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Challenges in Using LLVM as a Quantum Intermediate Representation

Andrew Litteken, Albert Schmitz, Xin-Chuan Wu, Anne Matsuura

LLVM Developer's Meeting - October 24, 2024

Using LLVM as a Quantum IR

- Quantum Compilation has specific constraints
- High-Level Programmers need to tools to express themselves
- Non-Compiler Users need familiar tools for Optimization

Processing Quantum Programs

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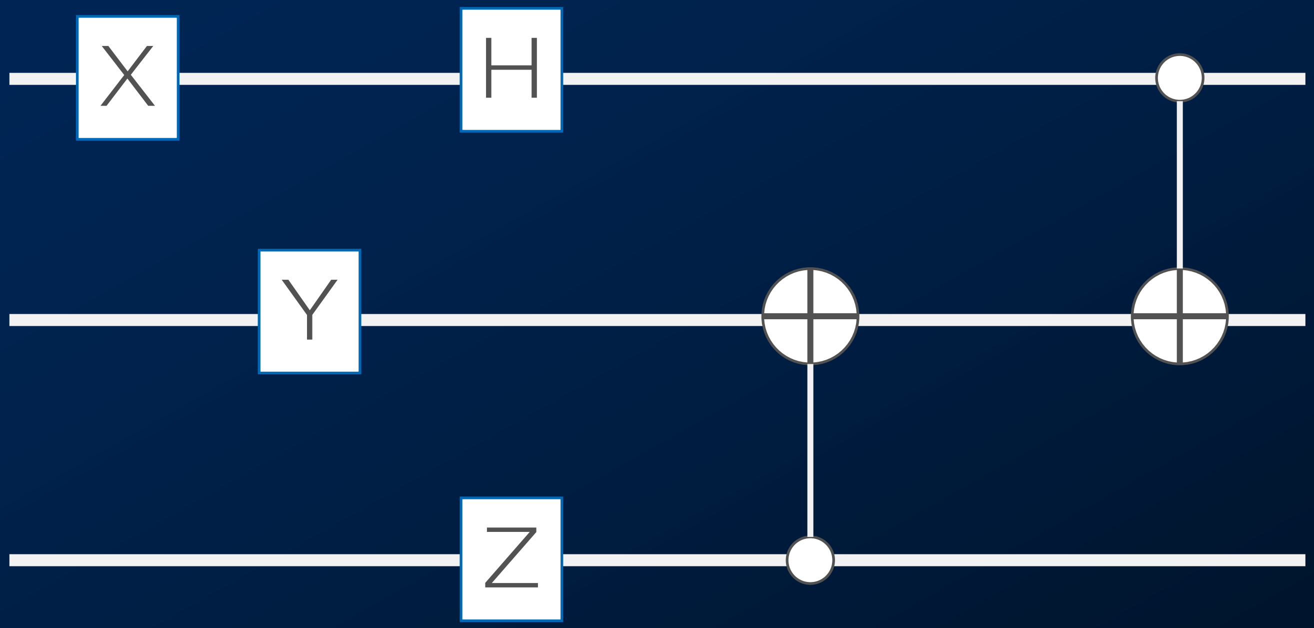
Quantum Programs



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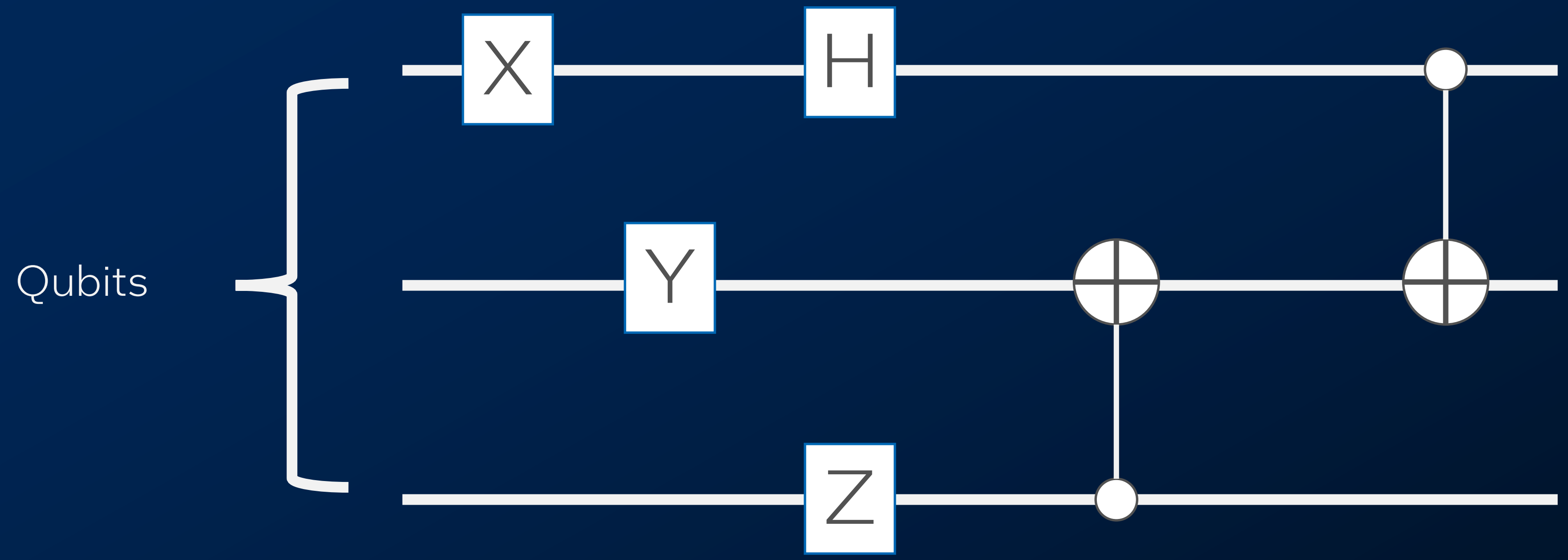

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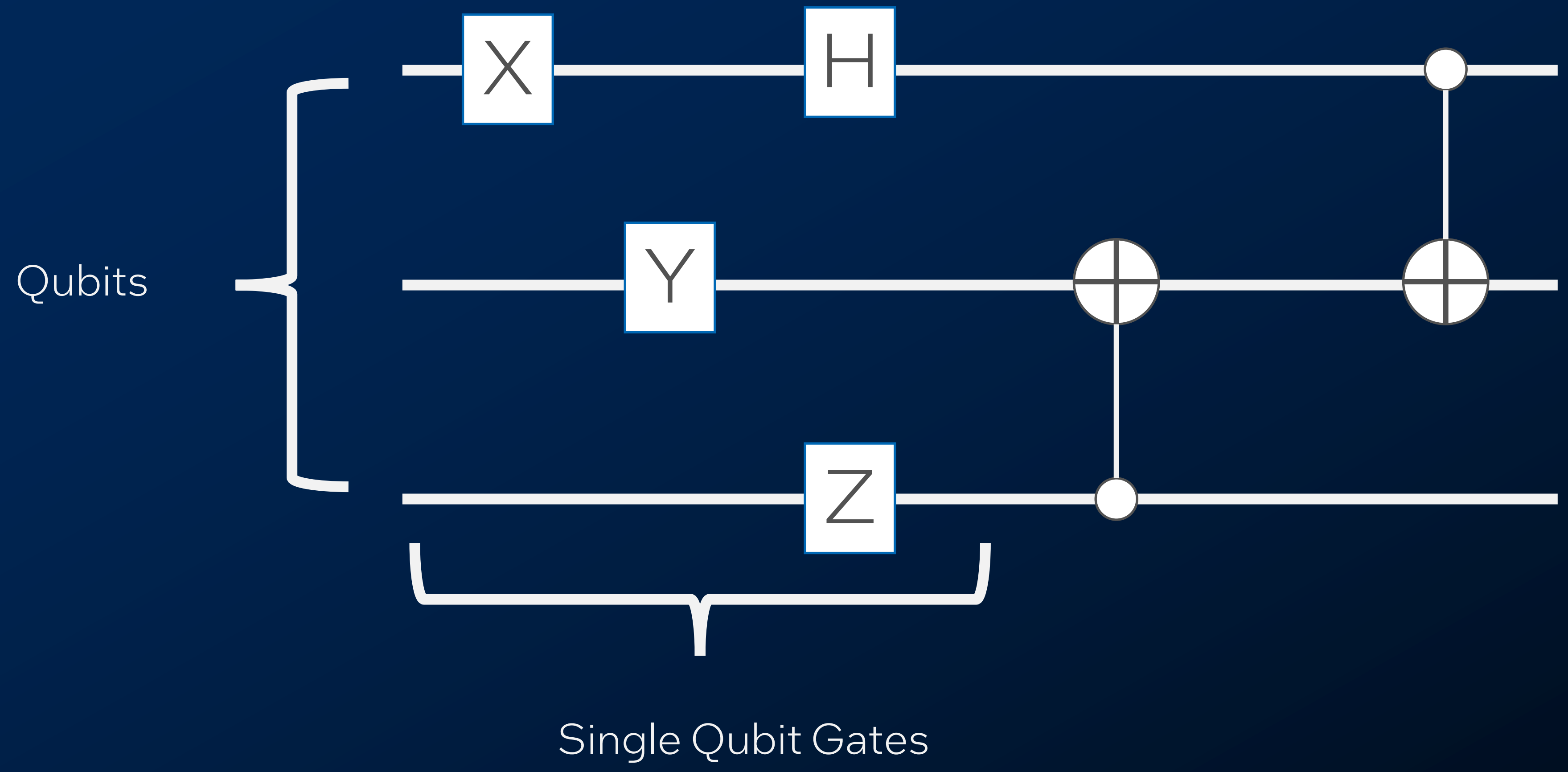

