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Genesis: A Hybrid CV-DV Compiler for Hamiltonian Simulation

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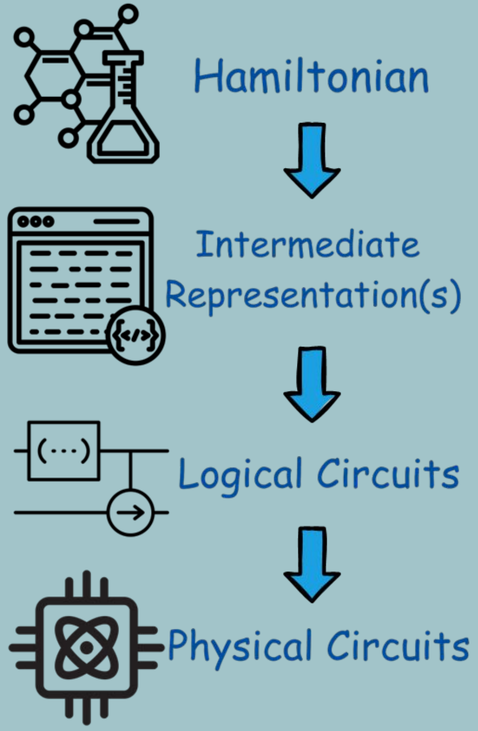
Genesis



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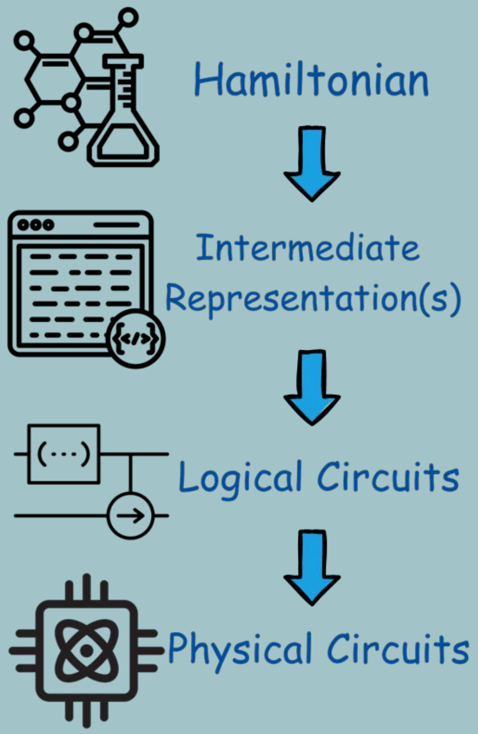
Genesis: A Compiler for Hamiltonian Simulation on Hybrid CV-DV Quantum Computers

Genesis is a compiler framework for Hamiltonian simulation targeting hybrid continuous-variable (CV) and discrete-variable (DV) quantum systems.

It supports multi-level logical circuit compilation, Hybrid CV-DV domain-specific language (DSL), and hardware circuit mapping and routing.

Genesis



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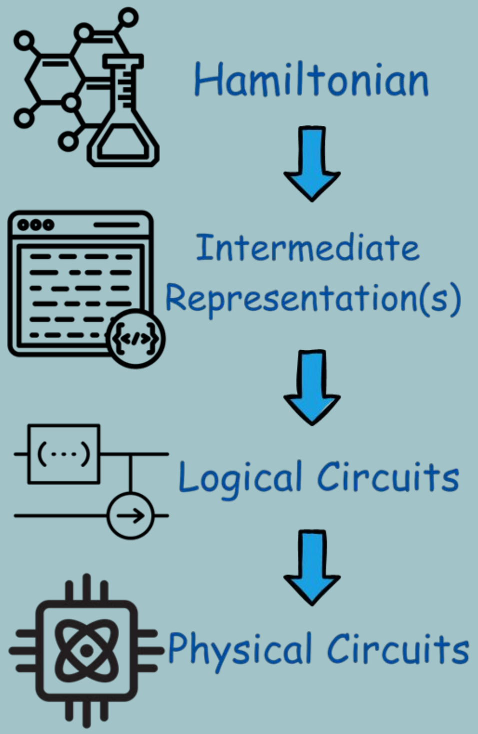
Collaborative Work(Rutgers & NCSU)

- To appear in **ISCA ’25:** Zihan Chen*, Jiakang Li*, Minghao Guo*, Henry Chen, Zirui Li, Joel Bierman, Yipeng Huang, Huiyang Zhou, Yuan Liu, and Eddy Z. Zhang. 2025. Genesis: A Compiler for Hamiltonian Simulation on Hybrid CV-DV Quantum Computers. In *Proceedings of the 52nd Annual International Symposium on Computer Architecture (ISCA ’25), June 21–25, 2025, Tokyo, Japan.* ACM, New York, NY, USA, 15 pages. https://doi.org/10.1145/3695053.3731065
- **arXiv preprint**:2505.13683, 2025
- Software access: https://github.com/ruadapt/Genesis-CVDV-Compiler

