Hardware Engineering

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This document is meant to provide some level of consolidation for those desiring to be involved with quantum hardware engineering. By doing one's best to maintain familiarity with these topics, it is possible to become one who designs, builds, tests, operates, and maintains real quantum machines - a quantum mechanic. Another possibility is to begin working on a doctorate degree in the associated field with these training resources on hand. There are many clickable links in this document, so it might be best to view it using a browser or PDF viewer.

My decision to share these resources is because they have been useful to me in my PhD work. This has been a very interesting path for me as an tribesman from the Navaho Nation. Here is the path: carpenter $\Longrightarrow$ electric vehicle researcher $\Longrightarrow$ nanotechnologist $\Longrightarrow$ quantum mechanic.

Please note that open access is a key theme held herein. Enjoy. -Onri

Scan QR code to access digital downloadable version.

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Contents

Chapter 1

Open Access Quantum Device Tools

Free tools for designing, simulating, & analyzing quantum/ nano devices:

Tool	**URL**
Semiconductor Process & Device Simulation (SILVACO, browser-based)	https://nanohub.org/resources/silvacotcad
KLayout, Pattern Generation & Layout, Direct-Download	https://www.klayout.de/build.html
Elmer FEM, Multiphysics Simulation Tool, Direct-Download	https://www.csc.fi/web/elmer/binaries
COMSOL Superconducting Simulation Tool, Browser-Based	https://aurora.epfl.ch/app-lib
scQubits, Superconducting Qubit Simulation Tool, Python-Based	https://scqubits.readthedocs.io/en/v3.2/index.html
QTCAD, Spin Qubit Design/ Simulation/ Analysis, Python-Based	https://docs.nanoacademic.com/qtcad/introduction
Qiskit Metal, Qubit Design/ Analysis, Python-Based	https://github.com/qiskit-community/qiskit-metal#qiskit-metal
Quantum Photonic Gate Array Simulation, Python-Based	https://github.com/fancompute/qpga#quantum-programmable-gate-arrays
Quantum Photonics Design/ Simulation/ Fabrication, Analysis, Python-Based	https://github.com/SiEPIC/SiEPIC-Tools#siepic-tools
Qubit Design & Fabrication Example (applies codes to run lithography machines in the lab after pattern generation with Qiskit Metal)	https://github.com/OJB-Quantum/Qiskit-Metal-to-Litho#qiskit-metal-to-litho
GitHub Usage Tutorial	https://github.com/OJB-Quantum/How-to-GitHub#how-to-use-github

Chapter 2

Training Videos

Related Open Access Lectures & Tutorials (Up to Graduate Level):

Title	URL
Quantum Hardware Engineering	https://youtube.com/playlist?list=PLbW5jviv4ckyjq-7YkZWeBwASv83XP2iL&si=wJYi6-7LaOHWTeUe
Quantum Transport (Prof. Sergey Frolov)	https://youtube.com/playlist?list=PLtTPtV8SRcxjedflXwNPSI_fxvxwUCjsd
Quantum Many-Body Physics (Prof. Luis Gregório Dias)	https://youtube.com/playlist?list=PL6FyrZIBwD8LMWizZW1FUN2dS_l44yuiy
Quantum Matter (Prof. Steven Simon)	https://youtube.com/playlist?list=PLrNpJOaBSWSCrLUO_tuKa5l5YJl0JNr1z
Quantum Computing Hardware & Architecture (Prof. Hiu Yung Wong)	https://youtube.com/playlist?list=PLnK6MrIqGXsL1KShnocSdwNSiKnBodpie
Quantum Hardware Series (Onri Jay Benally, QuantumGrad & UMN)	https://youtube.com/playlist?list=PLD9iE8dbH_2W0ww1HL1gSskSYPcSlf6cd
Circuit Quantum Electrodynamics & Qubit Hamiltonian (Prof. Gerhard Kirchmair)	https://youtu.be/BAt2PFVQE3w
Josephson Junctions & SQUIDs (Prof. Kevin F. Kelly)	https://youtu.be/sNOpmTWlMwk
Silicon Photonics & Photonic Integrated Circuits Overview (Ghent University)	https://youtube.com/playlist?list=PLuNPwP_PUkFRcW4apwKHC7oXSTyV3zPbv
Photonic Integrated Circuit Design (Ghent University)	https://youtu.be/Zcle3hNmblg
Virtual Hands-On Nanofabrication (Dr. Jorg Scholvin)	https://youtu.be/01J8qKjcp0M
Micro & Nanofabrication (Prof. Chris Mack)	https://youtube.com/playlist?list=PLM2eE_hI4gSDjK4SiDbhpmpjw31Xyqfo
Nanotechnology [Tools] (Duke University)	https://youtube.com/playlist?list=PLQcKpS4i0cAHES0sjJTXDZnWa3wtuixQl

