

Creating
World Changing
Technologies

Intel Quantum Computing:

Developing quantum workloads for workload-driven
co-design

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intel®

Potential future applications

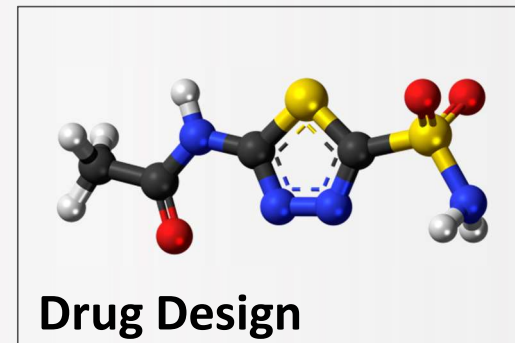
TIME

**“Quantum Will
Change
Everything”**

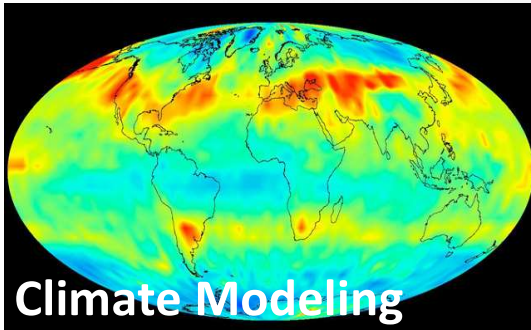
(Time, Feb 16, 2014)



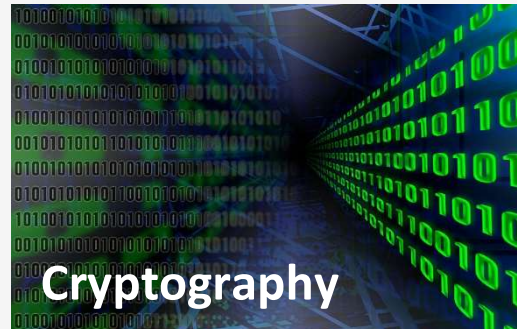
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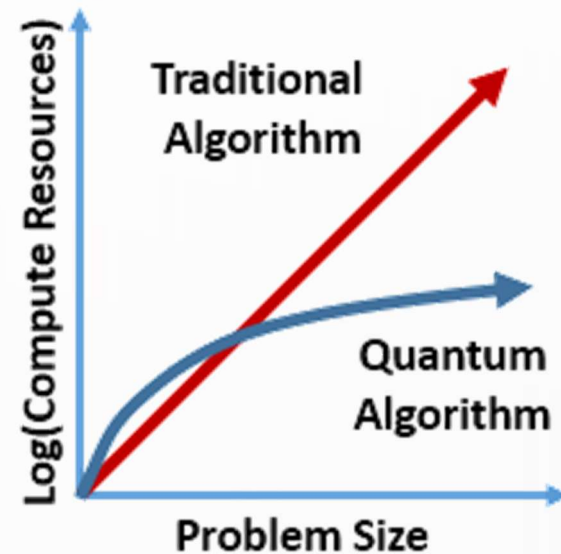
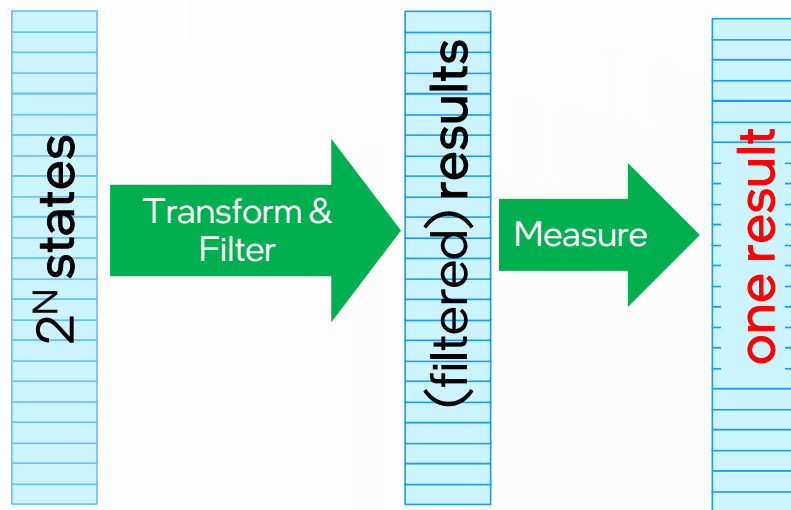