Preprint: **Code:**

Genesis



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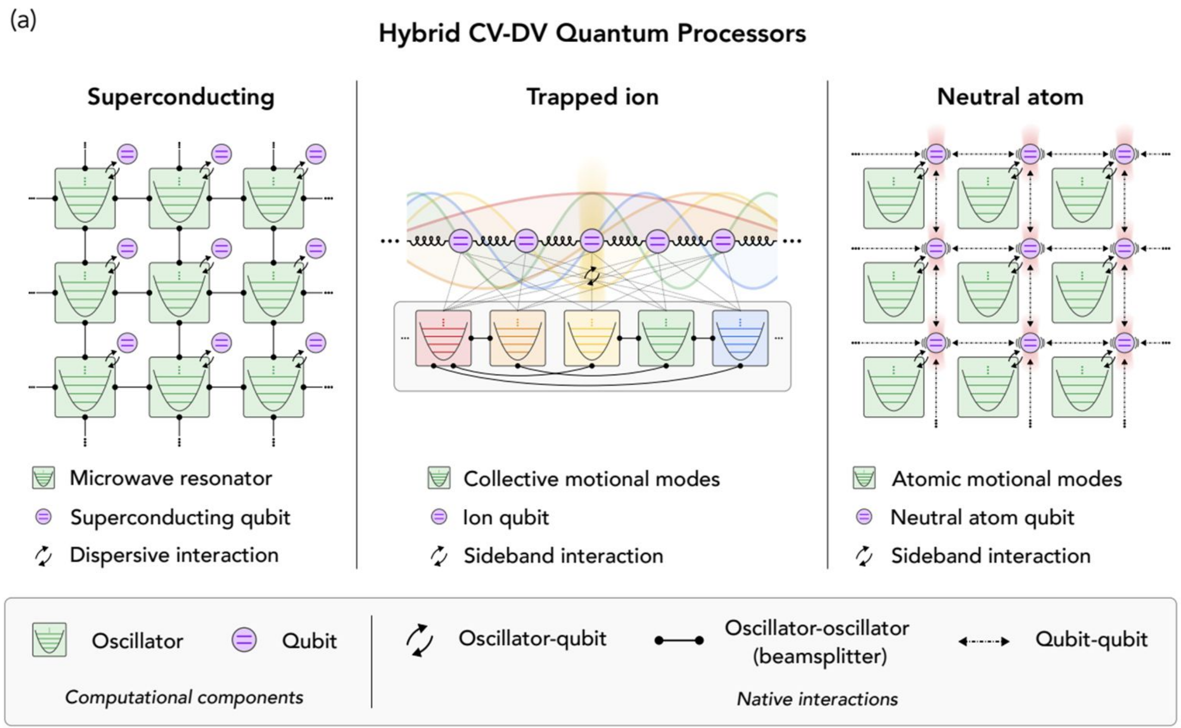
1. Background and Motivation
2. Domain Specific Language Design
3. Logical Circuit Synthesis
4. Physical Circuit Mapping
5. End-to-end Implementation

1.1 Hybrid CV-DV Background

- Most current quantum machines use qubits that are **discrete-variable (DV)** systems – essentially two-state quantum systems.
- In contrast, a **continuous-variable (CV)** quantum system (qumode) has a spectrum of many possible states, theoretically an infinite continuum of states. It can retain more robust quantum states and has the potential to achieve excellent quantum error correction.

- **CV-only** hardware is limited to generate non-Gaussian resources.
- **DV-only** hardware needs truncation for simulating CV states, also it is difficult to simulate native bosonic operators.
- **Hybrid CV-DV** hardware takes the best of both system and is well-suited for the physical simulation with fermion-boson mixtures

1.1 Hybrid CV-DV Background



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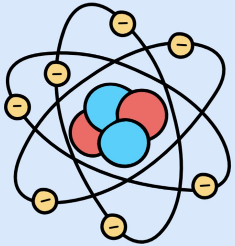
Source: **"Hybrid Oscillator-Qubit Quantum Processors: Instruction Set Architectures, Abstract Machine Models, and Applications."** Liu et al. arXiv 2407.10381v2

1.2 Hamiltonian Simulation Background

Hamiltonian

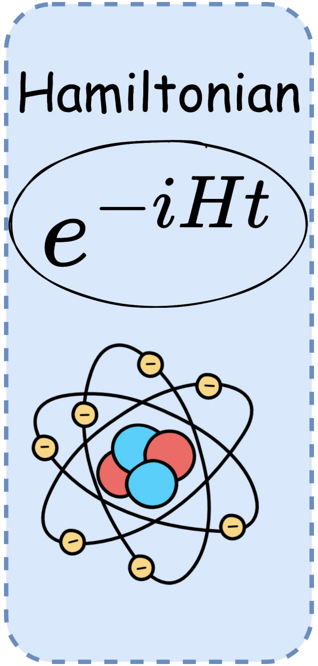
$$e^{-iHt}$$



- Hamiltonian Simulation is a “killer” quantum computing application currently
- Hamiltonian Simulation could unlock insights into chemistry, physics, and materials science.

