Creating
World Changing
Technologies

Intel Quantum Computing:
Developing quantum workloads for workload-driven co-design

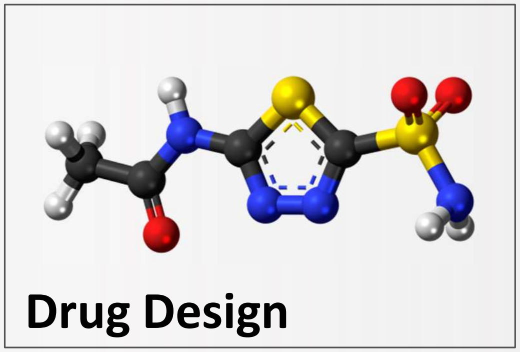
Anne Matsuura, Ph.D.
Director, Quantum Applications & Architecture
Intel Labs

intel.

Potential future applications

TIME
"Quantum Will Change Everything"
(Time, Feb 16,2014)

Pixabay



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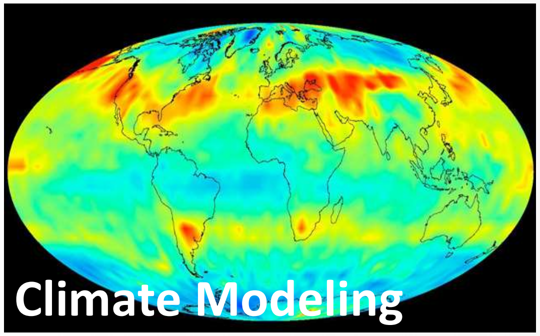
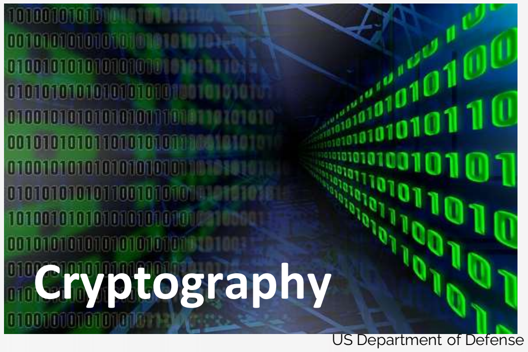


