QuAD-FORGE

Quantum-Aided Design for Manufacturability Exploration

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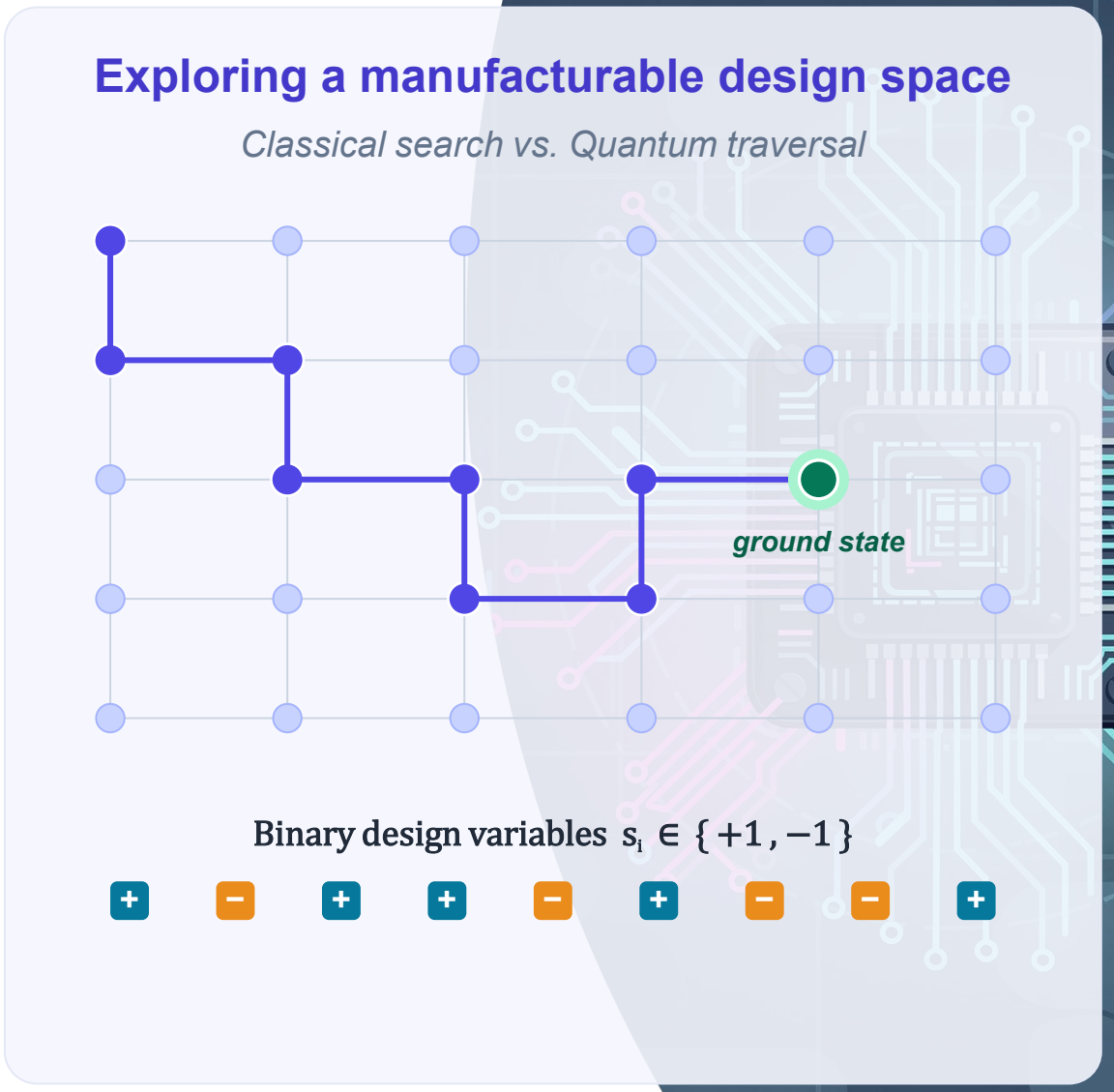
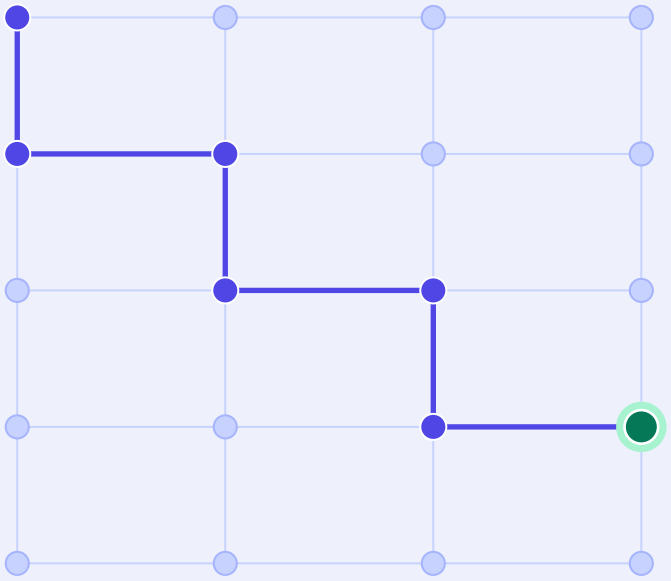


“If you think you understand quantum mechanics, then you don’t.”

– Richard Feynman

(Don’t worry! We don’t either!! ☺)



