Near-term quantum computing SW/HW co-design

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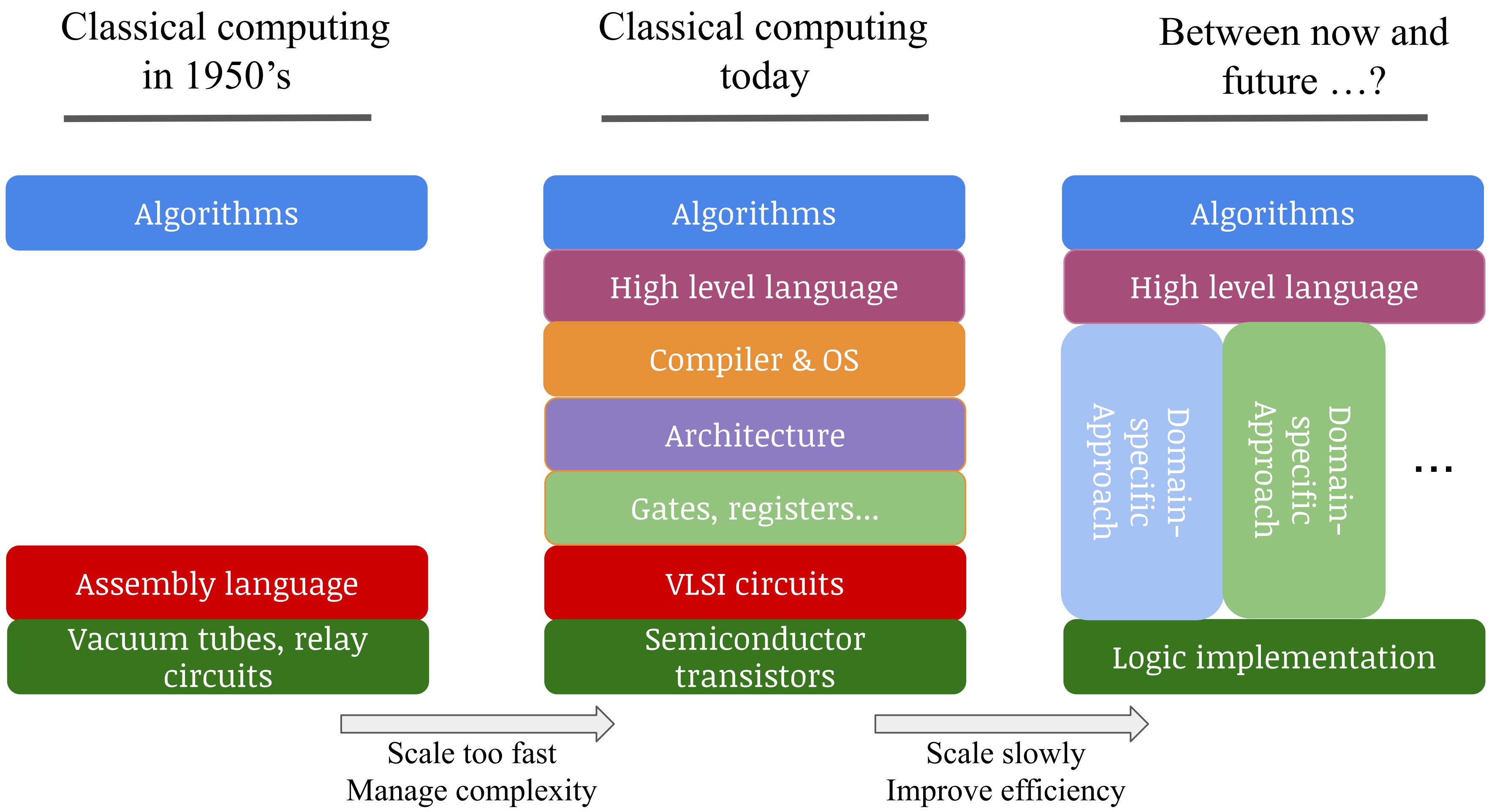

Classical computing in 1950's
Classical computing today
Between now and future …?
Algorithms
Assembly language
Vacuum tubes, relay circuits
Algorithms
High level language
Compiler & OS
Architecture
Gates, registers...
VLSI circuits
Semiconductor transistors
Algorithms
High level language
Domain-specific Approach
Domain-specific Approach
…
Logic implementation
Scale too fast
Manage complexity
Scale slowly
Improve efficiency

What about quantum computing?

Quantum computing now

Near-term goal

vs classical computing in 1950's

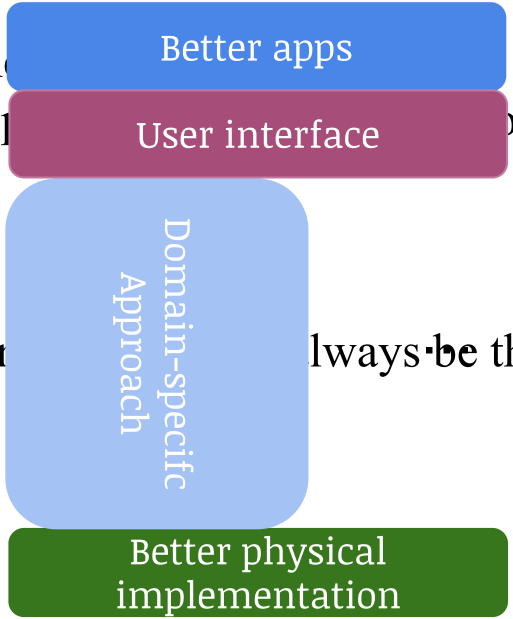
Pro:

The

So l system.

Con:

Er lways be there.