US Department of Defense



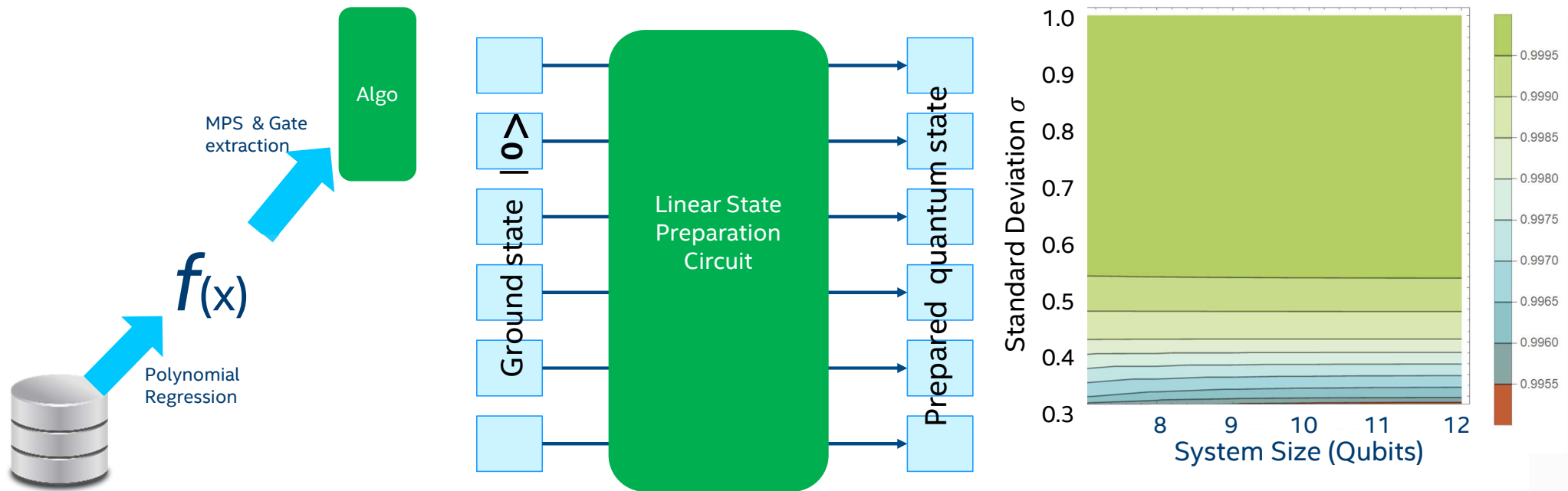
Pixabay

The Promise of Quantum Computing



Exponential Speedup $\leftrightarrow$ Surpassing The Limits Of Traditional Scaling

Efficient state preparation: loading classical data in quantum registers

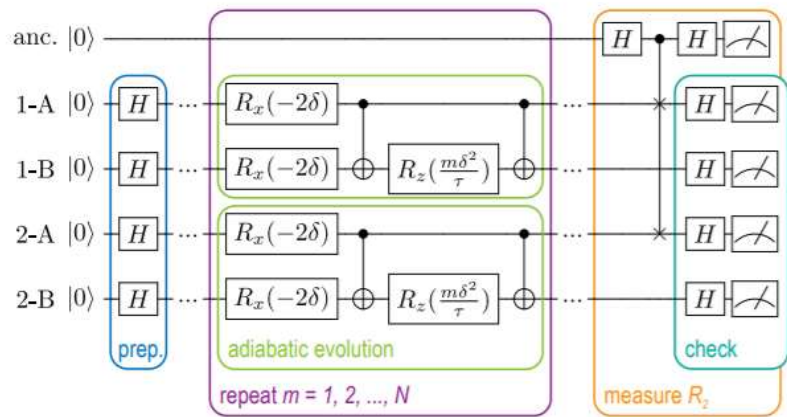


State preparation -generally exponentially hard
Designed algorithm to create states in linear time

