Department of Computer Sciences
UNIVERSITY OF WISCONSIN–MADISON
Celebrating 60 Years

Compiling Quantum Circuits

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SPLASH 2025 Tutorial

Outline

Part I: Quantum Computing Fundamentals

A. Qubits, gates, and circuits

B. Quantum Hardware & Error-correction

Part II: Quantum-Circuit Optimization

A. Rewrite rules

B. Circuit resynthesis

C. Scheduling

Part III: Qubit Mapping and Routing

A. QMR for near-term devices

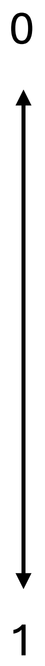
B. QMR for fault-tolerant devices

` C. A programing language for QMR problems

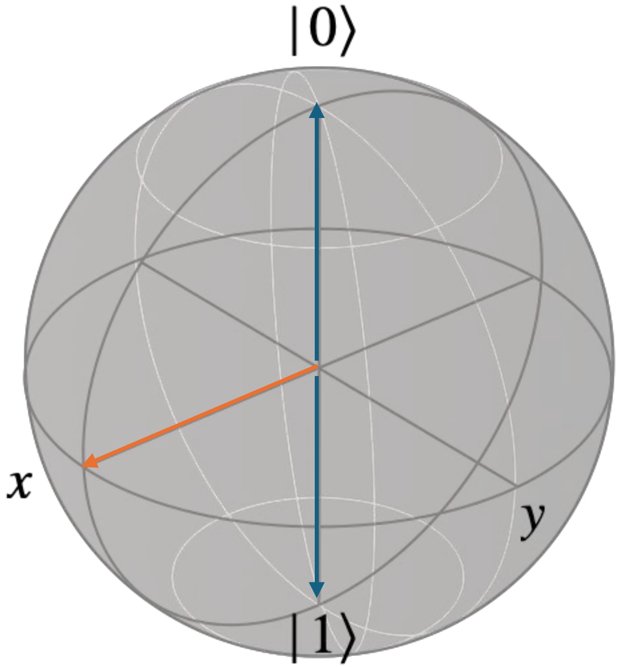
Part IV: A tour of wisq

Quantum Computing Fundamentals

Bits and qubits



Classical bit



Qubit

Qubit states

Position on the surface of a sphere is a 2D vector

We write these vectors like this:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

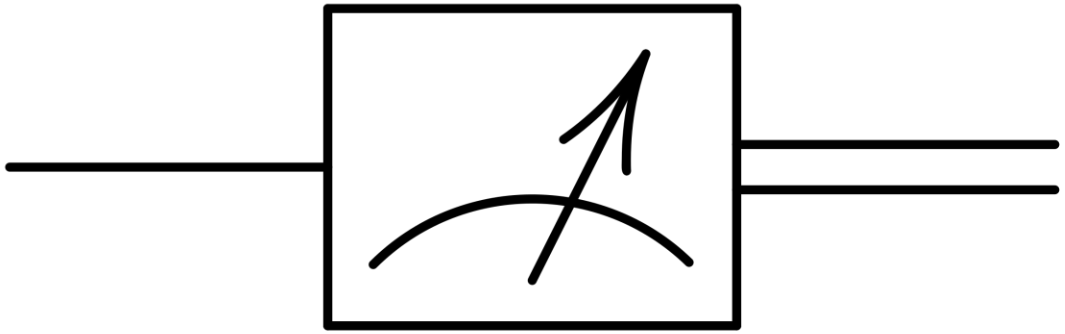
Basis vectors

Complex numbers

Measurement

Quantum mechanics forbids direct access to α and β

$\alpha|0\rangle + \beta|1\rangle$



$|0\rangle$ with prob. $|\alpha|^2$

$|1\rangle$ with prob. $|\beta|^2$

Implication: $|a|^2 + |\beta|^2 = 1$

The X gate

Gates transform the state of a qubit

Classical NOT: 0 → 1, 1→ 0
Quantum NOT: $\alpha|0\rangle + \beta|1\rangle \rightarrow \beta|0\rangle + \alpha|1\rangle$

In other words,

$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

$$X \begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} \beta \\ \alpha \end{bmatrix}$$

