



# ORNL CUDA-Q Workshop

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# Agenda

- Setup and Intro
- Advanced Features
- Advanced applications in physics & chemistry
- Advanced applications in ML
- End

# Logistics

Let's debug any setup issues first

- Workshop materials: <https://github.com/justinlietz/ornl-cudaq-workshop> (including these slides and links)
- Three modes to follow along:
  - OLCF Ascent
  - X-Lab
  - Laptop
- OLCF Ascent
  - Everyone here should have access to TRN024 training account.
  - Ascent user guide: [https://docs.olcf.ornl.gov/systems/ascent\\_user\\_guide.html](https://docs.olcf.ornl.gov/systems/ascent_user_guide.html)
- X-Lab
  - A10 nodes available for us for today.
  - Tested Jupyter notebook environment.
  - You will not be able to access these machines after the workshop.
  - Make account at <https://learn.nvidia.com>, use code:
- Laptop
  - Quick start guide: [https://nvidia.github.io/cuda-quantum/latest/using/quick\\_start.html](https://nvidia.github.io/cuda-quantum/latest/using/quick_start.html)
  - Can easily install CUDA-Q either via conda, pip, or docker.
  - CPU only unless your laptop has NVIDIA GPU.



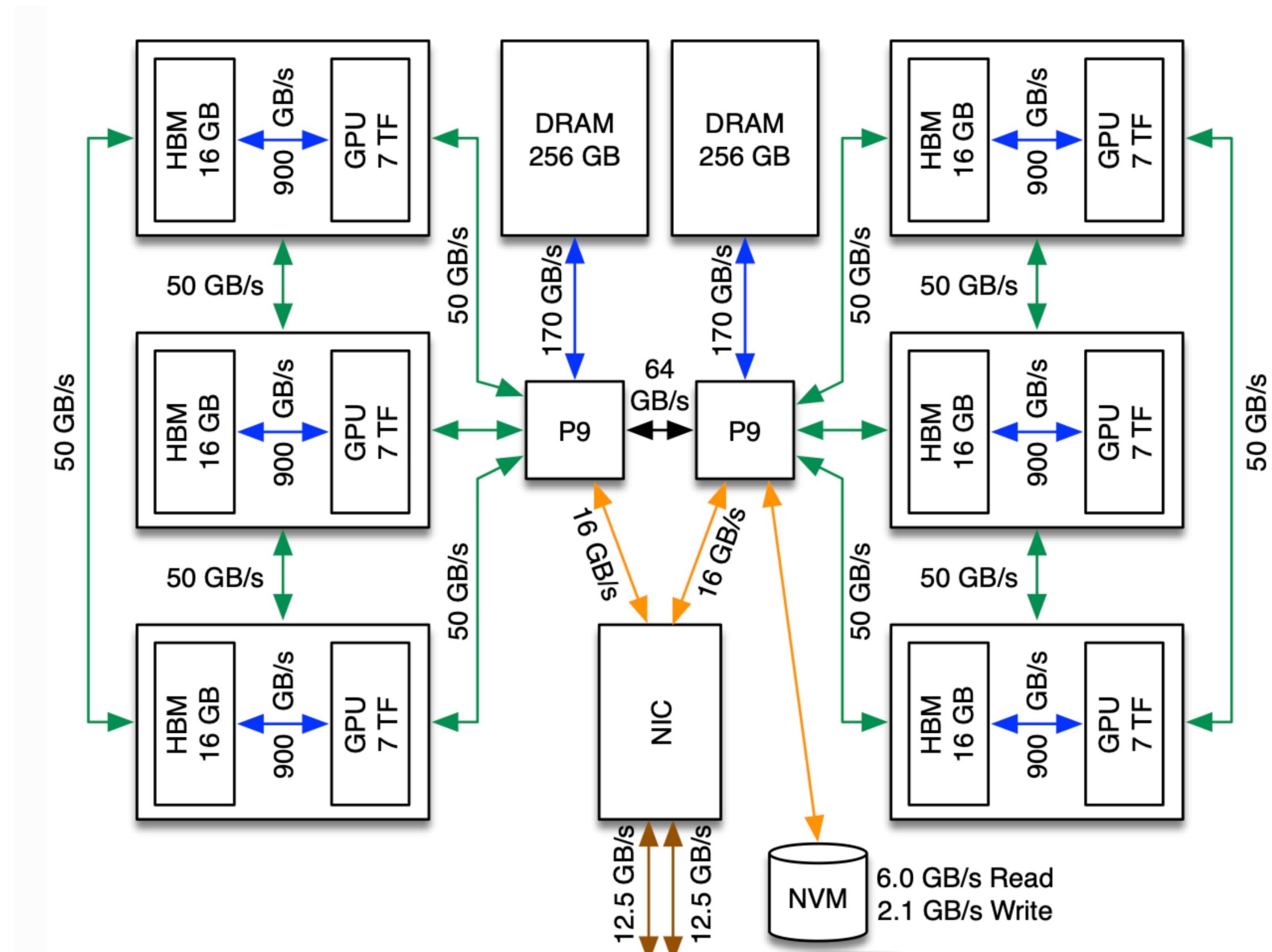
# X-Lab

Best to grab these resources now.

- If you haven't already, make an account at: <http://learn.nvidia.com/join>
- Log in (link below works better if you log in first then click link below)
- Go to <https://learn.nvidia.com/dli-event>
- Enter code: ORNL\_XLAB\_JY24
- Click "start" to spin up a lab. If you think you'll want to follow along with the Jupyter notebooks.
- Hot labs have already been spun up for us, but we can spin up more later, they may take ~15 minutes though.
- We'll start with `cudaq-Intro/cudaq-introduction.ipynb` after these slides.

# Ascent Crash Course

- Ascent user guide:  
[https://docs.olcf.ornl.gov/systems/ascent\\_user\\_guide.html](https://docs.olcf.ornl.gov/systems/ascent_user_guide.html)
- Workshop materials: <https://github.com/justinlietz/ornlcudaq-workshop>
- 18 Summit nodes, each with 6 v100 GPUs.
  - Please limit time on interactive nodes so there's enough to share
- Job scripts and environment script is in the `batch\_scripts` dir
  - Launch environment with `source load\_env.sh`
  - Submit job with `bsub -L\$SHELL <scriptname.sh>
  - A good test code is `targets.py` in the scripts folder
- Everyone will be on the same login node, so only run small tests
- The environment script uses a conda env, so try not to run it twice. If you do, just log out and back in again.



# Ascent Crash Course

- Our training account is TRN024
- Example script showing how to use 1, 6, and 12 GPUs.
- Notice resources are requested at the top, but then accessed only with jsrun command (even if only requesting 1 node)
- This example script is in `batch\_scripts` and uses a relative path to the script. You can `cd` here as well.

```
#BSUB -P TRN024
#BSUB -W 0:10
#BSUB -nnodes 2
#BSUB -alloc_flags gpudefault
#BSUB -J cudaq_py_nvidia
#BSUB -o cudaq_py_nvidia_%J.output
#BSUB -e cudaq_py_nvidia_%J.error

module purge
module use /gpfs/wolf2/olcf/trn024/proj-shared/modulefiles
module load gcc/11.2.0
module load cudaq/0.8.0
module load spectrum-mpi/10.4.0.3-20210112

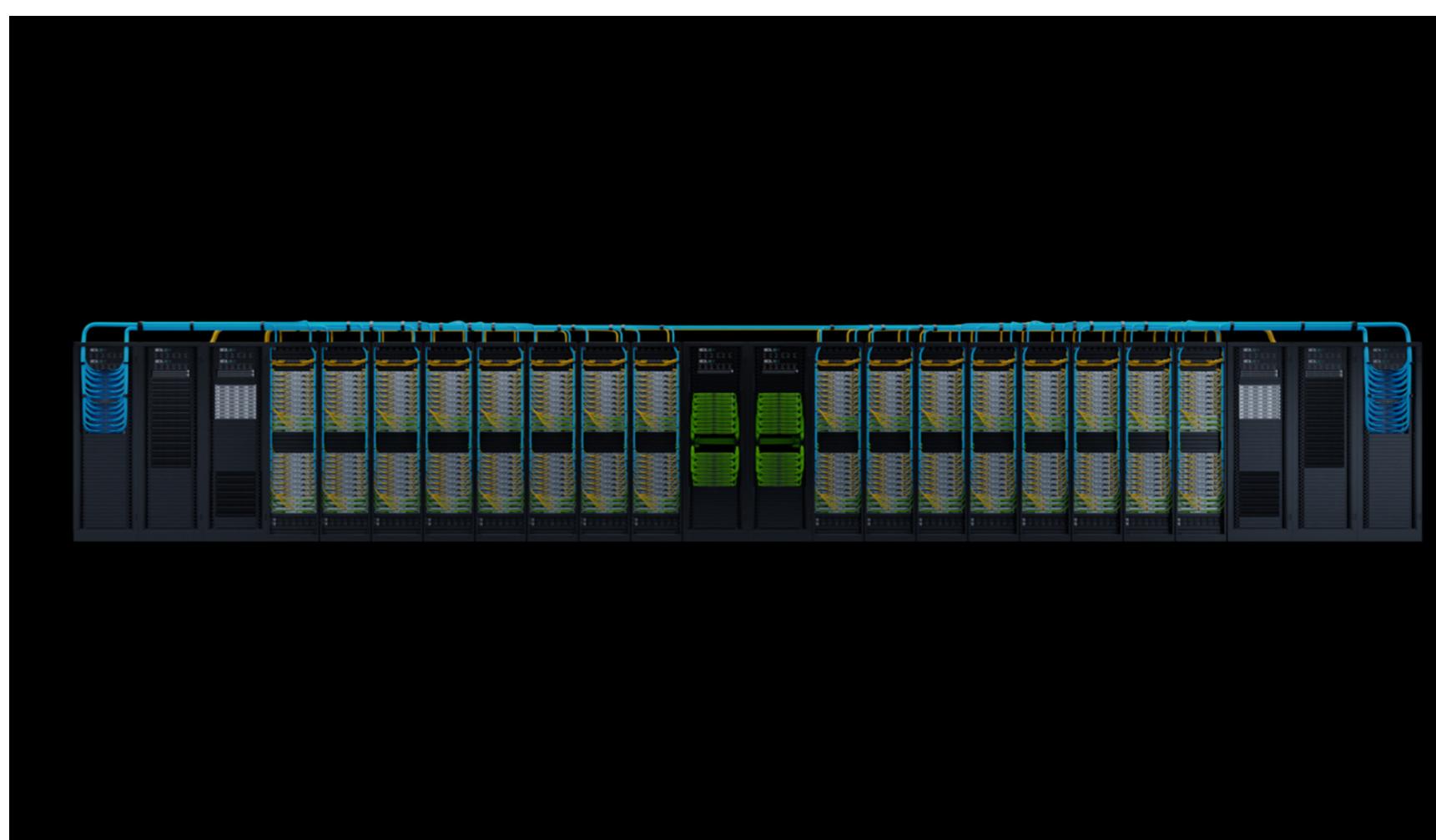
# 1 rank with 1 GPU
jsrun -n 1 -a 1 -c 1 -g 1 time python3 ./demos/MQPU-MGPU/observe-qml-mnmgpu.py
# 1 rank with 6 GPUs
jsrun -n 1 -a 1 -c 1 -g 6 time python3 ./demos/MQPU-MGPU/observe-qml-mnmgpu.py
# 2 ranks each with 6 GPUs
jsrun -n 2 -a 1 -c 1 -g 6 time python3 ./demos/MQPU-MGPU/observe-qml-mnmgpu.py
```

# Quantum-Accelerated Supercomputing

GPU Supercomputers are the foundation of Quantum R&D

## Simulation

- Quantum computers are small and error-prone
  - simulation is an essential tool
- **Today:** Powerful simulators enable algorithm and application R&D - new approaches (e.g. tensor networks)
- **Future:** Digital twins of quantum computers for design and architecture optimization



## HPC Quantum Integration

- Useful quantum computing will be hybrid
- **Today:** Enable domain scientists to start developing for QPUs, enable quantum researchers to use accelerated computing
- **Future:** quantum computers will integrate tightly with supercomputers as accelerators and be co-programmed



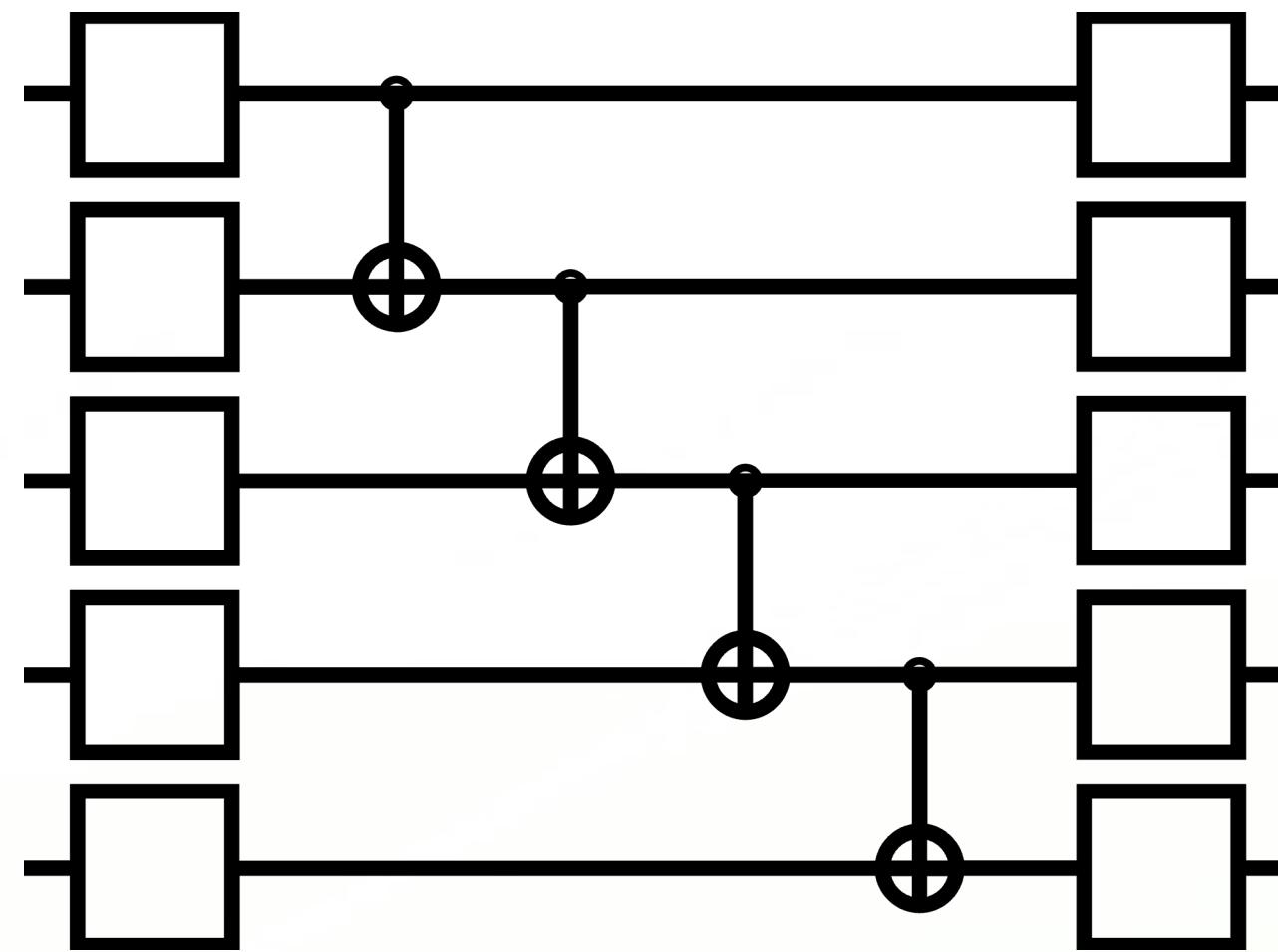
## AI for Quantum

- Error correction, calibration, control, compilation are challenging computationally, real-time compute often needed
- Accelerated computing and AI can solve these problems
- **Today:** Enable AI research for all of the above
- **Future:** Hybrid Quantum+AI supercomputer with low-latency link



# NVIDIA Quantum

Powering the Global Quantum Computing Community

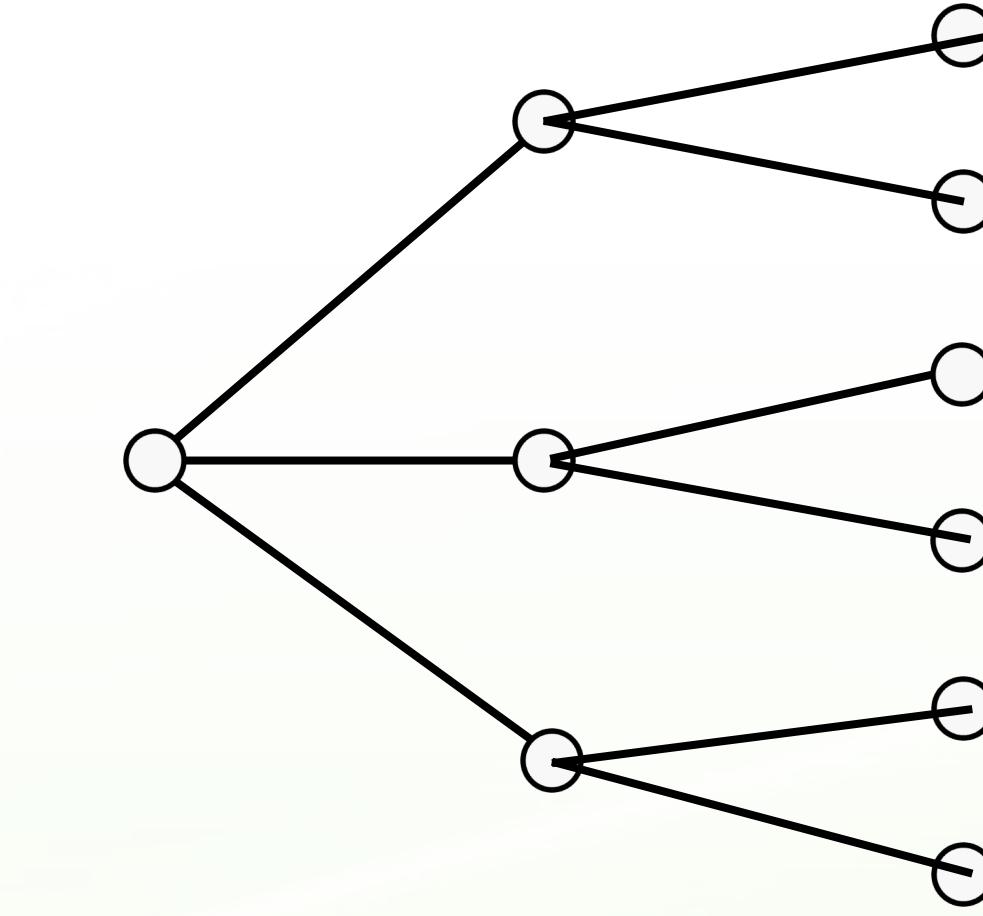


## Simulation

Algorithm Design, Resource Estimation, QPU Design



## HPC Quantum Integration



## AI for Quantum

QEC, Calibration, Algorithms

## CUDA-Q

Libraries

Programming Model

Tools

Infrastructure

### cuQuantum

Quantum Simulation

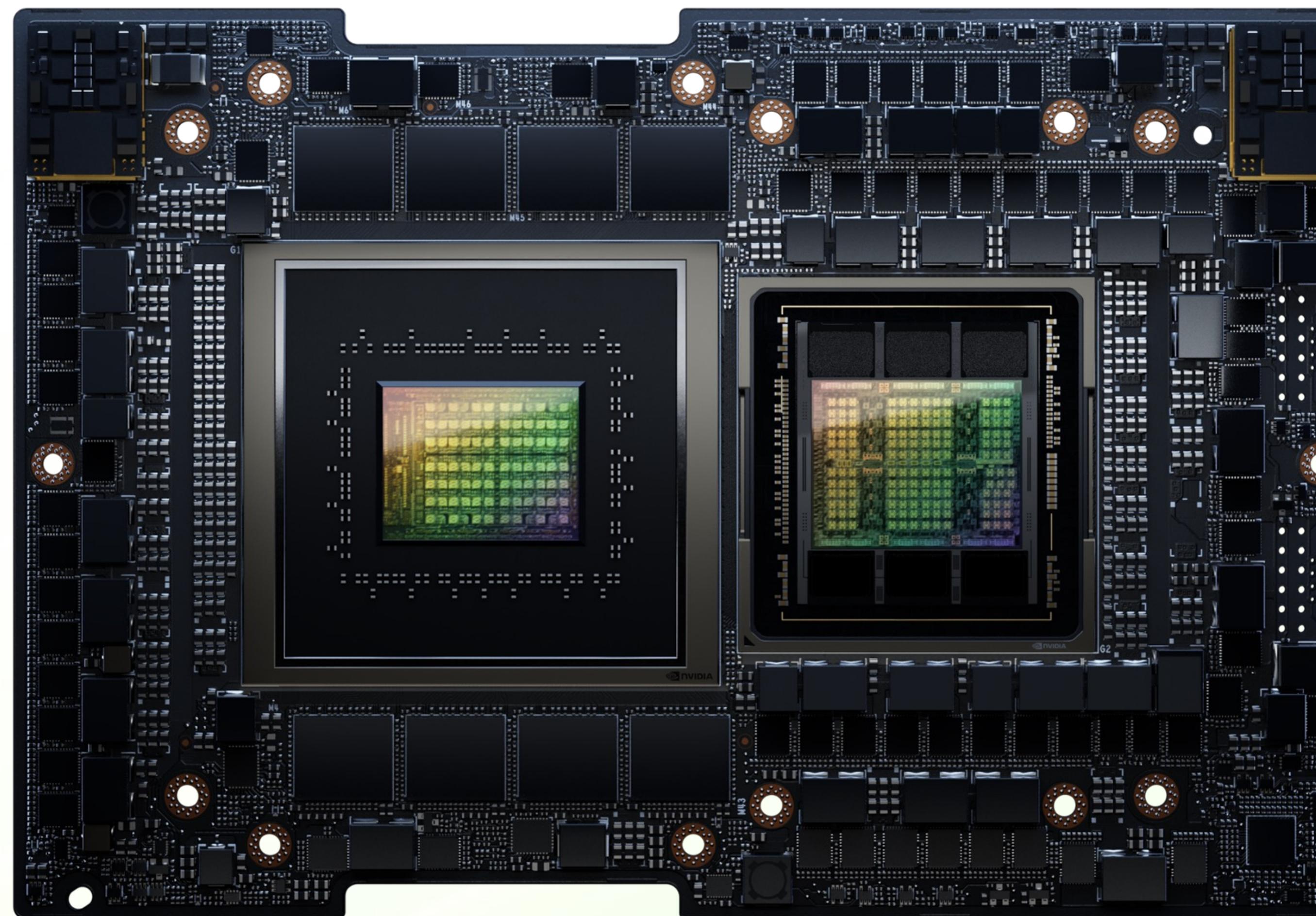
### DGX-Q

Quantum Integrated Computing

GPU  
Supercomputing

# Grace Hopper: The Engine for Quantum Research

## New Grace Hopper Deployments for Quantum Research



Simulation Performance

Simulation Scale

HPC-QC Integration

1x Intel 8480CL + H100

1x GH200 Superchip

1x Intel 8480CL + H100

1x GH200 Superchip

Remote QPU, Web API

Local QPU, Ethernet

Typical Error Correction Budget

DGX Quantum (GH200+OPX)

36 Qubit QPE Runtime

298 (s)

93 (s)

85% fewer GPUs required at any Qubit Scale

1-direction latency

1-10 seconds

10 microseconds

10 microseconds

400 nanoseconds

# **CUDA-Q**

## **Enabling the QPU-accelerated GPU Supercomputer**

A library-based C++ language extension  
that compiles directly to the MLIR

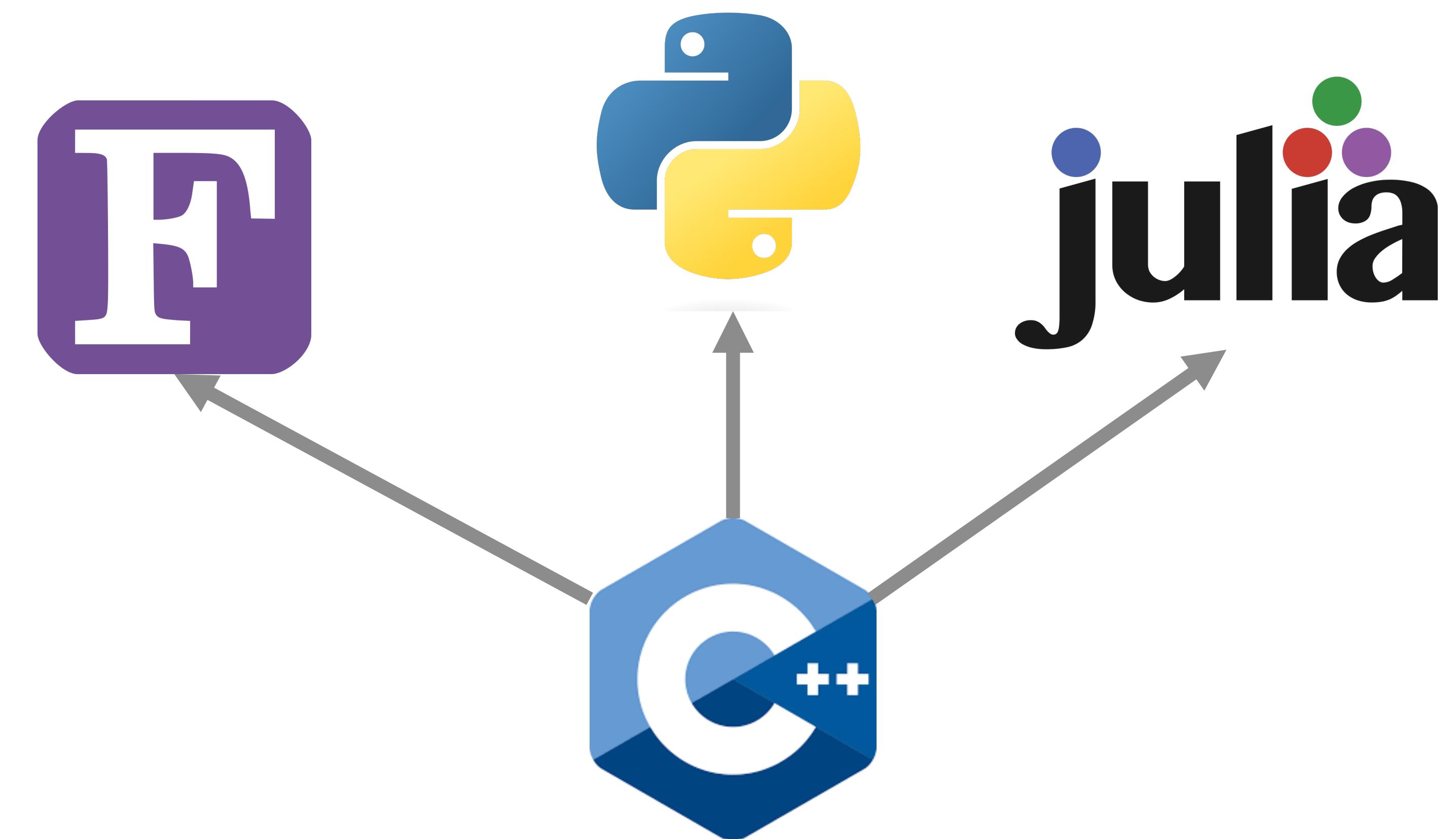
*Focus – requirements, programming  
model, architecture*

# Requirements for Programming the Hybrid Quantum-Classical Node

What can we learn from experience in the purely classical programming space?