- Fermions → discrete states → qubits (DV)
- Bosons → continuous/infinite states → qumodes (CV)

1.2 Hamiltonian Simulation Background



- Hybrid CV-DV hardware takes the best of both system and is well-suited for the physical simulation with fermion-boson mixtures
- However, compiler and programming systems are largely undeveloped for hybrid CV-DV systems.
- Fermion-Boson mixtures interactions have not been thoroughly investigated, Genesis tries to bridge this gap and offers a complete end-to-end hamiltonian simulation compilation support!

1.3 Challenges and Motivation

1. Complex Cross-Domain Problem
   - Hamiltonian Grammar(DSL) and Multi-level Compilation
2. Qumode-centric Gate Synthesis
   - Rule-Based Recursive Template Matching
3. Multi-qubit Pauli-string Synthesis
   - Traveling Ancilla Qumode
4. Limited Connectivity Constraints
   - Hybrid CVDV Hardware Mapping and Routing

2.1 Hamiltonian Grammar

Hamiltonian Model Example:

$$H = -t\sum_{i,j,\sigma} c_{i\sigma}^{\dagger} c_{j\sigma} + U\sum_{i} b_i^{\dagger} b_i + g\sum_{i,\sigma} \hat{n}_{i\sigma}(b_i^{\dagger} + b_i)$$

Corresponds Hamiltonian Grammar Representation:

```
Const t = 1;
Const U = 1;
Const g = 1;

Range i = [0, 10, 1];
Range j = [0, 10, 1];
Range sigma = [0, 2, 1];

Result = - t *Sum_over(i, j, sigma){FC[i][sigma]* FA[j][sigma]}
         + U *Sum_over(i){BC[i]* BA[i]}
         + g * Sum_over(i, sigma){TensorProd(FN[i][sigma], BC[i] + BA[i])};
```

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2.2 CVDVQASM and Multi-level Compilation

1. Hamiltonian Formula

$$H = -t \sum_{i,j,\sigma} c_{i\sigma}^{\dagger} c_{j\sigma} + U \sum_{i} b_i^{\dagger} b_i + g \sum_{i,\sigma} \hat{n}_{i\sigma}(b_i^{\dagger} + b_i)$$

2. Hamiltonian Grammar

```
- t *Sum_over(i, j, sigma){FC[i][sigma]* FA[j][sigma]}
+ U *Sum_over(i){BC[i]* BA[i]}
+ g * Sum_over(i, sigma){TensorProd(FN[i][sigma], BC[i] + BA[i])};
```

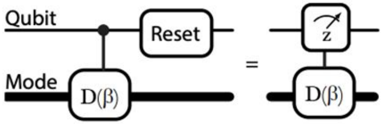
3. Intermediate Representation

```
pauli(0.392699075j): IXIZIYII;
pauli(0.392699075j): IIYIXIII;
bosonic: exp(prod((-1j),dagger(b(0)),b(0)));
bosonic: exp(prod((-1j),dagger(b(1)),b(1)));
hybrid: exp(prod((-0.78539815j),sigma(0, 0),sum(dagger(b(0)),b(0))));
hybrid: exp(prod((0.78539815j),sigma(3, 0),sum(dagger(b(0)),b(0))));
```

4. Logical CVDVQASM file

```
// Pauli String with Parameter
pauli(pi/4) YIYZXXIIIIIIII;
pauli(pi/4) XZYZXYIIIIIIII;
...
// Phase Space Rotation Gate
R(pi/4) qm[1];
R(pi/4) qm[2];
...
// Control Displacement Gate
CD(pi/4) q[2], qm[1];
CD(pi/4) q[3], qm[1];
...
// Displacement Gate
D(pi/4) qm[2];
D(pi/4) qm[2];
...
```