design space → quantum optimum

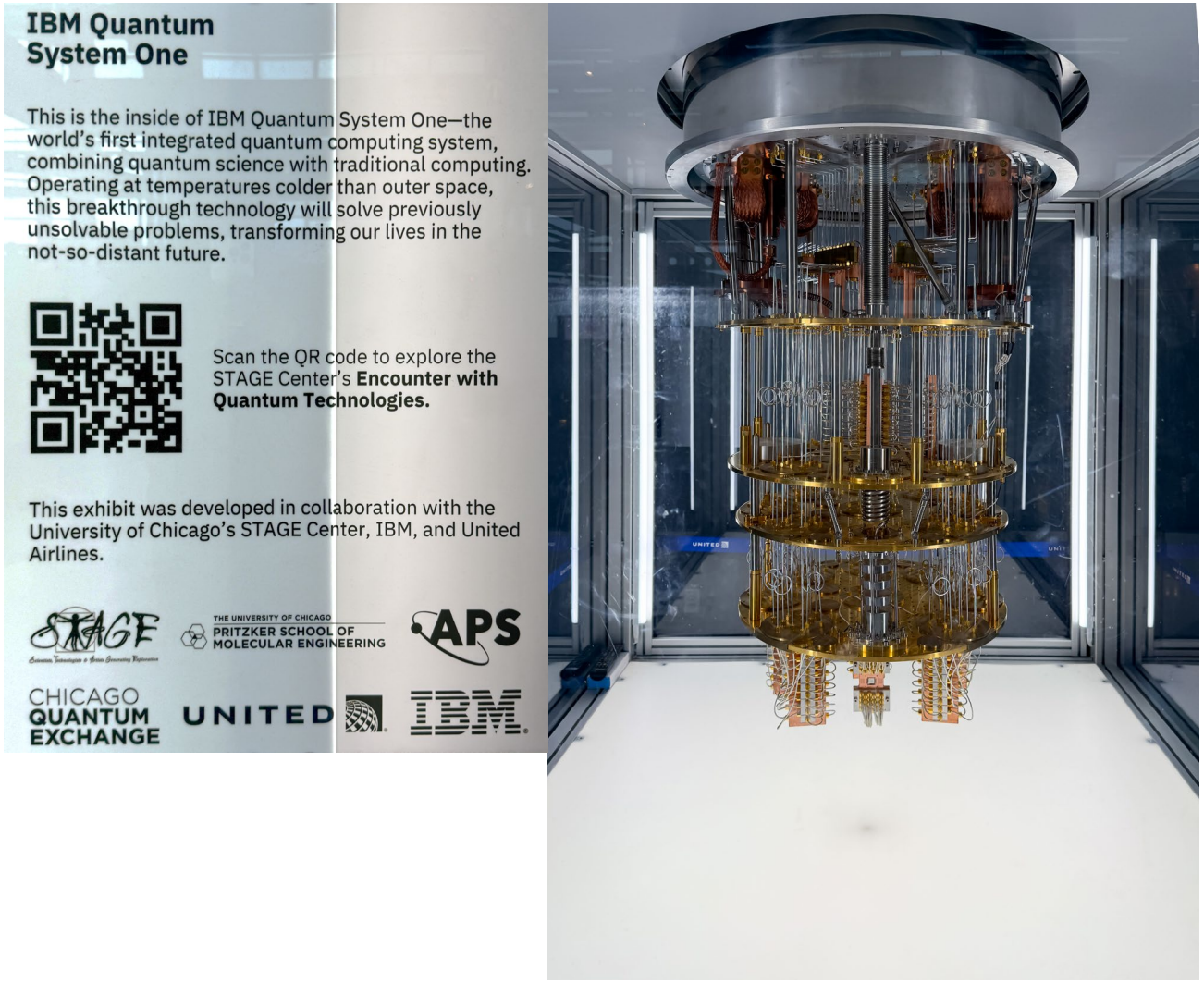
Outline

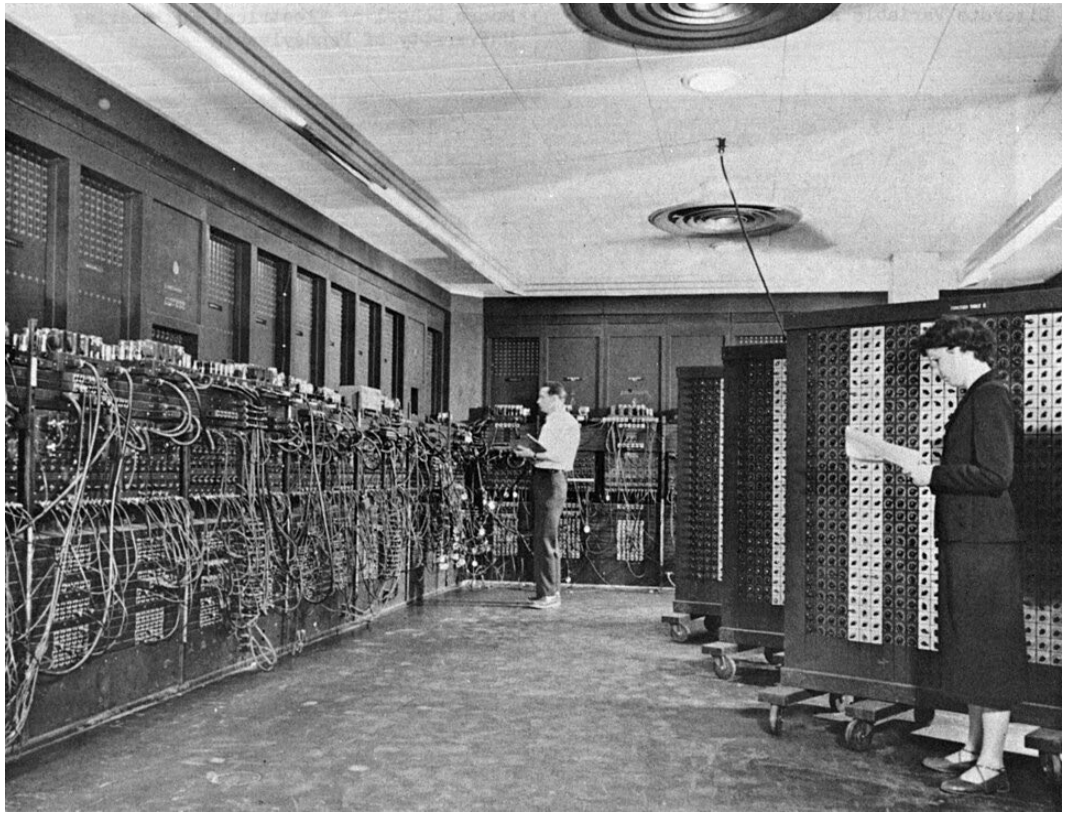
- Core Problem and Quantum Computing
- Evolution of Computing
- The Encoding Problem and Framework
- Applications and Impact

The Core Problem

- **Modern engineered systems are defined by design spaces of extraordinary dimensionality.**
  - A single turbine blade involves hundreds of geometric parameters:
  - Aerodynamic performance constraints, material property bounds, manufacturing limits, tool accessibility, minimum feature size, surface finish…
- Classical optimization navigate these spaces through gradient-based local search or population heuristics that scale polynomially at best with dimensionality.
- **The consequence: engineers accept near-optimal designs constrained by the limits of classical computation.**