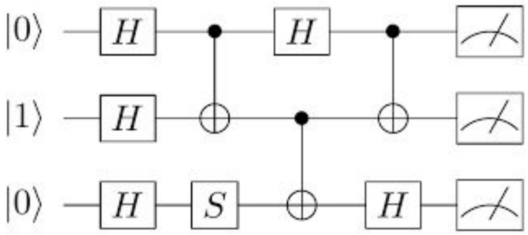


Near-term applications

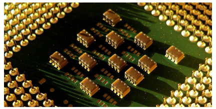
- Only needs noisy qubits and short circuit depth
  (Co-processing with classical computers)
- Easily-verifiable solution
- Compact problem representation
- High complexity computation
- Compact solution

Supremacy test

Giving a random quantum circuit description



Question: Will the probability of getting some certain output x_i string larger than half of the strings?



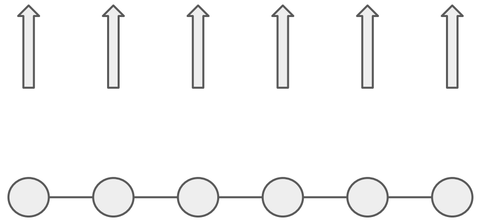
Quantum computer

Classical computer

Quantum chemistry

$$H = \sum_{i,\alpha} c^{i}_{\alpha}\sigma^{i}_{\alpha} + \sum_{ij\alpha\beta} c^{ij}_{\alpha\beta}\sigma^{i}_{\alpha}\sigma^{j}_{\beta}$$

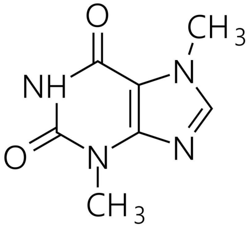
Example: 1-d Ising chain with nearest neighbor interaction



$$H = \begin{pmatrix} \epsilon & -t & 0 & 0 & & \cdots & 0 \\ -t & \epsilon & -t & 0 & & \cdots & 0 \\ 0 & -t & \epsilon & -t & & \cdots & 0 \\ 0 & 0 & -t & \epsilon & -t & \cdots & 0 \\ \vdots & & & & & & \vdots \\ 0 & \cdots & & & & \epsilon & -t \\ 0 & \cdots & & & & -t & \epsilon \end{pmatrix}$$

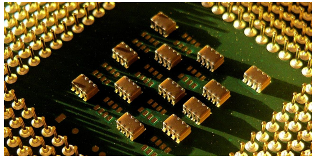
What's the minimal E(ground energy) so that $H\psi = E\psi$

Quantum chemistry



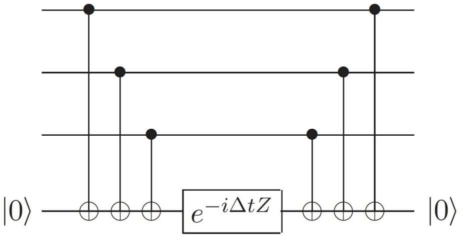
Chemistry systems

map



Qubits

Digitize & Evolve



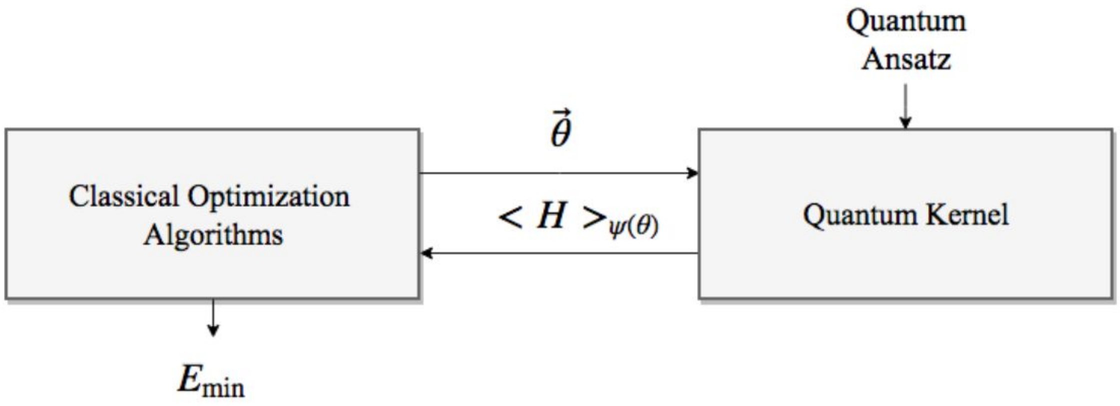
Quantum phase estimation

Ground energy E

Variational Quantum Eigensolver

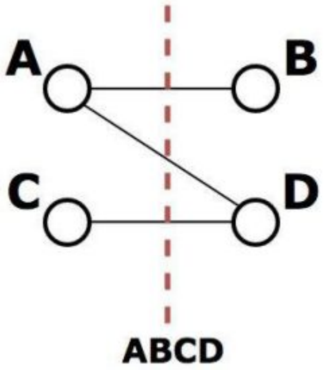
$$\langle \Psi_{\text{trial}} | H | \Psi_{\text{trial}} \rangle \geq E_0$$

$$\langle H \rangle = \sum_{i,\alpha} c^i_\alpha \langle \sigma^i_\alpha \rangle + \sum_{ij\alpha\beta} c^{ij}_{\alpha\beta} \langle \sigma^i_\alpha \sigma^j_\beta \rangle$$



Optimization

QAOA Maxcut:



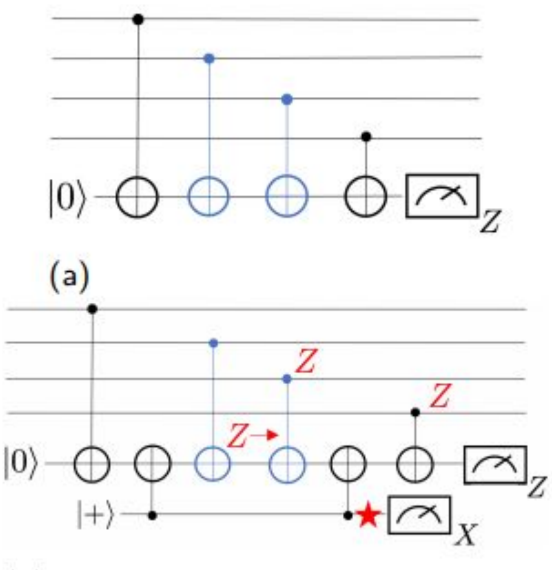
$|0101>$

$$\sigma_z = \begin{pmatrix} 1 & 0 \\ 0, & -1 \end{pmatrix}$$

$$H_{ij} = \frac{1}{2}(I - \sigma_z^i \otimes \sigma_z^j)$$

Demonstrate QEC

Flag qubits:



Simulate big quantum circuits with small quantum computers

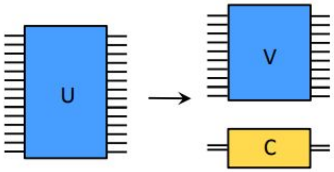


Fig. 1. A compiled quantum circuit U is decomposed into a smaller quantum circuit V and some classical computation C.