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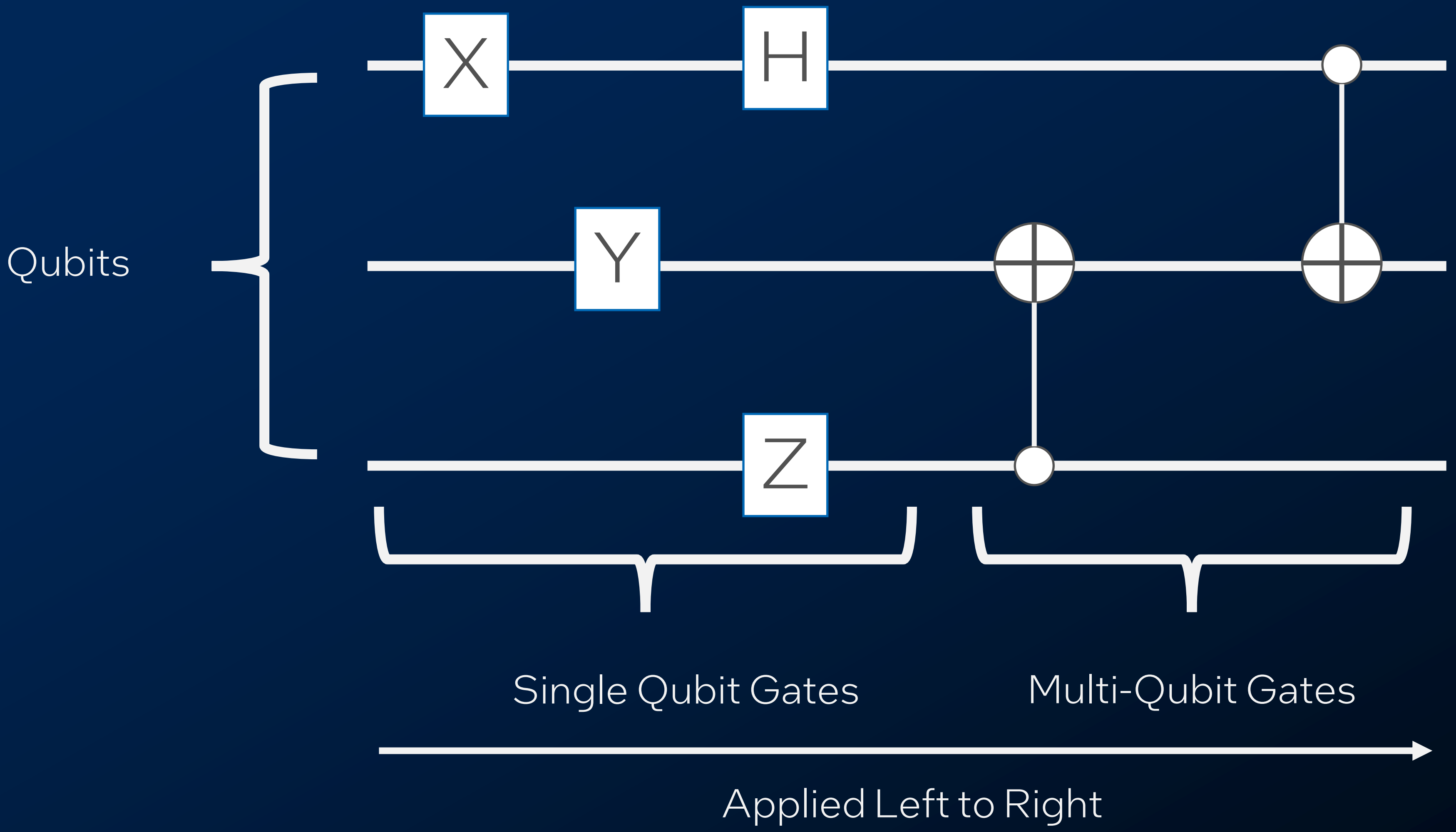

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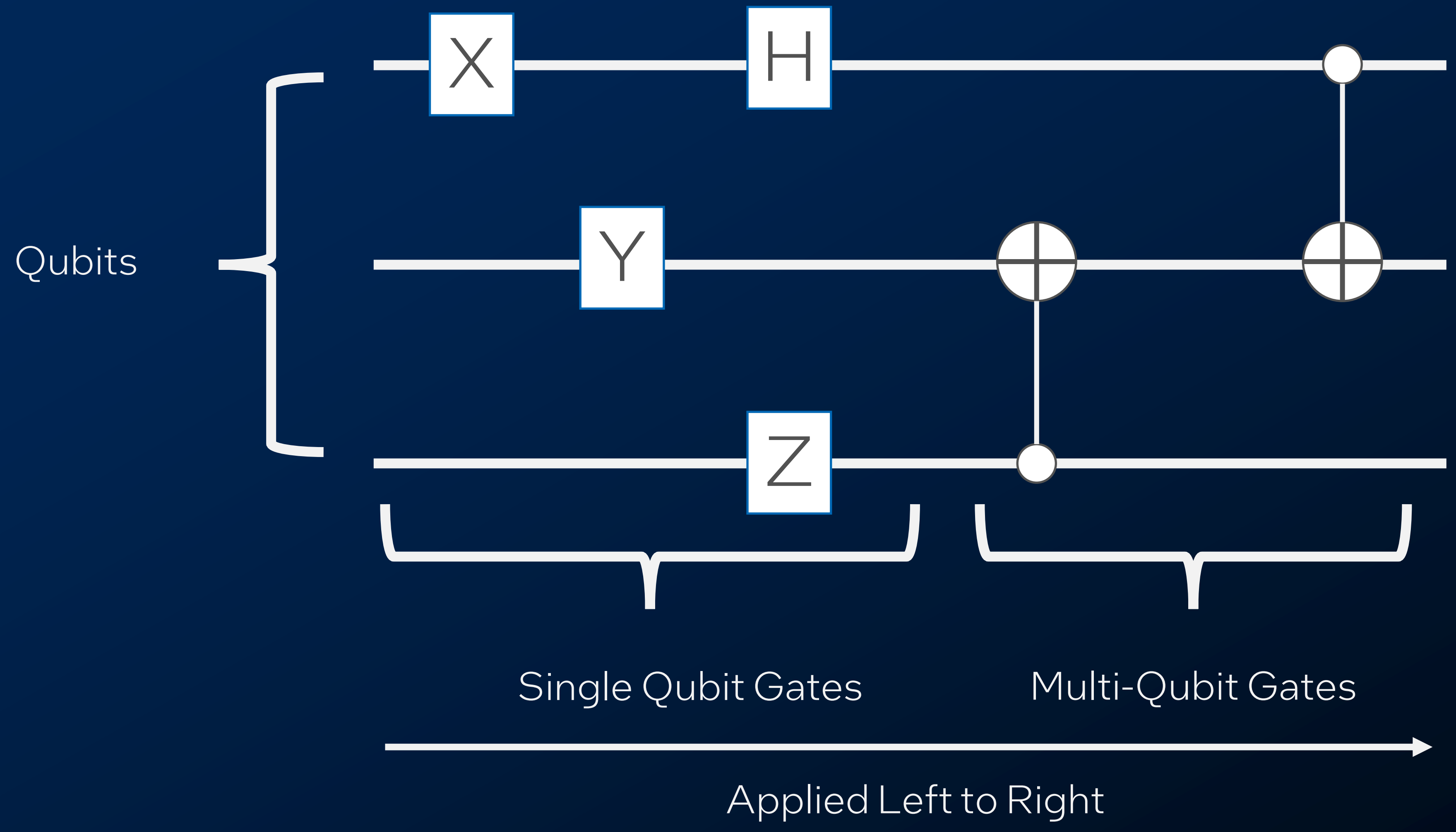
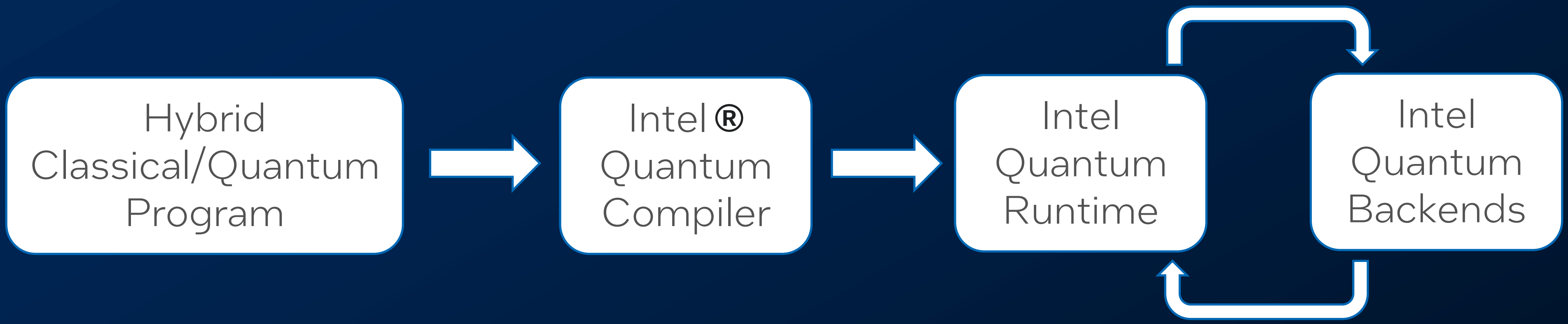


