Quantum Singular Value Transformation on NISQ Hardware

Yale Quantum Institute Visiting Student Researcher Program

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July 31, 2026

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   - What is the Quantum Singular Value Transformation?
   - What Are Noisy Intermediate Quantum (NISQ) Devices?
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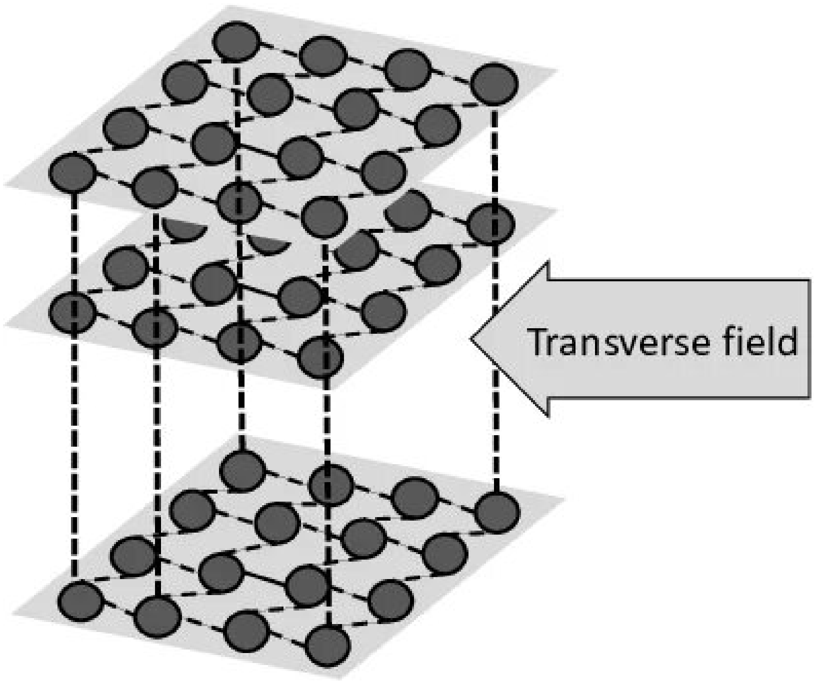

The Mixed Field Ising Hamiltonian:

$$H = -J\sum_{i=0}^{n-2} Z_i Z_{i+1} - \sum_{i=0}^{n-1} h_i X_i - m\sum_{i=0}^{n-1} Z_i$$

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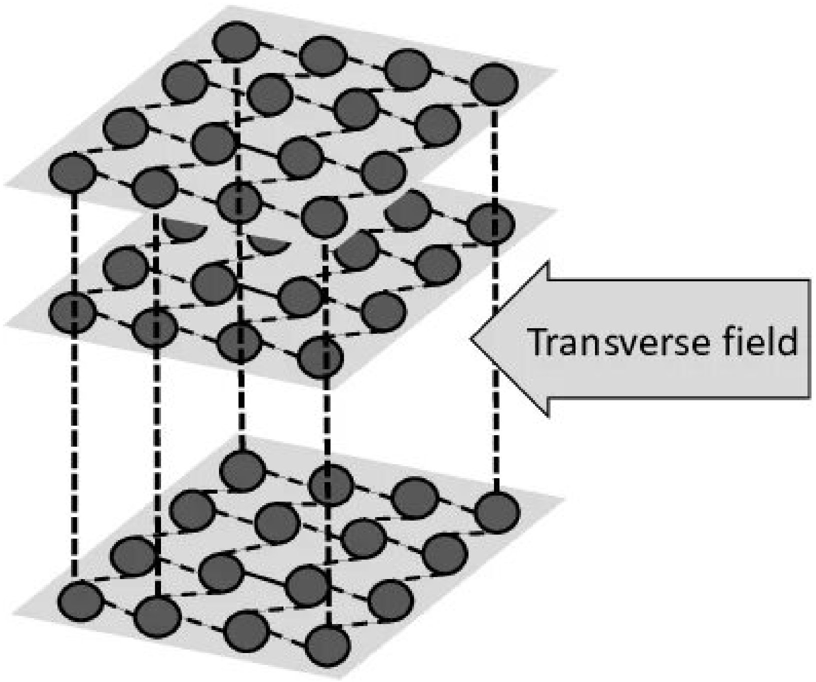