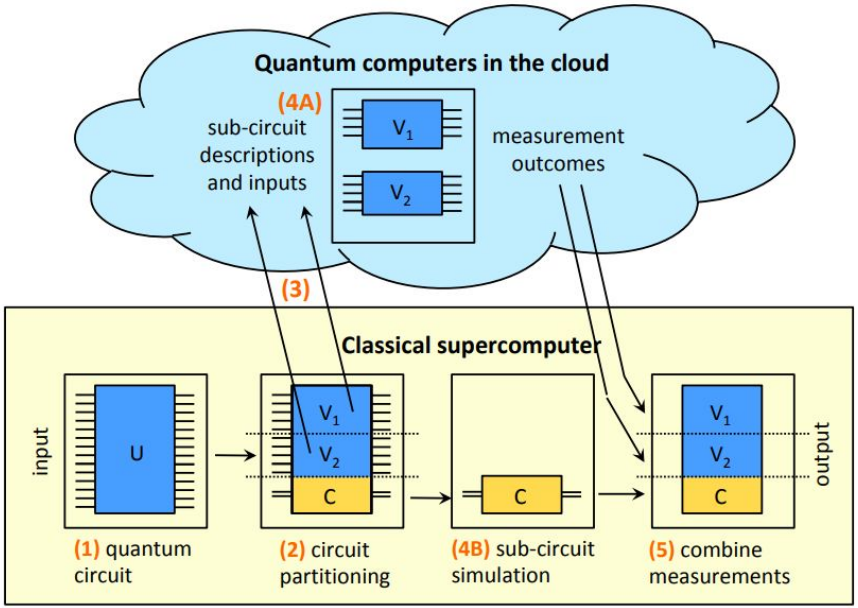


Fig. 2. The quantum circuit U is decomposed into a classical circuit C and quantum circuits $V_1 ... V_n$. The quantum circuits are evaluated on quantum computers in the cloud and the classical circuit on a classical supercomputer.

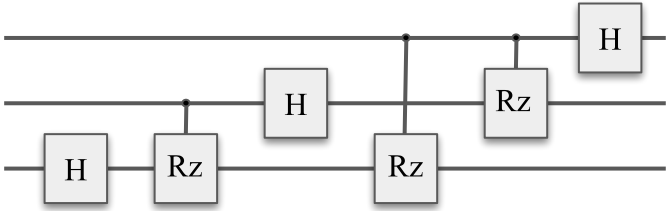
“Hybrid Quantum-Classical Computing Architectures,” Martin Suchara, Yuri Alexeev, Frederic Chong, Hal Finkel, Henry Hoffmann, Jeffrey Larson, James Osborn, and Graeme Smith

Quantum compilation

Quantum program

```
def qft(circ, q, n):
    """n-qubit QFT on q in circ."""
    for j in range(n):
        for k in range(j):
            circ.cu1(math.pi/float(2**(j-k)), q[j], q[k])
        circ.h(q[j])
```

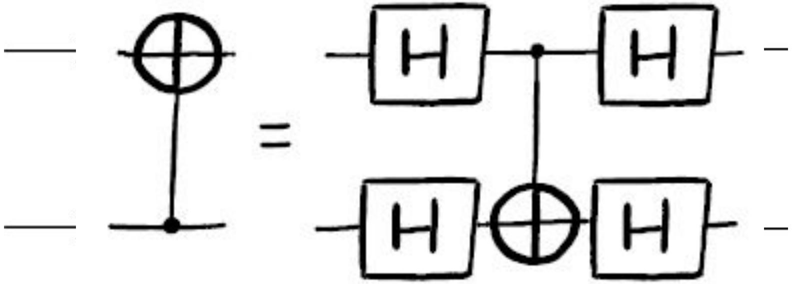
Quantum circuit



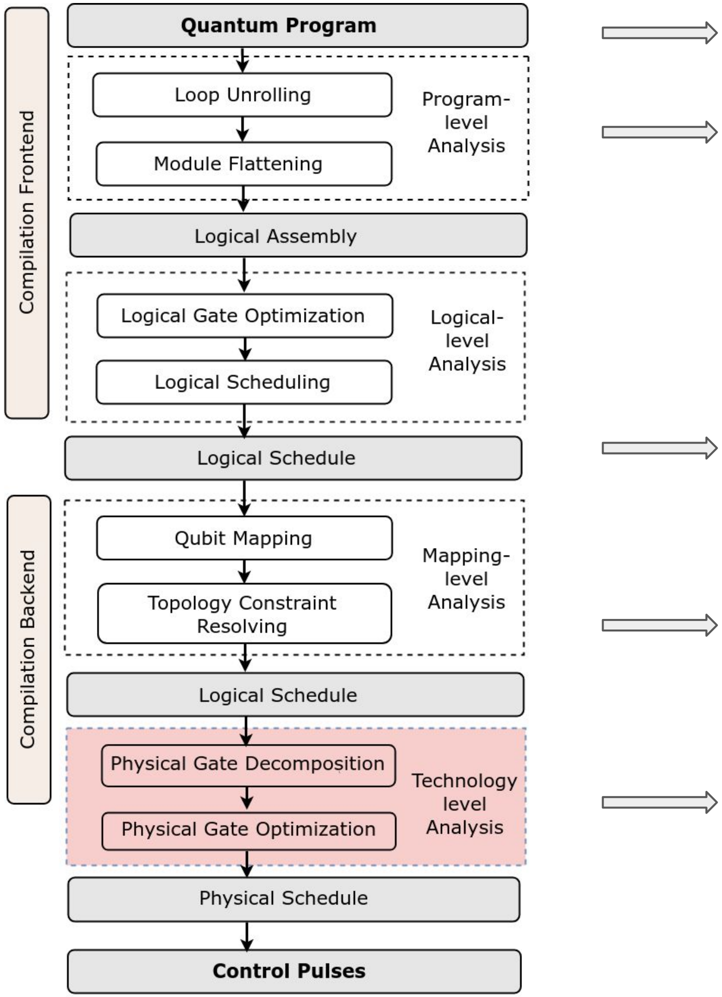
Compiled!

