An MLIR Dialect for Fault-Tolerant Quantum Computing

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Objectives

1. Introduce *ftqc*, an open-source Multi-Level Intermediate Representation (MLIR) dialect and its framework.
2. Provide a dedicated compilation pipeline for *ftqc* by treating error-correcting codes (ECC), syndrome extraction, and magic-state distillation as key intermediate representation (IR) constructs.

Approach

- Introduces *ftqc*, a domain-specific MLIR dialect that treats fault-tolerant concerns—such as error-correcting codes, syndrome extraction, and magic-state distillation—as first-class, type-safe SSA (Static Single Assignment) constructs.
- Utilizes 31 operations and 19 transformation passes to enable a progressive lowering pipeline toward OpenQASM 3.0, the Quantum Intermediate Representation (QIR), and Stim, while integrating automated resource estimation directly into the compiler workflow.

Custom Types

Type	Meaning
`!ftqc.logical_qubit <#ftqc.ecc<K,d>>`	Logical qubit
`!ftqc.syndrome<N>`	N-bit syndrome
`!ftqc.magic_state`	$\|T\rangle$ magic state
`!ftqc.magic_state<CCZ>`	$\|CCZ\rangle$ state
`!ftqc.pauli_frame<N>`	$2N$-bit Pauli frame

Resource Estimates

n_L: logical qubits; **T**: T-gate count; **CNOT**: CNOT count; **Cl**: other Clifford gates; **EC**: error-correction rounds; **Dist. q**: distillation ancilla qubits; **n_{phys}**: total physical qubits (data + ancilla + distillation); **p_{total}**: estimated overall logical error probability ($p=10^{-3}$)

Circuit	n_L	T	CNOT	Cl	EC	Dist. q	n_{phys}	p_{total}
Bell (St.$d3$)	2	0	1	1	4	0	26	8×10^{-3}
GHZ-4 (St.$d3$)	4	0	3	1	8	0	52	3.2×10^{-2}
Grover (Su.$d5$)	2	0	0	12	20	0	98	4×10^{-3}
QFT-3 (St.$d3$)	3	6	9	3	36	195	234	1.1×10^{-1}

Simulation Comparison

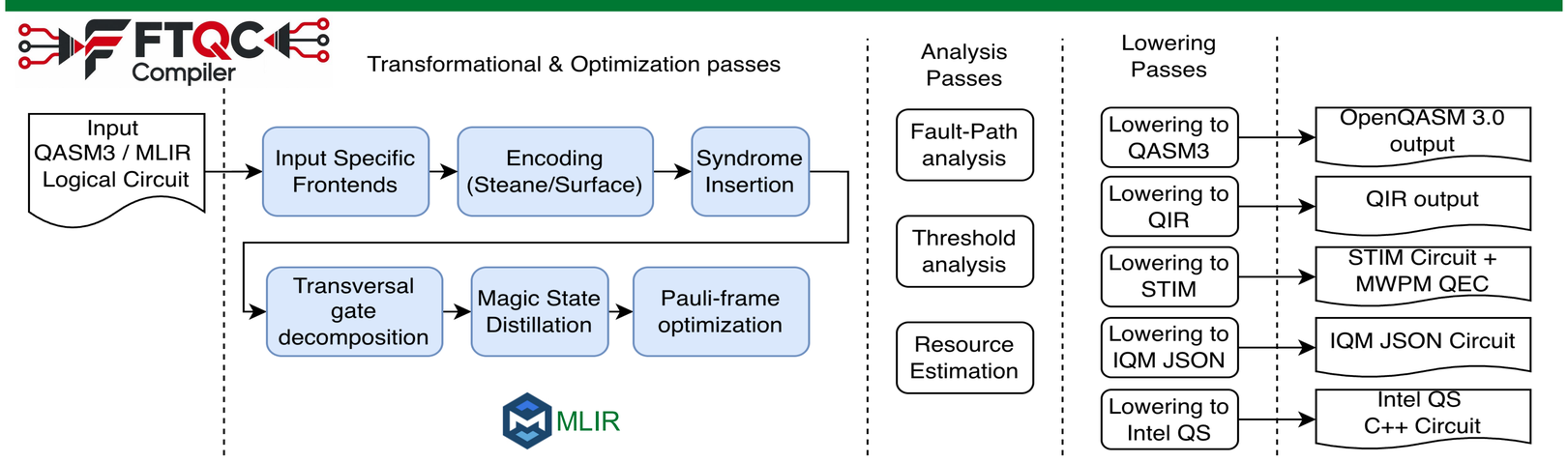
PennyLane's density matrix (DM) simulator without QEC vs. FTQC+Stim stabilizer circuit with minimum-weight perfect-matching (MWPM) decoding