The Hadamard gate

Produces equal *superposition* of states

$$H = \frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}$$

$$\mathrm{H}|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

$$\mathrm{H}|1\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$$

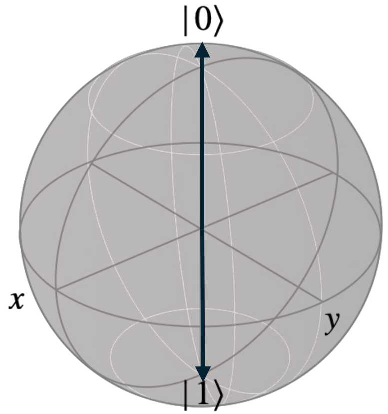
Single qubit gates

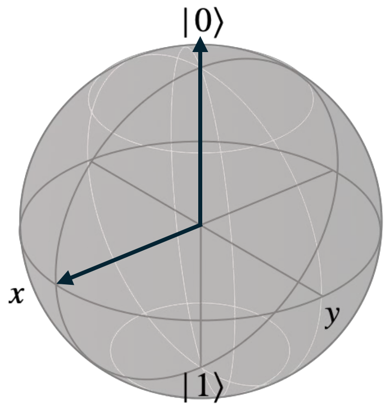
2x2 (unitary) matrices

$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

Rotations on the Bloch Sphere





Multi-qubit systems

Two qubit state:

$$\alpha_1|00\rangle + \alpha_2|01\rangle + \alpha_3|10\rangle + a_4|11\rangle$$

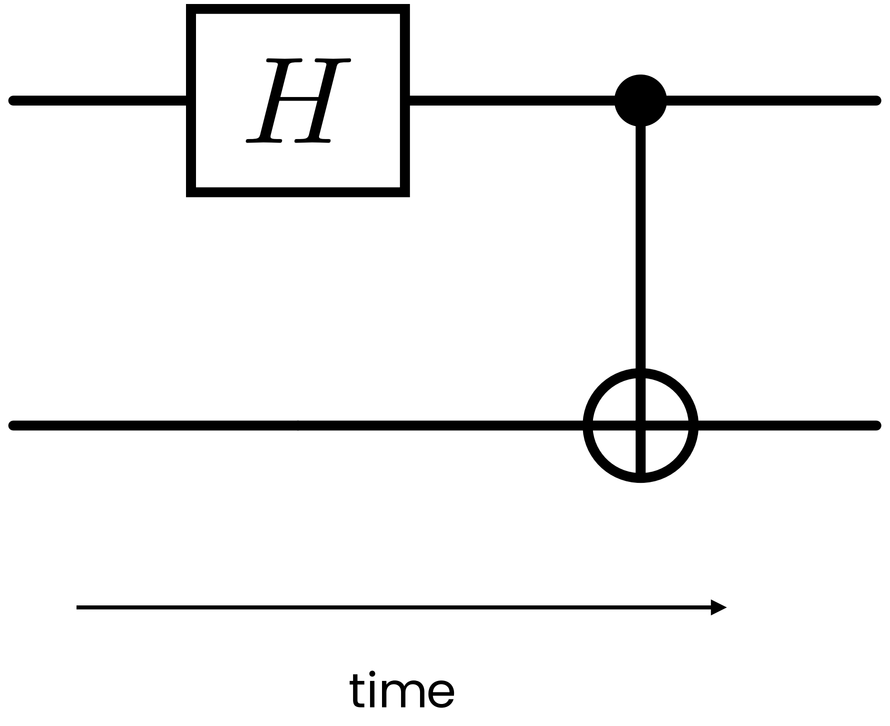
Controlled-NOT (CNOT gate):

"Quantum XOR"

