Quantum Algorithms for Patent Portfolio Analysis Using OpenModelica and IBM Qiskit

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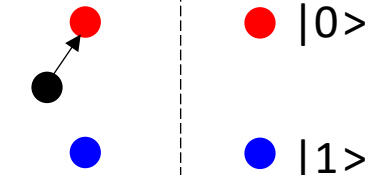
McCormick, Paulding & Huber PLLC
Intellectual Property Law

Quantum Computing

What is a “quantum computer”?

A *quantum computer* is a high-performance advanced computing device that uses the *principles of quantum physics* to process data.

- Superposition



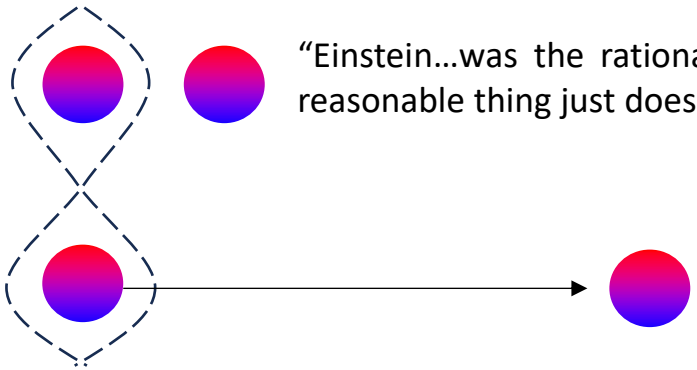
Classical “bit”

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

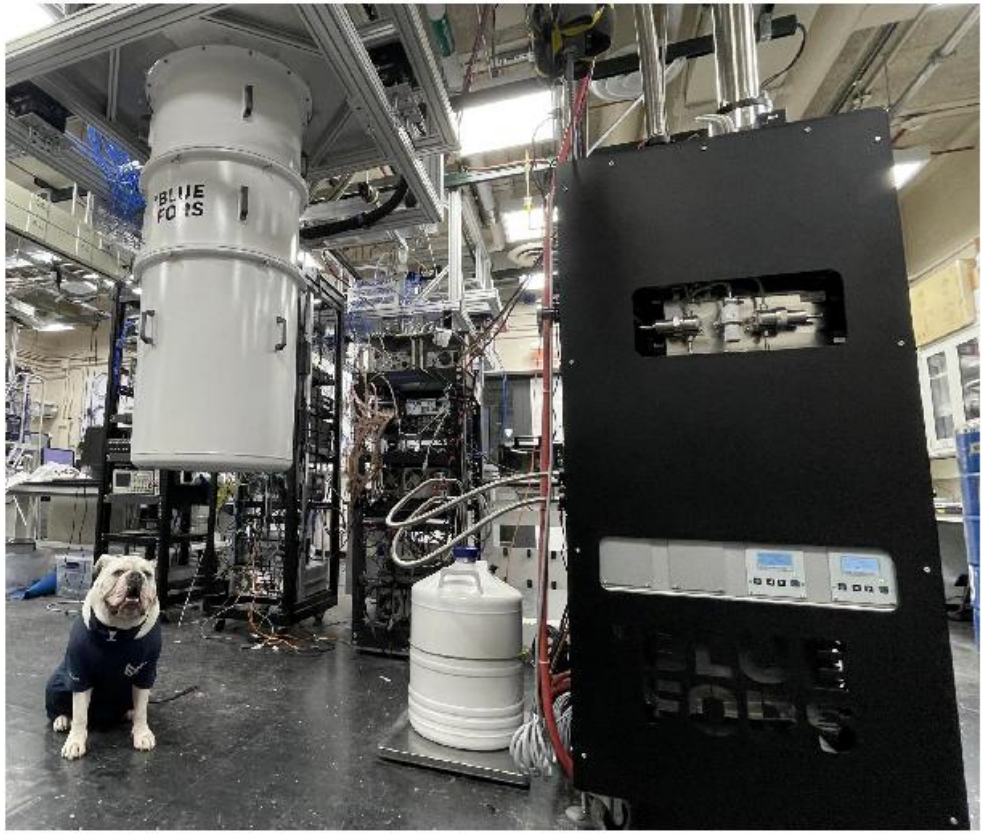
$$|\alpha|^2 + |\beta|^2 = 1$$

Quantum Bit “qubit”

- Entanglement



“Einstein…was the rational man…the reasonable thing just doesn’t work”
John Bell

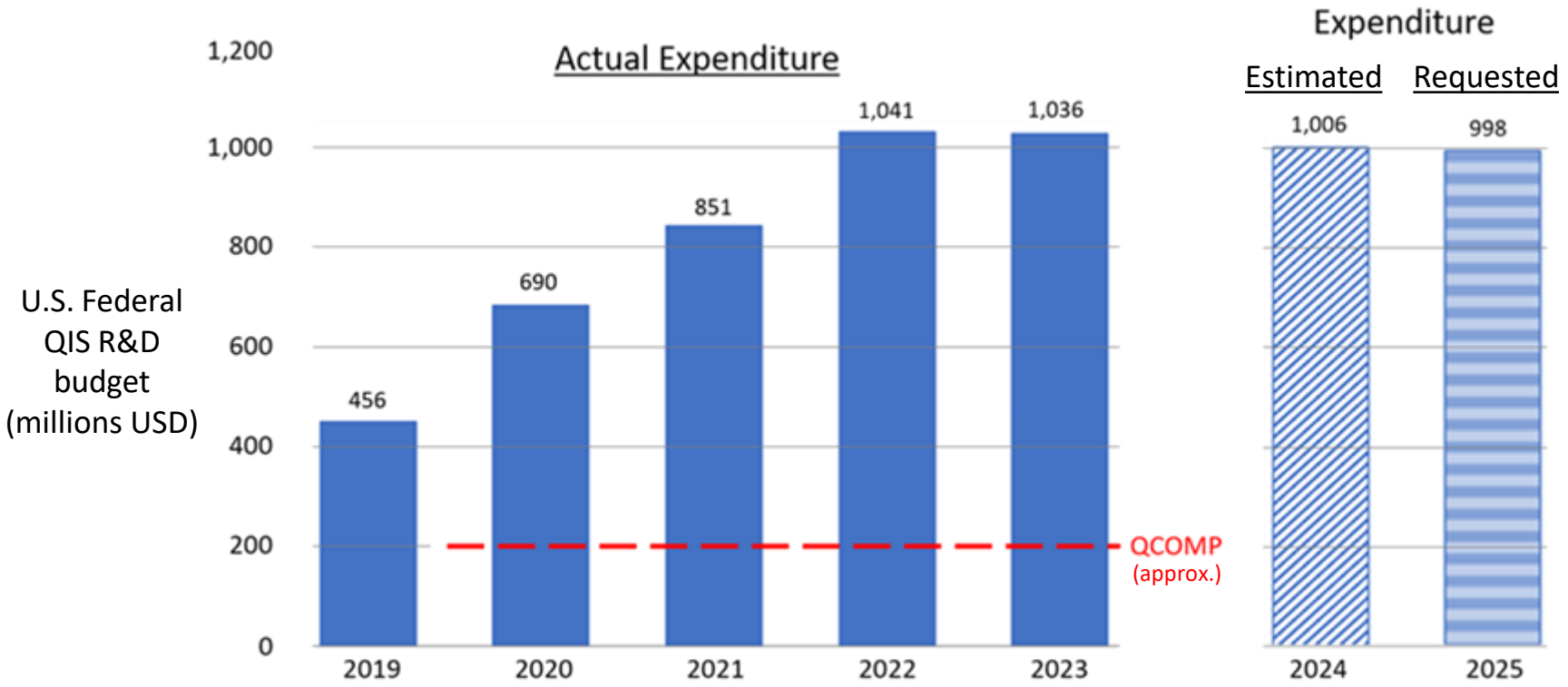


Note: Photo of an experimental quantum computer. Used by permission from Yale University and the Yale Quantum Institute.

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Government Investment

Federal QIS R&D Budget (FY2019 – FY2025) Across Federal Agencies*



Sources:

- National Science & Technology Council, National Quantum Initiative Supplement to the President's FY2025 Budget (Dec. 2024) — FY2019–23 actual expenditures, FY2024 estimated, FY2025 requested. *Federal agencies included are NIST, NSF, DOE, DOD, DHS and NASA.
- U.S. GAO, Quantum Computing, GAO-26-107759 (Mar. 2026): Quantum-computing reference band, "about $200 million per year" since FY2020, roughly one-fifth of total QIS R&D.
- Federal *only*. Excludes state, endowment, private and corporate internal R&D.

What does "QIS" mean on this chart?

Statutory definition: 15 U.S.C. § 8801(6)

"the use of the laws of quantum physics for the storage, transmission, manipulation, computing, or measurement of information."

