An Invitation to the intersection of
Quantum Computing & Programming Languages

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QuICS & UMD

UNIVERSITY OF MARYLAND

JOINT CENTER FOR QUANTUM INFORMATION AND COMPUTER SCIENCE

Analysis of Algorithms Artificial Intelligence
Combinatorial Algorithms Compilers Computational Complexity
Computer Architecture Computer Hardware Cryptography
Data Structures Databases Education Error Correcting Codes Finite Automata Graphics
Interactive Computing Internet Communications List Processing Numerical Analysis
Numerical Methods Object Oriented Programming Operating Systems Personal Computing
Program Verification Programming
Programming Languages Proof Construction Software
Theory Software Engineering
Verification of Hardware and Software Models Computer Systems Machine Learning
Parallel Computation

Computational Thinking in Quantum Computing

Quantum Application

Algorithm & Complexity

Variational Methods

Programming Languages

How to effectively express quantum applications and do trouble shooting?

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Quantum Application

Algorithm & Complexity

Variational Methods

Programming Languages

System

Architecture

Quantum Control

Quantum Hardware Design

How to effectively translate high-level descriptions of quantum applications to quantum machine instructions?

How to automate the design of quantum devices and its verification?

PL as a tool for non-PL expert to explore

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- **(computational thinking)** developing abstractions is at the heart of developing PL/FM techniques

The Role of Programming Languages

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Disclaimer: perspectives and claims are potentially limited or biased by personal knowledge.

How to Program Q. Applications, Debug, and Verify Correctness?

How to Develop Software for Q. Computing, e.g., compiler, system?

How to Design and Implement Architecture for Quantum Computing?

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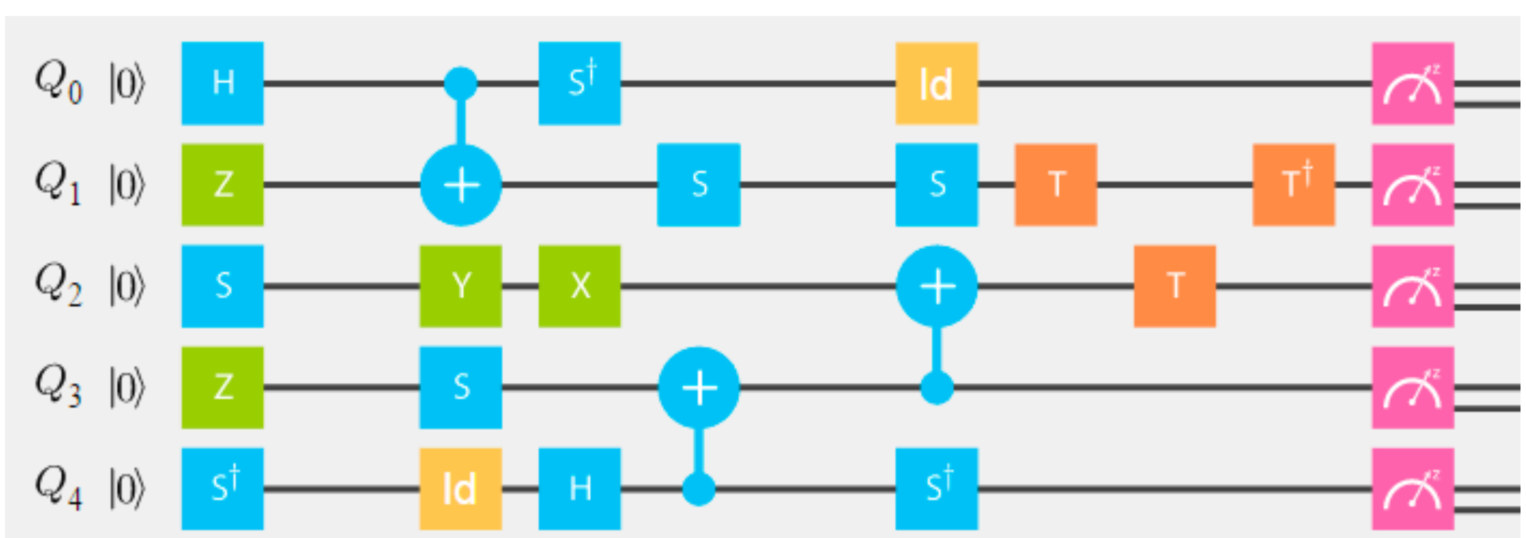

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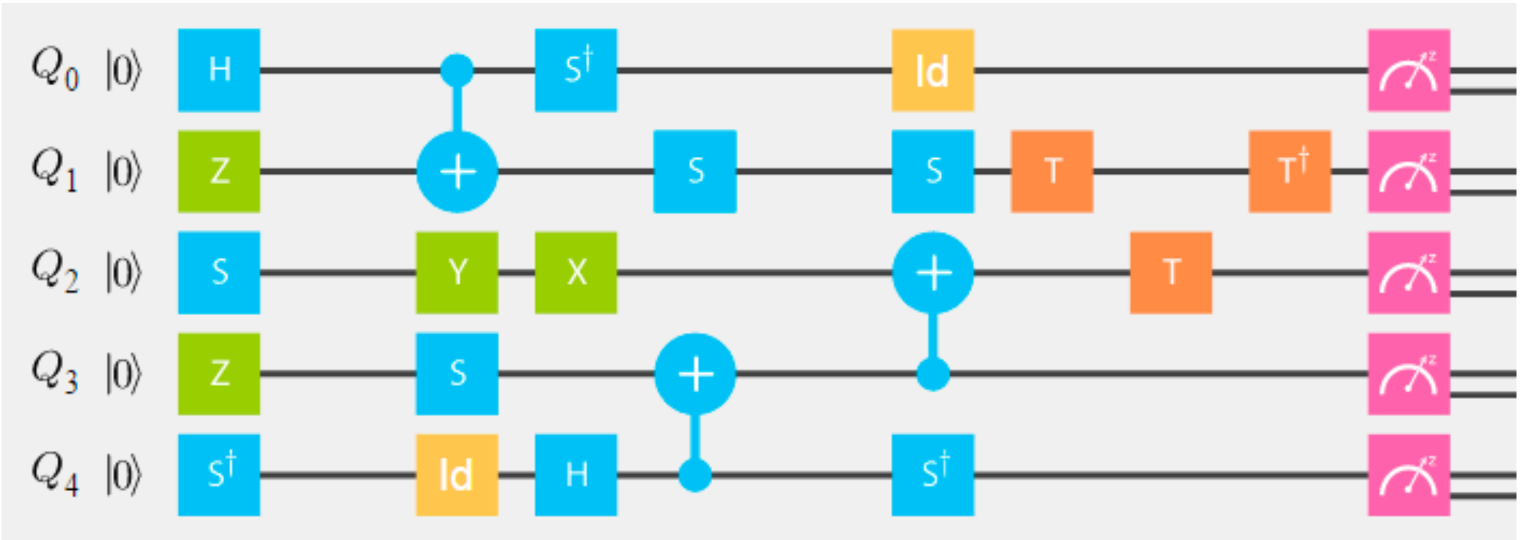

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(3) lack of many desirable analyses, automation, & optimization: a lot of burdens on the programmers

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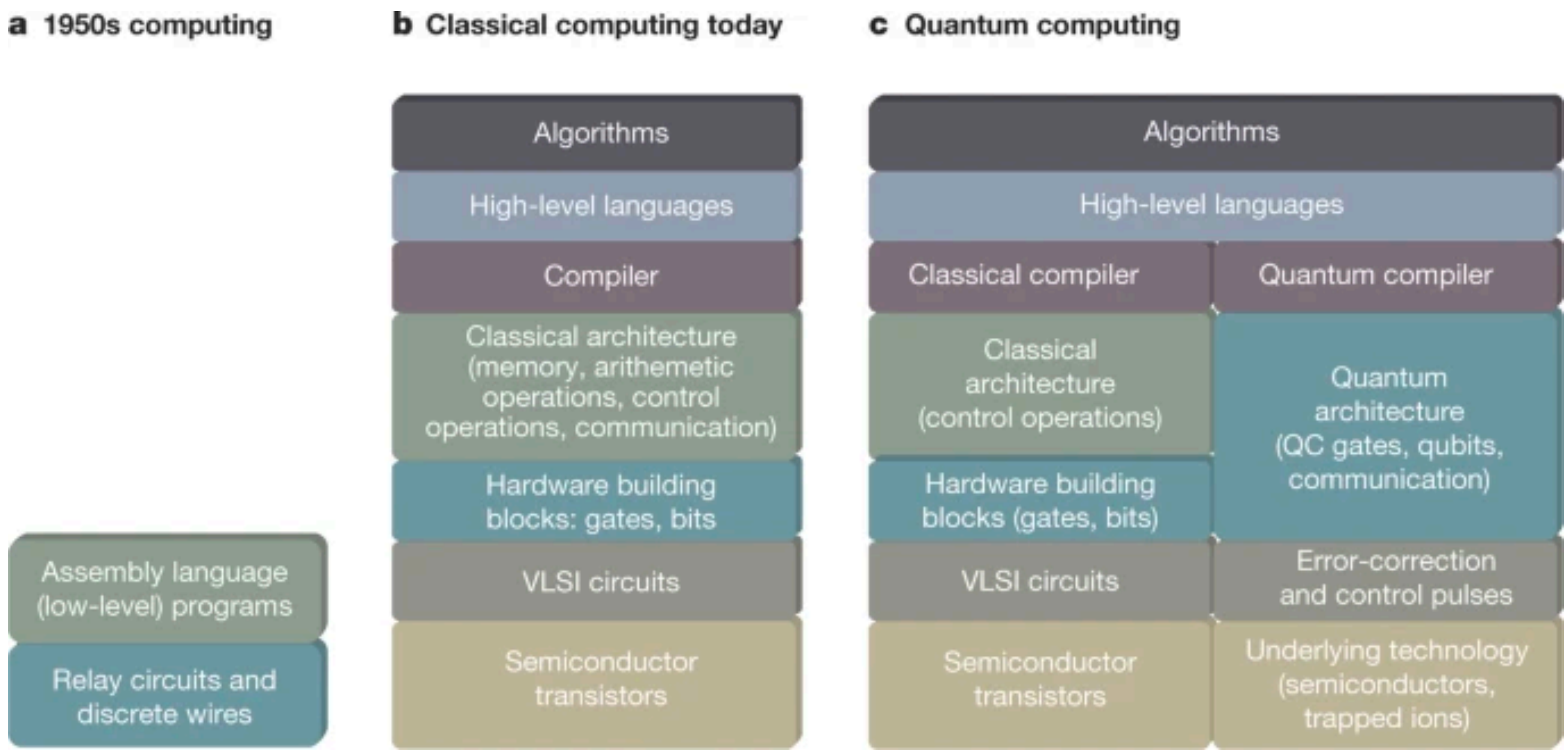

F. Chong, D. Franklin, M. Martonosi, Nature 549, 180

Large Design Space for System Software for Quantum Computers.

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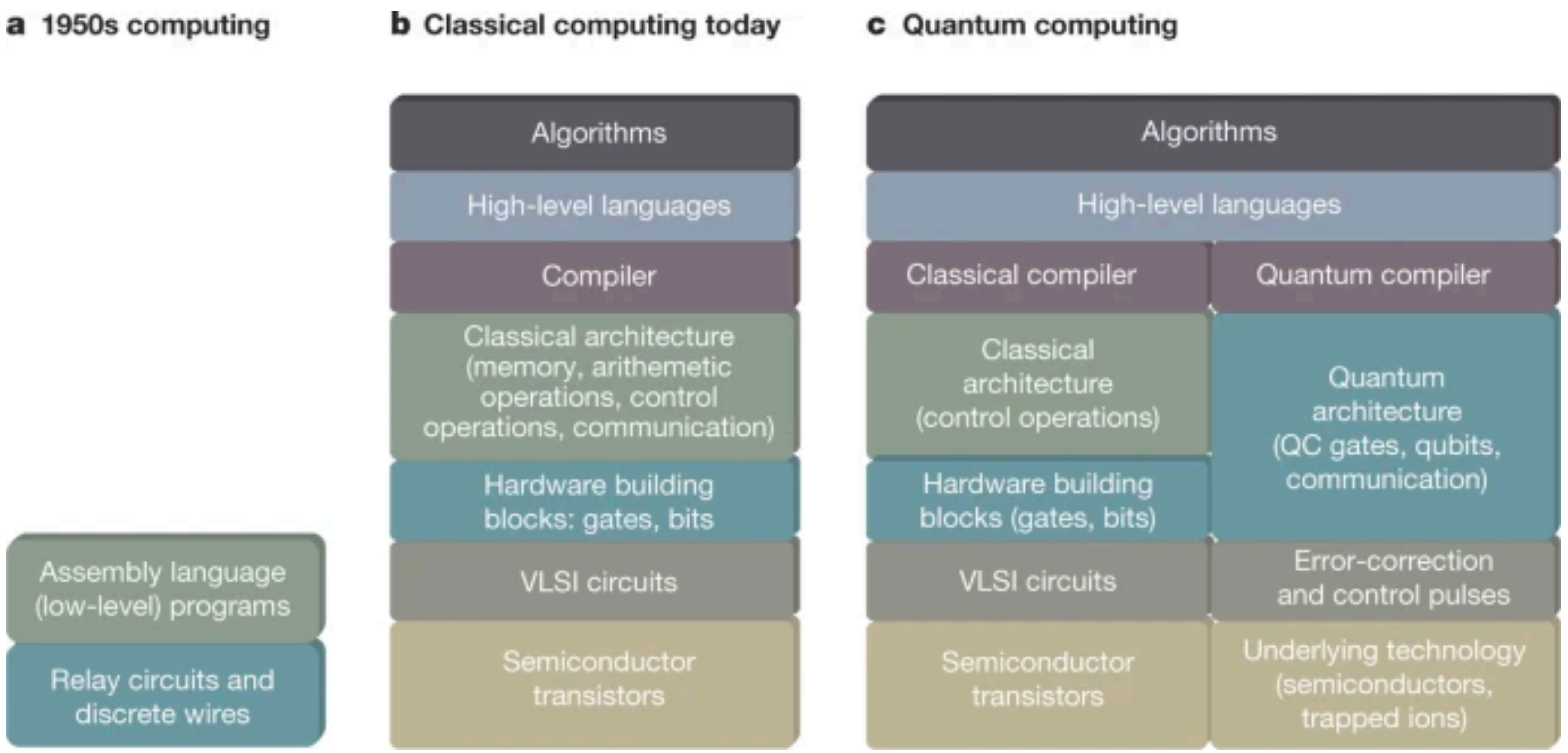

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High-Assurance Software Tool-chain both desirable and challenging.

- standard software assurance techniques, e.g., black-box / unit test, expensive in q.
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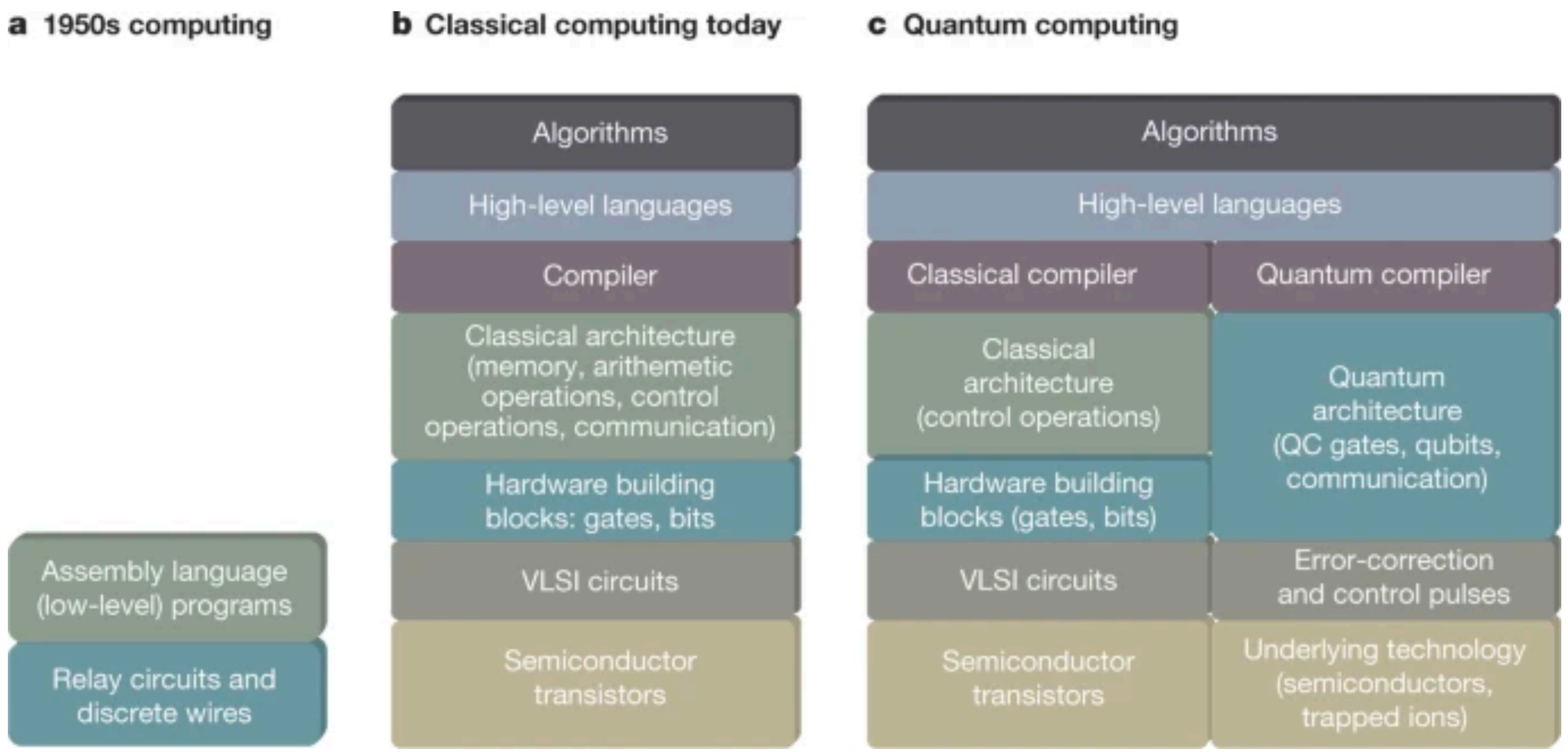

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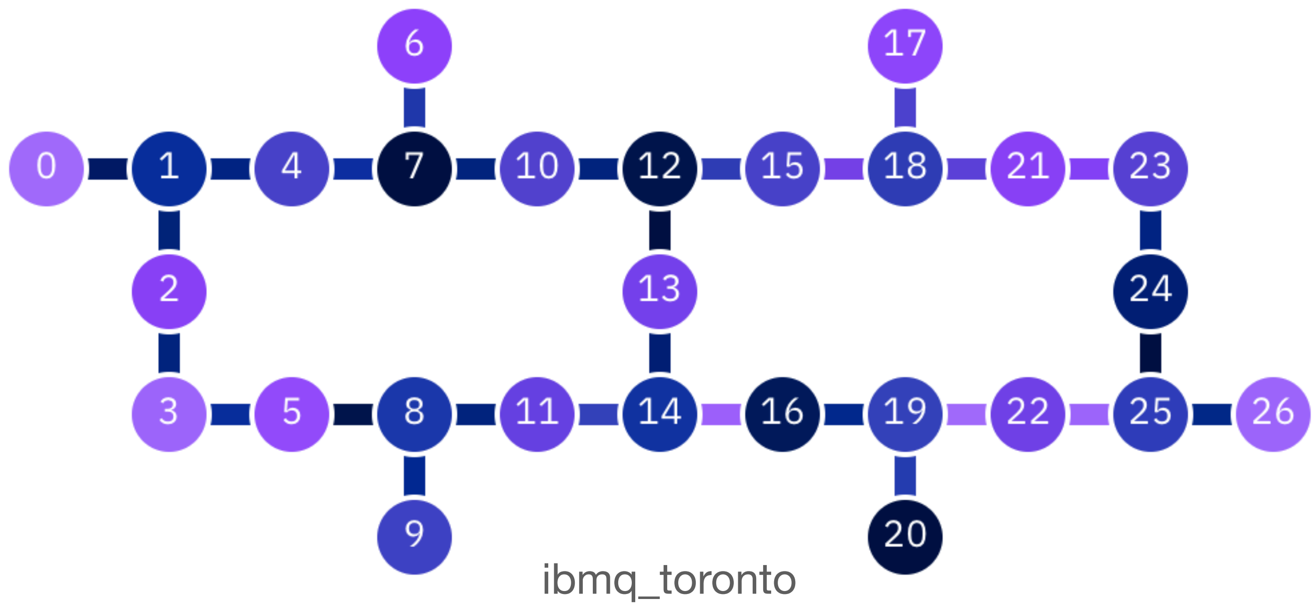
A possible solution : fully certified software, e.g., VOQC (POPL 2021)

How to Design and Implement **Architecture** for Quantum Computing?