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For $n = 3$:

$$H = -J Z_0 Z_1 - J Z_1 Z_2 - h_0 X_0 - h_1 X_1 - h_2 X_2$$
$$-m(Z_0 + Z_1 + Z_2)$$

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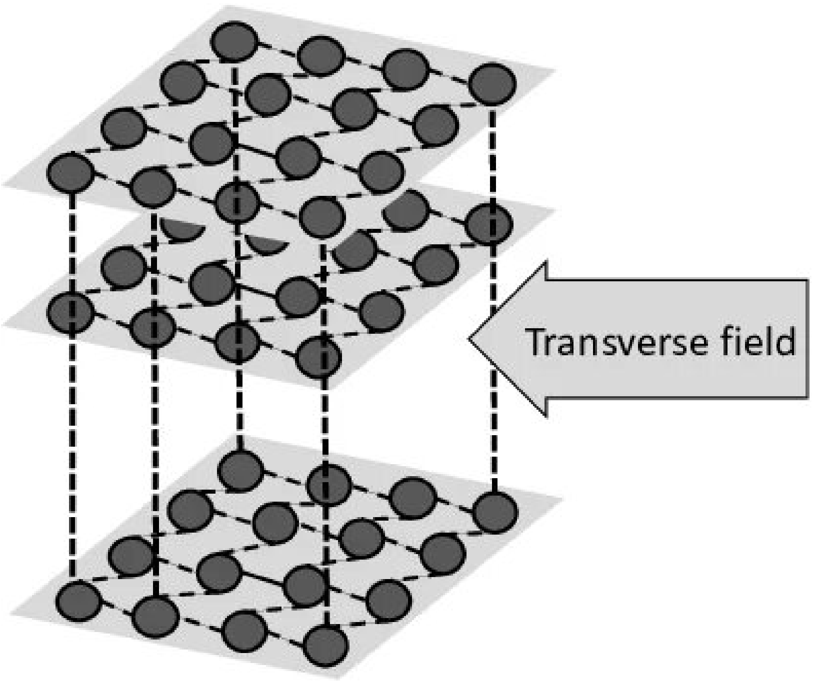

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We consider the $n = 3$ Ising spin chain with $h_i/J = -1.05$ for all i and $m/J = 0.5$ in our baseline Hamiltonian simulation.

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$$f(H) \text{ such that } f(x) = e^{-ixt}$$

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Quantum Singular Value Transformation (In Words)

The **quantum singular value transformation (QSVT)** is a technique that allows one to polynomially transform the singular values of a given matrix.

- For square matrices, the singular values are equal to the eigenvalues.
- Importantly, the QSVT has been shown to be an important primitive for many other quantum algorithms.
- **Three components:** Quantum Signal Processing, Block Encoding, Upscaling (Qubitization)

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Two big limitations with current hardware:

- Deeper circuits decohere states
- Cannot correct our errors at scale

Quantum Circuit Basics

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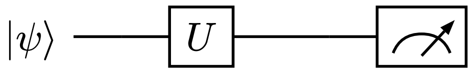
Quantum gates are modeled by unitary operations. This is required by quantum mechanics.

$$UU^\dagger = U^\dagger U = \mathbb{1} \text{ (identity)}$$



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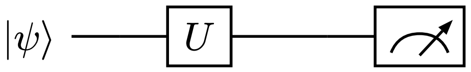

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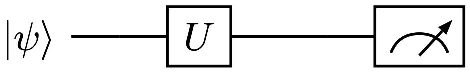