$|xy\rangle \mapsto |x(x \oplus y)\rangle$

Quantum circuits

$H\ q_0;$
$CNOT\ q_0,\ q_1;$



You can run circuits on real devices!

```python
import os
from qiskit import QuantumCircuit
from qiskit.transpiler.preset_passmanagers import generate_preset_pass_manager
from qiskit_ibm_runtime import QiskitRuntimeService, SamplerV2

# --- 0) IBM Cloud authentication ---------------------------------------------
service = QiskitRuntimeService(
    channel="ibm_quantum_platform",
    token=os.environ.get("QISKIT_IBM_TOKEN"),
    instance=os.environ.get("QISKIT_IBM_INSTANCE"),
)

# --- 1) Create the circuit ---------------------------------------------------
qc = QuantumCircuit(2, 2, name="bell")
qc.h(0)
qc.cx(0, 1)
qc.measure([0, 1], [0, 1])  # gives classical register "meas" by default

# --- 2) Pick a real backend & transpile to its native basis gates -----------
backend = service.least_busy(simulator=False, operational=True)
pm = generate_preset_pass_manager(backend=backend, optimization_level=1)
native_basis_circuit = pm.run(qc)

# --- 3) Run on hardware with SamplerV2 ------------------------------------

sampler = SamplerV2(backend=backend, options={"default_shots": 4096})

job = sampler.run([native_basis_circuit])  # submit
result = job.result()  # wait for completion
counts = result[0].data.meas.get_counts()  # get measurement outcome counts
```

The NISQ era

***N**oisy **I**ntermediate-**S**cale **Q**uantum*

Lack resources for error correction (instead rely on error *mitigation*)
Sample many runs due to low probability of error-free outcome

Most promising applications find approximate solutions:

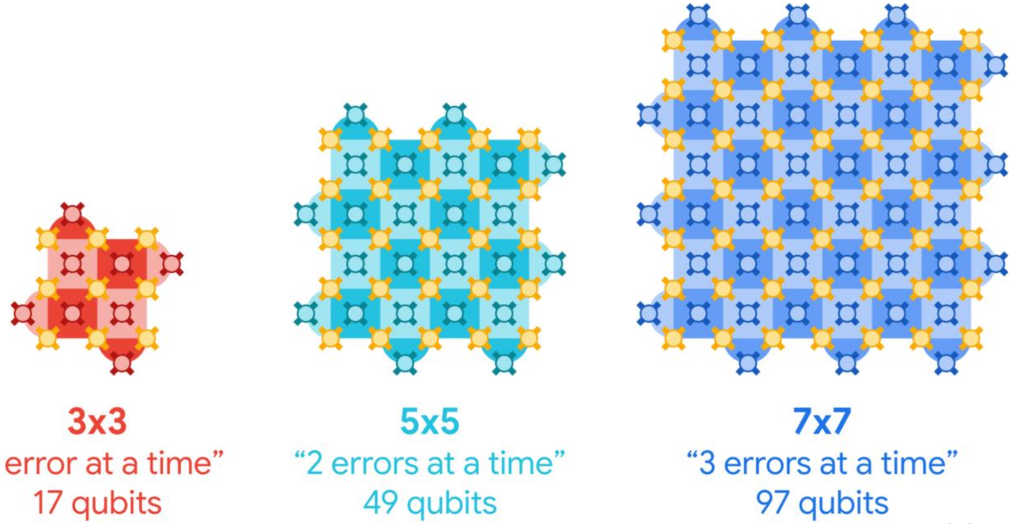
- Quantum Approximate Optimization Algorithm
- Variational Quantum Eigensolver

Quantum Error Correction

Encode a logical qubit into several physical qubits
Reduce error by scaling the logical qubit

Prerequisite for exciting applications like Shor's, Quantum simulation

One promising approach
Surface Codes



https://research.google/blog/making-quantum-error-correction-work/

Surface codes in hardware

Article | Published: 25 May 2022

Realizing repeated quantum error correction in a distance-three surface code

Sebastian Krinner, Nathan Lacroix, Ants Remm, Agustin Di Paolo, Elie Genois, Catherine Leroux

Realization of an Error-Correcting Surface Code with Superconducting Qubits

Youwei Zhao[1,2,3,*], Yangsen Ye[1,2,3,*], He-Liang Huang[1,2,3,*], Yiming Zhang[1,2,3], Dachao Wu[1,2,3], Huijie Guan[1,2,3], Qingling Zhu[1,2,3], Zuolin Wei[1,2,3], Tan He[1,2,3] *et al.*

Show more

Phys. Rev. Lett. **129**, 03

DOI: https://doi.org/10

Article | Published: 09 December 2024

Quantum error correction below the surface code threshold

Google Quantum AI and Collaborators

Nature (2024) | Cite this article

The Quantum Software Stack