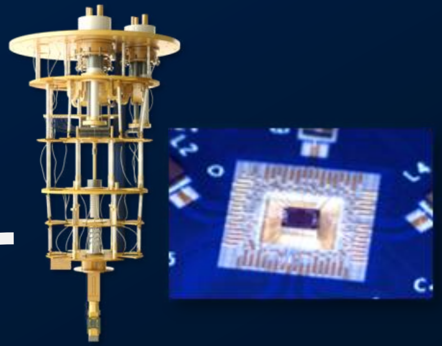
Quantum Circuit

The Intel Quantum SDK



The Intel Quantum SDK

Hybrid Classical/Quantum Program → Intel® Quantum Compiler → Intel Quantum Runtime ⇄ Intel Quantum Backends



Physical Device

Simulator

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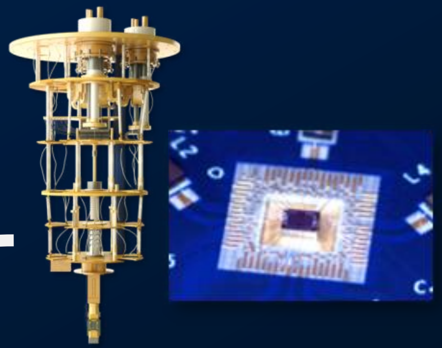

Physical Device

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This Presentation's Focus

- Uses LLVM with Quantum Intrinsics
- Main frontend is SDK's C++ style frontend
- Could be targeted with different frontends

The Intel Quantum SDK

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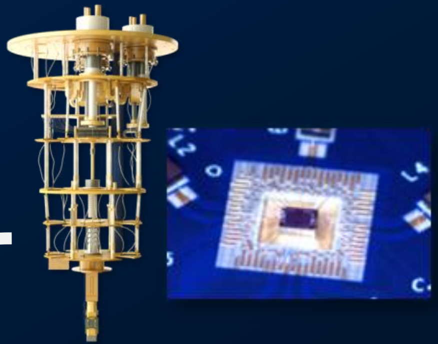
- Must perform classical and quantum compilation alongside each other
- Results in a module with only classical operations, and one with only quantum operations



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- Deploys quantum programs to the device
- Runs classical instructions in between quantum components

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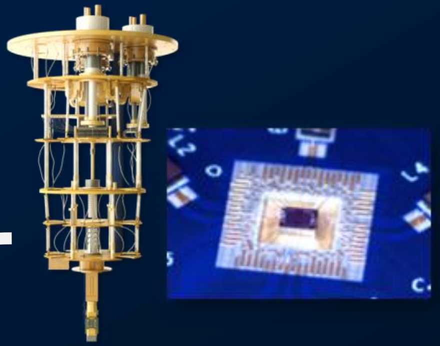

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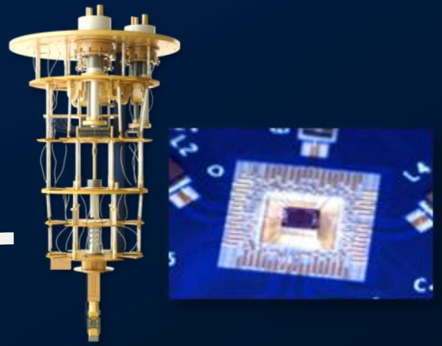

Physical Device

Simulator

- Must perform classical and quantum compilation alongside each other
- Results in a module with only classical operations, and one with only quantum operations

- Uses runtime instructions for execution
- Currently cannot perform conditional execution
- Returns execution information to the run time
- Limited resources

The Compiler has many Quantum Challenges

- No Branching
- Match Device Constraints
- Reduce Quantum Operations
- No Classical Operations in Quantum Code

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- No Branching
- Match Device Constraints
- Reduce Quantum Operations
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These are constraints based on today’s technology

Handling Constraints with LLVM

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Quantum Primitives for Hybrid Programs

Quantum Kernel
(Can be nested)

```
#include <clang/Quantum/quintrinsics.h>

/// Quantum Runtime Library APIs
#include <quantum_full_state_simulator_backend.h>

const int total_qubits = 2;
qbit qubit_register[total_qubits];

quantum_kernel void ghz_total_qubits() {
  for (int i = 0; i < total_qubits; i++) {
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  H(qubit_register[0]);

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Kernel Annotation

- `quantum_kernel` adds section attribute

Quantum Primitives for Hybrid Programs

Quantum Type

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Kernel Annotation

Quantum Operations

- **`quantum_kernel`** adds section attribute
- **`qbit`** and **`cbit`** are typedefs over particular integer types
- **`quintrinsics.h`** defines quantum functions

Users Can Write Code that Mixes Classical And Quantum Computation

Quantum Type

Quantum Kernel
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Kernel Annotation

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Quantum Operations

Classical Component
(calls quantum components)

```
int main() {
  iqsdk::DeviceConfig qd_config("QD_SIM");
  iqsdk::FullStateSimulator quantum_8086(qd_config);
  if (iqsdk::QRT_ERROR_SUCCESS != quantum_8086.ready())
    return 1;

  // get references to qbits
  std::vector<std::reference_wrapper<qbit>> qids;
  for (int id = 0; id < total_qubits; ++id) {
    qids.push_back(std::ref(qubit_register[id]));
  }

  ghz_total_qubits();

  iqsdk::QssMap<double> probability_map;
  probability_map = quantum_8086.getProbabilities(qids, bases);
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Users Can Write Code that Mixes Classical And Quantum Computation

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Kernel Annotation

Quantum Operations

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LLVM Provides a Leg Up to Compilation

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Conditional Structures
with Quantum Operations

Structures are Found in Classical and Quantum

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Conditional Structures
with Quantum Operations and classical

Pass Managers Provide Flexibility

Inlining Kernels and Adding Intrinsics

Pre-Unrolling Preparation

Loop Unrolling and Constant Folding

Post Unrolling Cleanup

Quantum Handling

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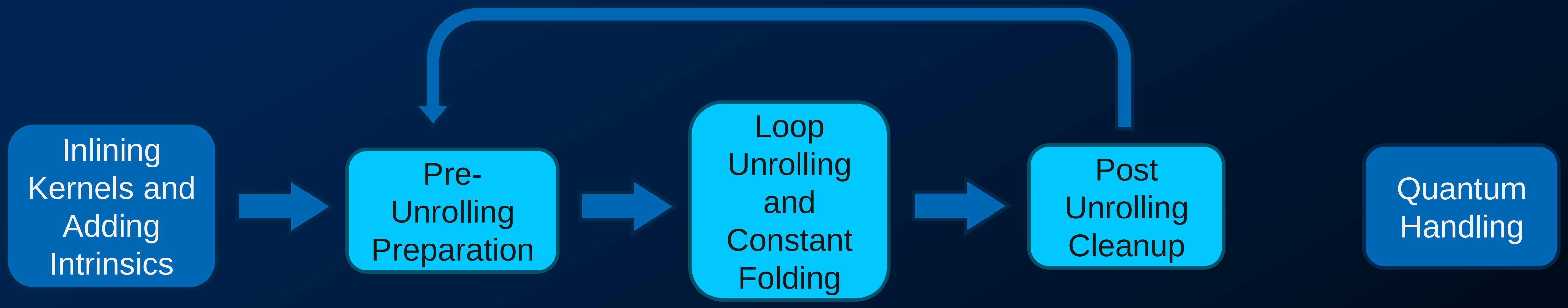
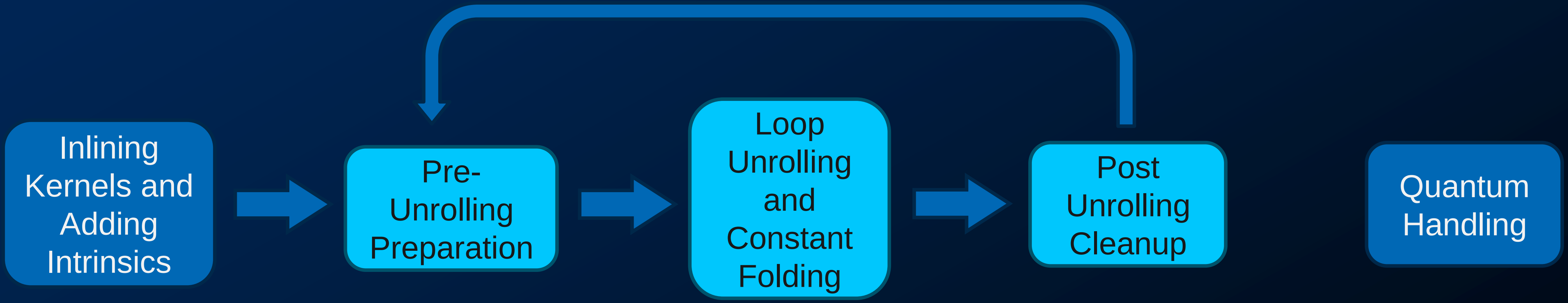


Pass Managers Provide Flexibility

Re-runs until all marked kernels valid, or attempt number exceeded.