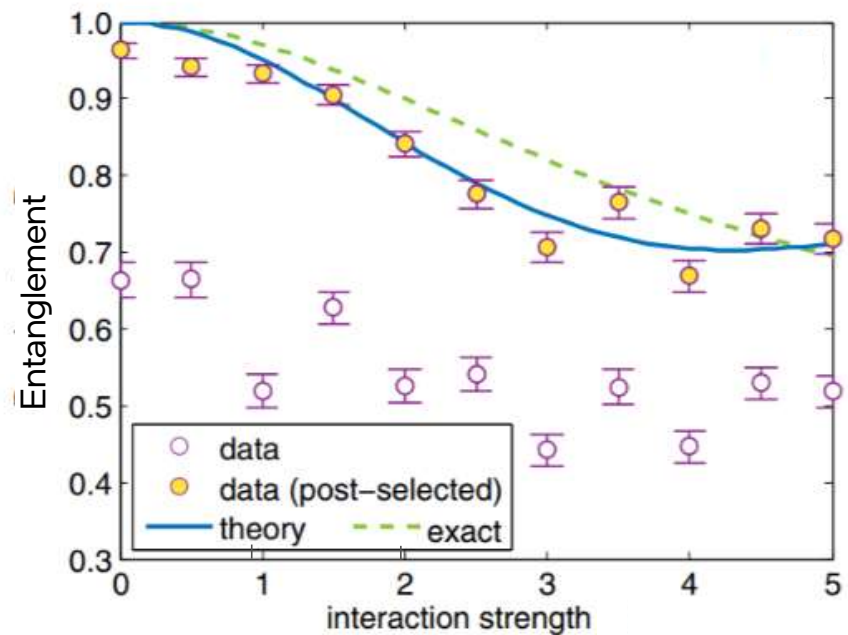
A. Holmes et al, Proceedings of the IEEE International Conference on Quantum Computing & Engineering, p.169 (2020)

Materials Design: Quantifying entanglement

Key to understanding electronic properties of material like high Tc superconductors



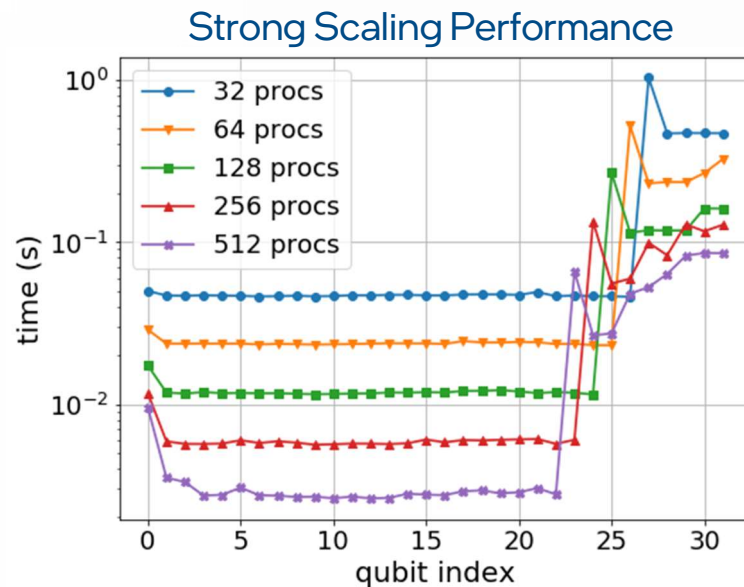
Linke et al, PRA 98 (2018), 052334.



Intel Quantum Simulator- open source qubit simulator

Universal: single and two-qubit controlled operations

Open Source Release



Guerreschi et al, Quantum Sci. Tech 5, 034007 (2020).

<https://github.com/iqusoft/intel-qsim>



iqusoft / intel-qsim

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master 12 branches 1 tag Go to file Add file Code

About

High-performance simulator of quantum circuits

github.com/iqusoft/intel-qsim

quantum-computing

README.md

C++ build with CMake passing Python build (no MPI) passing arXiv 2001.10554 arXiv 1601.07195

Intel Quantum Simulator

Intel Quantum Simulator (Intel-QS), also known as qHIPSTER (The Quantum High Performance Software Testing Environment), is a simulator of quantum circuits optimized to take maximum advantage of multi-core and multi-nodes architectures. It is based on a complete representation of the qubit state, but avoids the explicit representation of gates and other quantum operations in terms of matrices. Intel-QS uses MPI (message-passing-interface) protocols to handle the communication between distributed resources that are used to store and manipulate the quantum state.