NASA/JPL



US Department of Defense

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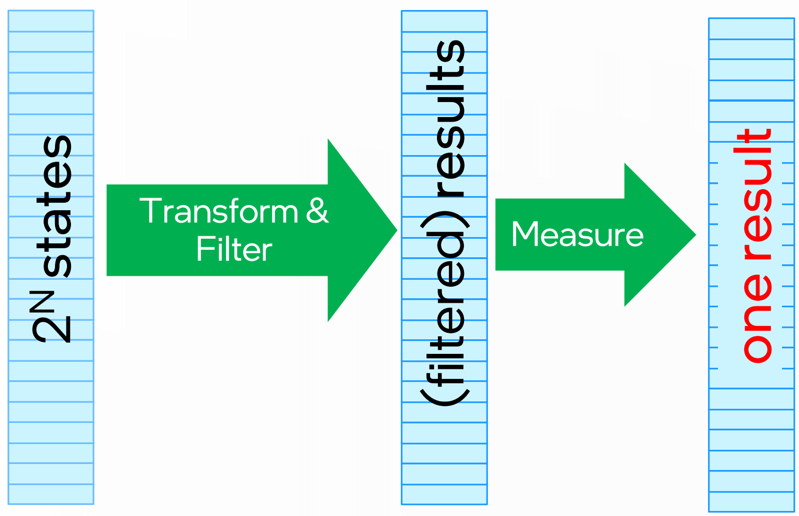
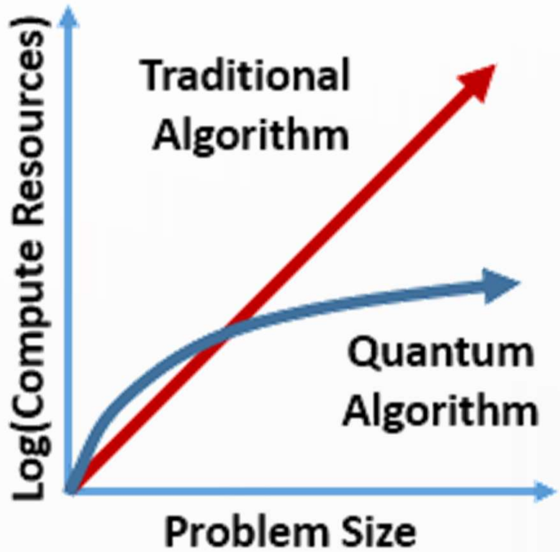
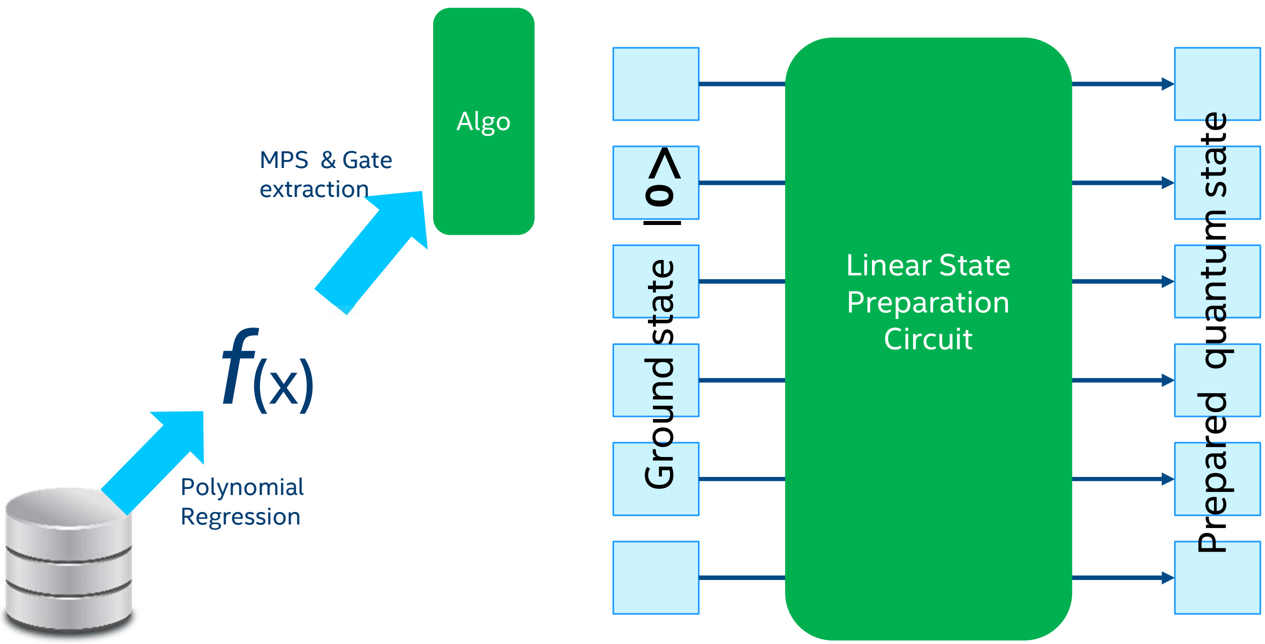
The Promise of Quantum Computing