Budget definition. OMB collects government investments across five Program Component Areas. Every bar contains all five:

QCOMP: Quantum computing — qubits, gates, algorithms, simulators, machines. Only QCOMP is quantum computing.
QSENS: Sensing & metrology — atomic clocks, precision measurement
QNET: Networking — distributed entangled states
QADV: Other science done with quantum tools — biology, chemistry, cosmology, materials, nuclear
QT: Enabling tech — cryogenics, photonics, manufacturing, and post-quantum cryptography

QADV uses quantum tools; QT includes PQC — classical cryptography built to resist quantum attack. No quantum hardware.

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Quantum Computing

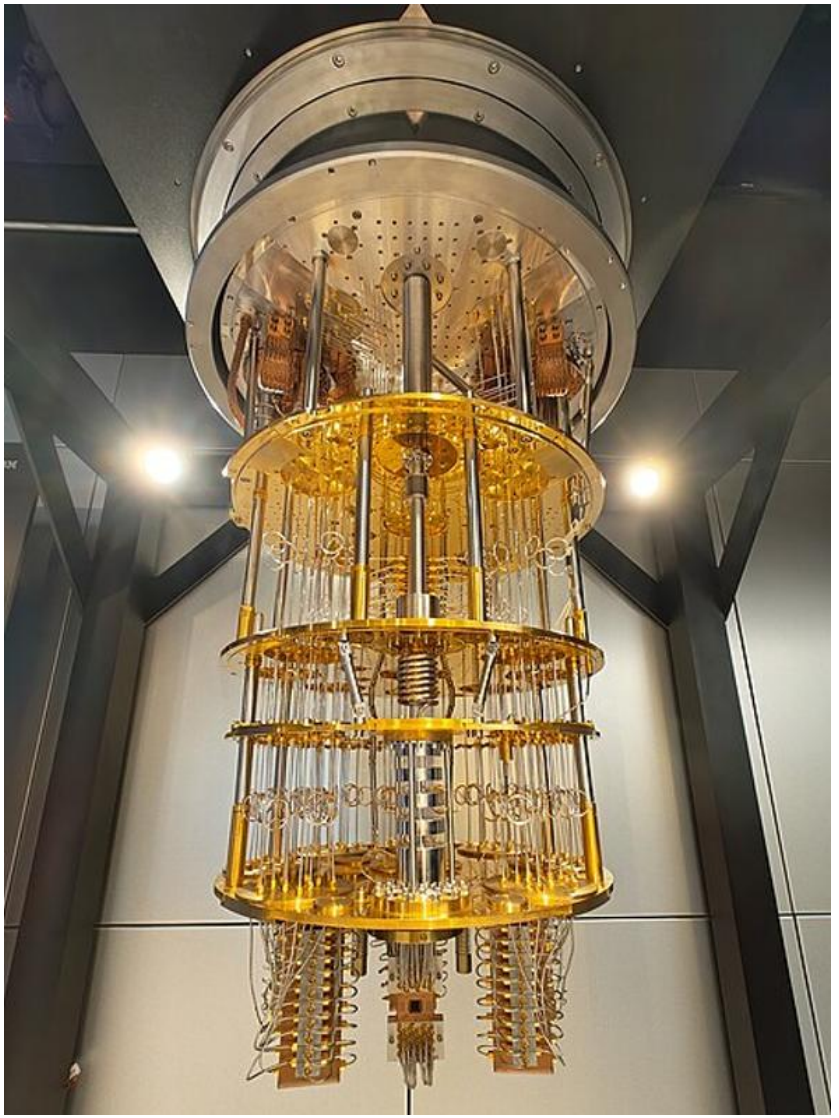
OpenModelica-Qiskit Interface Project Goals

Objectives:

- Integrate the Qiskit-C API as a callable computation engine within OpenModelica
- Demonstrate that an NP-hard problem can be posed and solved within OpenModelica using a quantum solver

Why:

- *HIL answer*: Integrating components of a quantum computer and implementing controls is often accomplished in Python
- *Funding answer*: Applications to hard problems, like patent portfolio analysis, may soon be enabled by commercial quantum computers
- *The **real** answer*: Calling an IBM quantum solver from OpenModelica would be ***SO*** cool

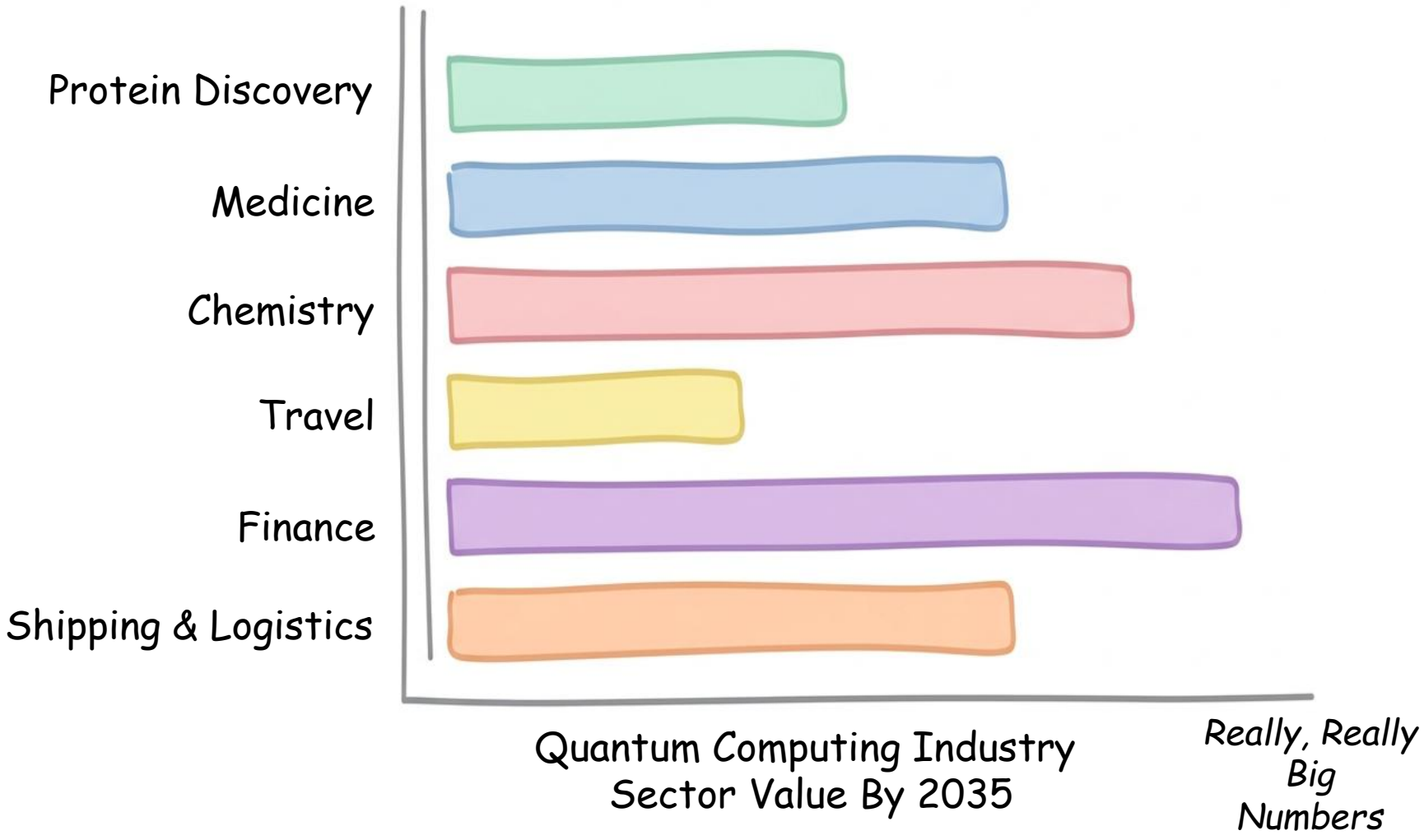


Note: Photo of an IBM Quantum System One, taken at the ThinkLab of IBM's TJ Watson Research Center in Yorktown Heights, New York. Licensed under the Creative Commons Attribution 4.0 International license.

