Noise Aware Compilation of AWS Braket Circuits

Team iCuHack

iQuHACK 2024

Inspirations

How do we apply ideas from:

- Compiler infrastructure for classical programs
- Programming Language Theory

to compiling quantum circuits?

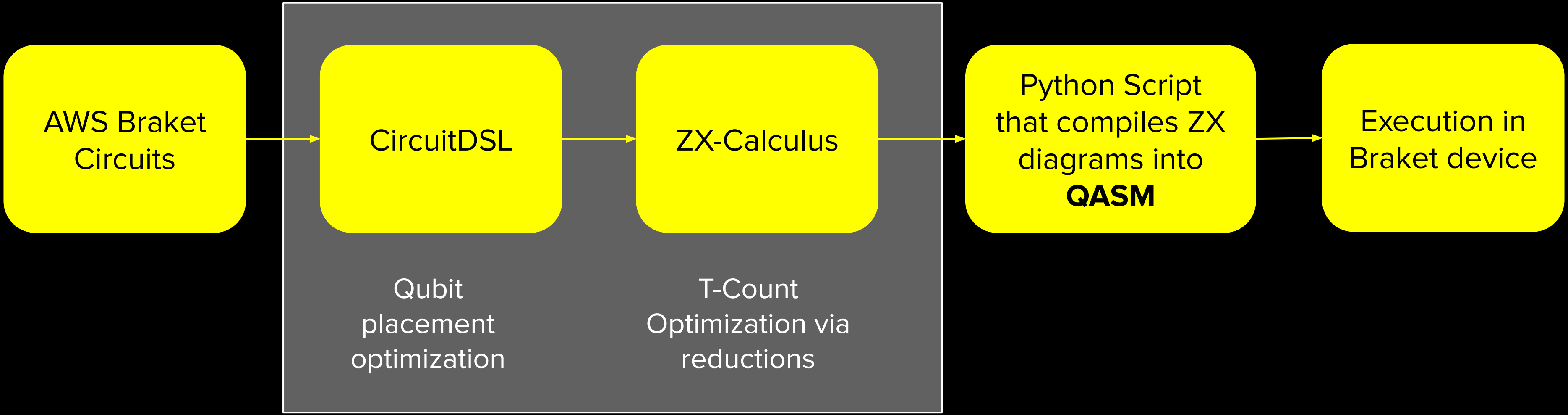
What optimizations can we implement on that for noise-awareness?

Sneak peak:

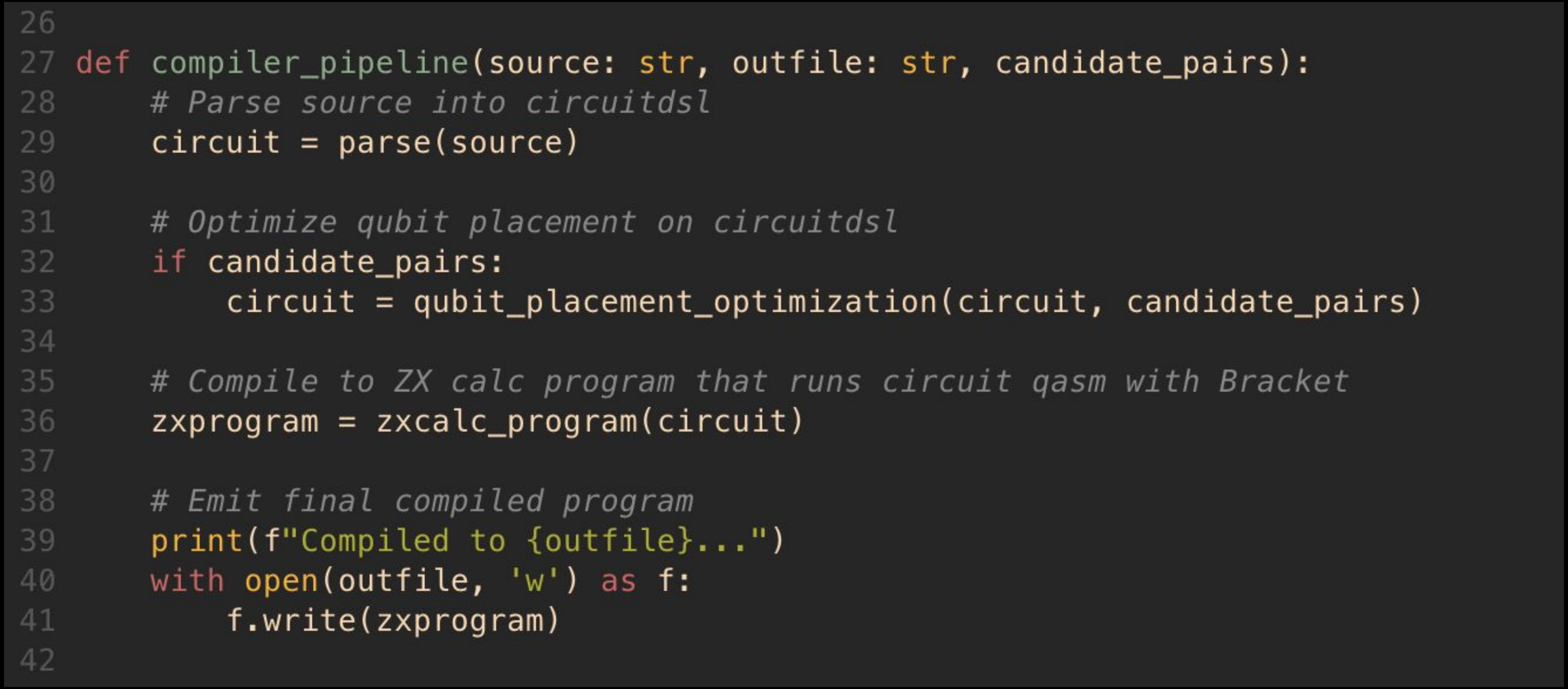
CircuitDSL for qubit placement optimization