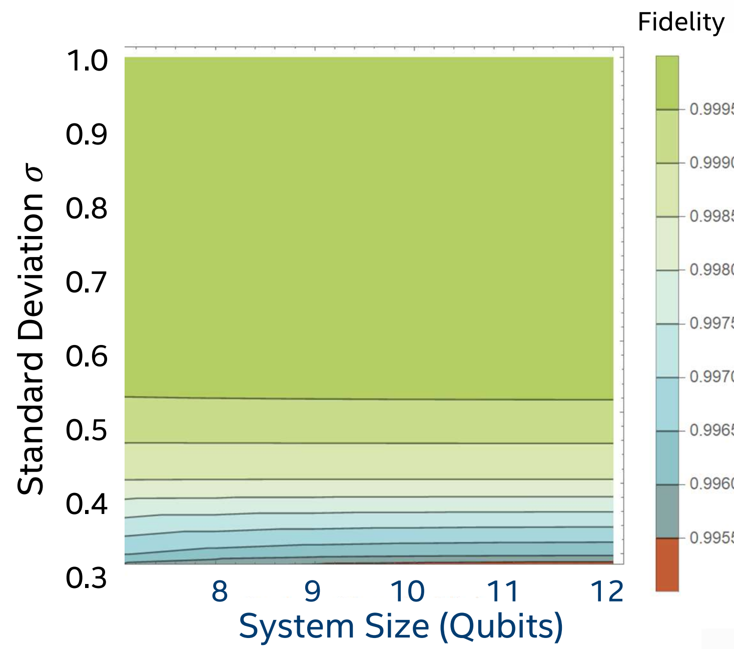




Exponential Speedup ←→ Surpassing The Limits Of Traditional Scaling

Efficient state preparation:
loading classical data in quantum registers



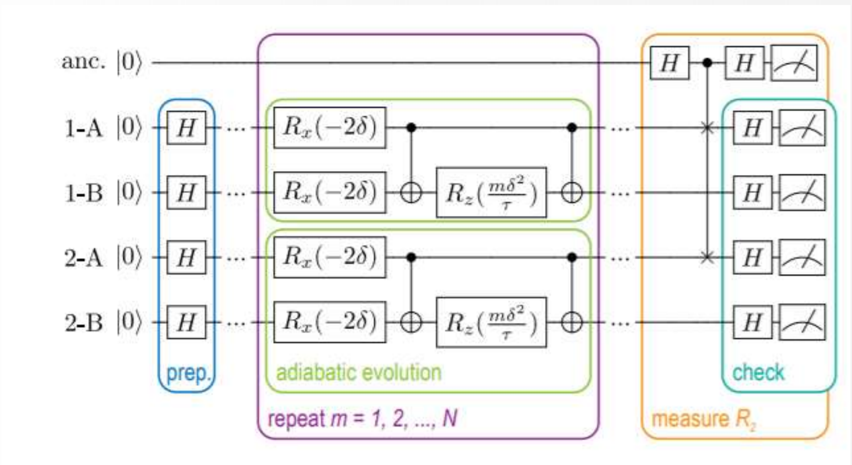


State preparation -generally exponentially hard
Designed algorithm to create states in linear time

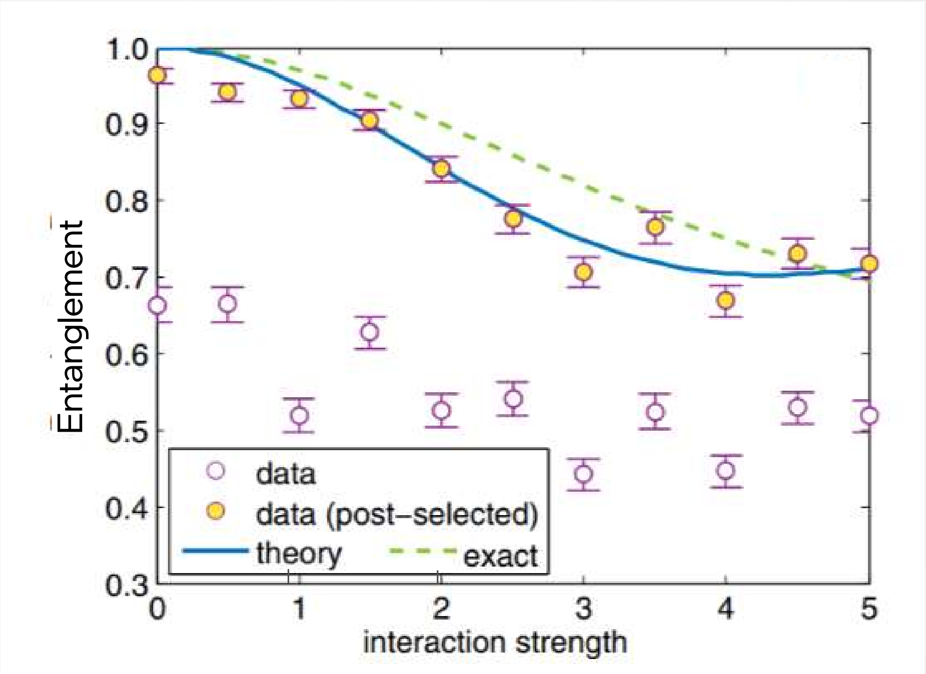
A. Holmes et al, Proceedings of the IEEE International Conference on Quantum Computing & Engineering, p.169 (2020)