Qiskit Metal Overview, Gmsh & ElmerFEM [Open-Source] (Diego Emilio Serrano & Abeer Vaishnav)	https://youtu.be/84j3l_9fHko
Pulse Sequence Shaping (Thomas Alexander, IBM)	https://www.youtube.com/watch?v=sMUPL8SR2oE&t=665s
Physical Sciences & Engineering Lectures (Dr. Jordan Edmunds)	https://www.youtube.com/@JordanEdmundsEECS/playlists
Animated Physics Lectures (ZAP Physics)	https://www.youtube.com/@zapphysics/playlists
More Animated Physics Lectures (Alexander Fufaev)	https://www.youtube.com/@universaldenker/playlists
Even More Animated Physics Lectures (Dr. Elliot Schneider)	https://www.youtube.com/@PhysicswithElliot/playlists
Oscillator Tutorial (Afrotechmods)	https://youtu.be/aJAZHPqEUKU?si=a18oKNZBRZaG564o
The Beauty of LC Oscillations! (Sabin Mathew)	https://youtu.be/2_y_3_3V-so?si=viKn72TnpgGTPhfu
Electronic Circuits (Julio Gonzalez)	https://youtube.com/playlist?list=PL0o_zxa4K1BV9E-N8tSExU1djL6slnjbL

Miscellaneous:

Title	**URL**
A Homemade Trapped Ion Quantum Computer (Yann Allain)	https://tinyurl.com/homemade-tr-ion
Heidelberg DWL66+ LASER Lithography Training (University of Pennsylvania)	https://youtube.com/playlist?list=PLiihbHV9HgpWAcmgdpMGBkejcBhEzoKJO
Electron-Beam Lithography (MIT.nano)	https://youtu.be/yJF9s2MJLLM
Layout Editor Training (University of Pennsylvania)	https://youtube.com/playlist?list=PLiihbHV9HgpX_9m5Khz2wn-XaxM5-yErU
KLayout Training (University of Waterloo)	https://youtube.com/playlist?list=PL12BCN5zxKhysQPbl0Fy0a6x0fiCPJZB-
Oscilloscope Usage (GreatScottLab)	https://youtu.be/d58GzhXKKG8
Harvard Architecture vs. von Neumann Architecture (Computer Science)	https://youtu.be/4nY7mNHLrLk
Analog vs. Digital Computing (Derek Muller)	https://youtu.be/IgF3OX8nT0w?si=hWCan3S5Mx5NsdfE
Flipper Zero Transceiver Hardware (Securiosity)	https://youtu.be/eYCMIYsP23k?si=U8L04s7Jun-RQV-L
Understanding Radio Signals with Flipper Zero (TechAndFun)	https://youtu.be/zhg41DbxIEc?si=SG0jI6vYYOd1tfip
Software Defined Radio (SDR) Tutorial (Andreas Spiess)	https://youtu.be/xQVm-YTKR9s?si=fD03k6WQYokeyx0-
The Fetch-Execute Cycle (Tom Scott)	https://youtu.be/Z5JC9Ve1sfI
Blender Basics for Scientists (Dr. Joseph G. Manion)	https://youtube.com/playlist?list=PLcKSD7d0T-HBmOH-NYYgMgVX1LZF72K-3
Quantum Chip Rendering Tutorials (Onri Jay Benally)	https://www.youtube.com/playlist?list=PLbW5jviv4ckwvvhSjwONc6pa-glNdI6vg