Compilation to ZX Calculus for T-Count Reduction

What We Built


AWS Braket Circuits
CircuitDSL
ZX-Calculus
Python Script that compiles ZX diagrams into **QASM**
Execution in Braket device
Qubit placement optimization
T-Count Optimization via reductions

What we built



```python

def compiler_pipeline(source: str, outfile: str, candidate_pairs):
    # Parse source into circuitdsl
    circuit = parse(source)

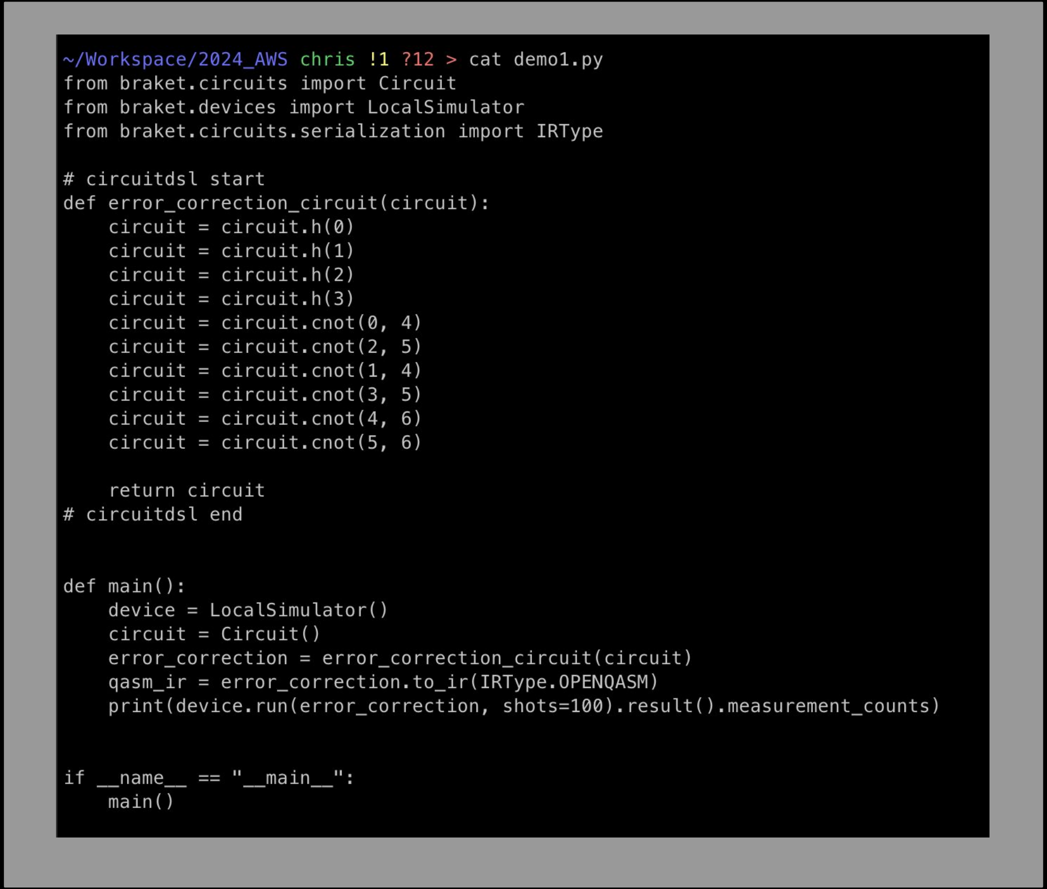
    # Optimize qubit placement on circuitdsl
    if candidate_pairs:
        circuit = qubit_placement_optimization(circuit, candidate_pairs)

    # Compile to ZX calc program that runs circuit qasm with Bracket
    zxprogram = zxcalc_program(circuit)

    # Emit final compiled program
    print(f"Compiled to {outfile}...")
    with open(outfile, 'w') as f:
        f.write(zxprogram)

```

Source Program to be Compiled:



```
~/Workspace/2024_AWS chris !1 ?12 > cat demo1.py
from braket.circuits import Circuit
from braket.devices import LocalSimulator
from braket.circuits.serialization import IRType

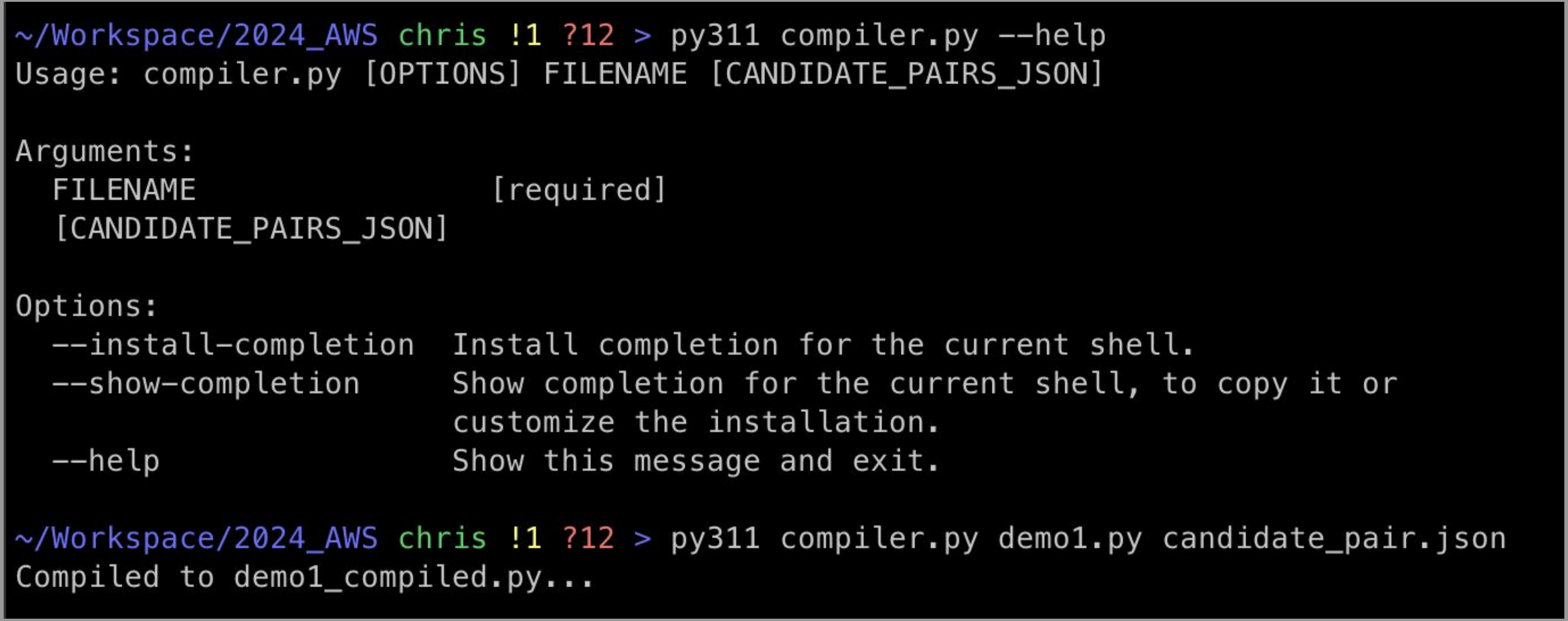
# circuitdsl start
def error_correction_circuit(circuit):
    circuit = circuit.h(0)
    circuit = circuit.h(1)
    circuit = circuit.h(2)
    circuit = circuit.h(3)
    circuit = circuit.cnot(0, 4)
    circuit = circuit.cnot(2, 5)
    circuit = circuit.cnot(1, 4)
    circuit = circuit.cnot(3, 5)
    circuit = circuit.cnot(4, 6)
    circuit = circuit.cnot(5, 6)

    return circuit
# circuitdsl end


def main():
    device = LocalSimulator()
    circuit = Circuit()
    error_correction = error_correction_circuit(circuit)
    qasm_ir = error_correction.to_ir(IRType.OPENQASM)
    print(device.run(error_correction, shots=100).result().measurement_counts)


if __name__ == "__main__":
    main()
```