Materials Design: Quantifying entanglement

Key to understanding electronic properties of material like high Tc superconductors



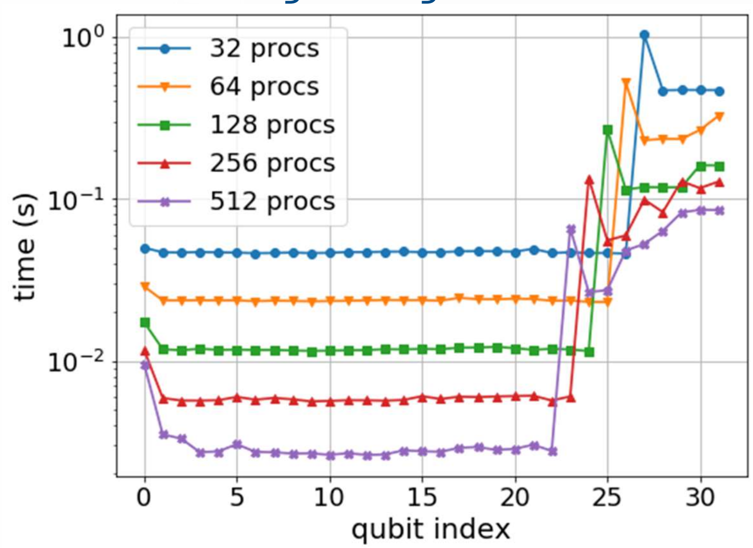
Linke et al, PRA 98 (2018), 052334.