Quantum gate synthesis

Example:



Layered approach to quantum compilation



Reversible logic synthesis

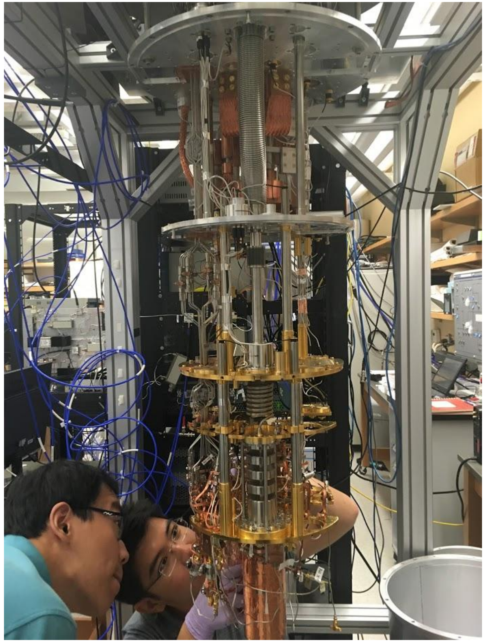
Quantum circuit synthesis

Parallelism and commutativity

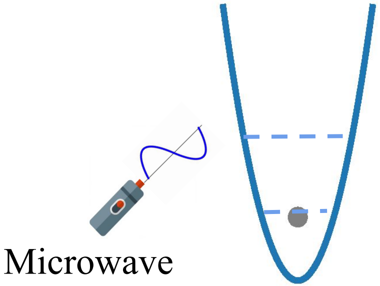
Mapping

From logical gate to physical gate

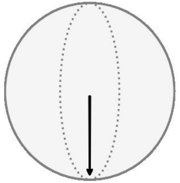
Quantum Control



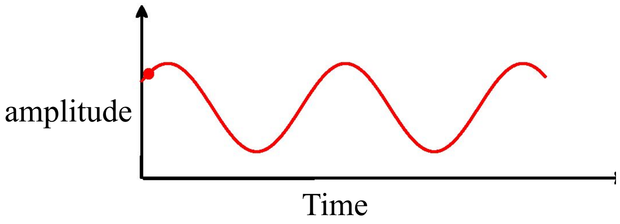
Cavity



Bloch sphere



Control pulse



Qubit state

$$|\psi\rangle = \begin{bmatrix} 0.00 \\ 1.00 \end{bmatrix}$$

Quantum Control

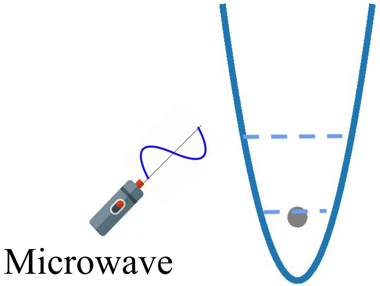
$$e^{iHt} = U$$

$$H = \omega \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

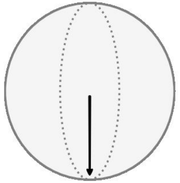
$$\Downarrow$$

$$U = \begin{bmatrix} \cos\frac{\omega t}{2} & -i\sin\frac{\omega t}{2} \\ -i\sin\frac{\omega t}{2} & \cos\frac{\omega t}{2} \end{bmatrix}$$

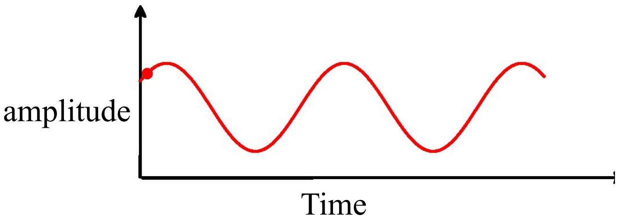
Cavity



Bloch sphere



Control pulse



Qubit state

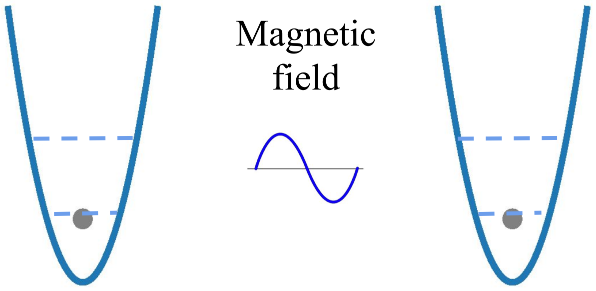
$$|\psi\rangle = \begin{bmatrix} 0.00 \\ 1.00 \end{bmatrix}$$