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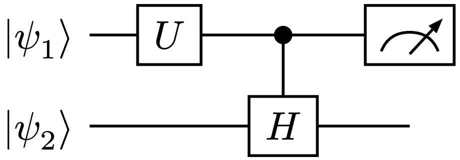

$$|\psi_1\rangle \otimes |\psi_2\rangle$$

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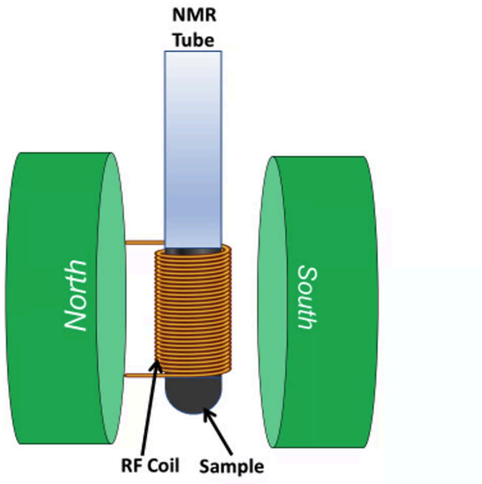

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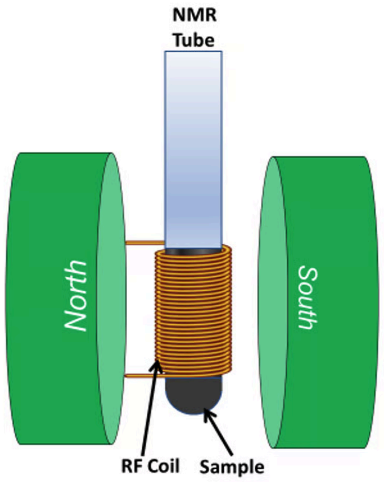

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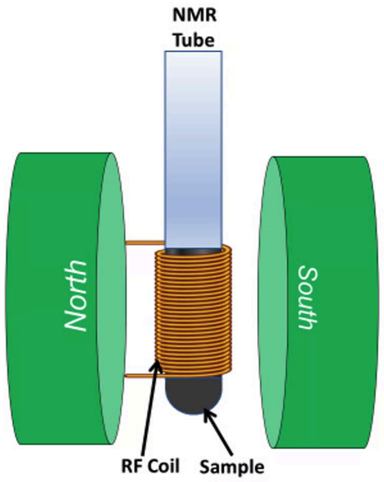

$$|\psi\rangle \;—\; \boxed{e^{i\varphi_2 Z}} \;—\; \boxed{W(a)} \;—\; \boxed{e^{i\varphi_1 Z}} \;—\; \boxed{W(a)} \;—\; \boxed{e^{i\varphi_0 Z}}$$

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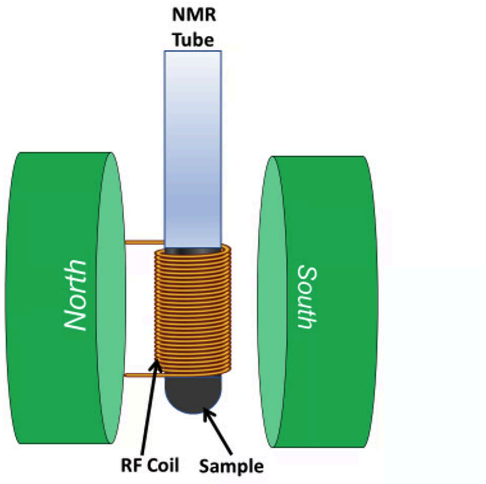

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Quantum Signal Processing (QSP)

Given a rotation matrix parameterized by a and a rotation matrix parameterized by a set of angles $\{\varphi_k\}$, we can interleave these operators to create a matrix $U_{\vec{\varphi}}$ that is a polynomial of a in the top left corner:

$$e^{i\varphi_0 Z}W(a)e^{i\varphi_1 Z}W(a)e^{i\varphi_2 Z}...W(a)e^{i\varphi_k Z} = \begin{pmatrix} P(a) & \cdot \\ \cdot & \cdot \end{pmatrix}$$