Method →	PennyLane DM	STIM & MWPM
Physical Qubits	7-14	26-52
Time	617s	<4s (18-pt sweep)
Max Feasible	14 qubits	>52 qubits
Decoder	None	MWPM
p_L at $p = 10^{-3}$	5.3% (1L, 7P)	9.9% (Bell, 26P)

Motivation for the *ftqc* Dialect and Potential Impact

- **Problem:** The transition from noisy intermediate-scale quantum (NISQ) to fault-tolerant quantum computing requires robust quantum error correction (QEC).
- **Gap:** Existing compilers target NISQ optimizations and lack support for fault-tolerant constructs (ECC metadata, syndrome extraction, magic-state distillation).
- **Solution:** A type-safe compilation framework with first-class fault-tolerant IR to manage resources and abstractions for scalable QEC.
- **Potential Impact:** A fully inspectable and scalable workflow exposing costs that can drive compilation optimizations throughout the software stack.

A Type-Safe MLIR Compiler Pipeline for Fault-Tolerant Quantum Computing



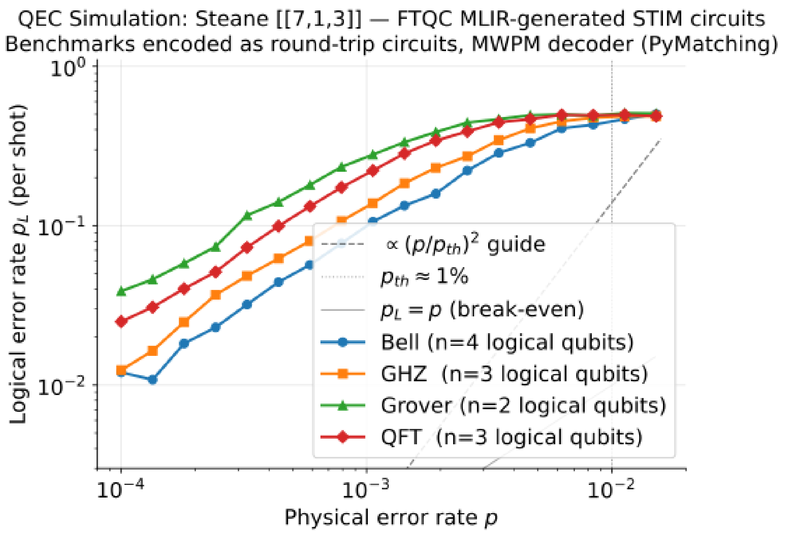
Operations Implemented

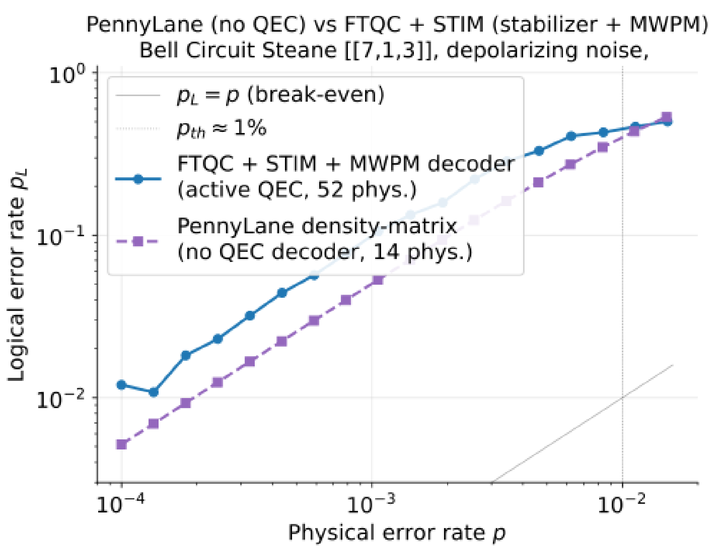
Category	Ops
Qubit lifecycle (init, encode, decode, dealloc)	5
Clifford gates (single- and two-qubit)	7
Non-Clifford gates (T, Toffoli, magic prep)	4
Syndrome extraction	5
Error correction & measurement	4
Pauli-frame management	3
Distillation & teleportation	3
Total	**31**