- Only runs on marked quantum kernels
- Only runs Loop optimizations on loops that contain quantum operations

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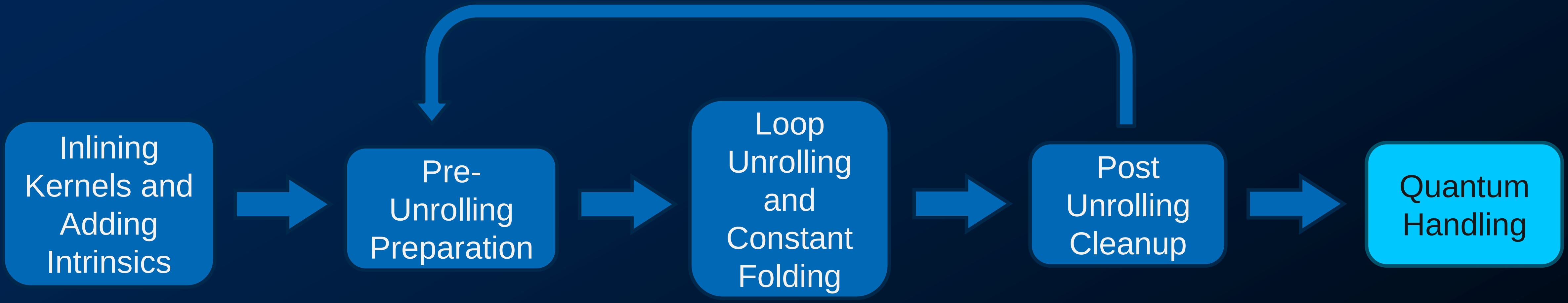

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Quantum Optimizations Need Quantum Types in IR

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Declaration of Quantum Operation in
Intermediate Representation

```
define dso_local void @_Z1HRt(ptr noundef nonnull align 2 dereferenceable(2) %q) #0 {
entry:
  call void @llvm.quantum.qubit(ptr noundef nonnull %q)
  ret void
}
```

Quantum Optimizations Need Quantum Types in IR

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Mapping Qubit to an Argument

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```

Marking as a qubit reference

```
define dso_local void @_Z1HRt(ptr noundef nonnull align 2 dereferenceable(2) "qubit_ref" %q) #0 {
entry:
  call void @llvm.quantum.qubit(ptr noundef nonnull %q)
  ret void
}
```

Providing Tools to Users

Writing Code Within these Constraints is Hard

Standard SDK

```
quantum_kernel void qft() {
  // qft non-recursive implementation

  // Apply H and rotations
  // Starting from qubit 0
  for (int index = 0; index < N; index++) {
    H(QubitReg[index]);
    for (int index_r = 1; index_r < N - index; index_r++) {
      double angle = 2 * (1 / M_1_PI) / std::pow(2, index_r
+ 1);
      CPhase(QubitReg[index + index_r], QubitReg[index],
angle);
    }
  }

  // Add SWAP gates
  for (int q_index = 0; q_index < std::floor(N / 2);
q_index++) {
    SWAP(QubitReg[q_index], QubitReg[N - q_index - 1]);
  }
}
```

Functional Language Extension for Quantum (FLEQ) Makes it Easier

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  }
}
```

FLEQ

```
PROTECT QExpr qftCPhaseLadder(qbit& q, qlist::QList
reg){
  int sz = reg.size();
  double theta = - M_PI / pow(2, sz);

  return qexpr::cIfTrue(sz > 0,
              qexpr::_CPhase(q, reg[0], theta)
              + qftCPhaseLadder(q, reg+1));
}
PROTECT QExpr qftHelper(qlist::QList reg){
  int sz = reg.size();
  return qexpr::cIfTrue(sz > 0,
      qexpr::_H(reg[sz-1]) +
        qftCPhaseLadder(reg[sz-1],
                        reg<<1)
         + qftHelper(reg<<1));
}

QExpr qft(qlist::QList reg){
  return qftHelper(reg) + reverseRegister(reg);
}
```

Clang Plugins Enable FLEQ

```
PROTECT QExpr ghz(qlist::QList qs){
  int len = qs.size();
  return (
    qexpr::map(qexpr::_PrepZ, qs)
    + qexpr::_H(qs[0])
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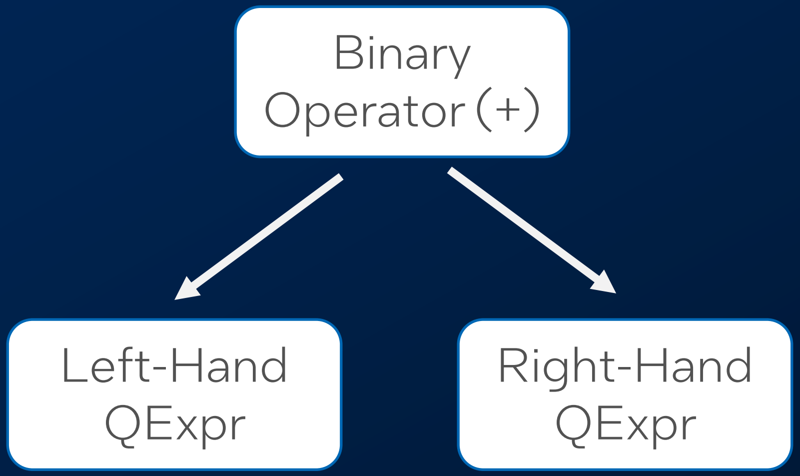

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```

→ FLEQ Clang Plugin →

```
PROTECT QExpr ghz(qlist::QList qs){
  int len = qs.size();
  return (
    qexpr::join(
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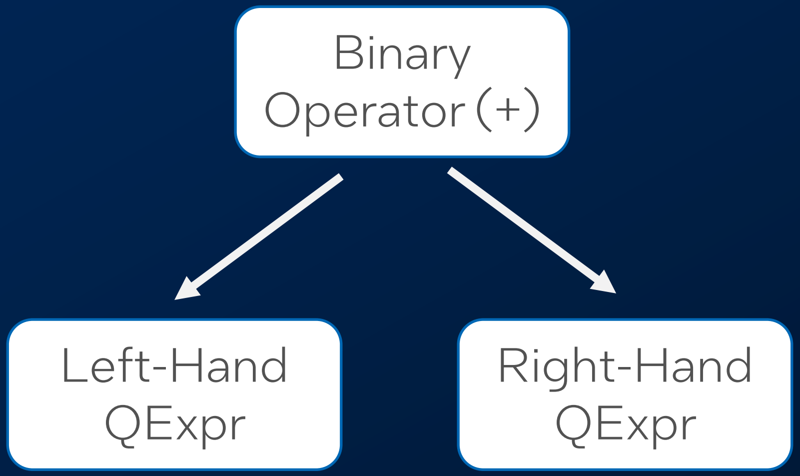

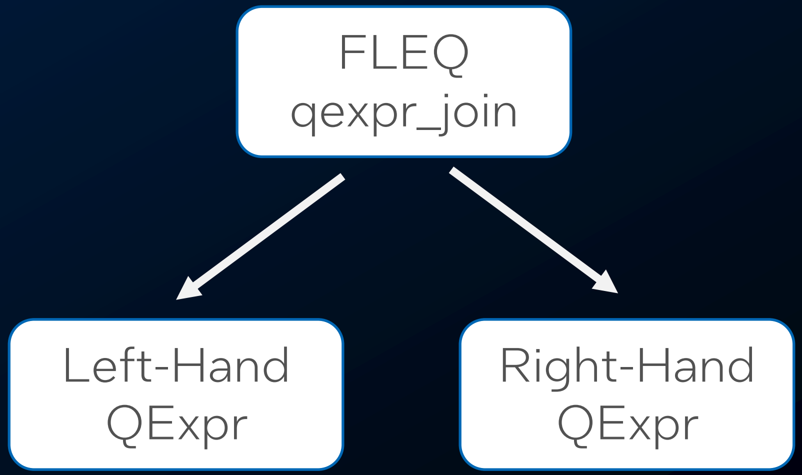

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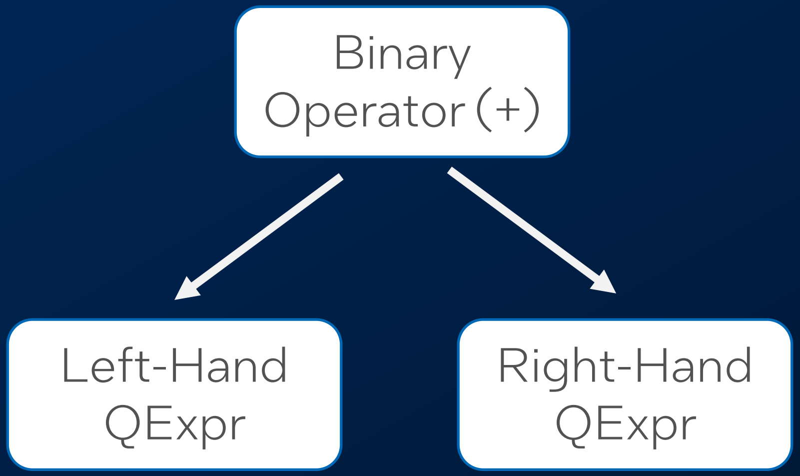
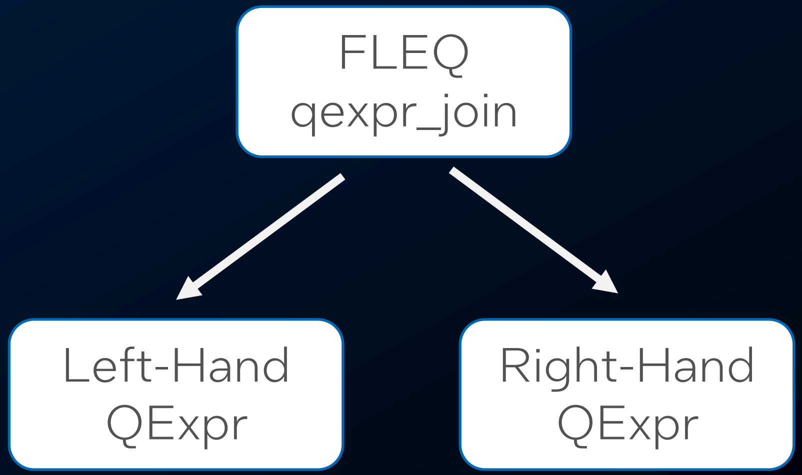
      ));
}
```