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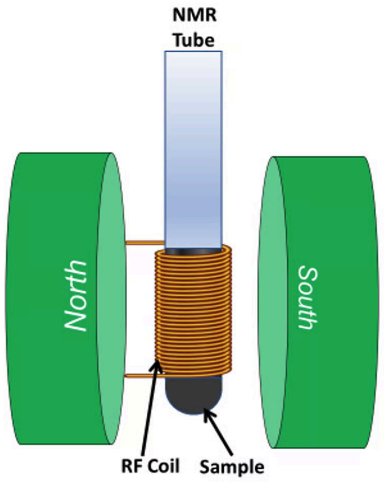

$$e^{-iHt} = \cos(Ht) - i\sin(Ht)$$

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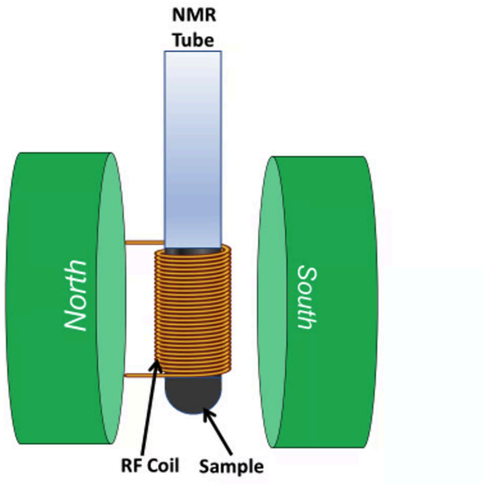

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Quantum Signal Processing (QSP)

Given a signal rotation operator $W(a) = \begin{pmatrix} a & i\sqrt{1-a^2} \\ i\sqrt{1-a^2} & a \end{pmatrix}$ and a signal processing rotation operator $e^{i\varphi Z}$, we may interleave these operators to create a matrix $U_{\vec{\varphi}}$ that can be expressed as a polynomial function of a (given various restrictions on the polynomials):

$$e^{i\varphi_0 Z} \prod_{k=1}^{d} W(a) e^{i\varphi_k Z} = \begin{pmatrix} P(a) & iQ(a)\sqrt{1-a^2} \\ iQ^*(a)\sqrt{1-a^2} & P^*(a) \end{pmatrix}$$

Block Encoding and Linear Combination of Unitaries

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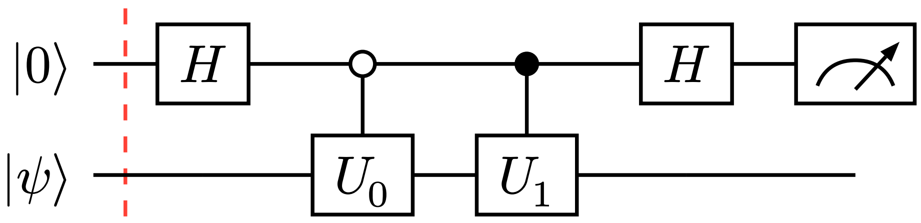

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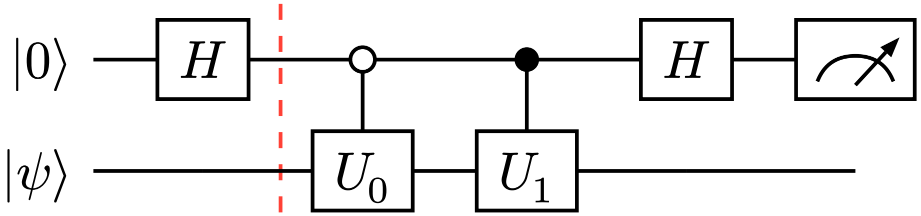

$$U = \frac{1}{\sqrt{2}} \begin{pmatrix} \mathbb{1} & \mathbb{1} \\ \mathbb{1} & -\mathbb{1} \end{pmatrix}$$

