

# QPL: A Relations-First Programming Language for Measurement-Based Quantum Computing

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## Abstract

We present the Quantum Process Language (QPL), a programming language where quantum entanglement is a first-class primitive rather than a derived gate operation. Unlike gate-based quantum languages (Qiskit, Q#, Cirq), QPL expresses quantum programs as relations and measurements, naturally aligning with Measurement-Based Quantum Computing (MBQC).

We formalize QPL’s operational semantics and present a **complete working implementation** of the MBQC compilation pipeline, including graph state extraction, measurement pattern generation for standard quantum gates, and adaptive Pauli corrections. Our implementation comprises 2,555 lines of Python code validated by 47 tests achieving 100% physics correctness on Bell correlations, cross-basis measurements, and quantum teleportation (fidelity = 1.0).

This relations-first approach provides a direct compilation path to photonic quantum computers and surface code architectures without intermediate gate decomposition, addressing a critical gap in current quantum software stacks.

**Keywords:** Quantum programming languages, measurement-based quantum computing, quantum entanglement, photonic quantum computing, quantum compilation

## 1 Introduction

The standard model of quantum computation is the *quantum circuit model* [11], where computation proceeds through sequences of unitary gates applied to qubits. This paradigm, inherited from classical digital circuits, has dominated quantum programming language design for three decades. Languages like Qiskit [14], Cirq [3], and Q# [20] all express quantum programs as gate sequences.

However, gates are **not** how quantum mechanics fundamentally operates. Quantum systems evolve continuously under Hamiltonians:

$$i\hbar \frac{d|\psi\rangle}{dt} = H|\psi\rangle \quad (1)$$

Gates are discretizations of this continuous evolution—a useful approximation, but fundamentally classical thinking applied to quantum systems.

This gate-centric paradigm persists for historical reasons: it directly inherits from classical circuit design, and unitary matrices compose cleanly as mathematical objects. However, for emerging quantum hardware architectures—particularly photonic quantum computers and fault-tolerant surface codes—the gate model represents an unnecessary abstraction layer.

## 1.1 Measurement-Based Quantum Computing

An alternative paradigm, *Measurement-Based Quantum Computing* (MBQC) [17], computes via measurements on highly entangled resource states rather than gate application. MBQC has proven computationally equivalent to the circuit model [18], yet offers distinct advantages for certain hardware implementations.

Notably, MBQC is the *native* computational model for:

- **Photonic quantum computers** [19] (PsiQuantum, Xanadu), where creating photonic gates is challenging but generating entangled photons is easier
- **Fault-tolerant quantum computing** [5] via surface codes, where logical gates are implemented as measurement patterns
- **Neutral atom systems** [2] that can prepare cluster states natively via Rydberg blockade

Despite this, current quantum programming languages target gate-based circuits, requiring inefficient conversion:

$$\text{Algorithm} \rightarrow \text{Gates} \rightarrow \text{MBQC} \rightarrow \text{Hardware}$$

## 1.2 Contributions

We present QPL (Quantum Process Language), a programming language designed to compile *directly* to MBQC without gate decomposition:

$$\text{QPL Program} \rightarrow \text{MBQC Patterns} \rightarrow \text{Hardware}$$

Our key contributions are:

1. **Language Design:** A relations-first programming model where entanglement (`QuantumRelation`) and contextual measurement (`ask`) are primitives
2. **Operational Semantics:** Formal semantics for QPL grounded in quantum information theory
3. **MBQC Compilation:** A complete compilation pipeline from QPL relations to cluster states, measurement patterns, and adaptive corrections
4. **Implementation:** A working compiler with graph state extraction (285 lines), pattern generation for standard gates (342 lines), and adaptive Pauli corrections (280 lines)—totaling 2,555 lines of validated Python code
5. **Validation:** 47 comprehensive tests verifying quantum correlations, teleportation fidelity (1.0), and MBQC pattern correctness across all major quantum states (Bell, GHZ, W)

The remainder of this paper is organized as follows: Section 2 presents QPL’s language design; Section 3 formalizes its operational semantics; Section 4 describes the MBQC compilation strategy; Section 5 details our implementation and validation; Section 6 surveys related work; Section 7 outlines future research directions; and Section 8 concludes.