Replaced Operands

- Binary Add (join)
- Binary Multiply (join)
- ~, !, - (invert)
- ^ (power)
- << (bind)
- >> (bind)





FLEQ Enables More Advanced Optimization

FLEQ Enables More Advanced Optimization

FLEQ Modified IR Module → Internal Graph Representation → Graph Based Quantum Optimizations → IR Module with Reduced Quantum Resources

Original Hybrid Program

```
quantum_kernel void qft() {
  . . .
}

quantum_kernel void qft_inverse() {
  . . .
}

quantum_kernel void qft_all() {
  prepZAll();
  qft();
  qft_inverse();
}
```

Explicit Inverse

FLEQ with inferred inversion

```
QExpr qft(qlist::QList reg){
  return qftHelper(reg) + reverseRegister(reg);
}

int main() {
  qexpr::eval_hold(fourierBasis(qs, compBasisIndex)
                    + -qft(qs));
}
```

Implicit Inverse

Simplifying Optimization Development

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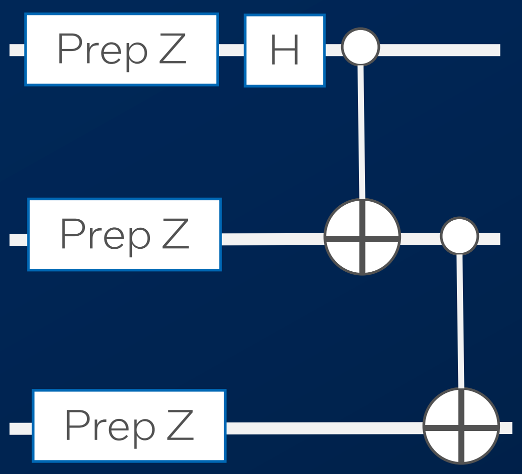
LLVM Doesn't Match Quantum Abstractions



Circuit Form

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    PrepZ(q[i]);
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  H(q[0]);

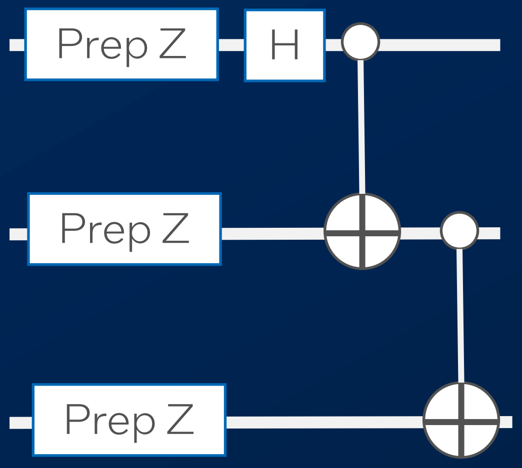
  for (int i = 0; i < total_qubits - 1;
i++) {
    CNOT(q[i], q[i + 1]);
  }
}
```

SDK Form

```
aqcc.quantum:
  %arrayidx34 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 0
  call void @_Z5PrepZRt(ptr %arrayidx34)
  %arrayidx33 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 1
  call void @_Z5PrepZRt(ptr %arrayidx33)
  %arrayidx32 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 2
  call void @_Z1HRt(ptr %arrayidx22)
  %arrayidx20 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 0
  %arrayidx21 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 1
  call void @_Z4CNOTRtS_(ptr %arrayidx20,
ptr %arrayidx21)
  %arrayidx18 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 1
  %arrayidx19 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 2
  call void @_Z4CNOTRtS_(ptr %arrayidx18,
ptr %arrayidx19)
  br label %aqcc.meas.move.end
```

IR Form (Post Unrolling)

LLVM Doesn’t Match Quantum Abstractions



Circuit Form

Typical Abstraction for Optimization

```
quantum_kernel void ghz_total_qubits() {
  for (int i = 0; i < total_qubits; i++) {
    PrepZ(q[i]);
  }

  H(q[0]);

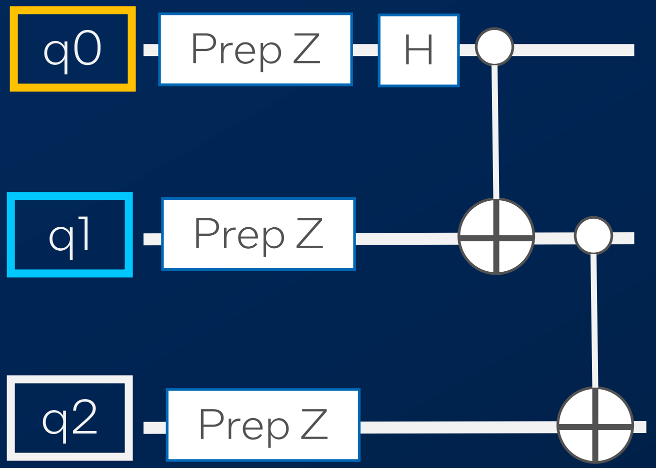
  for (int i = 0; i < total_qubits - 1;
i++) {
    CNOT(q[i], q[i + 1]);
  }
}
```

SDK Form

```
aqcc.quantum:
  %arrayidx34 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 0
  call void @_Z5PrepZRt(ptr %arrayidx34)
  %arrayidx33 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 1
  call void @_Z5PrepZRt(ptr %arrayidx33)
  %arrayidx32 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 2
  call void @_Z1HRt(ptr %arrayidx22)
  %arrayidx20 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 0
  %arrayidx21 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 1
  call void @_Z4CNOTRtS_(ptr %arrayidx20,
ptr %arrayidx21)
  %arrayidx18 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 1
  %arrayidx19 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 2
  call void @_Z4CNOTRtS_(ptr %arrayidx18,
ptr %arrayidx19)
  br label %aqcc.meas.move.end
```

IR Form (Post Unrolling)

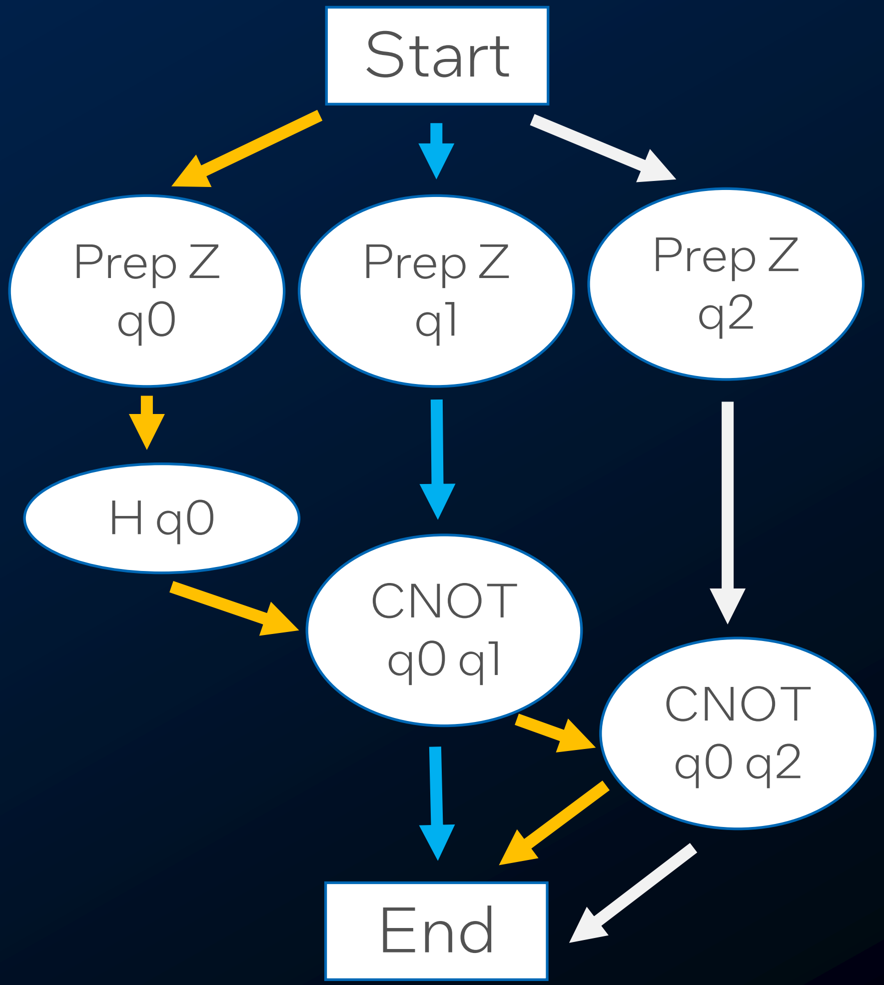
The Quantum Circuit Object is an LLVM Wrapper



Circuit Form