How to architect something like CUDA-Q?

- Requirements
  - Performance
  - Familiar Programming Models
  - Integration with existing compilers and runtimes
- C++ as the Least Common Denominator for Programming Languages
  - Leads to optimal performance / control for developers
  - Easily bind to high-level language approaches
  - Most HPC applications are in C++ or Fortran
  - Most AI / ML frameworks are in Python, but APIs are often bound to performant C code (or JIT compiled)
  - Python user-surface is necessary, but only part of solution
- CUDA-like programming models
  - Cleanly separate device and host code
  - Direct vs library-based language extension
  - Split-compilation - map user kernel code to GPU instruction set (PTX)



```
// Kernel functions enable clean separation of
// host and device code

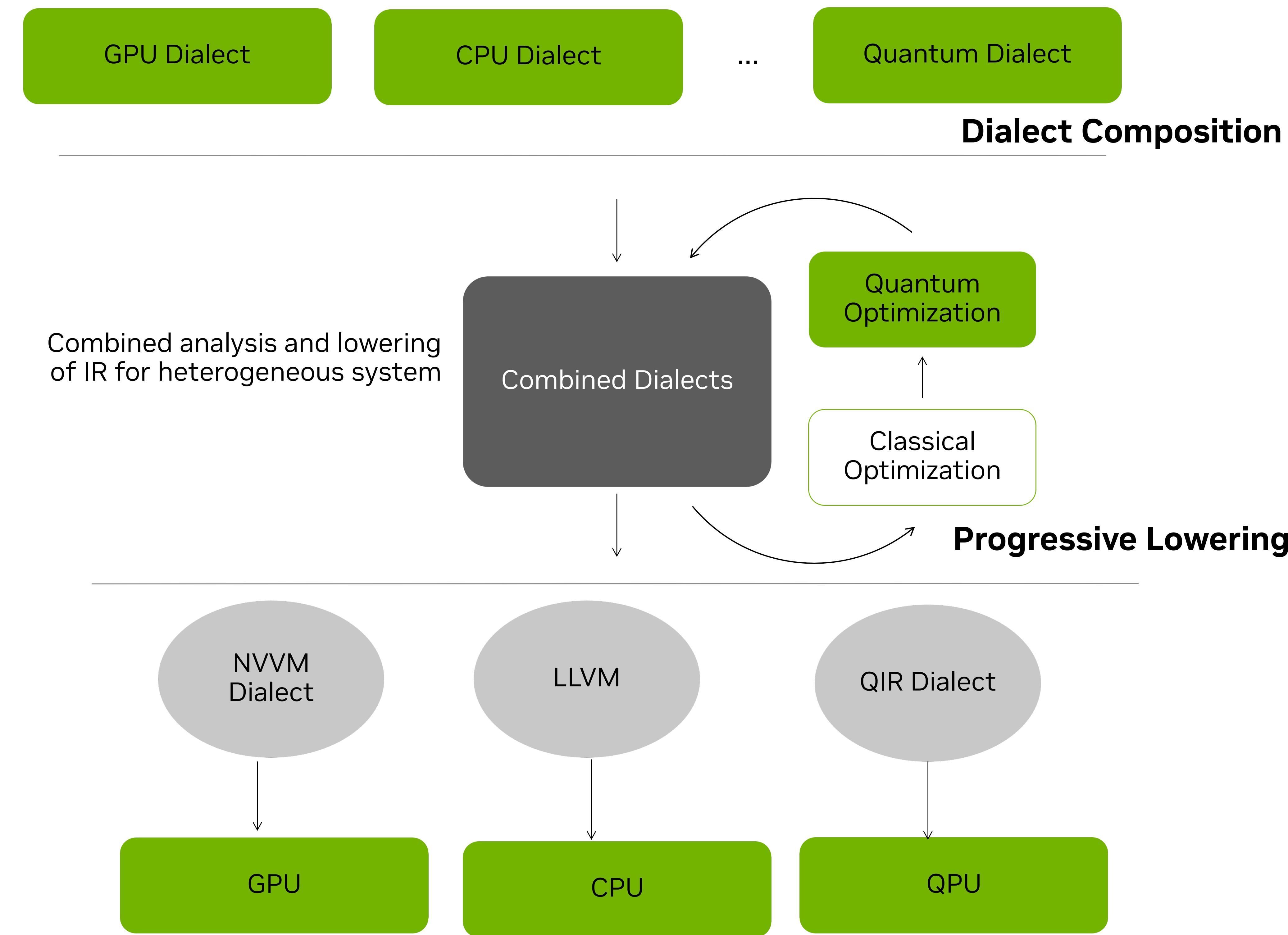
__global__ void VecAdd(float* A, float* B, float* C) {
    int i = threadIdx.x;
    C[i] = A[i] + B[i];
}

int main() {
    ...
    // Invoke kernel from host code
    VecAdd<<<1, N>>>(A, B, C);
    ...
}
```

# Leveraging Today's Compiler Technologies

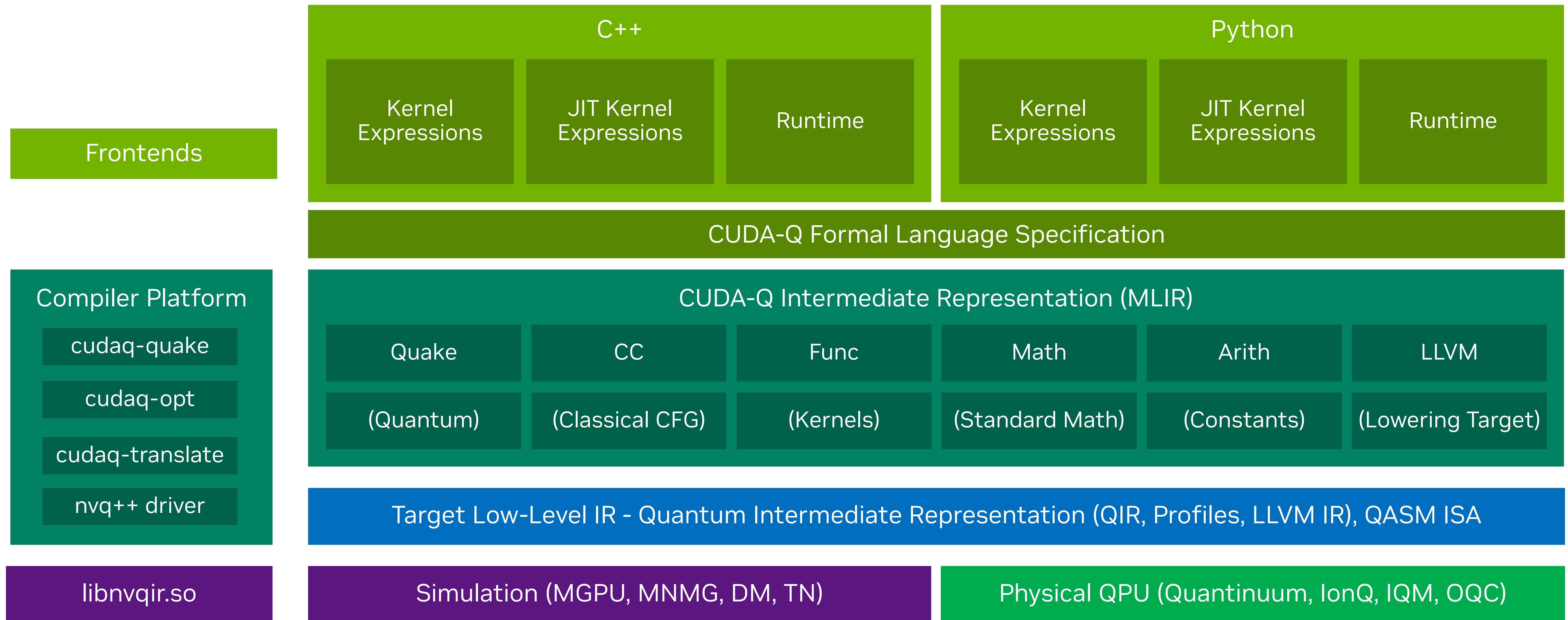
Leverage existing state-of-the-art and enable tight quantum-classical integration at IR level

- ***Our goal should be - do not reinvent the wheel...***
- We want quantum extensions to classical
- LLVM as the gold standard...
  - Toolchain for generating executable code
  - Modular
- Control Flow is a solved problem
  - Recursive nature of the core abstractions (regions, blocks, operations)
- MLIR – Framework for creating custom compiler IRs
  - Dialects and Dialect Composition
  - Progressive Lowering
  - Control Flow
  - Optimization, Transformation, and Conversion
    - Language level abstractions



# The CUDA-Q Stack

Platform for unified quantum-classical accelerated computing



# The CUDA-Q Language

Formal specification for quantum programming concepts that span classical language embeddings

- CUDA-Q starts with a general language specification.
  - Language implementations must adhere to the specification
- Meant to be classical language agnostic
  - Implementations now in C++ and Python
- Defines common concepts for quantum programming
  - Quantum types and operations
  - Quantum kernels
  - Library APIs
- This is an evolving specification.
  - We are interested in feedback and collaboration
  - There is a formal proposal process for contributions (coming soon)

## Language Specification

NVIDIA CUDA Quantum is a programming model in C++ for heterogeneous quantum-classical computing. As such, the model provides primitive types, concepts, syntax, and semantics that enable the integration of quantum processing units (QPUs) with existing NVIDIA multi-node, multi-GPU parallel programming models and architectures. The language is designed for C++. Extensions to other languages is fully supported via appropriate bindings.

CUDA Quantum implementations are intended to be enabled via library-based language extensions that define quantum code as callables in the classical language being extended. These callables are meant to be compiled with standard compilers and runtimes and run via quantum computer simulators or available physical quantum architectures. The language callables intended for quantum coprocessing must be annotated for compilers and runtimes to process. These annotations should directly enable quantum-specific optimization and transformation for optimal execution on simulators and QPUs.

The rest of this document will detail all aspects of the language specification - its machine model, primitive types and operations, core concepts and abstractions, and algorithmic primitives. All code specification and demonstrative examples are provided in C++ (the native CUDA Quantum classical language). Where possible, bindings for higher-level languages (e.g. Python) will be displayed to aid in understanding.

## CUDA Quantum

- 1. Machine Model
- 2. Namespace and Standard
- 3. Quantum Types
- 4. Quantum Operators
- 5. Quantum Operations
- 6. Quantum Kernels
- 7. Sub-circuit Synthesis
- 8. Control Flow
- 9. Just-in-Time Kernel Creation
- 10. Quantum Patterns
- 11. Platform
- 12. Algorithmic Primitives
- 13. Example Programs

<https://nvidia.github.io/cuda-quantum/latest/specification/cudaq.html>

Next: let's dive into the specifics of the language...

# GHZ State Example

Running on CPU

```
import cudaq
@cudaq.kernel
def ghz_state(N: int):
    qubits = cudaq.qvector(N)
    h(qubits[0])
    for i in range(N - 1):
        x.ctrl(qubits[i], qubits[i + 1])
    mz(qubits)
    cudaq.set_target("qpp-cpu")
    n = 3
    print("Preparing GHZ state for", n,
          "qubits.")
    counts = cudaq.sample(ghz_state, n)
    counts.dump()
```

Output:

Preparing GHZ state for 3 qubits.  
{ 000:494 111:506 }

# GHZ State Example

Running on GPU

```
import cudaq
@cudaq.kernel
def ghz_state(N: int):
    qubits = cudaq.qvector(N)
    h(qubits[0])
    for i in range(N - 1):
        x.ctrl(qubits[i], qubits[i + 1])
    mz(qubits)
    cudaq.set_target("nvidia")
    n = 29
    print("Preparing GHZ state for", n,
          "qubits.")
    counts = cudaq.sample(ghz_state, n)
    counts.dump()
```

Output:

```
Preparing GHZ state for 29 qubits.
{ 00000000000000000000000000000000:509
 111111111111111111111111111111111111111111:491 }
```

# What is a CUDA-Q Kernel?

Cleanly separate host code from quantum device code

```
struct phase_estimation {
    template <typename StatePrep, typename Unitary>
    void operator()(int numCountingQubits, int numStateQubits,
                     StatePrep && statePrep,
                     Unitary && oracle) __qpu__ {
        // Allocate a register of qubits
        cudaq::qvector q(numCountingQubits + numStateQubits);

        // Extract sub-registers, one for the counting qubits
        // another for the eigenstate register
        auto& countingQubits = q.front(numCountingQubits);
        auto& stateRegister = q.back(numStateQubits);

        // Prepare the eigenstate
        statePrep(stateRegister);

        // Put the counting register into uniform superposition
        h(countingQubits);

        // Perform `ctrl-U^j`
        for (int i = 0; i < numCountingQubits; ++i)
            for (int j = 0; j < (1 << i); ++j)
                cudaq::control(oracle, countingQubits[i],
                               stateRegister);

        // Apply inverse quantum Fourier transform
        iqft(countingQubits);

        // Measure to gather sampling statistics
        mz(countingQubits);
    }
};
```

C++

```
@cudaq.kernel
def phase_estimation(numCounting: int, numQubits : int,
                     statePrep : Callable[[cudaq.qview], None],
                     oracle : Callable[[cudaq.qview], None]):

    # Allocate a register of qubits
    q = cudaq.qvector(numCounting + numQubits)

    # Extract sub-registers, one for the counting qubits
    # another for the eigenstate register
    countingQubits = q.front(numCounting)
    stateRegister = q.back(numQubits)

    # Prepare the eigenstate
    statePrep(stateRegister)

    # Put the counting register into uniform superposition
    h(countingQubits)

    # Perform `ctrl-U^j`
    for i in range(numCounting):
        for j in range(2**i):
            cudaq.control(oracle, countingQubits[i],
                          stateRegister)

    # Apply inverse quantum Fourier transform
    iqft(countingQubits);

    # Measure to gather sampling statistics
    mz(countingQubits);
```

Python

Any callable in the language

Annotated in some way

Quantum memory management

Kernels are composable

Control flow inherited from classical language

Automated multi-control synthesis

Enable generic application libraries

*Ultimately a kernel defines a template for quantum circuits. Circuits are concretized / synthesized with runtime information.*



# What is a CUDA-Q Kernel?

Cleanly separate host code from quantum device code

```
--qpu__ double RWPE(int N, double mu, double sigma) {
    cudaq::qubit q, r;
    x(q);
    while (i < N) { // while loops available
        h(q);
        rz(1-(mu / sigma), q);
        rz(.25 / sigma, r);
        x<cudaq::ctrl>(q, r);
        rz(-.25 / sigma, r);
        x<cudaq::ctrl>(q, r);
        h(q);
        if (mz(q)) { // Condition code on qubit measurements
            x(q);
            mu += sigma * .6065;
        } else {
            mu -= sigma * .6065;
        }
        sigma *= .7951;
        i++;
    }
    return 2 * mu;
}
```

```
@cudaq.kernel
def RWPE(N: int, mu : float, sigma : float) -> float:
    q, r = cudaq.qubit(), cudaq.qubit()
    x(q)
    while i < N:
        h(q)
        rz(1.-(mu / sigma), q)
        rz(.25 / sigma, r)
        x.ctrl(q, r)
        rz(-.25 / sigma, r)
        x.ctrl(q, r)
        h(q)
        if mz(q): // Condition code on qubit measurements
            x(q)
            mu += sigma * .6065
        else:
            mu -= sigma * .6065
        sigma *= .7951
        i += 1
    return 2 * mu;
```

Dynamic circuits (control dictated by qubit measurement results) and user-defined return types fit into this model too.

# Quantum Operations and Control Modifiers

Single qubit operations and compiler-synthesized controlled operations

- Quantum operations are unique functions that take a qubit reference and optional floating-point parameters.
  - CUDA-Q starts with a specification of logical single-target quantum operations
- General multi-control operations are expressed via ***modification*** of these single-target operations
  - Control operations expressed with `cudaq::ctrl` modifier
  - Multi-qubit operations are synthesized by the compiler
  - Control qubits are first  $N-1$  qubit arguments
  - Control qubits can be also negated with operator `!`
- Entire kernel expressions can be controlled with `cudaq::control(...)`
- Adjoint kernels can be synthesized with `cudaq::adjoint(...)`

```
--qpu__ void cnotKernel(cudaq::qubit& q, cudaq::qubit& r) {
    x<cudaq::ctrl>(q, r);
}

--qpu__ void toBeAdjoined(cudaq::qubit& q, cudaq::qubit& r) {
    h(q);
    x(r);
    x<cudaq::ctrl>(q, r);
    ry(-M_PI_2, q);
}

--qpu__ void multipleWaysToExpressToffoli(std::size_t N) {
{
    cudaq::qarray<3> q;

    // Toffoli
    x<cudaq::ctrl>(q[0], q[1], q[2]);
} // qubits deallocated at scope exit
{
    cudaq::qvector q(N);

    // Toffoli
    cudaq::control(cnotKernel, {q[0]}, q[1], q[2]);
}

--qpu__ void showNegationAndAdjoint() {
    cudaq::qvector q(2);

    h<cudaq::ctrl>(!q[0], q[1]); // negated control

    // adjoint modifier
    t<cudaq::adj>(q[0]);
    // compiler synthesizes the adjoint
    cudaq::adjoint(toBeAdjoined, q[0], r[1]);
}
```

# Quantum Operations and Control Modifiers

Single qubit operations and compiler-synthesized controlled operations

- Quantum operations are unique functions that take a qubit reference and optional floating-point parameters.
  - CUDA-Q starts with a specification of logical single-target quantum operations
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- Entire kernel expressions can be controlled with `cudaq::control(...)`
- Adjoint kernels can be synthesized with `cudaq::adjoint(...)`

```
@cudaq.kernel
def cnotKernel(q : cudaq.qubit, r : cudaq.qubit):
    x.ctrl(q, r)

@cudaq.kernel
def toBeAdjoined(q : cudaq.qubit, r : cudaq.qubit):
    h(q)
    x(r)
    x.ctrl(q, r)
    ry(-np.pi / 2, q)

@cudaq.kernel
def multipleWaysToExpressToffoli():
    q = cudaq.qvector(3)

        // Toffoli
    x.ctrl(q[0], q[1], q[2]);

        # Toffoli
    cudaq.control(cnotKernel, [q[0]], q[1], q[2]);

@cudaq.kernel
def showNegationAndAdjoint(N : int):
    q = cudaq.qvector(N);

    h.ctrl(!q[0], q[1]); // negated control

        # adjoint modifier
    t.adj(q[0])
        // compiler synthesizes the adjoint
    cudaq.adjoint(toBeAdjoined, q[0], r[1]);
```