Quantum Control

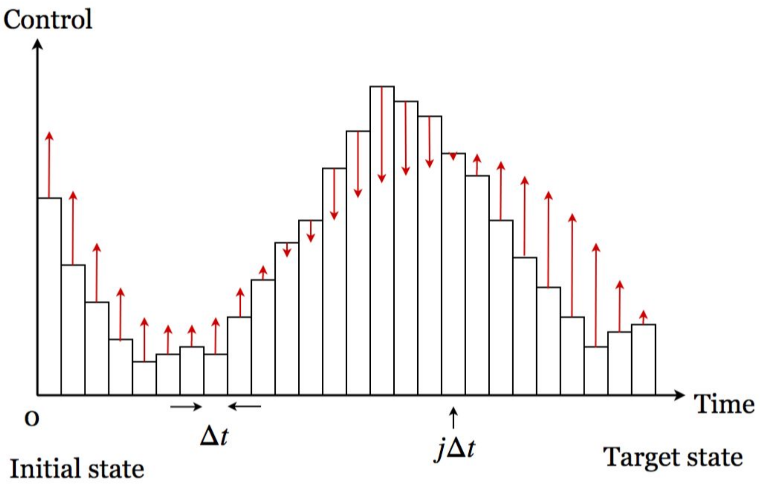
$$U = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(Jt) & i\sin(Jt) & 0 \\ 0 & i\sin(Jt) & \cos(Jt) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

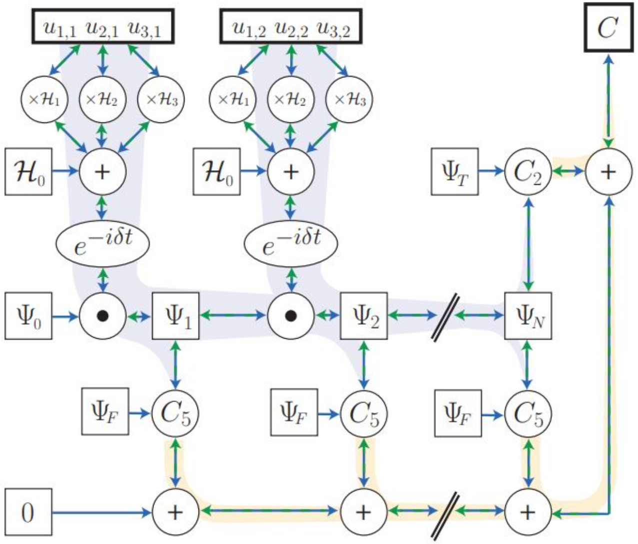
$$t = \frac{\pi}{J}$$

$$iSWAP = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$



GRAPE (GRadient Ascent Pulse Engineering)

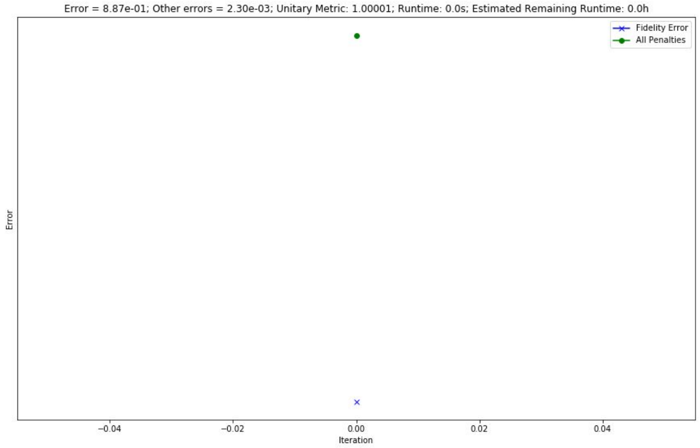




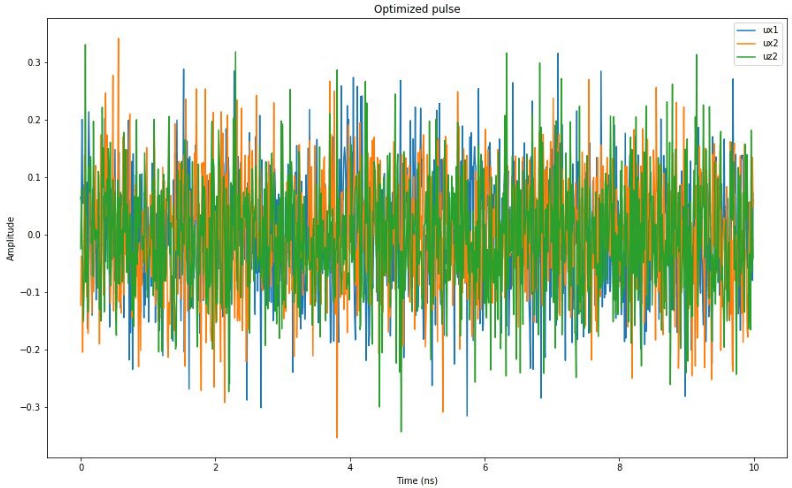
Pulse shape update

Computational graph

GRAPE (GRadient Ascent Pulse Engineering)