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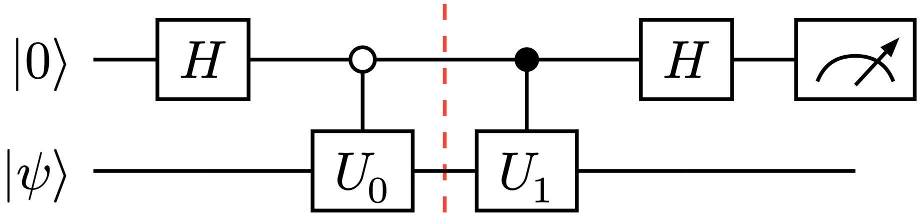

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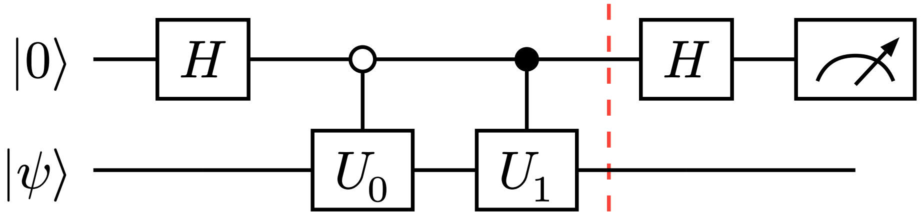

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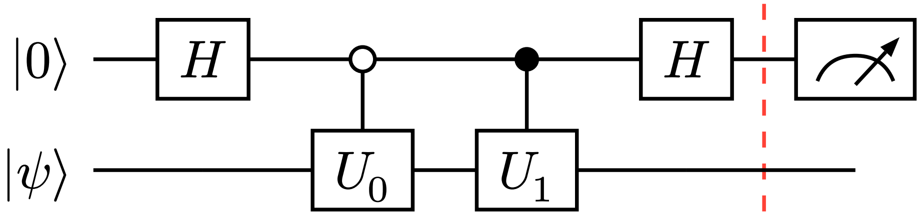

$$U = \frac{1}{2}\begin{pmatrix} U_0 + U_1 & U_0 - U_1 \\ U_0 - U_1 & U_0 + U_1 \end{pmatrix}$$

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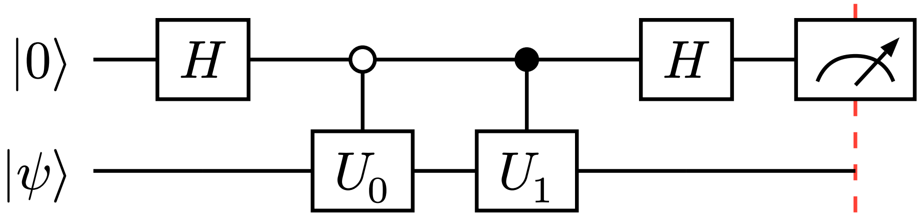

$$U = \begin{pmatrix} \frac{1}{2}(U_0 + U_1) & \cdot \\ \cdot & \cdot \end{pmatrix}$$

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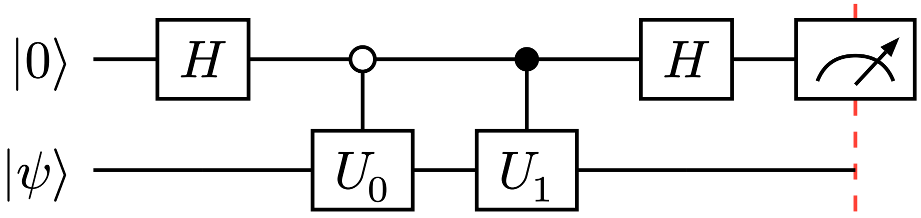