Mapping, Error Mitigation, …

approximate computing

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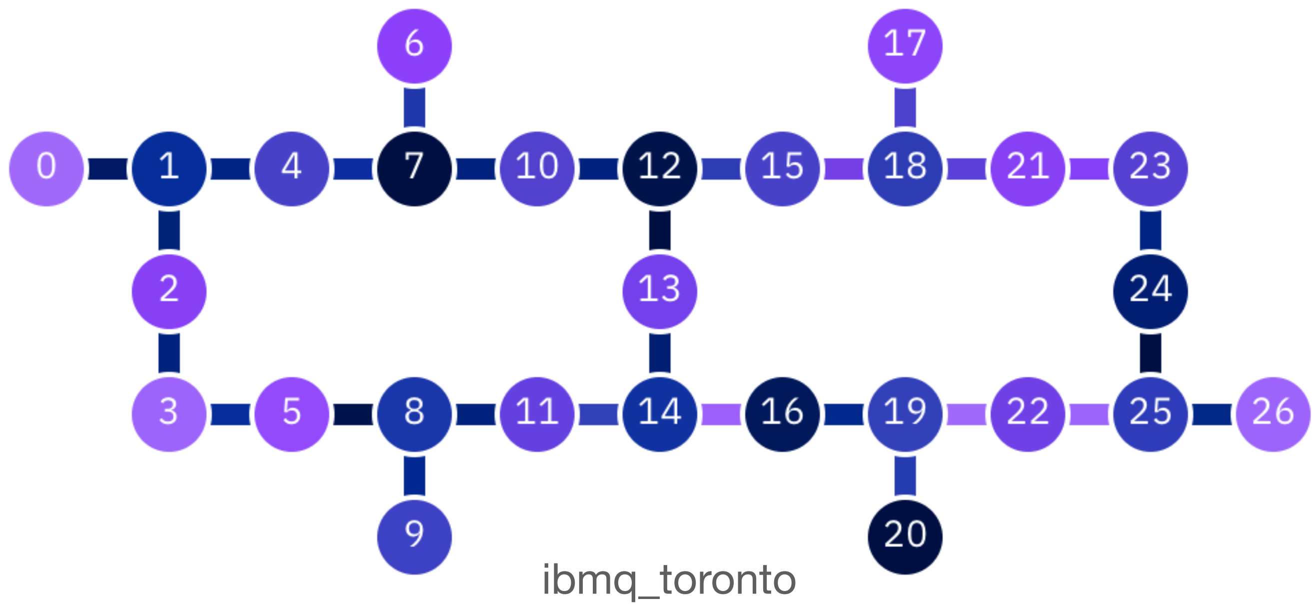

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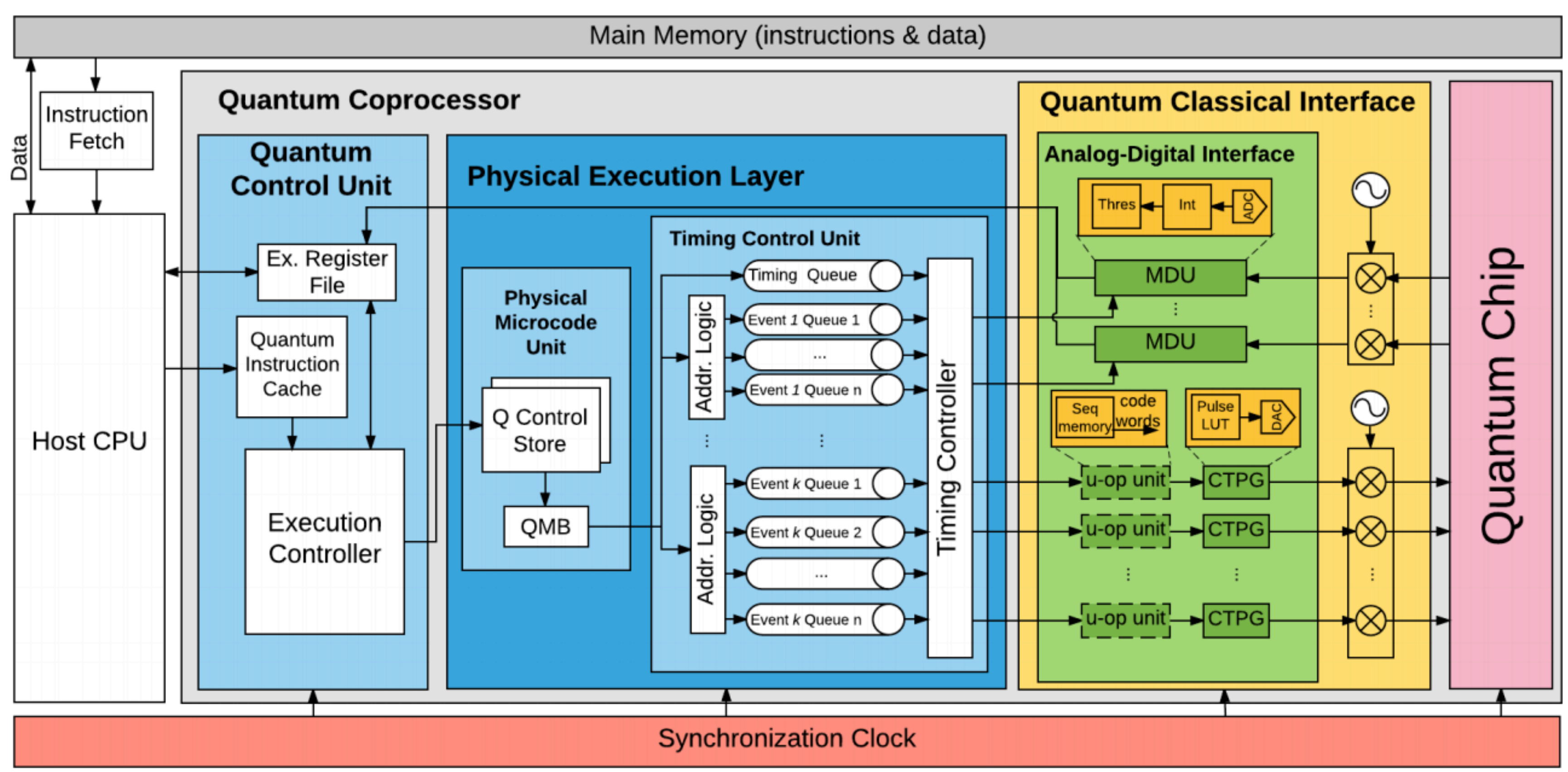
A lot of controlling operations need to be located close to quantum chips for small responsive time.

ISA + Fast Compilation



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How to Handle Quantum Security Issues in Design and Implementation?

Verification of Quantum Cryptography:

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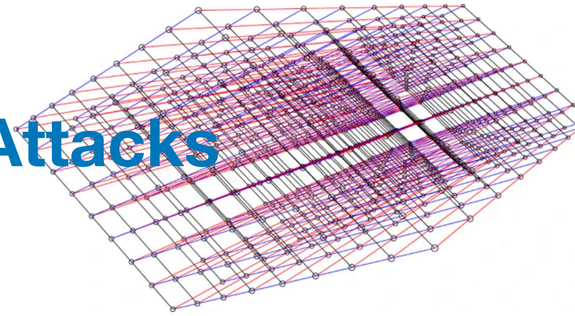
Post-Quantum Cryptography:

Classical Cryptographic Systems Resilient to Quantum Attacks

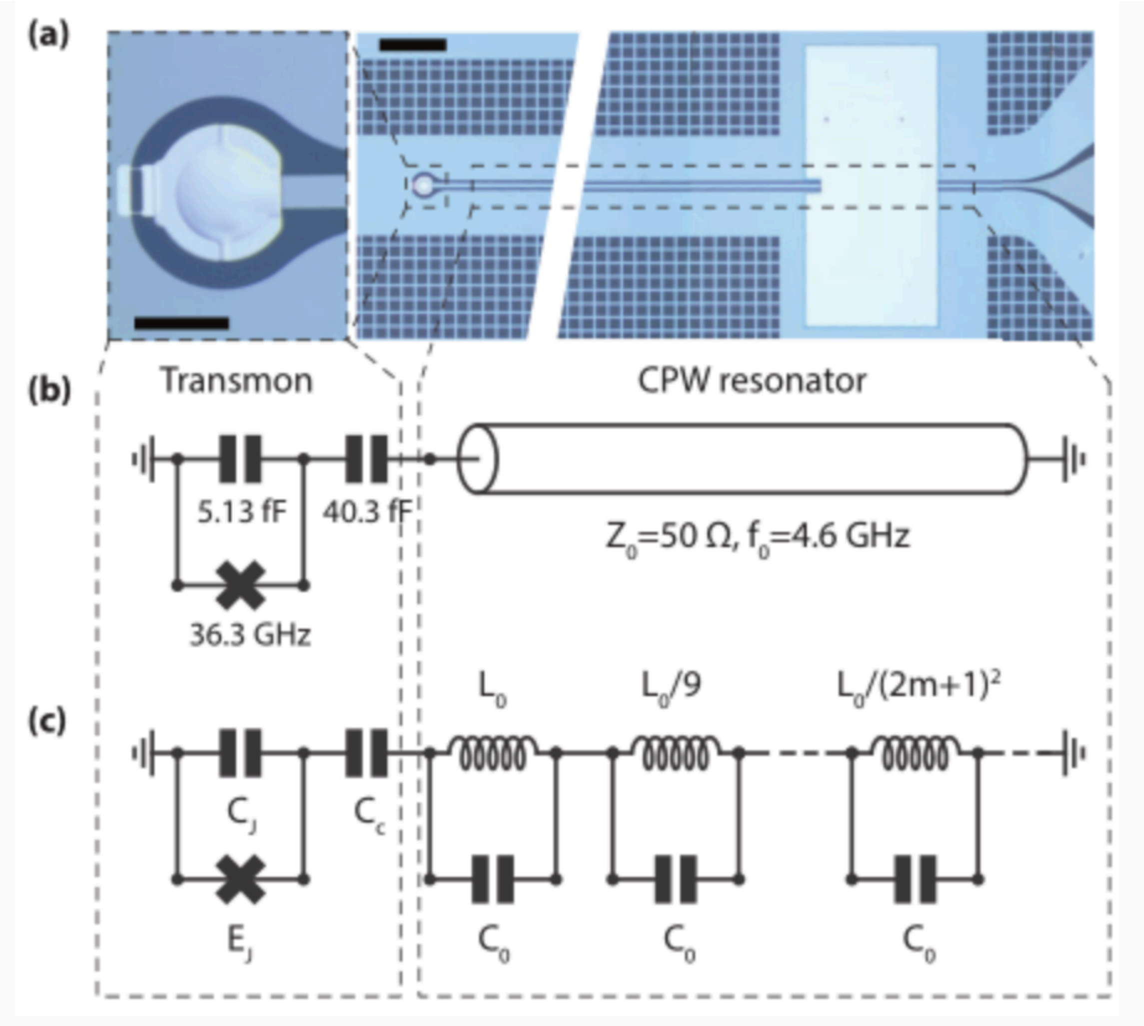


For Classical Cryptographic Systems

(1) Identify their post-quantum security
(2) automate the procedure to upgrade its post-quantum security
(3) formal post-quantum security proofs

Formally generated security analysis will provide not only efficient and high assurance proofs that can replace the tedious and error-prone analysis for experts, but also independently verifiable proofs that can be used by security practitioners without much quantum knowledge.

How to Scale and Automate the Design of Quantum Hardware ?



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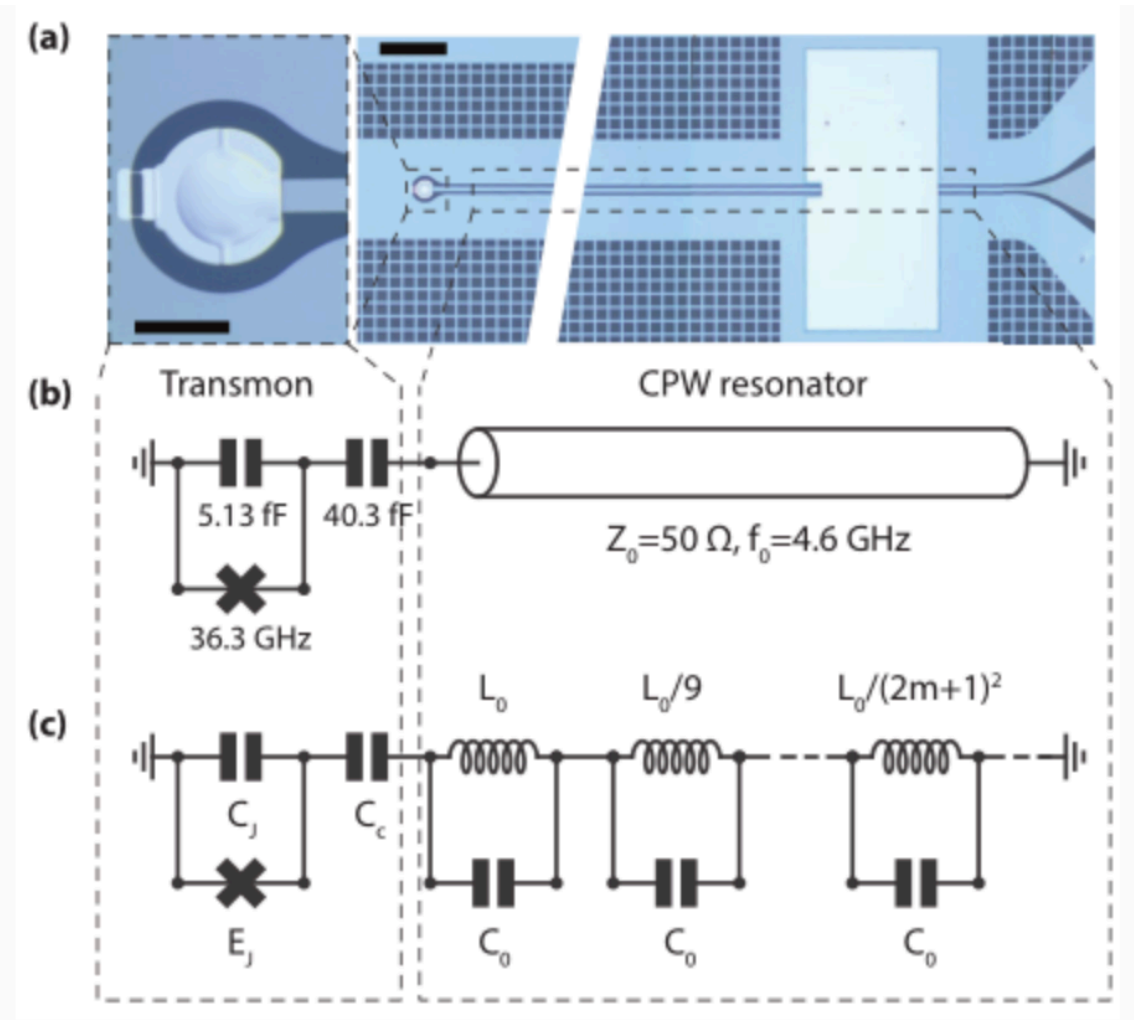