Intel Quantum Simulator- open source qubit simulator

Universal: single and two-qubit controlled operations

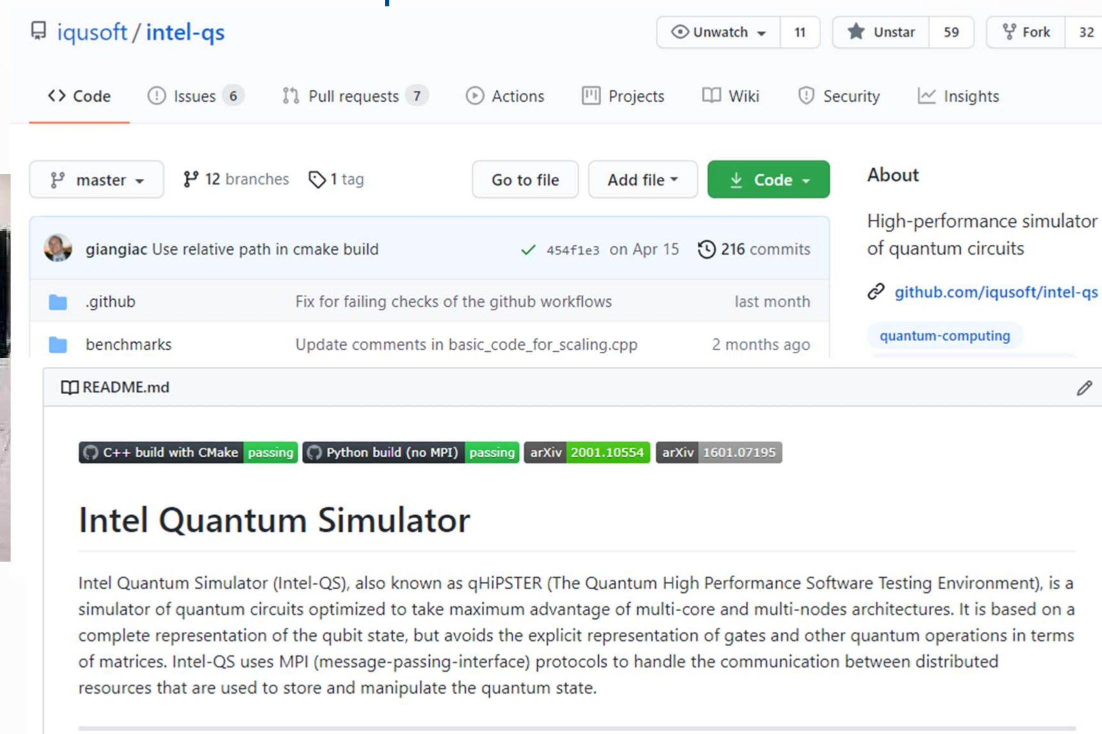
Strong Scaling Performance



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

https://github.com/iqusoft/intel-qs

Open Source Release



Intel® Quantum Software Dev Kit

2022

Beta Version

- 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)