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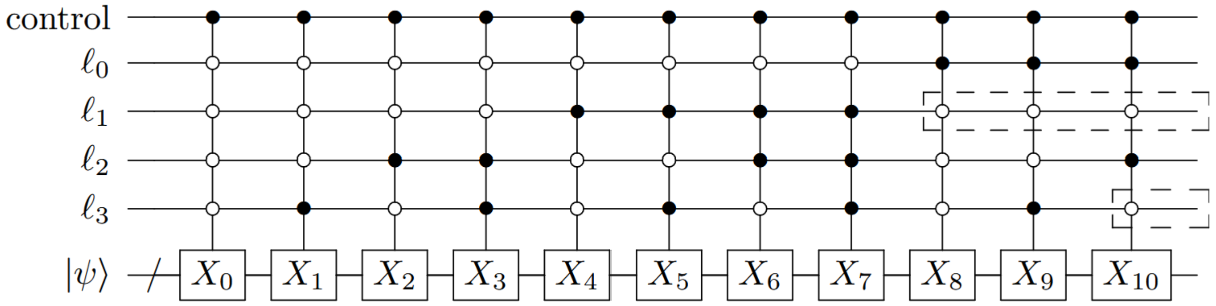

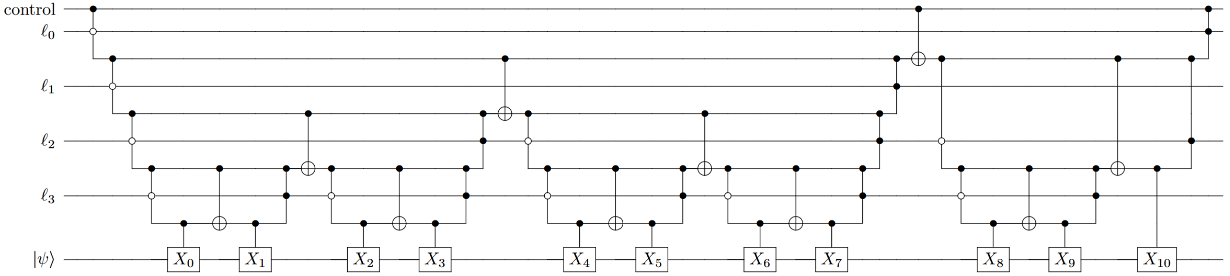

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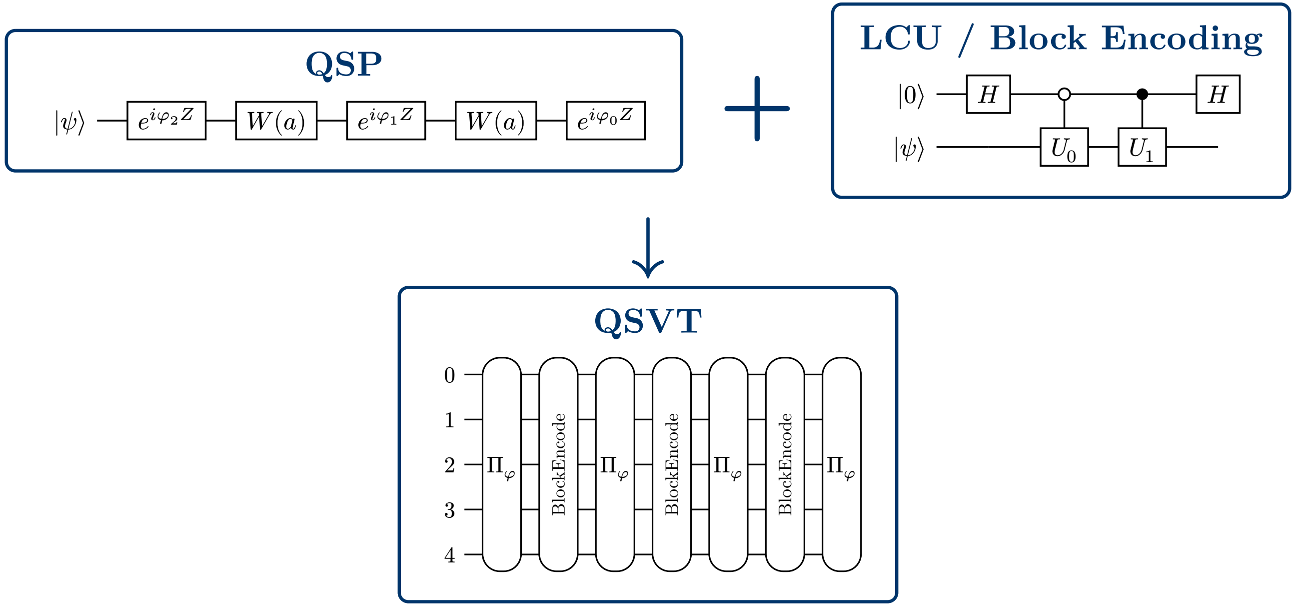