```
aqcc.quantum:
  %arrayidx34 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 0
  call void @_Z5PrepZRt(ptr %arrayidx34)
  %arrayidx33 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 1
  call void @_Z5PrepZRt(ptr %arrayidx33)
  %arrayidx32 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 2
  call void @_Z1HRt(ptr %arrayidx22)
  %arrayidx20 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 0
  %arrayidx21 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 1
  call void @_Z4CNOTRtS_(ptr %arrayidx20,
ptr %arrayidx21)
  %arrayidx18 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 1
  %arrayidx19 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 2
  call void @_Z4CNOTRtS_(ptr %arrayidx18,
ptr %arrayidx19)
  br label %aqcc.meas.move.end
```

IR Form (Post Unrolling)

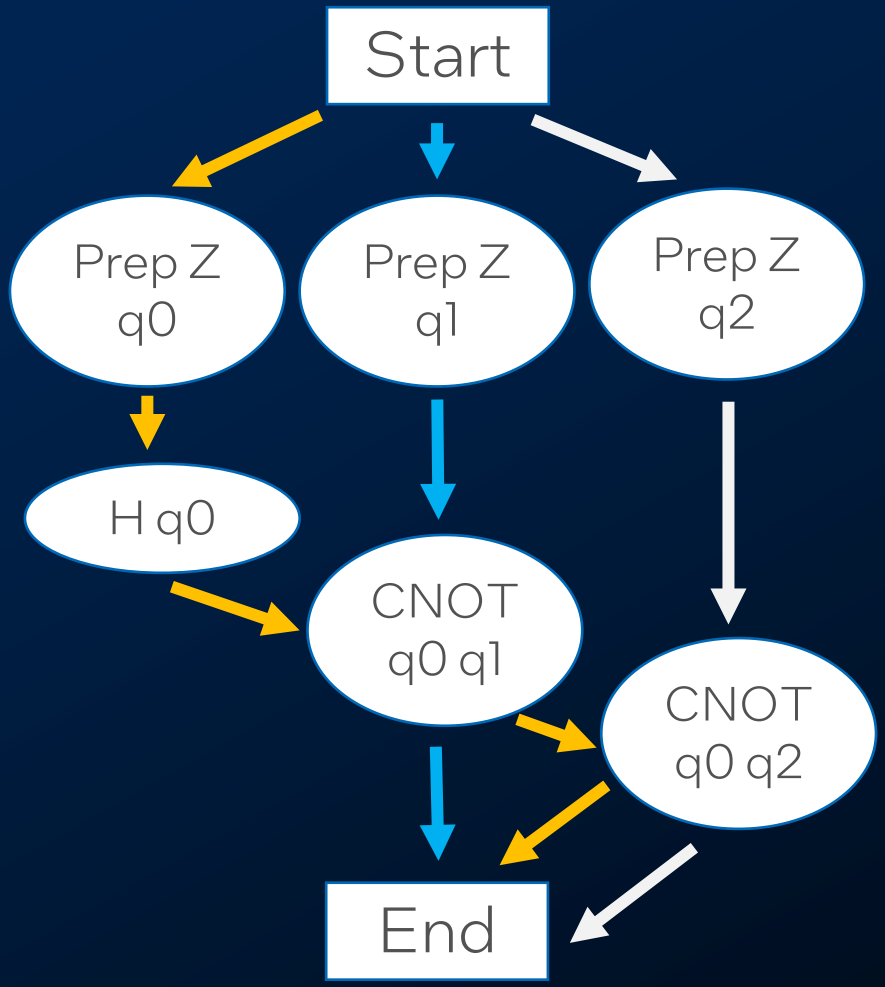


Quantum Circuit Object

Circuit Object Manipulation is Reflected in IR

```
aqcc.quantum:
  . . .
  %arrayidx33 = getelementptr inbounds [12
x i16], ptr @Qumem, i64 0, i64 1
  . . .
  %arrayidx20 = getelementptr inbounds [12
x i16], ptr @Qumem, i64 0, i64 0
  %arrayidx21 = getelementptr inbounds [12
x i16], ptr @Qumem, i64 0, i64 1
  call void @_Z4CNOTRtS_(ptr %arrayidx20,
ptr %arrayidx21)
  . . .
```

IR Form



Quantum Circuit Object

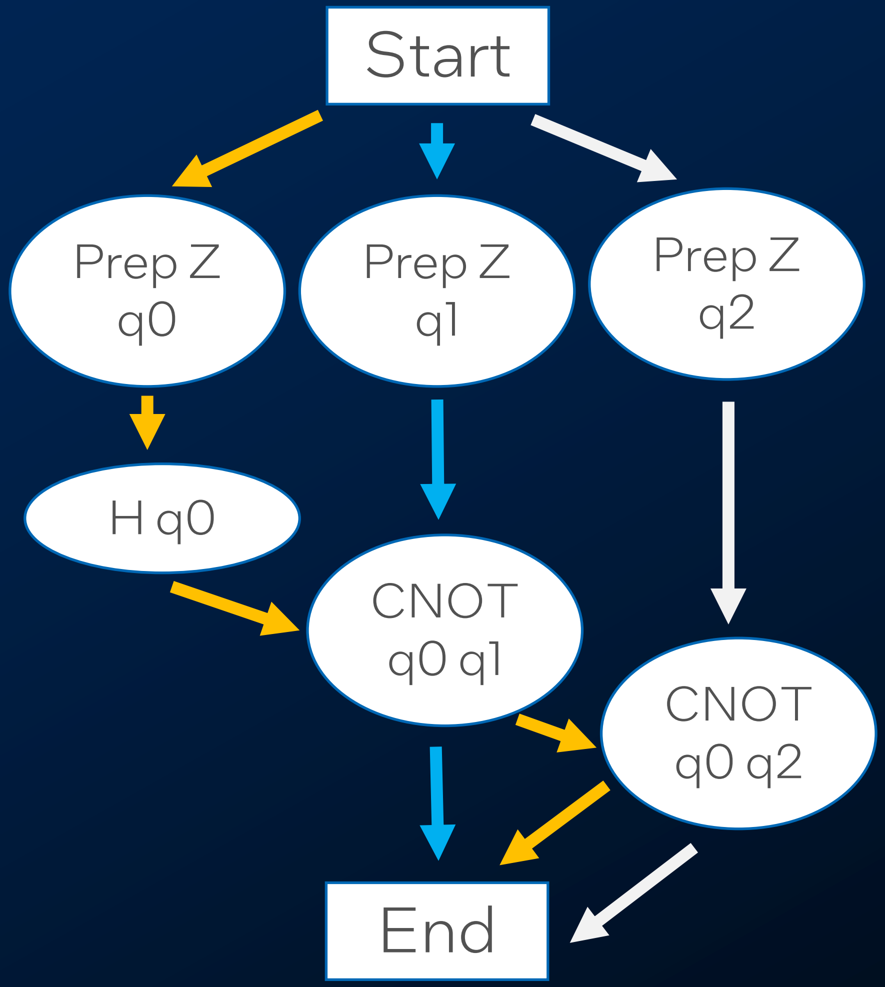
Supported Options

- Deletion
- Insertion
- Moving Operations
- New Operations
- New Qubits
- Consistent Iteration

Circuit Object Manipulation is Reflected in IR