Running the compiler



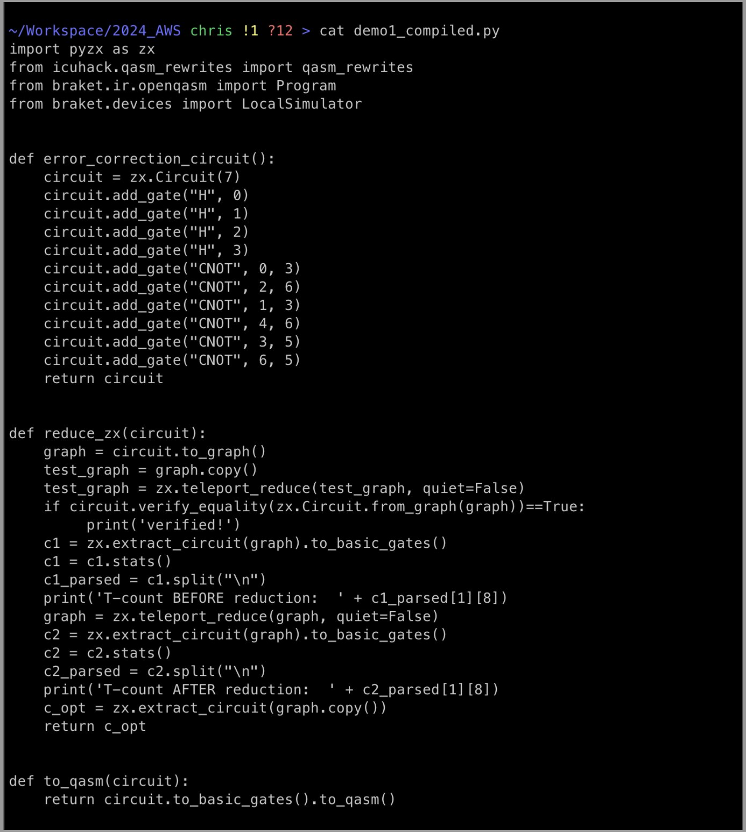
```
~/Workspace/2024_AWS chris !1 ?12 > py311 compiler.py --help
Usage: compiler.py [OPTIONS] FILENAME [CANDIDATE_PAIRS_JSON]

Arguments:
  FILENAME                        [required]
  [CANDIDATE_PAIRS_JSON]

Options:
  --install-completion  Install completion for the current shell.
  --show-completion     Show completion for the current shell, to copy it or
                        customize the installation.
  --help                Show this message and exit.

~/Workspace/2024_AWS chris !1 ?12 > py311 compiler.py demo1.py candidate_pair.json
Compiled to demo1_compiled.py...
```

