Quantum AI

Expressing and analyzing quantum algorithms with QUALTRAN

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IWQC Workshop

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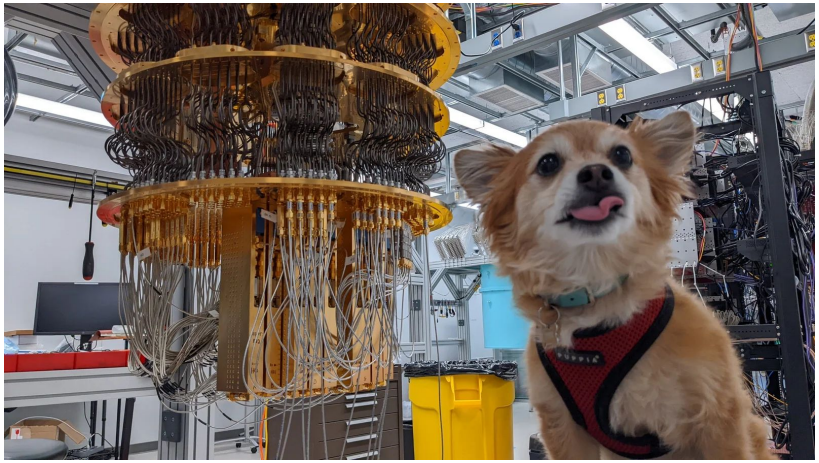
Google

Why

Google is building error-corrected quantum computers

We want to know what we'll run and when. So should you!



Researchers are puzzling through the details:

- [1905.09749] How to factor 2048 bit RSA integers in 8 hours using 20 million noisy qubits
- [2202.01244] Reliably assessing the electronic structure of cytochrome P450 on today's classical computers and tomorrow's quantum computers
- [2302.05531] Fault-tolerant quantum simulation of materials using Bloch orbitals

Why (cont'd)

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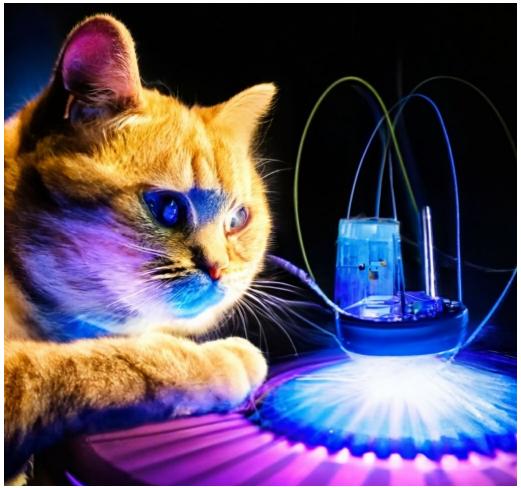
- [2302.05531] Fault-tolerant quantum simulation of materials using Bloch orbitals

It's **tedious**! Tooling and software will let us:

- Reduce toil and error
- Re-use common of algo primitives
- Demo algos in a more accessible way with visualization, code, and examples.



Expressing and Analyzing algorithms

We **cannot** currently run the algorithms we write down

We **can** make meaningful statements about their costs, composition, correctness, …

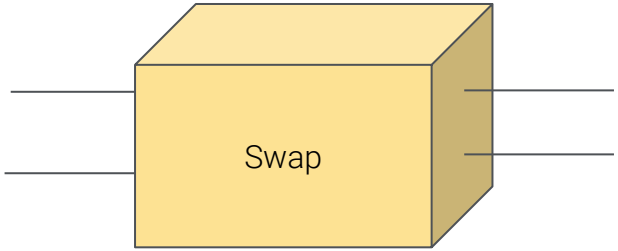
The bargain: the more you write down, the more you get out

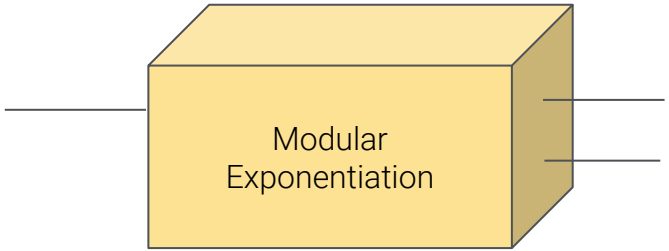
The corollary: you don't need to write down everything to get started