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Formal QSVT (Odd Parity)

Given a unitary U that block-encodes a matrix $A = \tilde{\Pi} U \Pi$ via projectors Π and $\tilde{\Pi}$, and projector-controlled phase shifts

$$\Pi_\varphi := e^{i\varphi(2\Pi - \mathbb{1})}, \quad \tilde{\Pi}_\varphi := e^{i\varphi(2\tilde{\Pi} - \mathbb{1})},$$

for odd degree d and phases $\vec{\varphi} = (\varphi_1, \ldots, \varphi_d)$ the interleaved sequence

$$U_{\vec{\varphi}} = \tilde{\Pi}_{\varphi_1} U \prod_{k=1}^{\frac{d-1}{2}} \left(\Pi_{\varphi_{2k}} U^\dagger \tilde{\Pi}_{\varphi_{2k+1}} U \right)$$

implements an odd polynomial transform of the singular values of A:

$$\tilde{\Pi} U_{\vec{\varphi}} \Pi = P^{(SV)}(A).$$

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Unoptimized resource estimation:

```
gateset = {"X", "Z", "S", "T", "Hadamard", "CNOT"}
  --- Resources: ---
  Total wires: 14
    algorithmic wires: 8
    allocated wires: 6
      zero state: 6
      any state: 0
  Total gates : 6.562E+4
    'T': 3.665E+4,
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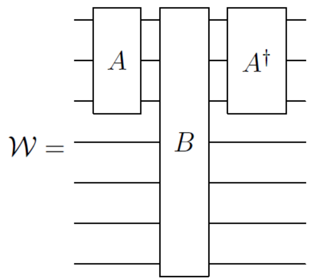

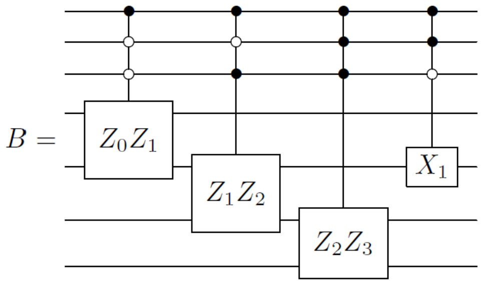

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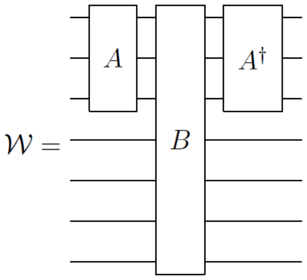
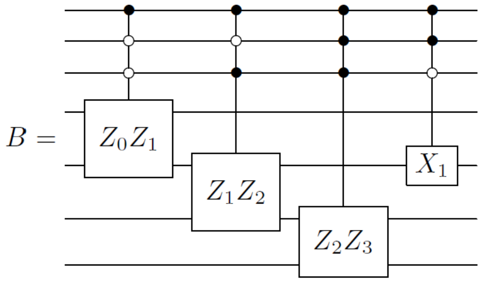




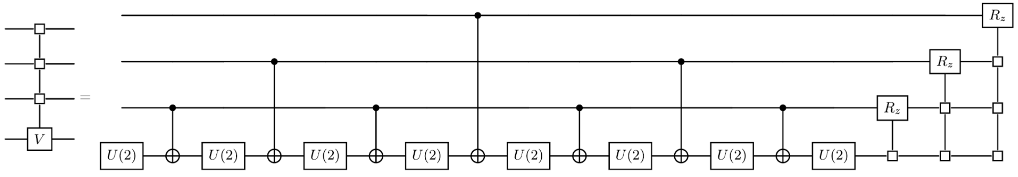


Figure 3. Decomposition for $M_n^{\mathcal{C}}(V)$ where V is a list of U(2) unitaries, $n = 1$, and $\mathcal{C} = 3$. The open squares indicate multiplexed controls. (See figures 2 and 9).