## 2 QPL Language Design

### 2.1 Design Principles

QPL is built on four core principles:

1. **Relations over Objects:** Entanglement is a first-class primitive, not derived from gates
2. **Questions over Measurements:** Measurement is asking a question with explicit basis and observer
3. **Processes over Gates:** Quantum programs are relations and interactions, not sequential transformations
4. **Physics over Abstraction:** Language semantics match quantum mechanics directly

### 2.2 Core Abstractions

QPL introduces four core abstractions that mirror the structure of quantum information theory:

**Definition 1** (Quantum Relation). A *QuantumRelation* represents an entangled quantum system as a tuple  $(\mathcal{S}, |\psi\rangle, S)$  where:

- $\mathcal{S} = \{s_1, s_2, \dots, s_n\}$  is a set of quantum system identifiers
- $|\psi\rangle \in \mathcal{H}^{\otimes n}$  is the joint quantum state (Hilbert space  $\mathcal{H}^{\otimes n}$ )
- $S \in [0, 1]$  is the entanglement entropy (von Neumann entropy of reduced density matrix)

**Definition 2** (Quantum Question). A *QuantumQuestion* represents a contextual measurement as a tuple  $(B, i, t)$  where:

- $B \in U(2)$  is the measurement basis (unitary matrix defining eigenbasis)
- $i \in \mathbb{N}$  is the target subsystem index
- $t \in \{SPIN\_Z, SPIN\_X, SPIN\_Y, CUSTOM\}$  is the question type

**Definition 3** (Perspective). A *Perspective* identifies an observer context from which measurements are performed. In QPL, perspectives are named identifiers (strings) with optional metadata capturing the observer's role in the quantum system.

**Definition 4** (QPL Program). A *QPLProgram* maintains program state as a tuple  $(Q, R, P, H)$  where:

- $Q$  is the set of quantum systems
- $R$  is the set of quantum relations
- $P$  is the set of observer perspectives
- $H$  is the operation history (audit trail)

## 2.3 Syntax and Examples

Listing 1: Creating a Bell state in QPL

```
1 from qpl import QPLProgram, create_question, QuestionType
2
3 # Initialize program
4 program = QPLProgram("Bell State Example")
5
6 # Create two quantum systems
7 alice = program.create_system()
8 bob = program.create_system()
9
10 # Entangle them (creates Bell pair)
11 bell_pair = program.entangle(alice, bob)
12
13 # Check entanglement
14 print(f"Entropy: {bell_pair.entanglement_entropy}") # 1.0
```

Listing 2: Same Bell state in Qiskit (gate-based)

```
1 from qiskit import QuantumCircuit
2
3 # Gate-based approach
4 qc = QuantumCircuit(2)
5 qc.h(0) # Hadamard gate on qubit 0
6 qc.cx(0, 1) # CNOT gate from 0 to 1
7 qc.measure_all()
```

The key difference: in Qiskit, you think in sequential gate operations (H, then CNOT). In QPL, you think in relational terms: “these two systems are entangled.” The Bell pair is the relation itself, not a consequence of gate application.

## 2.4 n-Qubit Entanglement: GHZ and W States

QPL naturally extends to arbitrary n-qubit systems:

Listing 3: Creating a 5-qubit GHZ state in QPL

```
1 # Create five quantum systems
2 qubits = [program.create_system() for _ in range(5)]
3
4 # Create GHZ state: ( $|00000\rangle + |11111\rangle$ )/sqrt(2)
5 ghz5 = program.entangle(*qubits)
6
7 print(f"State dimension: {ghz5.state.shape}") # (32,) = 2^5
8 print(f"Entanglement entropy: {ghz5.entanglement_entropy}") # 1.0
```

For different entanglement classes, QPL supports W states:

Listing 4: Creating a W state in QPL

```
1 # W state: ( $|100\rangle + |010\rangle + |001\rangle$ )/sqrt(3)
2 w3 = program.entangle(q0, q1, q2, state_type="w")
```

GHZ and W states represent fundamentally different entanglement structures. Under local operations and classical communication (LOCC), they belong to distinct equivalence classes [11], yet QPL expresses both naturally through the `entangle()` primitive.

## 2.5 Contextual Measurement as Questions

Measurement in QPL is explicit about basis and observer:

Listing 5: Contextual measurement in QPL

```

1 # Create Bell pair
2 bell = program.entangle(alice_sys, bob_sys)
3
4 # Alice measures in Z basis
5 question_z = create_question(QuestionType.SPIN_Z, subsystem=0)
6 result = program.ask(bell, question_z, perspective="alice")
7 # Result: 0 or 1
8
9 # Bob measures in X basis
10 question_x = create_question(QuestionType.SPIN_X, subsystem=1)
11 result = program.ask(bell, question_x, perspective="bob")
12 # Different physics: cross-basis measurement

```

This makes quantum contextuality [4]—the fact that measurement outcomes depend on the measurement basis—a first-class language feature rather than an implicit detail.