Reminder: Cirq-FT

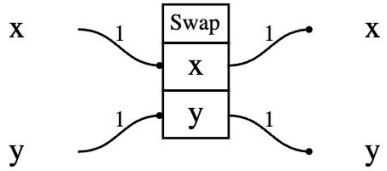
- Arithmetic Gates
  - AdditionaGate, AddMod, ContiguousRegisterGate, LessThanGate etc.
- State Preparation
  - PrepareUniformSuperposition: using a single round of amplitude amplification.
  - StatePreparationAliasSampling: QROM based state prep using classical alias sampling.
- Data Loading
  - QROM: Unary iteration based data loading using O(iteration_length) T-gates.
  - SelectSwapQROM: “advanced” QROM using O(sqrt(iteration_length)) T-gates.
- Qubitization
  - QubitizationWalkOperator, ReflectionUsingPrepare, SelectOracle, PrepareOracle
- Robin’s Mean Estimation Algorithm
  - MeanEstimationOperator, ComplexPhaseOracle, ArcTan etc.
- Others
  - UnaryIteration base class to enable expressing nested coherent for-loops using multi-dimensional selection registers.
  - ProgrammableRotationGateArray: QROM based rotation synthesis introduced in Guang Hao’s double factorization paper

Expressing algorithms with Bloqs

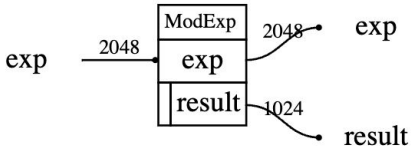





```python
class Swap(Bloq):
    @property
    def signature(self) -> 'Signature':
        return Signature.build(x=1, y=1)


swap = Swap()
show_bloq(swap)
```




```python
@dataclass(frozen=True)
class ModExp(Bloq):
    n: int

    @property
    def signature(self) -> 'Signature':
        return Signature([
            Register('exp', bitsize=2*self.n),
            Register('result', bitsize=self.n, side=Side.RIGHT)
        ])

mod_exp = ModExp(n=1024)
show_bloq(mod_exp)
```



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https://qualtran.readthedocs.io/en/latest/_infra/Bloqs-Tutorial.html

Bloqs are built out of other bloqs

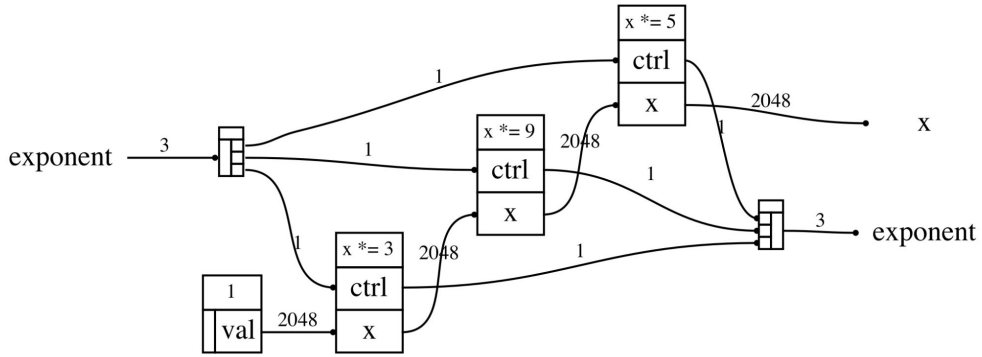
```python
def build_composite_bloq(self, bb: BloqBuilder, exponent):
    x = bb.add(IntState(val=1, bitsize=self.x_bitsize))
    exponent = bb.split(exponent)

    for j in range(self.exp_bitsize - 1, 0 - 1, -1):
        exponent[j], x = bb.add(CtrlModMul(k=self.base),
                                ctrl=exponent[j], x=x)
        base = base * base % self.mod

    return {'exponent': bb.join(exponent), 'x': x}
```

Define your bloq's implementation in terms of smaller bloqs.