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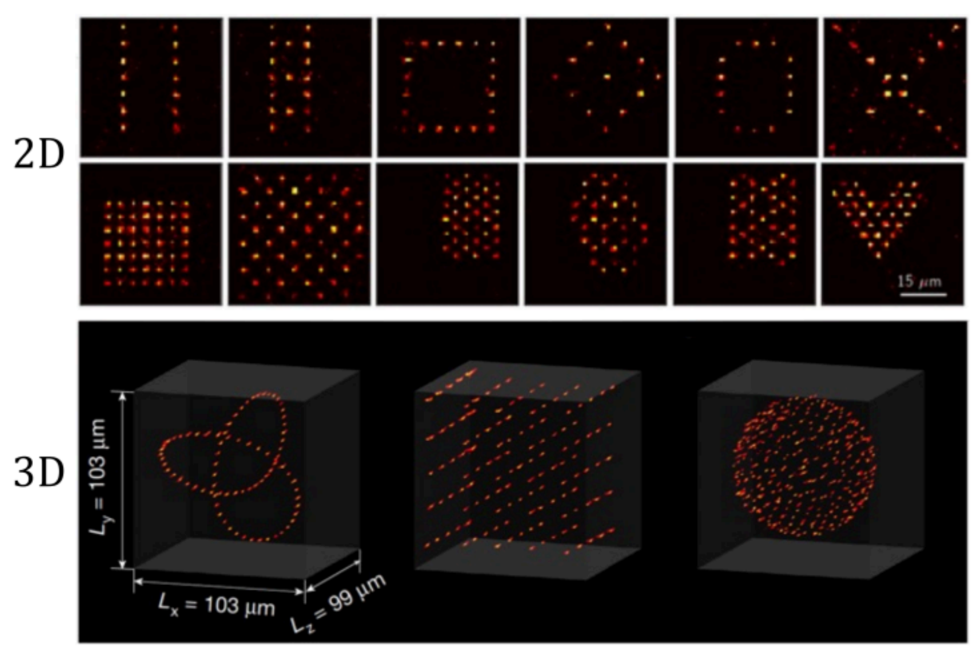

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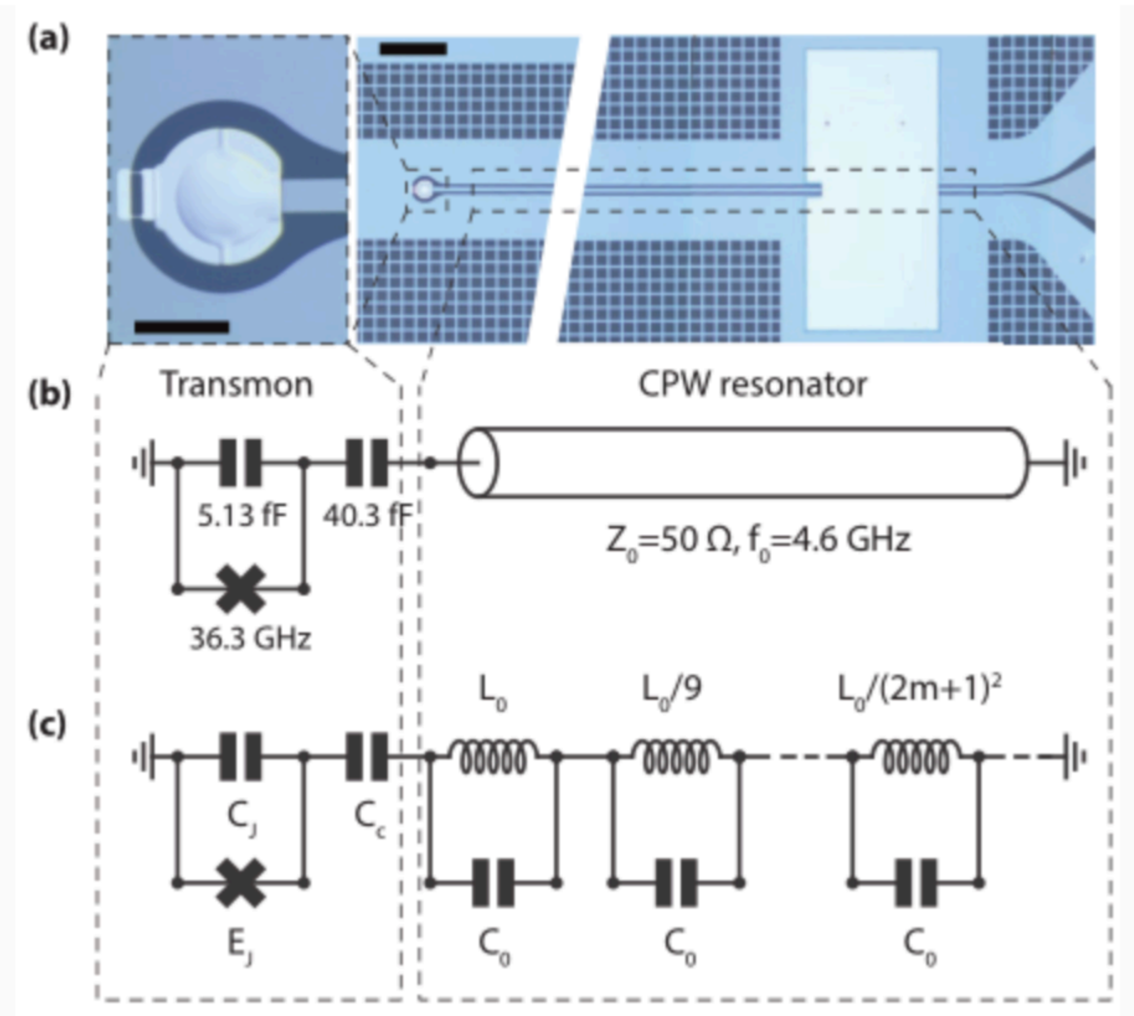

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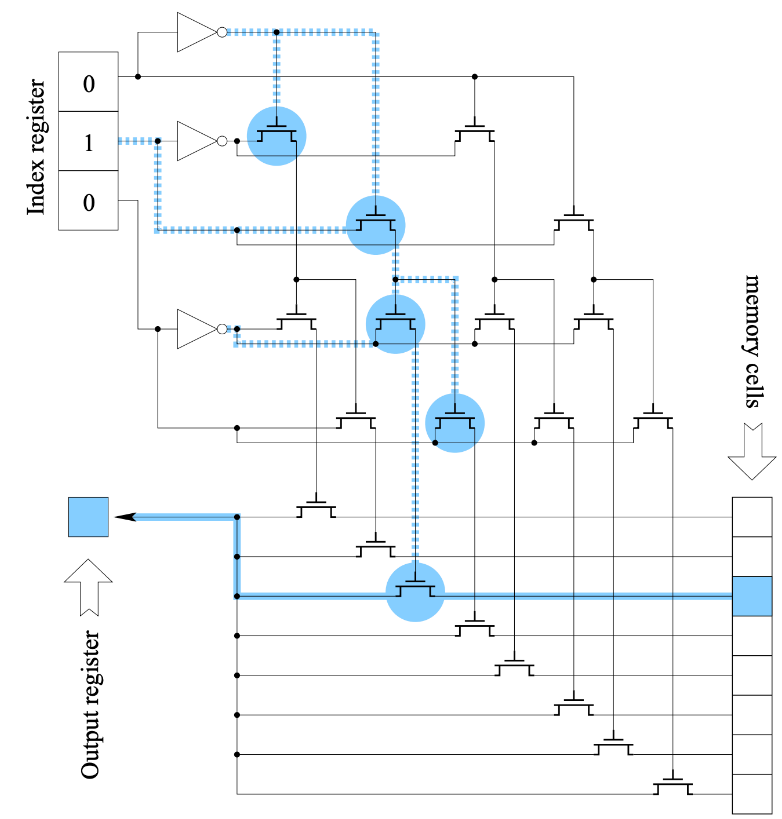
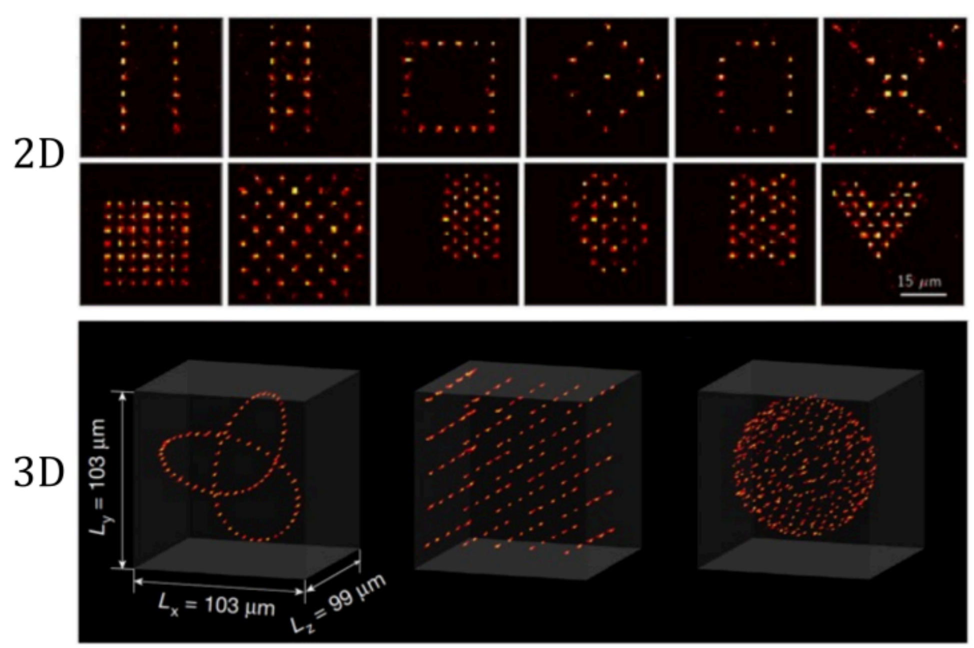


QRAM Architecture
Credit: ArXiv 0807.4994



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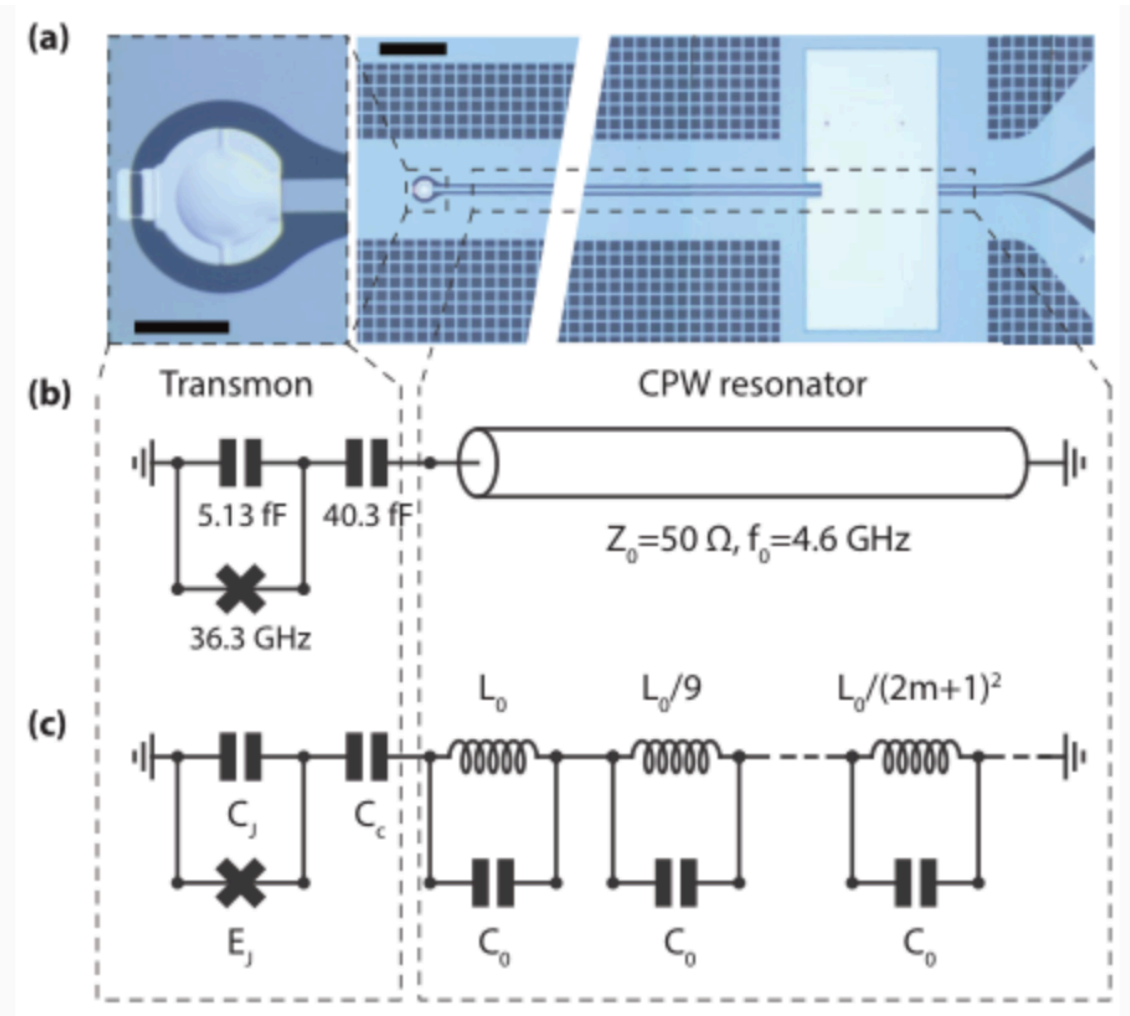

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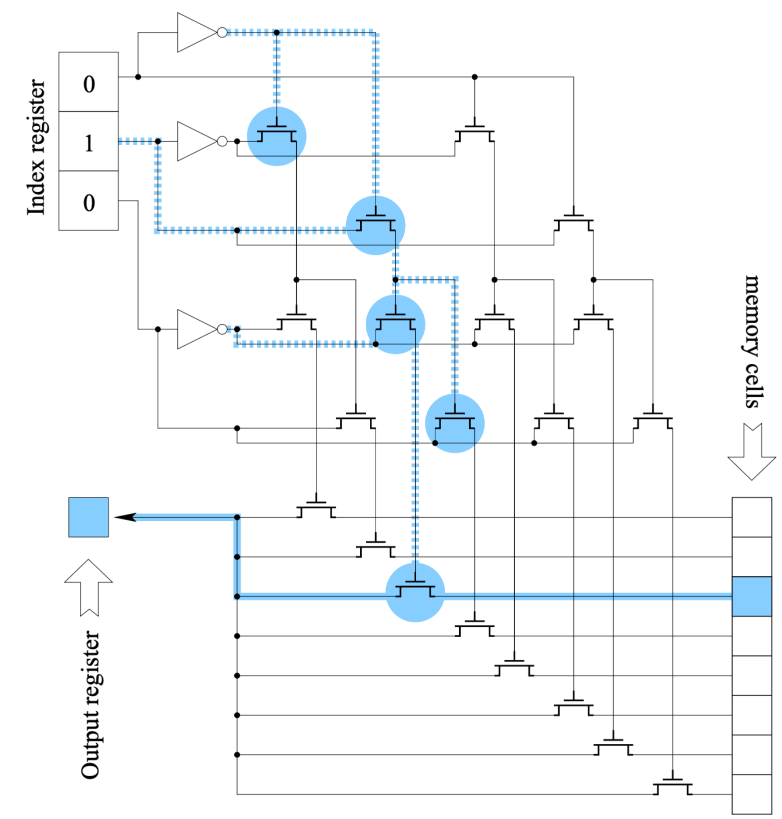

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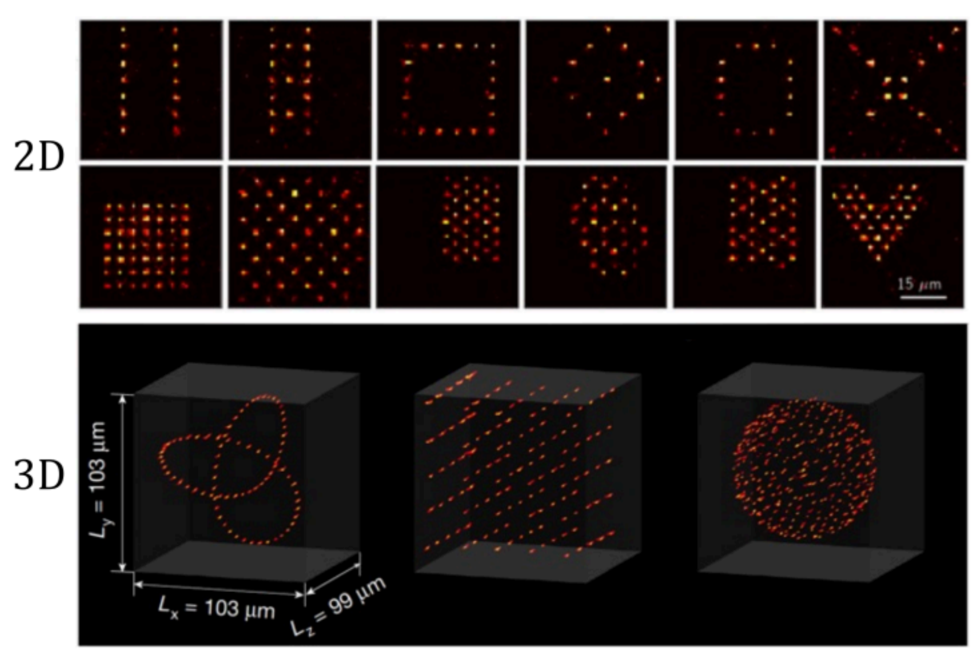
Demonstrate A Lot of Design Choices
Hard to Scale without Automatic Tools