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Quantum Computing

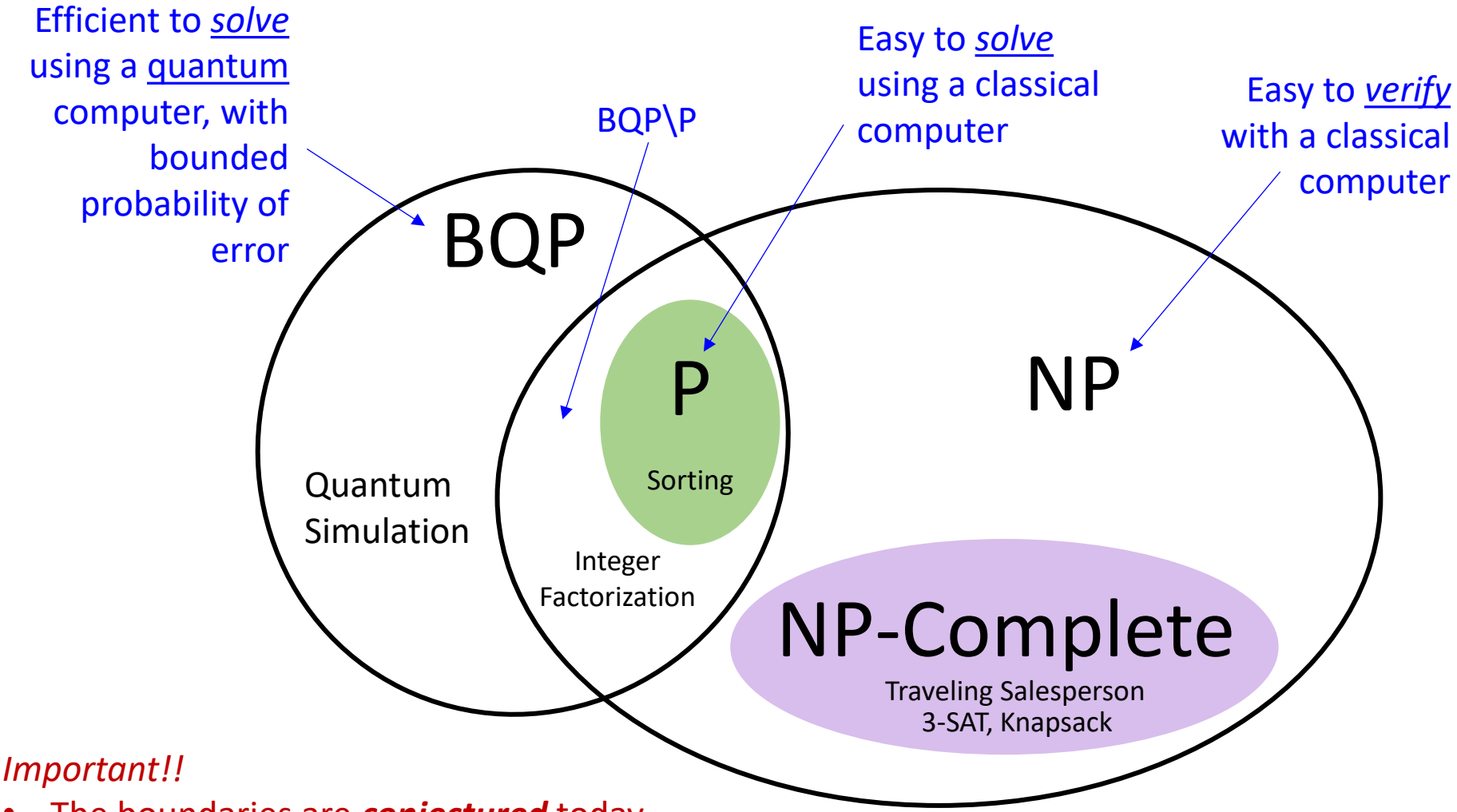
"Predictions" of Impact



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Quantum Computing

Computational Complexity Framework



Important!!

- The boundaries are ***conjectured*** today
- If P = NP, then (BQP $\cap$ NP) $\subseteq$ P and the distinction collapses (i.e., integer factorization becomes classically "easy"!)
- P = NP does not imply BQP\NP is empty

Note: Based on relationships depicted in Nielsen & Chuang, *Quantum Computation and Quantum Information*, 10th Anniversary Edition, Cambridge University Press (2010).

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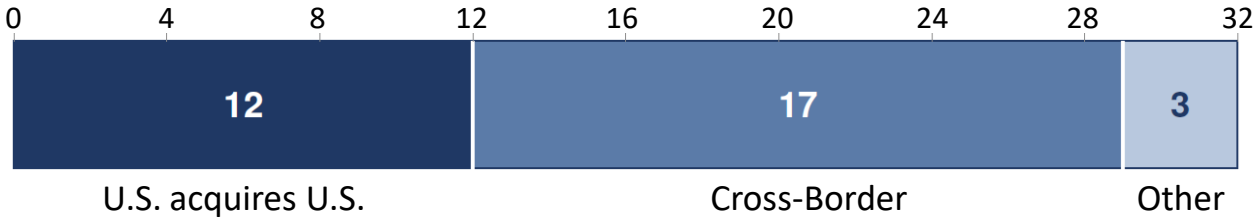
Commercialization

Investment Measures – Selected Quantum Ecosystem Transactions

Acquirer	*Target*	*Year*	*Consideration*	*Notes*
IonQ	SkyWater	2026	~$1.8B cash & stock	Definitive agreement 25 Jan. 2026. Completed on 31 July 2026.
D-Wave	Quantum Circuits	2026	$550M ($300M stock + $250M cash)	Yale spin-out. Dual-rail qubit
IonQ	Oxford Ionics	2025	$1,589.7M booked ($1.075B announced)	Acq. 16 Sept. 2025. Trapped-ion qubit HW, SW and cloud services
QCi	Luminar Semicond.	2025	$110M reported	SPA dated 15 Dec. 2025.
IonQ	Lightsynq	2025	$306.2M	Acq. 30 May 2025
IonQ	Vector Atomic	2025	$181.5M	Acq. 2 Oct 2025. $8.7M post-acq revenue to 31 Dec 2025
IonQ	id Quantique (~86%)	2025	$116.2M	Controlling stake acq. 30 Apr 2025.
IonQ	Qubitekk Federal	2024	$22.1M	Acq. 27 Dec 2024. 118 US and Int. issued patents in quantum networking
[HQS + CQ]*	Quantinuum	2021	Undisclosed	Foundational merger. Trapped-ion HW plus full SW stack.

*Honeywell Quantum Solutions + Cambridge Quantum

Quantum Ecosystem - Number of Deals: 2016 - 2024



A key takeaway:
The most important asset "walks"

Sources: See slide number 22.

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Patent Portfolios

NP-Complete Knapsack as a tool for patent portfolio analysis

Hypothetical: Attorney Penny Pincher is Chief Counsel for Maybe Bits Inc., a leading qubit development company that has assembled a 330-patent portfolio primarily through corporate acquisitions. Chief Counsel Pincher seeks to prune the company's portfolio to achieve the greatest value for the ongoing investment. Her Board has allocated her a budget of $50,000 for *remaining* patent maintenance fees for the current portfolio in an effort to free funds for further acquisitions.

Attorney Pincher needs to select a subset of her current patent portfolio. She has decided to use:

- forward citations as an initial index for value; and,
- remaining lifetime maintenance fees as an index of cost.

Attorney Pincher's portfolio analysis is a 0/1 knapsack problem that, given her budget cost constraint of W = $50,000, can be stated as:

Let N be the number of patents available in the Maybe Bits Inc. patent portfolio. (N = 330). If x_i is a binary variable, $x_i \in \{0,1\}$ for $1 \leq i \leq N$, her initial patent portfolio cut is given by:

$$max \sum_{i=1}^{N} v_i x_i \qquad \text{subject to:} \qquad \sum_{i=1}^{N} c_i x_i \leq W$$

where v_i are the values (forward citations) of each patent to Maybe Bits Inc., and c_i are the individual costs (remaining lifetime maintenance fees).