Compiled Code

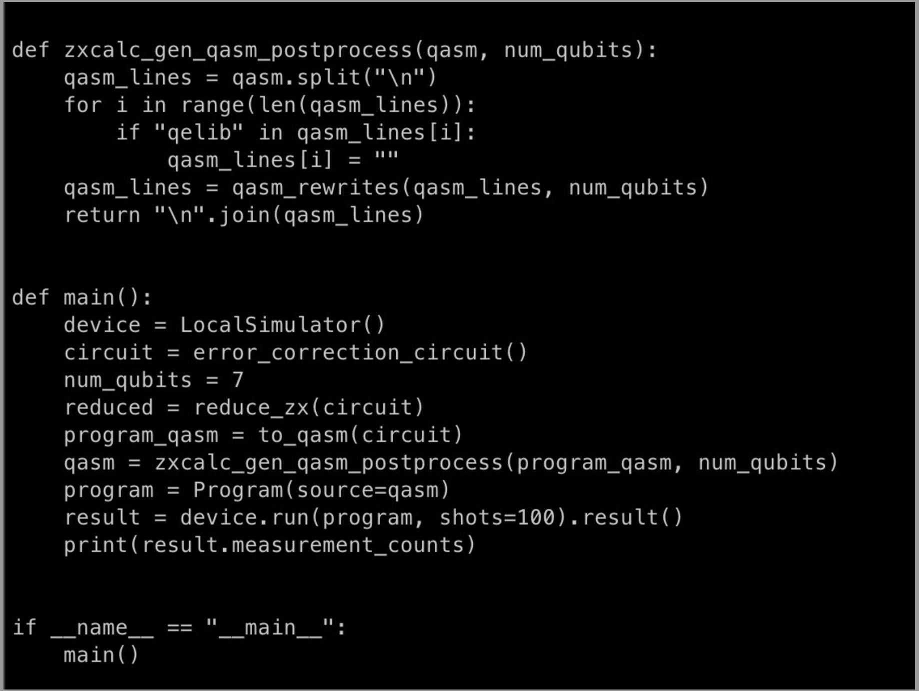


```
~/Workspace/2024_AWS chris !1 ?12 > cat demo1_compiled.py
import pyzx as zx
from icuhack.qasm_rewrites import qasm_rewrites
from braket.ir.openqasm import Program
from braket.devices import LocalSimulator


def error_correction_circuit():
    circuit = zx.Circuit(7)
    circuit.add_gate("H", 0)
    circuit.add_gate("H", 1)
    circuit.add_gate("H", 2)
    circuit.add_gate("H", 3)
    circuit.add_gate("CNOT", 0, 3)
    circuit.add_gate("CNOT", 2, 6)
    circuit.add_gate("CNOT", 1, 3)
    circuit.add_gate("CNOT", 4, 6)
    circuit.add_gate("CNOT", 3, 5)
    circuit.add_gate("CNOT", 6, 5)
    return circuit


def reduce_zx(circuit):
    graph = circuit.to_graph()
    test_graph = graph.copy()
    test_graph = zx.teleport_reduce(test_graph, quiet=False)
    if circuit.verify_equality(zx.Circuit.from_graph(graph))==True:
        print('verified!')
    c1 = zx.extract_circuit(graph).to_basic_gates()
    c1 = c1.stats()
    c1_parsed = c1.split("\n")
    print('T-count BEFORE reduction:  ' + c1_parsed[1][8])
    graph = zx.teleport_reduce(graph, quiet=False)
    c2 = zx.extract_circuit(graph).to_basic_gates()
    c2 = c2.stats()
    c2_parsed = c2.split("\n")
    print('T-count AFTER reduction:  ' + c2_parsed[1][8])
    c_opt = zx.extract_circuit(graph.copy())
    return c_opt


def to_qasm(circuit):
    return circuit.to_basic_gates().to_qasm()
```

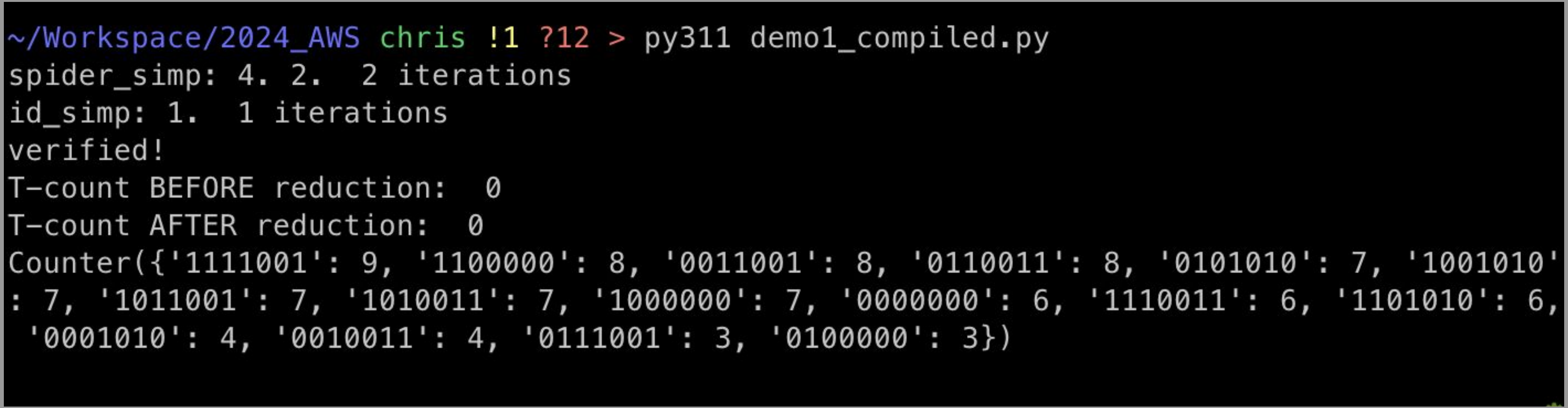


```
def zxcalc_gen_qasm_postprocess(qasm, num_qubits):
    qasm_lines = qasm.split("\n")
    for i in range(len(qasm_lines)):
        if "qelib" in qasm_lines[i]:
            qasm_lines[i] = ""
    qasm_lines = qasm_rewrites(qasm_lines, num_qubits)
    return "\n".join(qasm_lines)


def main():
    device = LocalSimulator()
    circuit = error_correction_circuit()
    num_qubits = 7
    reduced = reduce_zx(circuit)
    program_qasm = to_qasm(circuit)
    qasm = zxcalc_gen_qasm_postprocess(program_qasm, num_qubits)
    program = Program(source=qasm)
    result = device.run(program, shots=100).result()
    print(result.measurement_counts)


if __name__ == "__main__":
    main()
```

Running the Compiled Code



```
~/Workspace/2024_AWS chris !1 ?12 > py311 demo1_compiled.py
spider_simp: 4. 2.  2 iterations
id_simp: 1.  1 iterations
verified!
T-count BEFORE reduction:  0
T-count AFTER reduction:  0
Counter({'1111001': 9, '1100000': 8, '0011001': 8, '0110011': 8, '0101010': 7, '1001010'
: 7, '1011001': 7, '1010011': 7, '1000000': 7, '0000000': 6, '1110011': 6, '1101010': 6,
 '0001010': 4, '0010011': 4, '0111001': 3, '0100000': 3})
```