Intel® Quantum Software Dev Kit

2022

- In Beta Version SDK Beta

Applications/
Algorithms

C++ Quantum Compiler

Quantum Runtime

⋮

Intel Quantum Simulator

Today

Intel Quantum SDK 1.0

Applications/
Algorithms

C++ Quantum Compiler

Quantum Runtime

Qubit Control Simulator

Quantum Dot Simulator

Future

Full System (HW+SW)

Applications/
Algorithms

C++ Quantum Compiler

Quantum Runtime

Qubit Control Processor

Control Electronics

Spin Qubit Processor

Software

Hardware

Materials Design: Metal-insulator transition

```

for  $k = 0$  to  $\text{int}(T/\tau)$  do
  reset  $q0$ 
  reset  $q1$ 
   $R_x(\pi)$   $q0$ 
  for  $m = 0$  to  $k$  do
    cNOT  $q1, q0$ 
    in parallel do
       $R_z(2wh_0^z\tau)$   $q0$ 
       $R_z(2\tau)$   $q1$ 
    end do
    cR $_x(4\tau)$   $q0, q1$ 
    cNOT  $q1, q0$ 
     $R_z(2wh_1^z\tau)$   $q1$ 
    in parallel do
       $R_x(2wh_0^x\tau)$   $q0$ 
       $R_x(2wh_1^x\tau)$   $q1$ 
    end do
  end for
   $q0mZ[k] \leftarrow \text{measure } q0$ 
   $q1mZ[k] \leftarrow \text{measure } q1$ 
end for
  