# CUDA-Q Platform and Asynchronous Execution

Expose the underlying system architecture to the programmer

- The system architecture model considers access to multiple quantum accelerators
- CUDA-Q provides programmatic access to this configuration via the **quantum\_platform**
- Exposes a native platform that models a virtual QPU for every CUDA device.
- Each CUDA device gets a cuQuantum-based simulator
- Enables experimentation with distributed quantum computing and further simulation scalability
- **Targets:** CUDA-Q programs are compiled to specific targets which define the multi-QPU granularity (or the physical QPU characteristics).

```
// Programmer can query info about the platform
auto& platform = cudaq::get_platform();

// Get number of QPUs available
auto numQpus = platform.num_qpus();

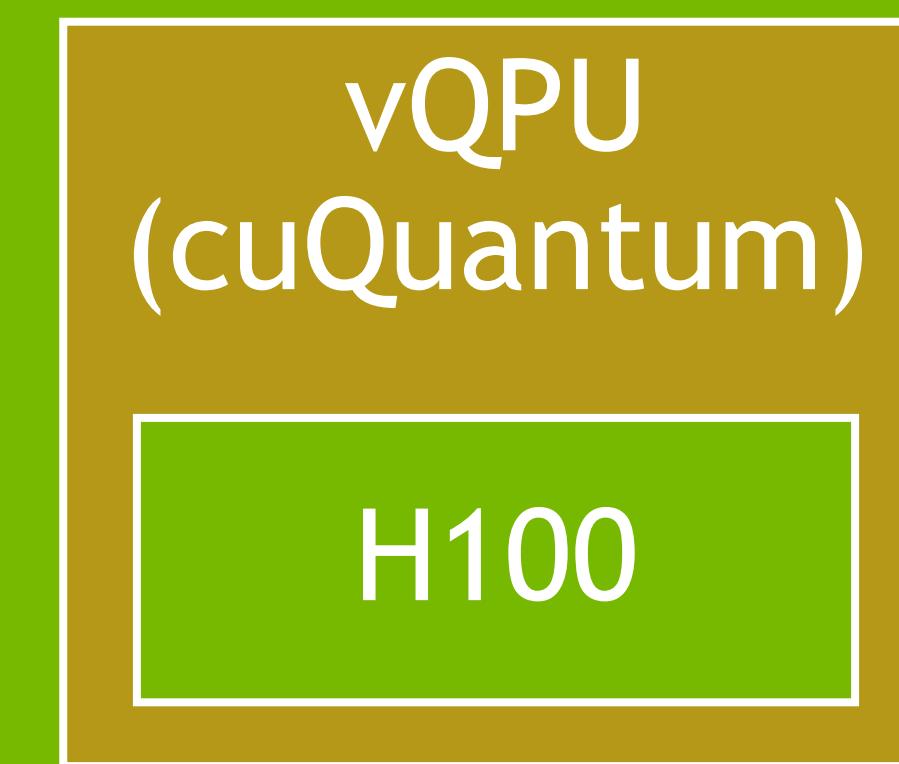
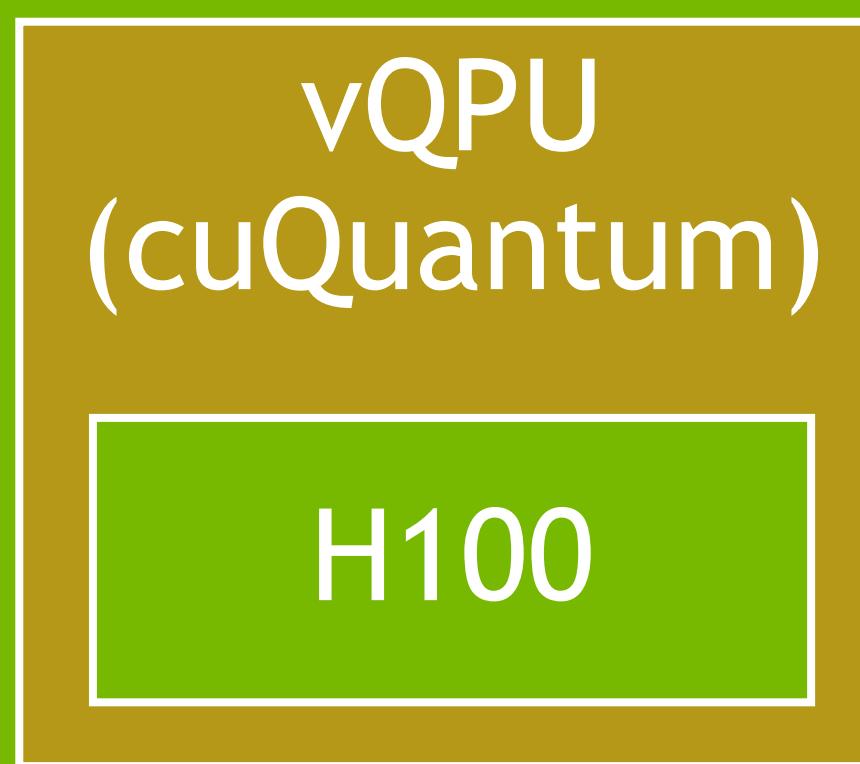
// Get the number of qubits on QPU 1
auto nQ1 = platform.get_num_qubits(1)

// Get QPU 0 connectivity.
auto connectivity = platform.get_connectivity(0);

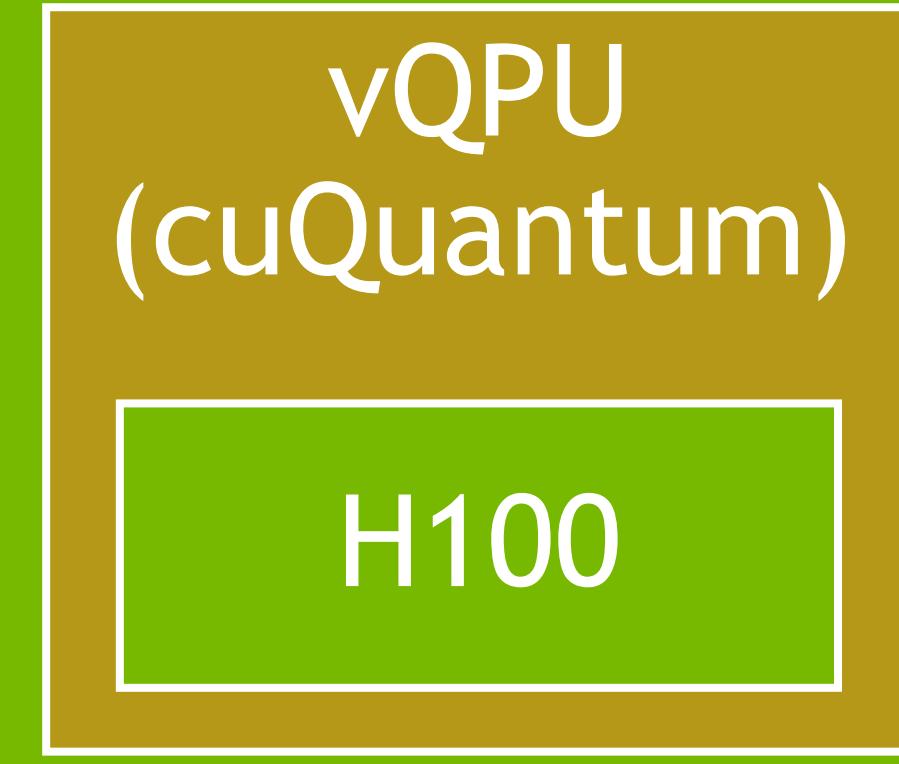
// Async task execution on available QPUs
std::vector<std::future<double>> subs;
for (auto qpuIdx : cudaq::range(numQpus))
    subs.emplace_back(cudaq::my_async_task(qpuIdx, ...));

auto sum = std::reduce(std::execution::par,
                      cudaq::when_all(subs), 0.0);
```

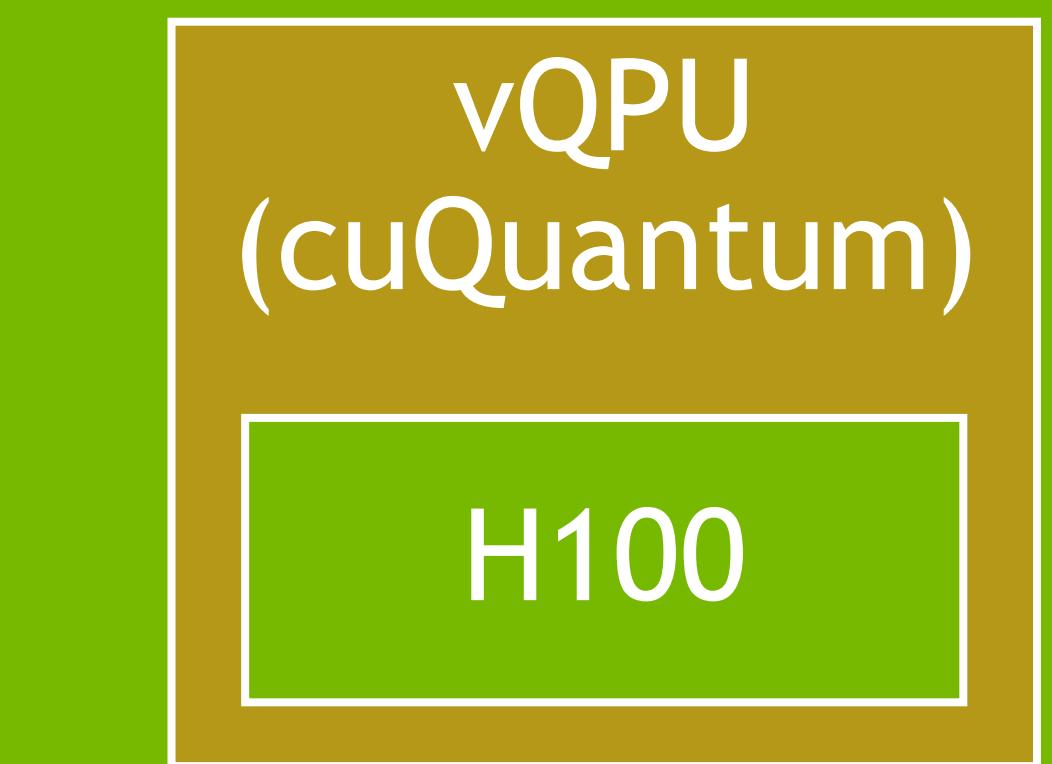
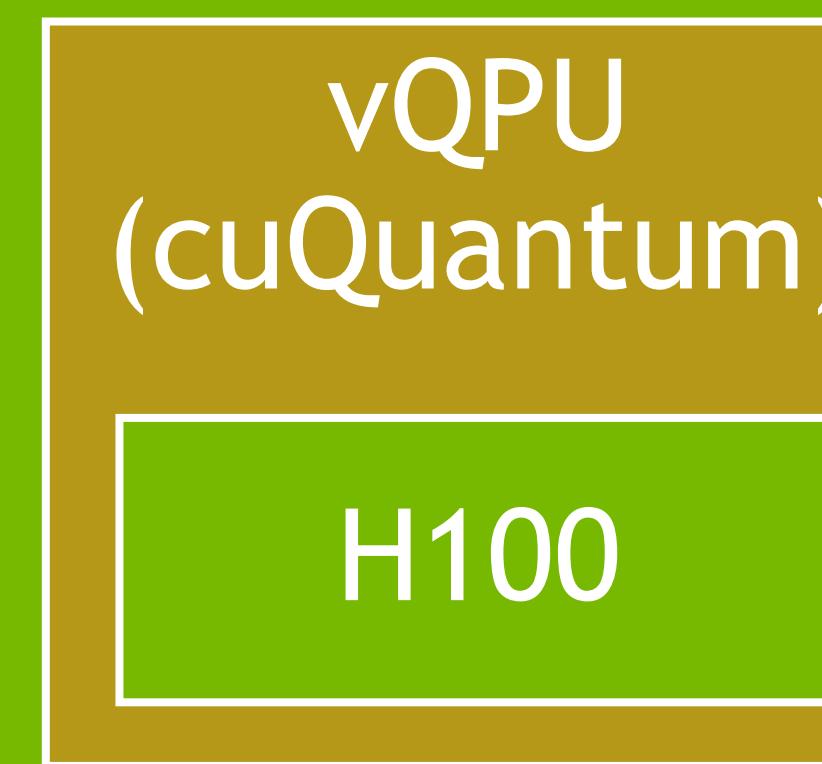
Node 0, MPI Rank 0



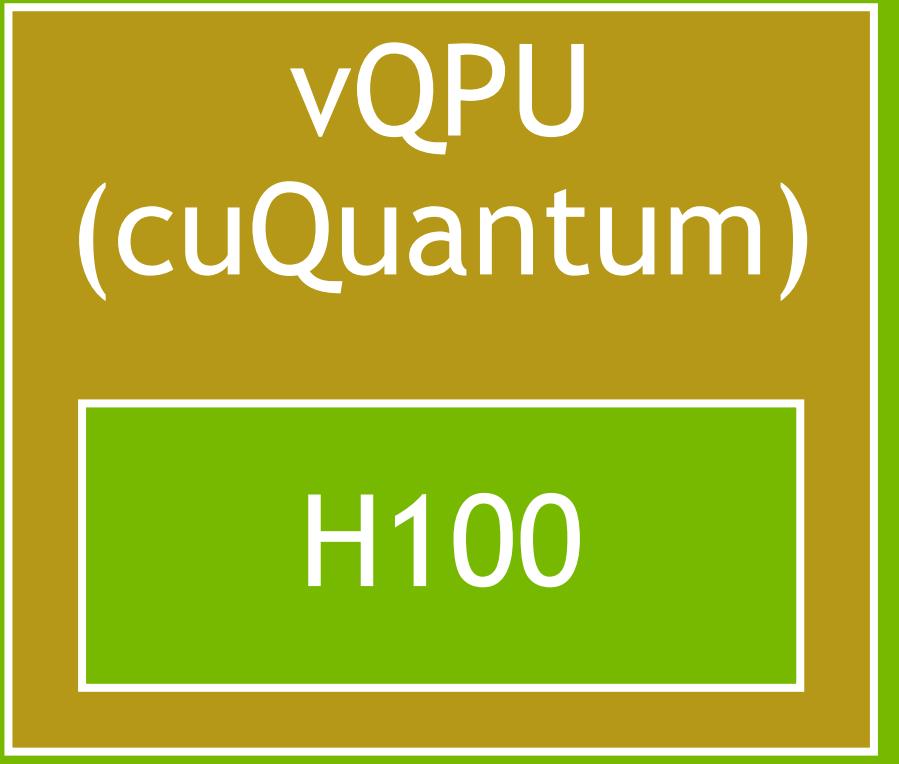
...



Node 1, MPI Rank 1



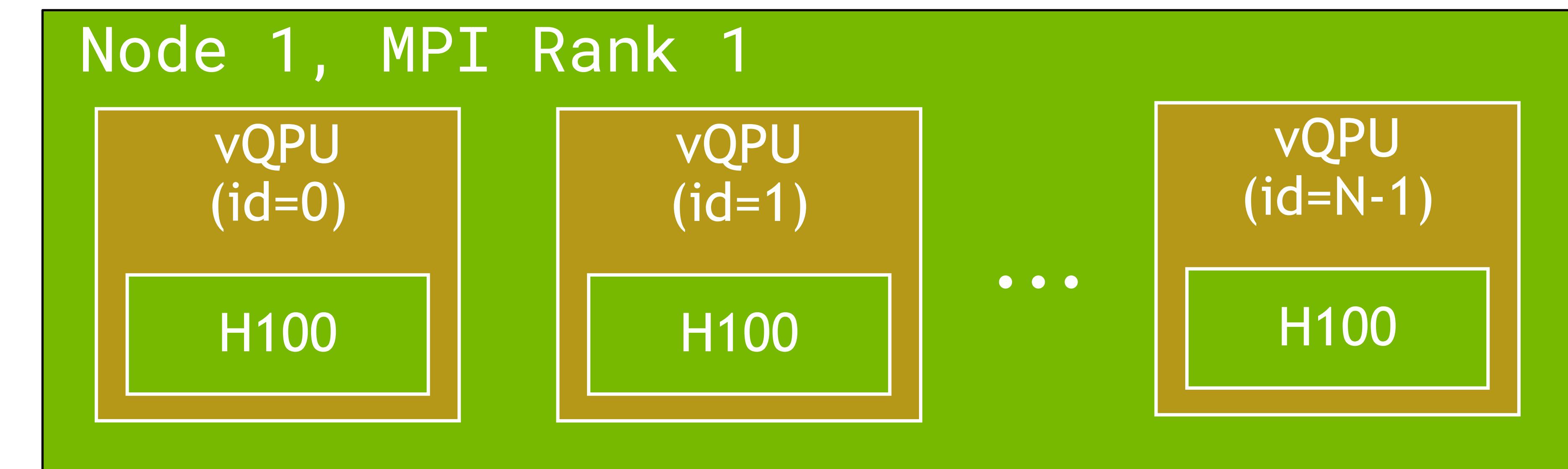
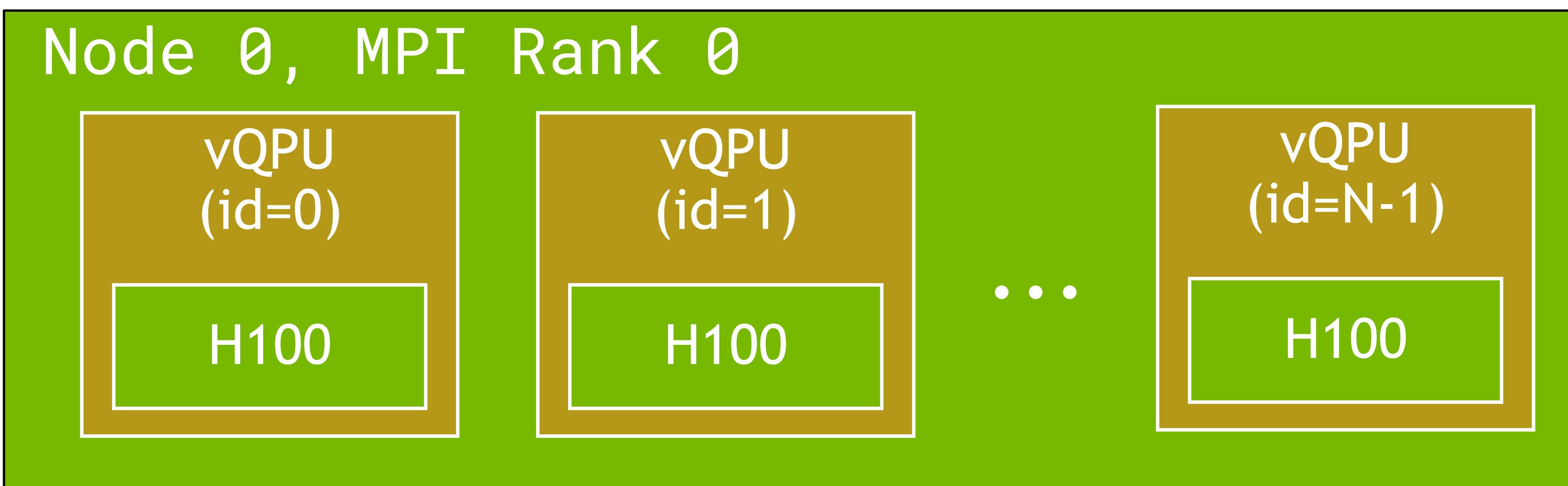
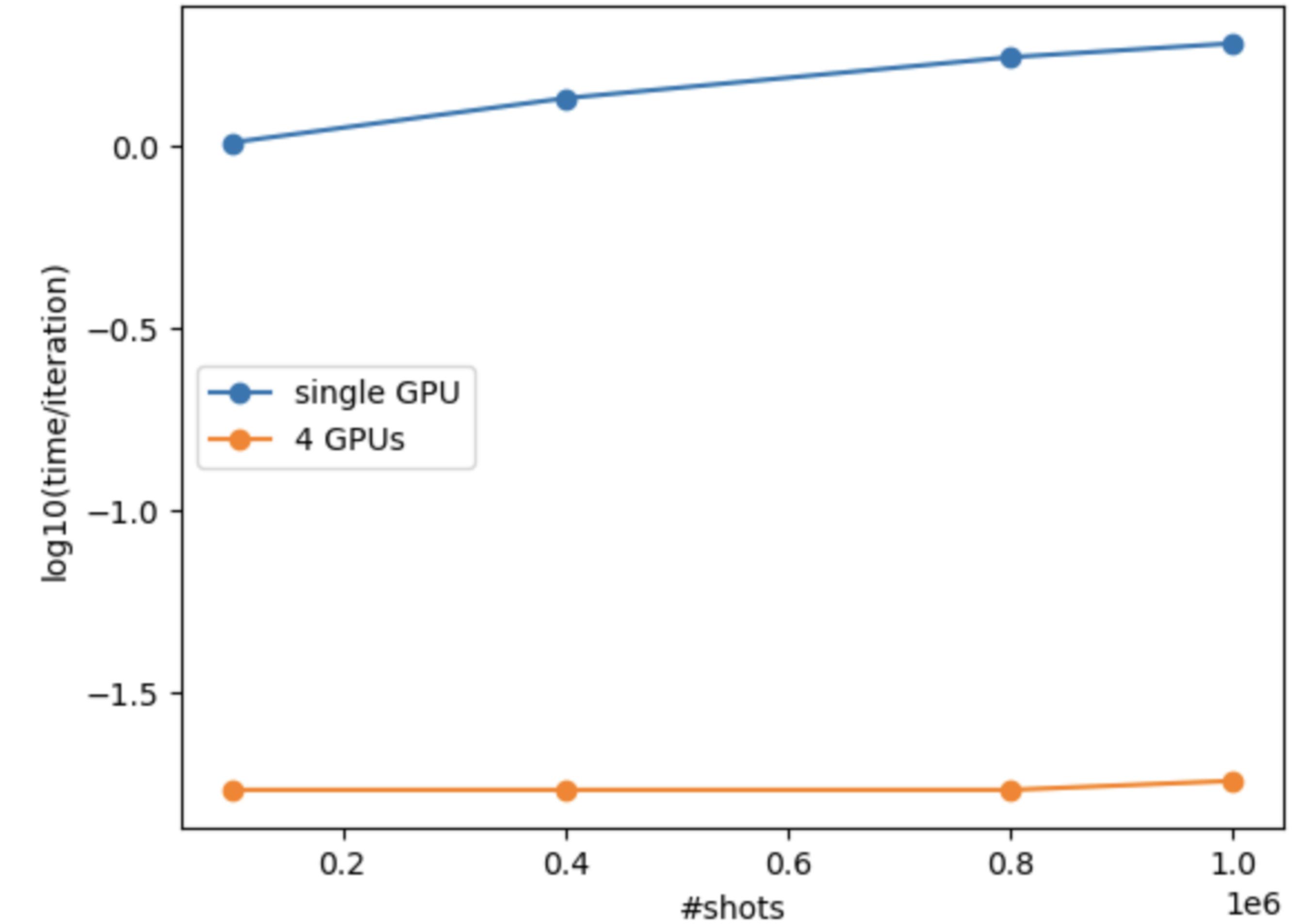
...



# CUDA-Q Platform and Asynchronous Execution

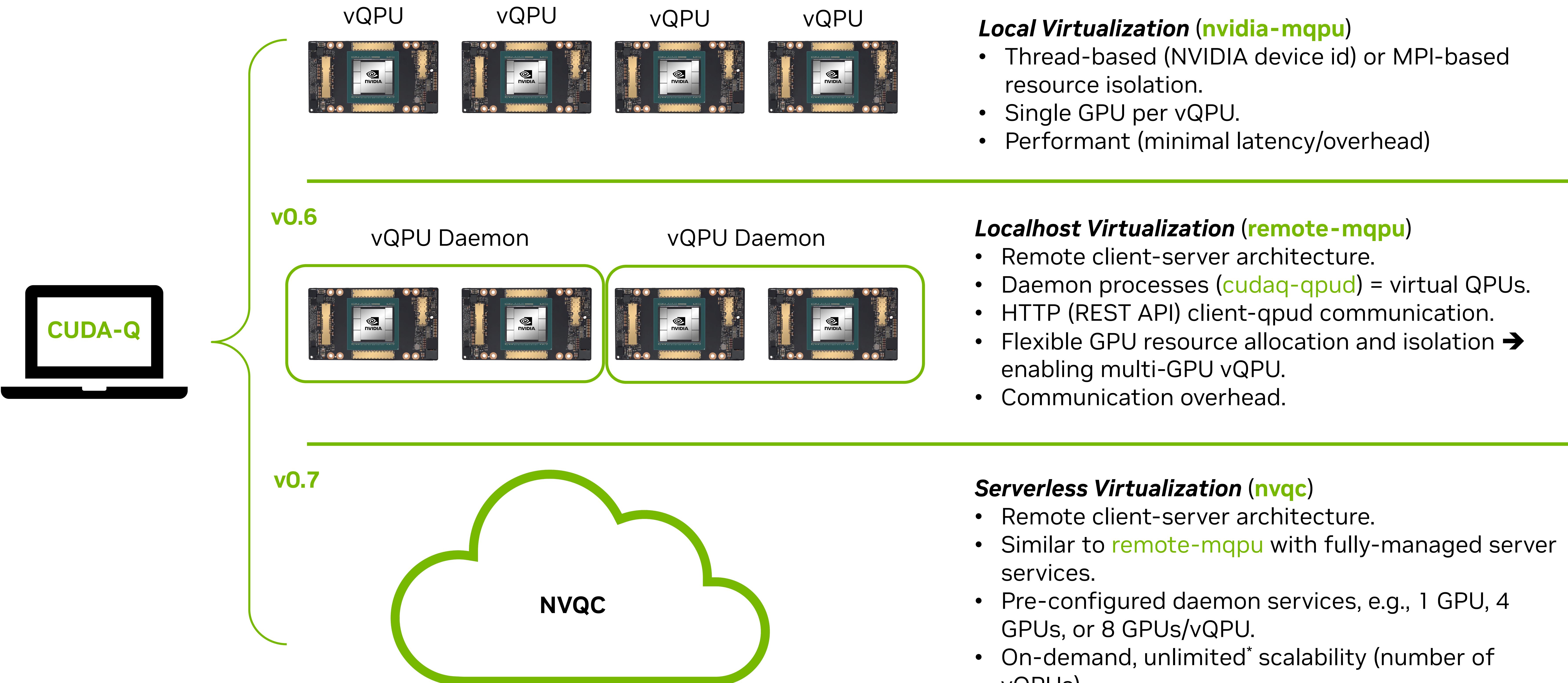
Expose the underlying system architecture to the programmer

- Example use-case – Sampling a Quantum Restricted Boltzmann Machine model
- Find the ground state wavefunction for electronic Hamiltonian
- Find ground state wavefunction for a Transverse Field Ising (TFS) model and Antiferromagnetic Heisenberg model (AFH)
- Anomaly detection (DOI: <https://doi.org/10.1038/s42005-023-01390-y>)
- Cybersecurity (arXiv:2011.13996)



# CUDA-Q Platform and Asynchronous Execution

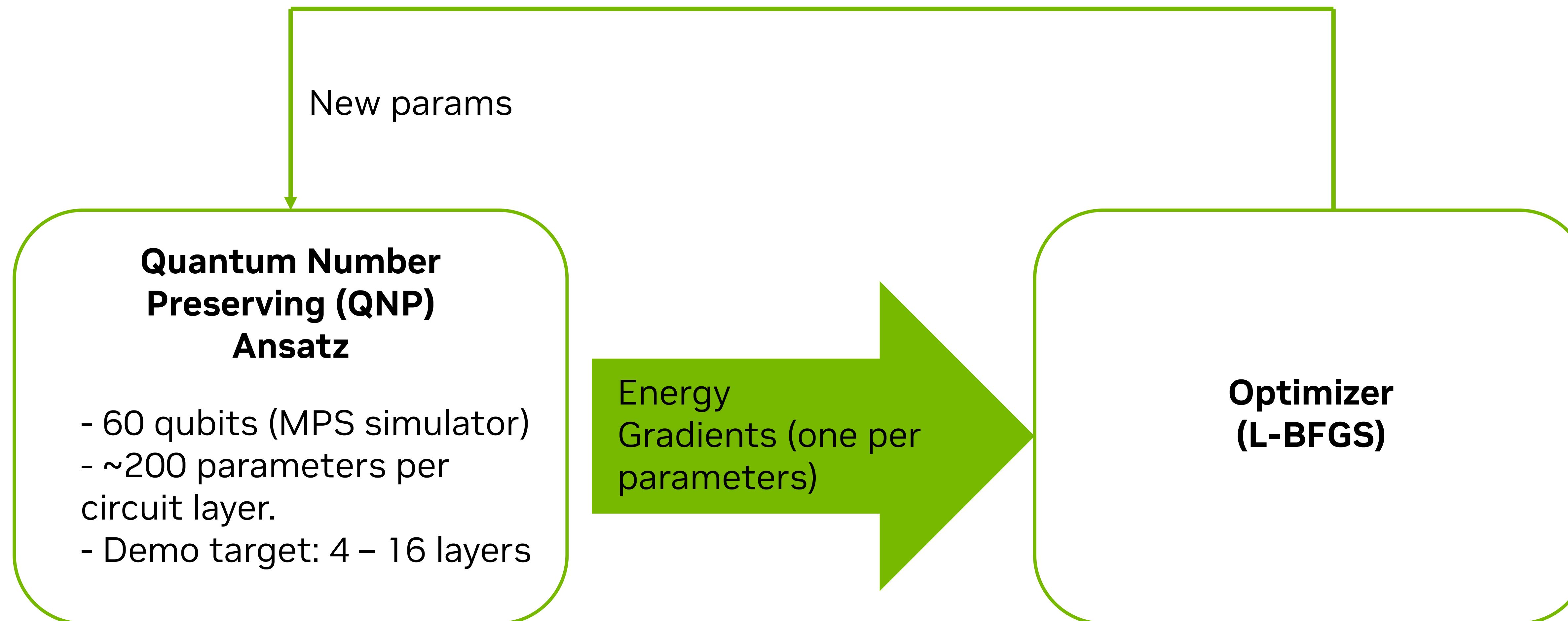
Expose the underlying system architecture to the programmer



\* theoretically, depending on NVCF auto-scaling capabilities

# CUDA-Q Platform and Asynchronous Execution

Expose the underlying system architecture to the programmer



## CUDA-Q Solution:

- Parameter-shift gradient calculation: one parameter → 2 circuits (+/- delta).
- Task-based virtualization: each iteration →  $1 + 2 * \text{num\_params}$  tasks (each task is a circuit with different rotation angles).
- vQPUs grab tasks from the task pool.
- Executed on EOS: 59 nodes – 472 GPUs (each vQPU, aka GPU, only needs to run one task).
- Optimizer check-pointing to fit EOS wall-time limit.