## 3 Operational Semantics

We formalize QPL’s operational semantics through three components: state representation, entanglement operations, and contextual measurement.

### 3.1 State Representation

Quantum states in QPL are represented as normalized vectors in the computational basis:

$$|\psi\rangle = \sum_{i=0}^{2^n-1} \alpha_i |i\rangle, \quad \sum_{i=0}^{2^n-1} |\alpha_i|^2 = 1 \quad (2)$$

For an  $n$ -qubit system,  $|\psi\rangle \in \mathbb{C}^{2^n}$  where basis states  $|i\rangle$  correspond to binary strings  $i \in \{0, 1\}^n$ .

**Example:** A Bell state  $|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$  is represented as:

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}[1, 0, 0, 1]^T \in \mathbb{C}^4 \quad (3)$$

**Example:** A GHZ state for  $n$  qubits  $|GHZ_n\rangle = \frac{1}{\sqrt{2}}(|0\rangle^{\otimes n} + |1\rangle^{\otimes n})$  has non-zero amplitudes only at indices 0 and  $2^n - 1$ :

$$|GHZ_n\rangle[0] = \frac{1}{\sqrt{2}}, \quad |GHZ_n\rangle[2^n - 1] = \frac{1}{\sqrt{2}}, \quad \text{all others} = 0 \quad (4)$$

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**Algorithm 1** Entangle Operation (GHZ)

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**Input:** Systems  $\{s_1, \dots, s_n\}$

**Output:** QuantumRelation  $R$

$|\psi\rangle \leftarrow$  zero vector of dimension  $2^n$

$|\psi\rangle[0] \leftarrow 1/\sqrt{2} \{|0\rangle^{\otimes n} \text{ amplitude}\}$

$|\psi\rangle[2^n - 1] \leftarrow 1/\sqrt{2} \{|1\rangle^{\otimes n} \text{ amplitude}\}$

$S \leftarrow \text{COMPUTEENTANGLEMENTENTROPY}(|\psi\rangle, \text{partition}=[1, n-1])$

**return** QuantumRelation( $\{s_1, \dots, s_n\}, |\psi\rangle, S$ )

---

### 3.2 Entanglement Semantics

The `entangle(*systems)` operation creates a quantum relation from  $n$  quantum systems. For GHZ-type entanglement:

For W-type entanglement, the state is an equal superposition of single-excitation basis states:

$$|W_n\rangle = \frac{1}{\sqrt{n}} \sum_{i=0}^{n-1} |0\rangle^{\otimes i} \otimes |1\rangle \otimes |0\rangle^{\otimes (n-1-i)} \quad (5)$$

### 3.3 Measurement Semantics

Measurement in QPL follows the Born rule with explicit basis transformation. Given a Quantum-Relation  $R = (\mathcal{S}, |\psi\rangle, S)$ , a question  $(B, i, t)$ , and perspective  $p$ , the `ask` operation:

**Basis transformation:** For a 2-qubit system measuring subsystem 0 in basis  $B$ :

$$|\psi'\rangle = (B^\dagger \otimes I) |\psi\rangle \quad (6)$$

For  $n$ -qubit systems, the basis transformation is embedded at the target subsystem index.

### 3.4 Entanglement Entropy Computation

Entanglement entropy quantifies the entanglement between subsystems. For a bipartition  $A|B$  with  $|A| = k$  qubits and  $|B| = n - k$  qubits:

For maximally entangled states (Bell states, GHZ states for 1— $n-1$  partition),  $S = 1$ . For separable states,  $S = 0$ .

## 4 Compilation to Measurement-Based Quantum Computing

We now describe QPL's compilation strategy to MBQC. The key insight is that QPL's `QuantumRelation` abstraction naturally maps to cluster states, enabling direct compilation without gate decomposition.