5. Physical CVDVQASM file



3.1 Direct Qumode-centric Gate Synthesis

Type	Gate Name	Definition
Qubit	x, y Rotation	$r_\varphi(\theta) = \exp\left[-i\frac{\theta}{2}(\cos\varphi\sigma_x + \sin\varphi\sigma_y)\right]$
	z Rotation	$r_z(\theta) = \exp\left(-i\frac{\theta}{2}\sigma_z\right)$
Qumode	Phase-Space Rotation	$\mathrm{R}(\theta) = \exp\left[-i\theta a^\dagger a\right]$
	Displacement	$\mathrm{D}(\alpha) = \exp\left[\left(\alpha a^\dagger - \alpha^* a\right)\right]$
	Beam-Splitter	$\mathrm{BS}(\theta, \varphi) = \exp\left[-i\frac{\theta}{2}\left(e^{i\varphi}a^\dagger b + e^{-i\varphi}ab^\dagger\right)\right]$
Hybrid	Conditional Phase-Space Rotation	$\mathrm{CR}(\theta) = \exp\left[-i\frac{\theta}{2}\sigma_z a^\dagger a\right]$
	Conditional Parity	$\mathrm{CP} = \exp\left[-i\frac{\pi}{2}\sigma_z a^\dagger a\right]$
	Conditional Displacement	$\mathrm{CD}(\alpha) = \exp\left[\sigma_z\left(\alpha a^\dagger - \alpha^* a\right)\right]$
	Conditional Beam-Splitter	$\mathrm{CBS}(\theta, \varphi) = \exp\left[-i\frac{\theta}{2}\sigma_z\left(e^{i\varphi}a^\dagger b + e^{-i\varphi}ab^\dagger\right)\right]$
	Rabi Interaction	$\mathrm{RB}(\theta) = \exp\left[-i\sigma_x\left(\theta a^\dagger - \theta^* a\right)\right]$

3.2 Product Formula and Block Encoding

- Trotterization(Trotter-Suzuki formula)

$$e^{(M+N)t} \approx \left(e^{Mt'} e^{Nt'}\right)^n$$

- BCH(Baker Campbell Hausdorff formula)

$$e^{[M,N]t^2} \approx e^{Mt} e^{Nt} e^{-Mt} e^{-Nt}.$$

- Block Encoding

$$O = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$$

$$O = |0\rangle\langle 0| \otimes A + |0\rangle\langle 1| \otimes B + |1\rangle\langle 0| \otimes C + |1\rangle\langle 1| \otimes D.$$

- Commutator $[A, B]$ and anticommutator $\sigma_z\{A, B\}$ implementation in CVDV architecture

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Source: **"Leveraging Hamiltonian Simulation Techniques to Compile Operations on Bosonic Devices."** Kang, Christopher, et al. arXiv:2303.15542

3.3 Rule-Based Recursive Template Matching

Rules	Operator Template	Conditions	Decomposition Output	Reference	Precision
1	$\exp(Mt+Nt) \approx \mathrm{Trotter}(Mt,Nt)$		$(\exp(Mt/k)\exp(Nt/k))^k$	Trotterization	Approx
2	$\exp([Mt,Nt]) \approx \mathrm{BCH}(Mt,Nt)$		$\exp(Mt)\exp(Nt)\exp(-Mt)\exp(-Nt)$	BCH	Approx
3	$\exp(t^2[M,N])$	M,N Hermitian	$\exp([it\sigma_i N, it\sigma_i M])$	[20]	Exact
4	$\exp(-it^2\sigma_i\{M,N\})$	M,N Hermitian	$\exp([it\sigma_j M, it\sigma_k N])$	[20]	Exact
5	$\exp(-it^2\sigma_z[M,N])$		$\exp([(itN, it\sigma_z M])$	This paper	Exact
6	$\exp(t^2\sigma_z((MN-(MN)^\dagger)))$	$[M,N]=0$	$\exp([X\cdot it\mathcal{B}_N\cdot X, it\mathcal{B}_M])$	[20]	Exact
7	$\exp(it^2\sigma_z((MN+(MN)^\dagger)))$	$[M,N]=0$	$\exp([S\cdot it\mathcal{B}_M\cdot S^\dagger, X\cdot it\mathcal{B}_N\cdot X])$	[20]	Exact
8	$\exp\left(-2it\begin{pmatrix} MN & 0 \\ 0 & -MN\end{pmatrix}\right)$	M,N Hermitian	$\exp(-it\sigma_z[M,N]-it\sigma_z\{M,N\})$	This paper	Exact
9	$\exp\left(2it^2\begin{pmatrix} MN & 0 \\ 0 & -MN\end{pmatrix}\right)$	$[M,N]=0$ $MN=(MN)^\dagger$	$\exp([(S\cdot it\mathcal{B}_M\cdot S^\dagger, X\cdot it\mathcal{B}_N\cdot X])$	[20]	Exact
10	$\exp(2it\mathcal{B}_{MN})$	$[M,N]=0$	$X\cdot\exp(t\sigma_y(MN-(MN)^\dagger)+it\sigma_x(MN+(MN)^\dagger))\cdot X$	[20]	Exact
11	$\exp\left(it\begin{pmatrix} 2MN & 0 \\ 0 & -NM-(NM)^\dagger\end{pmatrix}\right)$	$MN=(MN)^\dagger$	$\exp([S\cdot it\mathcal{B}_M\cdot S^\dagger, X\cdot it\mathcal{B}_N\cdot X])$	[20]	Exact
12	$\mathcal{B}_a=\exp\left(2i\alpha\begin{pmatrix} 0 & a \\ a^\dagger & 0\end{pmatrix}\right)$	$\alpha=\alpha^*$	$\exp(i(\pi/2)a^\dagger a)\exp(i(\alpha(a^\dagger+a))\otimes\sigma_y)\exp(-i(\pi/2)a^\dagger a)\exp(i(\alpha(a^\dagger+a))\otimes\sigma_x)$	[20]	Approx
13	$\mathcal{B}_{a^\dagger}=\exp\left(2i\alpha\begin{pmatrix} 0 & a^\dagger \\ a & 0\end{pmatrix}\right)$	$\alpha=\alpha^*$	$\exp(i(\pi/2)a^\dagger a)\exp(i(\alpha(a^\dagger+a))\otimes\sigma_y)\exp(-i(\pi/2)a^\dagger a)\exp(-i(\alpha(a^\dagger+a))\otimes\sigma_x)$	This paper	Approx
14	$e^{(P_1P_2\cdots P_n)(\alpha a_k^\dagger-\alpha^* a_k)}$		Multi-qubit-controlled displacement: Right hand side (RHS) of Equation (11) first line	[28]	Exact
15	$e^{2i\alpha^2 P_1P_2\cdots P_n}$		Multi-Pauli Exponential: Right hand side (RHS) of Equation (9) first line	This Paper	Exact
16	All Native Gates RHS in Table 2		All Native Gates Left Hand Side (LHS) Table 2	[28]	Exact