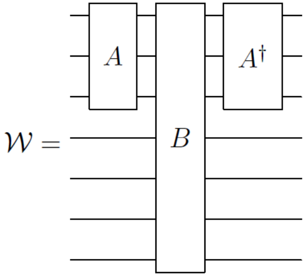
Implementing the QSVT on NISQ Hardware

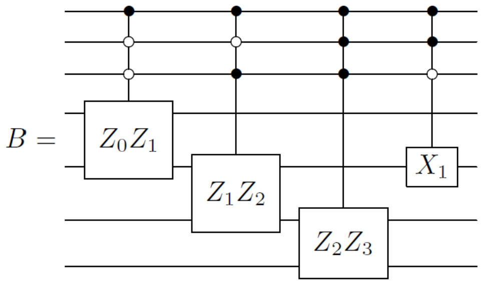
Unoptimized resource estimation:

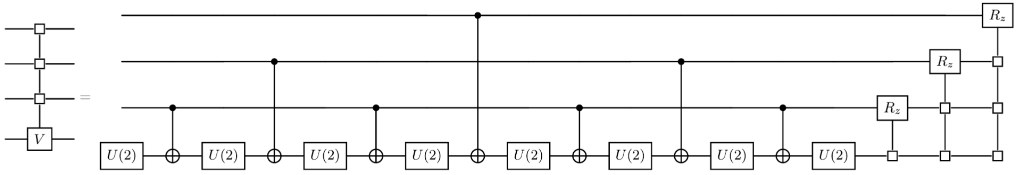
```
gateset = {"X", "Z", "S", "T", "Hadamard", "CNOT"}
  --- Resources: ---
  Total wires: 14
    algorithmic wires: 8
    allocated wires: 6
      zero state: 6
      any state: 0
  Total gates : 6.562E+4
    'T': 3.665E+4,
    'CNOT': 1.289E+4,
    'X': 236,
    'Z': 3.800E+3,
    'S': 4.807E+3,
    'Hadamard': 7.244E+3
```

Optimized Resource Estimation

Not finished yet... Current progress — more efficient block encoding via multiplexor compilation of SELECT gates.







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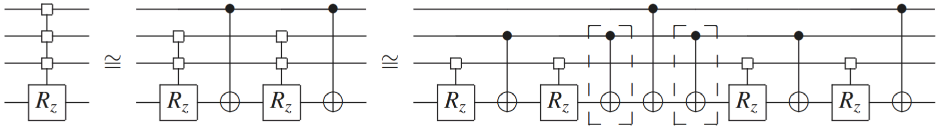

Figure 2: The recursive decomposition of a multiplexed R_z gate. The boxed CNOT gates may be canceled.

Future Considerations (Rest of the Summer and Beyond)

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Only $\approx \frac{2}{3}$ of the way through the project term so a lot is still planned. Some of these ideas may extend further into the future as well.

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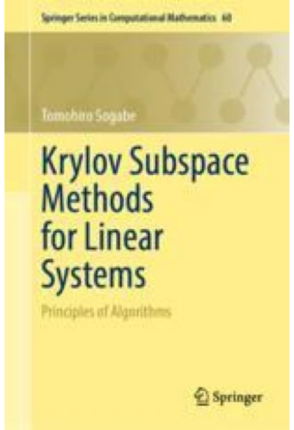

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- We can formulate many algorithms in terms of the QSVT, but it is computationally expensive.
- Block encoding is the most expensive step of QSVT, but it can be simplified in many ways by looking for structure.

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