EOS

# CUDA-Q Platform and Asynchronous Execution

Expose the underlying system architecture to the programmer

```
// Toy model: H2
cudaq::spin_op H(h2_data, /*nQubits*/ 4);
auto ansatz = [](std::vector<double> thetas) __qpu__ {
    ... Quantum Number Preserving kernel.
    qnp_fabric(q, numLayers, thetas);
};

// Get the number of virtual QPUs.
auto numQpus = platform.num_qpus();
auto objectiveDistributeGradients = [&](const std::vector<double> &x,
                                         std::vector<double> &dx) -> double {
    std::vector<std::vector<double>> allParams;
    // Task lists: all parameter sets
    allParams.reserve(2 * x.size() + 1);
    allParams.emplace_back(x);
    for (std::size_t paramId = 0; paramId < x.size(); ++paramId) {
        ... Shift params up and down
    }

    // Splice the task list (for QPUs)
    const std::vector<std::vector<std::vector<double>>> paramsForQpus =
        splitVec(allParams, std::min(numQpus, allParams.size()));

    ...
    std::vector<cudaq::async_observe_result> expectation_futures;
    // Async. dispatch
    for (std::size_t qpuId = 0; qpuId < numQpus; ++qpuId)
        for (const auto &param : paramsForQpus[qpuId])
            expectation_futures.emplace_back(
                cudaq::observe_async(qpuId, ansatz, H, param));

    ... Do something else

    // Retrieve results
    std::vector<double> allData;
    for (auto &fut : expectation_futures)
        allData.emplace_back(fut.get().expectation());

    // Return the <H> energy
    const double energy = allData[0];
    for (std::size_t paramId = 0; paramId < x.size(); ++paramId)
        ... Compute the gradients
        dx[paramId] = (shiftPlus - shiftMinus) / 2.0;
    ...

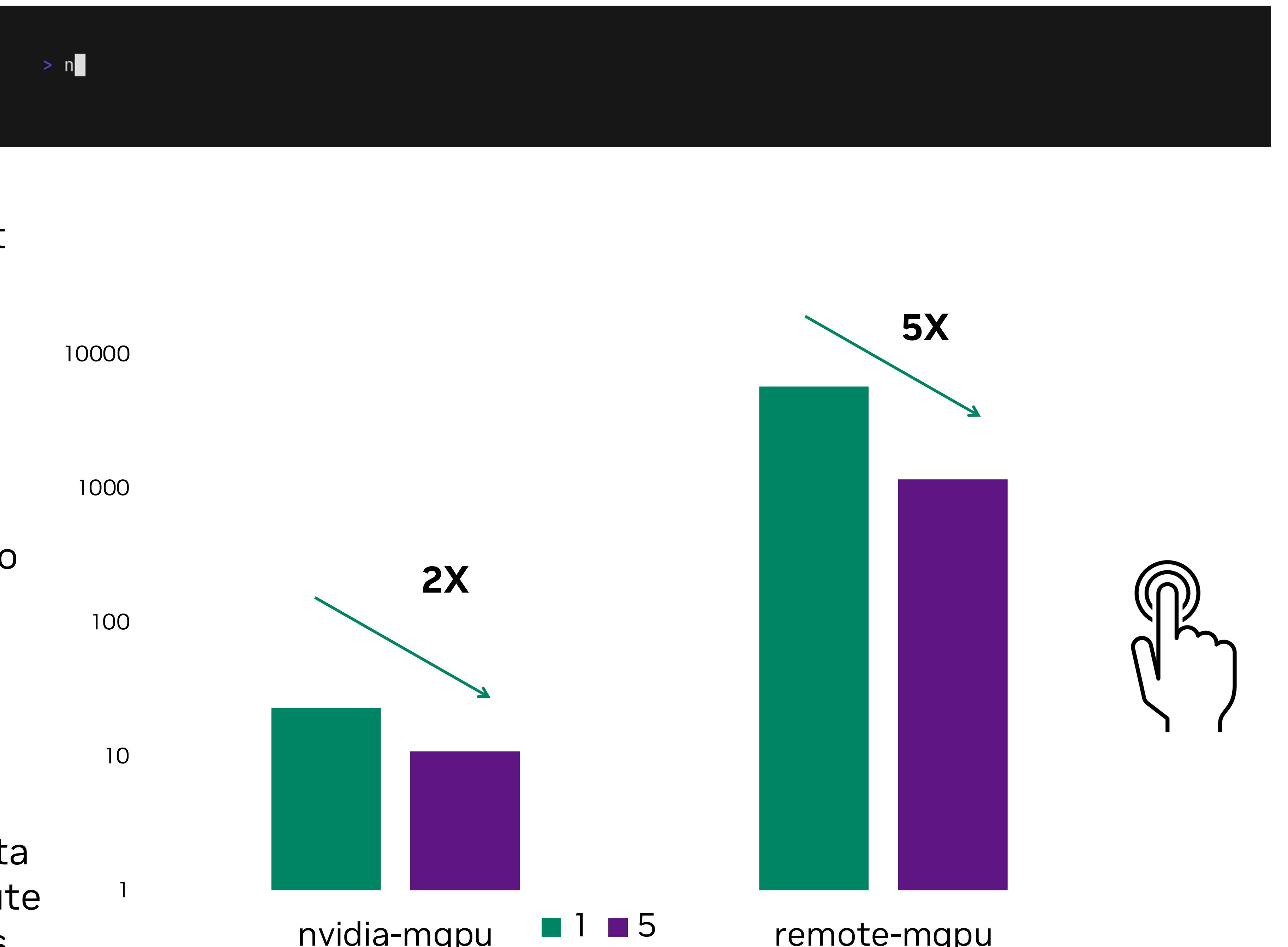
    return energy;
};
```

Task List

Async.  
Dispatch to  
vQPUs

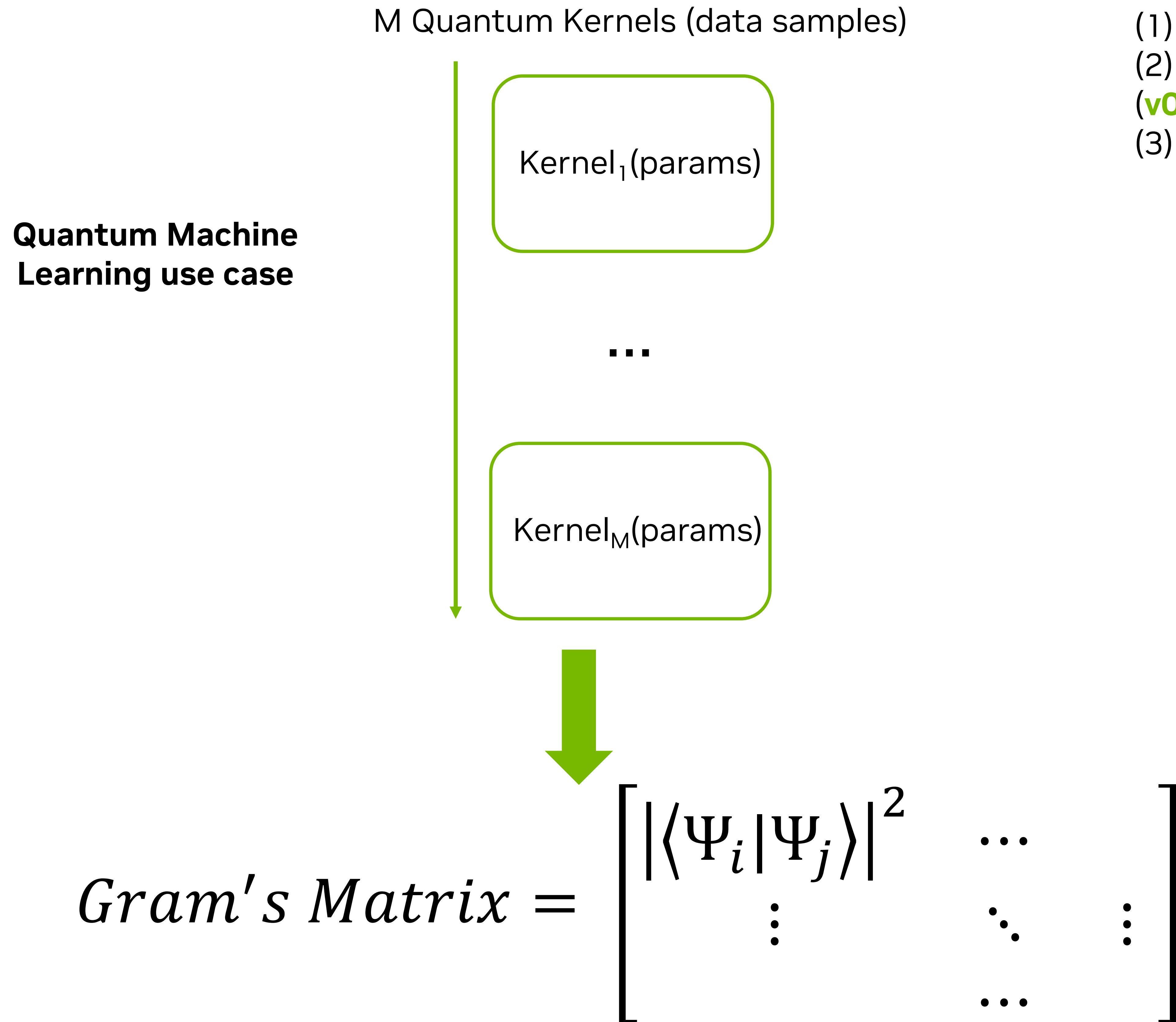
Gather Data  
and Compute  
Gradients

- Platform agnostic programming (vQPU programming model)
- Interchange backend, scale resources up and down



# CUDA-Q Platform and Asynchronous Execution

Expose the underlying system architecture to the programmer



## CUDA-Q Solution:

- (1) Python-based mpi4py parallelization (user code)
- (2) Direct access to GPU memory (tensor network state representation)  
**(v0.8)**
- (3) CUDA integration: cupy and CUDA-aware MPI (data movement)

```
import cudaq
import cupy as cp
import mpi4py
from mpi4py import MPI

comm = MPI.COMM_WORLD

# distribute the parameters across the available vQPU
param_vals_split = comm.scatter(param_vals, root = 0)
states_split = comm.scatter(states, root = 0)

# quantum computation (aka. get_state)
for i in range(param_vals_split.shape[0]):
    states_split[i] = cudaq.get_state(kernel, param_vals_split[i])

# gather the results from the different ranks
results = comm.gather(states_split, root = 0)

# Post-processing to calculate the gram matrix which is the input to SVM

if rank == 0:
    kets = cp.concatenate(results)
    bras = cp.transpose(cp.conj(kets))
    gram_matrix = cp.zeros((m,m))

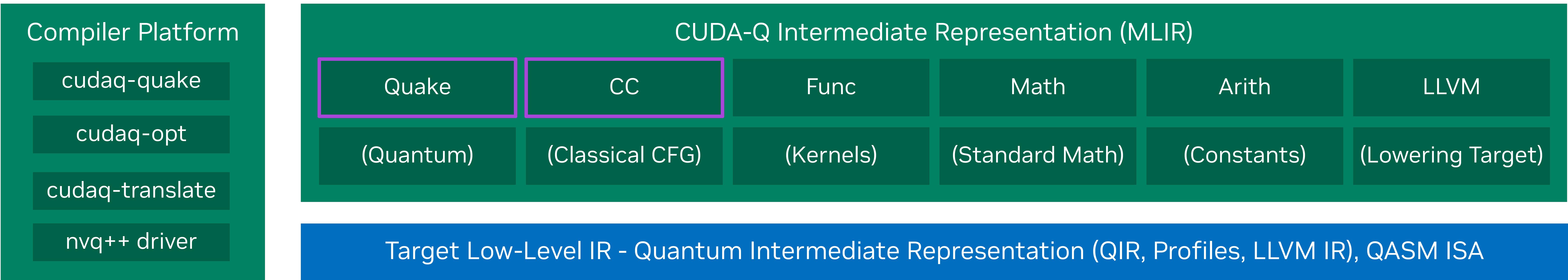
    for i in range(m):
        for j in range(m):
            ith_bra = bras[:,i].reshape(1,-1)
            jth_ket = kets[j].reshape(-1,1)
            gram_matrix[i][j] = np.abs(jth_ket.overlap(ith_bra))**2
```

# CUDA-Q Compiler Platform

The compiler is composed of MLIR dialects and a set of discrete tools

# The CUDA-Q Compiler Stack

Platform for unified quantum-classical accelerated computing



CUDA-Q provides a collection of tools that enables the compilation of language representations to external representations like the QIR.

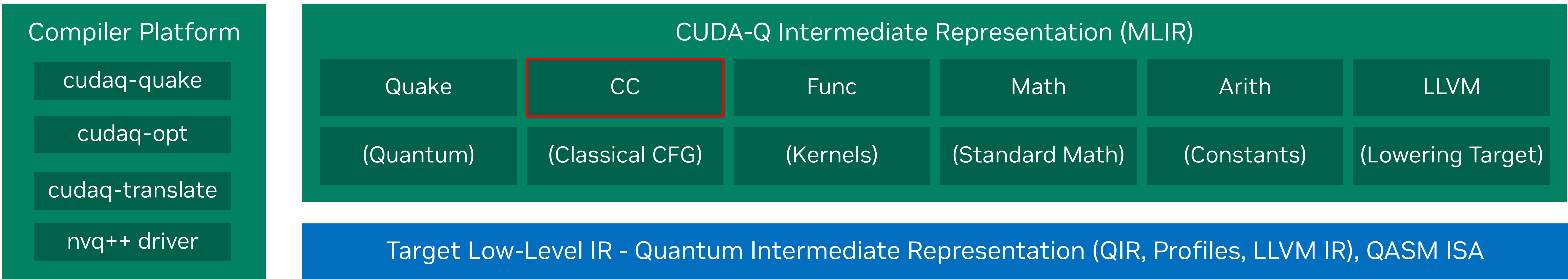
The nvq++ driver orchestrates this collection of these tools to produce hybrid quantum-classical executables and library code.

CUDA-Q targets define the architecture and native gate set for the specific QPU, as well as whether it is physical or emulated.

```
$ nvq++ -o simulatedExample.x example.cpp  
$ ./simulatedExample.x  
  
$ nvq++ -o gpuAccelerated.x example.cpp --target nvidia -I path/includes  
$ ./gpuAccelerated.x  
  
$ nvq++ -o noisyExample.x example.cpp --target density-matrix-gpu  
$ ./noisyExample.x  
  
$ nvq++ -o emulateQuantinuum.x example.cpp --target quantinuum --emulate  
$ ./emulateQuantinuum.x  
  
$ nvq++ -o quantinuumH2.x example.cpp --target quantinuum  
$ ./quantinuumH2.x
```

# The CUDA-Q Compiler Stack

Platform for unified quantum-classical accelerated computing



```
--qpu__ double kernel(int N,
                      std::vector<double> params) {
    int another = 5;
    return params[0] + params[1];
}
```

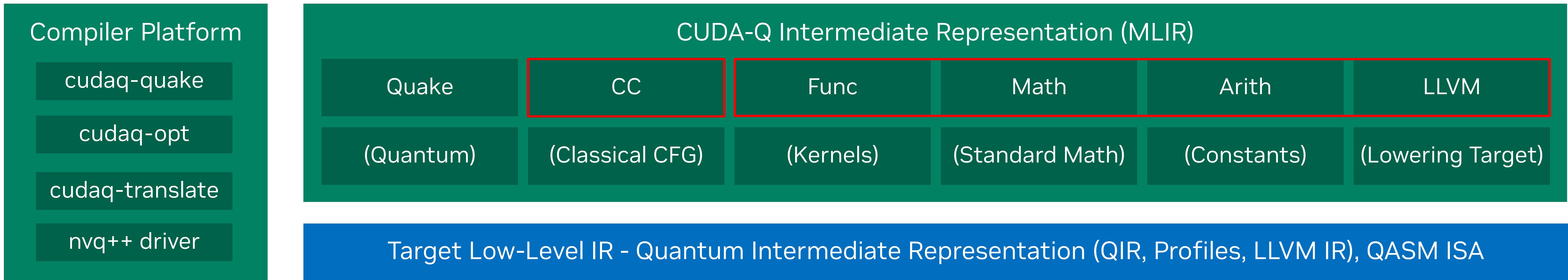


```
module {
  func.func @kernel(%arg0: i32, %arg1: !cc.stdvec<f64>) -> f64 {
    %c5_i32 = arith.constant 5 : i32
    %0 = cc.alloca i32
    cc.store %arg0, %0 : !cc.ptr<i32>
    %1 = cc.alloca i32
    cc.store %c5_i32, %1 : !cc.ptr<i32>
    %2 = cc.stdvec_data %arg1 : (!cc.stdvec<f64>) -> !cc.ptr<f64>
    %3 = cc.compute_ptr %2[0] : (!cc.ptr<f64>) -> !cc.ptr<f64>
    %4 = cc.load %3 : !cc.ptr<f64>
    %5 = cc.stdvec_data %arg1 : (!cc.stdvec<f64>) -> !cc.ptr<f64>
    %6 = cc.compute_ptr %5[1] : (!cc.ptr<f64>) -> !cc.ptr<f64>
    %7 = cc.load %6 : !cc.ptr<f64>
    %8 = arith.addf %4, %7 : f64
    return %8 : f64
  }
}
```

- CC Dialect (Classical Computing)
  - Model C++ types and behavior
  - Control flow
  - Span-like types, callables, variables
  - Loop normalization and unrolling, lambda lifting, mem2reg, reg2mem, lower to LLVM CFG
  - This dialect will grow over time to support more and more of C++

# The CUDA-Q Compiler Stack

Platform for unified quantum-classical accelerated computing



```
--qpu__ double kernel(int N,
                      std::vector<double> params) {
    int another = 5;
    return params[0] + params[1];
}
```

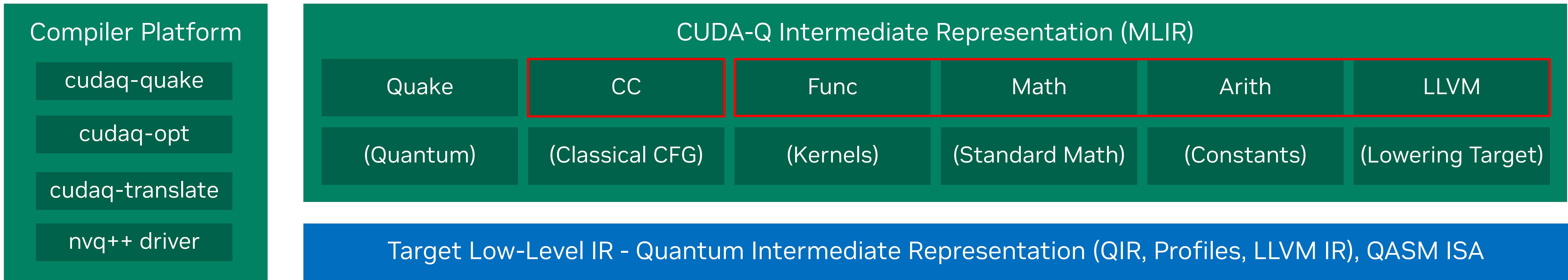


```
module {
  func.func @kernel(%arg0: i32, %arg1: !cc.stdvec<f64>) -> f64 {
    %c5_i32 = arith.constant 5 : i32
    %0 = cc.alloca i32
    cc.store %arg0, %0 : !cc.ptr<i32>
    %1 = cc.alloca i32
    cc.store %c5_i32, %1 : !cc.ptr<i32>
    %2 = cc.stdvec_data %arg1 : (!cc.stdvec<f64>) -> !cc.ptr<f64>
    %3 = cc.compute_ptr %2[0] : (!cc.ptr<f64>) -> !cc.ptr<f64>
    %4 = cc.load %3 : !cc.ptr<f64>
    %5 = cc.stdvec_data %arg1 : (!cc.stdvec<f64>) -> !cc.ptr<f64>
    %6 = cc.compute_ptr %5[1] : (!cc.ptr<f64>) -> !cc.ptr<f64>
    %7 = cc.load %6 : !cc.ptr<f64>
    %8 = arith.addf %4, %7 : f64 Reuse other dialects
    return %8 : f64
  }
}
```

- MLIR Dialect Reuse
  - Leverage the work from the community
  - Functions, Math and Constants, and the LLVM Dialects
- Optimizations from the community
  - Function inlining, canonicalization, common subexpression elimination
- Lower to the QIR in MLIR before translating MLIR to LLVM IR (also get that for free)

# The CUDA-Q Compiler Stack

Platform for unified quantum-classical accelerated computing



```
--qpu__ double kernel(int N,
                      std::vector<double> params) {
    int another = 5;
    return params[0] + params[1];
}
```



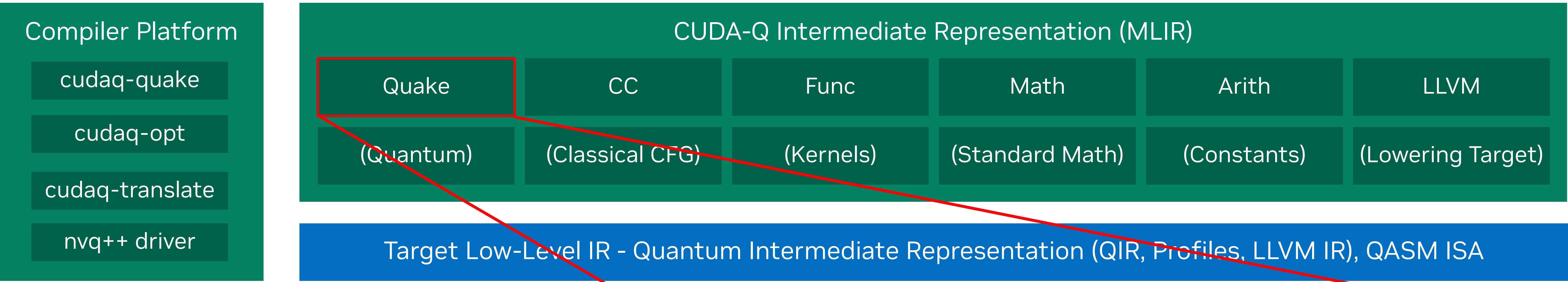
```
llvm.func @kernel(%arg0: i32, %arg1: !llvm.struct<(ptr, i64)>) -> f64 {
    %0 = llvm.mlir.constant(5 : i32) : i32
    %1 = llvm.mlir.constant(1 : i32) : i32
    %2 = llvm.alloca %1 x i32 : (i32) -> !llvm.ptr
    llvm.store %arg0, %2 : i32, !llvm.ptr
    %3 = llvm.alloca %1 x i32 : (i32) -> !llvm.ptr
    llvm.store %0, %3 : i32, !llvm.ptr
    %4 = llvm.extractvalue %arg1[0] : !llvm.struct<(ptr, i64)>
    %5 = llvm.load %4 : !llvm.ptr -> f64
    %6 = llvm.extractvalue %arg1[0] : !llvm.struct<(ptr, i64)>
    %7 = llvm.getelementptr inbounds %6[1] : (!llvm.ptr) -> !llvm.ptr, f64
    %8 = llvm.load %7 : !llvm.ptr -> f64
    %9 = llvm.fadd %5, %8 : f64
    llvm.return %9 : f64
}
```