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[20] **"Leveraging Hamiltonian Simulation Techniques to Compile Operations on Bosonic Devices."** Kang, Christopher, et al. arXiv:2303.15542

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Decomposition Rules Set

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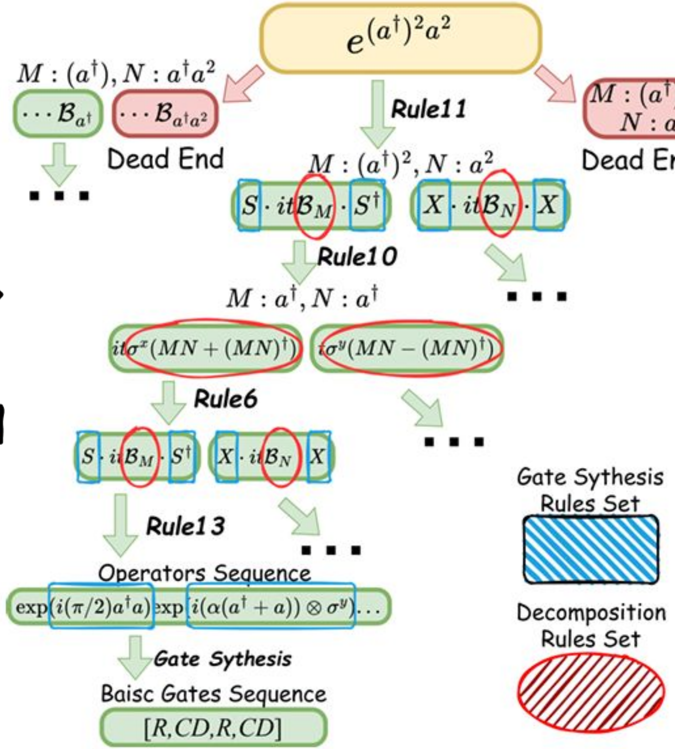


$e^{(a^\dagger)^2 a^2}$

Basic Gates Sequence
(Logical CVDVQASM Circuit)