Highlights & Takeaways

Highlights:

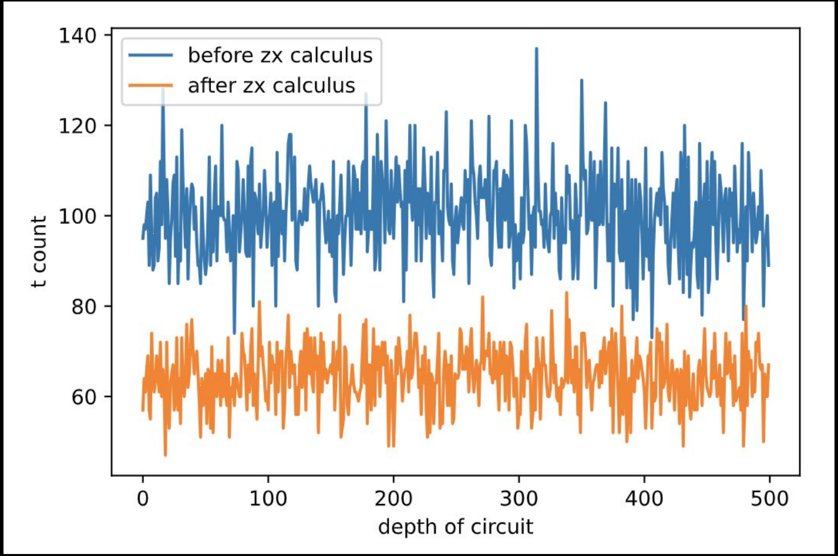
- CircuitDSL as an IR between Braket circuits and ZX calculus
- Greedy Iterative Qubit Placement Optimization on the CircuitDSL
- ZX Calculus as an IR / CircuitDSL-to-ZX compiler
- ZX Calculus Reductions as program optimization and verification

Takeaways:

- QC needs more mature, standardized IRs (like LLVM, MLIR for classical programs)
- Exciting field for more engineering & development

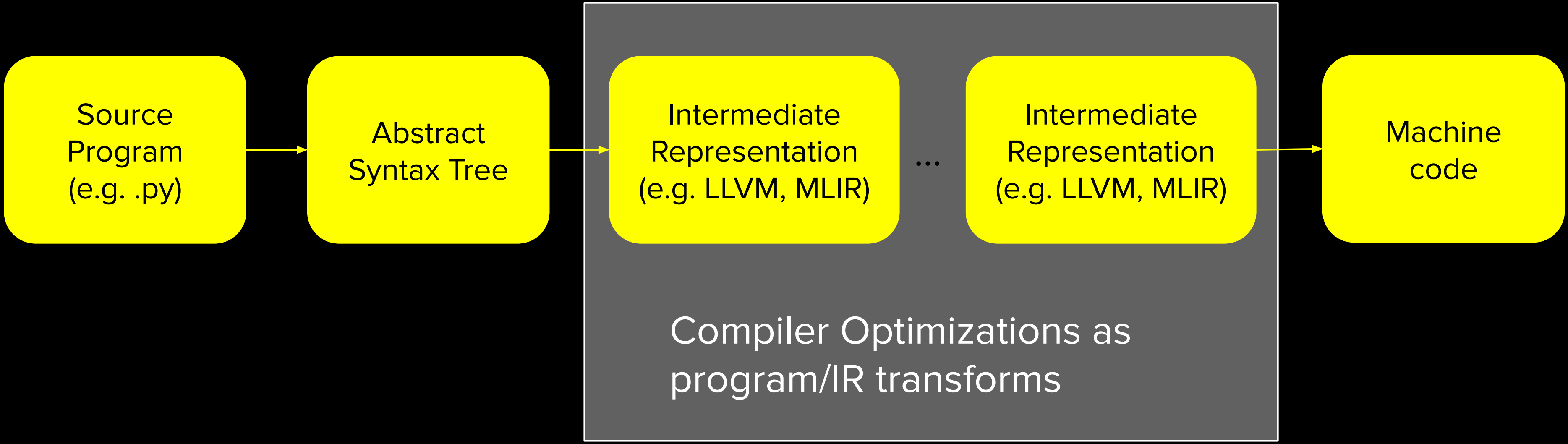
ZX Calculus Reductions Reduces T-count

ZX Calculus Reductions reduces complexity for randomly generated circuits of any depth