### 4.1 Cluster States and Graph States

A cluster state  $|G\rangle$  on graph  $G = (V, E)$  is defined as:

$$|G\rangle = \prod_{(i,j) \in E} CZ_{ij} |+\rangle^{\otimes n} \quad (7)$$

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**Algorithm 2** Ask Operation (Contextual Measurement)

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**Input:** Relation  $R$ , Question  $(B, i, t)$ , Perspective  $p$

**Output:** Measurement outcome  $m \in \{0, 1\}$

```
// Transform state to measurement basis
 $|\psi'\rangle \leftarrow \text{APPLYBASISTRANSFORM}(|\psi\rangle, B, \text{subsystem}=i)$ 

// Compute measurement probabilities
 $P(0) \leftarrow \sum_{j:j_i=0} |\psi'_j|^2$  {Sum over basis states with  $i$ -th qubit = 0}
 $P(1) \leftarrow \sum_{j:j_i=1} |\psi'_j|^2$  {Sum over basis states with  $i$ -th qubit = 1}

// Sample outcome
 $m \sim \text{Bernoulli}(P(1))$ 

// Collapse state
 $|\psi_{\text{new}}\rangle \leftarrow \text{COLLAPSESUBSYSTEM}(|\psi'\rangle, \text{subsystem}=i, \text{outcome}=m)$ 
 $|\psi_{\text{new}}\rangle \leftarrow |\psi_{\text{new}}\rangle / |||\psi_{\text{new}}\rangle||$  {Renormalize}

// Update relation (remove measured system)
 $R.\text{state} \leftarrow |\psi_{\text{new}}\rangle$ 
 $R.\text{systems} \leftarrow R.\text{systems} \setminus \{s_i\}$ 

return  $m$ 
```

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**Algorithm 3** Compute Entanglement Entropy

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**Input:** State  $|\psi\rangle \in \mathbb{C}^{2^n}$ , partition  $[k, n - k]$

**Output:** von Neumann entropy  $S$

```
// Reshape state to matrix form
 $M \leftarrow \text{RESHAPE}(|\psi\rangle, \text{shape}=(2^k, 2^{n-k}))$ 

// Schmidt decomposition via SVD
 $U, \Sigma, V^\dagger \leftarrow \text{SVD}(M)$ 

// Compute entropy from singular values
 $S \leftarrow 0$ 
for  $\lambda \in \Sigma$  do
  if  $\lambda > 10^{-10}$  then
     $p \leftarrow \lambda^2$ 
     $S \leftarrow S - p \log_2(p)$ 
  end if
end for
return  $S$ 
```

---

where  $|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$  is the Hadamard basis state and  $CZ_{ij}$  is the controlled-Z gate between vertices  $i$  and  $j$ .

Cluster states are the resource states for MBQC. Each vertex represents a qubit, and edges represent entanglement. The graph topology determines which measurements implement which logical operations.

**Example:** A 4-qubit linear cluster state:

$$G = (V = \{0, 1, 2, 3\}, E = \{(0, 1), (1, 2), (2, 3)\}) \quad (8)$$

$$|G\rangle = CZ_{23} \cdot CZ_{12} \cdot CZ_{01} |+\rangle^{\otimes 4} \quad (9)$$

This cluster can implement arbitrary single-qubit gates and two-qubit entangling gates via adaptive measurements.

## 4.2 Graph Extraction from QuantumRelation

Every QPL `QuantumRelation` corresponds to a graph state. The compilation strategy extracts this graph structure:

**For GHZ states:** An  $n$ -qubit GHZ state created by `entangle(q_0, ..., q_{n-1})` maps to a star graph:

$$G_{GHZ} = (V = \{0, \dots, n-1\}, E = \{(0, i) : i \in \{1, \dots, n-1\}\}) \quad (10)$$

One central qubit (index 0) connected to all others. This graph generates the GHZ state when qubits are prepared in  $|+\rangle$  and  $CZ$  gates applied along edges.

**For Bell states:** A Bell pair `entangle(q_0, q_1)` maps to a simple edge:

$$G_{Bell} = (V = \{0, 1\}, E = \{(0, 1)\}) \quad (11)$$

**Graph extraction algorithm:**

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**Algorithm 4** Extract Graph from QuantumRelation

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**Input:** QuantumRelation  $R = (\mathcal{S}, |\psi\rangle, S)$

**Output:** Graph  $G = (V, E)$

$V \leftarrow \mathcal{S} \text{ \{Vertices = quantum systems\}}$

**if**  $R$  is GHZ-type **then**

$E \leftarrow \{(s_0, s_i) : i \in \{1, \dots, |\mathcal{S}| - 1\}\} \text{ \{Star graph\}}$

**else if**  $R$  is W-type **then**

$E \leftarrow \{(s_i, s_{i+1}) : i \in \{0, \dots, |\mathcal{S}| - 2\}\} \text{ \{Linear chain\}}$

**else if**  $R$  is Bell-type **then**

$E \leftarrow \{(s_0, s_1)\} \text{ \{Single edge\}}$

**else**

$E \leftarrow \text{ANALYZEENTANGLEMENTSTRUCTURE}(|\psi\rangle) \text{ \{General case\}}$

**end if**

**return**  $G = (V, E)$

---

For arbitrary quantum states, graph extraction requires analyzing the stabilizer structure or performing entanglement witness tests to determine connectivity.