Quantum Computing

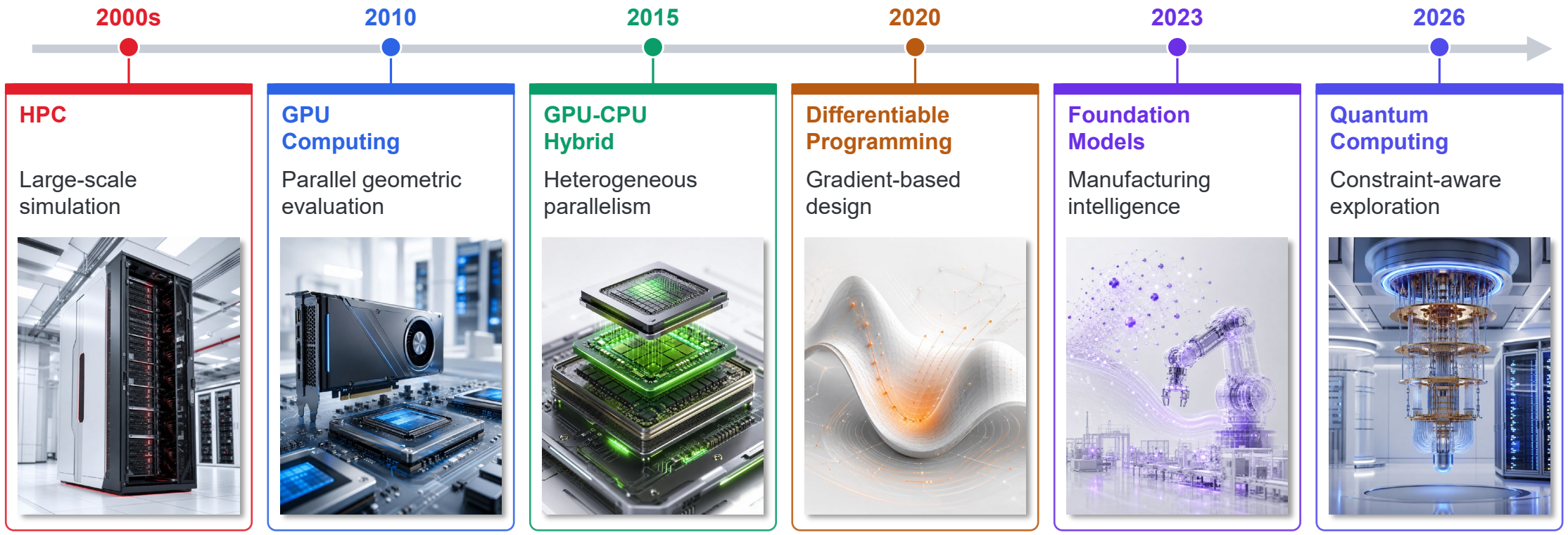




ENIAC (Electronic Numerical Integrator And Computer) in Philadelphia, Pennsylvania, 1947.

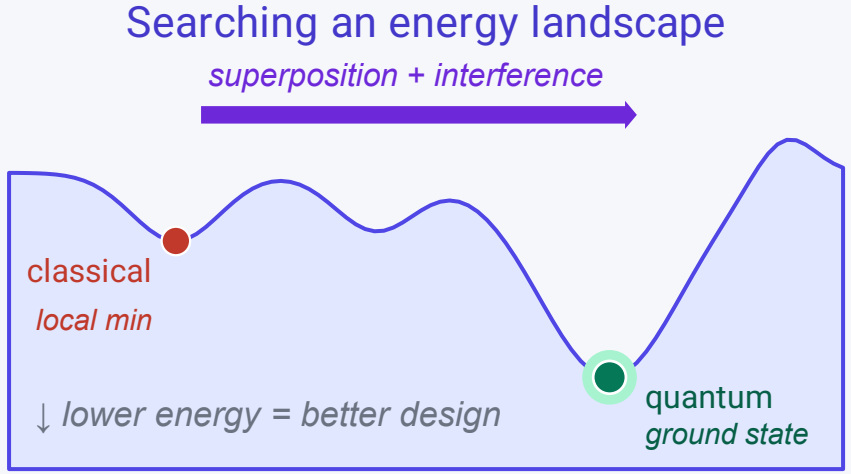
Evolution of Computing

- Computing paradigm shifts increasingly compress design exploration cycles



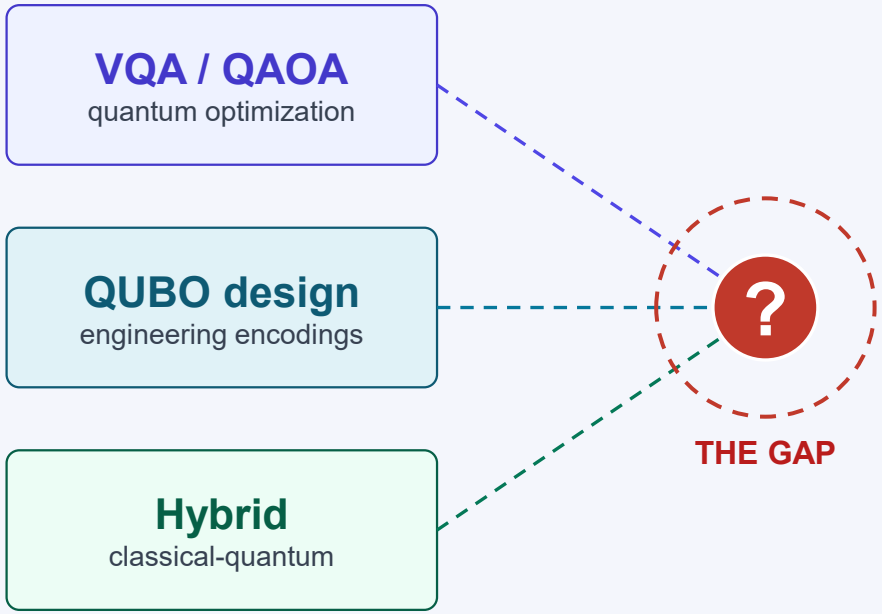
The Quantum Opportunity

- Quantum algorithms use
  - **Superposition** to evaluate exponentially many candidate solutions simultaneously
  - **Interference** to amplify the amplitude of high-quality solutions
- NISQ: Noisy Intermediate-Scale Quantum
  - Tens to a few hundred Qubits
  - Significant noise that limit their capabilities
- Key insight:
  - CAD-derived geometric and process constraint spaces are structured in precisely the sense NISQ advantage requires



Encoding Problem
Binary variables + pairwise couplings form an Ising energy landscape, executable on quantum annealers.

The research landscape



No framework encodes the **full** CAD and manufacturing constraint space as a single quantum-compatible Hamiltonian.

Prior Work

VQA

Quantum Optimization

QAOA + Grover mixers (Stein 2025); VQEC; DQI proves interference advantage (Jordan 2025).