Fully reuse LLVM dialect to go out  
to executable code

- MLIR Dialect Reuse
  - Leverage the work from the community
  - Functions, Math and Constants, and the LLVM Dialects
- Optimizations from the community
  - Function inlining, canonicalization, common subexpression elimination
- Lower to the QIR in MLIR before translating MLIR to LLVM IR (also get that for free)

# The CUDA-Q Compiler Stack

Platform for unified quantum-classical accelerated computing



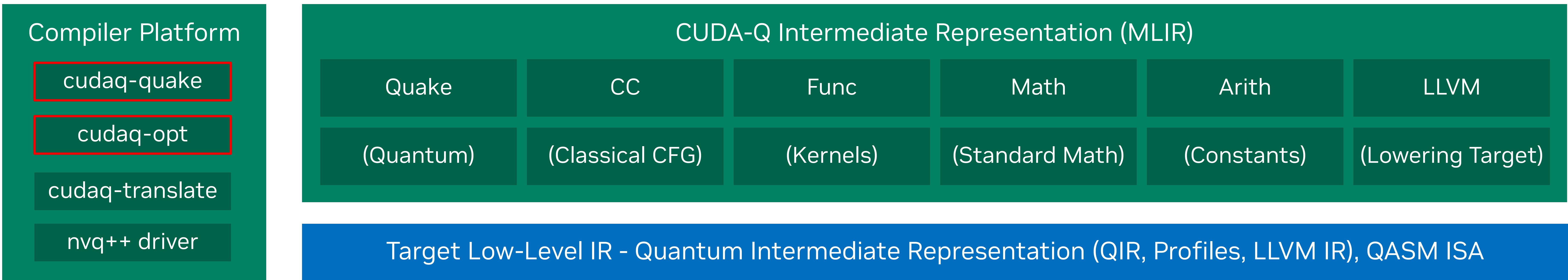
- Quake (Quantum Kernel Execution) Dialect
  - Model quantum types and operations
- Quake can be in one of 2 forms:
  - Memory semantic model
    - easier to generate, QASM-like
  - Value semantic model
    - easier for optimizations
- Optimizations and Transformations may be better suited for either of these forms
  - Track the use-def chains

The diagram shows two examples of Quake code. The left example, under 'Memory Semantic Model', is a QASM-like representation:func.func foo(%veq : !quake.veq<2>) {  
 // Boilerplate to extract each qubit from the vector  
 %c0 = arith.constant 0 : index  
 %c1 = arith.constant 1 : index  
 %q0 = quake.extract\_ref %veq[%c0] :  
 (!quake.veq<2>, index) -> !quake.ref  
 %q1 = quake.extract\_ref %veq[%c1] :  
 (!quake.veq<2>, index) -> !quake.ref  
  
 // We apply some operators to those extracted qubits  
 // ... bunch of operators using %q0 and %q1 ...  
 quake.h %q0 : (!quake.ref) -> ()  
  
 // We decide to measure the vector  
 %result = quake.mz %veq : (!quake.veq<2>) -> cc.stdvec<i1>  
  
 // And then apply another Hadamard to %q0  
 quake.h %q0 : (!quake.ref) -> ()  
 // ...  
}

The right example, under 'Value Semantic Model', is optimized for finding optimizations:func.func @foo() {  
 %0 = quake.null\_wire  
 %1 = quake.null\_wire  
 %2 = quake.h %0 : (!quake.wire) -> !quake.wire  
 %3 = quake.h %2 : (!quake.wire) -> !quake.wire  
 %4 = quake.h %3 : (!quake.wire) -> !quake.wire  
 %5 = quake.h %4 : (!quake.wire) -> !quake.wire  
 %6 = quake.h %5 : (!quake.wire) -> !quake.wire  
 %7 = quake.x %6 : (!quake.wire) -> !quake.wire  
 %8 = quake.x %7 : (!quake.wire) -> !quake.wire  
 %9:2 = quake.x [%8] %1 : (!quake.wire, !quake.wire) ->  
 (!quake.wire, !quake.wire)  
 %10:2 = quake.x [%9#0] %9#1 : (!quake.wire, !quake.wire) ->  
 (!quake.wire, !quake.wire)  
 %11:2 = quake.x [%10#0] %10#1 : (!quake.wire, !quake.wire) ->  
 (!quake.wire, !quake.wire)  
 return  
}

# The CUDA-Q Compiler Stack

Platform for unified quantum-classical accelerated computing



- Lower C++ CUDA Quantum Kernels to Quake
- Leverage Clang to build AST, walk the tree and map `__qpu__ FunctionDecls` to MLIR Functions containing Quake and CC operations
- `cudaq-opt` - Transform / Optimize Quake

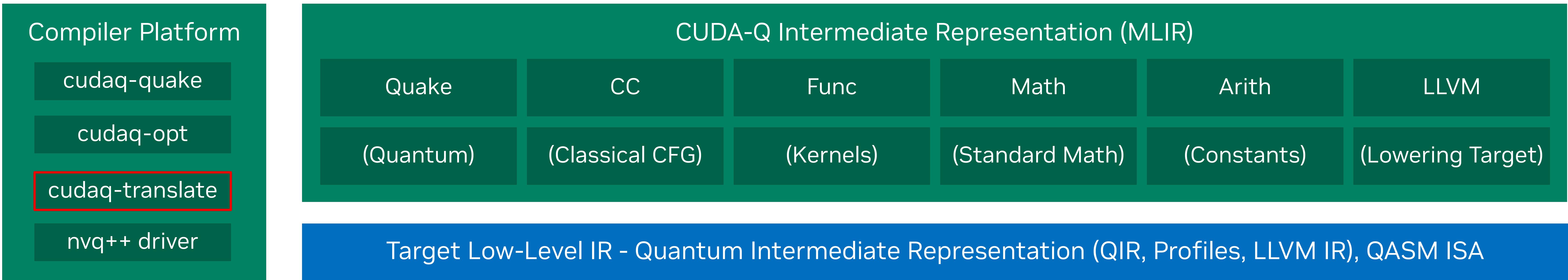
```
__qpu__ void ghzForLoop(int N) {
    cudaq::qreg q(N);
    h(q[0]);
    for (std::size_t i = 0; i < N - 1; i++)
        x<cudaq::ctrl>(q[i], q[i + 1]);
    mz(q);
}
```

`cudaq-quake` ghz.cpp | `cudaq-opt --canonicalize`

```
func.func ghzForLoop (%arg0: i32) {
    %c0_i64 = arith.constant 0 : i64
    ... (skipped for brevity) ...
    %0 = cc.alloca i32
    cc.store %arg0, %0 : !cc.ptr<i32>
    ... (skipped for brevity) ...
    quake.h %4 : (!quake.ref) -> ()
    %5 = cc.alloca i64
    cc.store %c0_i64, %5 : !cc.ptr<i64>
    cc.loop while {
        ... (skipped for brevity) ...
        cc.condition %11
    } do {
        ... (skipped for brevity) ...
        %11 = quake.extract_ref %3[%10] : (!quake.veq<?>, i64) -> !quake.ref
        quake.x [%8] %11 : (!quake.ref, !quake.ref) -> ()
        cc.continue
    } step {
        ... (skipped for brevity) ...
    }
```

# The CUDA-Q Compiler Stack

Platform for unified quantum-classical accelerated computing



- Translate Quake to external representations

- **QIR**
- QIR Profiles
- OpenQASM 2.0
- IQM JSON

```
--qpu__ void simple() {
    cudaq::qubit q, r;
    h(r);
    x(q);
}
```

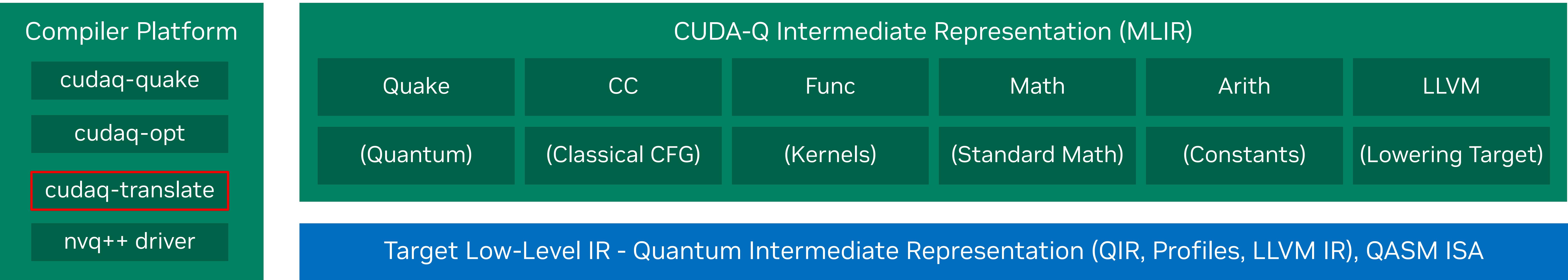
```
cudaq-quake ghz.cpp |
  cudaq-opt --canonicalize |
  cudaq-translate --convert-to=qir
```

```
%Array = type opaque
%Qubit = type opaque
...
... (skipped for brevity) ...

define void @_nvqpp_mlirgen_function_test._Z4testv() local_unnamed_addr {
    %1 = tail call %Array* @_quantum_rt_qubit_allocate_array(i64 2)
    %2 = tail call i8* @_quantum_rt_array_get_element_ptr_1d(%Array* %1, i64 0)
    %3 = bitcast i8* %2 to %Qubit**
    %4 = load %Qubit*, %Qubit** %3, align 8
    %5 = tail call i8* @_quantum_rt_array_get_element_ptr_1d(%Array* %1, i64 1)
    %6 = bitcast i8* %5 to %Qubit**
    %7 = load %Qubit*, %Qubit** %6, align 8
    tail call void @_quantum_qis_h(%Qubit* %7)
    tail call void @_quantum_qis_x(%Qubit* %4)
    tail call void @_quantum_rt_qubit_release_array(%Array* %1)
    ret void
}
```

# The CUDA-Q Compiler Stack

Platform for unified quantum-classical accelerated computing



- Translate Quake to external representations

- QIR
- **QIR Profiles**
- OpenQASM 2.0
- IQM JSON

```
--qpu__ void simple() {
    cudaq::qubit q, r;
    h(r);
    x(q);
}
```

```
cudaq-quake ghz.cpp |
  cudaq-opt --canonicalize |
  cudaq-translate --convert-to=qir-base
```

```
%Qubit = type opaque

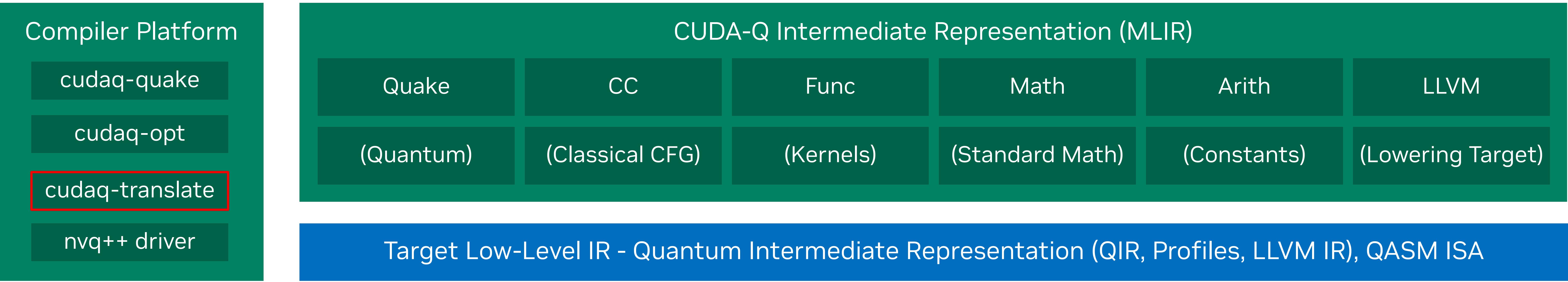
declare void @_quantum_qis_h_body(%Qubit*) local_unnamed_addr
declare void @_quantum_qis_x_body(%Qubit*) local_unnamed_addr
declare void @_quantum_rt_array_end_record_output() local_unnamed_addr
declare void @_quantum_rt_array_start_record_output() local_unnamed_addr

define void @_nvqpp_mlirgen_function_test._Z4testv() local_unnamed_addr #0 {
    tail call void @_quantum_qis_h_body(%Qubit*nonnull inttoptr
                                         (i64 1 to %Qubit*))
    tail call void @_quantum_qis_x_body(%Qubit* null)
    tail call void @_quantum_rt_array_start_record_output()
    tail call void @_quantum_rt_array_end_record_output()
    ret void
}

attributes #0 = { "EntryPoint" "requiredQubits"="2" "requiredResults"="0" }
```

# The CUDA-Q Compiler Stack

Platform for unified quantum-classical accelerated computing



- Translate Quake to external representations

- QIR
- QIR Profiles
- **OpenQASM 2.0**
- IQM JSON

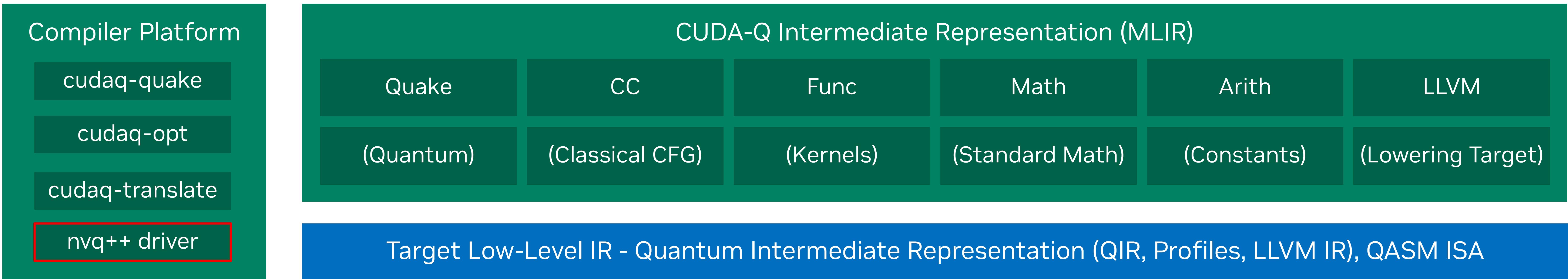
```
--qpu__ void simple() {
    cudaq::qubit q, r;
    h(r);
    x(q);
}
```

```
OPENQASM 2.0;
include "qelib1.inc";
qreg var0[1];
qreg var1[1];
h var1[0];
x var0[0];
```

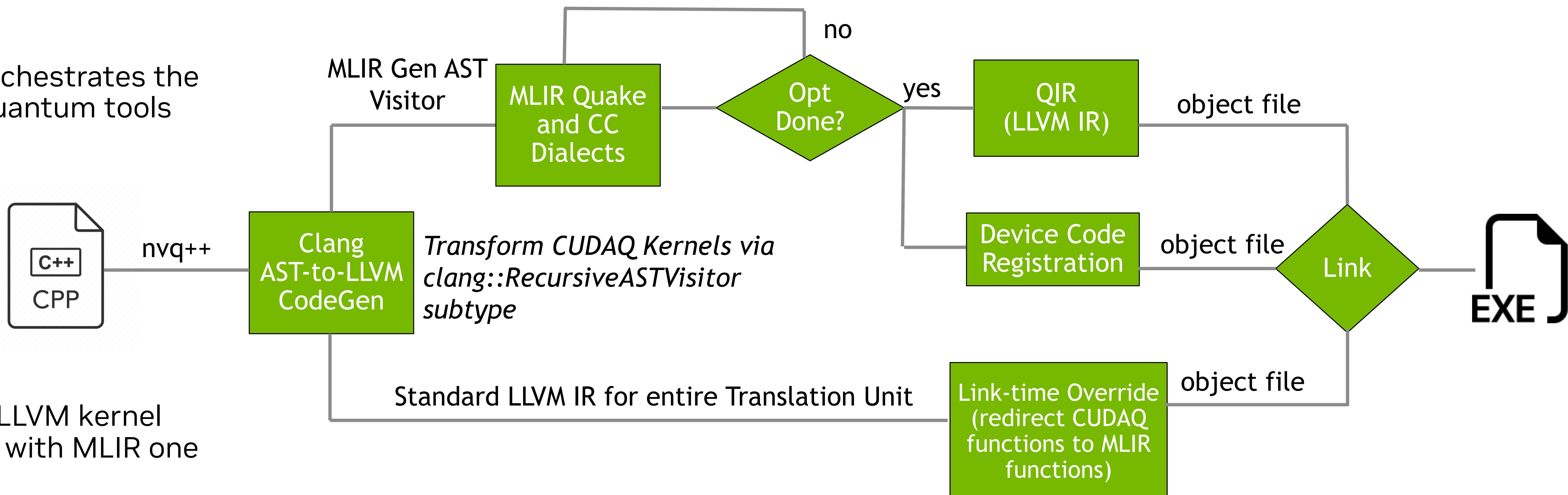
```
cudaq-quake ghz.cpp |
  cudaq-opt --canonicalize |
  cudaq-translate --convert-to=openqasm
```

# The CUDA-Q Compiler Stack

Platform for unified quantum-classical accelerated computing



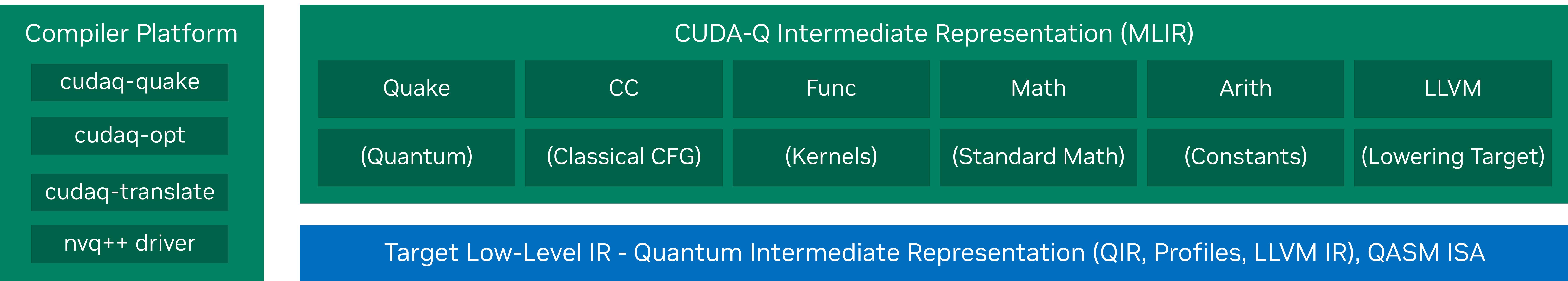
- nvq++ orchestrates the CUDA Quantum tools



- Replace LLVM kernel function with MLIR one

# The CUDA-Q Compiler Stack

Platform for unified quantum-classical accelerated computing



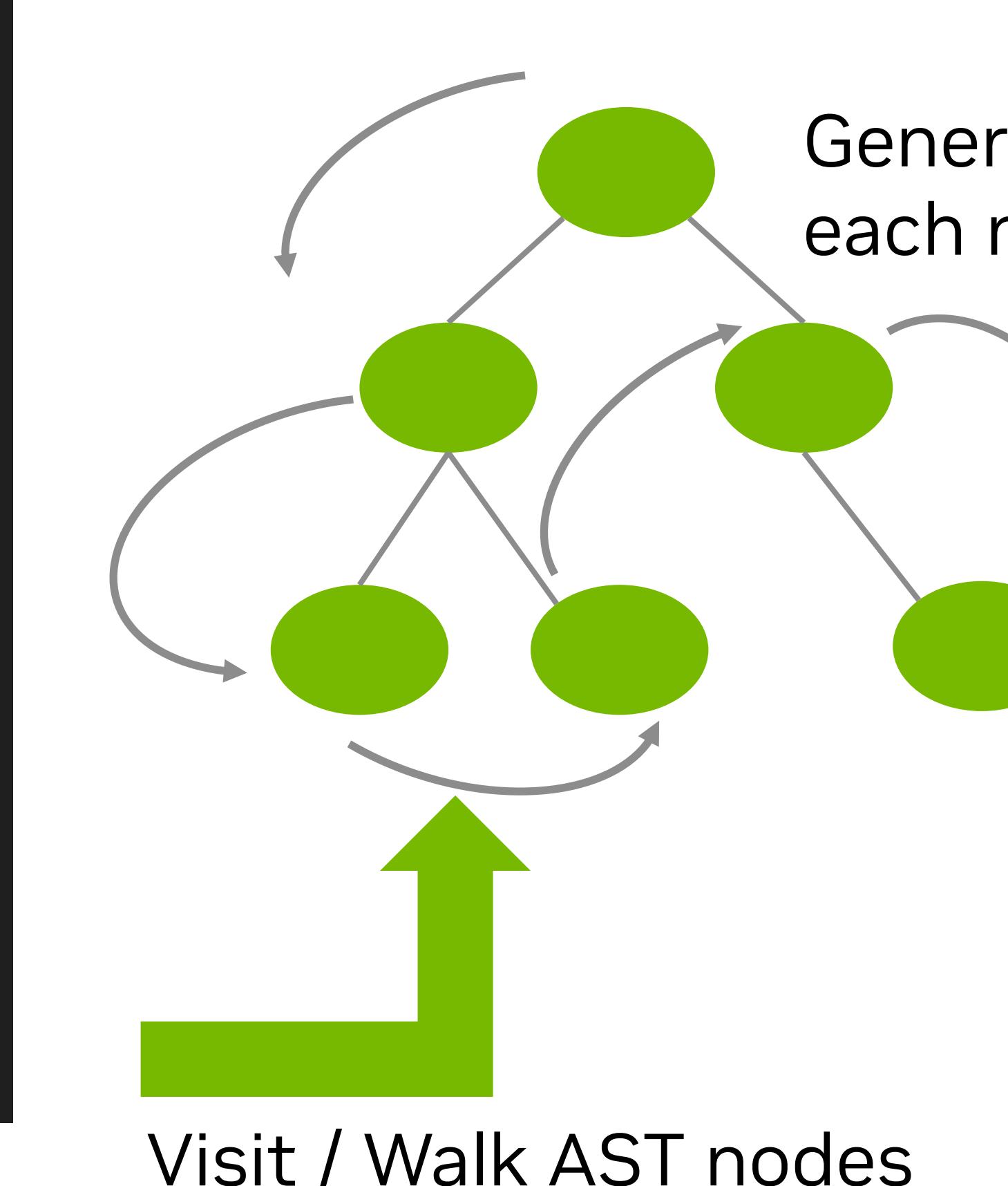
```
@cudaq.kernel
def bell():
    q = cudaq.qvector(2)
    h(q[0])
    x.ctrl(q[0], q[1])
```

Map function to  
Python AST

```
FunctionDef(
    lineno=2,
    col_offset=0,
    end_lineno=5,
    end_col_offset=22,
    name='bell',
    args=arguments(posonlyargs=[], args=[], vararg=None, kwonlyargs=[], kw_defaults=[], kwarg=None, defaults=[]),
    body=[
        Assign(
            lineno=3,
            col_offset=4,
            end_lineno=3,
            end_col_offset=24,
            targets=[Name(lineno=3, col_offset=4, end_lineno=3, end_col_offset=5, id='q', ctx=Store())],
            value=Call(
                lineno=3,
                col_offset=8,
                end_lineno=3,
                end_col_offset=24,
                func=Attribute(
                    lineno=3,
                    col_offset=8,
                    end_lineno=3,
                    end_col_offset=21,
                    value=Name(lineno=3, col_offset=8, end_lineno=3, end_col_offset=13, id='cudaq', ctx=Load()),
                    attr='qvector',
                    ctx=Load(),
                ),
                args=[Constant(lineno=3, col_offset=22, end_lineno=3, end_col_offset=23, value=2, kind=None)],
                keywords=[],
            ),
            type_comment=None,
        ),
    ],
)
```