Quantum variables follow linear logic

Our container type is `CompositeBloq`, which implements the `Bloq` interface

It is a directed, acyclic graph



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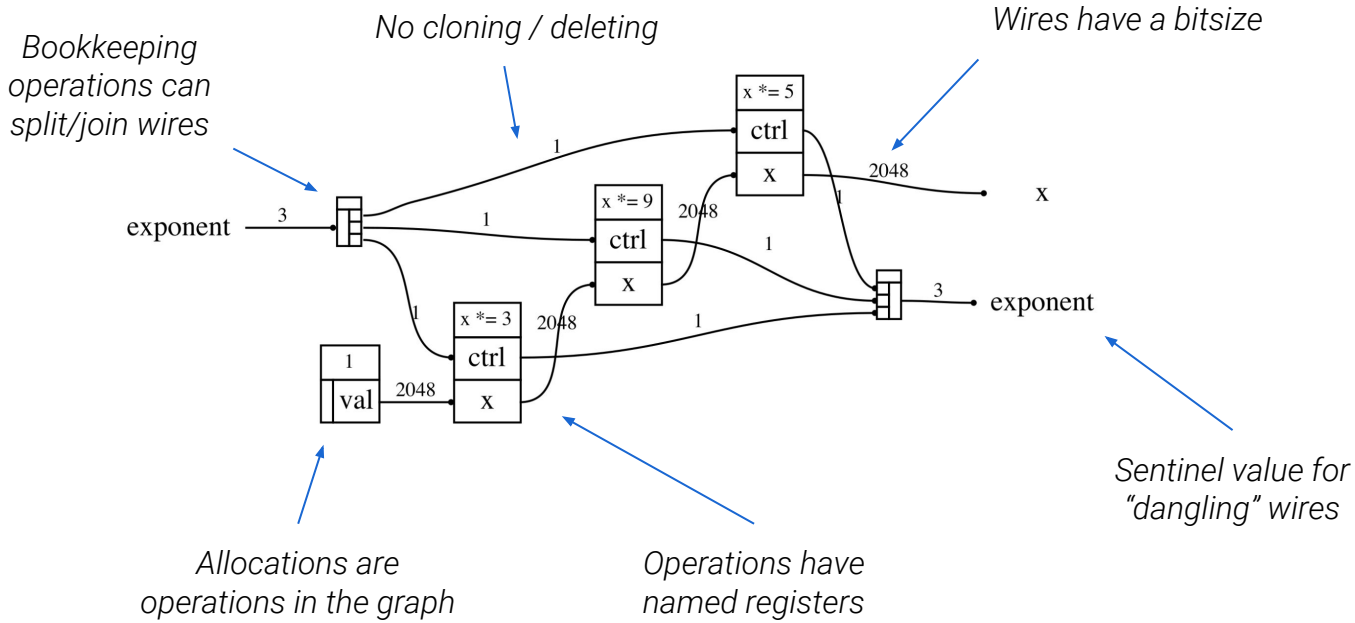
Features of CompositeBloq