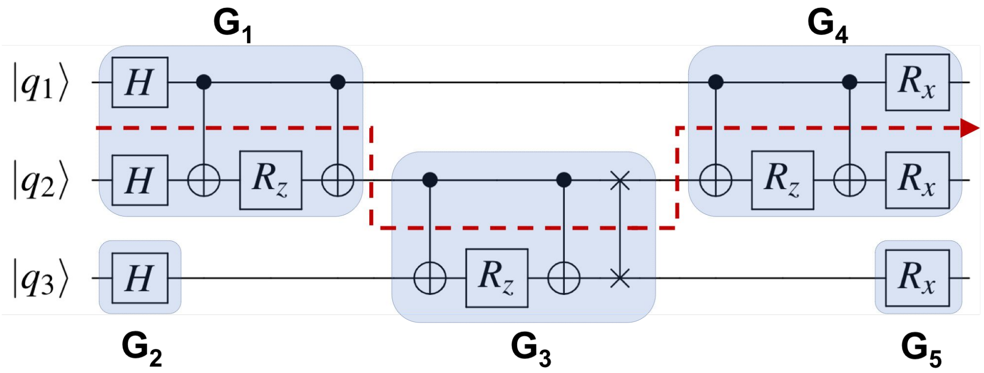
Convergence



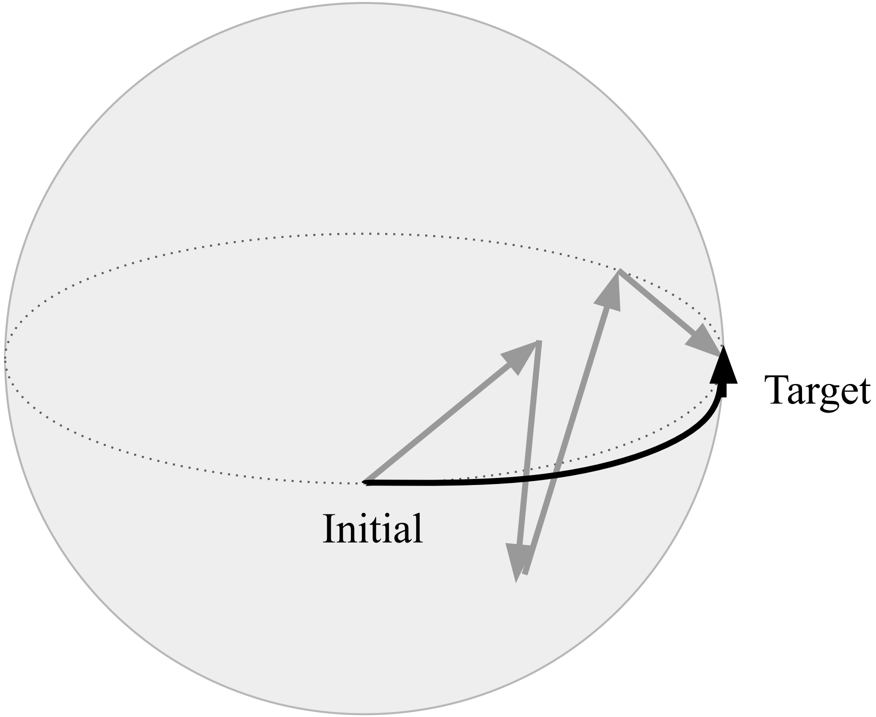
Pulse shape

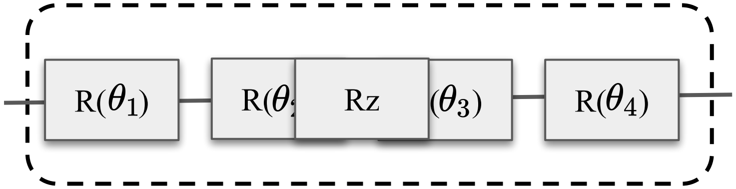
How to maximally utilize optimal control?