QUBO

Engineering Design

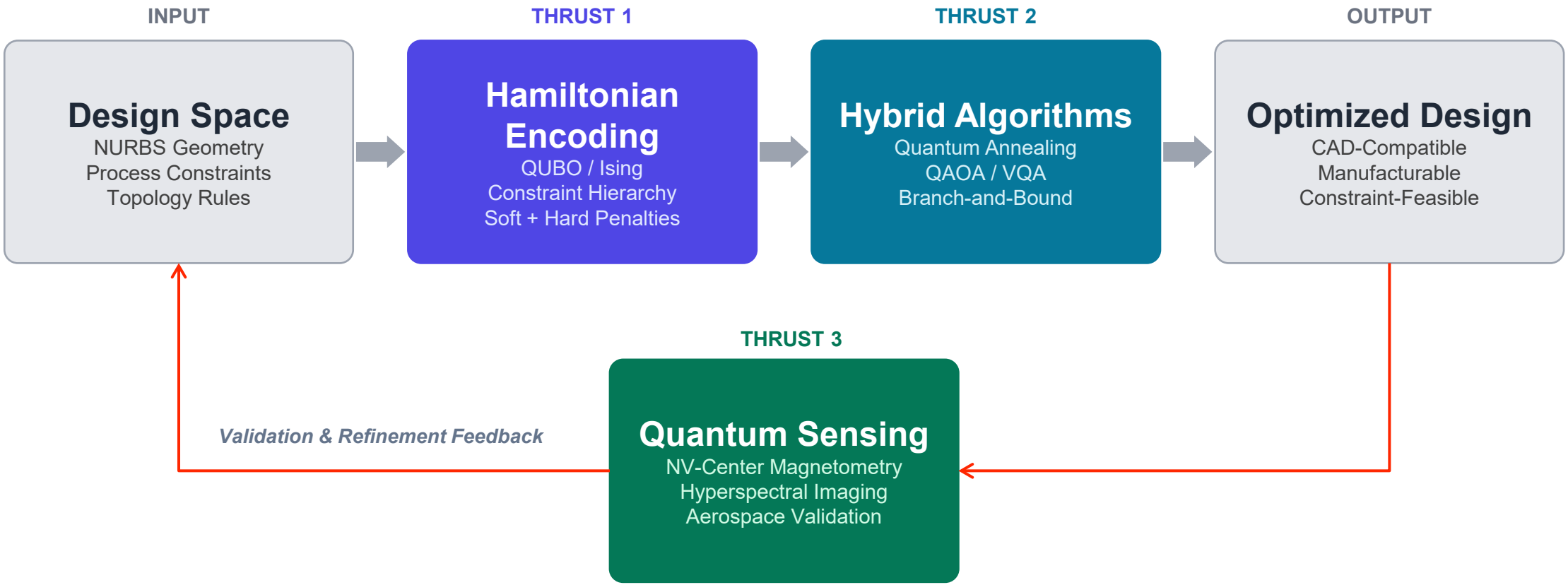
Slack-variable encoding (Ozawa 2024); CAD-interference QUBO on D-Wave (Despotovic 2025).

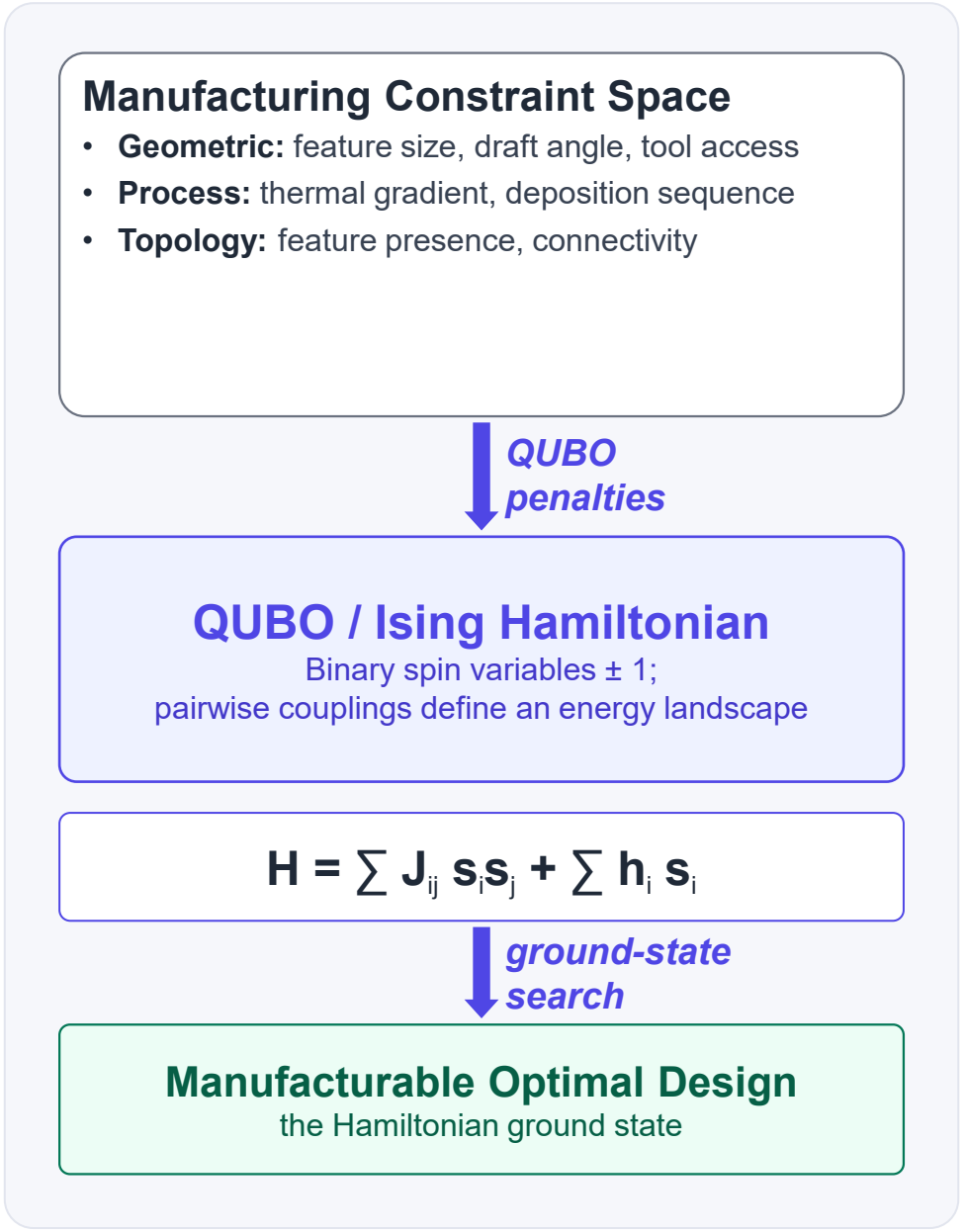
Hybrid

Classical-Quantum

Branch-and-bound with quantum sub-solvers (Sanavio 2024); FEM-class speedup (Liu 2024).

Framework Overview





Quantum-Compatible Encoding

Foundational challenge

- Translate manufacturability constraints, expressed as geometric predicates, process-parameter bounds, and topological requirements, into QUBO formulations.

Example encoded constraint classes

- Minimum feature size and draft angles
- Tool accessibility
- Additive-manufacturing overhang limits
- Thermal gradients and deposition sequence

Existing approaches address only narrow constraint types or approximate continuous objectives with surrogates that sacrifice manufacturability fidelity.