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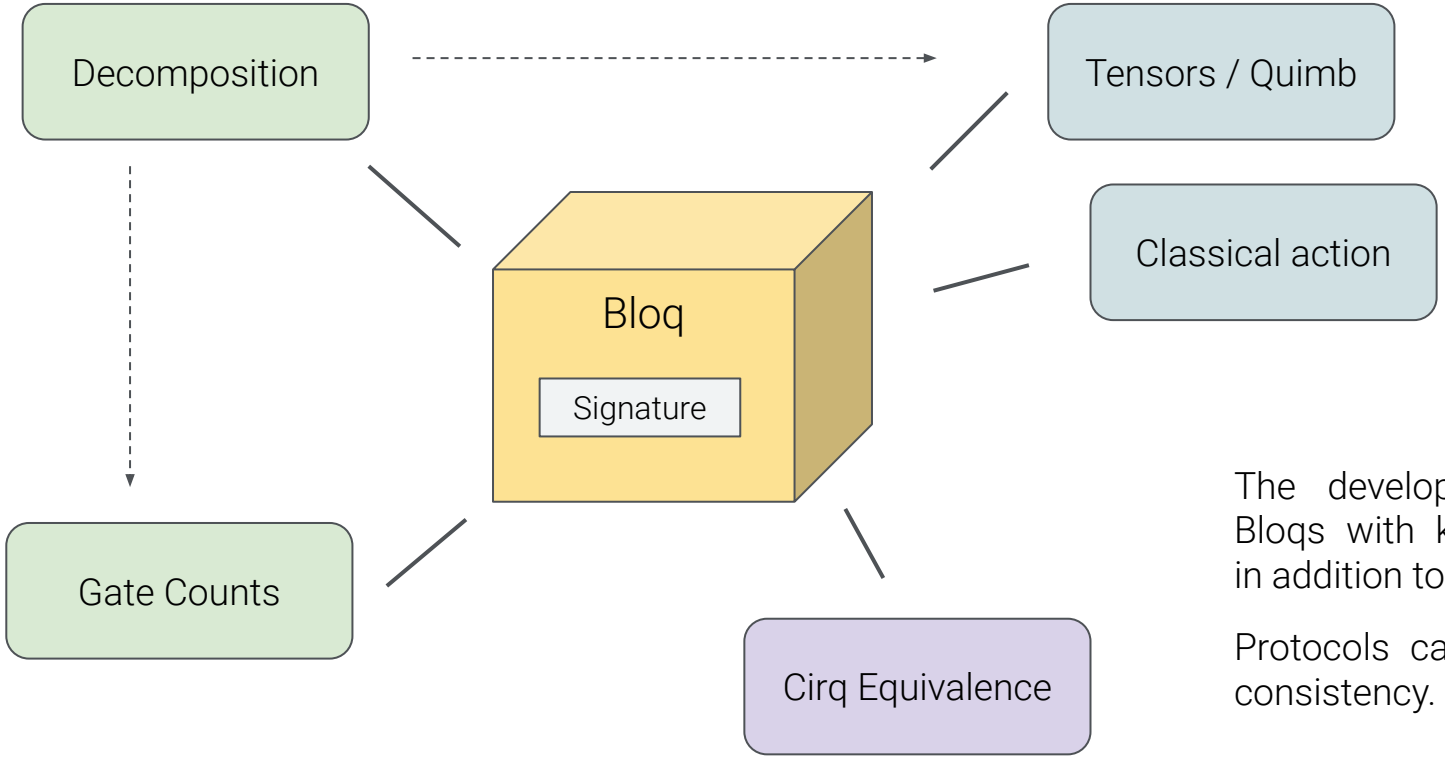
Analyzing algorithms



The developer can annotate Bloqs with known information in addition to its decomposition

Protocols can be checked for consistency.

Classical Reversible Simulation

```python
class ModExp(Bloq):

    ...

    def on_classical_vals(self, exponent: int):
        return {'exponent': exponent,
                'x': (self.base ** exponent) % self.mod}
```

```python
class CtrlModMul(Bloq):

    ...

    def on_classical_vals(self, ctrl: int, x: int):
        if ctrl == 0:
            return {'ctrl': ctrl, 'x': x}

        return {'ctrl': ctrl,
                'x': (x * self.k) % self.mod}
```

Annotate with classical action (where appropriate)

```python
N = 13*17
n = int(np.ceil(np.log2(N)))
g = 8

mod_exp = ModExp(base=g, mod=N, exp_bitsize=32, x_bitsize=32)
mod_exp_decomp = mod_exp.decompose_bloq()

for e in range(20):
    ref = (g ** e) % N
    _, bloq_eval = mod_exp.call_classically(exponent=e)
    _, decomp_eval = mod_exp_decomp.call_classically(exponent=e)

    print(f'{e:5d}: {ref:5d} {bloq_eval:5d} {decomp_eval:5d}')
```

```
    0:     1     1     1
    1:     8     8     8
    2:    64    64    64
    3:    70    70    70
    4:   118   118   118
    5:    60    60    60
    6:    38    38    38
    7:    83    83    83
    8:     1     1     1
    9:     8     8     8
   10:    64    64    64
   11:    70    70    70
   12:   118   118   118
   13:    60    60    60
   14:    38    38    38
   15:    83    83    83
```