Repeat the rewrite process until it produces only basis gates

3.4 Multi-qubit Pauli-string Synthesis

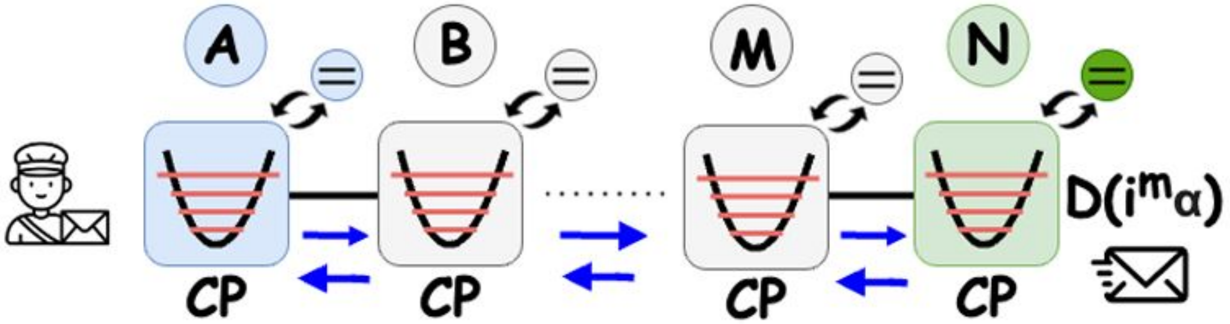
- Qubits are not directly connected with each other, we propose a scheme to synthesize an arbitrary multi-qubit Pauli-string on Hybrid CV-DV platforms.
- It is inspired by phase kickback in DV systems, where the phase of the control qubit is influenced by the operation on the target qubits.

$$
\begin{aligned}
U &= D^k(i\alpha)\, CD^{(k,P_{1\cdots n})}(-\alpha)\, D^k(-i\alpha)\, CD^{(k,P_{1\cdots n})}(\alpha) \\
&= e^{2i\alpha^2 P_1 P_2 \cdots P_n}
\end{aligned}
$$

3.4 Multi-qubit Pauli-string Synthesis

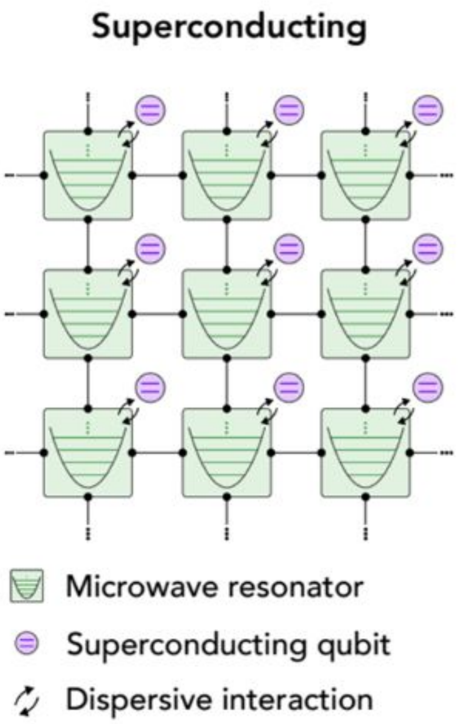
- Our final multi-Pauli exponential decomposition makes use of a multi-qubit controlled CD gate proposed by Liu et al., as below:

$$\mathrm{CD}^{(k,P_1P_2\cdots P_n)}(\alpha) = U_{\mathrm{seq}}^{\dagger} D(i^n\alpha) U_{\mathrm{seq}}$$
$$= e^{(P_1P_2\cdots P_n)(\alpha a_k^{\dagger} - \alpha^* a_k)}$$



Source: **"Hybrid Oscillator-Qubit Quantum Processors: Instruction Set Architectures, Abstract Machine Models, and Applications."** Liu et al. arXiv 2407.10381v2

4.1 Limited Hardware Connectivity



- **Qumode-qumode Mapping.**

Interactions are limited to adjacent qumodes. For non-adjacent qumodes, qumode SWAP gates are used, with routing optimized to minimize such SWAPs.

- **Qubit-qumode Mapping.**

Each qumode interacts only with its associated qubit. For interactions with other qumodes, adjacency is established by moving qumodes, similar to qumode-qumode mapping.

- **Qubit-qubit Mapping.**

Qubits interact indirectly via an ancilla qumode, which is moved between qubits to mediate interactions and complete gate operations.

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Source: **"Hybrid Oscillator-Qubit Quantum Processors: Instruction Set Architectures, Abstract Machine Models, and Applications."** Liu et al. arXiv 2407.10381v2

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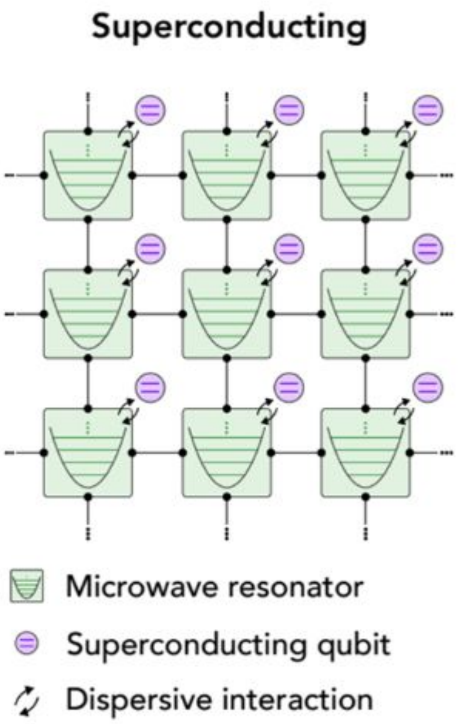