Break the 1- and 2-qubit ISA abstraction

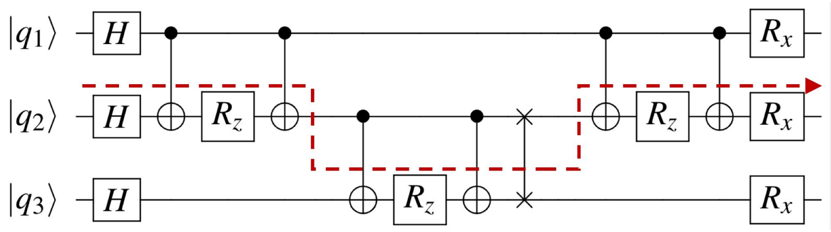


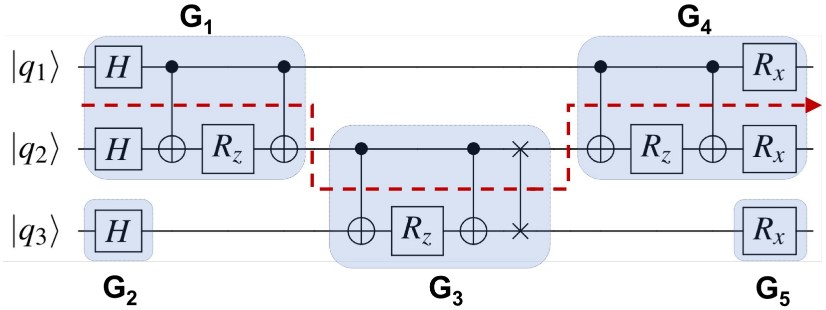
Aggregated Instructions: an example

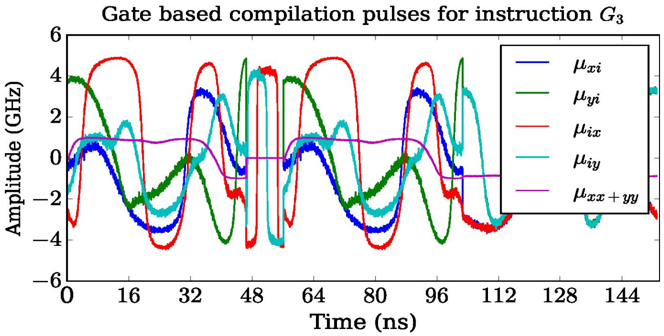




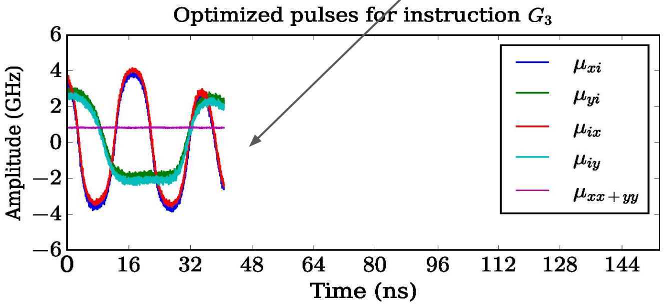
Aggregated Instructions: QAOA



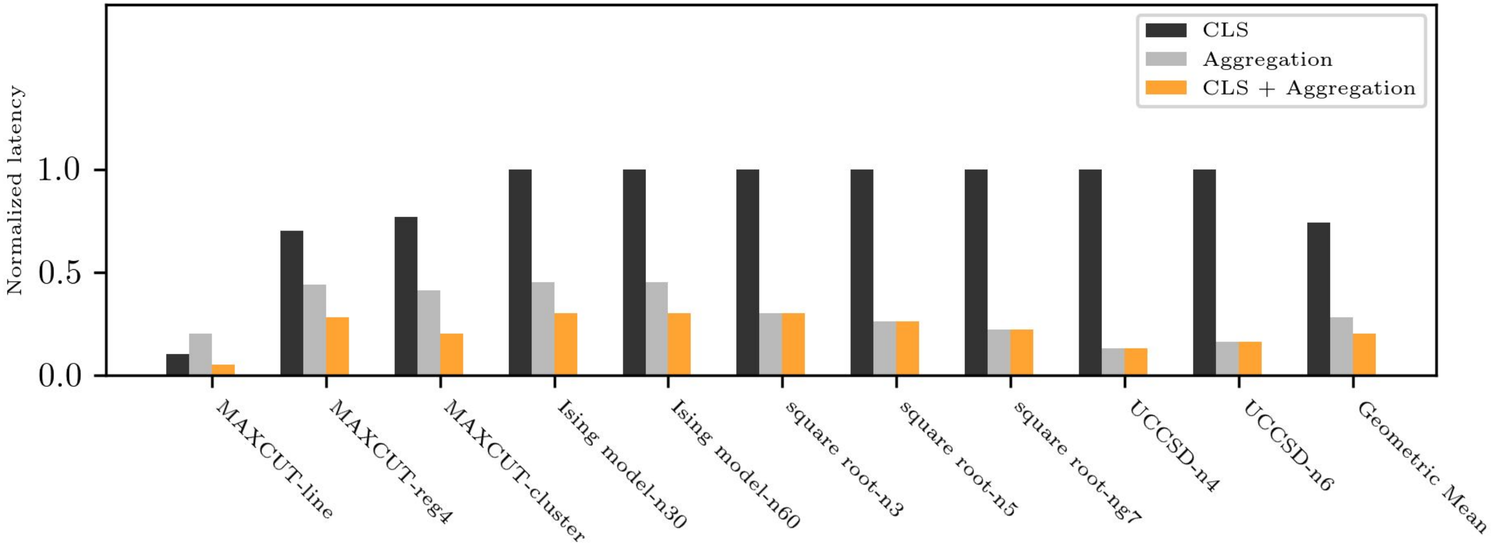




3X shorter

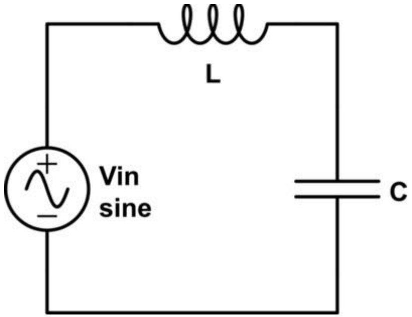


Performance

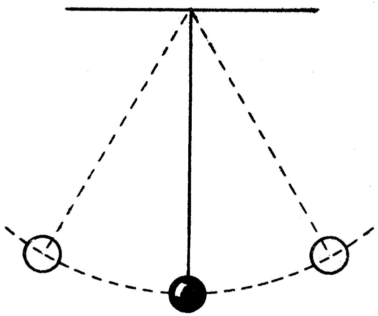


Physical implementation: Transmon

LC circuit