Fuzz test your decomposition on classical inputs

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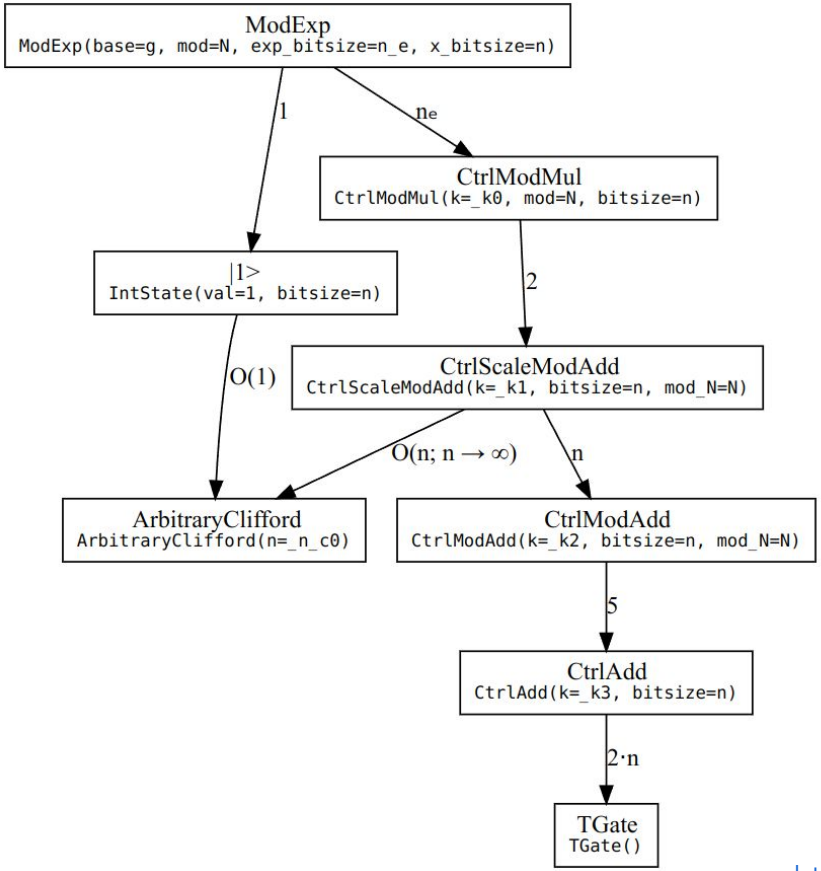
https://qualtran.readthedocs.io/en/latest/simulation/classical_sim.html

Symbolics and Gate Counting



Annotate bloqs with expressions for (sub-)bloq counts

Big-O the parts you don't care about

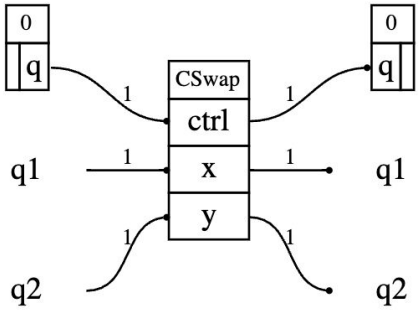
More consistency checks

Visualize your decomposition hierarchy

https://qualtran.readthedocs.io/en/latest/bloqs/factoring/ref-factoring.html

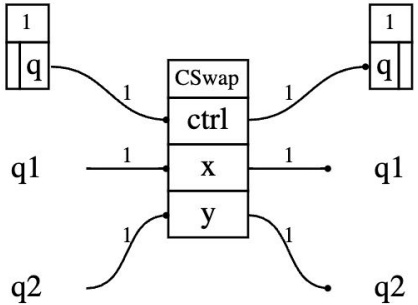
Numerical Simulation and Tensor Contraction

```
ctrl = bb.add(ZeroState())
ctrl, q1, q2 = bb.add(CSwap(), ctrl=ctrl, x=q1, y=q2)
bb.add(ZeroEffect(), q=ctrl)
deactivated_cswap = bb.finalize(q1=q1, q2=q2)

show_bloq(deactivated_cswap)
deactivated_cswap.tensor_contract().real
```




```
array([[1., 0., 0., 0.],
       [0., 1., 0., 0.],
       [0., 0., 1., 0.],
       [0., 0., 0., 1.]])
```

```
ctrl = bb.add(OneState())
ctrl, q1, q2 = bb.add(CSwap(), ctrl=ctrl, x=q1, y=q2)
bb.add(OneEffect(), q=ctrl)
activated_cswap = bb.finalize(q1=q1, q2=q2)


show_bloq(activated_cswap)
activated_cswap.tensor_contract().real
```




```
array([[1., 0., 0., 0.],
       [0., 0., 1., 0.],
       [0., 1., 0., 0.],
       [0., 0., 0., 1.]])
```