### 4.3 Measurement Pattern Generation

Once the graph  $G$  is extracted, QPL compiles `ask()` operations to MBQC measurement patterns.

A measurement pattern  $\mathcal{M}$  is a sequence of measurements:

$$\mathcal{M} = \{M_i(\theta_i, s_i, \alpha_i)\}_{i=1}^k \quad (12)$$

where for measurement  $i$ :

- $\theta_i$  is the measurement angle in the  $XY$ -plane
- $s_i$  is the set of qubits measured before  $i$  (signal shifting)
- $\alpha_i$  is the outcome-dependent angle correction

**Compilation rules:**

1. **Z-basis measurement:** `ask(R, SPIN_Z, subsystem=i)` compiles to:

$$M_i(\theta = 0, s = \emptyset, \alpha = 0) \quad (13)$$

Measuring in the  $|+\rangle / |-\rangle$  eigenbasis (equivalent to computational basis for cluster states).

2. **X-basis measurement:** `ask(R, SPIN_X, subsystem=i)` compiles to:

$$M_i(\theta = \pi/2, s = \emptyset, \alpha = 0) \quad (14)$$

Measuring in the  $|0\rangle / |1\rangle$  eigenbasis.

3. **Adaptive measurement:** If measurement  $M_j$  depends on outcome of  $M_i$ :

$$M_j(\theta_j, s = \{i\}, \alpha_j = (-1)^{m_i} \pi) \quad (15)$$

where  $m_i \in \{0, 1\}$  is the outcome of measurement  $i$ .

**Example: Compiling QPL Bell state measurement to MBQC**

Listing 6: QPL Bell measurement program

```

1 bell = program.entangle(q0, q1)
2 result_z = program.ask(bell, create_question(SPIN_Z, subsystem=0), "alice"
  )
3 result_x = program.ask(bell, create_question(SPIN_X, subsystem=1), "bob")

```

**Compiled MBQC pattern:**

$$G = (\{0, 1\}, \{(0, 1)\}) \quad (\text{Bell graph}) \quad (16)$$

$$\mathcal{M} = \{M_0(\theta = 0), M_1(\theta = \pi/2)\} \quad (17)$$

Measurement pattern: Measure qubit 0 in Z, then qubit 1 in X.

**Pauli corrections:** In general MBQC, measurement outcomes  $m_i \in \{0, 1\}$  determine Pauli corrections applied to subsequent qubits. QPL tracks these corrections in the `QuantumRelation.history` field, enabling automatic Pauli frame tracking during compilation.

## 5 Implementation and Validation

We have implemented QPL in Python with a focus on correctness and extensibility. The implementation progressed through four stages: Stage 0 (2-qubit foundations), Stage 1 (n-qubit generalization), Stage 2 (graph extraction), and Stage 3 (MBQC pattern generation and adaptive corrections).

## 5.1 Stage 0: Two-Qubit Foundations

Stage 0 established the core abstractions and verified physics correctness for 2-qubit systems.

### Implementation:

- **Core module** (`src/qp1/core.py`, 418 lines): Implements `QPLProgram`, `QuantumRelation`, `QuantumQuestion`, and `Perspective` classes
- **Measurement module** (`src/qp1/measurement.py`, 312 lines): Implements basis transformations, Born rule sampling, and state collapse
- **Test suite** (14 tests): Validates Bell correlations, cross-basis measurements, entanglement entropy, and state collapse

### Key capabilities:

- Bell state creation via `entangle(s0, s1)`
- Partial measurement (measure one qubit, preserve partner's state)
- Arbitrary single-qubit measurement bases (Z, X, Y, custom)
- Automatic entanglement entropy computation via Schmidt decomposition
- Perspective tracking for observer-dependent measurements

Stage 0 validated that relations-first abstractions match quantum mechanics: all 14 tests passed with 100% physics correctness on deterministic tests and statistical correctness (< 2% deviation) on stochastic tests.

## 5.2 Stage 1: n-Qubit Quantum Relations

Stage 1 generalized all operations to arbitrary n-qubit systems, enabling real multi-qubit quantum algorithms.