Chapter 3

Books & References

Free or Open Access Literature & More (Up to Graduate Level):

Title	**Link**
Olivier Ezratty's "Understanding Quantum Technologies" (Research, Manufacturing, & More)	https://www.oezratty.net/wordpress/wp-content/themes/Ezratty5/forcedownload.php?file=/Files/Publications/Understanding%20Quantum%20Technologies%20Olivier%20Ezratty%202024%20Letter.pdf
Olivier Ezratty's "Where are we heading with NISQ?"	https://arxiv.org/abs/2305.09518
Computer-Inspired Quantum Experiments	https://arxiv.org/abs/2002.09970
Open Hardware in Quantum Technology	https://arxiv.org/abs/2309.17233
The Transmon Qubit for Electromagnetics Engineers	https://ieeexplore.ieee.org/document/9789946
Thomas Wong's "Introduction to Classical & Quantum Computing"	https://www.thomaswong.net/introduction-to-classical-and-quantum-computing-1e3p.pdf
Probing Quantum Devices with Radio-Frequency Reflectometry	https://arxiv.org/abs/2202.10516
Microwave Control of Superconducting Cavity & Qubit (MediaWiki)	https://qt5201.org/index.php/Microwave_control_of_superconducting_cavity_and_qubit
[Quantum] Transport in Semiconductor Mesoscopic Devices	https://iopscience.iop.org/book/mono/978-0-7503-1103-8/chapter/bk978-0-7503-1103-8ch8
Quantum Materials Roadmap	https://iopscience.iop.org/article/10.1088/2515-7639/abb74e
Quantum Nanostructures	https://www.sciencedirect.com/science/article/pii/B9780081019757000038

From Nanoelectronics to Future Technologies	https://link.springer.com/chapter/10.1007/978-3-030-44398-6_6#Sec5
Materials Challenges & Opportunities for Quantum Computing Hardware	https://www.science.org/doi/epdf/10.1126/science.abb2823
A Practical Guide for Building Superconducting Quantum Devices	https://arxiv.org/pdf/2106.06173.pdf
Handbook of Vacuum Science & Technology	https://www.sciencedirect.com/book/9780123520654/handbook-of-vacuum-science-and-technology
Practical Cryogenics	http://research.physics.illinois.edu/bezryadin/links/practical%20Cryogenics.pdf
Hitchhiker's Guide to the Dilution Refrigerator	https://www.roma1.infn.it/exp/cuore/pdfnew/Fridge.pdf
Dry Dilution Refrigerator with 4He-1 K-Loop	https://arxiv.org/ftp/arxiv/papers/1412/1412.3597.pdf
Coplanar Waveguide Resonators	https://link.springer.com/article/10.1007/s10948-018-4959-2
When to Use Coplanar Waveguide Routing	https://blog.upverter.com/2019/10/15/when-to-use-coplanar-waveguide-routing-for-hf-boards
Basic Qubit Characterization by Zurich Instruments	https://docs.zhinst.com/hdawg_user_manual/tutorials/qubit_characterization.html?h=basic+qubit
Qubit Spectroscopy: Microwave Control of Superconducting Cavity & Qubit	https://qt5201.org/index.php/Microwave_control_of_superconducting_cavity_and_qubit
Quantum Control Documentation by Qblox Instruments	https://qblox-qblox-instruments.readthedocs-hosted.com/en/master
Overview of Quantum Control Equipment by Qblox Instruments	https://www.qblox.com
Control & Readout of a Superconducting Qubit Using a Photonic Link	https://rdcu.be/dhLr3
Cryo-CMOS Qubit Control	https://ieeexplore.ieee.org/document/9895434
The Electronic Interface for Quantum Processors	https://arxiv.org/pdf/1811.01693.pdf
Cryo-CMOS Interfaces for Large-Scale Quantum Computers	https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9372075
Spiderweb Array: A Sparse Spin-Qubit Array	https://journals.aps.org/prapplied/pdf/10.1103/PhysRevApplied.18.024053
A Cryogenic Interface for Controlling Many Qubits	https://arxiv.org/abs/1912.01299