```

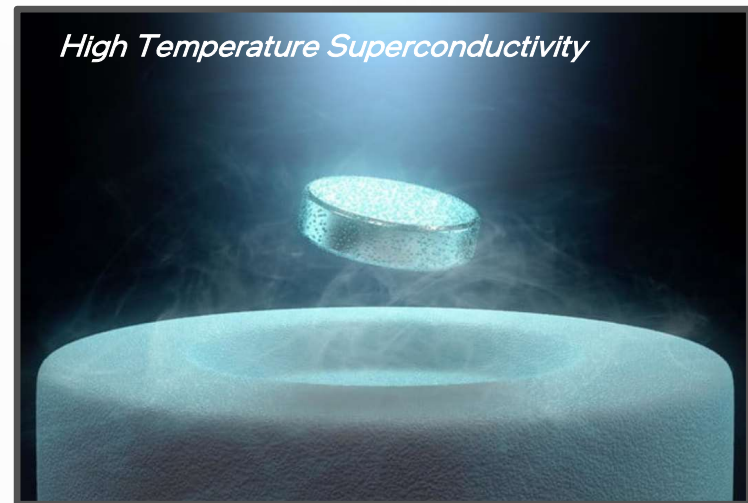
Total number of time steps

k - index of time steps

τ : time step size

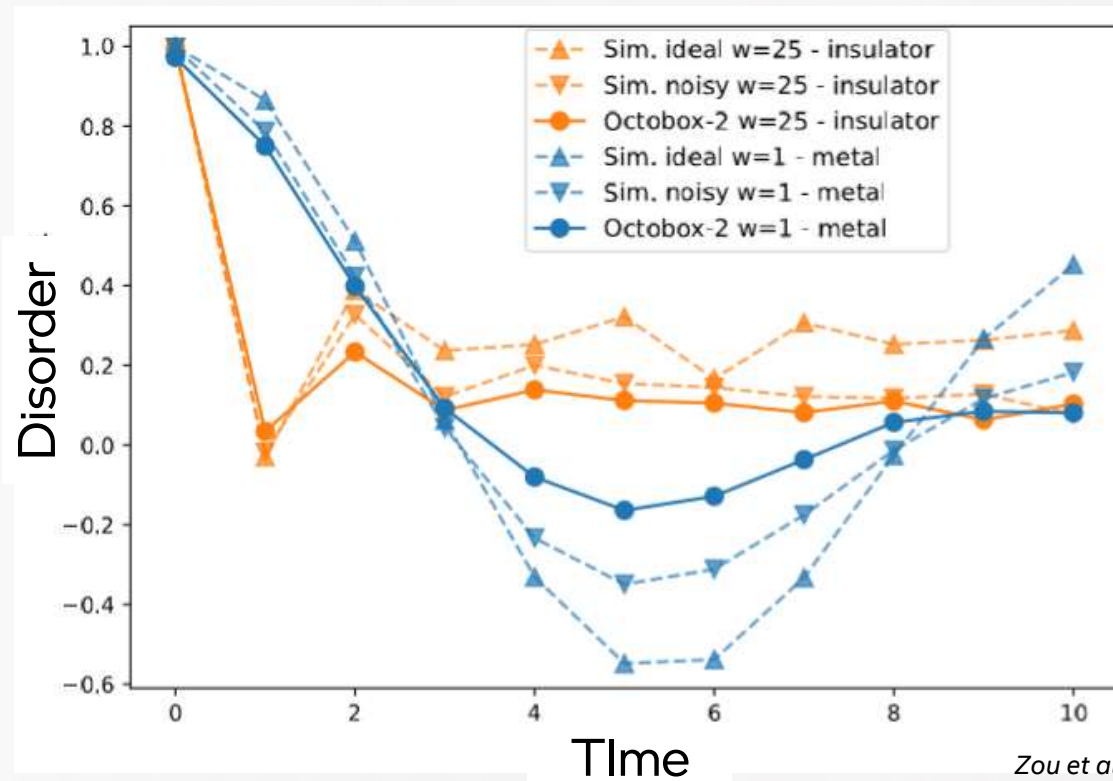
$h_i^{x/z}$: random numbers

w : disorder strength



US Department of Energy

Metal-Insulator Transition Workload Results



Zou et al, IEEE Trans. In Quantum Eng. 1 (2020), 1.

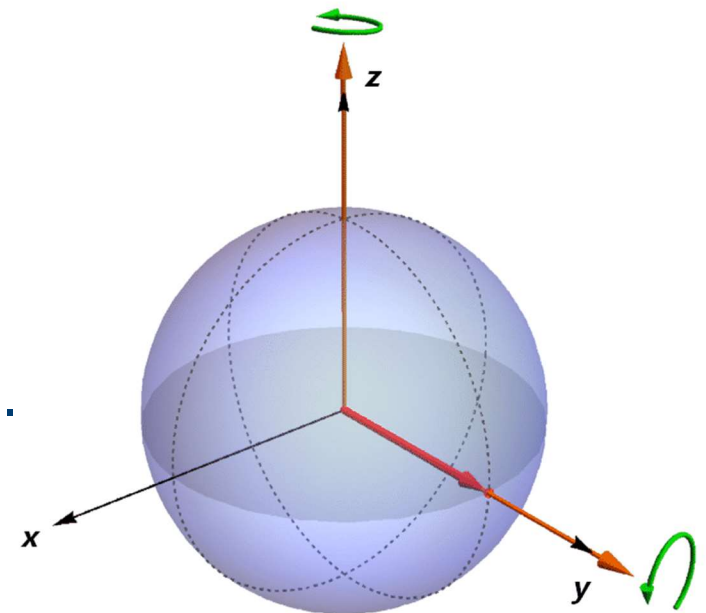
Intel Materials Design Algorithm with ~140 Qubit Operations

Resulted in New Instruction

Single qubit operations described by vector rotations.

For Materials Design:

- Necessary to have arbitrary angle rotation operation.
- Intel implemented 1 step arb rotation instruction.
- Done by competitors in 2 instructions/steps.



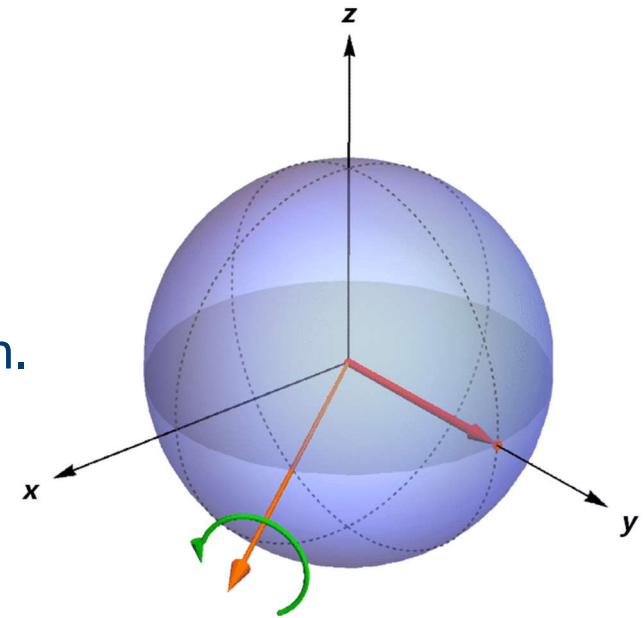
Zou et al, IEEE Trans. In Quantum Eng. 1 (2020), 1.