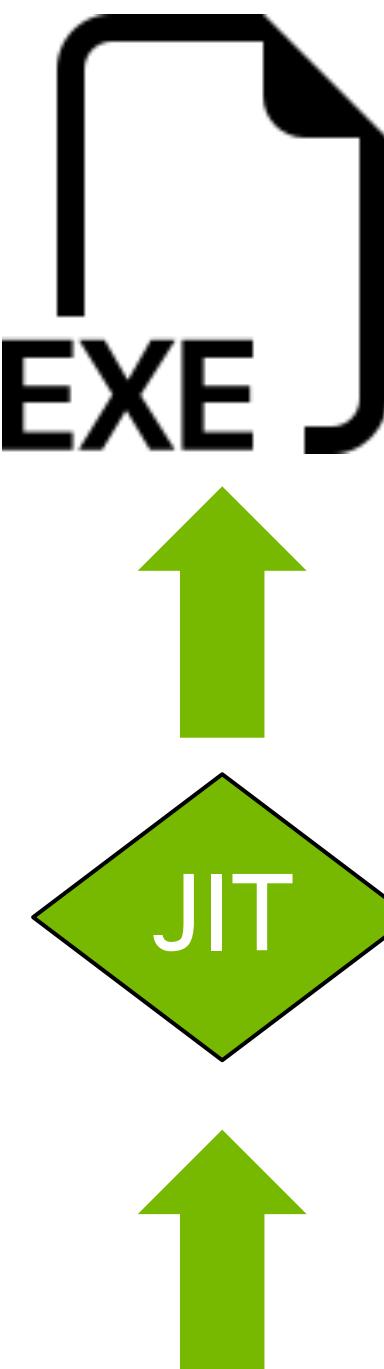
Map function to  
Python AST

AST Visitor



```
func.func @bell() {
    %0 = quake.alloca !quake.veq<2>
    %1 = quake.extract_ref %0[0] : (!quake.veq<2>) -> !quake.ref
    quake.h %1 : (!quake.ref) -> ()
    %2 = quake.extract_ref %0[1] : (!quake.veq<2>) -> !quake.ref
    quake.x [%1] %2 : (!quake.ref, !quake.ref) -> ()
    return
}
```

JIT compile,  
extract  
function  
pointer



# CUDA-Q in Action

- Dramatic performance improvements
- Hybrid QPU-GPU applications

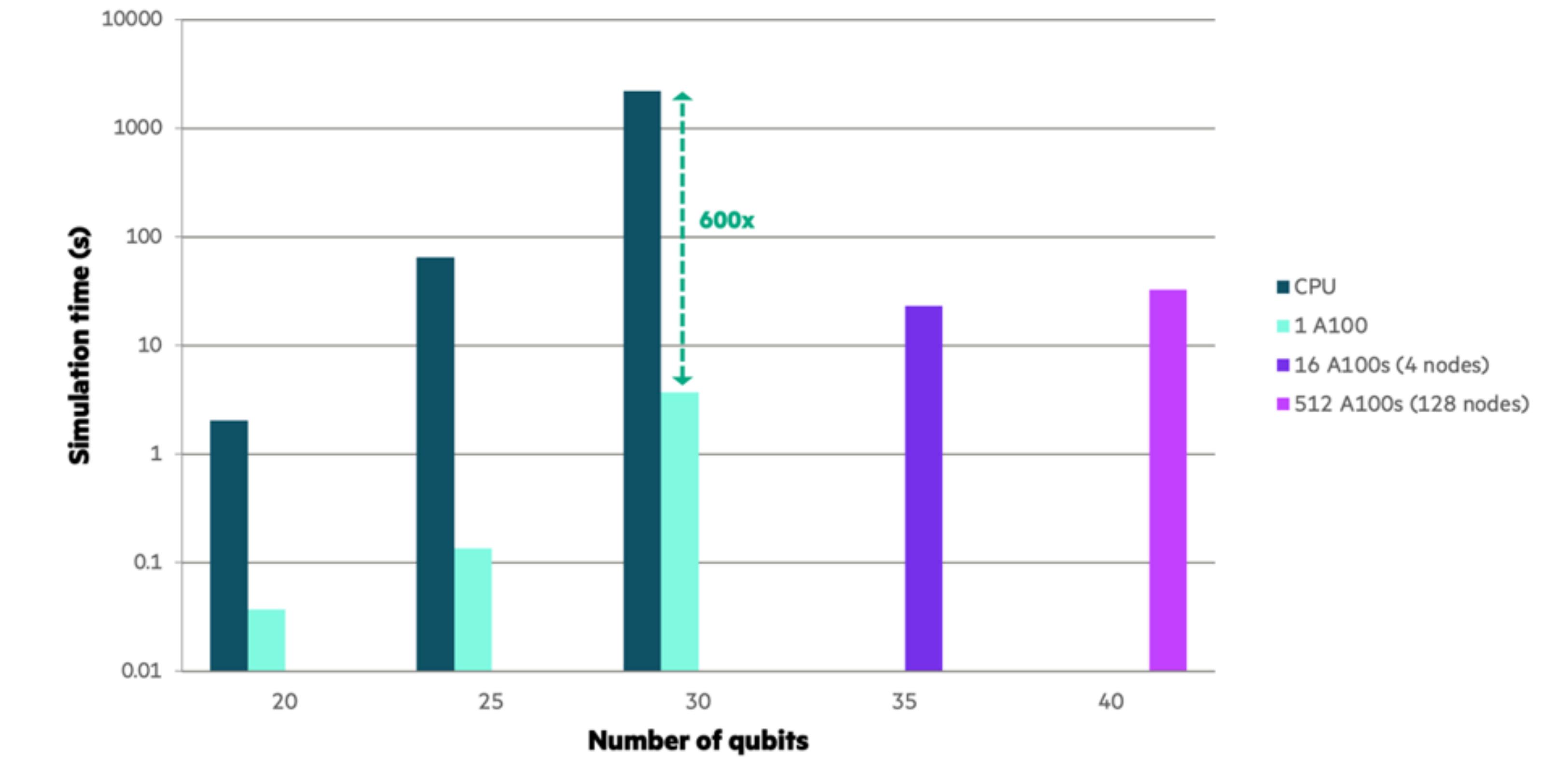
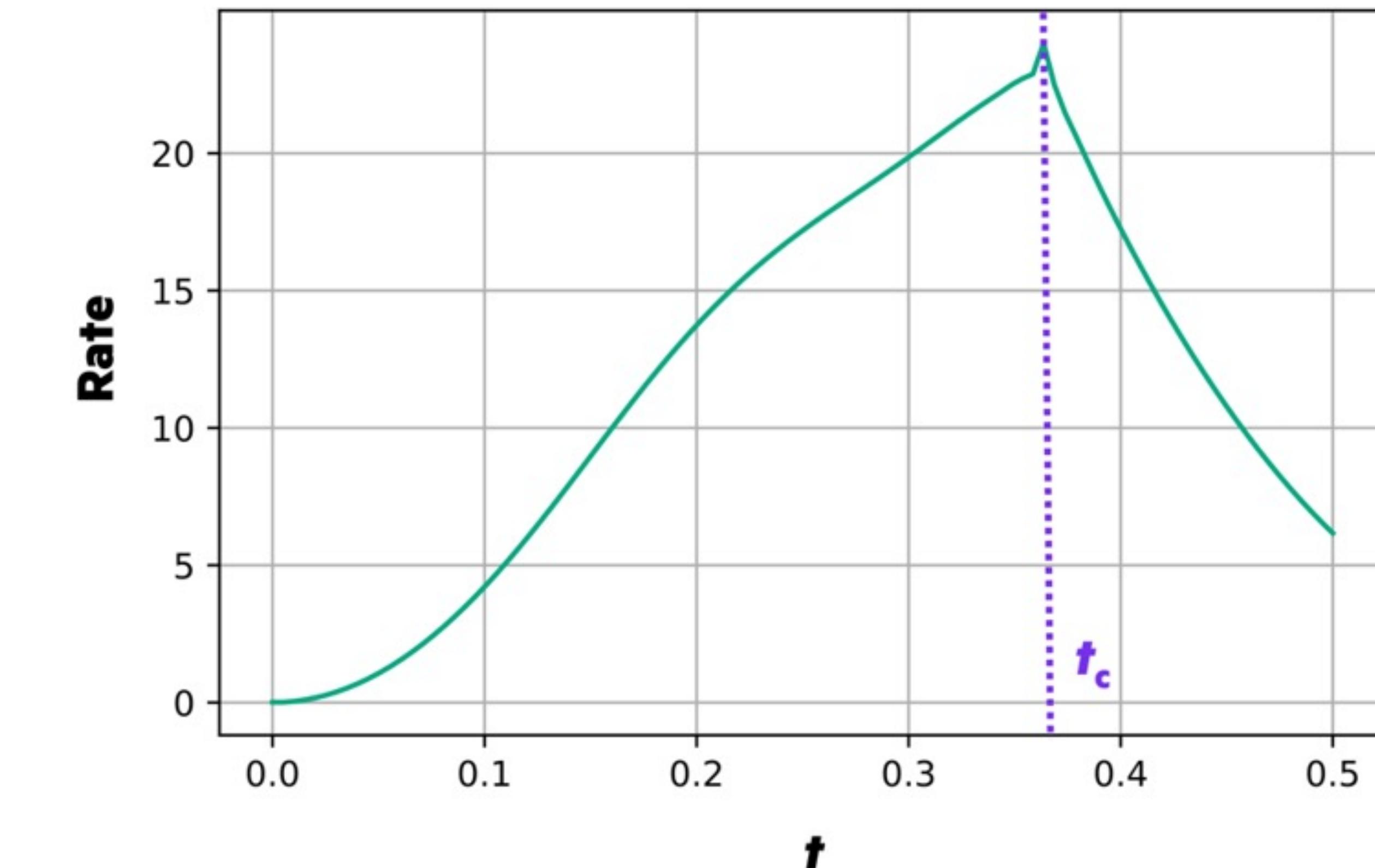
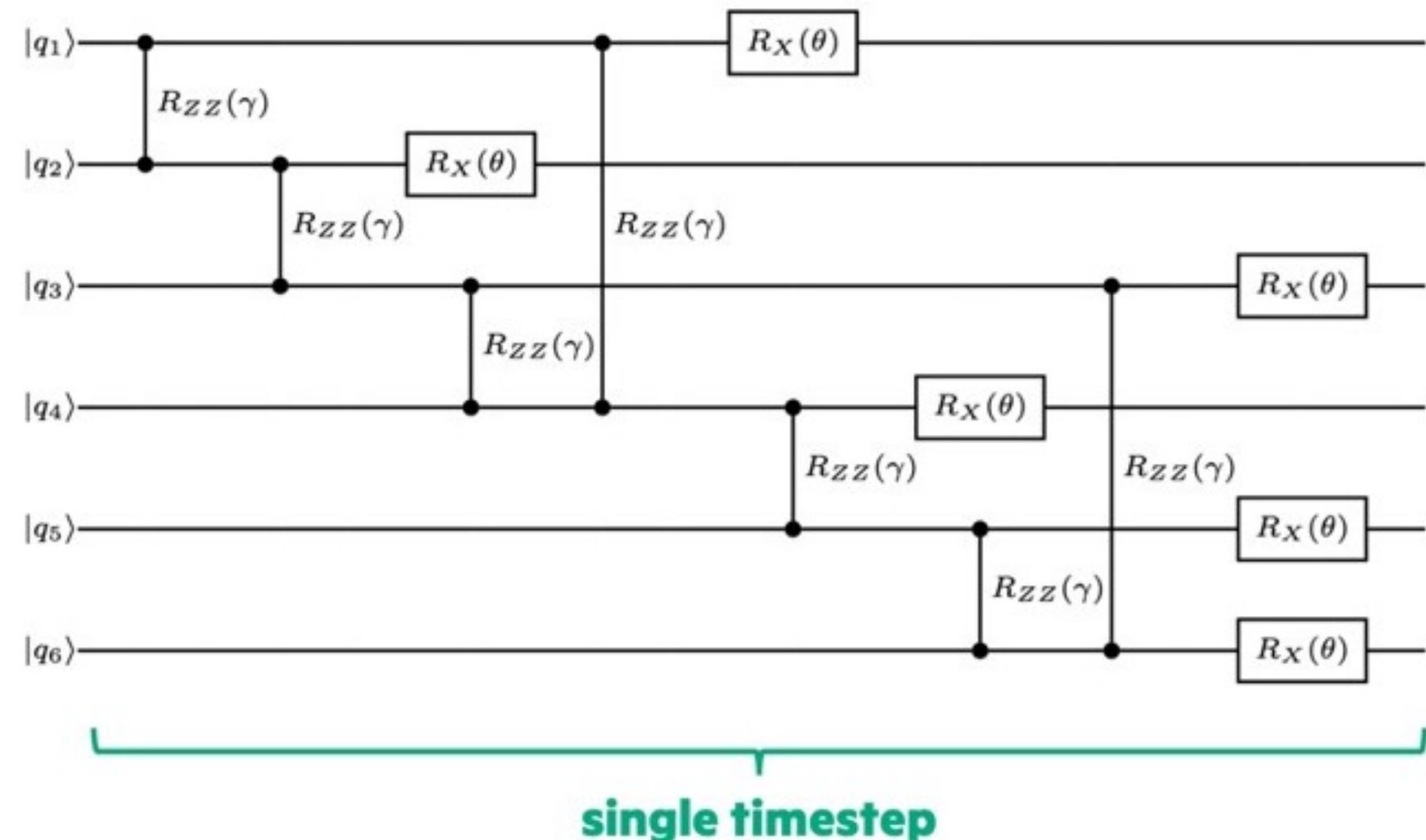
# CUDA-Q in Action

## Speed-ups for time-evolution of the transverse field Ising model (TFIM)

- Collaboration with Hewlett Packard Labs
- Study dynamical quantum phase transitions
  - Requires computation of overlap of initial state with time evolved state
- Leverage NVIDIA multi-node, multi-GPU simulation backend.
  - Distributed state-vector simulator
- 600x performance increase over multi-threaded CPU approaches

```
@cudaq.kernel()
def tfimEvolve(timeStep: float, params: list[float]):
    qubits = cudaq.qvector(40)
    ... Circuit, use input params ...

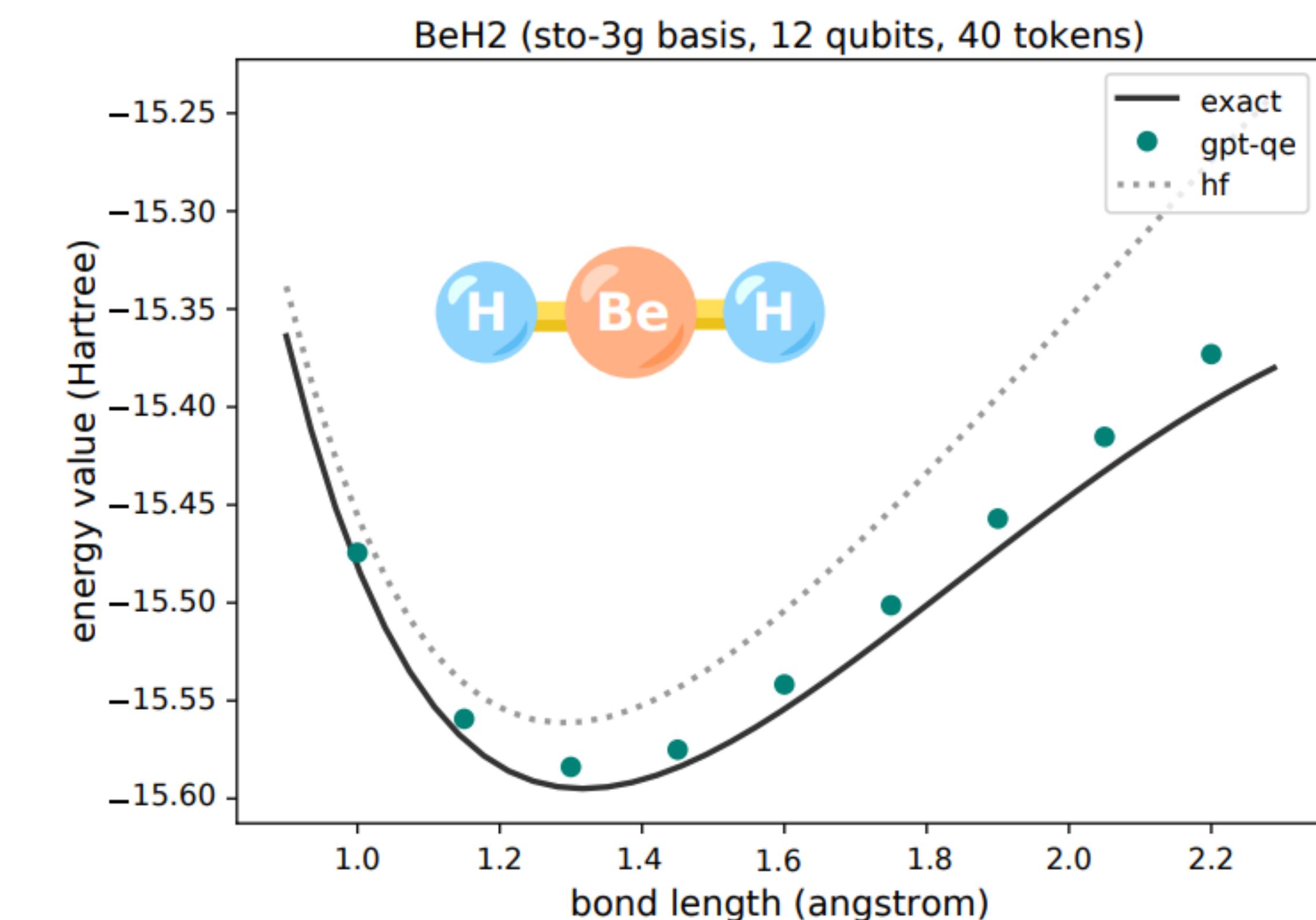
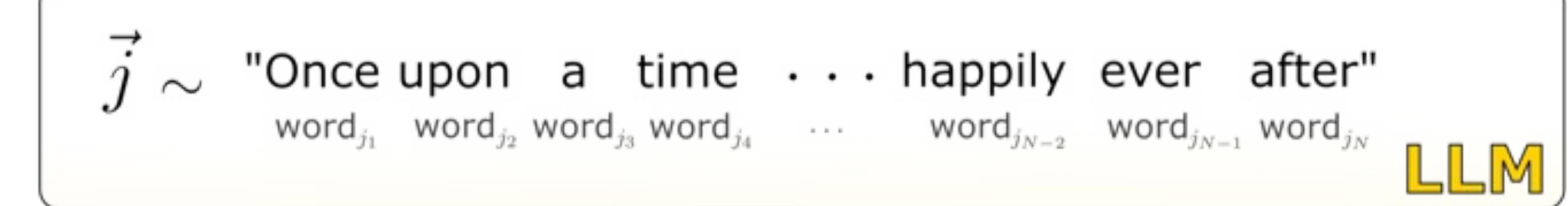
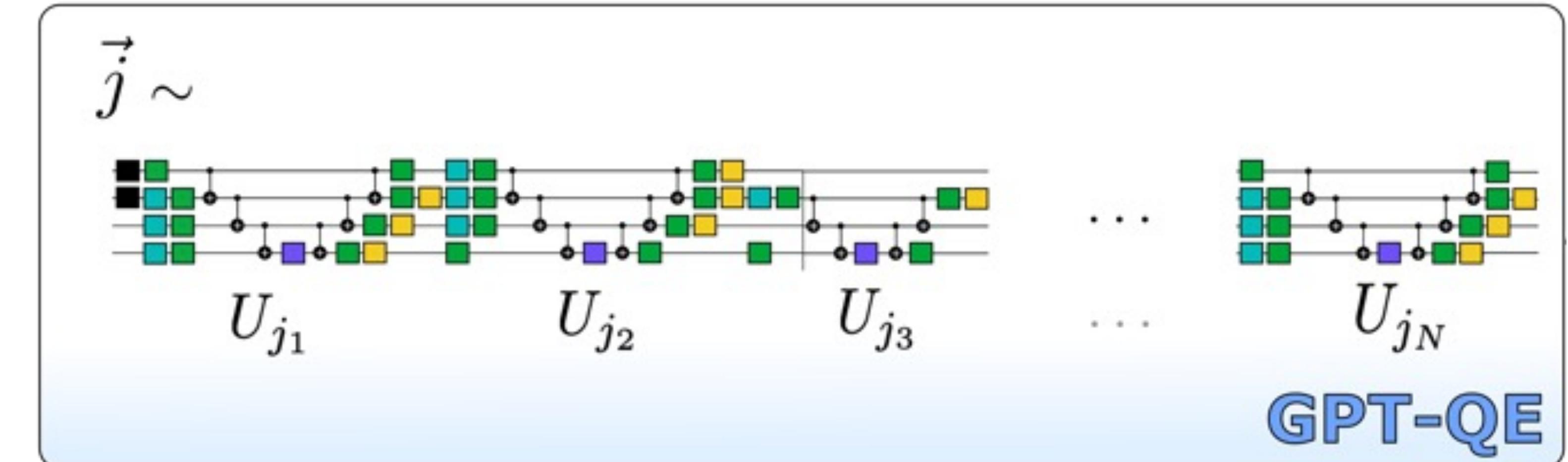
    for time in range(finalTime):
        state = cudaq.get_state(tfimEvolve, time, params)
        overlaps.append(state.overlap(initialState))
```



# CUDA-Q in Action

GPT-QE - University of Toronto and St. Jude Children's Research Hospital with CUDA-Q

- Developed a novel Generative Pre-Trained Transformer-based (GPT) method for computing the ground-state energy of molecules of interest
- The first demonstration of a GPT-generated quantum circuit in the literature
- A powerful example of leveraging AI to accelerate quantum computing
- Executed using CUDA-Q on A100 GPUs on Perlmutter
- Opens the door to a wide variety of novel Generative Quantum Algorithms (GQAs) for drug discovery, materials science, and environmental challenges



# New Performance Updates

# CUDA-Q performance updates

Improved Gate Fusion

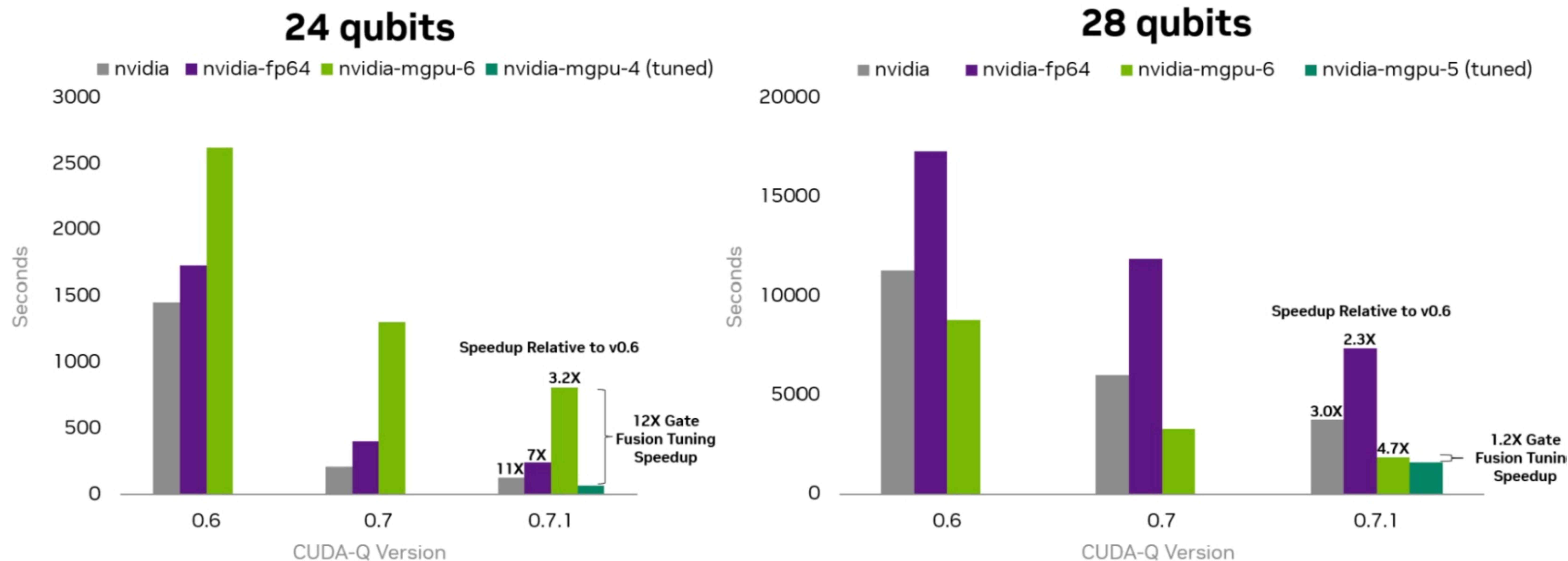


Figure 1. Execution times for 10 `observe` calls in 24 and 28 qubit UCCSD-VQE experiments

<https://developer.nvidia.com/blog/new-nvidia-cuda-q-features-boost-quantum-application-performance/>