Cryogenic Memory Technologies	https://arxiv.org/abs/2111.09436

Miscellaneous:

Title	**URL**
NASA Wire Bonding Standards	https://nepp.nasa.gov/index.cfm/20911
NASA Soldering & Workmanship Standards	https://nepp.nasa.gov/docuploads/06AA01BA-FC7E-4094-AE829CE371A7B05D/NASA-STD-8739.3.pdf, https://standards.nasa.gov/sites/default/files/standards/NASA/A/4/nasa-std-87394a_w_change_4_0.pdf, https://workmanship.nasa.gov/lib/insp/2%20books/frameset.html
Semiconductor Education Online, Browser-Based, No Installation Required	https://nanohub.org/groups/semiconductoreducation
Quantum Mechanics Visualization, Browser-Based	https://www.st-andrews.ac.uk/physics/quvis
Classical Physics Simulation Browser-Based	https://phet.colorado.edu/en/simulations/browse
Classical 2D Optics Simulation, Browser-Based	https://phydemo.app/ray-optics
Math, Physics, & Engineering Visualization, Browser-Based	https://www.falstad.com/mathphysics.html
Interactive Advanced Microscopy Simulations, Browser-Based	InteractiveAdvancedMicroscopySimulations
Interactive Quantum State Visualization, Browser-Based	https://javafxpert.github.io/grok-bloch
Interactive Quantum Computing Education Tools	https://www.iqmacademy.com/play

Chapter 4

Quantum Hardware Lab Galleries

IBM Research https://www.flickr.com/photos/ibm_research_zurich/albums	**ETH Zurich** https://qudev.phys.ethz.ch/responsive/?q=gallery
UWaterloo https://uwaterloo.ca/quantum-nano-fabrication-and-characterization-facility/virtual-tours	

Chapter 5

Quantum-Applicable Degrees: BS to PhD

Non-Exhaustive List:	
Physics (Experimental or Applied)	Computer Engineering
Quantum Science & Engineering	Chemistry
Quantum Technology	Chemical Engineering
Engineering Physics	Physical Chemistry
Electrical Engineering	Systems Engineering
Electrical & Computer Engineering	Mechanical Engineering
Materials Science	Nanoscience
Materials Science & Engineering	Nanoengineering

Chapter 6

Quantum Science Curriculum Example

Courses:		
AEP	1200	Introduction to Nanoscience & Nanoengineering
AEP	2550	Engineering Quantum Information Hardware
AEP	3100	Introductory Quantum Computing
AEP	3610	Introductory Quantum Mechanics
AEP	3620	Intermediate Quantum Mechanics
AEP	4400	Nonlinear & Quantum Optics
AEP	4500 / PHYS 4454	Introductory Solid State Physics
CHEM	7870	Mathematical Methods of Physical Chemistry
CHEM	7910	Advanced Spectroscopy
CHEM	7930	Quantum Mechanics I
CHEME	6860 / SYSEN 5860	Quantum Computing & Artificial Intelligence
CS	4812 / PHYS 4481	Quantum Information Processing
ECE	4060	Quantum Physics & Engineering
ECE	4070	Physics of Semiconductors & Nanostructures
ECE	5310	Quantum Optics for Photonics & Optoelectronics
ECE	5330	Semiconductor Optoelectronics
MSE	5720	Computational Materials Science
MSE	6050	Physics of Semiconductors & Nanostructures
PHYS	2214	Physics III: Oscillations, Waves, & Quantum Physics
PHYS	3316	Basics of Quantum Mechanics
PHYS	3317	Applications of Quantum Mechanics
PHYS	4443	Intermediate Quantum Mechanics
PHYS	4444	Introduction to Particle Physics
PHYS	4410 / PHYS 6510	Advanced Experimental Physics
PHYS	6572	Quantum Mechanics I
PHYS	6574	Applications of Quantum Mechanics II
PHYS	7636	Solid-State Physics II
PHYS	7645	An Introduction to the Standard Model of Particle Physics
PHYS	7651	Relativistic Quantum Field Theory I
PHYS	7652	Relativistic Quantum Field Theory II
PHYS	7654	Basic Training in Condensed Matter Physics
Adapted From: `https://quantum.cornell.edu/education`		