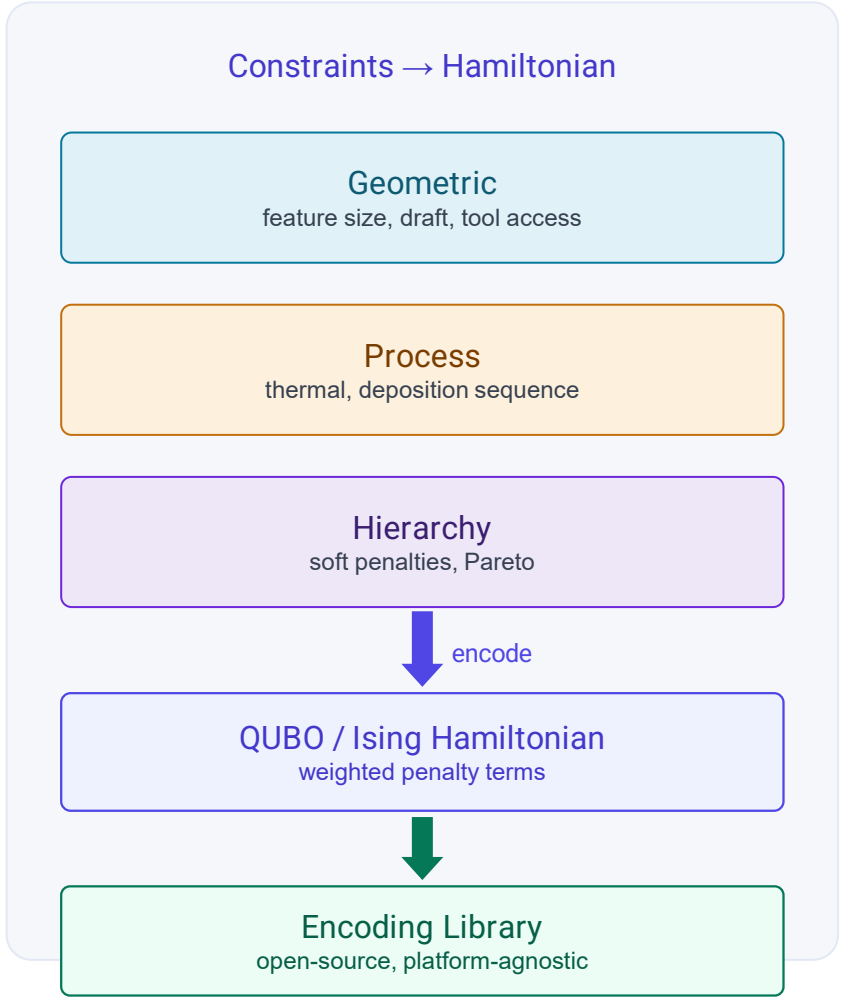
Encoding Strategy

Encoding strategies

- **Geometric constraints**
  - Signed distance fields discretized into binary spin variables; slack-variable methods encode inequalities without exponential auxiliary-variable overhead (Ozawa et al., 2024)
- **Process constraints**
  - Thermal gradients and deposition-sequence dependencies encoded as higher-order Hamiltonian coupling terms, extending Despotovic et al. (2025) beyond disassembly to additive/subtractive manufacturing
- **Constraint hierarchy**
  - Soft preferences as weighted penalties enable Pareto exploration of performance vs. manufacturability; factorization-machine surrogates (Nakano et al., 2022) handle non-quadratic objectives

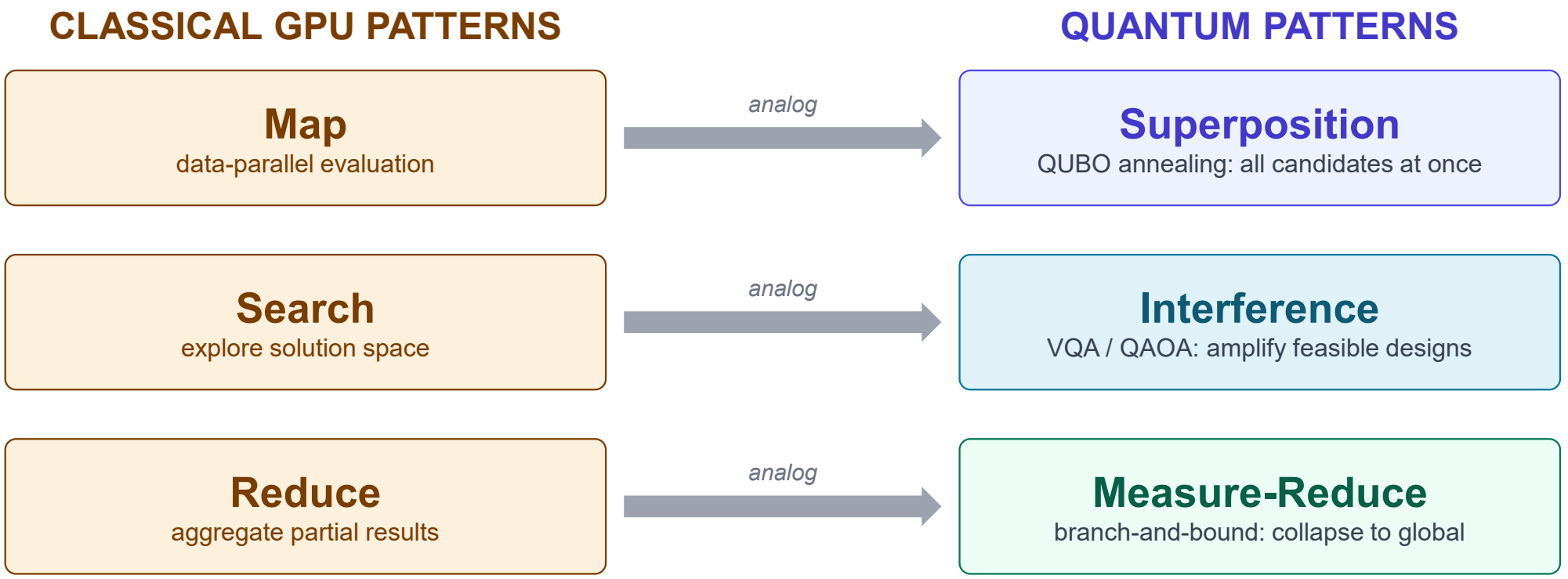
Research Questions

- Formal mapping from CAD geometric and process constraints to Hamiltonian formulations
- Open-source, quantum-platform-compatible constraint encoding library (via QUBOMaker)
- Theoretical analysis of encoding efficiency and constraint-violation penalties