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Knapsack Problem

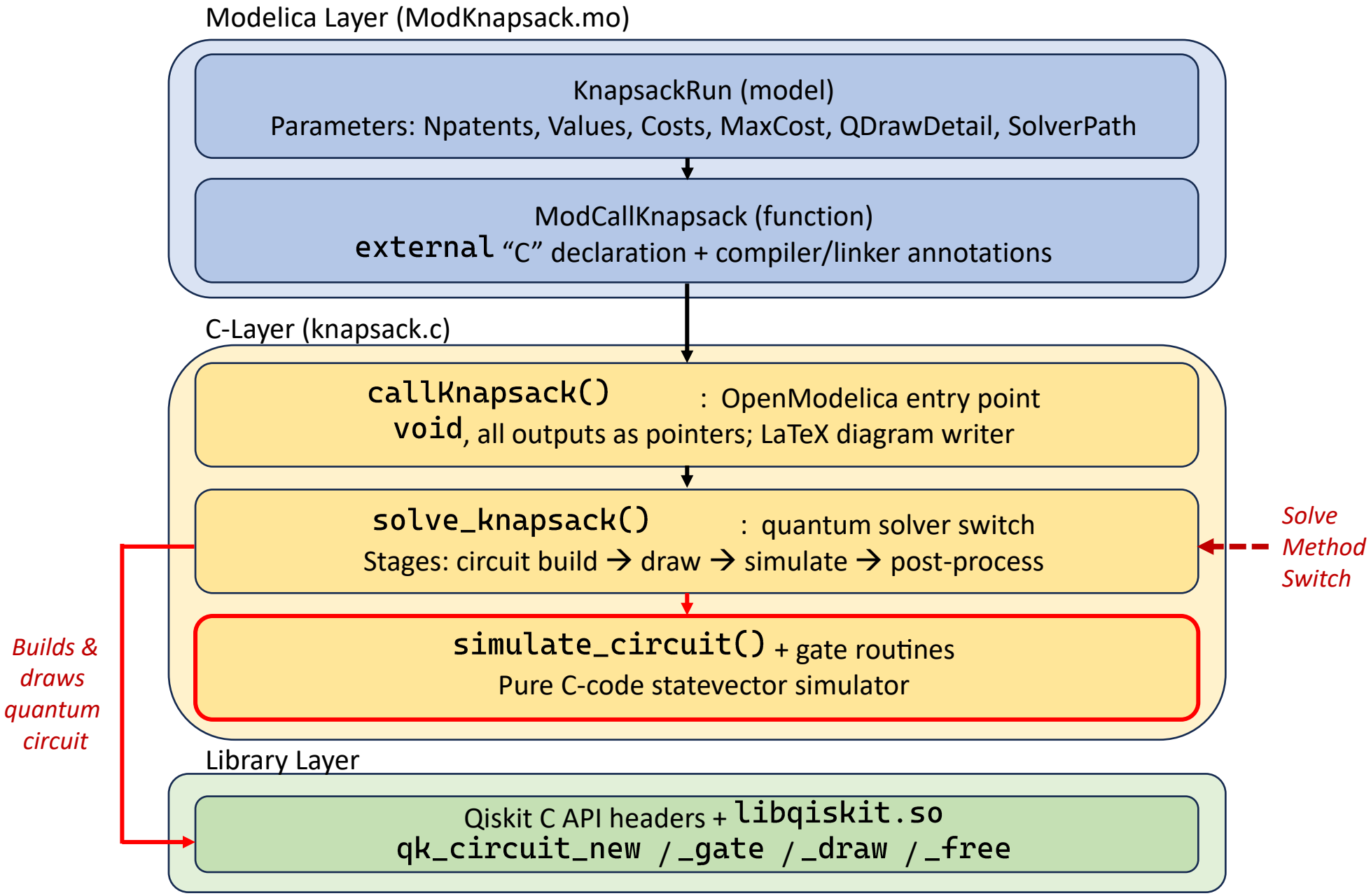
Notes on the knapsack problem

- The 0/1 knapsack problem is NP-Complete
- The 0/1 knapsack problem with integer weights is a dynamic programming problem that can be solved in pseudo-polynomial time (*weakly* NP-hard)
- Quantum computers can solve problems in P, but with – *at most* – polynomial improvement
- $P \subseteq BPP \subseteq BQP \subseteq PSPACE$
- The following are *conjectured*, but unknown:
  - $P \neq NP$
    - *Otherwise*, NP-complete $\subset$ P. If so, there is a polynomial time algorithm solving all 0/1 knapsack problems. (Not just pseudo-polynomial time)
  - BQP $\cap$ NP-complete = $\varnothing$
    - *Otherwise*, there is an algorithm that exhibits a quantum advantage on 0/1 knapsack problems
  - BQP $\not\subset$ NP [and BQP$\subseteq$PSPACE has been proven]
    - This implies that even if P = NP, there may be problems in BQP\NP where quantum algorithms may still display a quantum advantage

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Modelica-Qiskit Interface Architecture

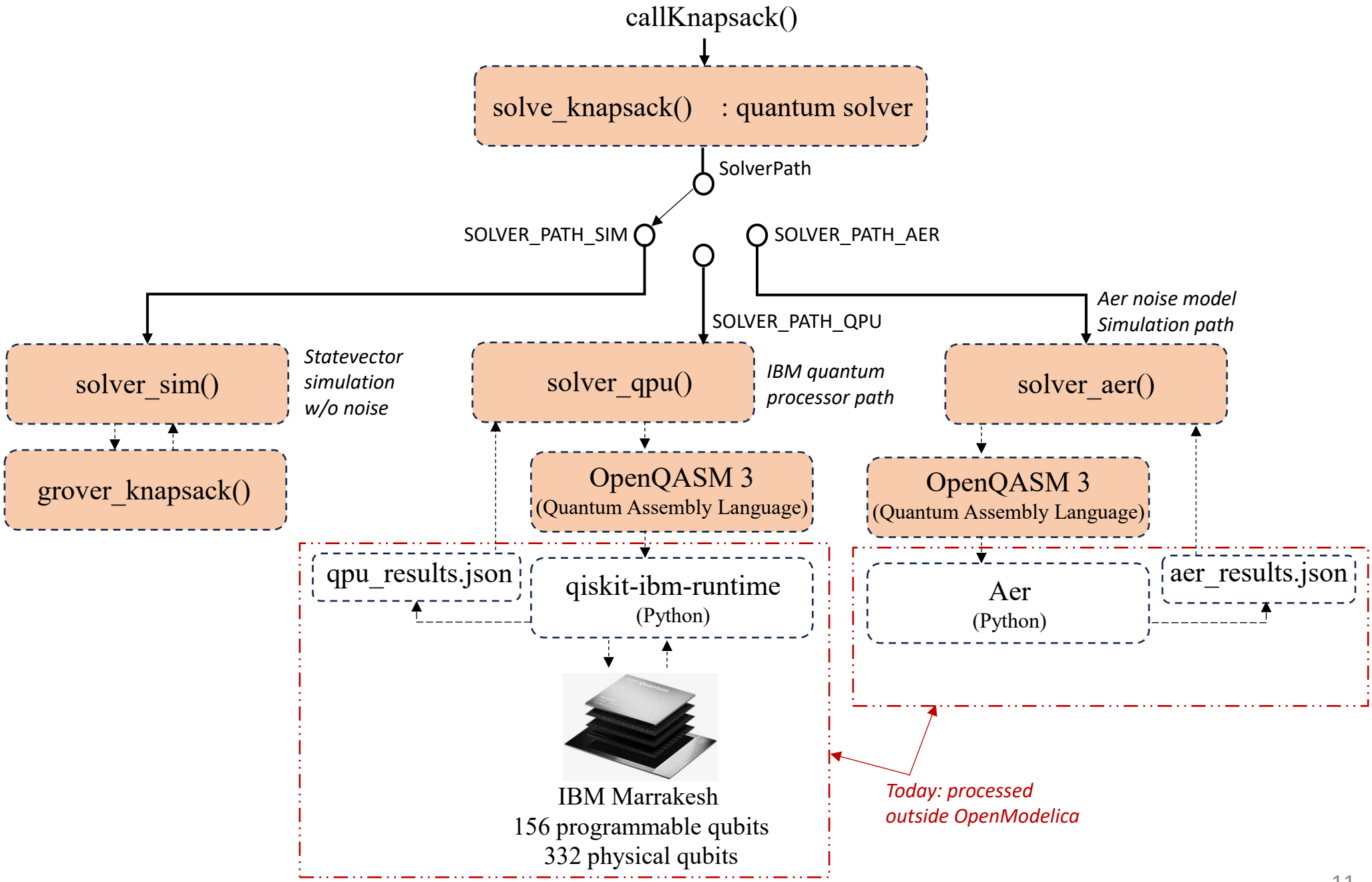
Software Stack



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OpenModelica-Qiskit-C Interface Architecture

Quantum solver path architecture



*https://quantum.cloud.ibm.com/computers

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Testcase Setup

What the quantum solver computes

Classical (brute force)

For each of 2^N subsets, x_k:
compute $cost(x)$
compute $value(x)$
find k, such that:
`is_good`(k) = TRUE *iff*
$cost(x_k) \leq W$
$value(x_k) \geq value(x_j)\ \forall\ j$ *with*
$cost(x_j) \leq W$
Return k else `error`

- 2^N comparisons
- One comparison at a time
- $O(2^N)$
- Answer is certain

Quantum (Grover search)

N qubits hold all 2^N subsets at once (one qubit/item)

↓

Oracle : A quantum circuit to:
Compute:
Cost and value of every subset
Marks each subset with:
$cost \leq W$
$value \geq T$ (T is an updated threshold)
(the circuit version of `is_good`(x))

↓

Amplify : A quantum circuit to:
Amplitude Amplification of each marked subset

↓

Measure : A quantum circuit to:
Read item qubits.
A marked subset results with probability ≈1

- Each pass the Oracle is an “Oracle call”
- Result is a random draw
- Weighted toward “good” subsets