# CUDA-Q performance updates

Improved JIT compilation and runtime

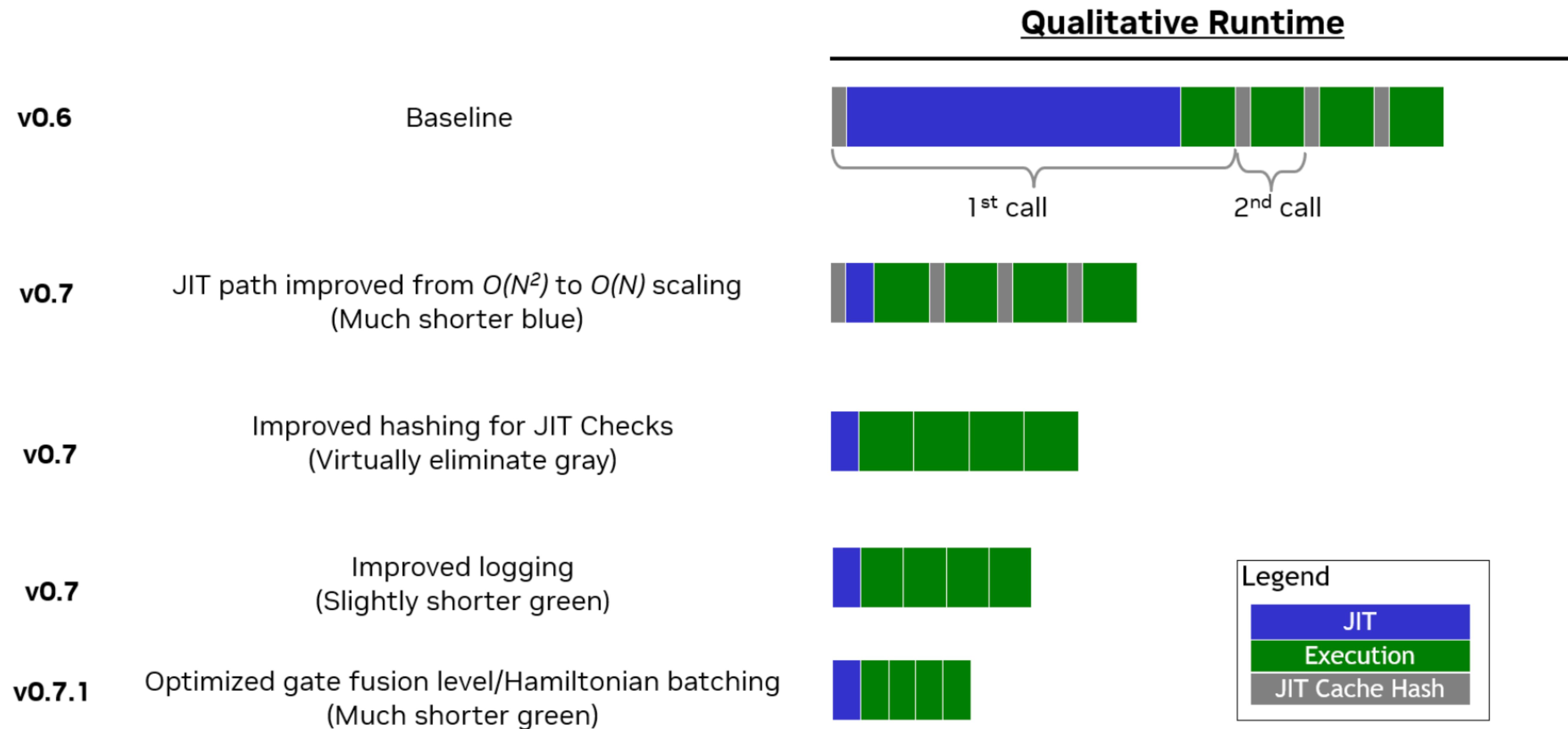


Figure 2. Representation of the changes included in CUDA-Q v0.7 and v0.7.1 and the runtime improvements to four observe calls

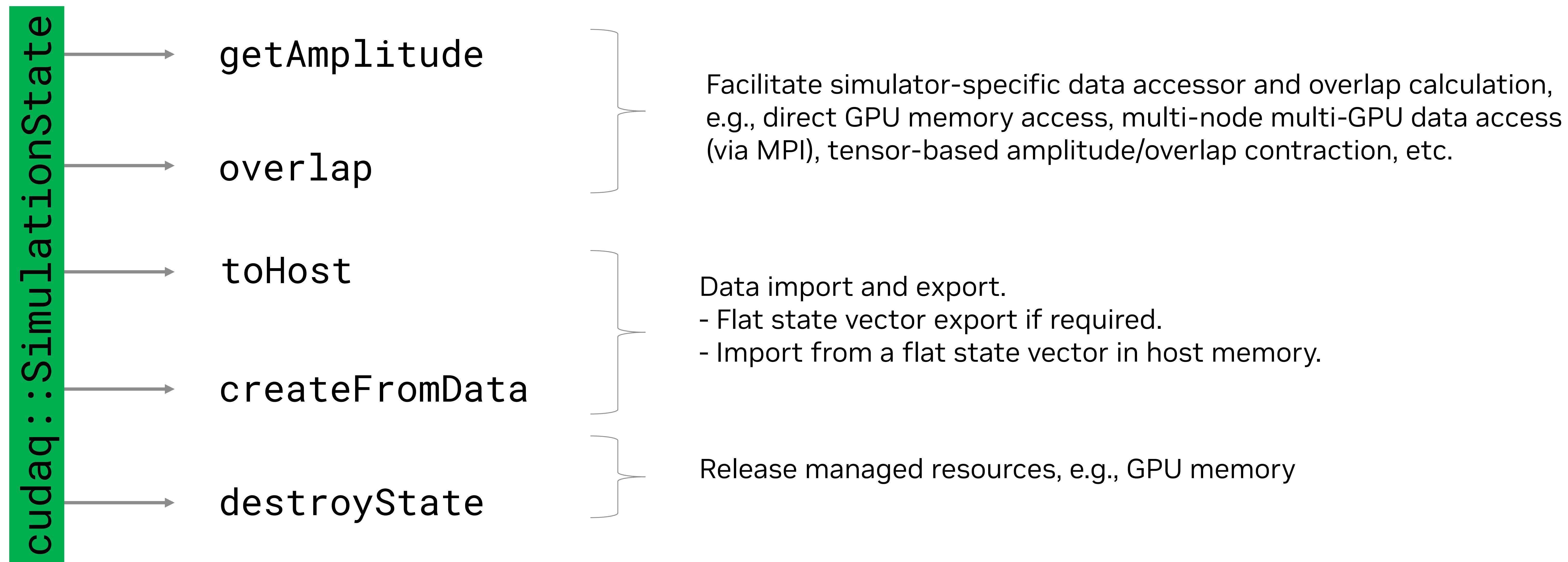
<https://developer.nvidia.com/blog/new-nvidia-cuda-q-features-boost-quantum-application-performance/>

# CUDA-Q: State Handling Simulator

Connecting to a simulator

- Simulator backend-specific state data representation (`cudaq::SimulationState`)

Abstract away state data and resources (e.g., simple arrays in GPU or host memory, distributed memory blobs, tensors' data along with the tensor network description, etc.)



- `cudaq::state` = user-facing class with simplified life-cycle management (RAII)

# CUDA-Q: State Handling in Python

## Python syntax and API

- Syntax change connects qubits and state vectors explicitly
  - state expressed as various aggregates of data
    - vector of float, numpy.float32, numpy.float64
    - vector of complex, numpy.complex64, numpy.complex128
    - numpy array with float or complex dtypes
    - `cudaq::state` (next)
- Design: kernels are converted to MLIR and JIT-ed
  - `log(len(state))` qubits are created and initialized with the state
  - Code works for any simulation precision
  - Initializer data type might not match the simulation precision
    - Automatically convert to the correct precision
    - Issue a performance warning if copy of a vector is created
- User code may be portable, simulator precision-agnostic
  - `cudaq::complex`, `cudaq::real` types
  - `cudaq::amplitudes` helper method that creates an array

```
# Passing complex vectors as params
c = [.70710678 + 0j, 0., 0., 0.70710678]
@cudaq.kernel
def kernel(vec: list[complex]):
    q = cudaq.qvector(vec)
    counts = cudaq.sample(kernel, c)

# Capturing complex vectors
c = [.70710678 + 0j, 0., 0., 0.70710678]
@cudaq.kernel
def kernel():
    q = cudaq.qvector(c)
    counts = cudaq.sample(kernel)

# Using precision-agnostic API
c = np.array([.70710678 + 0j, 0., 0., 0.70710678], dtype=cudaq.complex())
@cudaq.kernel
def kernel(vec: list[complex]):
    q = cudaq.qvector(vec)
    counts = cudaq.sample(kernel, c)

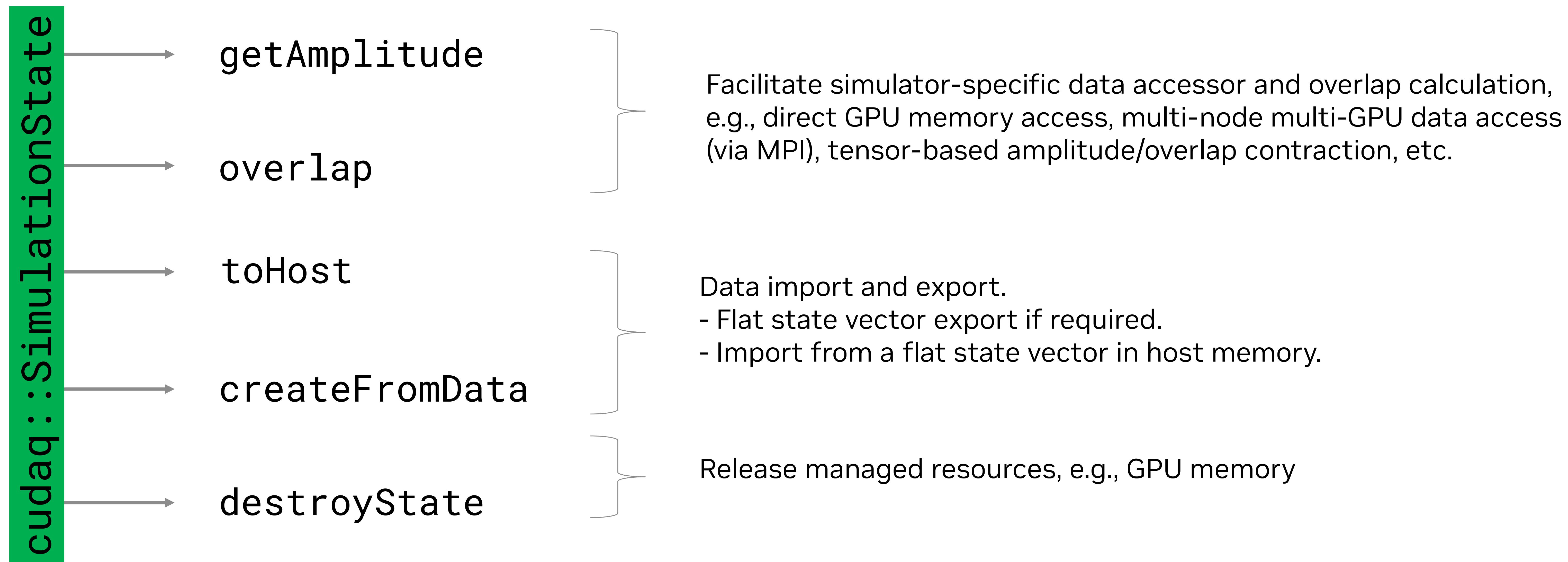
c = cudaq.amplitudes(.70710678, 0., 0., 0.70710678)
@cudaq.kernel
def kernel(vec: list[complex]):
    q = cudaq.qvector(vec)
    counts = cudaq.sample(kernel, c)
```

# CUDA-Q: State Handling Simulator

Connecting to a simulator

- Simulator backend-specific state data representation (`cudaq::SimulationState`)

Abstract away state data and resources (e.g., simple arrays in GPU or host memory, distributed memory blobs, tensors' data along with the tensor network description, etc.)

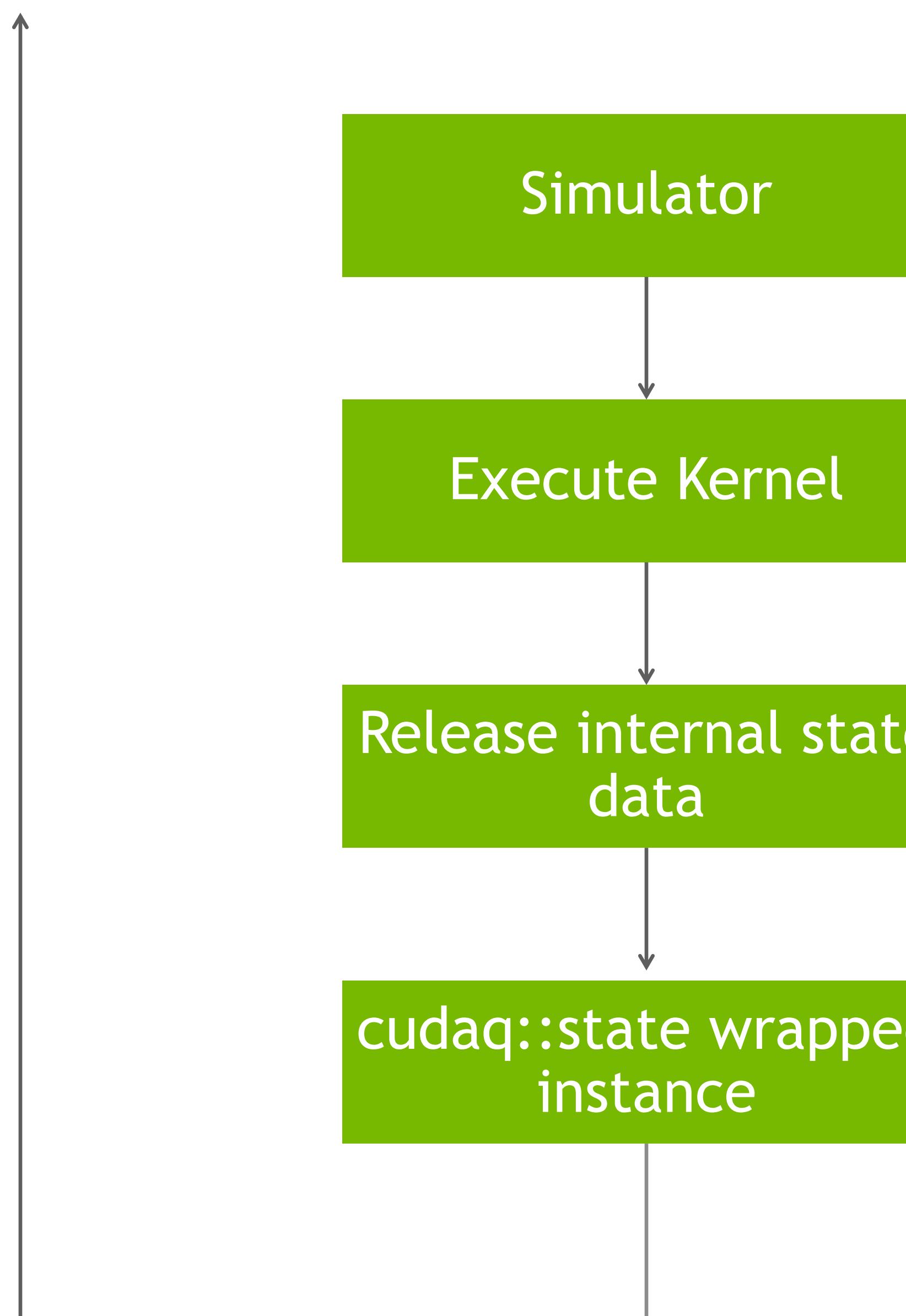


- `cudaq::state` = user-facing class with simplified life-cycle management (RAII)

# CUDA-Q: State Handling Simulator

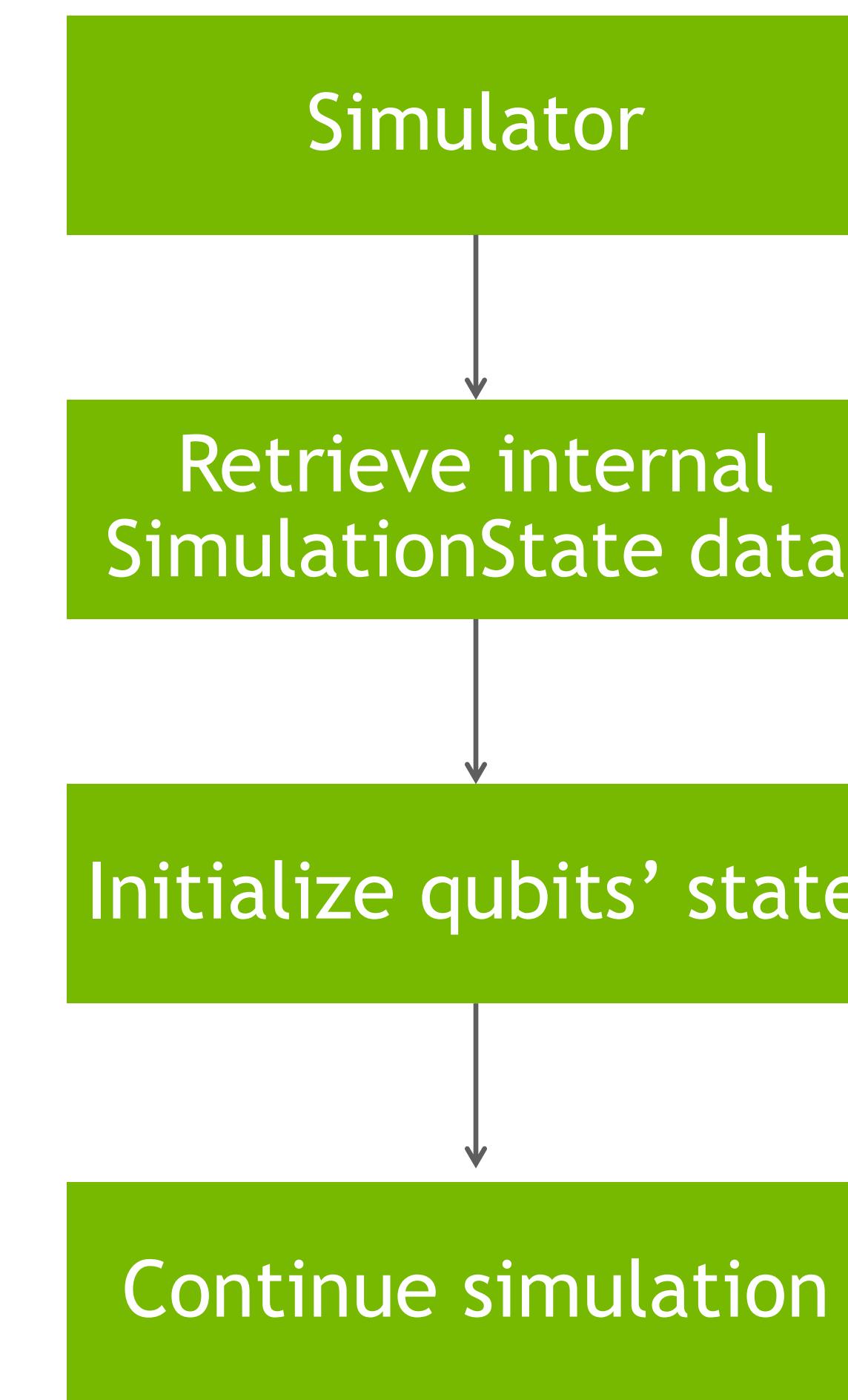
Connecting to a simulator

`cudaq::get_state(Kernel, Args...)`



**State Retrieval**

`qvector(cudaq::state)`



**State Initialization**

Native state data to the backend,  
already in GPU memory, or properly  
MPI-distributed; tensors in GPU  
memory, etc.

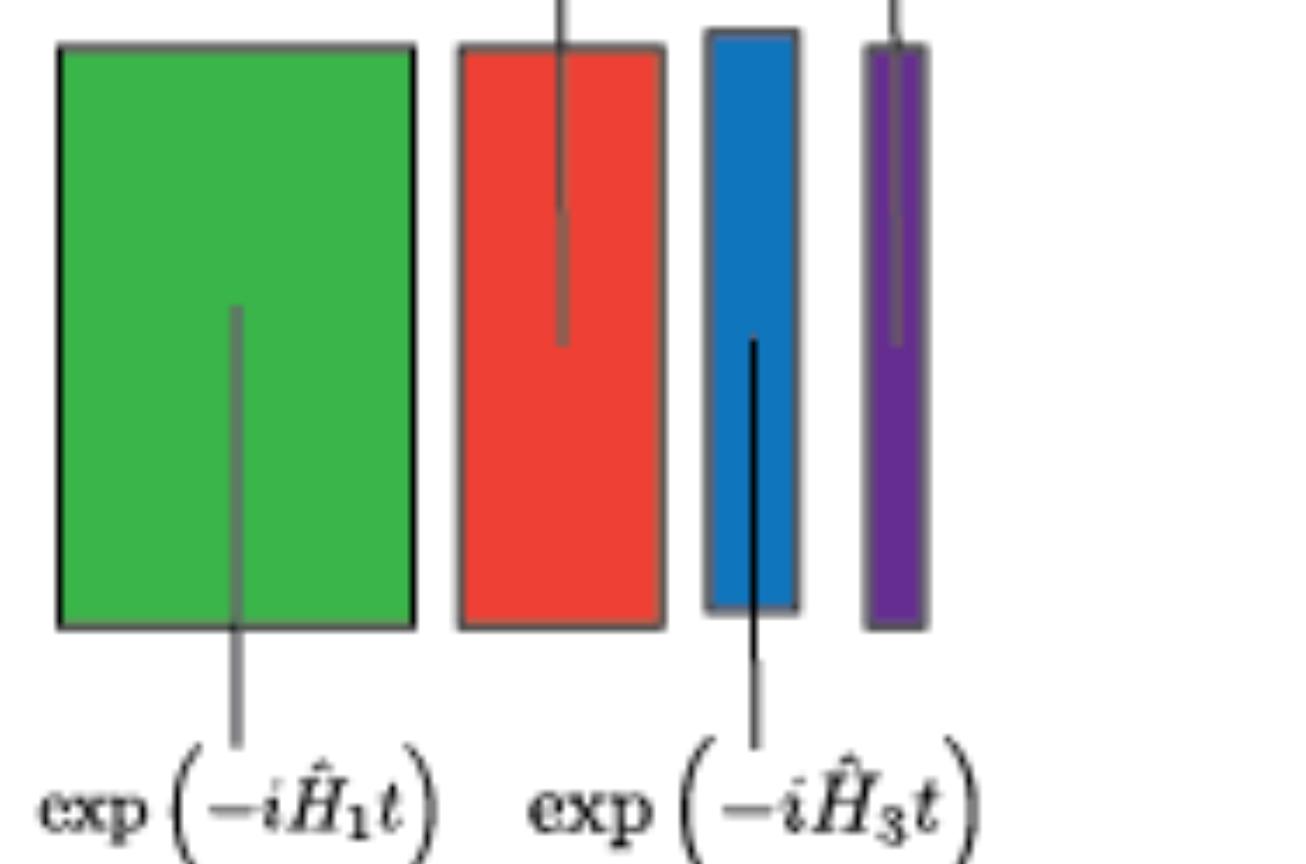
**FAST!**

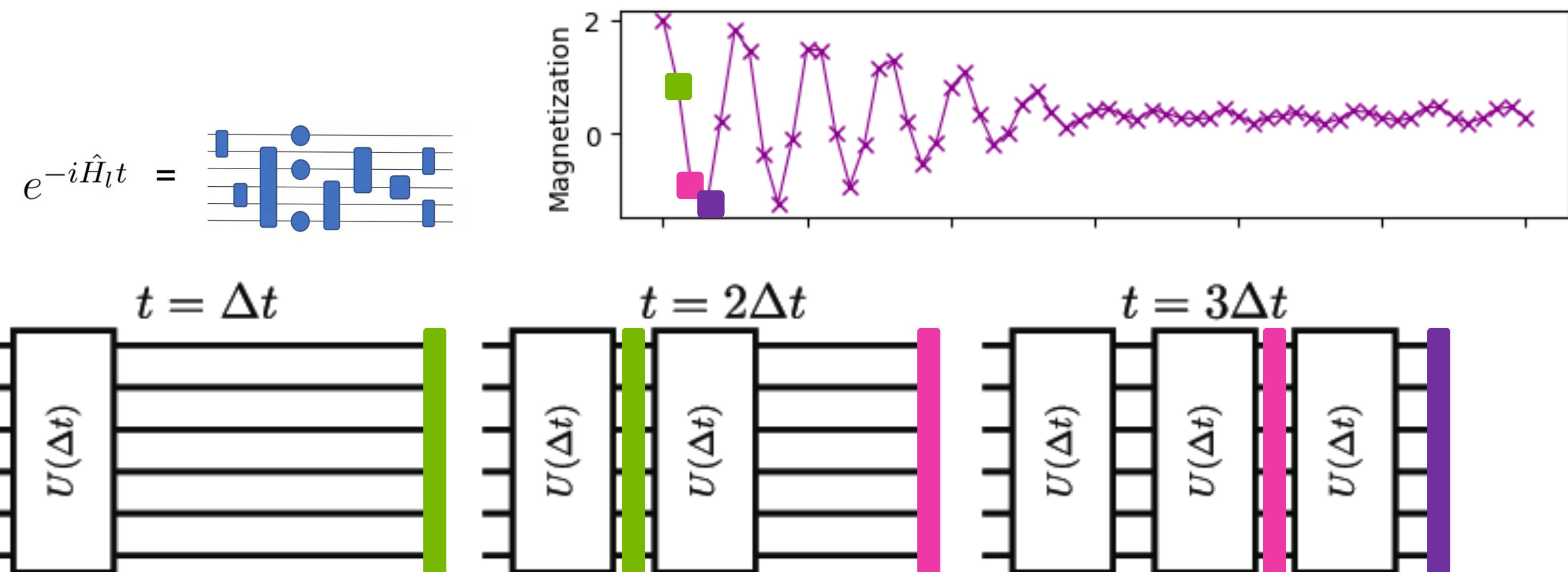
# CUDA-Q: State Handling Example

## Use Cases

Efficient state vector handling (retrieval and initialization) in simulation is an important requirement for various applications/algorithms