The Details

Classical Compiler Infrastructure


Source Program (e.g. .py)
Abstract Syntax Tree
Intermediate Representation (e.g. LLVM, MLIR)
…
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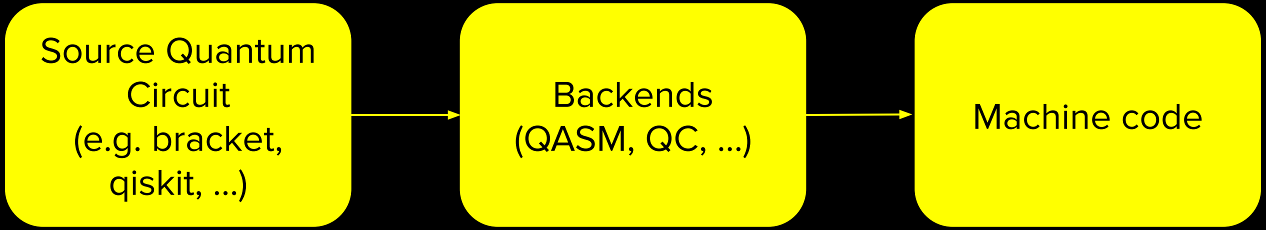
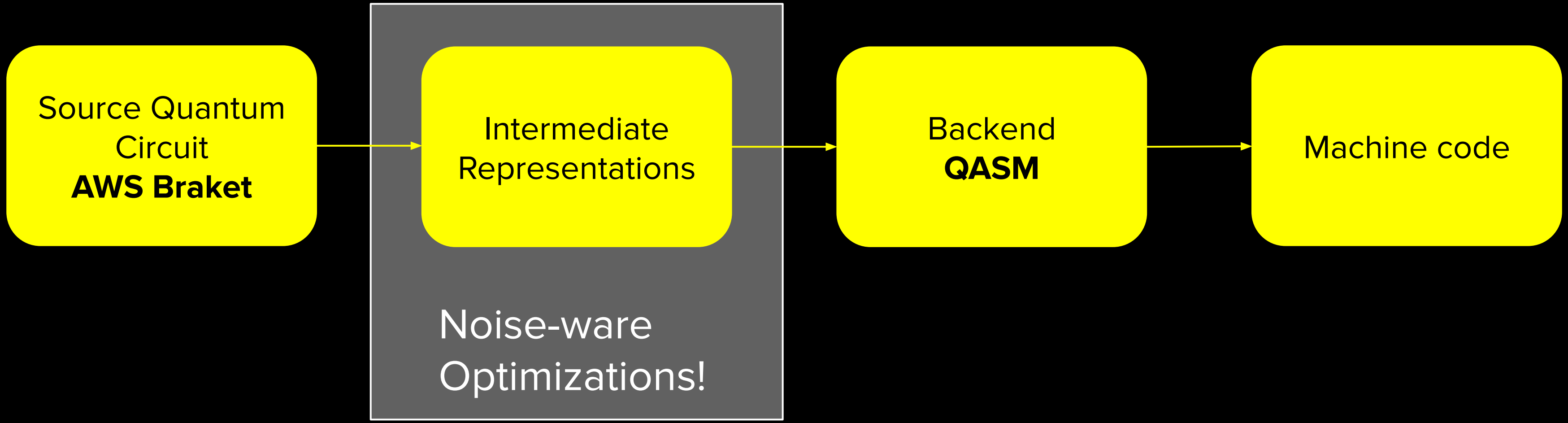
Machine code
Compiler Optimizations as program/IR transforms

Quantum Compiler Infrastructure



Our Approach

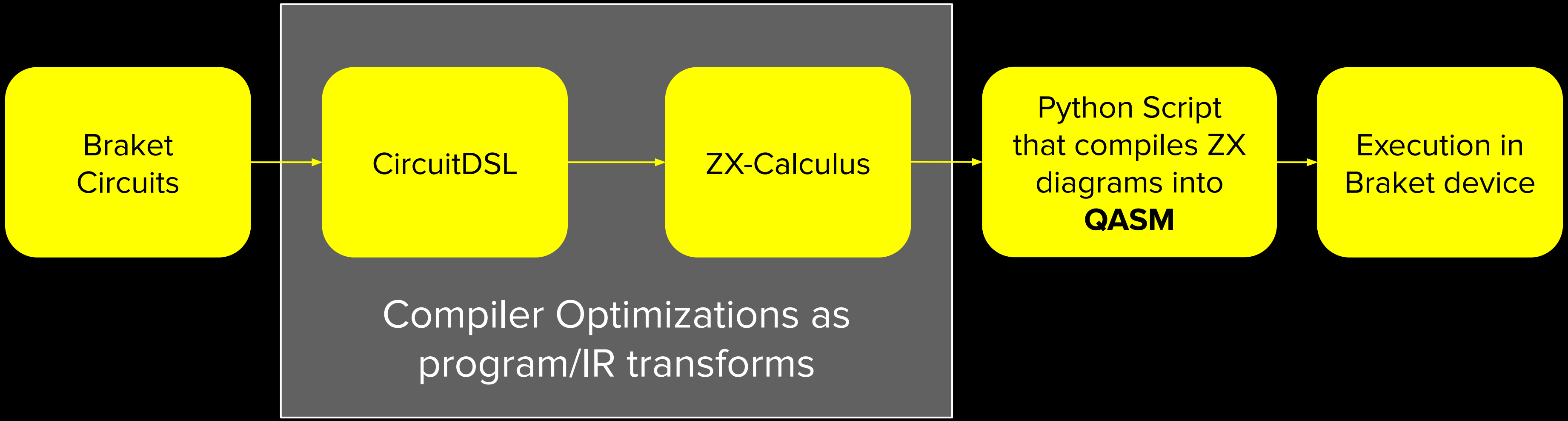


What Intermediate Representations? What optimizations?

- CircuitDSL: A simple grammar to parse Braket circuits into a stack of gates
    - Quantum circuits are mostly defined very sequentially:
        - e.g. circuit = Circuit.h(0).cnot(0, 1), ...
        - Easy to lower this to a stack based program representation
        - Easy to then swap/reorder gates and their input qubit arguments for optimization

- ZX-Calculus: A formal language and reduction rule for Quantum Circuits
    - Compile Braket circuits into the ZX-Calculus
    - Perform reductions to find equivalent circuits with lower T-counts
    - Inspired by lambda calculus, combinator calculi for classical programs

Our Approach (More specified)



Braket Circuits
CircuitDSL
ZX-Calculus
Compiler Optimizations as program/IR transforms
Python Script that compiles ZX diagrams into **QASM**
Execution in Braket device