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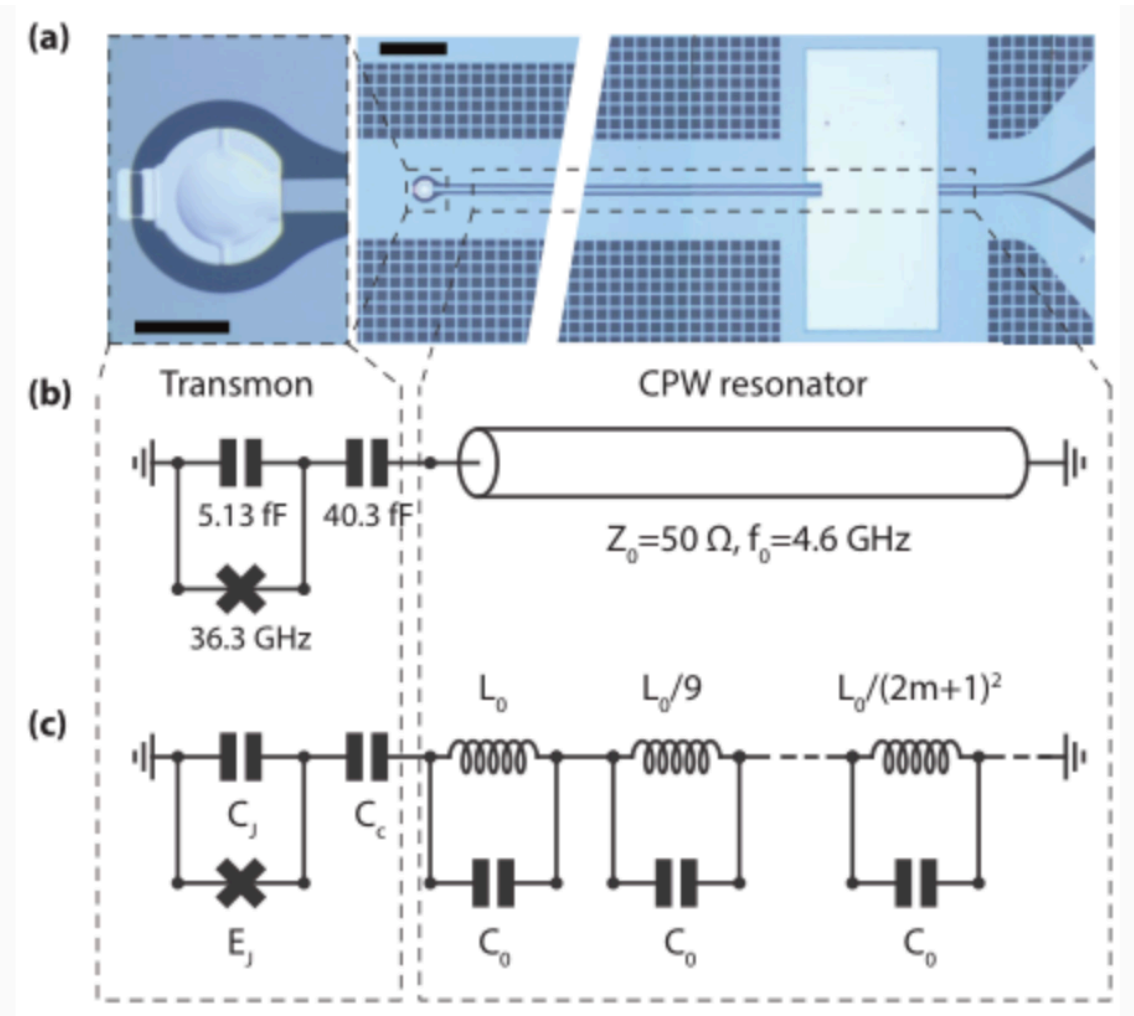

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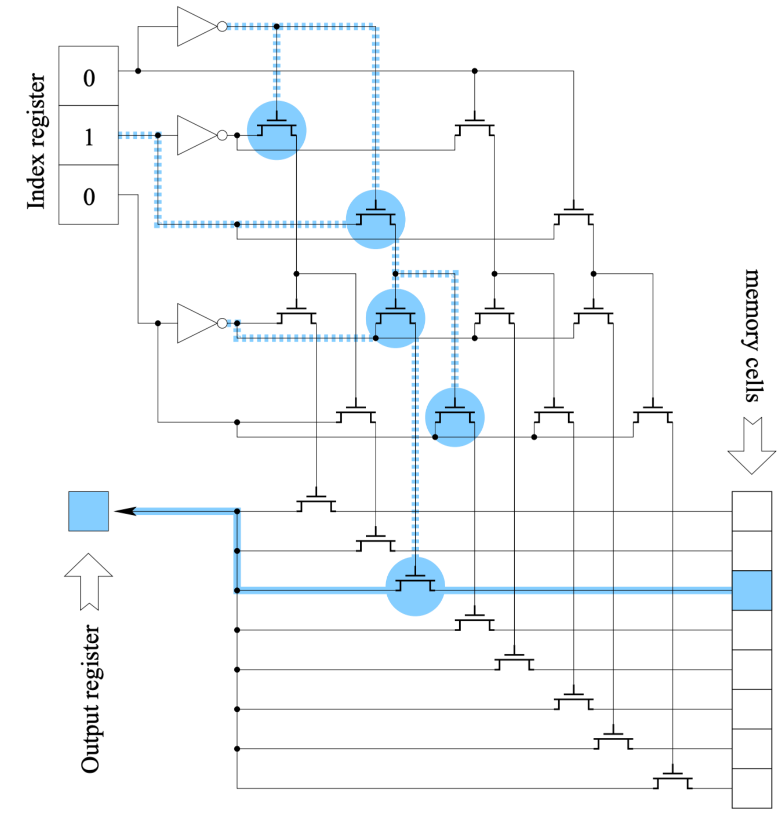

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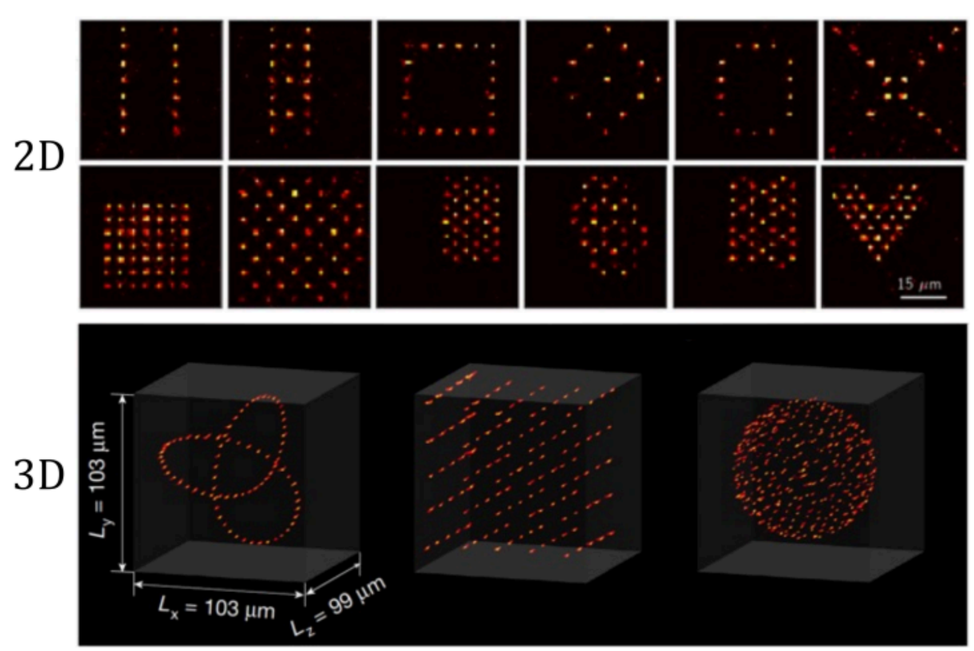

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A Golden Age of Hardware Description Languages: Applying Programming Language Techniques to Improve Design Productivity

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Pat Hanrahan
Stanford University, USA
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SNAPL 2019

Verilog
HDL

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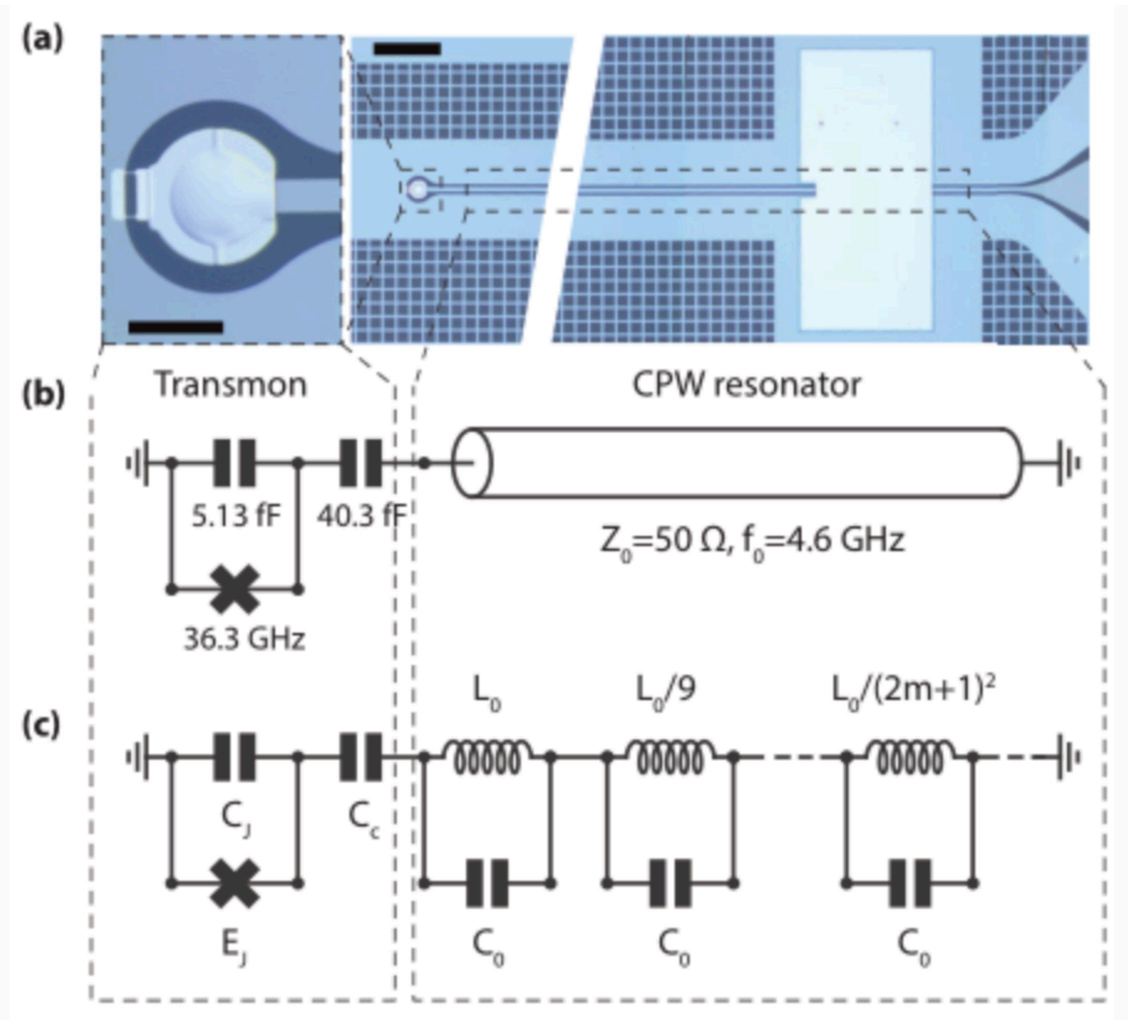

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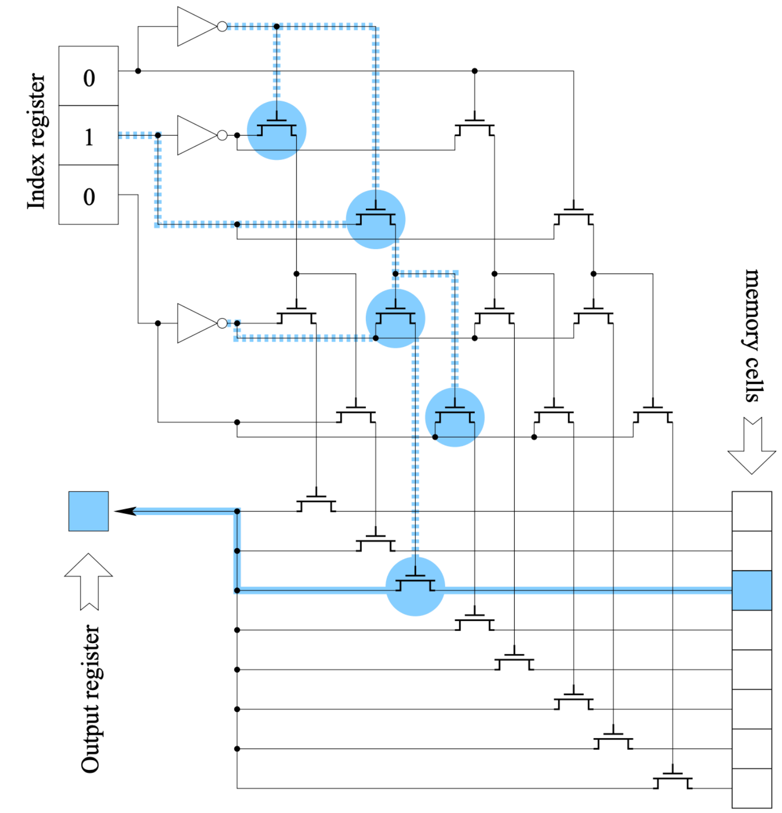

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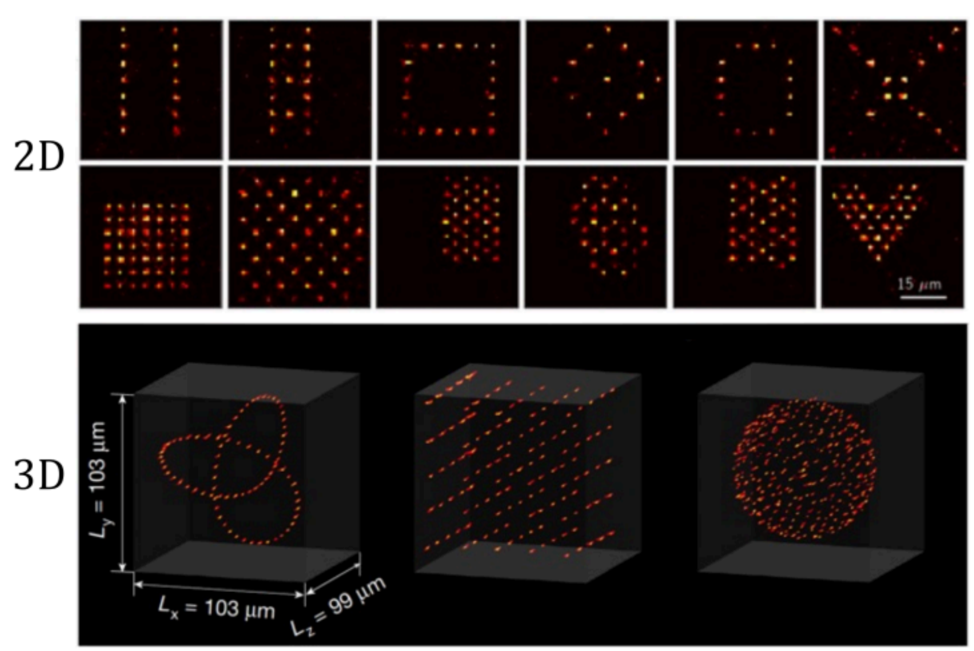

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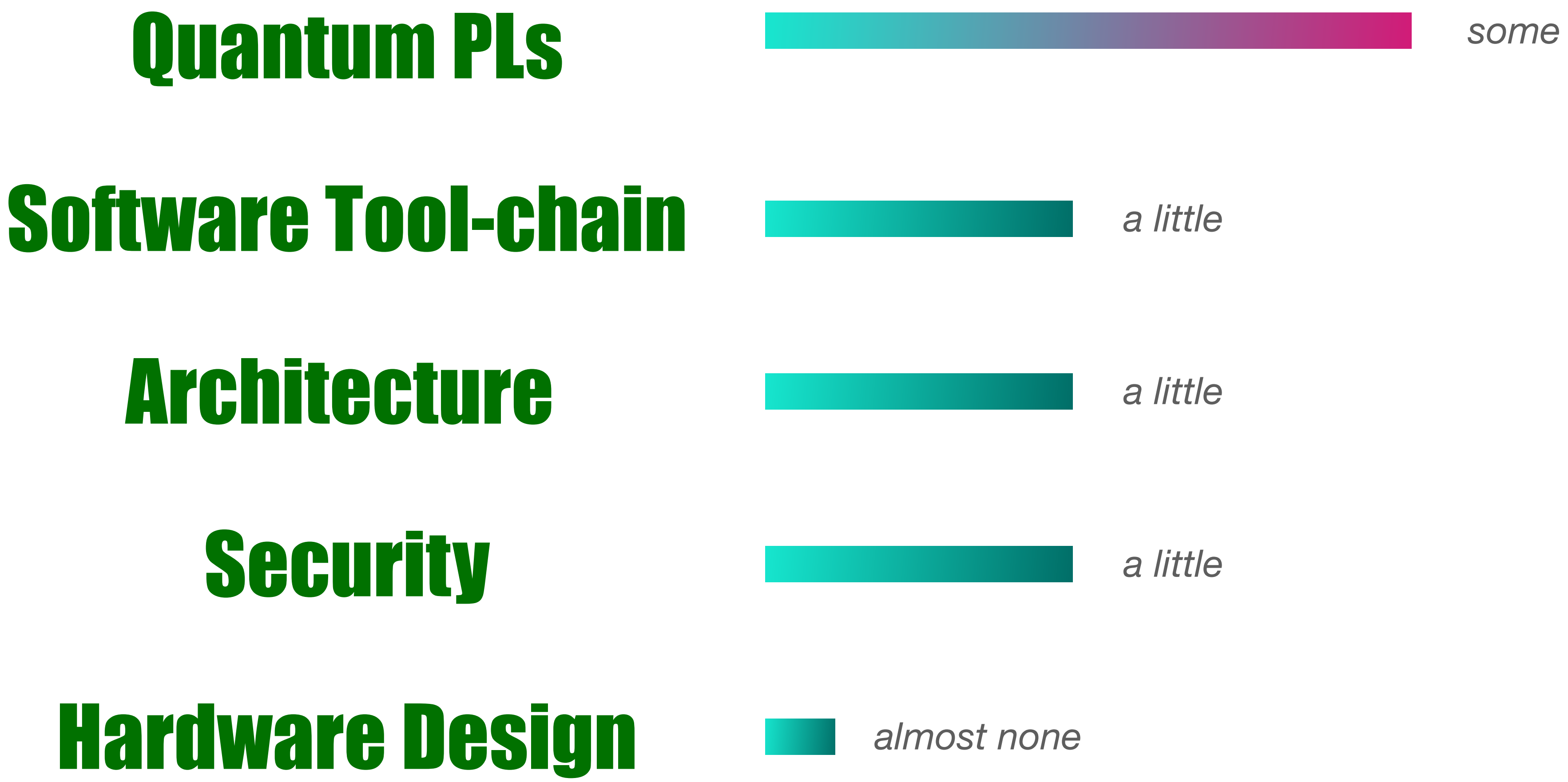
Applies to Quantum Hardware too!