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- **Qubit-qumode Mapping.**

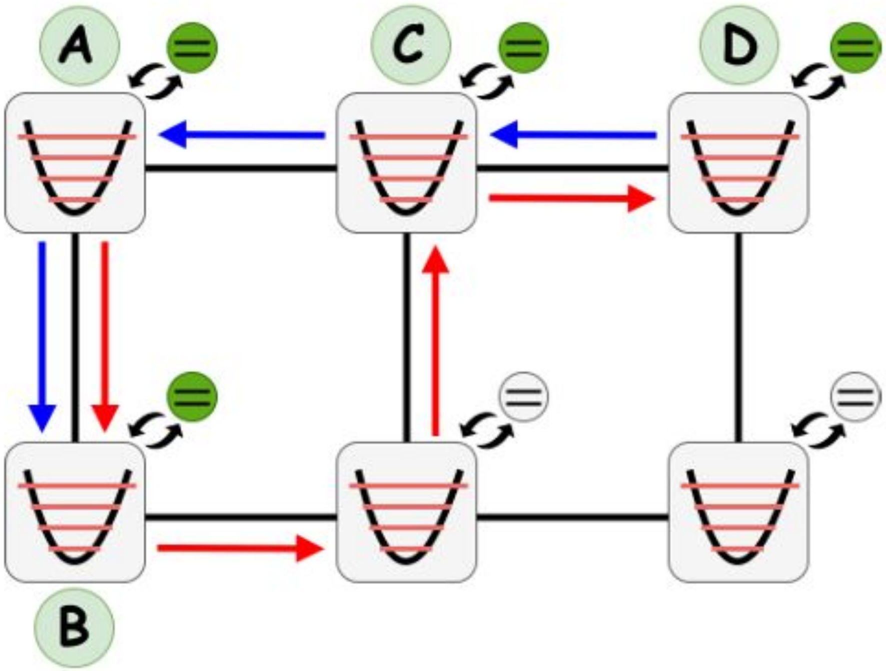
Each qumode interacts only with its associated qubit. For interactions with other qumodes, adjacency is established by moving qumodes, similar to qumode-qumode mapping.

Working Frontier: all unresolved gates whose dependence has been resolved

Using a Qiskit Sabre-like reward function to execute gate from the frontier and update it.

Source: **"Hybrid Oscillator-Qubit Quantum Processors: Instruction Set Architectures, Abstract Machine Models, and Applications."** Liu et al. arXiv 2407.10381v2

4.2 Optimized Ancilla Qumode Routing



A → B → V → D: 4 BS gates

D → C → A → B: 3 BS gates

The Optimized Ancilla Qumode Routing Problem can be reformulated as a relaxed **Hamiltonian Path Problem**, similar to a modified Traveling Salesman Problem (TSP). Unlike the closed-path TSP, this problem allows revisiting vertices and does not require returning to the starting vertex.

4.2 Optimized Ancilla Qumode Routing

Qumode-SWAP

1 Beam-Splitter gate

(20x depth/duration)

Qubit-SWAP
(in CVDV System)

12 control displacement gates

12 Qumode-SWAPs

(480x depth/duration)

- Dynamic Qubit Floating

Relocation strategy, when a qubit-qubit pair distance in a specific multi-qubit exponential is too far, and this qubit-qubit pair appear often in the following multi-qubit exponential, we will try to relocate the qubit using Qubit-SWAP to cluster them.