CircuitDSL

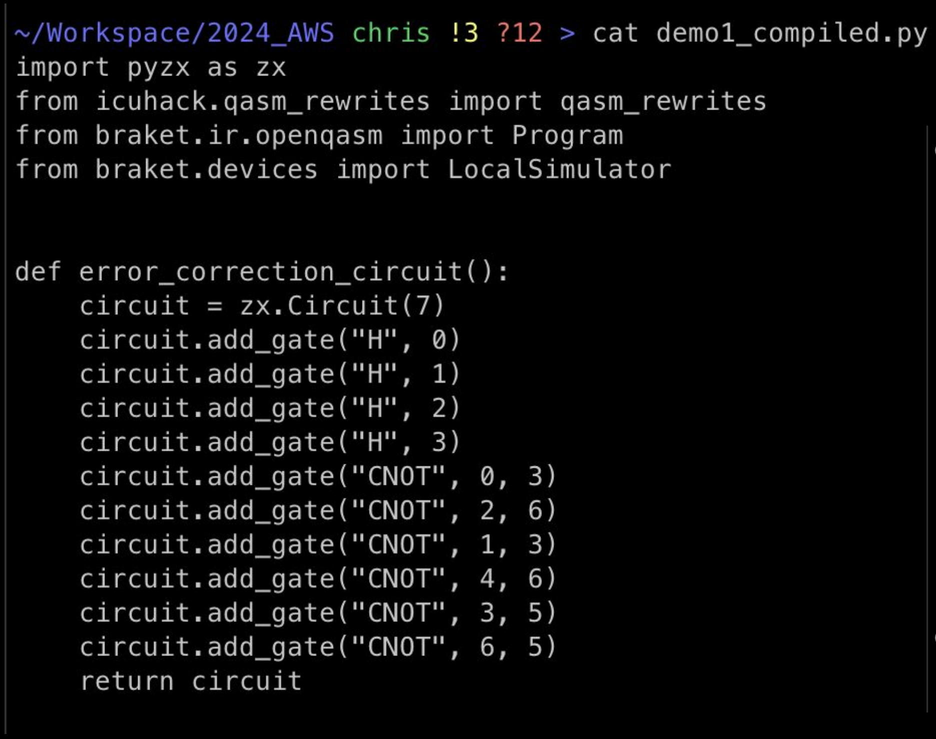
```
compiler.py demo1.py candidate_pair.json
```

```
CNOT control: 3 target: 5
CNOT control: 4 target: 6
CNOT control: 5 target: 6
```

Noise-Aware Optimization on CircuitDSL

- Prioritized correctness of transformation over superoptimization
- Greedy iterative algorithm
  - Given a list of qubit pairs and their fidelities (or noises), we iterate through the 2-qubit gates and reassign qubits, keeping track of the assignments to avoid overlap