Summary



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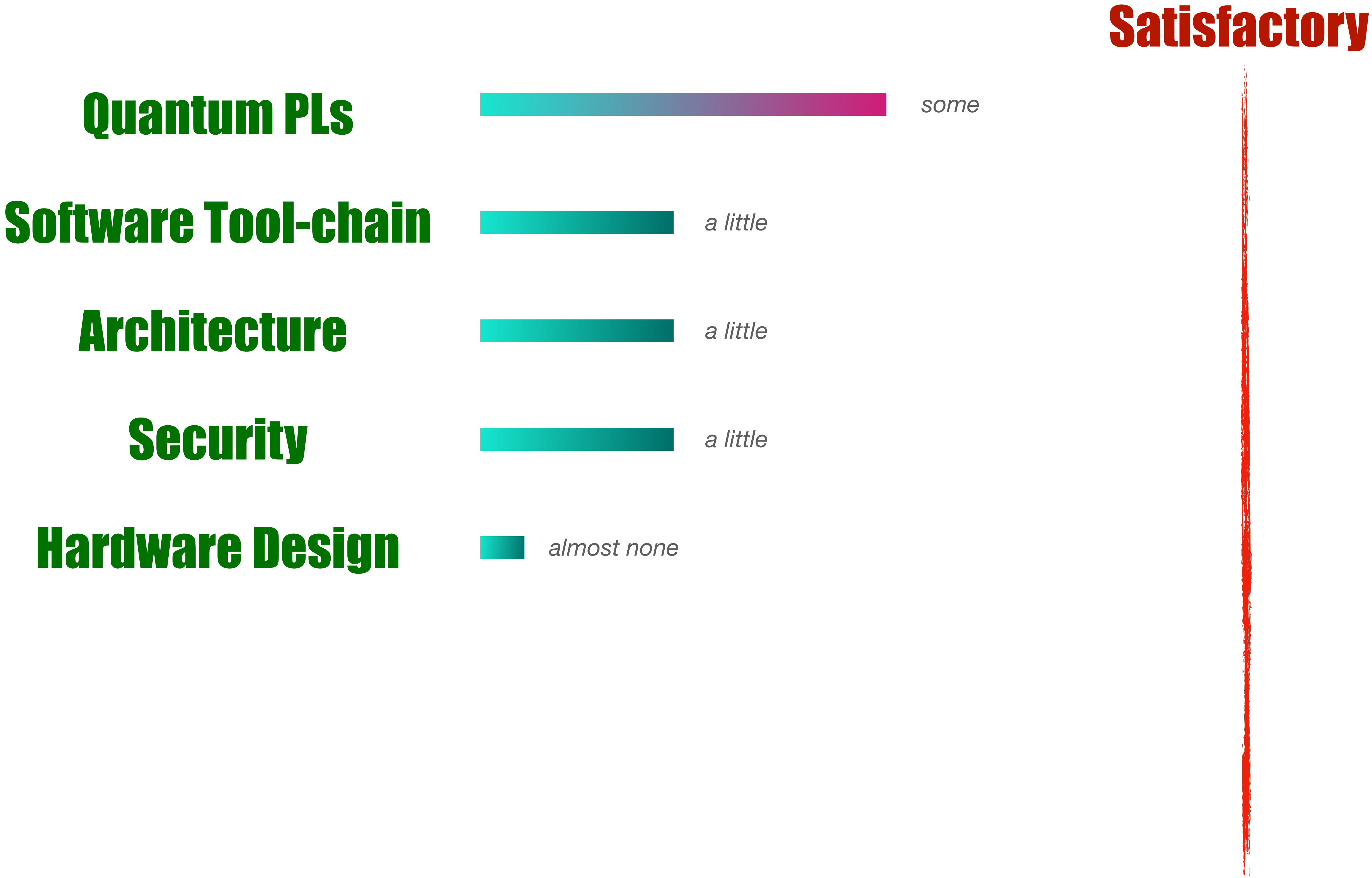
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More questions could be asked !

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More details will come back in Part III of the tutorial.

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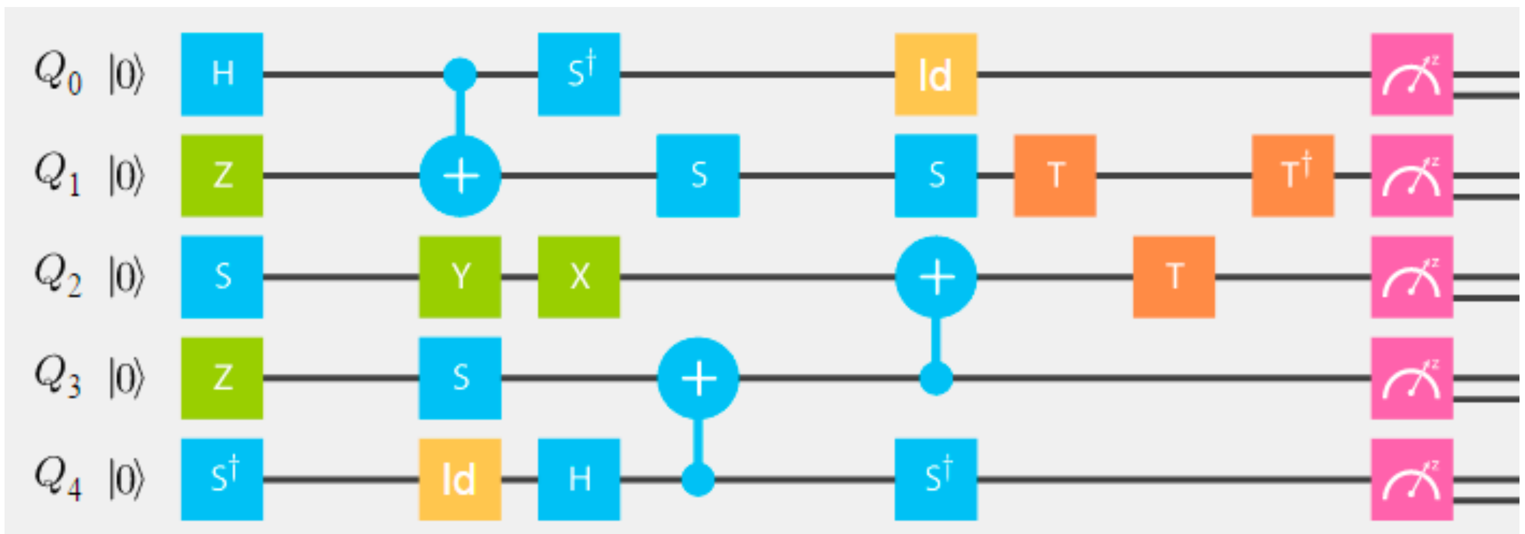
Gap: (1) too-low-level-abstraction: very hard to write **complex** programs

(2) lack of scalable verification: very hard to write **correct** programs



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by observation
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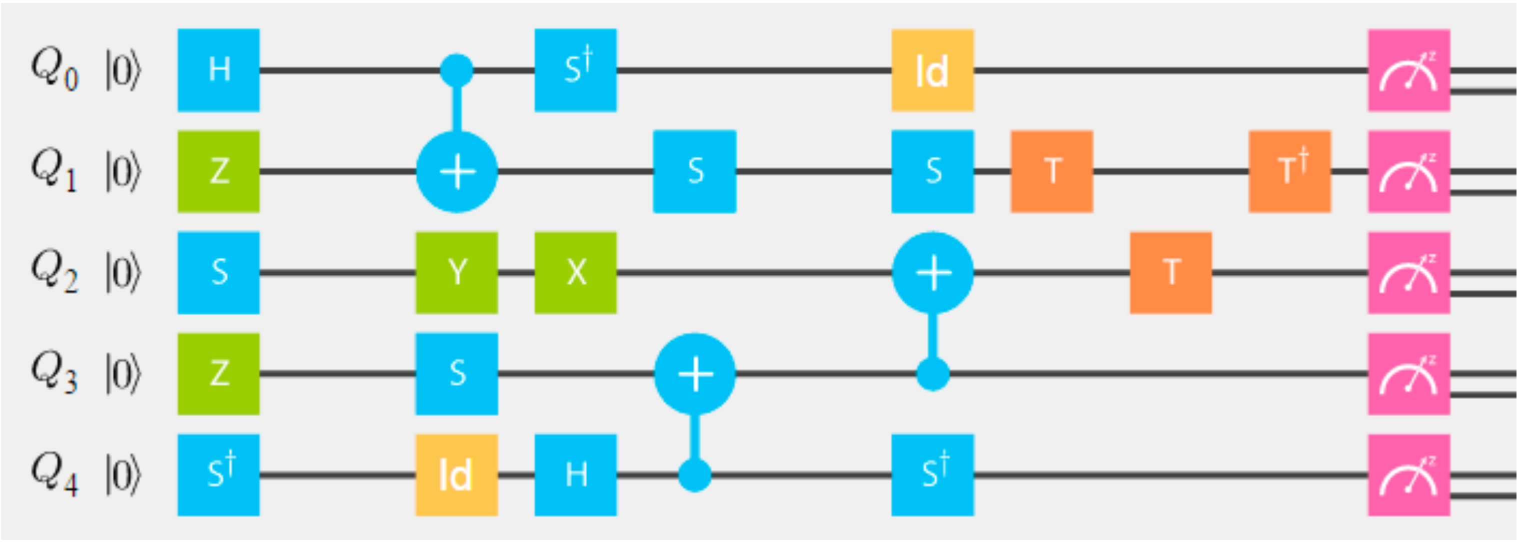

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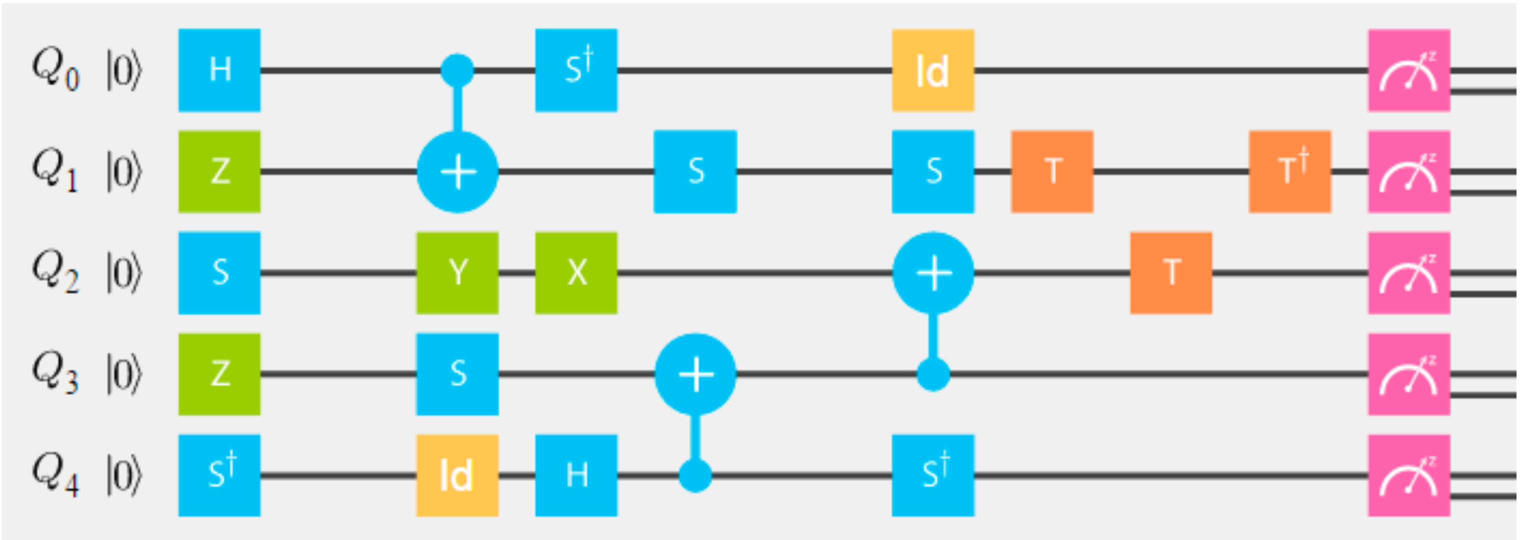

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Ancilla: keep track of the scope of ancilla qubits (Quipper)

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Develop Q Hoare logic for *parallel, concurrent, distributed* programs.

Some preliminary results exist. Essential difficulty exists due to quantum correlations.

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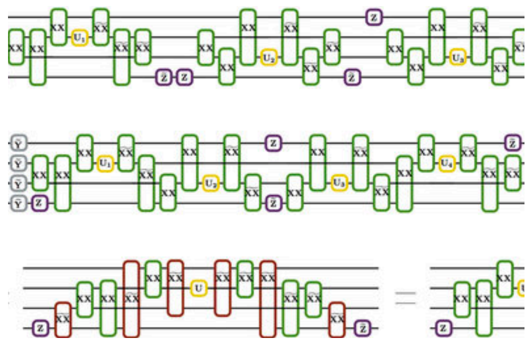
Likely to be application-specific



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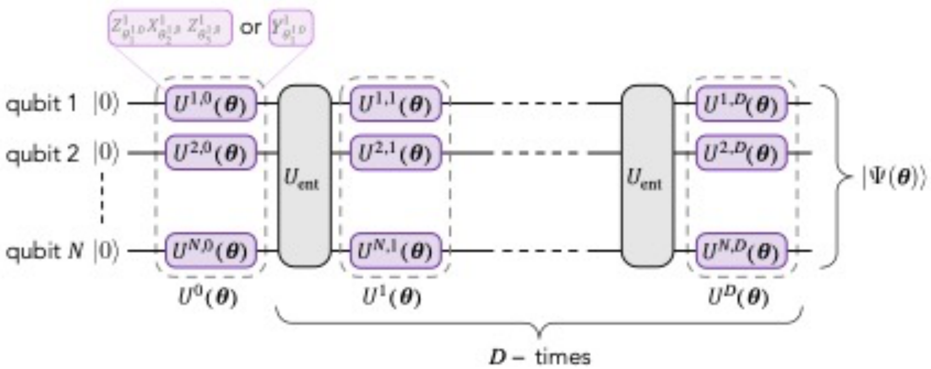

Variational Quantum Methods

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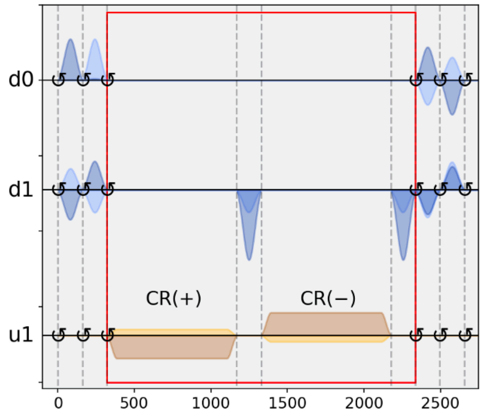

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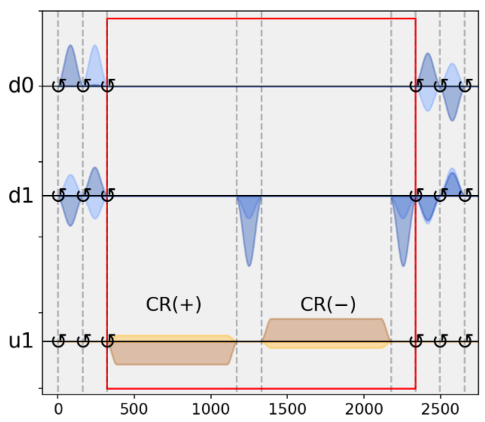

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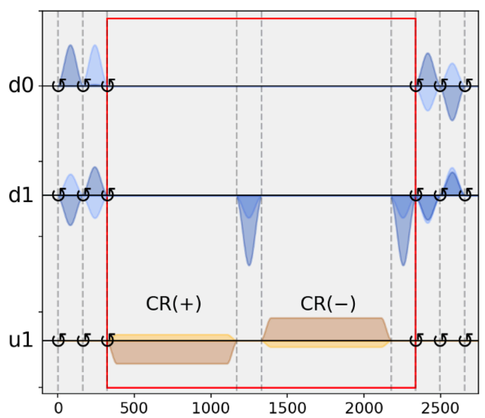

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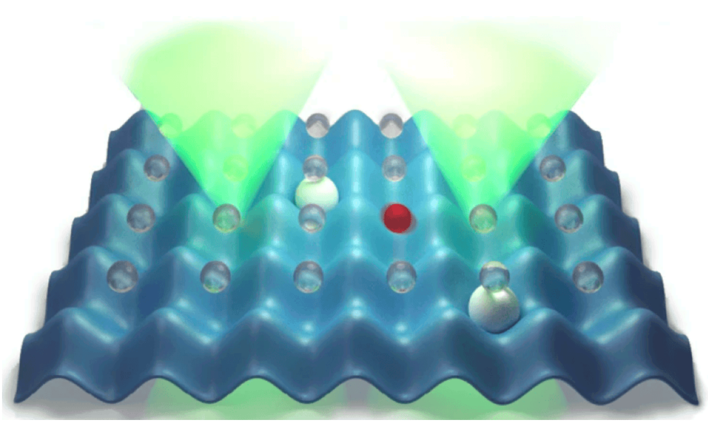

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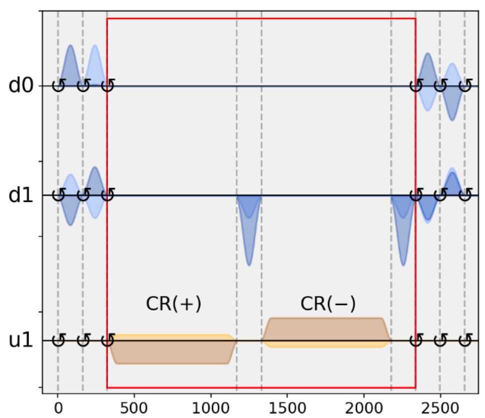