```
aqcc.quantum:
  . . .
  %arrayidx33 = getelementptr inbounds [12
x i16], ptr @Qumem, i64 0, i64 1
  . . .
  %arrayidx20 = getelementptr inbounds [12
x i16], ptr @Qumem, i64 0, i64 0
  %arrayidx21 = getelementptr inbounds [12
x i16], ptr @Qumem, i64 0, i64 1
  call void @_Z4CNOTRtS_(ptr %arrayidx20,
ptr %arrayidx21)
  . . .
```

IR Form



Quantum Circuit Object

Supported Options

- Deletion
- Insertion
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- New Operations
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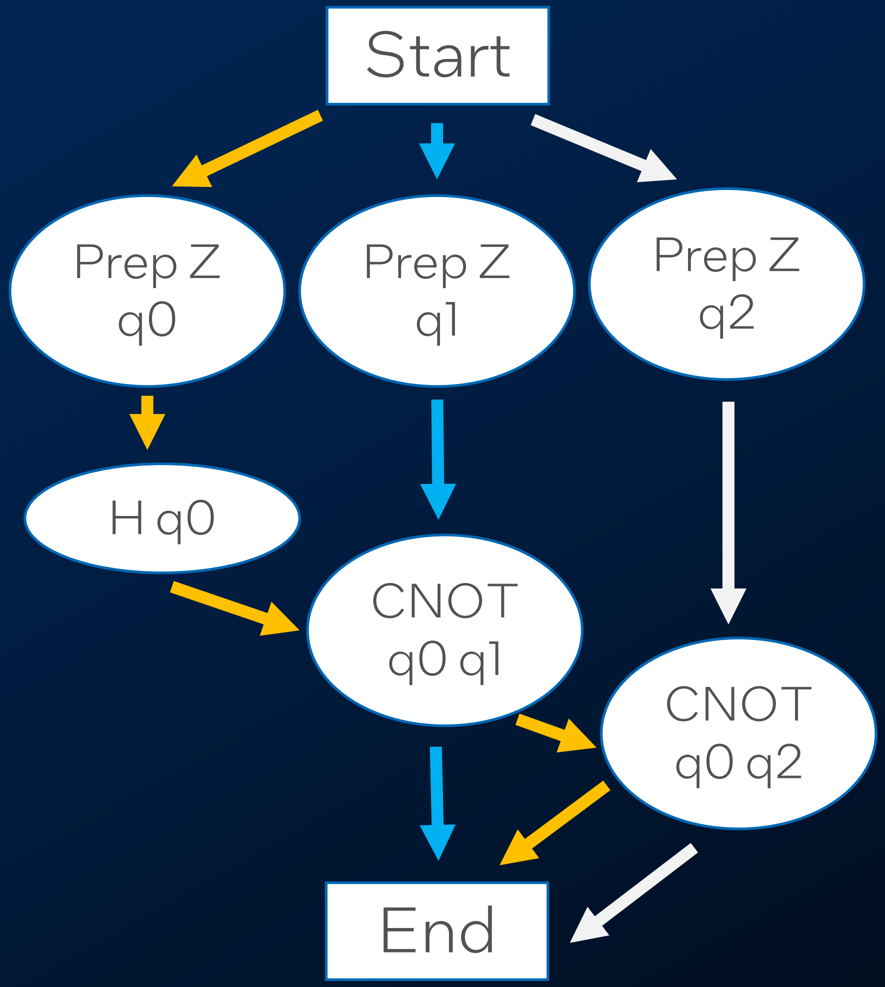
- Consistent Iteration

Circuit Object Manipulation is Reflected in IR

```
aqcc.quantum:
  . . .
  %arrayidx33 = getelementptr inbounds [12
x i16], ptr @Qumem, i64 0, i64 1
  . . .
  %arrayidx20 = getelementptr inbounds [12
x i16], ptr @Qumem, i64 0, i64 0
  %arrayidx21 = getelementptr inbounds [12
x i16], ptr @Qumem, i64 0, i64 1
  call void @_Z4CNOTRtS_(ptr %arrayidx20,
ptr %arrayidx21)
  . . .
```

IR Form



Quantum Circuit Object

Supported Options

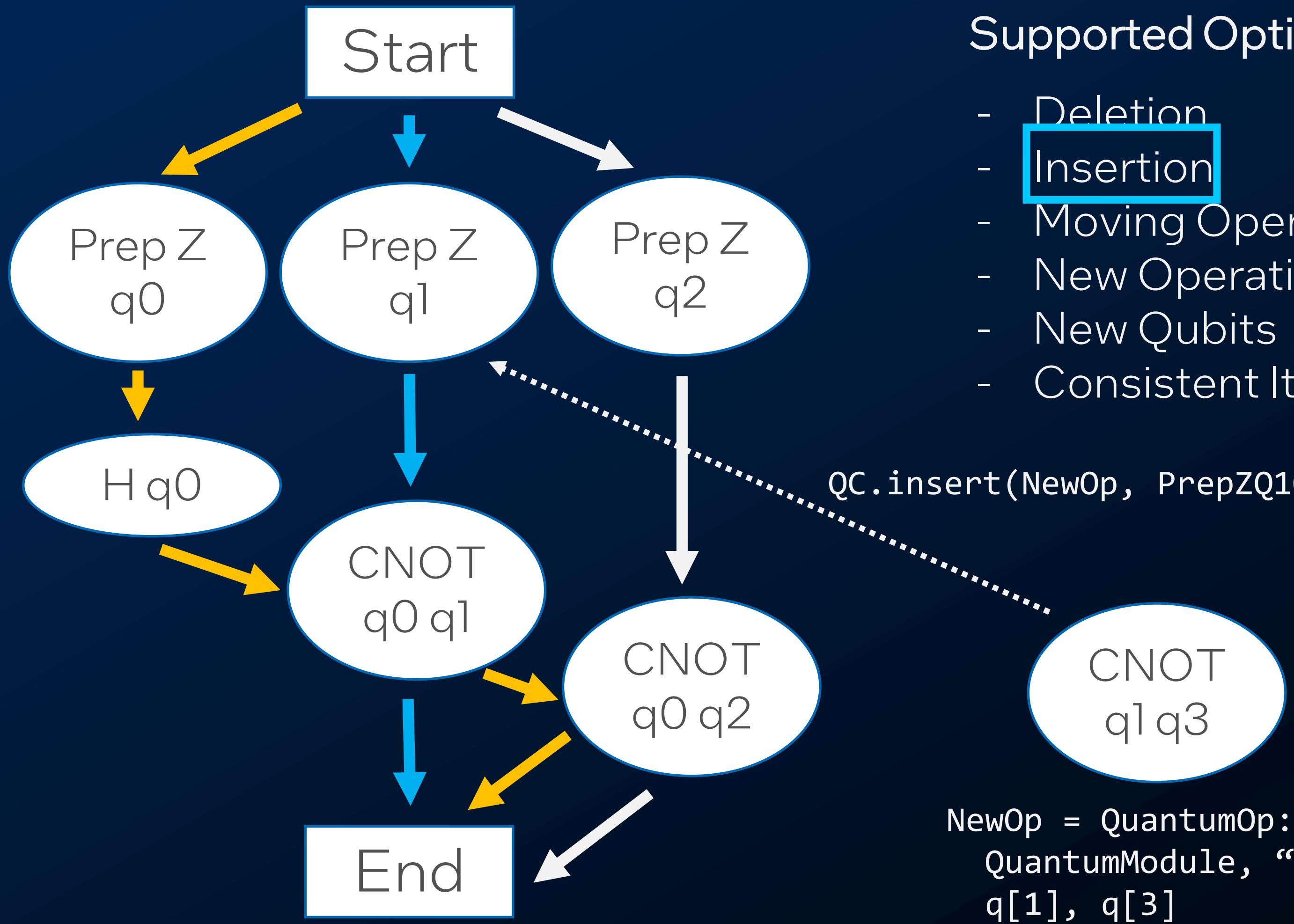
- Deletion
- Insertion
- Moving Operations
- New Operations
- New Qubits
- Consistent Iteration


```
NewOp = QuantumOp::Create(
  QuantumModule, “cnot”,
  q[1], q[3]
)
```

Circuit Object Manipulation is Reflected in IR