ZX Calculus



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def error_correction_circuit():
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    circuit.add_gate("H", 2)
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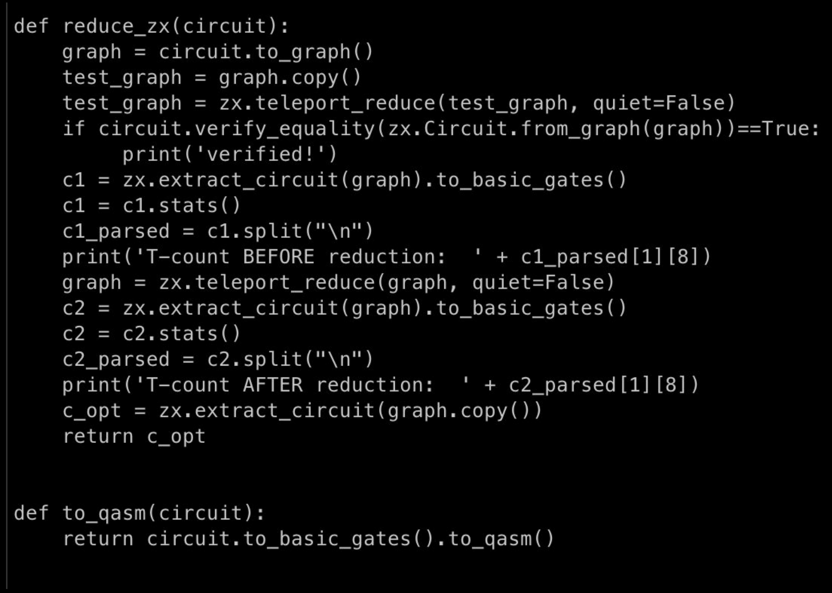
    return circuit
```



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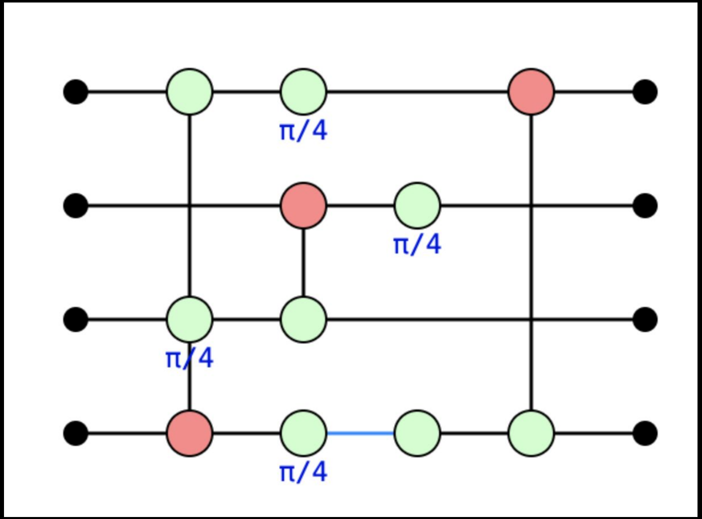
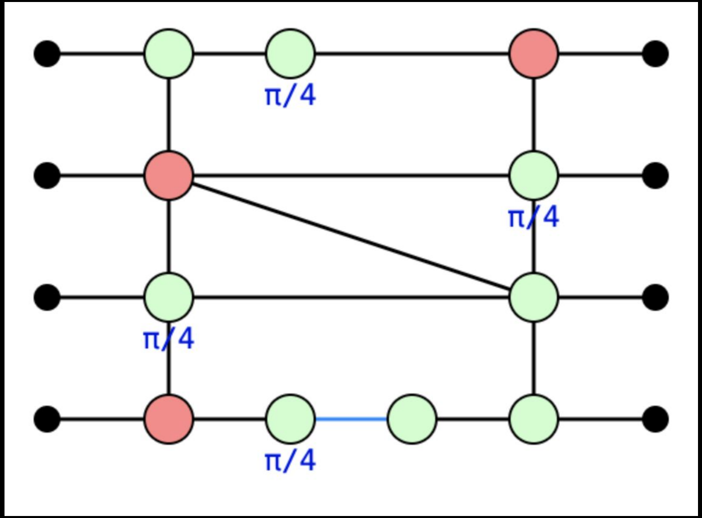
ZX Calculus



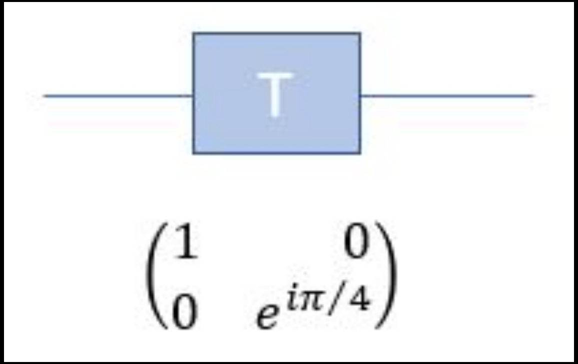


ZX-diagrams before and after applying rewrite rules

ZX Calculus for Noise Robustness

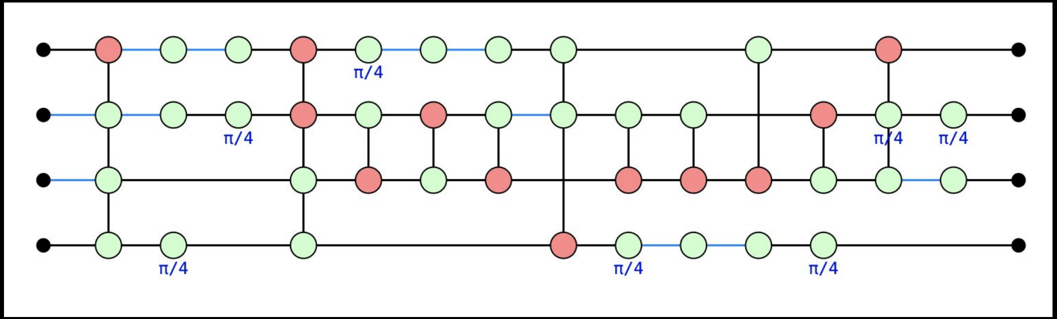
1. ZX Calculus **simplifies** quantum circuits to reduce complexity. One measure of circuit complexity is the T-Count.
2. **T-Count**: # of T-gates in a quantum circuit. **Reducing T-gates** reduces **noise** and **complexity** of the circuit.

T-Gate:

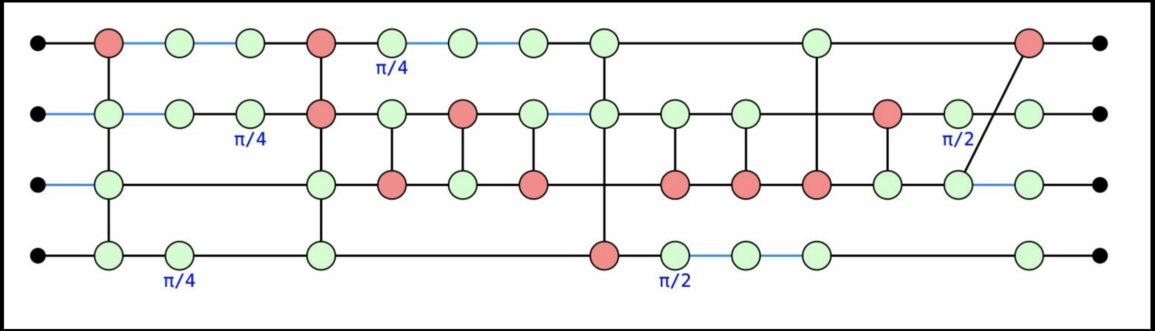


$$\begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{pmatrix}$$

ZX Calculus at Work

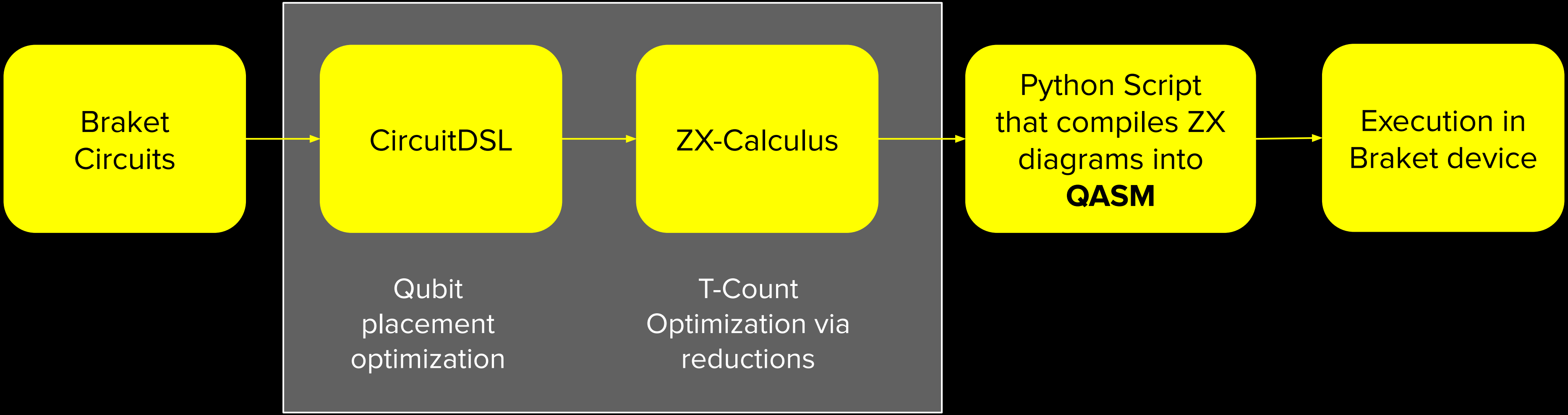


Note the # of T-Gates!



ZX-diagrams before and after applying rewrite rules

In Summary:



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34 Hackathons.
Synthetic Data, Data Pipelines,
Gen AI Builder.
Army Lieutenant.

Looking to move to work in US
😉

Thank you

Link to our repo