Resulted in New Instruction

Single qubit operations described by vector rotations.

For Materials Design:

- Necessary to have arbitrary angle rotation operation.
- Intel implemented 1 step arb rotation instruction.
- Done by others in 2 instructions/steps.



New Instruction Results in 2x Faster Single Qubit Operations

Zou et al, IEEE Trans. In Quantum Eng. 1 (2020), 1.

```

2: for  $i$  in  $\{1, 3, 5, \dots, n-3, n, n-2, n-4, \dots, 2\}$  do
3:    $l \leftarrow (i+1) \bmod(2)$ 
4:    $j \leftarrow i$ 
5: Start Parallel
6:   while  $j \geq 1$  do
7:      $CP_{j+l-1}(q_j, q_{j+(-1)^l})$ 
8:      $j \leftarrow j-2$ 
9:   end while
10: End Parallel
11:  $j \leftarrow i$ 
12: Start Parallel
13:   while  $j \geq 1$  and  $j+2(-1)^l \geq 1$ 
14:      $k \leftarrow (j+1) \bmod(2)$ 
15:      $CP_{j+2-2l-k}(q_j, q_{j+2(-1)^l})$ 
16:      $j \leftarrow j-1-2k$ 
17:   end while
18:    $H((j+1) \bmod(2) + 1)$ 
19: End Parallel
20:  $j \leftarrow i$ 
21: Start Parallel
22:   while  $j \geq 1$  and  $j+2(-1)^l \geq 1$  do
23:      $k \leftarrow (j+1) \bmod(2)$ 
24:      $SWAP(j, j+2(-1)^l)$ 
25:      $j \leftarrow j-1-2k$ 
26:   end while
27: End Parallel
28: end for