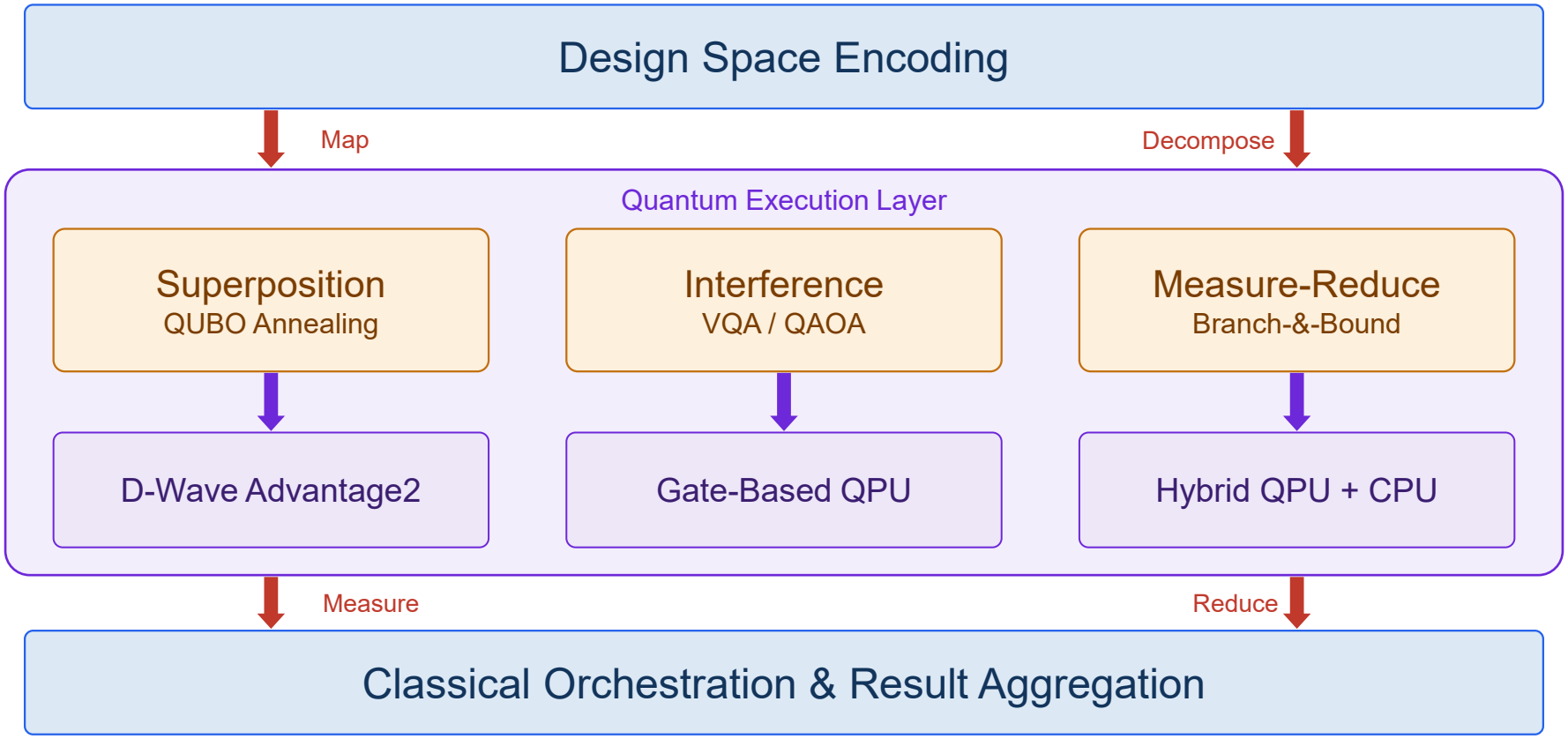


From GPU Patterns to Quantum Patterns

- Hybrid CPU/GPU framework structured parallel algorithms around Map, Search, and Reduce.



Quantum-Classical Patterns



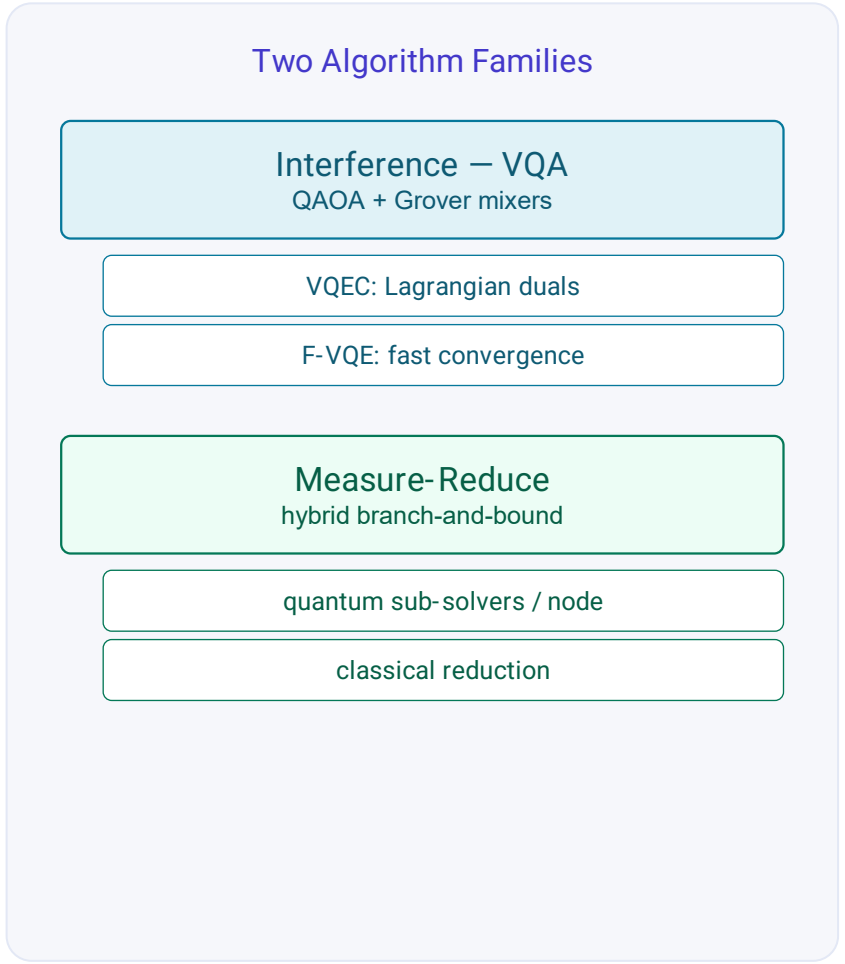
Algorithm Families

Interference Pattern: Variational Quantum Algorithms

- **Hard constraints**
  - **Quantum Approximate Optimization Algorithm** (QAOA) with Grover-mixer extensions enforces manufacturability directly within the circuit (Stein, 2025)
- **Constraint satisfaction**
  - **Variational Quantum Eigensolver with Constraints** (VQEC) encodes constraints via Lagrangian dual variables optimized classically with circuit parameters (VQEC, 2024)
- **Barren-plateau mitigation**
  - Problem-specific ansatz initialization informed by GPU-accelerated classical gradients; F-VQE shown to converge fastest on steel scheduling (Brandhofer et al., 2022)