### New implementation:

- **Tensor utilities** (`src/qp1/tensor_utils.py`, 388 lines): Implements tensor products, partial trace, general Schmidt decomposition, and n-qubit state creation
- **Extended core**: Generalized `entangle()` to accept arbitrary numbers of systems, with `state_type` parameter for GHZ vs. W states
- **Extended measurement**: Adapted basis transformations and state collapse to n-qubit systems via tensor product embedding
- **Expanded test suite** (7 new tests): Validates GHZ states up to 5 qubits, W states, partial n-qubit measurements, and backward compatibility

### Key functions:

- `create_ghz_state(n)`: Generates  $|GHZ_n\rangle = \frac{1}{\sqrt{2}}(|0\rangle^{\otimes n} + |1\rangle^{\otimes n})$
- `create_w_state(n)`: Generates W states (different entanglement class)
- `partial_trace(state, keep_qubits)`: Traces out subsystems for reduced density matrices

- `compute_entanglement_entropy(state, partition)`: Entropy for arbitrary bipartitions
- `embed_operator_at_positions()`: Apply gates to specific qubits in n-qubit systems

Stage 1 extended the paradigm to genuine multipartite entanglement while maintaining backward compatibility: all Stage 0 code runs unchanged in Stage 1.

### 5.3 Stage 2: Graph State Extraction

Stage 2 implements the MBQC compilation pipeline’s first component: automatic extraction of cluster state graphs from `QuantumRelation` objects.

**Implementation:**

- **Graph extraction module** (`src/qp1/mbqc/graph_extraction.py`, 285 lines): Implements `extract_graph()` function and topology analysis
- **Test suite** (10 tests): Validates graph extraction for Bell, GHZ, W states, and arbitrary entangled systems

**Key capabilities:**

- **Automatic topology detection**: Analyzes `QuantumRelation` to determine cluster state structure
- **Bell states**  $\rightarrow$  2-node edge graph
- **GHZ states**  $\rightarrow$  star graph (central node connected to  $n - 1$  peripheral nodes)
- **W states**  $\rightarrow$  ring topology
- Returns NetworkX graph objects with qubit indices as nodes and CZ entanglement as edges

The graph extraction validates the core QPL thesis: relations naturally encode graph state structure without explicit graph programming.

### 5.4 Stage 3: Pattern Generation and Adaptive Corrections

Stage 3 completes the MBQC compiler with measurement pattern generation and adaptive Pauli corrections.

**Implementation:**

- **Pattern generation** (`src/qp1/mbqc/pattern_generation.py`, 342 lines): Generates MBQC patterns for standard quantum gates
- **Adaptive corrections** (`src/qp1/mbqc/adaptive_corrections.py`, 280 lines): Implements Pauli frame tracking and teleportation
- **Test suite** (16 tests): Validates pattern correctness, correction computation, and teleportation fidelity

**Supported gates and operations:**

- Single-qubit gates: H, X, Y, Z, S, T
- Rotation gates:  $R_x(\theta)$ ,  $R_y(\theta)$ ,  $R_z(\theta)$

- Two-qubit gates: CNOT, CZ
- State preparation: Bell, GHZ, cluster states
- Quantum teleportation with full adaptive correction protocol

**Teleportation validation:** We implemented complete quantum teleportation including:

1. Bell pair preparation between sender and receiver
2. Bell measurement at sender (projecting onto Bell basis)
3. Classical communication of 2-bit measurement outcome
4. Adaptive Pauli corrections (I, X, Z, XZ) at receiver based on outcome

Testing on six quantum states ( $|0\rangle$ ,  $|1\rangle$ ,  $|+\rangle$ ,  $|-\rangle$ ,  $|i\rangle$ , arbitrary superposition) achieved teleportation fidelity  $F = |\langle\psi_{in}|\psi_{out}\rangle|^2 = 1.000$  in all cases, confirming perfect state transfer with correct adaptive corrections.

## 5.5 Validation Results

We validated QPL through comprehensive physics tests across all four stages. Table 1 shows results for key quantum correlations and MBQC operations.

Test	Stage	Expected	QPL Result
Bell Z-Z correlation	0	100%	100.0%
Bell Z-X correlation	0	$\sim 50\%$	48.6%
GHZ entanglement entropy	1	1.0	1.000
X-basis eigenstate measurement	0	100%	100.0%
3-qubit GHZ same-basis correlation	1	100%	99.8%
5-qubit GHZ entanglement entropy	1	1.0	1.000
W-state creation (3 qubits)	1	Success	Success
Graph extraction (Bell state)	2	2 nodes, 1 edge	Correct
Graph extraction (GHZ state)	2	Star topology	Correct
MBQC pattern generation (H gate)	3	Valid pattern	Correct
Teleportation $ 0\rangle$	3	$F = 1.0$	1.000
Teleportation $ +\rangle$	3	$F = 1.0$	1.000
Teleportation superposition	3	$F = 1.0$	1.000
Adaptive X correction	3	$ 0\rangle \rightarrow  1\rangle$	Correct
Adaptive Z correction	3	$ +\rangle \rightarrow  -\rangle$	Correct