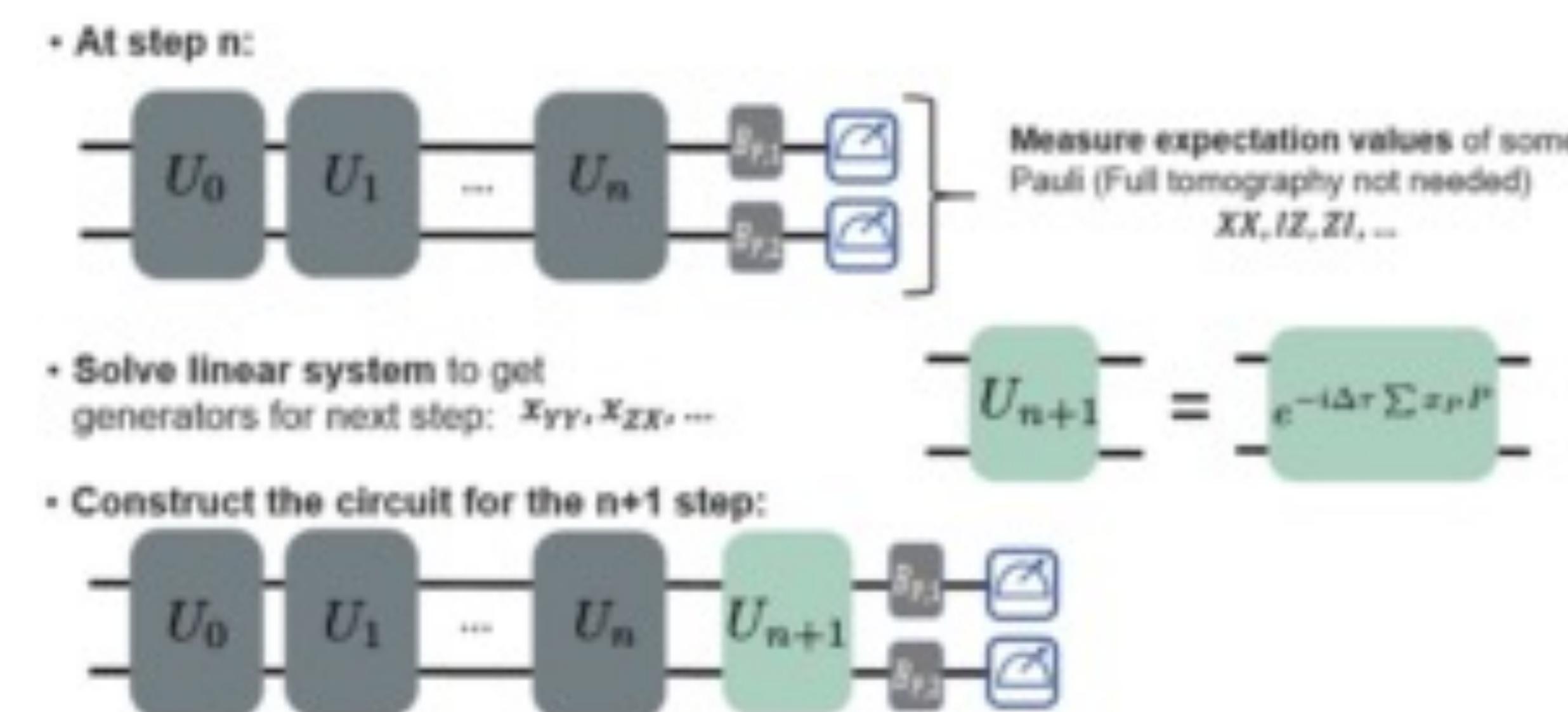
- Quantum state overlap ( $\langle \Psi_1 | \Psi_2 \rangle$ ) calculation (difficult to perform on quantum hardware)
- Dynamical quantum simulation

$$\hat{H} = \hat{H}_1 + \hat{H}_2 + \hat{H}_3 + \hat{H}_4$$
$$= \exp(-i\hat{H}_1 t) \exp(-i\hat{H}_2 t) \exp(-i\hat{H}_3 t) \exp(-i\hat{H}_4 t)$$




e.g., determining phase transition point via state vector inspection or expectation calculation at each time step.

- Quantum Imaginary Time Evolution (QITE)  
(repeating loop of applying a unitary, state tomography, solving linear equations to determine the next unitary block to apply)



# CUDA-Q: State Handling Example

Demo: Trotter Dynamical Simulation

**CUDA-Q v0.7**

```
struct trotter {
    // Note: this runs Trotter simulation from the initial state
    // (|00..00>) up to a certain time point (specified by num_step).
    void operator()(int num_spins,
                     std::function<cudaq::spin_op(double)> td_ham,
                     double dt, int num_step) __qpu__ {
        cudaq::qvector q(num_spins);
        // Alternating up/down spins
        for (int qId = 0; qId < num_spins; qId += 2)
            x(q[qId]);
        for (int j = 0; j < num_step; ++j) {
            auto ham = td_ham(j * dt);
            ham.for_each_term([&](cudaq::spin_op &term) {
                const auto coeff = term.get_coefficient();
                const auto pauliWord = term.to_string(false);
                const double theta = coeff.real() * dt;
                cudaq::exp_pauli(dt, q, pauliWord.c_str());
            });
        }
    }
};
```

**CUDA-Q v0.8**

```
struct trotter {
    // Note: This performs a single-step Trotter on top of an
    // initial state, e.g., result state of the previous Trotter
    // step.
    void operator()(cudaq::state initial_state,
                     cudaq::spin_op ham, double dt) __qpu__ {
        cudaq::qvector q(initial_state);
        ham.for_each_term([&](cudaq::spin_op &term) {
            const auto coeff = term.get_coefficient();
            const auto pauliWord = term.to_string(false);
            const double theta = coeff.real() * dt;
            cudaq::exp_pauli(dt, q, pauliWord.c_str());
        });
    }
};
```

- ✗ Qubit vector/register must be allocated in an uninitialized state.
- ✗ Starting the simulation from time 0 to time t at every step/data point.

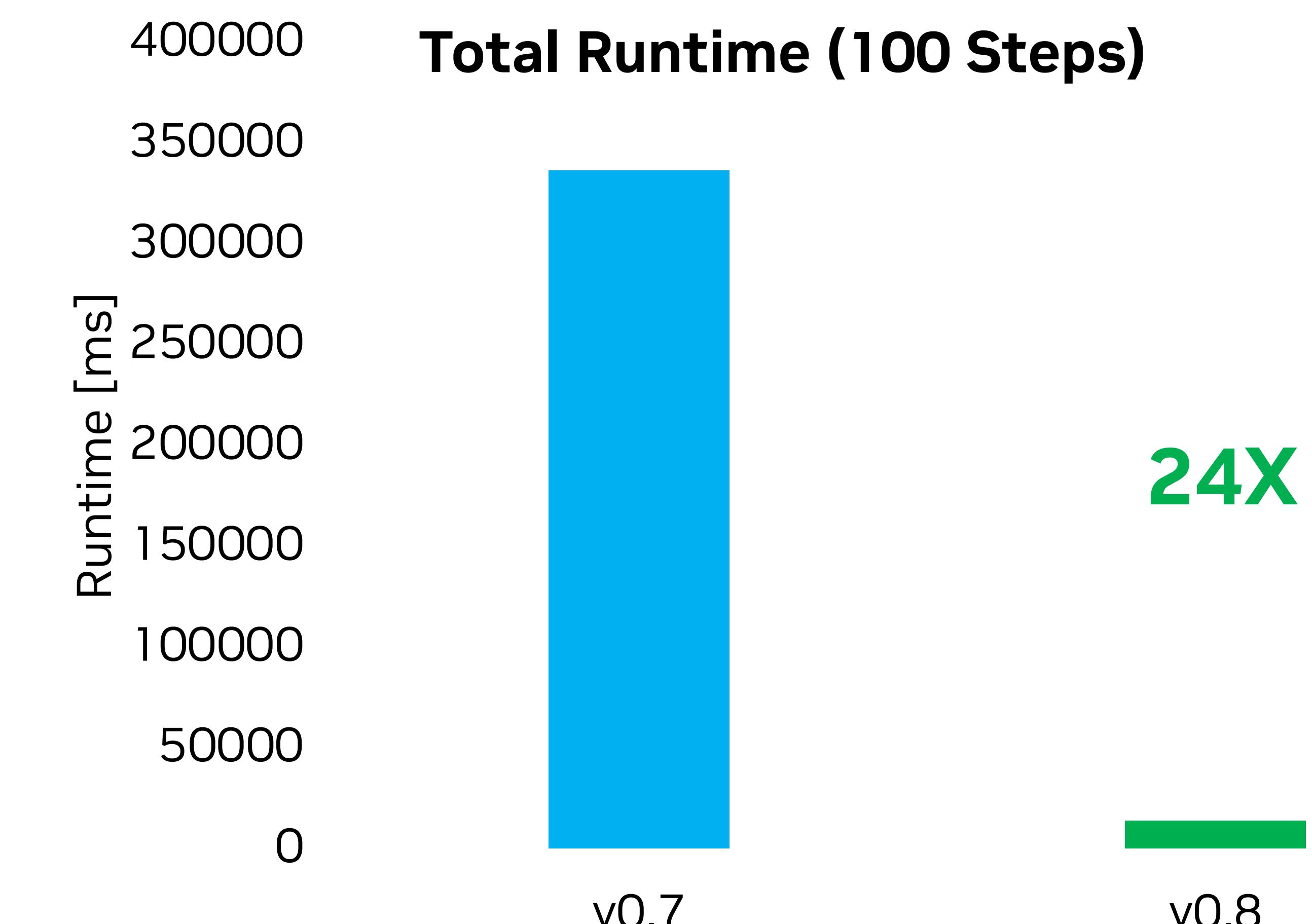
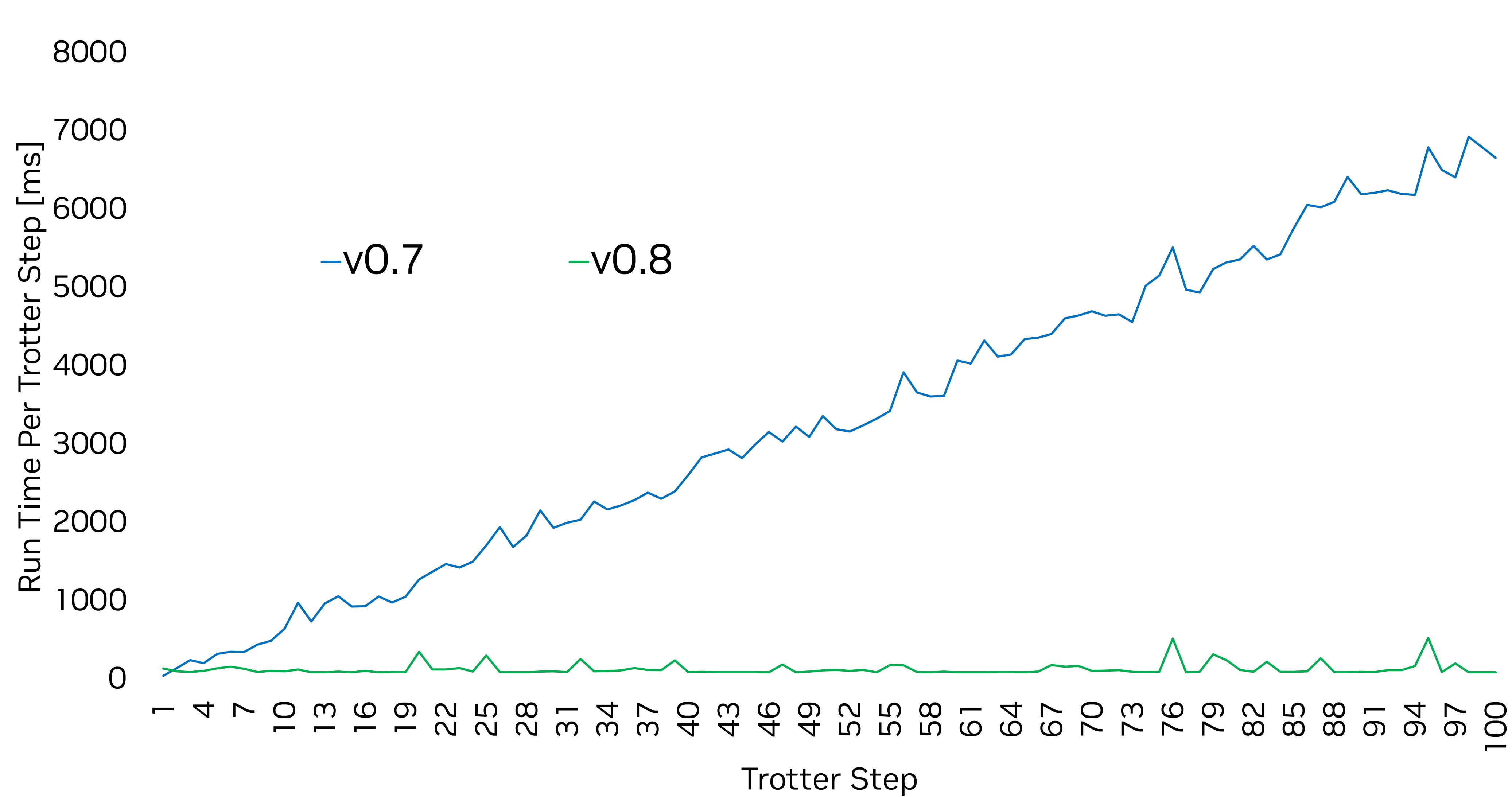
- ✓ Qubit vector/register can be initialized in a specific state.
- ✓ State data can be fed from a prior Trotter step to the next one.
- ✓ State data is ‘native’ to the current simulator backend, e.g., GPU memory, tensor network form, etc.



# CUDA-Q: State Handling Example

Demo: Trotter Dynamical Simulation

25-qubit Heisenberg Hamiltonian Simulation (100 Trotter steps)  
custatevec (fp32) on A100



Host vs. Device Memory State

# CUDA-Q: State Handling Example

## Host vs. GPU State

### CUDA-Q v0.8

#### *Passing the internal ‘state’*

```
struct trotter {
    // Note: This performs a single-step Trotter on top of an
    // initial state, e.g., result state of the previous Trotter
    // step.
    void operator()(cudaq::state initial_state,
                    cudaq::spin_op ham, double dt) __qpu__ {
        cudaq::qvector q(initial_state);
        ham.for_each_term([&](cudaq::spin_op &term) {
            const auto coeff = term.get_coefficient();
            const auto pauliWord = term.to_string(false);
            const double theta = coeff.real() * dt;
            cudaq::exp_pauli(dt, q, pauliWord.c_str());
        });
    }
};
```

### CUDA-Q v0.8

#### *Passing the host memory vector*

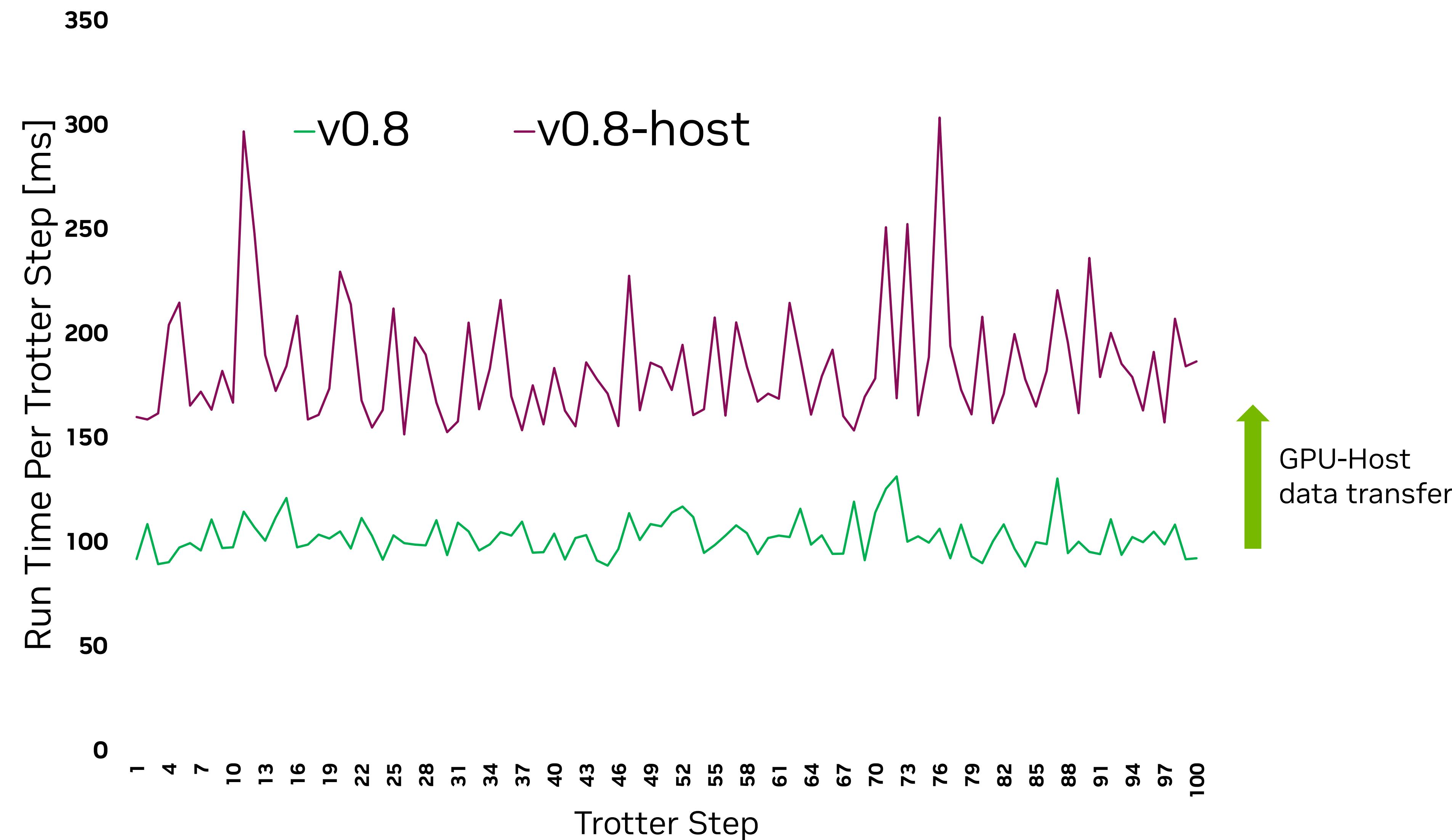
```
struct trotter {
    // Note: This performs a single-step Trotter on top of an initial state
    // vector
    void operator()(std::vector<cudaq::complex>& initial_state_vector,
                    cudaq::spin_op ham,
                    double dt) __qpu__ {
        cudaq::qvector q(initial_state_vector);
        ham.for_each_term([&](cudaq::spin_op &term) {
            const auto coeff = term.get_coefficient();
            const auto pauliWord = term.to_string(false);
            const double theta = coeff.real() * dt;
            cudaq::exp_pauli(dt, q, pauliWord.c_str());
        });
    }
};
```

State initialization from host memory is supported (all backends).

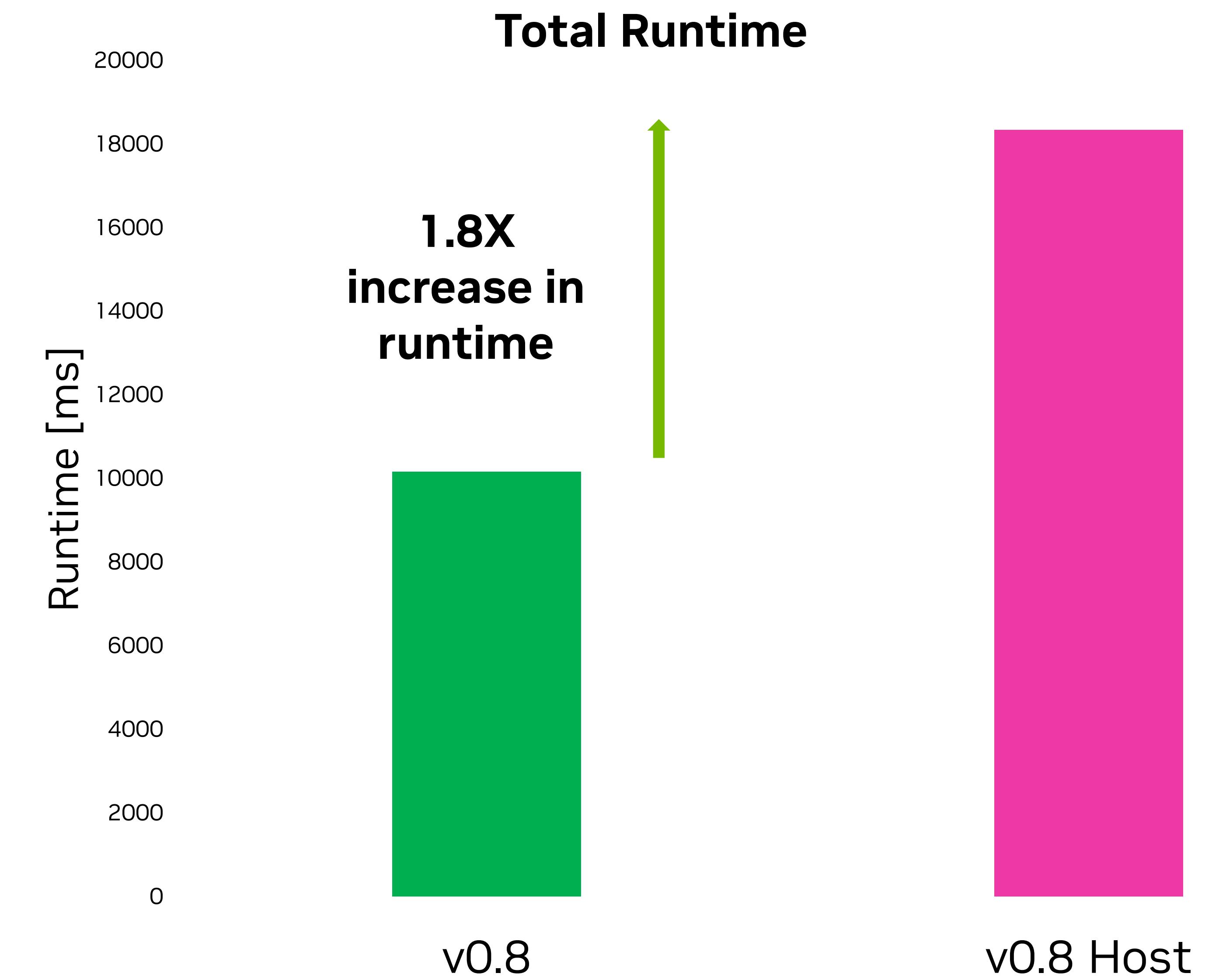
Extra overhead of data transfer.

# CUDA-Q: State Handling Example

Host vs. GPU State Data



GPU-Host  
data transfer



The data transfer overhead (ratio) depends on the number of qubits (data transfer size) vs. the depth of the circuit (GPU runtime).  
(Host – GPU BW << GPU memory BW)

# Conclusion and Looking Forward

## Areas of collaboration

- CUDA-Q is a system-level programming model and compilation platform geared toward enabling quantum acceleration to existing GPU Supercomputing architectures
- NVQ++ orchestrates a collection of modular tools enabling complex quantum-classical compilation workflows
- Explore quantum algorithm simulation scalability on GPU Supercomputing with NVIDIA GPUs and CUDA-Q Multi-QPU virtualization

# Resources

## Links

- CUDA-Q Repo for issues and contributions: [NVIDIA/CUDA-Q\\_Quantum \(github.com\)](https://github.com/NVIDIA/CUDA-Q_Quantum)
- CUDA-Q documentation: [CUDA-Q — NVIDIA CUDA-Q documentation](#)
- Quantum computing technical blogs: [Tag: Quantum Computing | NVIDIA Technical Blog](#)
- CUDA-Q marketing page: [CUDA-Q for Hybrid Quantum-Classical Computing | NVIDIA Developer](#)

## Documentation Reference

- [Quick Start](#)
- [Multi-GPU Workflows](#)
- [Simulator backends](#)
- [Hardware backends](#)
- [Python code examples](#)
- [C++ code examples](#)
- [Applications](#)