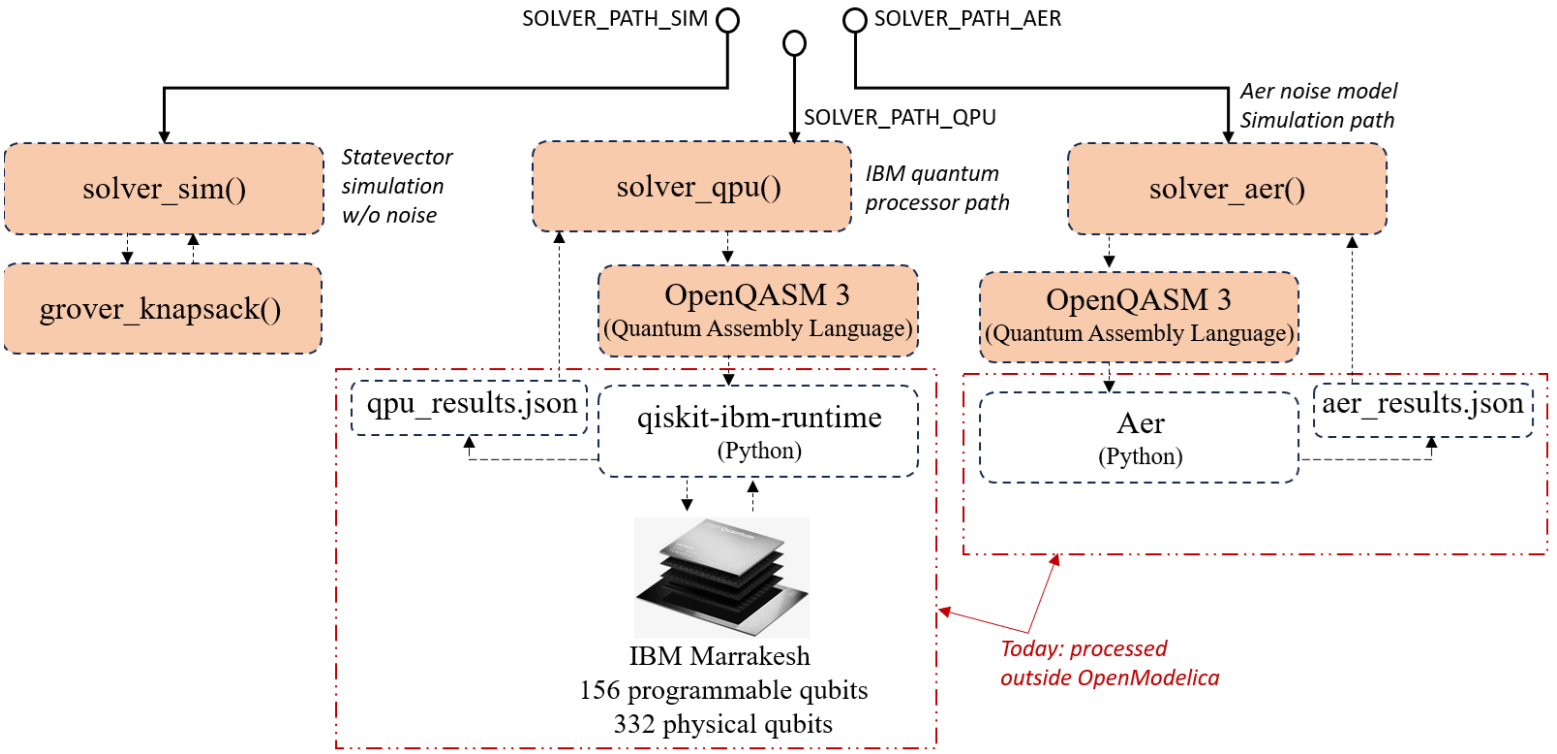
Notes:

1. L. K. Grover, A fast quantum mechanical algorithm for database search, Proc. 28th ACM STOC 212–219 (1996); arXiv:quant-ph/9605043
2. C. Dürr and P. Høyer, A quantum algorithm for finding the minimum, arXiv:quant-ph/9607014 (1996)
3. A. Gilliam, S. Woerner and C. Gonciulea, Grover Adaptive Search for Constrained Polynomial Binary Optimization, Quantum 5, 428 (2021); arXiv:1912.04088v3

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Testcase Setup

What the quantum solver computes

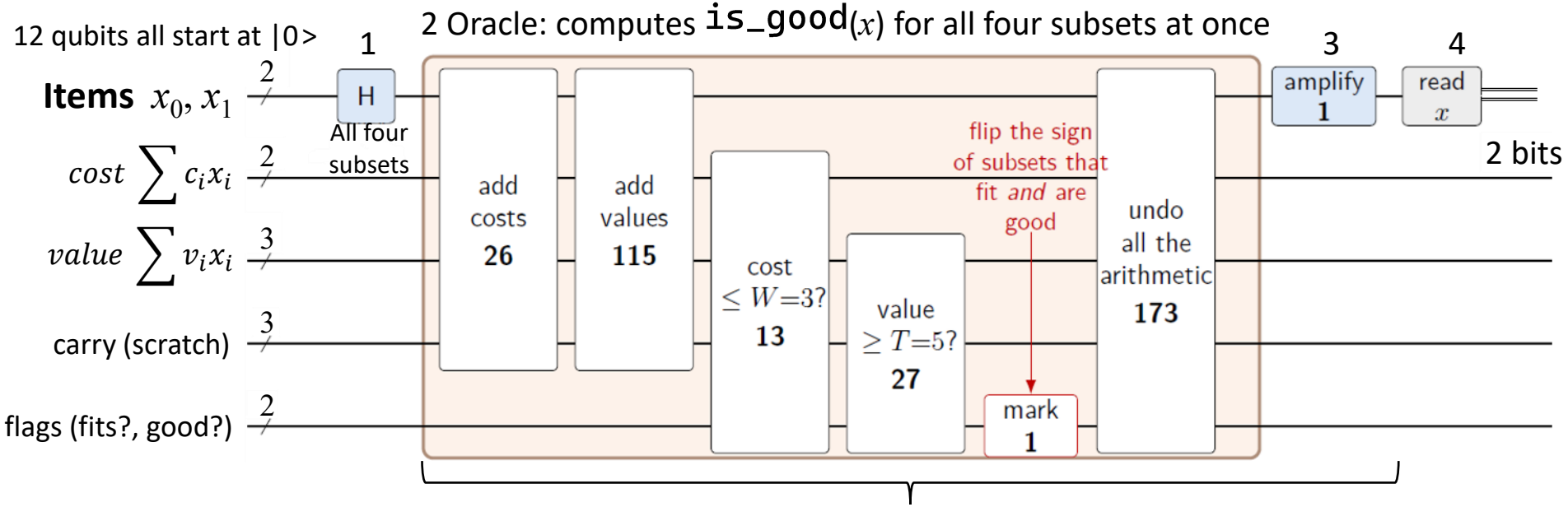


Solver Path	Performed	Results
`solver_sim()`	Full search with increasing T. Qubits emulated in digital memory (4,096 amplitudes in memory at N = 2, 12 qubits)	Best subset found and number of Oracle calls
`solver_aer()` `solver_qpu()`	One search with T set to the known optimum (verification run) repeated 4,096 times (“shot”)	A histogram of subsets. P(success) = share of shots that hit T Chance = $1/2^N$

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Testcase Setup

The N=2 circuit



- The problem data (costs {1,2}, values {2,3}, W=3, T=5) are fixed parameters inside the gates
- **Bold** = two-qubit gates per block: **356** as written, **354** arithmetic. **647** after compiling for Marrakesh

How to read the diagram

3 — **Wire**: a register, read left-to-right in time. The number is how many qubits are bundled. (12 in all.)

Step 2: **Oracle**. Everything inside the box is one "Oracle call".

amplify — **Step 3**: Amplify. Implements Grover diffusion, which makes the marked subsets more likely to be read.

H — **Step 1**: **Hadamard**. Initializes the two item qubits into all four subsets at once

mark — **Mark**: Flips the sign of each subset that fits the budget *and* beats the threshold. That is the Oracle "answer".

read — **Step 4**: **Read**. Measures the two item qubits. Double line carries two classical bits corresponding to one subset.