Table 1: Validation results showing physics correctness across all four stages (47 total tests)

**Test coverage:** The complete test suite comprises 47 tests:

- Stage 0: 14 tests (2-qubit foundations)
- Stage 1: 7 tests (n-qubit generalization)
- Stage 2: 10 tests (graph extraction)
- Stage 3: 16 tests (patterns and corrections)

**Statistical tests:** For stochastic measurements (e.g., cross-basis correlations), we ran 1000 trials and verified results fall within  $2\sigma$  of expected values.

**Availability:** QPL is open source and available at <https://github.com/dcoldeira/quantum-process-lang>. The implementation requires Python 3.8+ and NumPy. Installation via `pip install -e .` provides the `qpl` package with complete MBQC compilation (2,555 lines of code, 47 tests, all passing).

## 6 Related Work

We position QPL relative to existing quantum programming languages across four categories.

### 6.1 Gate-Based Quantum Languages

**Qiskit** [14], **Cirq** [3], and **Q#** [20] are the dominant quantum programming frameworks. All three compile to gate-based circuits:

- **Qiskit** (IBM): Python library for circuit construction, transpilation to IBM hardware, and simulation. Supports pulse-level control but fundamentally gate-centric.
- **Cirq** (Google): Similar to Qiskit but optimized for Google’s superconducting qubits. Focus on near-term NISQ algorithms.
- **Q#** (Microsoft): Domain-specific language with functional programming features and integrated simulator. Supports quantum error correction but still gate-based.

**Comparison to QPL:** These languages excel at gate-level quantum programming but require explicit gate decomposition. For MBQC hardware (photonic, surface codes), they must compile gates to measurement patterns—a two-step process. QPL targets MBQC directly, skipping gate decomposition.

**Silq** [1] is a high-level quantum language with automatic uncomputation and type-safe qubit management. While more abstract than Qiskit/Cirq, it still compiles to gates. QPL’s relations-first paradigm is orthogonal: we express entanglement directly rather than high-level gate patterns.

### 6.2 Formal Quantum Programming Languages

**QWIRE** [12, 16] provides formal semantics for quantum circuits with categorical foundations. QWIRE models quantum programs as morphisms in a symmetric monoidal category, enabling formal verification in Coq. This work inspired QPL’s use of categorical semantics (future work), but QWIRE remains gate-based.

**Quipper** [8] is a scalable quantum programming language embedded in Haskell, designed for large quantum algorithms. Like QWIRE, it’s gate-based but with strong type safety and circuit optimization.

**Comparison to QPL:** Both QWIRE and Quipper prioritize formal correctness, as does QPL. However, their gate-based foundations differ from QPL’s relations-first model. We envision QPL developing similar categorical semantics but for MBQC patterns rather than gates.

### 6.3 Photonic and MBQC Frameworks

**Strawberry Fields** [9] (Xanadu) is a photonic quantum computing framework. It supports both discrete-variable (qubit) and continuous-variable (qumode) quantum computing. While Strawberry

Fields can express MBQC, it’s designed around gates and measurements as separate operations rather than MBQC as the primary paradigm.

**Perceval** [15] (Quandela) is another photonic framework focusing on linear optical circuits. Like Strawberry Fields, it’s hardware-focused but gate-centric in abstraction.

**PennyLane** [13] (Xanadu’s quantum machine learning library) includes educational demonstrations of MBQC concepts, showing how to construct cluster states and implement adaptive measurement patterns. However, these tutorials construct cluster states via explicit Hadamard and CZ gate sequences, maintaining a gate-centric programming model. While valuable for teaching MBQC theory, this approach still requires users to think in gates when targeting MBQC-native hardware.

**Comparison to QPL:** Strawberry Fields and Perceval target the same hardware (MBQC-native photonic systems) as QPL, but approach programming from gates. QPL’s Stage 2 goal is to compile directly to Strawberry Fields’ MBQC backend, providing a higher-level relations-first interface that eliminates gate decomposition as an intermediate step.

## 6.4 Graphical Quantum Languages

**ZX-calculus** [4] represents quantum circuits as string diagrams with graphical rewrite rules. ZX-calculus is powerful for circuit optimization and proving equivalences. It’s closely related to MBQC: measurement patterns can be represented as ZX diagrams.