Software

- Applications / Algorithms
- C++ Quantum Compiler
- Quantum Runtime

Hardware

- Qubit Control Processor
- Control Electronics
- Spin Qubit Processor

Materials Design: Metal-insulator transition

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

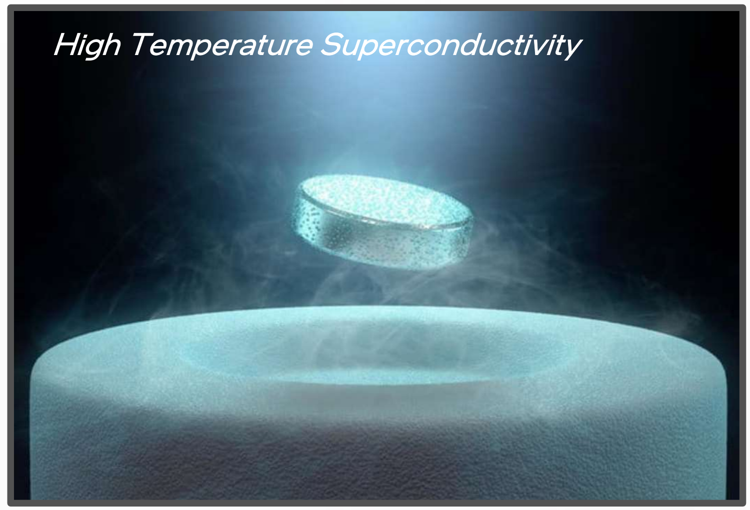
Total number of time steps

k - index of time steps

τ: time step size

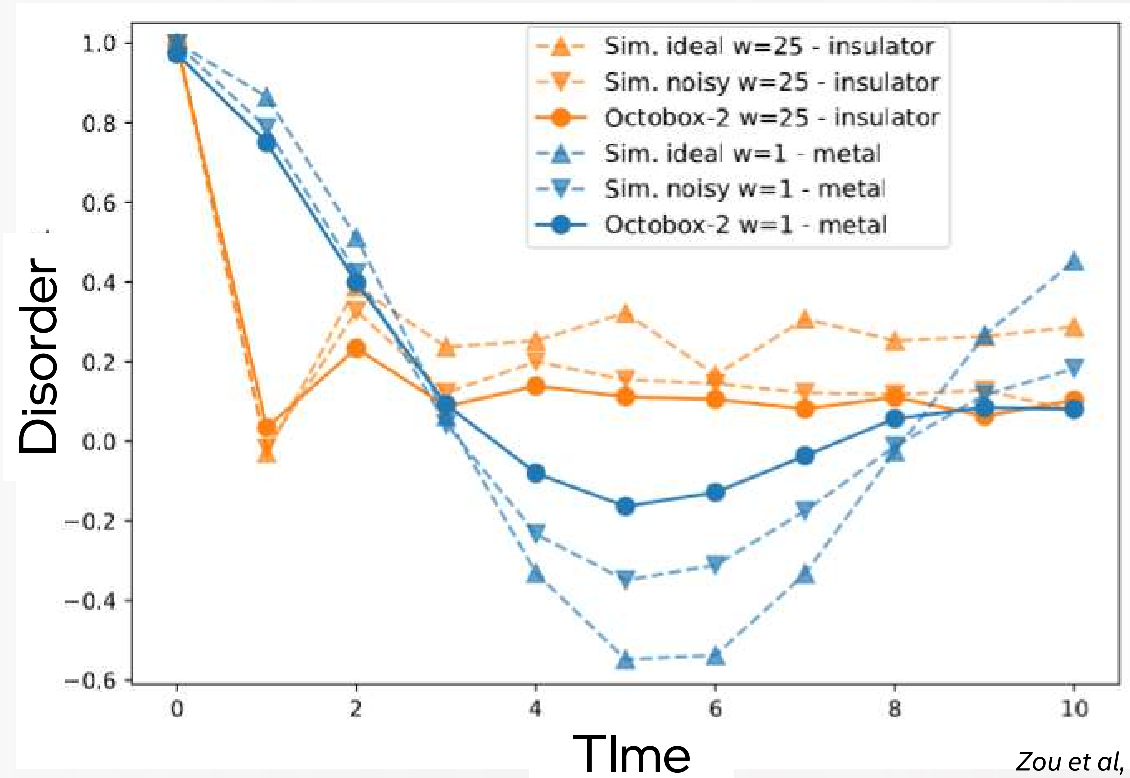
$h_i^{x/z}$: random numbers

w: disorder strength



US Department of Energy

Metal-Insulator Transition Workload Results



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

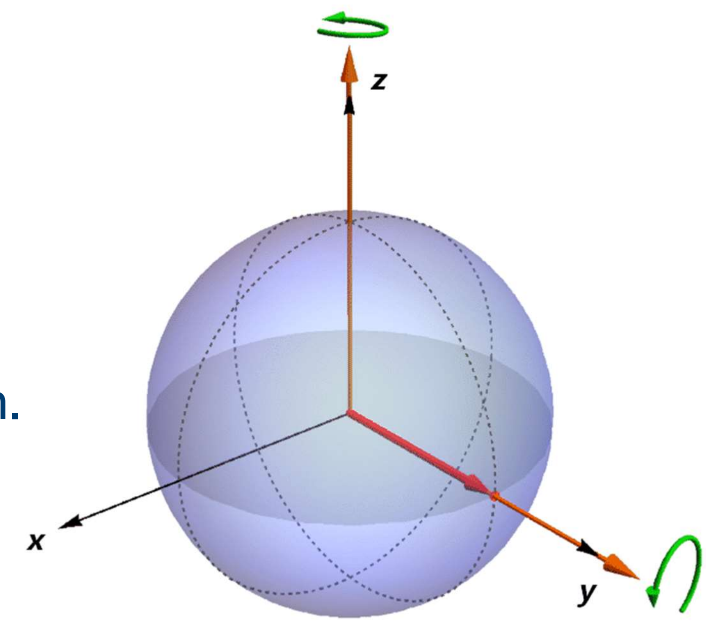
Intel Materials Design Algorithm with ~140 Qubit Operations

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.

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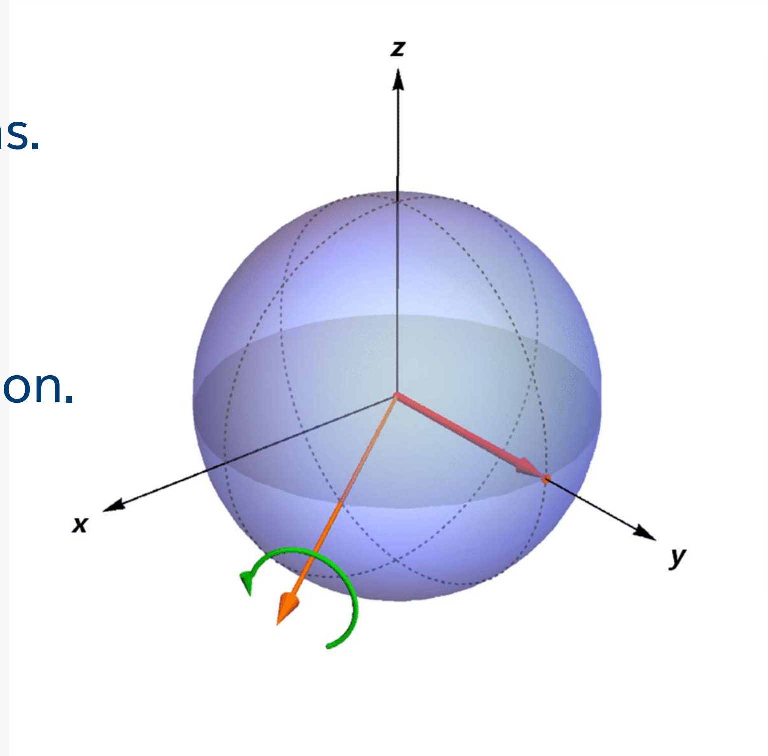