```

Set of horizontal controlled phase gates

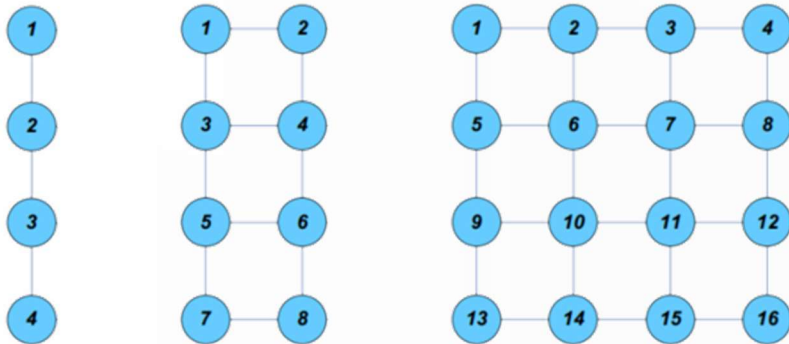
Set of vertical controlled phase gates

Set of SWAP operations to get qubits in right position

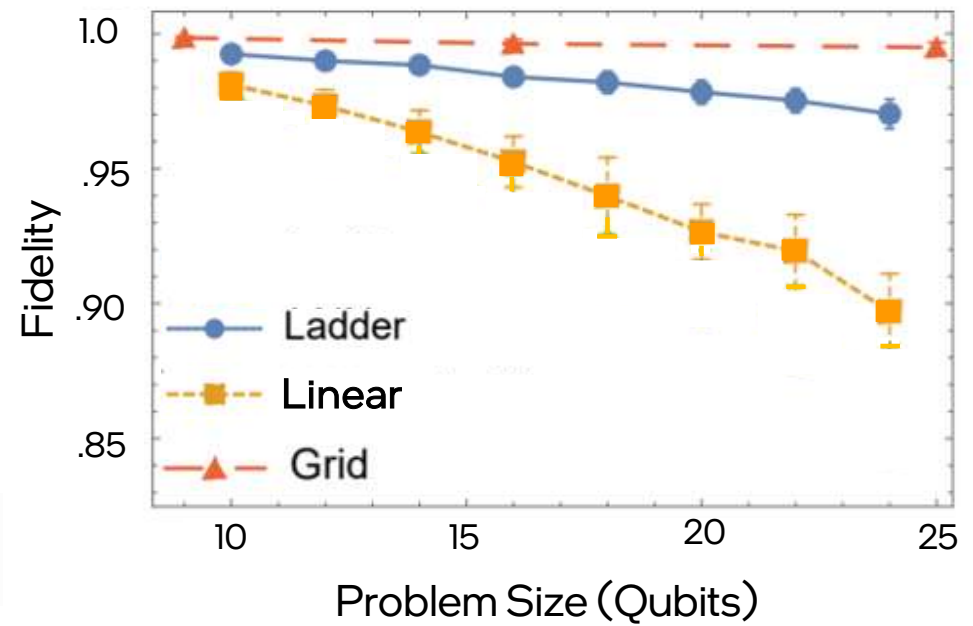
Quantum Fourier Transform

Co-Design can also Impact Choices on Qubit Connectivity Design

linear, ladder, grid layout devices



Quantum Fourier Transform

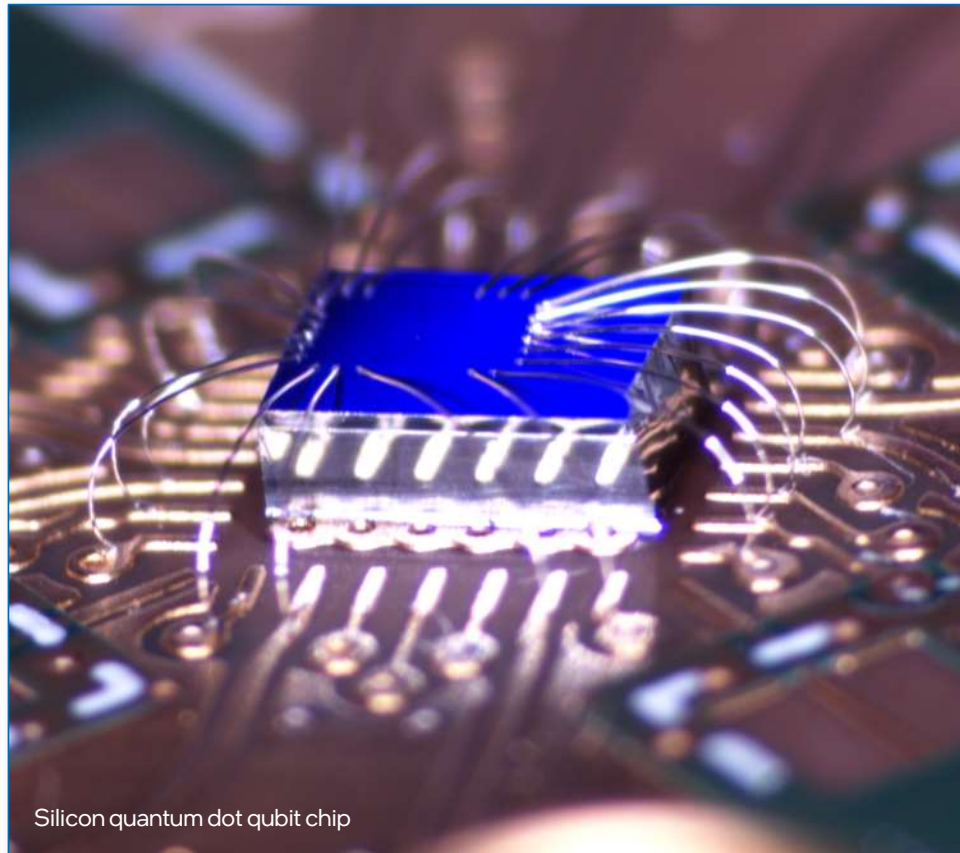


Holmes et al, Quantum Sci Tech 5 (2020), 025009

Conclusion

- We're at the beginnings of this new kind of compute
- Even with small qubit systems – workload-driven co-design is useful
- Use results of executing workloads on small systems as seeds for architectural research
- Important to co-design full system stack, rather than each component designed in isolation
- Area where physics meets computer engineering- we need more researchers who can do both!

Thank you!



Silicon quantum dot qubit chip

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