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Bi-directional Cirq Interop

`CirqGateAsBloq` and `BloqAsCirqGate` both exist

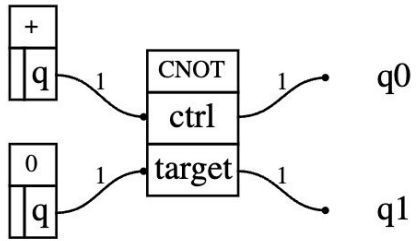
As does conversion to and from `cirq.Circuit`

Subject to Cirq limitations: Shim to flat array of individual qubits.

```
bb = BloqBuilder()
q0 = bb.add(PlusState())
q1 = bb.add(ZeroState())

q0, q1 = bb.add(CNOT(), ctrl=q0, target=q1)

bell = bb.finalize(q0=q0, q1=q1)
show_bloq(bell)
```




```
circuit, qubits = bell.to_cirq_circuit()
circuit
```

```
_c(0): ──H──@──
            │
_c(1): ─────X──
```

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https://qualtran.readthedocs.io/en/latest/cirq_interop/cirq_interop.html

Bi-directional Cirq Interop

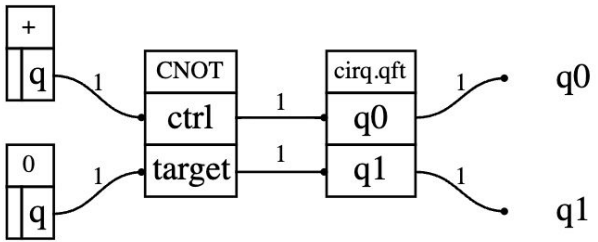
`CirqGateAsBloq` and `BloqAsCirqGate` both exist

As does conversion to and from `cirq.Circuit`

Subject to Cirq limitations: Shim to flat array of individual qubits.

```
qft = cirq.QuantumFourierTransformGate(num_qubits=2)
q0, q1 = bb.add(CirqGateAsBloq(qft), qubits=[q0,q1])

bell_qft = bb.finalize(q0=q0, q1=q1)
show_bloq(bell_qft)
```




```
circuit, qubits = bell_qft.to_cirq_circuit()
circuit
```

```
_c(0): ──H──@──qft──
            │  │
_c(1): ─────X──#2───
```

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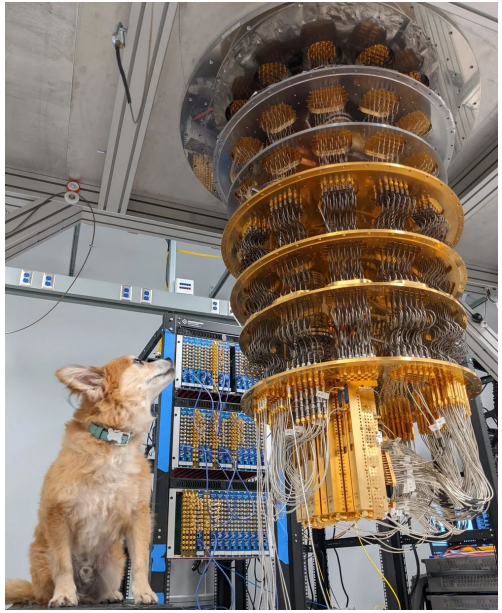
https://qualtran.readthedocs.io/en/latest/cirq_interop/cirq_interop.html