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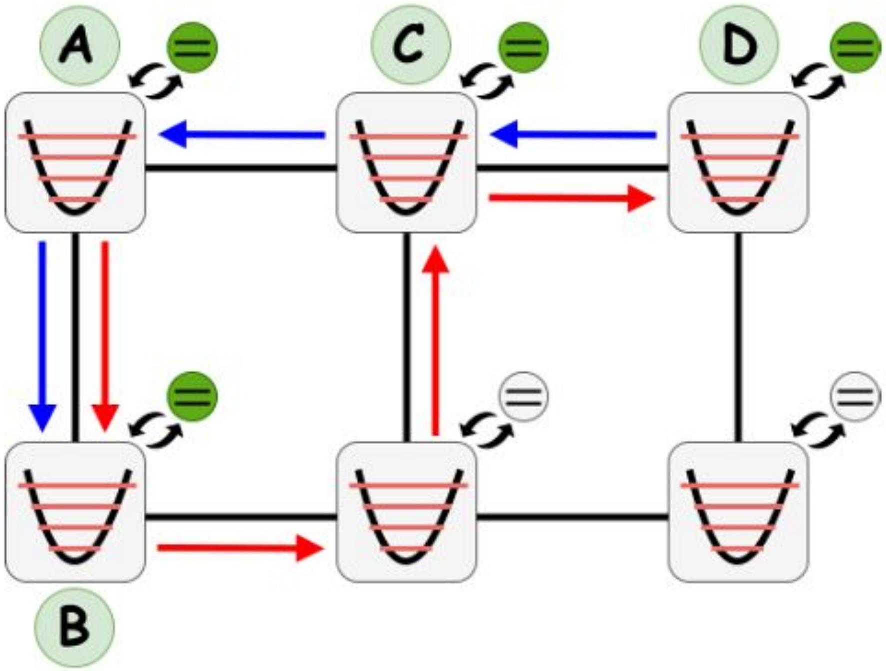
4.2 Optimized Ancilla Qumode Routing



- Christofides Algorithm

  Baseline
- Threshold Accepting Algorithm

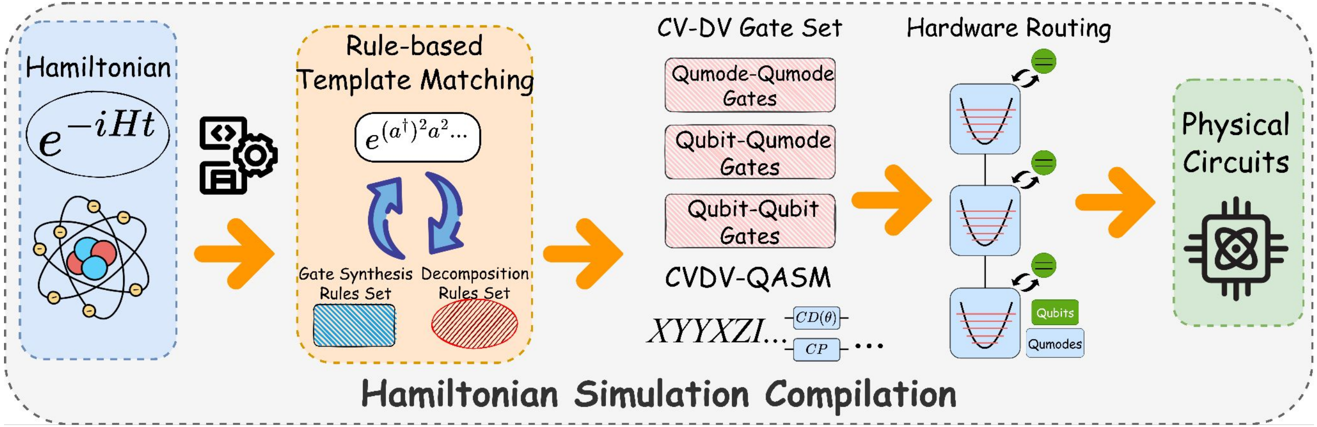
  3-7% better duration time, 4.8% in avg
- Dynamic Qubit Floating

  6% worse duration time in avg

  4/20 better than baseline and 2/20 better than Threshold Accepting

5. End-to-end Implementation

1. **Hamiltonian Parsing**: Translates a Hamiltonian from mathematical form into a DSL-based representation.
2. **Intermediate Representation (IR)**: Converts the DSL into an IR consisting of Pauli strings and operator expressions(bosonic, hybrid).
3. **Pattern Matching and Gate Synthesis**: Matches fermionic and bosonic operator terms and synthesizes them into logical CV-DV circuits in CVDVQASM format.
4. **Physical Mapping**: Maps logical circuits and Pauli terms to hardware-compliant physical circuits, and outputs the final(physical) CVDVQASM program(s).



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5. End-to-end Implementation

- Evaluation 1. Multi Pauli-String Synthesis
  - 20 Qubit Hamiltonian such as LiH(4,12), BeH2(6,14) …
  - # Pauli Strings from 631 to 1884
  - JW and BK encoding
- Evaluation 2. General Hamiltonian Simulation Compilation
  - 6 Hamiltonian Models such as Hubbard-Holstein Model, Bose-Hubbard Model … At most 60 Qubits and 120 Qumodes

5. End-to-end Implementation

- Intermediate Tools 1. CVDV Mapping and Routing
  - Support more architecture(neutral atom)
  - Better relocate strategy when compile multi pauli-strings
- Intermediate Tools 2. Operator Pattern Matching
  - Flexible customize rules and multiple decomposition perspectives
  - Better compilation efficiency and robustness
  - Error analysis and unitary verification

Thank You!