Everything You Need for Experimental Quantum Hardware Engineering

University of Minnesota

Onri Jay Benally

July 2023

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.

Creative Commons License

Contents

Chapter 1

Open Access Quantum Device Tools

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

- **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`for
- **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):

- **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:

- **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

Chapter 3

Books & References

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

- **Olivier Ezratty's "Understanding Quantum Technologies" (research, manufacturing, & more):**
  https://arxiv.org/abs/2111.15352
- **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:

- **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

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`		

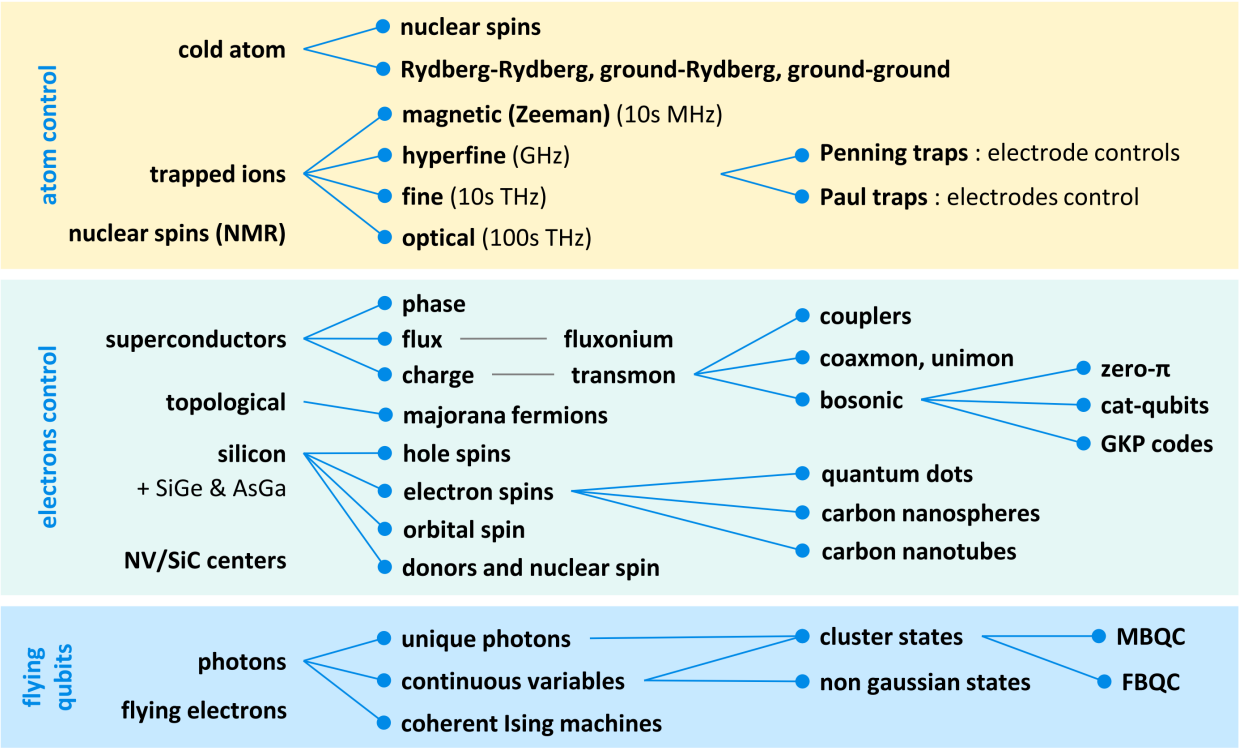
Chapter 7

Quantum Career Opportunities

Quantum Job Resources (Hardware & Software):

- 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://qubitjobs.com
- https://medium.com/@russfein/quantum-computing-jobs-5e67f72fb113
- https://quantumconsortium.org/quantum-jobs
- https://qhack.ai/job-board
- https://www.globalquantumleap.org/quantum-opportunities-1
- https://chicagoquantum.org/education-and-training/internships
- https://www.quantumgrad.com/jobs

Roughly All Physical Qubits:



Borrowed from: Ezratty, *Understanding Quantum Technologies*, p. 220,
https://doi.org/10.48550/arXiv.2111.15352
https://creativecommons.org/licenses/by-nc-nd/4.0/