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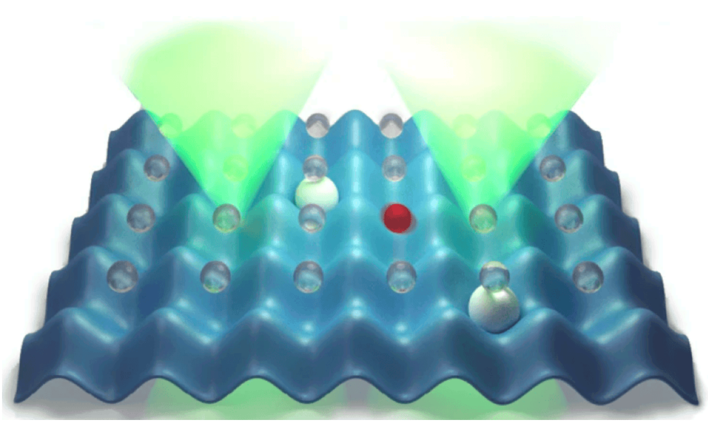

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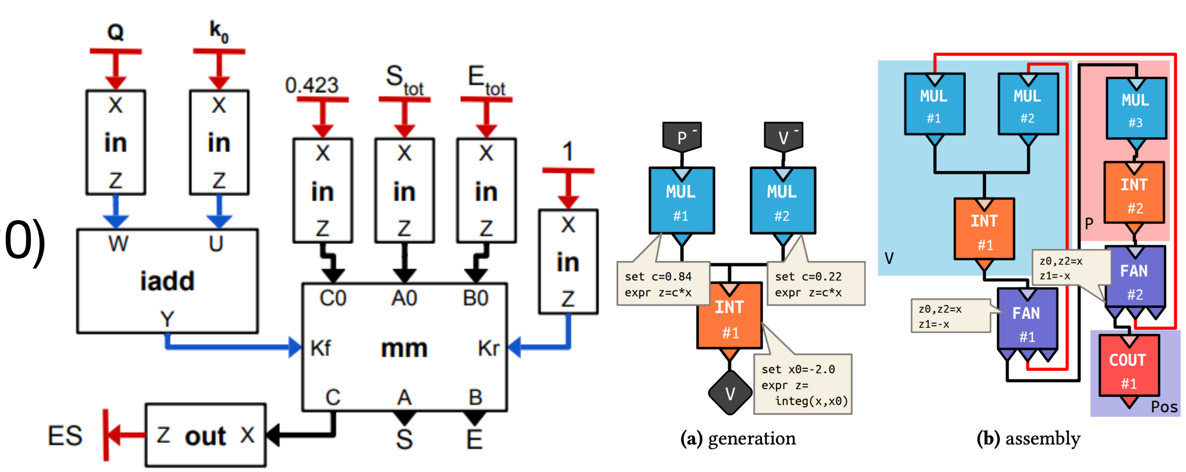
Classical Examples:

Achour et al. (PLDI16)

Achour & Rinard (ASPLOS 20)



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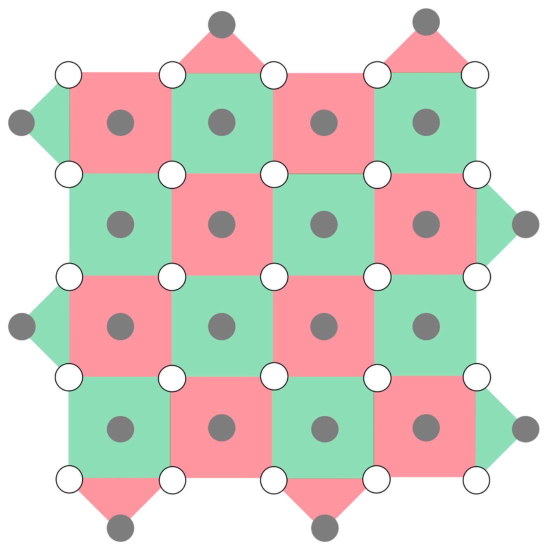

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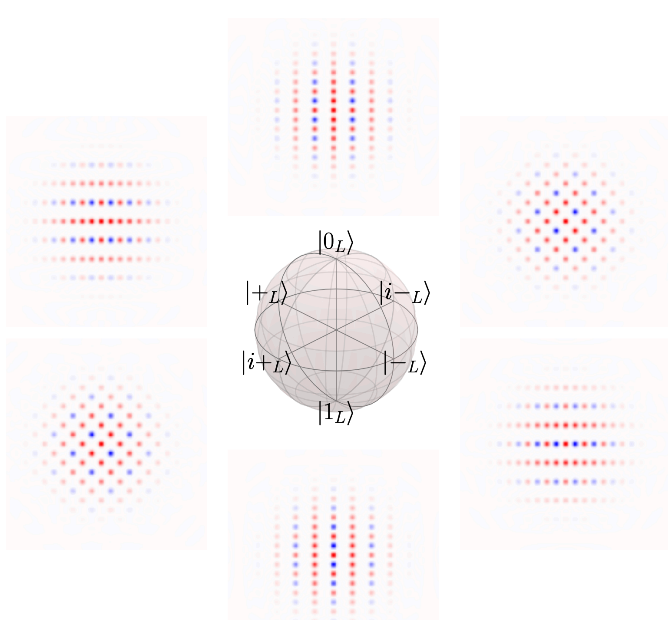

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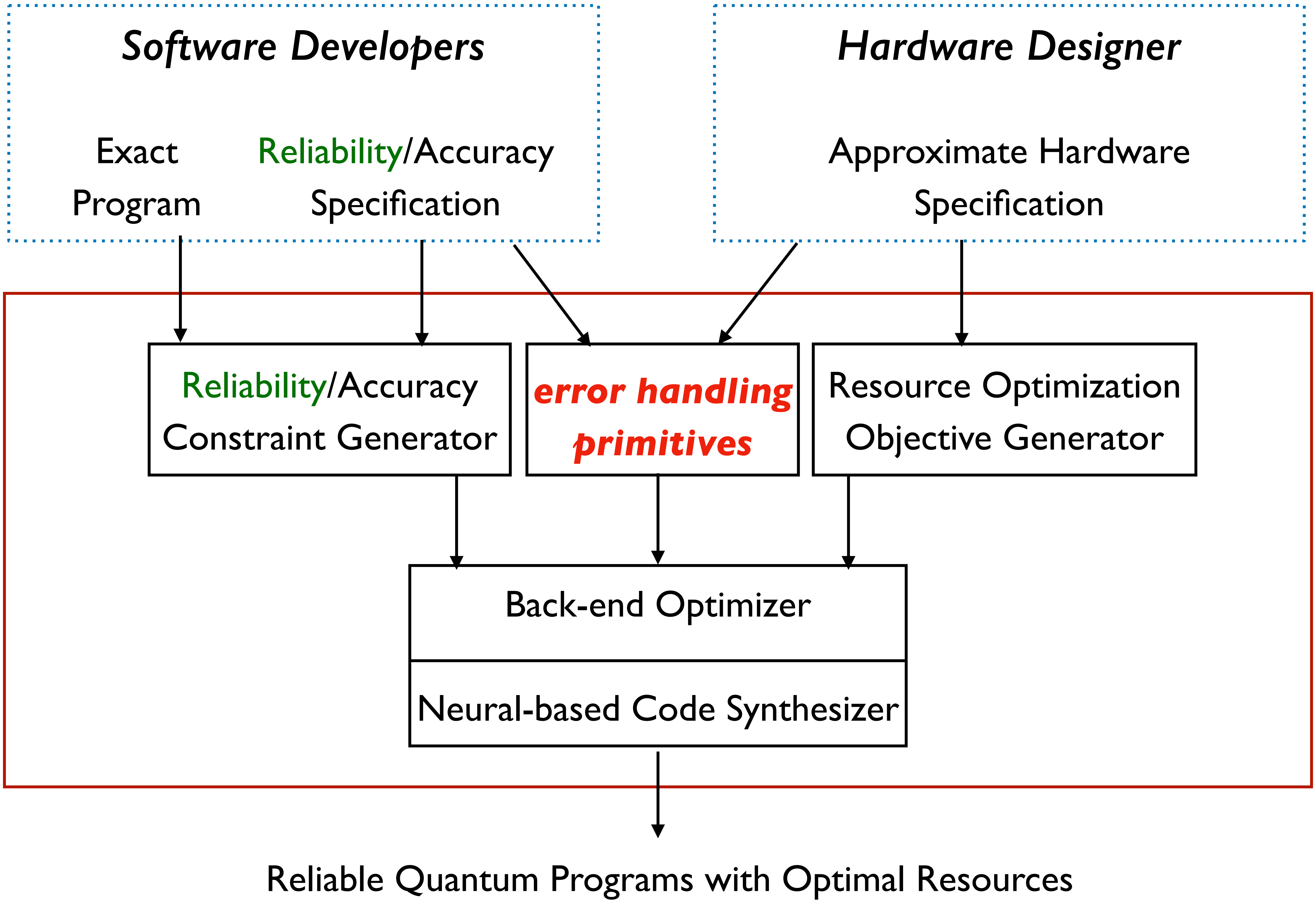
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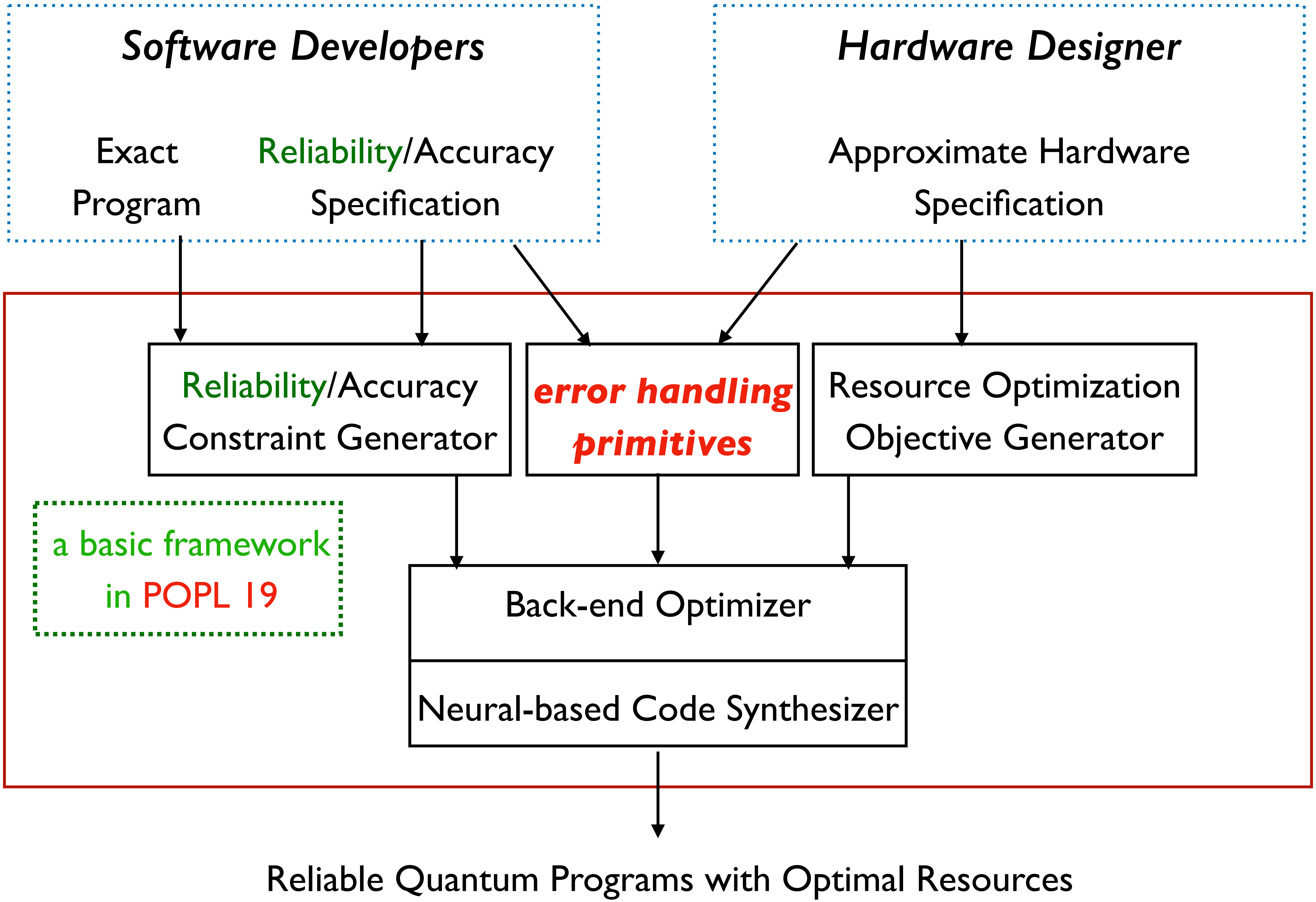

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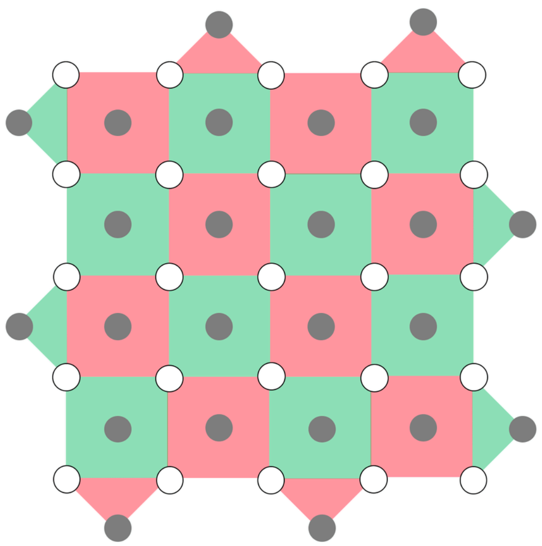

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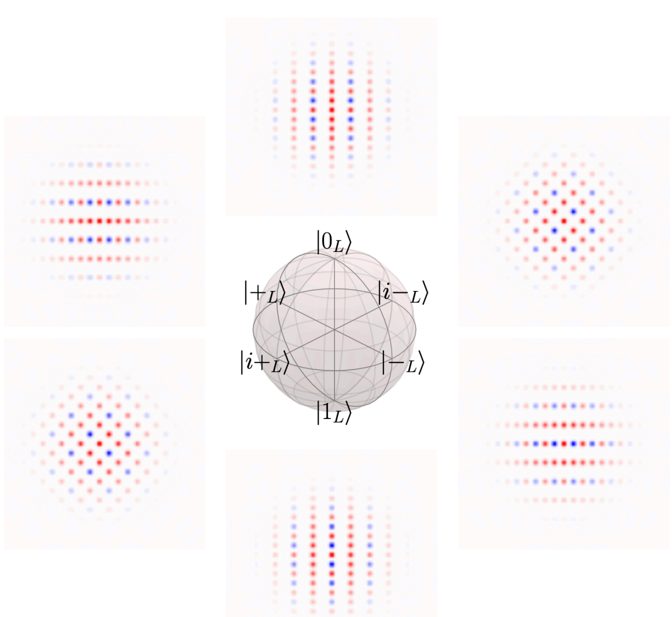

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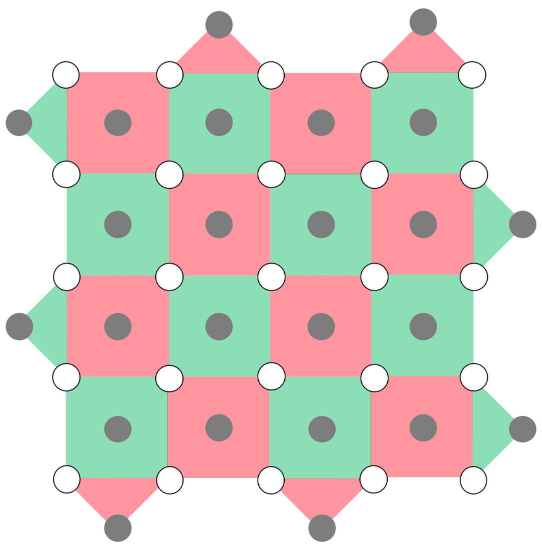

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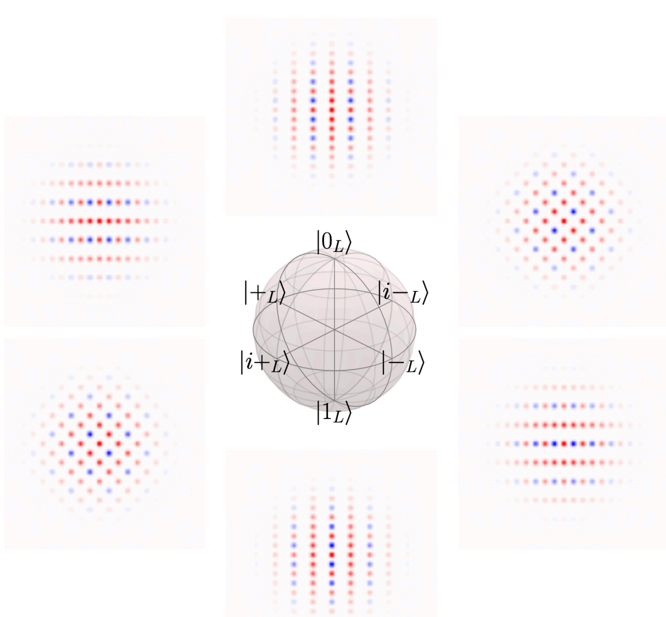
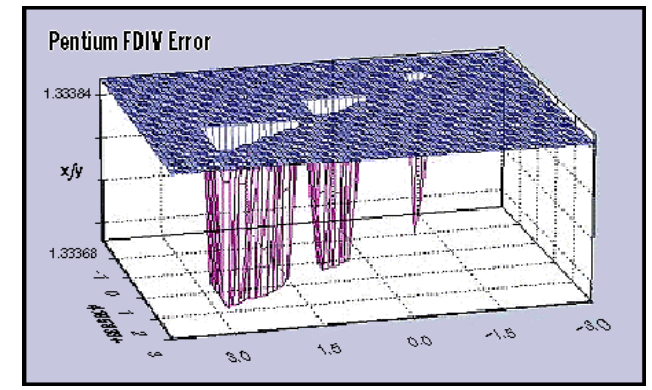
Fight
Quantum Decoherence



ERROR

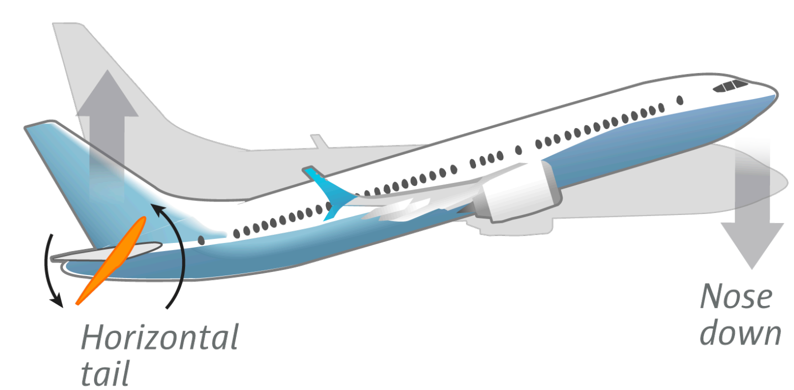
Human



Intel Pentium FPU error

Ariane 5

MCAS safety system engages



Human Errors in Quantum Software Engineering

Being careful cannot solve the human error problem in either classical or quantum.