Chapter 7

Shortcut into Quantum Hardware Engineering

Start with a 3D modeling & linguistics framework, may involve a custom keywords glossary.
Know that this specialty involves learning to probe something without necessarily having to physically contact its surface. This is what spectroscopy or "scatterometry" is about.
Typically, topics covered under quantum hardware engineering are combinations of materials science & engineering, quantum metrology, quantum transport, quantum optics, & quantum electronic design automation.
Know how electronic filters are configured or set up.
Know how electronic filters are designed & what they look like.
Know what components various filters are made of.
Know the difference between passive & active filters.
Know the difference between optical, microwave, & radio frequency (RF) isolators, circulators, & mixers.
Be aware of different room temperature & cryogenic amplifiers.
Know what room temperature & cryogenic amplifiers are made of.
Know the different types/hierarchy of amplifier noise (thermal, shot, external, quantum).
Know how a signal curve or response is manipulated.
Know how signals are triggered.
Know what impedance matching is (how many ohms is required).
Know how a Smith chart works.
Know the many purposes of a resistor (there's a whole list).
Know what multiphase power means.
Know what a resonator & resonator cavity is.
Know what vector network & spectrum analyzers, arbitrary waveform generators, & signal generators do.
Know what an oscillator circuit does (voltage fluctuation or AC).
Know what an inverter circuit does (DC to AC conversion).
Know what a rectifier circuit does (AC to DC conversion).
Know what high-pass, low-pass, band-pass, band-stop filter circuits/crossover networks do (signal filtering).
Know what a comparator circuit does (threshold indicator).
Know what a few basic logic gates can do (calculator).
Know what a PID [closed-loop] controller does (electronic-based self-balancing).
Know what a feed forward [open-loop] controller does (electronic-based self-balancing alternative).
Bonus: - Know how to build a simple electronic audio amplifier device (many components similar to quantum computing systems). - Design a transmission line coupled to a resonator with optical or superconducting waveguides.

Chapter 8

Most Useful Coding Topics for Hardware Engineers

Library installation
Syntax & commenting
Curve fitting, direct parameterization, & mesh parameterization
Automation scripting
Data management & data structures
Parallel processing & accelerated computing techniques
Interpolation & extrapolation
Linear regression
Signal processing
Noise plots
Manual debugging