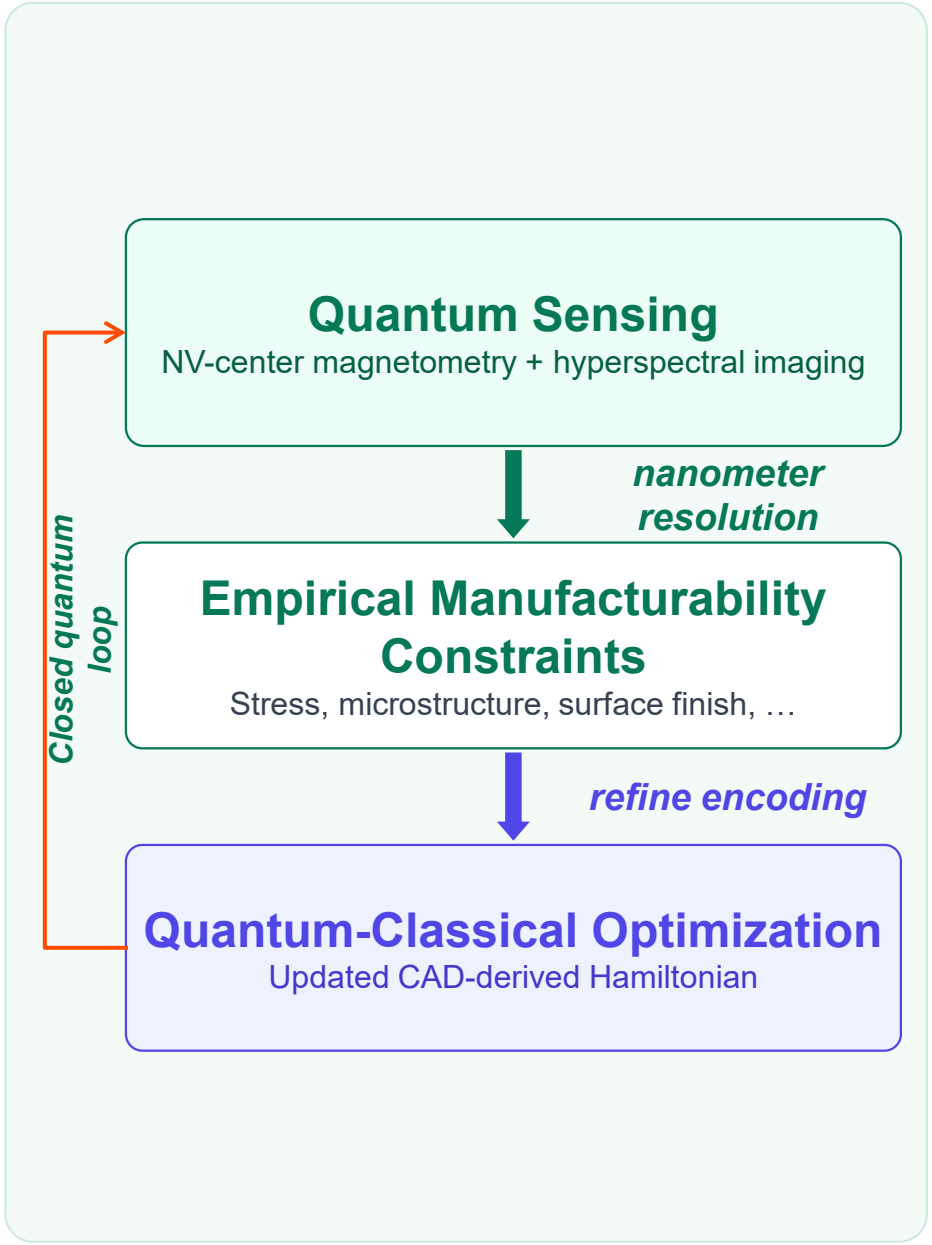
Measure-Reduce Pattern: Hybrid branch-and-bound

- Quantum sub-solvers at each node of a classically managed search tree (Sanavio et al., 2024)
- Each measurement collapses a subproblem to a candidate, classically reduced into a globally consistent design.



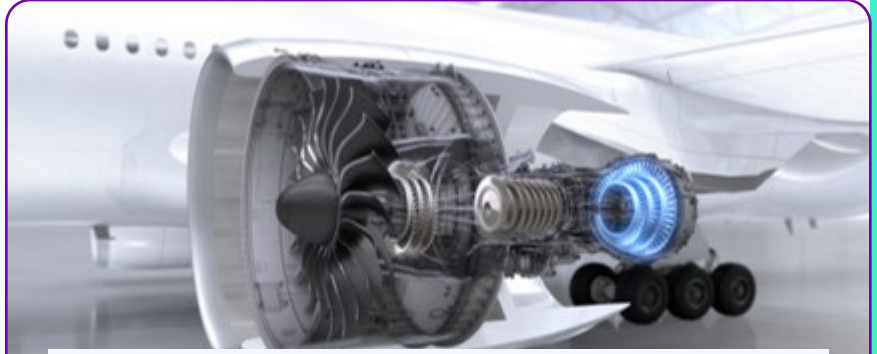
Quantum-Sensed Validation

- Quantum sensing grounds the computational framework in physical reality
- Nitrogen-Vacancy (NV) center magnetometry measure part geometry and residual stress at atomic resolution
- Closing the loop
  - Empirical manufacturability constraints refine CAD-derived encodings
  - Algorithms learn from real fabrication variability
  - Turbine blade design serves as the primary case study
- End-to-end framework in which both sensing and optimization operate through quantum modalities



Industry Applications

- **Aerospace**
  - Reduce design cycles for safety-critical structural components, enabling **geometries** that classical methods cannot feasibly explore.
- **Medical Devices**
  - Optimize patient-specific implant designs subject to geometric and biomechanical constraints.
- **Semiconductor Packaging**
  - Address design-space dimensionality and constraint complexity.