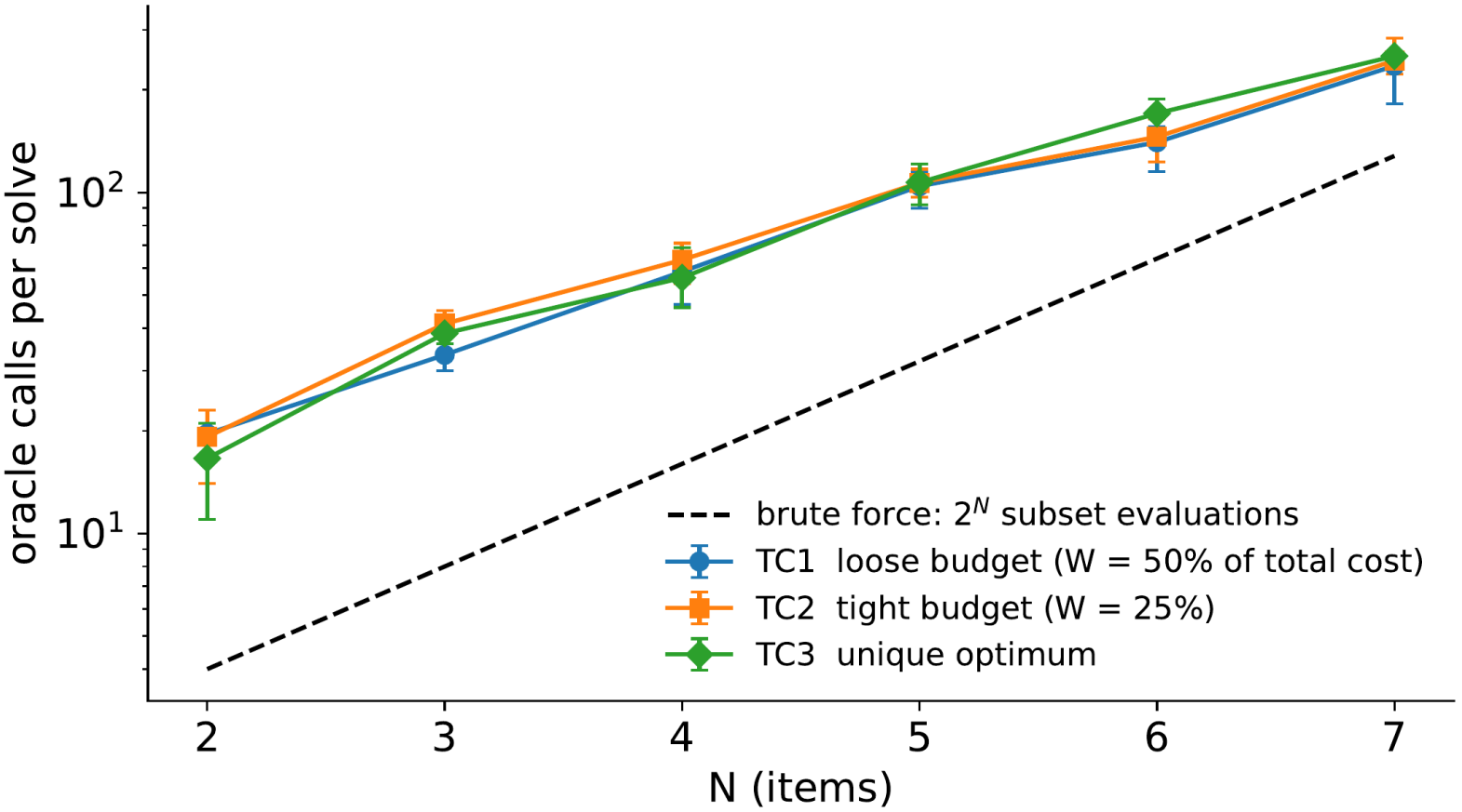
Add **26** — **Arithmetic block:** An adder or comparator built from gates. Bold number is its two-qubit gate count

undo — **Undo:** Runs the arithmetic backwards so the scratch registers return to |0>. (Step 3 requires this)

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Testcase Results

Noiseless simulation: Oracle calls vs. problem size



- For N = 2-7, the quantum search makes more Oracle calls than classical brute force
- The growth of the quantum Oracle calls is slower ($\approx 2^{0.7N}$) than brute force (2^N)

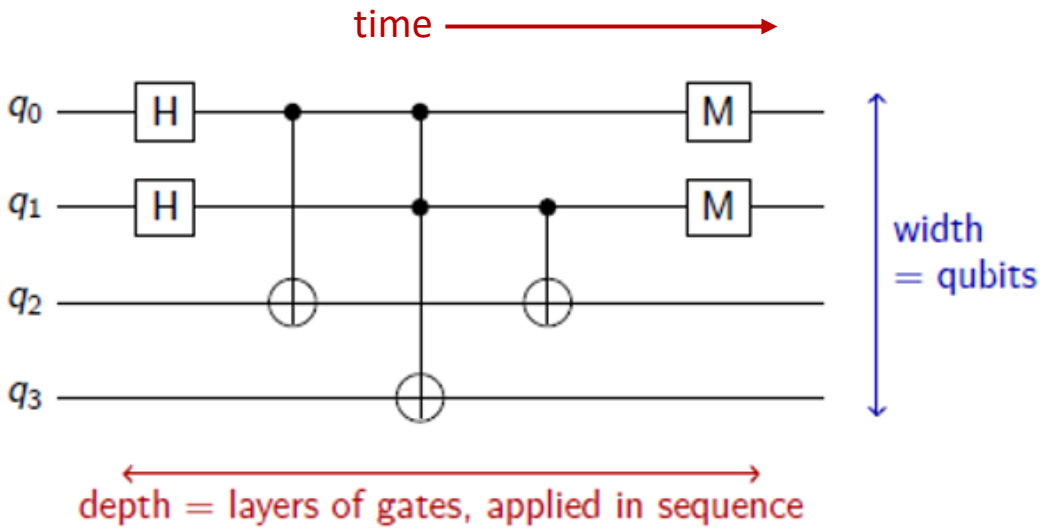
Notes:

1. M. Boyer, G. Brassard, P. Høyer and A. Tapp, *Tight bounds on quantum searching*, Fortschr. Phys. 46, 493–505 (1998); arXiv:quant-ph/9605034
2. C. Dürr and P. Høyer, *A quantum algorithm for finding the minimum*, arXiv:quant-ph/9607014 (1996)

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Testcase Results

What is a “quantum circuit” and what is its “depth”?



A “circuit” is the program a quantum processor executes comprising qubit lines acted on by “gates” (boxes, dots)

The “simple” case: N=2

- 12 qubits:

Two “items”	2
Cost, value, carry registers	8
Two flags	2

- Circuit by `grover_knapsack()` in knapsack.c
  ~90 multi-qubit gates (Oracle adders and comparator)
- Compiled for IBM Marrakesh
  - Native gates act only on neighboring qubits
  - 647 two-qubit gates
  - 1,788 layers

Why Depth Matters:

- Every two-qubit gate fails ~0.1%-0.6% of the time and qubits decay (decohere) while they wait
- Errors accumulate with depth
  - Marrakesh has 156 qubits (We use twelve)
  - The limit for the N=2 case is error per gate, not number of qubits
- Error correction promises to fix the errors-per-gate issue
  - A protected (logical) qubit is built from many physical qubits
  - The bundling of physical qubits limits today’s problem size

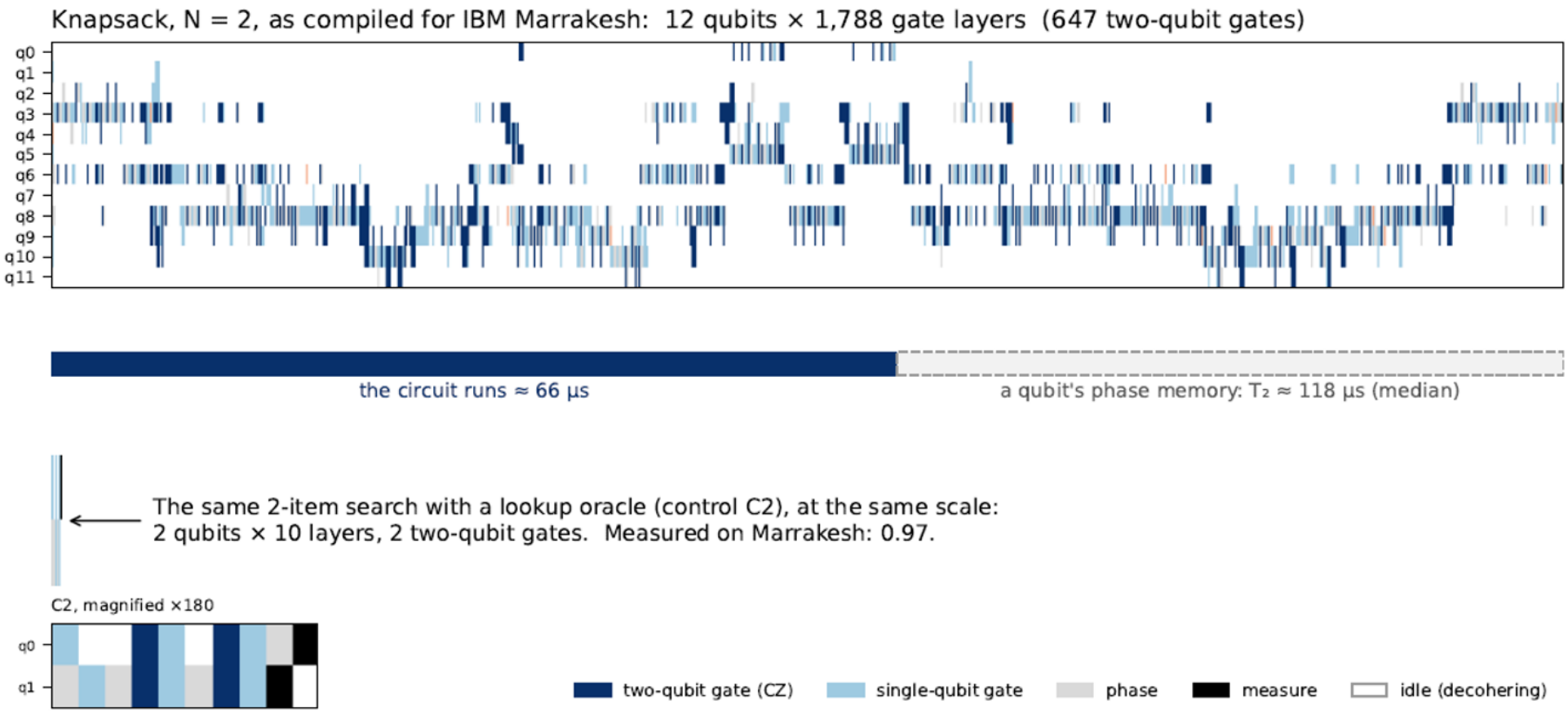
Notes:

1. D. C. McKay, I. Hincks, E. J. Pritchett, M. Carroll, L. C. G. Govia and S. T. Merkel, Benchmarking quantum processor performance at scale, arXiv:2311.05933 (2023)
2. Google Quantum AI (R. Acharya et al.), Quantum error correction below the surface code threshold, Nature 638, 920–926 (2025); arXiv:2408.13687

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Testcase Results

Why N=2 is not small



- Classically, two “items” means four (4) subset checks
- The quantum Oracle must compute each subset’s cost and value inside the circuit
- The search is cheap, but the arithmetic is not

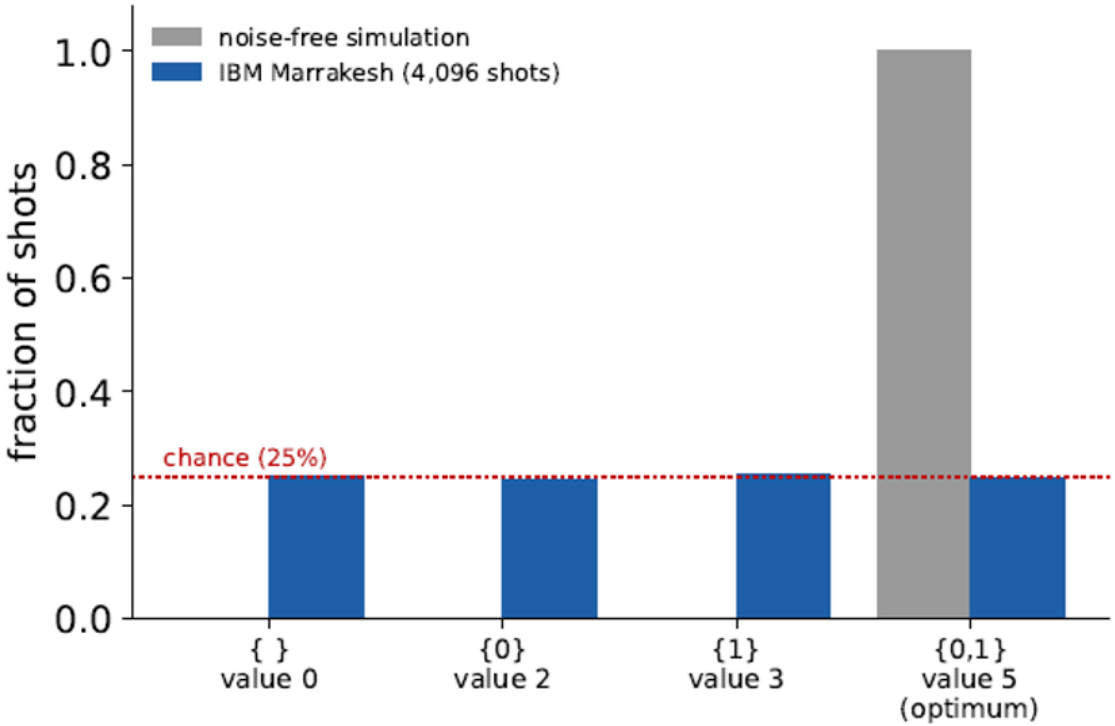
Notes:

1. J. Preskill, Quantum Computing in the NISQ era and beyond, Quantum 2, 79 (2018); arXiv:1801.00862
2. E. M. Stoudenmire and X. Waintal, Opening the black box inside Grover’s algorithm, Phys. Rev. X 14, 041029 (2024); arXiv:2303.11317

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Testcase Results

IBM Marrakesh: A full round-trip from OpenModelica



The Marrakesh experiment:

1. OpenModelica
   - N=2
   - `SolverPath`=2
2. `solver_qpu()`
   - Writes OpenQASM 3 (12 qubits)
3. Compiled for Marrakesh
   - 647 two-qubit gates
4. Executed on Marrakesh QPU
   - 4,096 shots, 4 seconds of QPU time
5. Result returned to OpenModelica

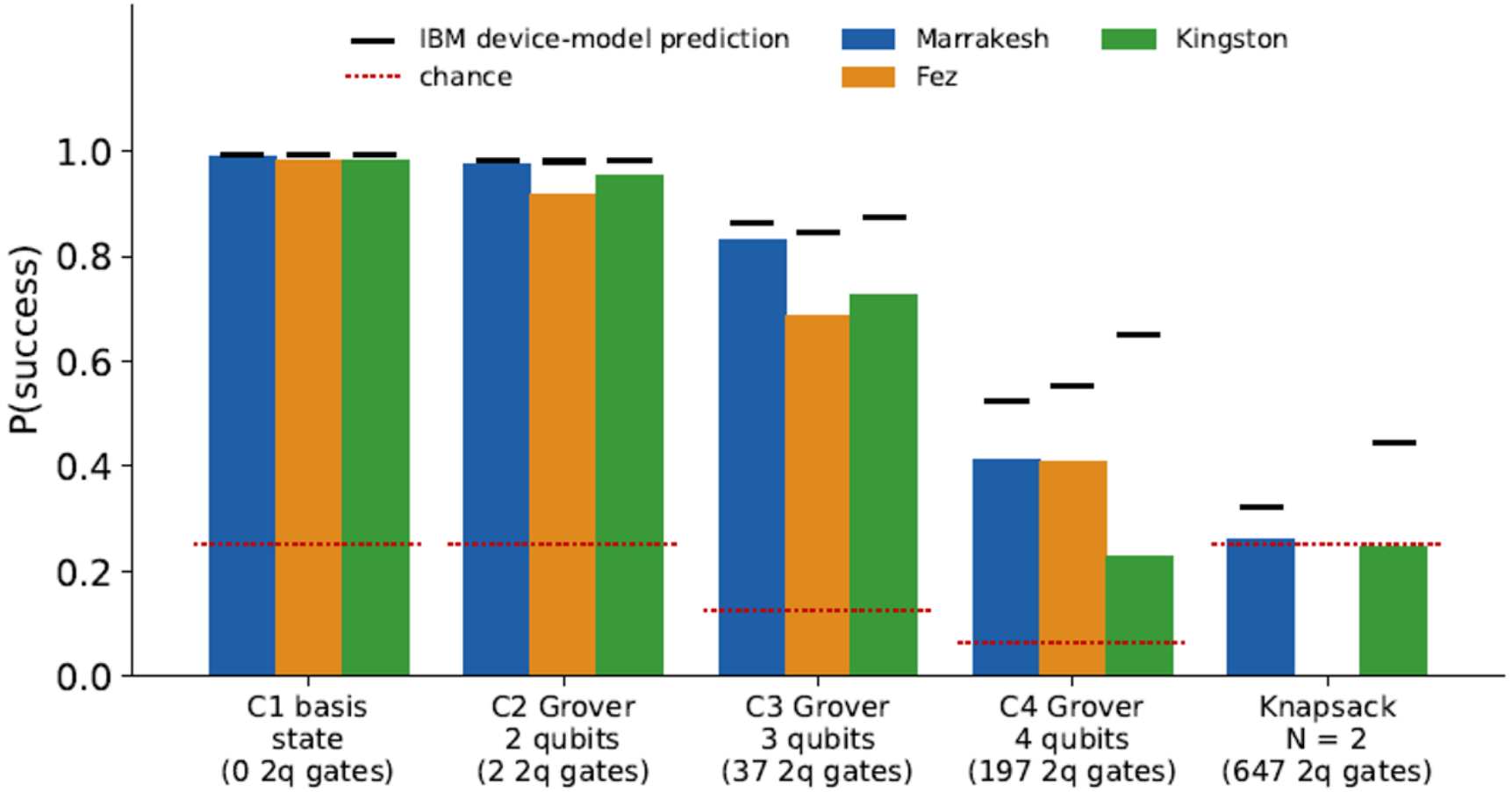
Conclusions:

- The toolchain works end-to-end
- At this circuit depth, the answer computed on Marrakesh is noise

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Testcase Results

Interpretation: Success falls with circuit depth on real QPU hardware



- Plain Grover still works on hardware at four qubits (197 two-qubit gates)
- Knapsack Oracle must do arithmetic inside the circuit
  - Costs 647 two-qubit gates even at N=2
  - At that depth, the answer is lost in noise
  - Chance on both machines that ran knapsack (Marrakesh 0.26, Kingston 0.25)

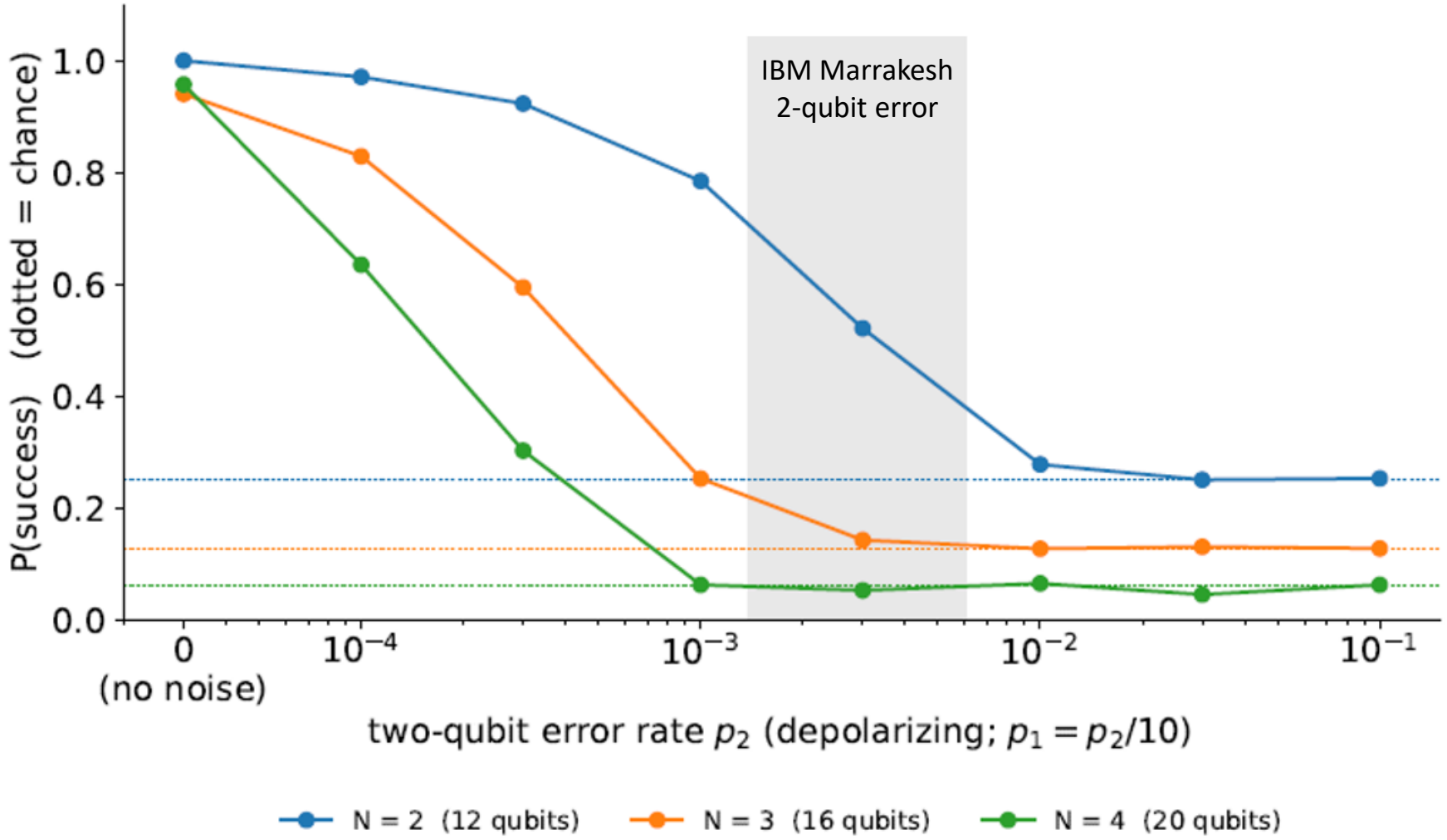
Notes:

1. K. Zhang, et al., Implementation of efficient quantum search algorithms on NISQ computers, Quantum Inf. Process. 20, 233 (2021); arXiv:2102.01783
2. T. Tenev, N. Nedev and N. V. Vitanov, Improvement of performance of Grover's algorithm on three generations of Heron family IBM QPUs, arXiv:2604.23228 (2026)

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Testcase Results

Aer Simulation with quantum noise



- Noise-free, the circuits find the solution 94%-100% of the time
- Each added item lowers the error rate the circuit can tolerate

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Key Points

Summary

- IBM Qiskit's C API runs as a solver inside OpenModelica.
  - A 0/1 knapsack posed in OpenModelica is solved by a quantum (Grover) algorithm through callKnapsack()

- One interface, three solver paths:
  - Statevector simulation
  - Aer with noise
  - IBM QPU hardware

  each returning its result to the OpenModelica model

- Simulation is correct, but not yet faster
  - 90 of 90 instances optimal ($N \leq 7$).
  - At these sizes the quantum search needs more oracle calls than brute force. The advantage is asymptotic.

- With IBM Marrakesh as the solver, the chain works, but the answer does not survive
  - OpenModelica runs end to end, but 647 two-qubit gates at today's error rates degrade the result to chance.

- Outlook: Real portfolios (N = 330) need fault-tolerant quantum computers, plus leaner oracle circuits

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Quantum Algorithms for Patent Portfolio Analysis Using OpenModelica and IBM Qiskit

Notes:

Slide 7: "Investment Measures – Selected Quantum Ecosystem Transactions"

1. Announced ≠ booked. Stock-funded values move with the acquirer's share price between signing and close. Oxford Ionics is the worked example: $1.075B announced, $1,589.7M booked — a 48% increase, driven by the collar, not by a change in the deal.
2. Stake ≠ whole company. The id Quantique figure is total consideration for approximately 86% of the shares, not a whole-company valuation.
3. Luminar was a stock purchase per QCi's 8-K/A. However, press reports have characterized otherwise. Stated as reported.
4. Excluded and why: Capella Space $424.8M (acquired 11 Jul. 2025) — SAR satellite imaging, a non-quantum target. Seed Innovations (ML/software).
5. For a counted population see OECD/EPO, Mapping the Global Quantum Ecosystem (Dec. 2025) §5.2: 32 completed deals, 2016–2024.
6. IonQ's five 2025 acquisitions, including Capella Space (note 4), total $2,618.4M of stated consideration against $130.0M of FY2025 revenue — itself up 202% from $43.1M — roughly twenty times annual revenue, spent in a single year.
7. IonQ, Inc. Form 10-K for FY2025 (CIK 0001824920), Note 3, Business Combinations; IonQ, D-Wave Quantum Inc. (CIK 0001907982) and Quantum Computing Inc. (CIK 0001758009) Forms 8-K / 8-K/A with exhibits. All retrieved from SEC EDGAR 26 Aug. 2026.
8. For number of deals 2016 – 2024:
   a) *Basis*. Counted completed deals, not announced values. 32 deals, equal to 32 companies, 2016–2024.
   b) *Source*: OECD/EPO, Mapping the Global Quantum Ecosystem (Dec. 2025) § 5.2, at 86–88, from the OECD STI Micro-data Lab integrated with Orbis M&A (Bureau van Dijk), Oct. 2025.
   c) Why no prices or multiples here? Because most targets at this stage are early-stage private companies, so consideration is rarely disclosed and comparables are thin. The absence of revenue/EBITDA/EBIT data is a characteristic of early-stage consolidation, not a gap in the source and a deal count is the measure that survives that absence.
   d) The dataset ends in 2024. The 2025–26 activity is outside the range.
   e) Sample of quantum companies with recorded quantum patents. Percentages are shares of that sample, not of all quantum companies.

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