Quantum case : Significantly More **CHALLENGING** than Classical

- standard software assurance techniques, e.g., black-box / unit test, expensive in q.
- quantum mechanics prohibits certain testing, e.g., assertions

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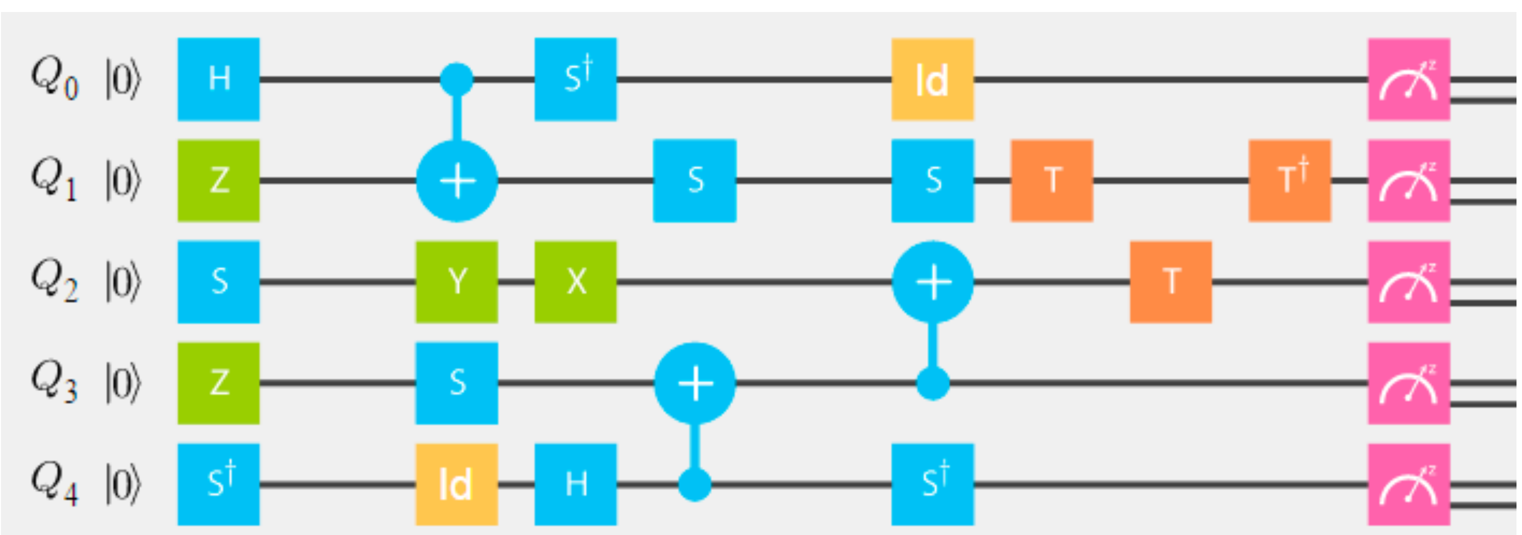
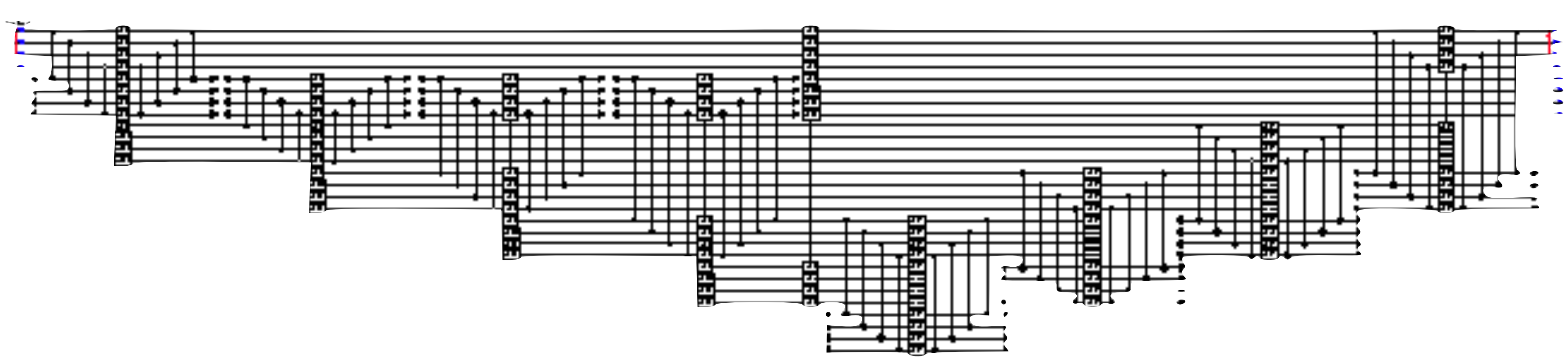
Reality: testing in quantum today



confirming the circuit by observation…. not scalable…



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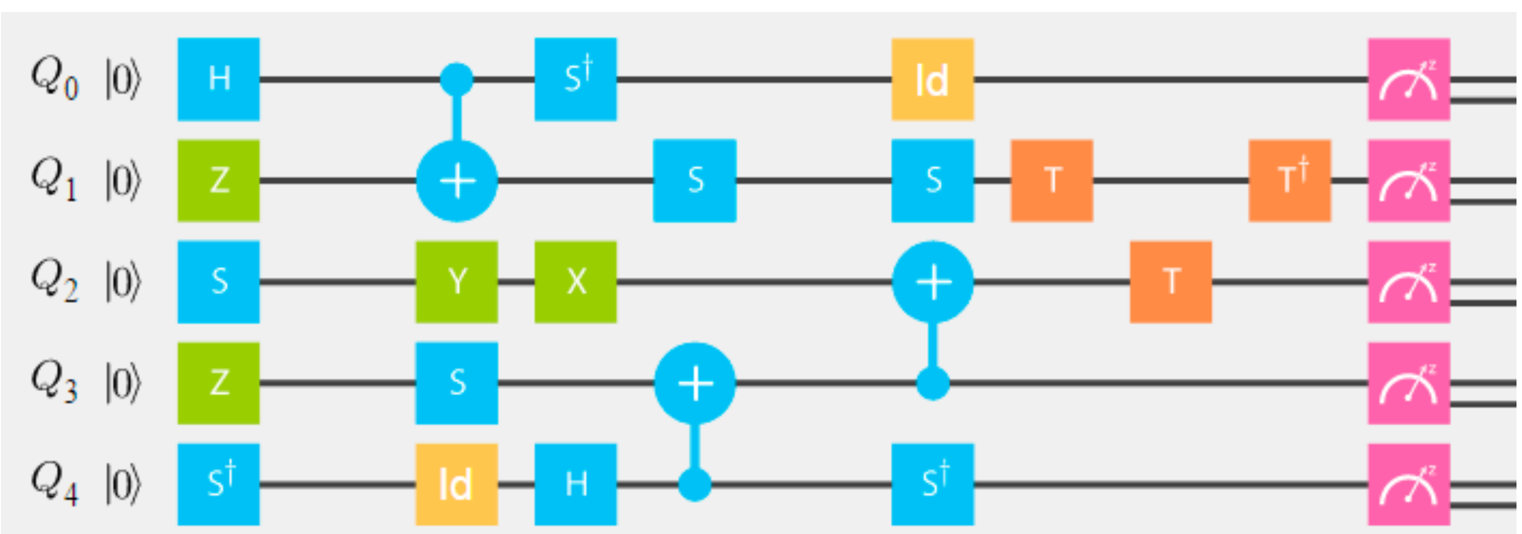

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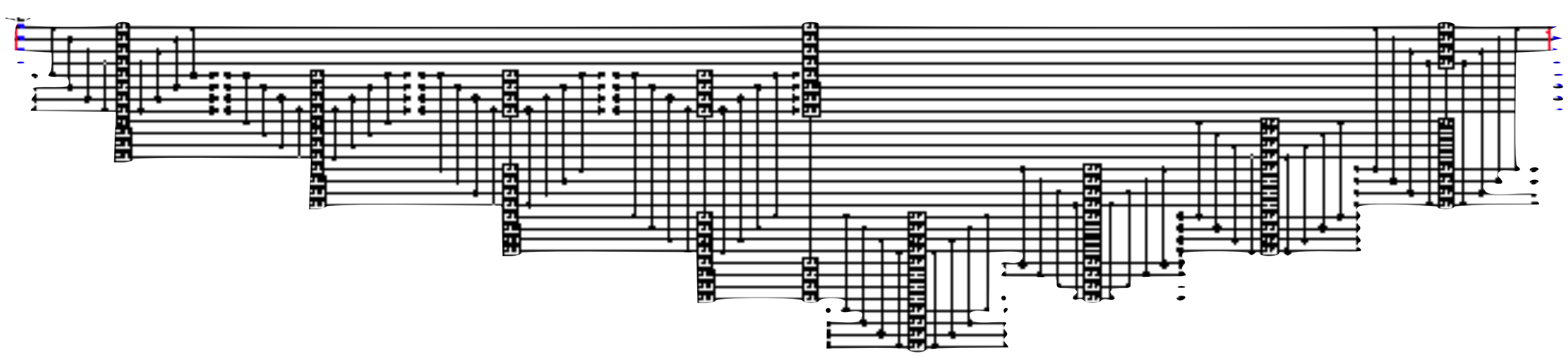

QISKIT Compiler ERRORs

Much **HARDER** to detect!

Serious Consequences!

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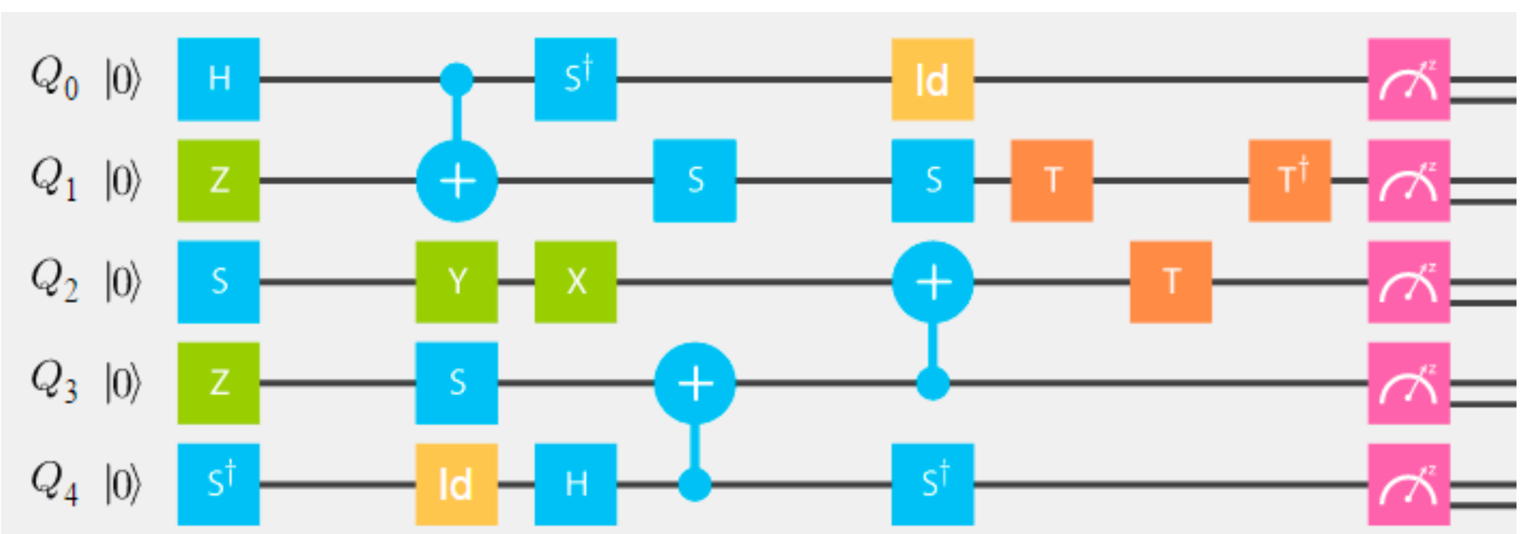

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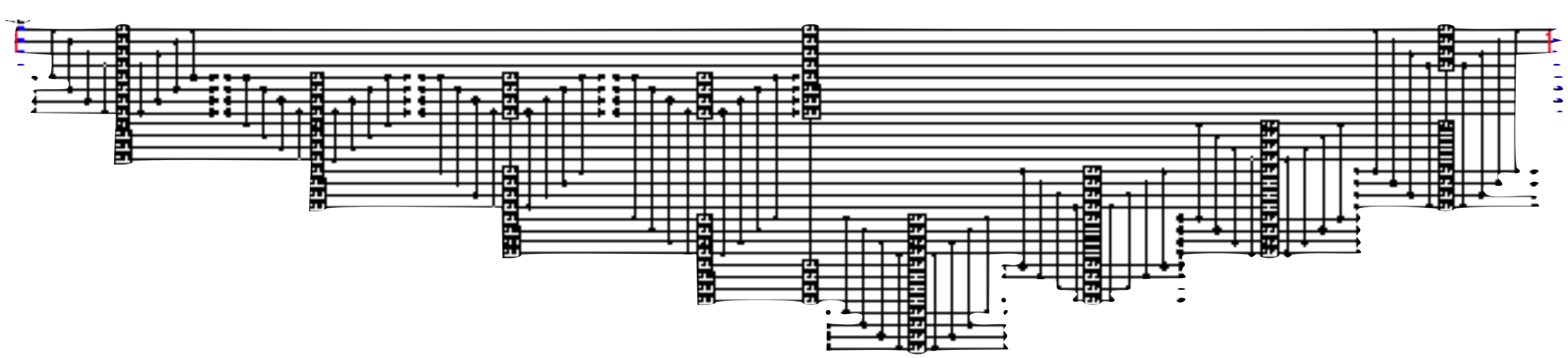

QISKIT Compiler ERRORs

Much **HARDER** to detect!

Serious Consequences!

Similar Concerns in classical !

More **SERIOUS** in quantum !

Certified software: a solution to validation of q. software

The Verifying Compiler: A Grand Challenge for Computing Research

TONY HOARE

Microsoft Research Ltd., Cambridge, UK

Journal of the ACM, Vol 50, 2003

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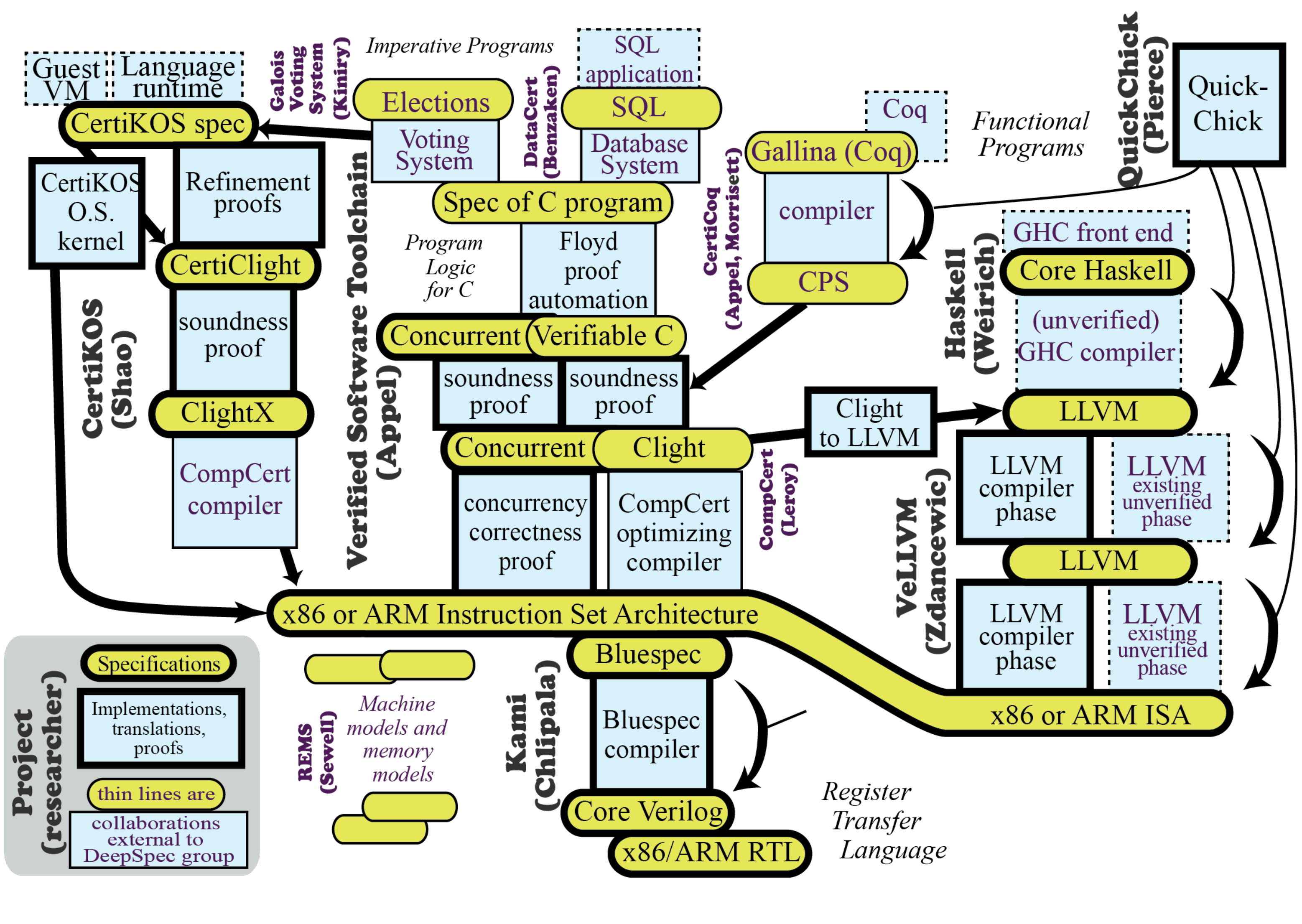