IR Example

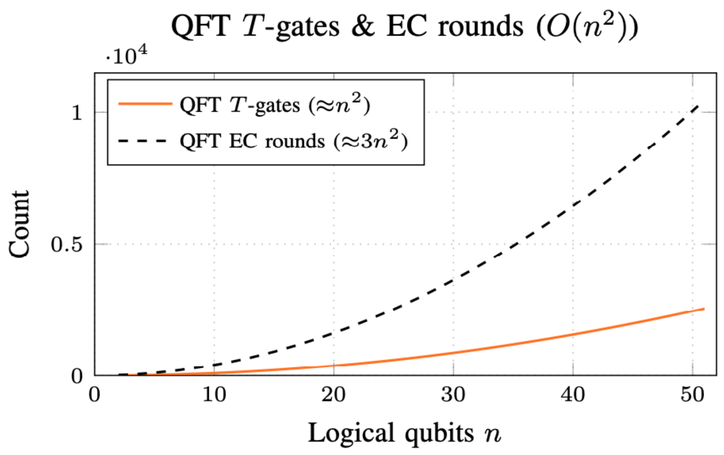
```
func.func @bell_state_ft() -> (i1, i1) {
  %lq0 = ftqc.init_zero : <<steane, 3>>
  %lq1 = ftqc.init_zero : <<steane, 3>>
  %h0  = ftqc.logical_h %lq0 : <<steane, 3>>
  %c, %t = ftqc.logical_cnot %h0, %lq1
      : (<<steane, 3>>, <<steane, 3>>)
      -> (<<steane, 3>>, <<steane, 3>>)
  %b0 = ftqc.logical_measure %c
      : (<<steane, 3>>) -> i1
  %b1 = ftqc.logical_measure %t
      : (<<steane, 3>>) -> i1
  func.return %b0, %b1 : i1, i1
}
```

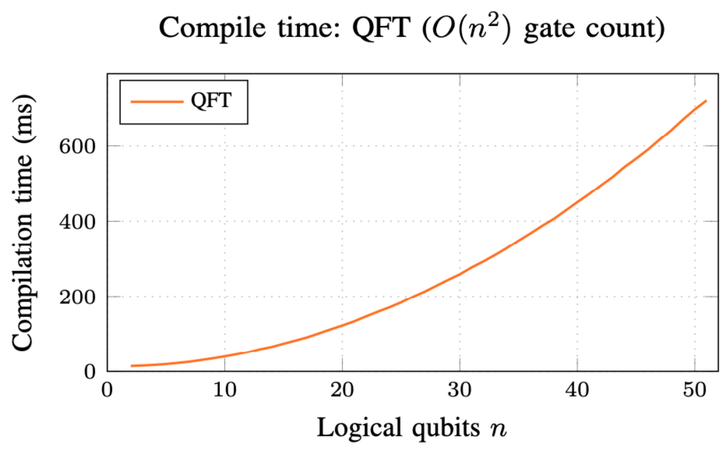
Logical Error Rates for FTQC+Stim+MWPM vs. Pennylane DM w/o QEC





Impact of T-Gate Counts in Fault-Tolerant Quantum Compilation





Summary

ftqc is an MLIR-based dialect for fault-tolerant quantum compilation with type-safe IR, a progressive lowering pipeline with integrated resource estimation, and scalable QEC simulation.

Acknowledgements: This material is based upon work supported by the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Quantum Science Center.