New Instruction Results in 2x Faster Single Qubit Operations

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

Quantum Fourier Transform

for i in $\{1, 3, 5, \dots n-3, n, n-2, n-4, \dots 2\}$ **do**
    $l \leftarrow (i+1)\mathrm{mod}(2)$
    $j \leftarrow i$
Start Parallel
    while $j \geqslant 1$ **do**
        $\mathrm{CP}_{j+l-1}(q_j, q_{j+(-1)^l})$
        $j \leftarrow j-2$
    end while
End Parallel
    $j \leftarrow i$
Start Parallel
    while $j \geqslant 1$ and $j + 2(-1)^l \geqslant 1$
        $k \leftarrow (j+1)\mathrm{mod}(2)$
        $\mathrm{CP}_{j+2-2l-k}(q_j, q_{j+2(-1)^l})$
        $j \leftarrow j - 1 - 2k$
    end while
    $\mathrm{H}((j+1)\mathrm{mod}(2)+1)$
End Parallel
    $j \leftarrow i$
Start Parallel
    while $j \geqslant 1$ and $j + 2(-1)^l \geqslant 1$ **do**
        $k \leftarrow (j+1)\mathrm{mod}(2)$
        $\mathrm{SWAP}(j, j+2(-1)^l)$
        $j \leftarrow j - 1 - 2k$
    end while
End Parallel
end for