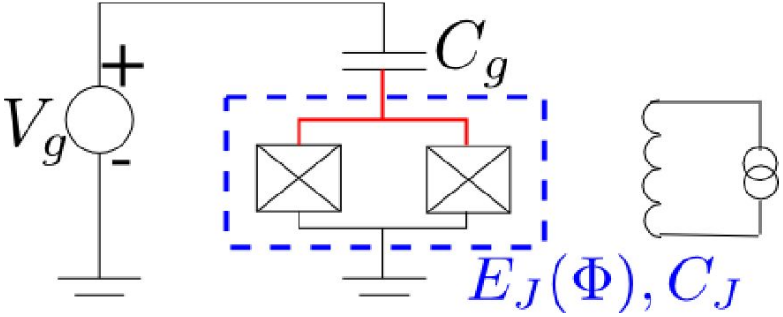
Pendulum

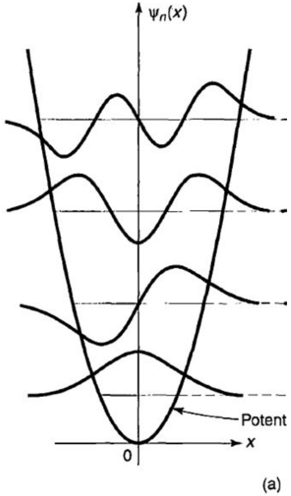


Physical implementation: Transmon

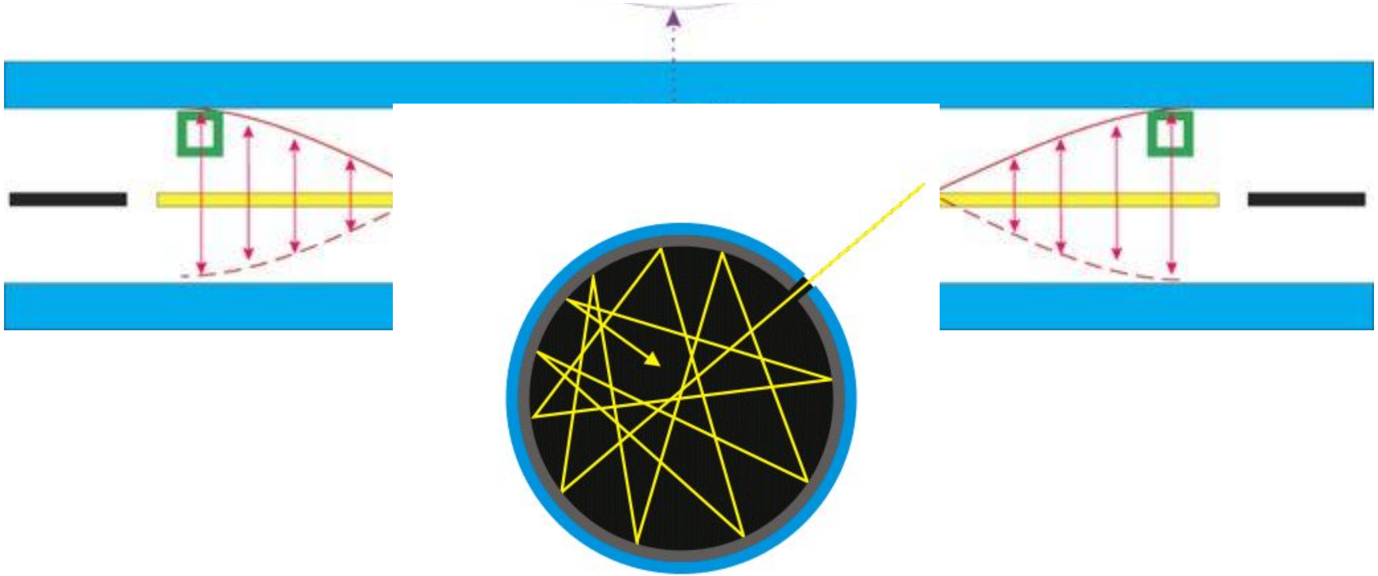
Transmon: quantized LC circuit

Quantized Pendulum





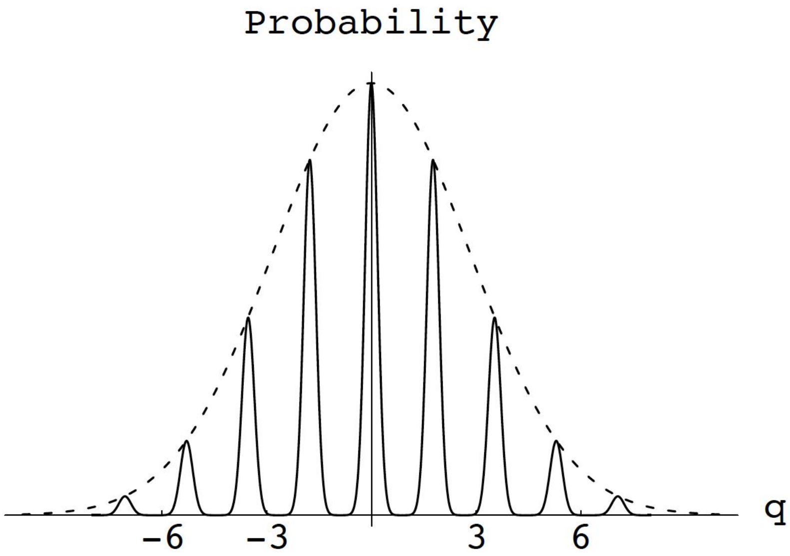
Physical implementation: Transmon



Encoding a qubit in a cavity

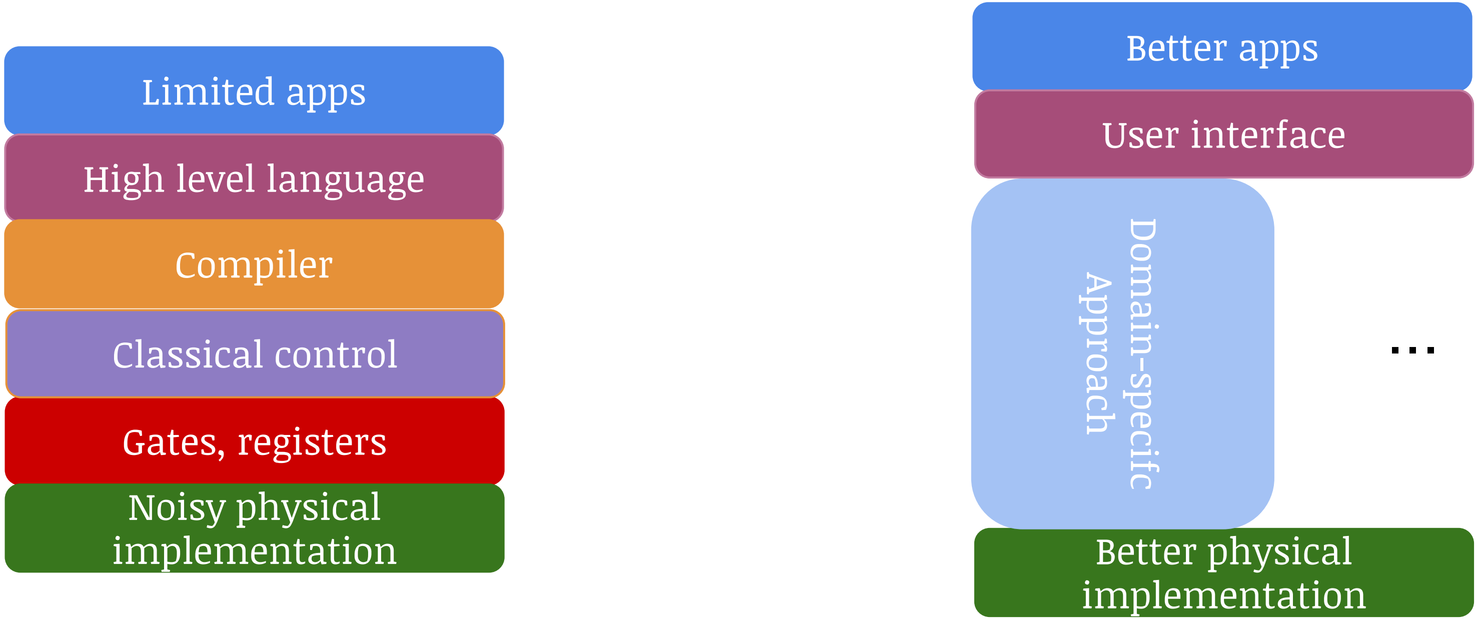
- Long qubit lifetime
- Enable smart encoding

Gottesman-Kitaev-Preskill code



Quantum computing now

Near-term goal



Thank you!