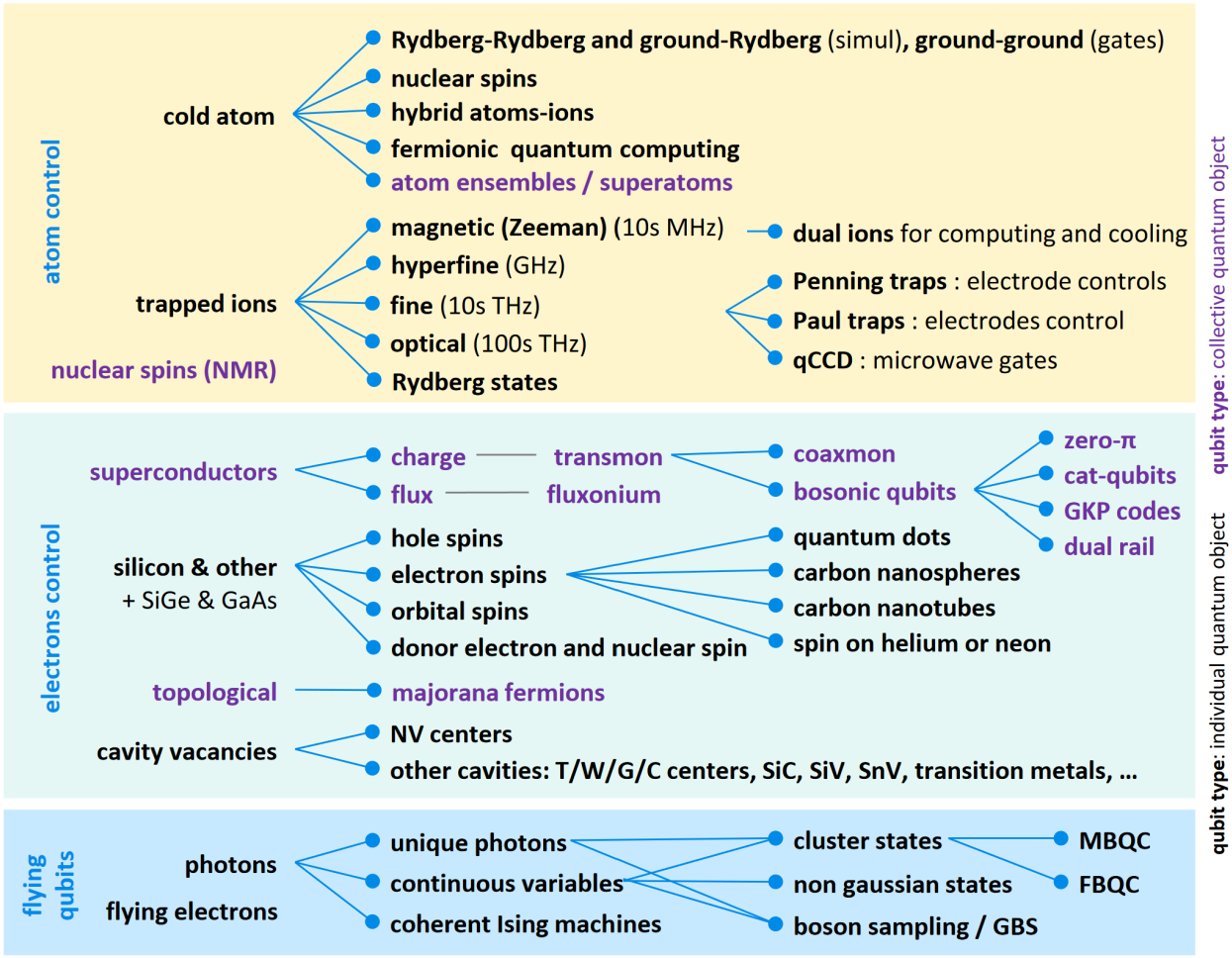
Chapter 9

Quantum Career Opportunities

Quantum Job Resources (Hardware & Software):

URLs
https://www.youtube.com/watch?v=7dfw8k2p1to
https://ieeexplore.ieee.org/document/9733176
http://ibm.techtechpotato.com
https://chicagoquantum.org/resources
https://www.quantiki.org/jobs
https://medium.com/@russfein/quantum-computing-jobs-5e67f72fb113
https://quantumconsortium.org/quantum-jobs
https://www.globalquantumleap.org/quantum-opportunities-1
https://chicagoquantum.org/education-and-training/internships
https://www.quantumgrad.com/jobs

Rough Zoology of All Physical Qubits:



Borrowed from: Ezratty, *Understanding Quantum Technologies*, p. 355,
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