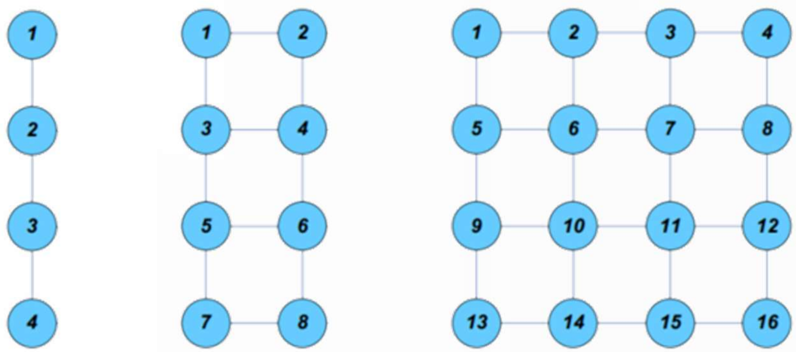
Set of horizonal controlled phase gates

Set of vertical controlled phase gates

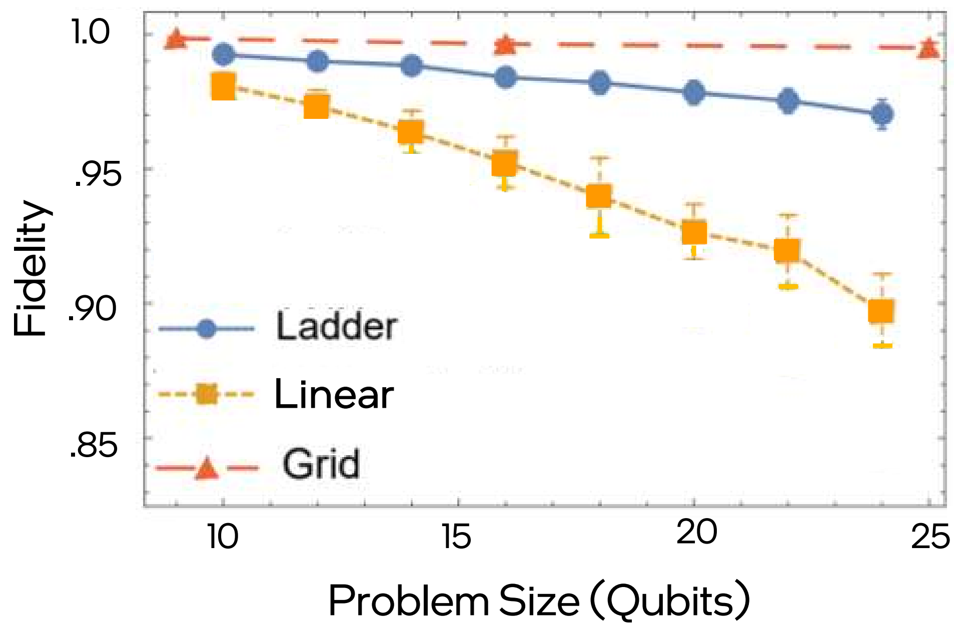
Set of SWAP operations to get qubits in right position

Co-Design can also Impact Choices on Qubit Connectivity Design

linear, ladder, grid layout devices



Quantum Fourier Transform

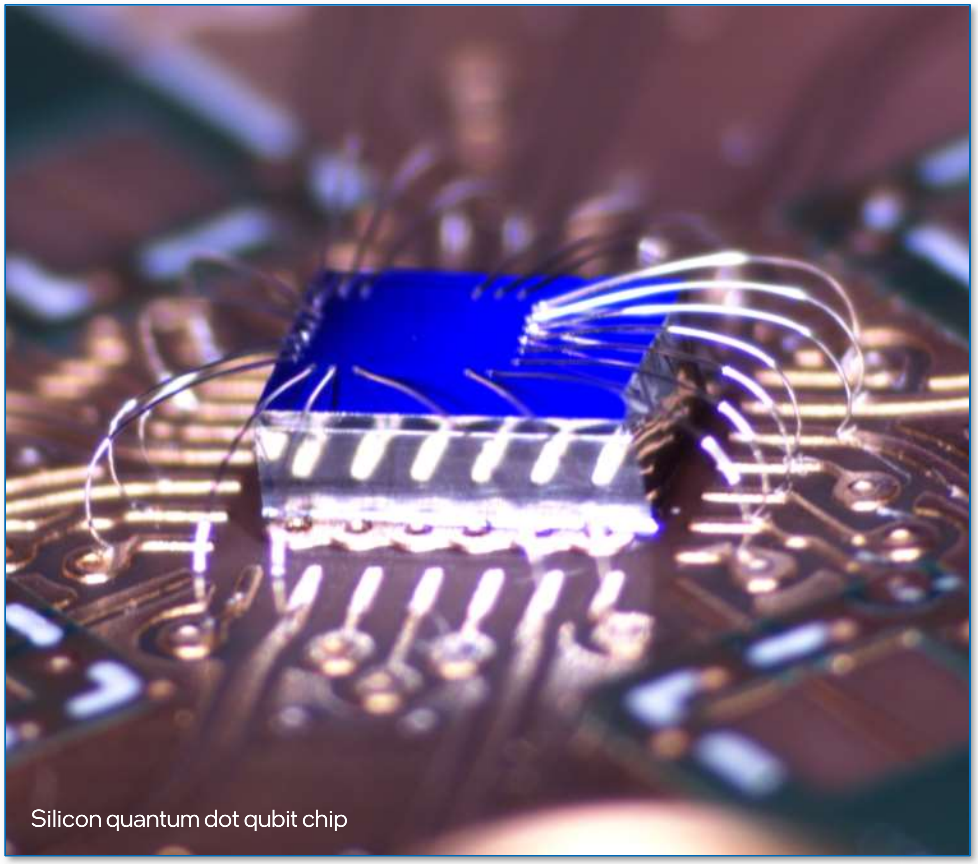


Holmes et al, Quantum Sci Tech 5 (2020), 025009

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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