```
aqcc.quantum:
  . . .
  %arrayidx33 = getelementptr inbounds [12
x i16], ptr @Qumem, i64 0, i64 1
  . . .
  %arrayidx20 = getelementptr inbounds [12
x i16], ptr @Qumem, i64 0, i64 0
  %arrayidx21 = getelementptr inbounds [12
x i16], ptr @Qumem, i64 0, i64 1
  call void @_Z4CNOTRtS_(ptr %arrayidx20,
ptr %arrayidx21)
  . . .
```

IR Form



Quantum Circuit Object

Supported Options

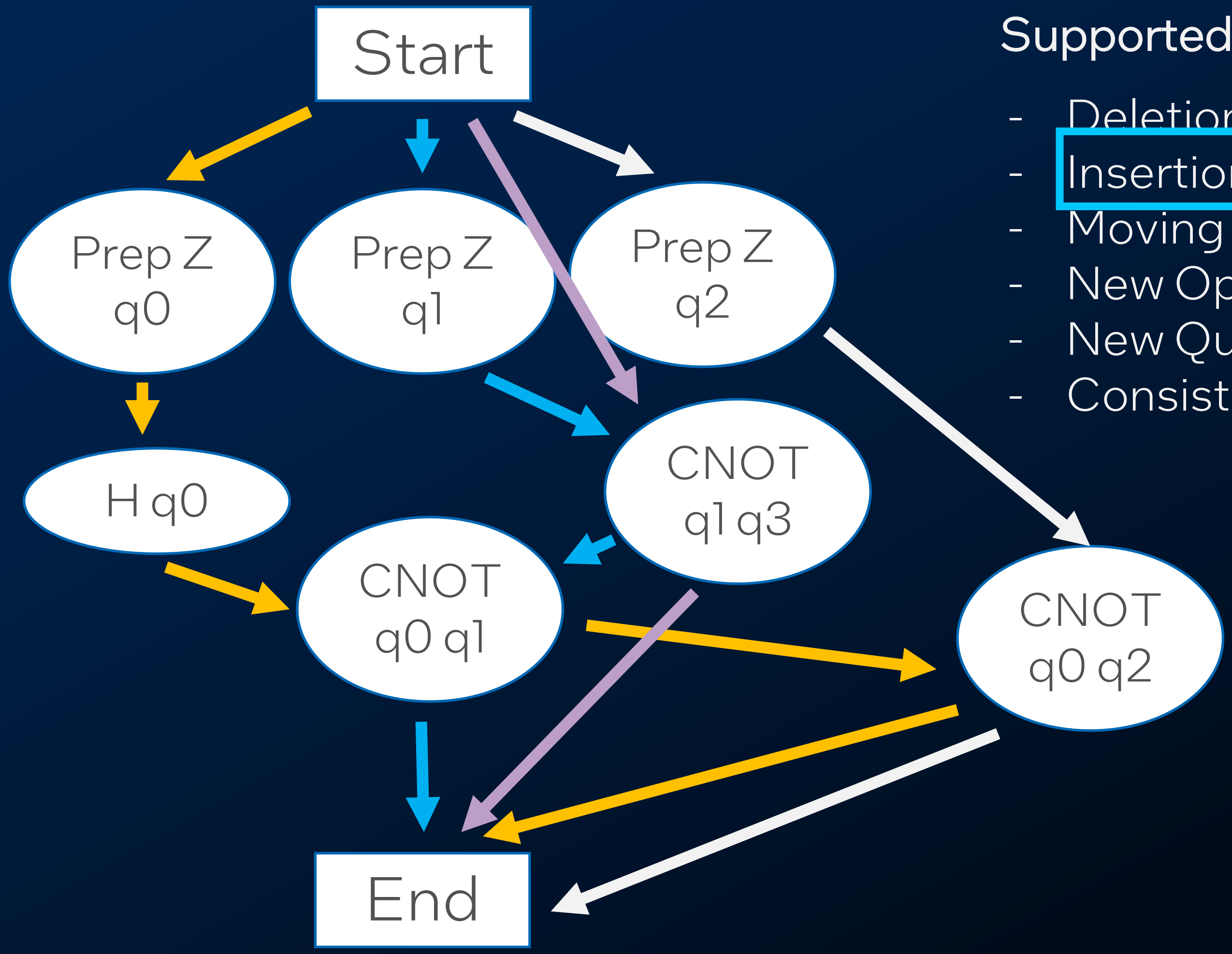
- Deletion
- Insertion
- Moving Operations
- New Operations
- New Qubits
- Consistent Iteration

```
NewOp = QuantumOp::Create(
  QuantumModule, “cnot”,
  q[1], q[3]
)
```

Circuit Object Manipulation is Reflected in IR

```
aqcc.quantum:
  . . .
  %arrayidx33 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 1
  . . .
% arrayidx21 = getelementptr inbounds [12
x i16], ptr @Qumem, i64 0, i64 1
  %arrayidx02 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 3
  call void @_Z4CNOTRtS_(ptr %arrayidx01,
ptr %arrayidx02)
  %arrayidx20 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 0
  call void @_Z4CNOTRtS_(ptr %arrayidx20,
ptr %arrayidx21)
  . . .
```

IR Form



Quantum Circuit Object

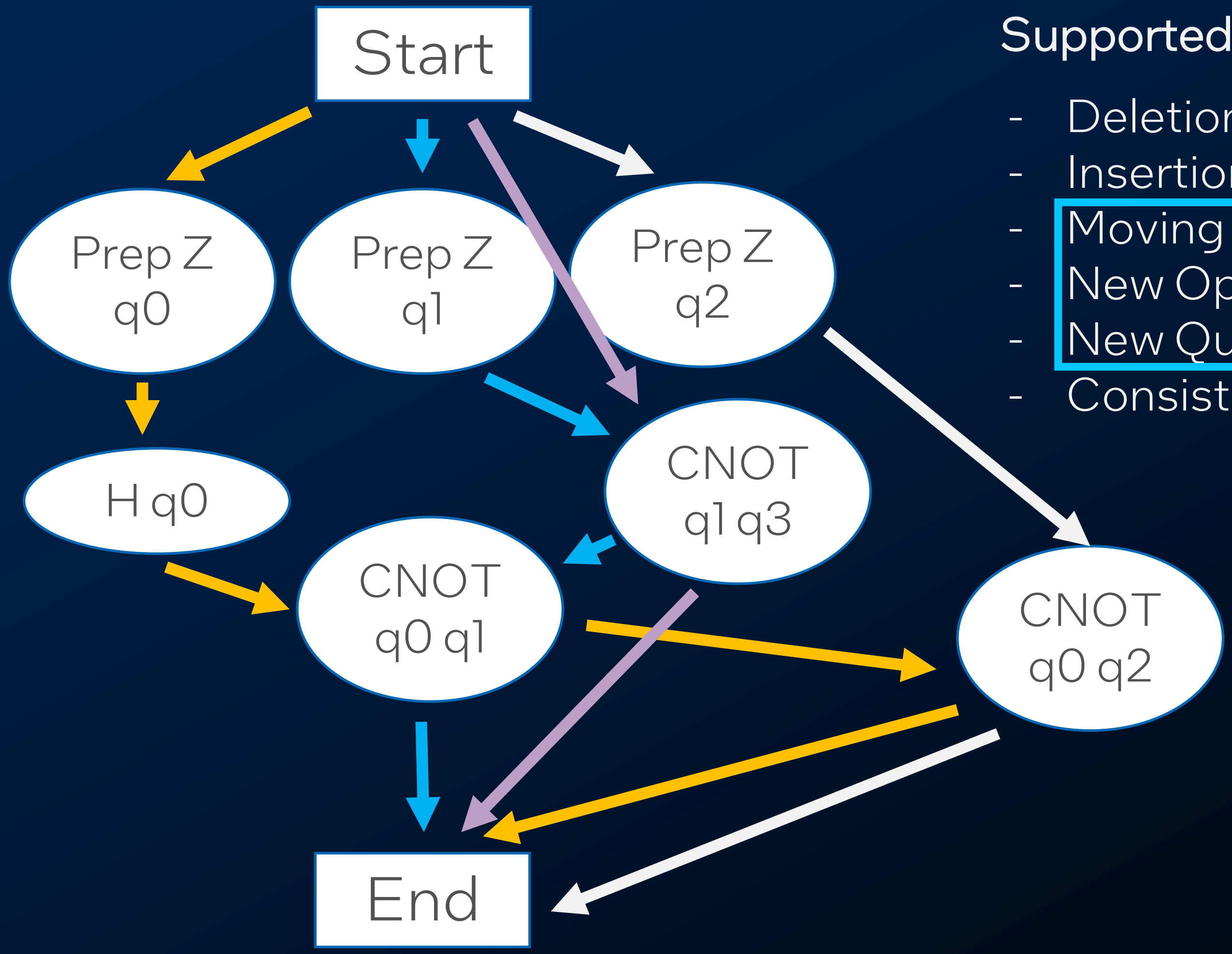
Supported Options

- Deletion
- Insertion
- Moving Operations
- New Operations
- New Qubits
- Consistent Iteration

Circuit Object Manipulation is Reflected in IR

```
aqcc.quantum:
  . . .
  %arrayidx33 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 1
  . . .
% arrayidx21 = getelementptr inbounds [12
x i16], ptr @Qumem, i64 0, i64 1
  %arrayidx02 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 3
  call void @_Z4CNOTRtS_(ptr %arrayidx01,
ptr %arrayidx02)
  %arrayidx20 = getelementptr inbounds
[12 x i16], ptr @Qumem, i64 0, i64 0
  call void @_Z4CNOTRtS_(ptr %arrayidx20,
ptr %arrayidx21)
  . . .
```

IR Form



Quantum Circuit Object

Supported Options

- Deletion
- Insertion
- Moving Operations
- New Operations
- New Qubits
- Consistent Iteration

Conclusions

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Conclusions

- Using LLVM is a powerful part of the Intel Quantum Compiler
- Flexibility and Plugins give powerful tools to high-level developers
- LLVM is complex, the Quantum Circuit Object can alleviate some difficulties

Open Source

- Improvements in structure
- More efficient ways to use LLVM
- Quantum Optimizations from researchers

https://developer.intel.com/quantumsdk

https://github.com/intel/quantum-passes

https://github.com/intel/quantum-intrinsics

Questions?

https://developer.intel.com/quantumsdk

https://github.com/intel/quantum-passes

https://github.com/intel/quantum-intrinsics

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