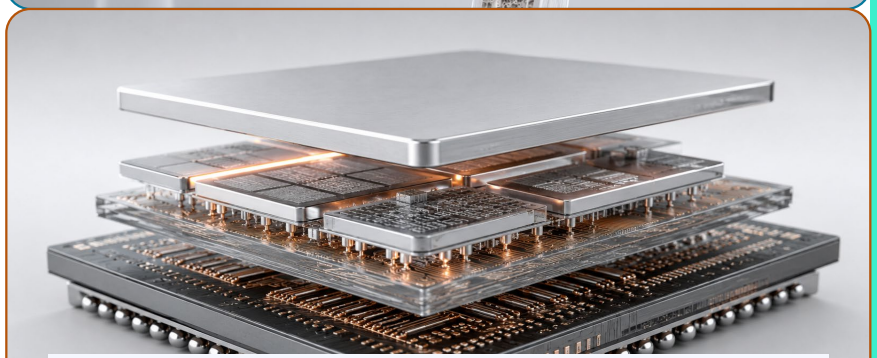


Aerospace

Turbine blade geometries for extreme environments

Medical Devices

Patient-specific implants with biomechanical constraints



Semiconductor Packaging

Extreme design-space dimensionality

Turbine Blade Case Study

Why turbine blade design

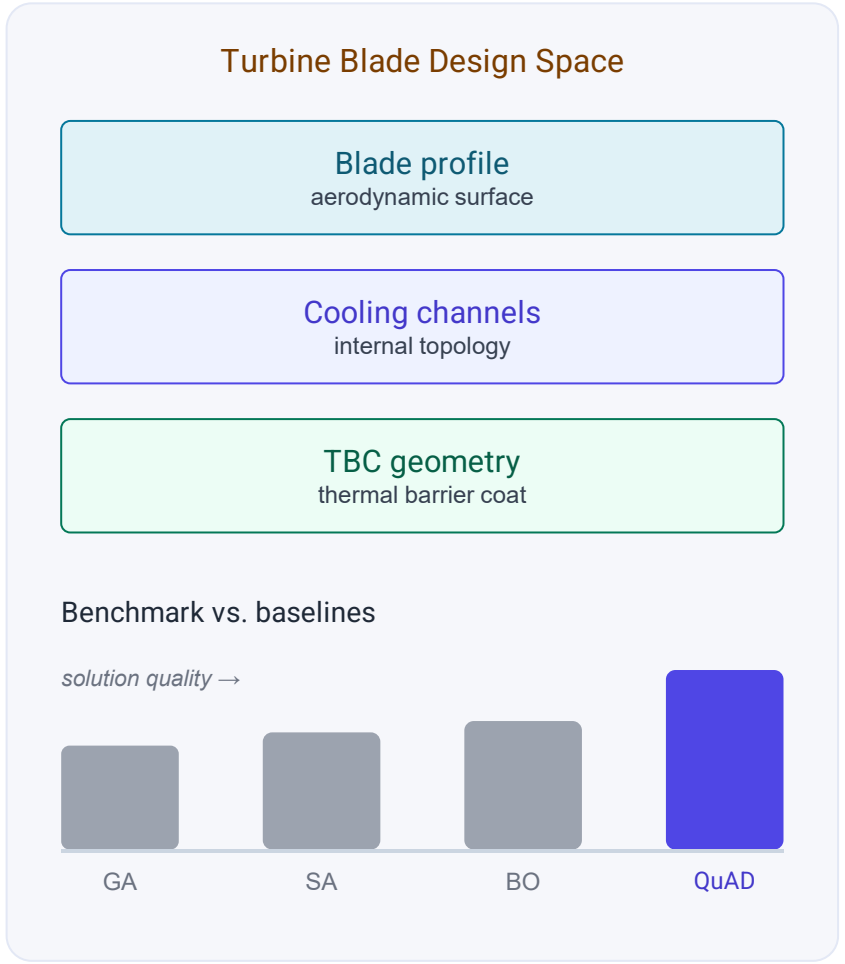
- High-dimensional parameter space (blade profile, cooling-channel topology, thermal-barrier-coating geometry) under tight aerodynamic, thermal, and manufacturing constraints, an ideal instance for quantum-classical optimization.

Quantum-sensed ground truth

- NV-center magnetometry and hyperspectral imaging characterize stress, microstructure, and surface finish at nanometer resolution
- Empirical constraint functions refine the CAD-derived encodings, closing a quantum sensing to quantum optimization loop

Benchmarking plan

- **Baselines:** Genetic algorithms, simulated annealing, Bayesian optimization



National Priorities

National Quantum Initiative

Establishes quantum information science as a strategic national investment in research, workforce, and technology transfer.

CHIPS and Science Act

Expands NSF authorization for use-inspired research in quantum computing, with an explicit focus on engineering and manufacturing.

Advanced Manufacturing

The 2022 National Strategy names computational design tools a critical enabling capability.

NAE Grand Challenge

Advances Engineer the Tools of Scientific Discovery by making quantum-classical computation a foundational design tool.

A dedicated center for quantum-classical computation, sharing quantum software, emulators, and cloud QPUs across engineering disciplines.

QuACC

Quantum-Accelerated Computing Center

Quantum Processor
annealing + gate-based QPUs

Classical Orchestrator
decompose, schedule, aggregate

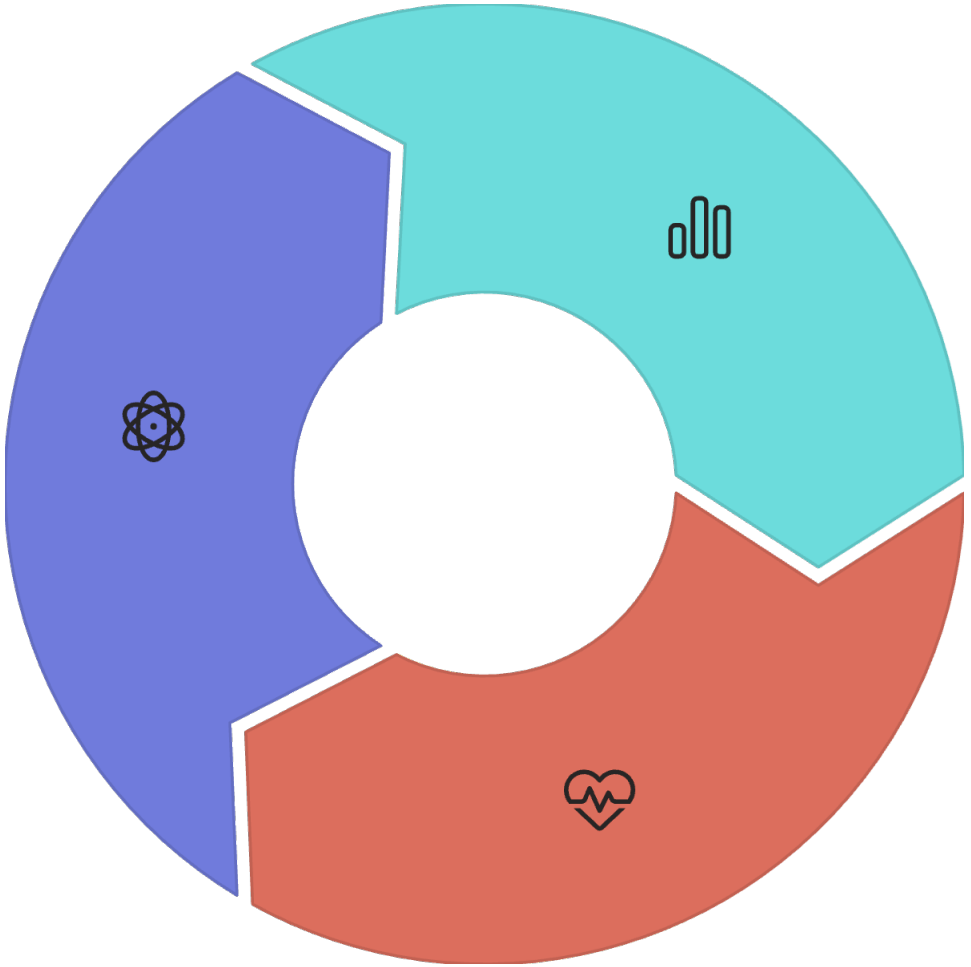
CAD / Manufacturing
design space + constraints

Shared infrastructure for quantum-classical engineering design

QuAD-FORGE Summary

Hamiltonian Encoding

CAD constraints as QUBO



Hybrid Algorithms

Superposition, interference, reduce

Quantum-Sensed Validation

Turbine blade case study

Dedication

Prof. David Dornfeld

Q&A

Acknowledgements:

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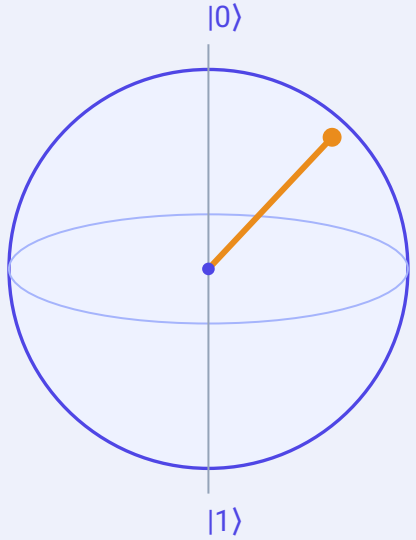

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