Qualtran Experimental Preview

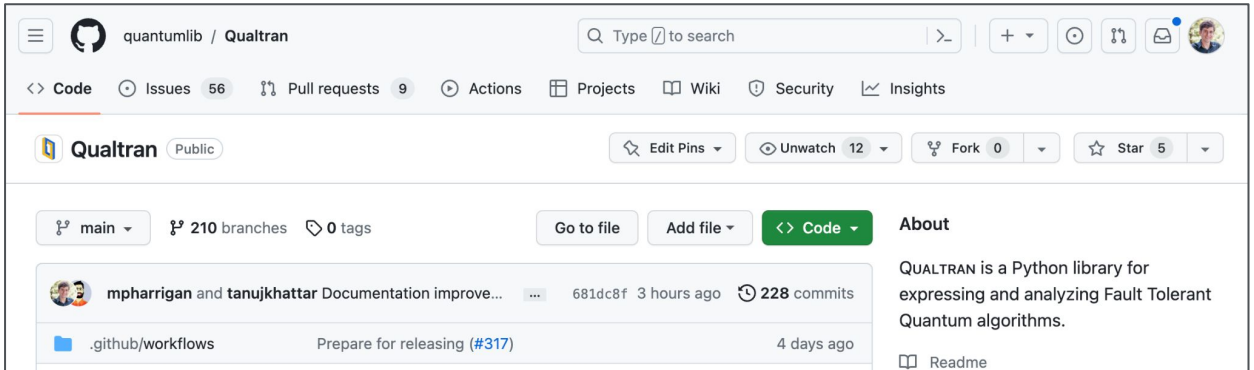
We know things about the algorithms. Let's write them down in a structured way!

Qualtran is open source as an experimental preview.
A lot more to come!

Please **get in touch** if you're interested in contributing!
mpharrigan@google.com
https://github.com/quantumlib/Qualtran



- *Raising issues…*
- *Writing Bloqs…*
- *Correctness protocols…*
- *Visualization protocols…*



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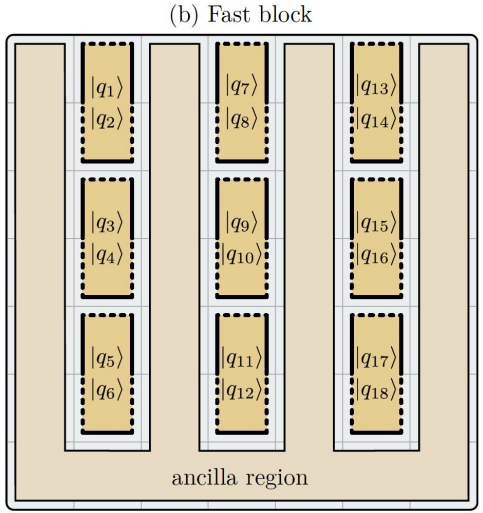
Physical costs

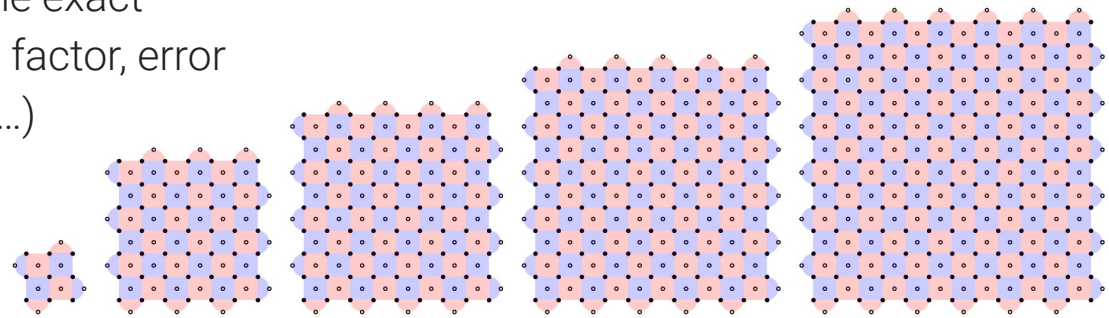
Google is targeting lattice surgery on the (rotated) surface code with T or CCZ factories with Lambda~10 and 1us cycle time.

“Game of surface codes” compilation is fully general and gives precise numbers.

Manual layout is very involved. Automated optimizing layout is a huge software challenge.

Still a lot of uncertainty around the exact architecture (shape, suppression factor, error tolerance, cosmic rays, timeline, …)





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