Verified Software Toolchain

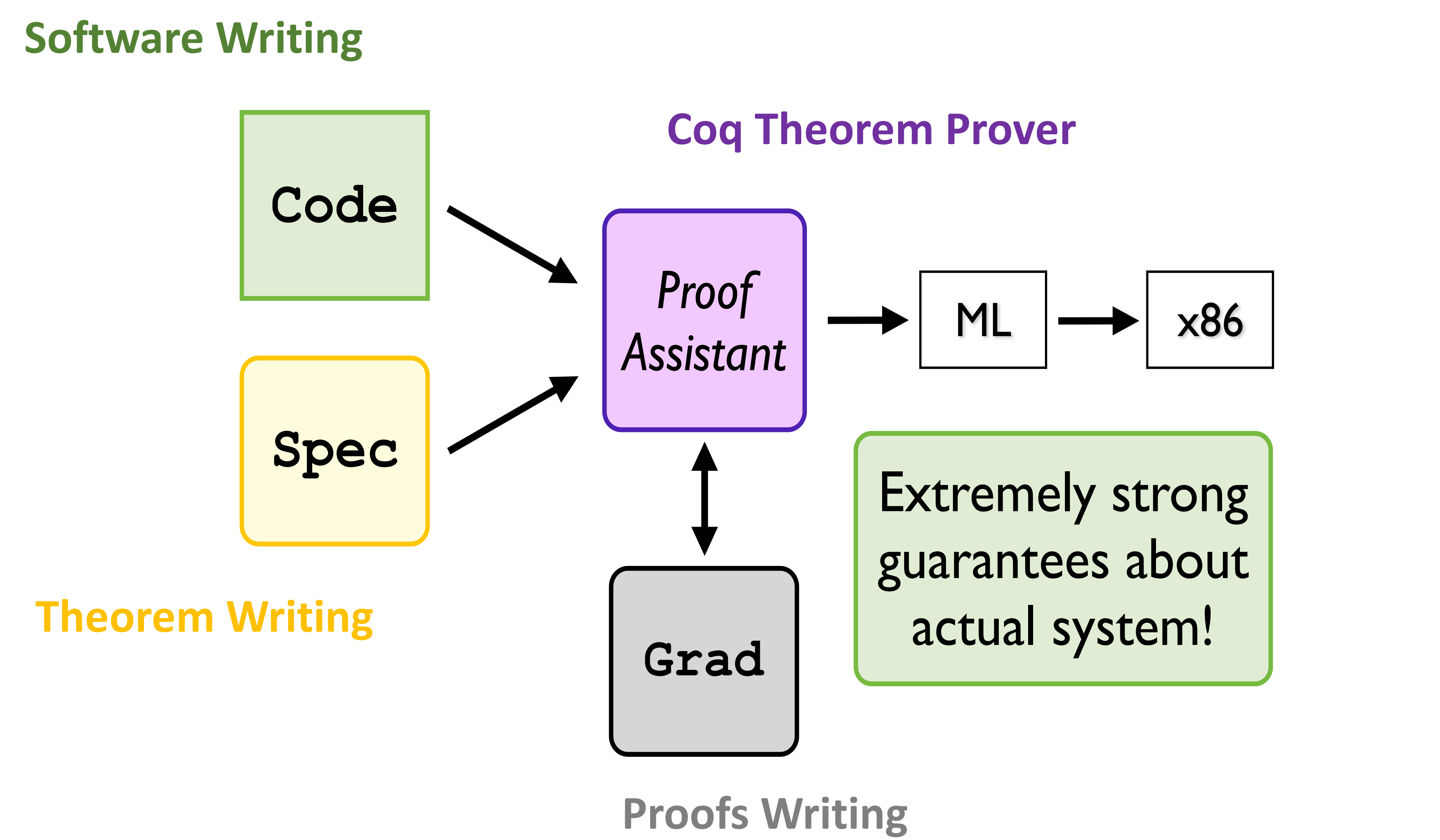
CERTIKOS

Vellvm verified LLVM

Certi Coq

Kami

Certified software: a solution to validation of q. software



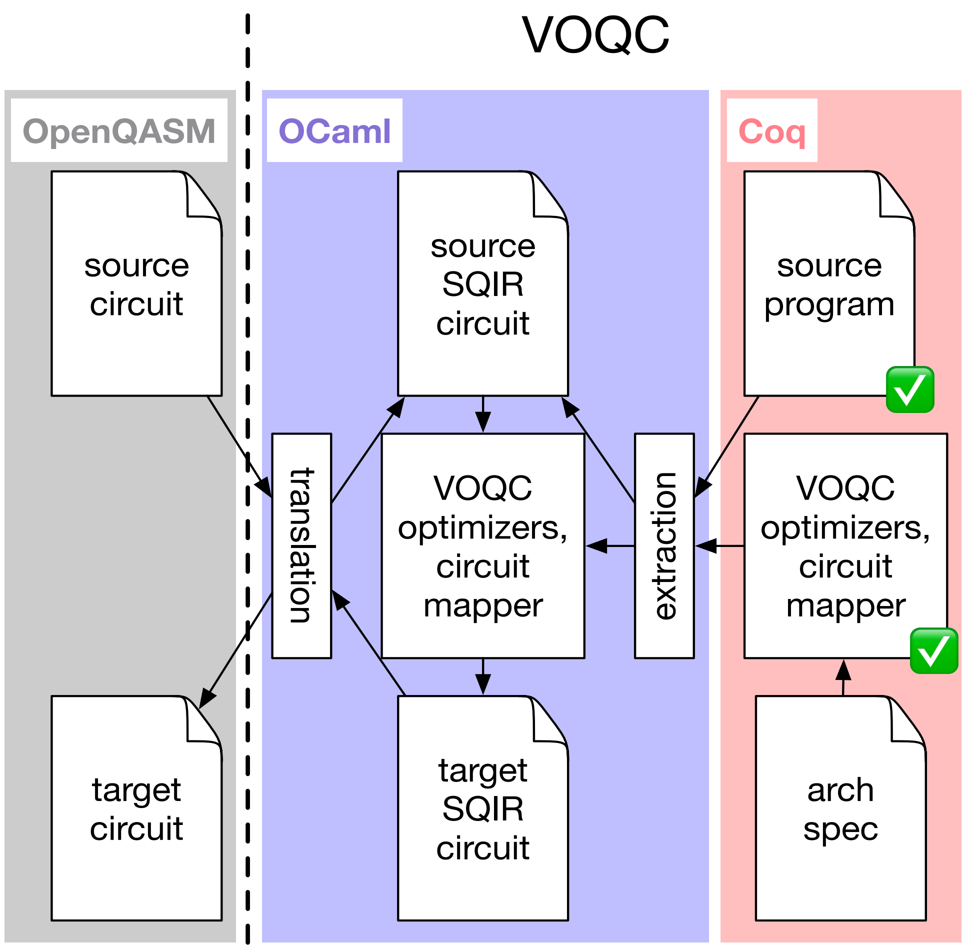
(1) Ensure correctness of code by construction.

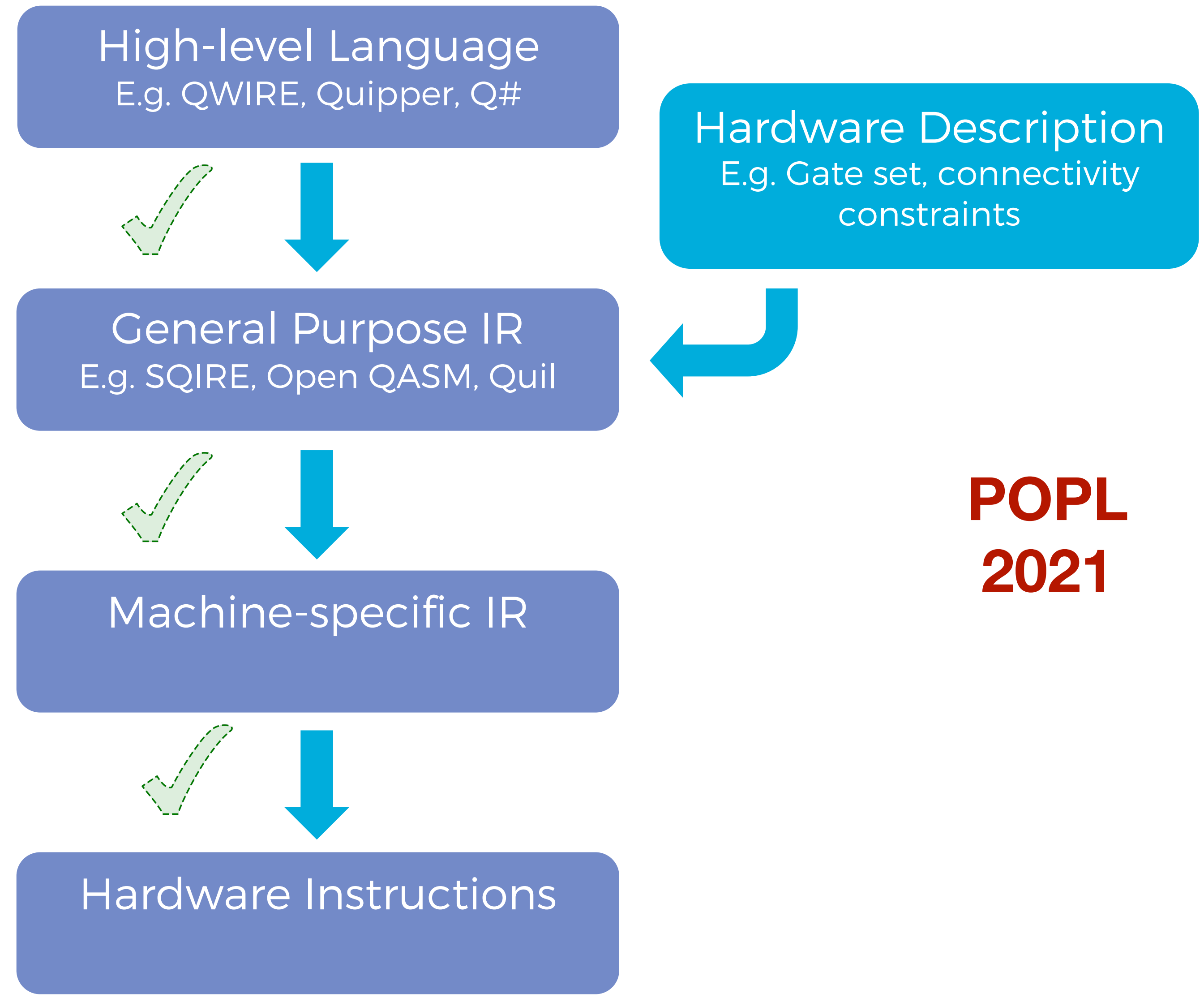
(2) Scalability for quantum based on symbolic proofs.

Joint Center for Quantum Information and Computer Science

PLUM

(Verified Optimizer for Quantum Circuits)





POPL 2021

VOQC: a first step towards a fully certified quantum compiler.

SQIRE: a simple quantum intermediate-representation embedded in Coq.

JOINT CENTER FOR QUANTUM INFORMATION AND COMPUTER SCIENCE

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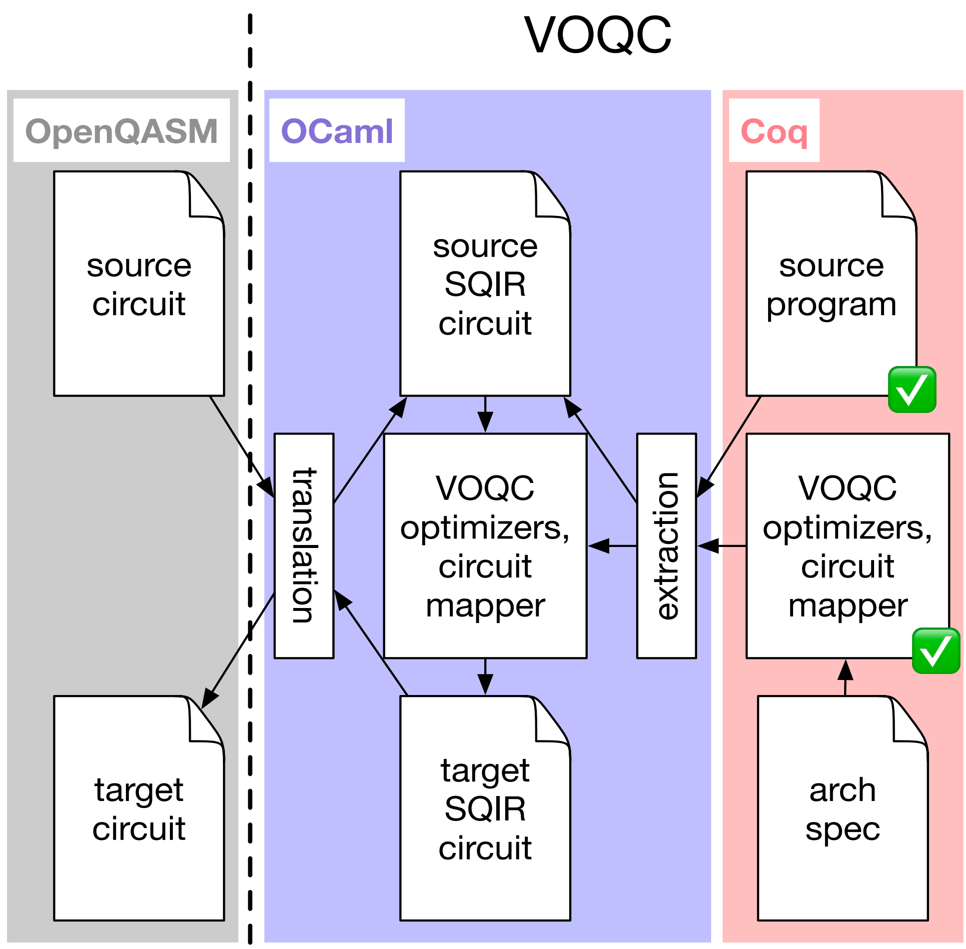

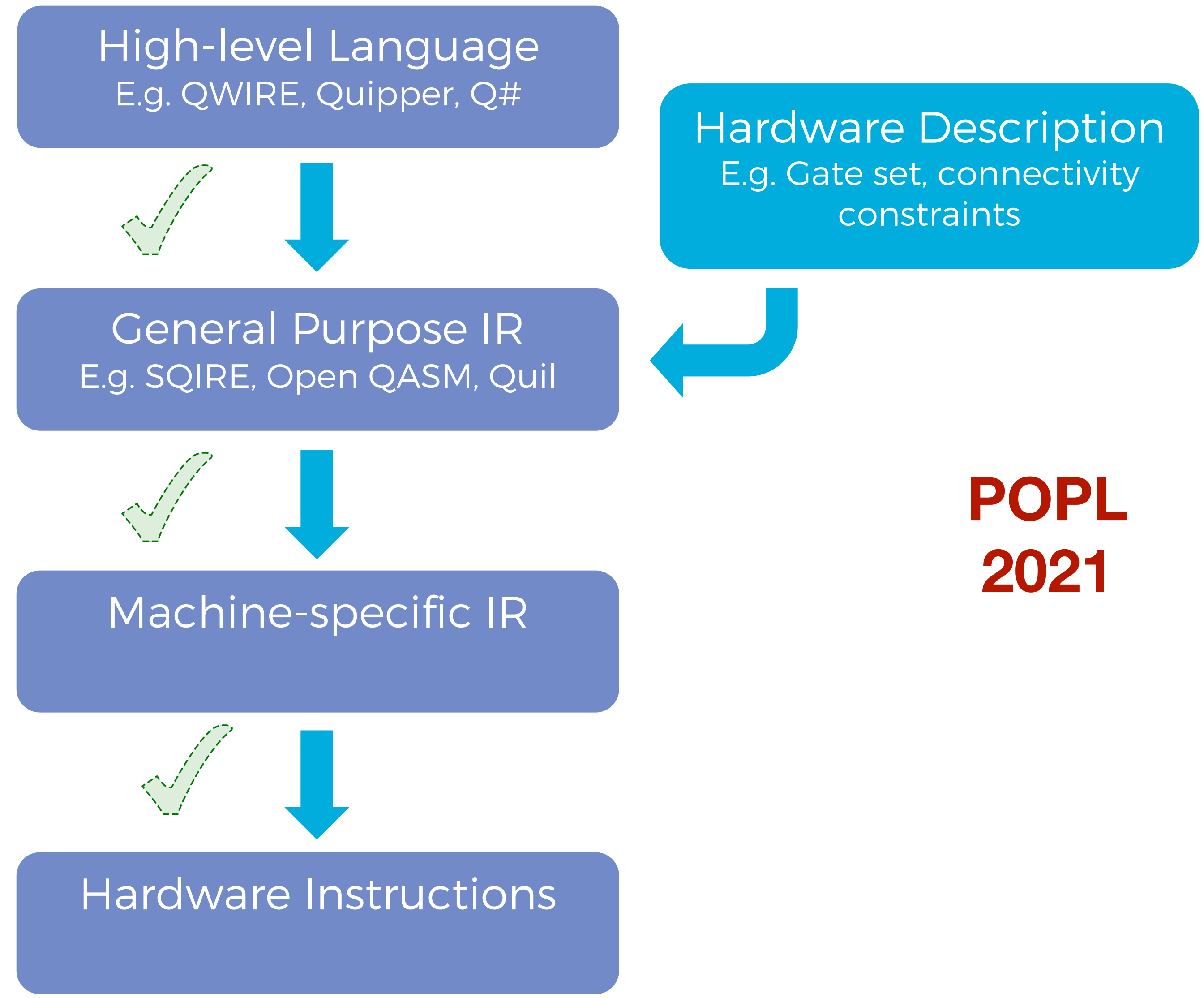

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Our infrastructure powerful enough:

an end-to-end implementation of Shor's algorithm & its correctness proof.