**PyZX** [10] implements ZX-calculus in Python with automatic circuit optimization and MBQC compilation.

**Comparison to QPL:** ZX-calculus is graphical; QPL is textual but with graph-state semantics. We view ZX-calculus and QPL as complementary: ZX for reasoning about entanglement structure, QPL for programming with it. Future work could integrate PyZX for QPL circuit optimization.

## 6.5 Positioning QPL

Language	Paradigm	MBQC Support	Entanglement Primitive
Qiskit	Gates	Via transpiler	No
Cirq	Gates	Via transpiler	No
Q#	Gates	No	No
QWIRE	Gates (categorical)	No	No
Strawberry Fields	Gates + MBQC	Yes (backend)	No
ZX-calculus	Graphical	Yes (native)	Yes (implicit)
<b>QPL</b>	<b>Relations</b>	<b>Yes (native)</b>	<b>Yes (explicit)</b>

Table 2: Comparison of QPL with existing quantum languages

QPL is the first textual quantum programming language where entanglement is a first-class primitive and MBQC is the primary compilation target. This positions it uniquely for photonic and fault-tolerant quantum hardware.

## 7 Future Work

QPL’s implementation (Stages 0-3) provides a complete MBQC compiler. Future work spans four research directions:

## 7.1 Tensor Networks for Efficient Simulation

The current implementation uses full state vectors ( $2^n$  amplitudes for  $n$  qubits), limiting simulation to 20-25 qubits. Tensor network representations can extend this:

**Matrix Product States (MPS):** For 1D cluster states (linear chains), MPS representation scales polynomially rather than exponentially. An MPS with bond dimension  $\chi$  requires  $O(n\chi^2)$  storage vs.  $O(2^n)$  for full state vectors.

**Projected Entangled Pair States (PEPS):** For 2D cluster states (surface codes), PEPS provides efficient representation of locally entangled systems.

**Research questions:**

- Can QPL’s `QuantumRelation` abstraction be efficiently implemented using MPS/PEPS?
- Do relations-first programs naturally produce sparse entanglement amenable to tensor network optimization?
- Can we achieve simulation of 50+ qubit MBQC programs?

**Target:** Integration with Google’s TensorNetwork library or QuTiP’s tensor network module.

## 7.2 Photonic Backend

Photonic quantum computers (PsiQuantum, Xanadu) are MBQC-native. QPL should compile to photonic hardware:

**Strawberry Fields integration:** Compile QPL programs to Strawberry Fields MBQC backend. QPL’s `QuantumRelation` graphs map to photonic cluster states; `ask()` operations map to photodetection.

**Continuous-variable extension:** Extend QPL to continuous-variable (CV) quantum computing using Gaussian states and homodyne measurements.

**Research questions:**

- Can QPL provide higher-level abstractions for photonic MBQC than current gate-based frameworks?
- Do relations-first programs compile to more efficient photonic circuits?

**Target:** Run QPL programs on Xanadu’s photonic quantum computers via Strawberry Fields.

## 7.3 Quantum Type System

QPL currently lacks compile-time enforcement of quantum constraints:

**Linear types:** Qubits cannot be cloned (no-cloning theorem). A linear type system ensures each quantum system is used exactly once, catching violations at compile time.

**Entanglement-aware types:** Type system tracking which systems are entangled. `TypeEntangled[A, B]` indicates systems  $A$  and  $B$  share entanglement.

**Process types:** Programs as typed processes: `Process[Input, Output]`, enabling compositional program construction.

**Research questions:**

- Can we develop a sound and complete type system for MBQC programs?
- How do types interact with adaptive measurements (measurement outcomes determine future operations)?

**Target:** Categorical quantum mechanics foundations (following QWIRE’s approach but for MBQC).

## 7.4 Fault-Tolerant Compilation

Surface codes implement fault-tolerant quantum computing via MBQC. QPL could compile to fault-tolerant MBQC:

**Surface code mapping:** Compile QPL relations to surface code stabilizer measurements. Logical gates implemented as measurement patterns on 2D qubit lattices.

**Topological error correction:** Integrate with Stim [7] (surface code simulator) and PyMatching [6] (decoder) for fault-tolerant simulation.

**Research questions:**

- Can QPL abstract fault-tolerance, letting programmers write logical-level code that compiles to surface codes?
- Do relations-first abstractions simplify reasoning about topological quantum codes?

**Target:** High-level fault-tolerant quantum programming without manual error correction code construction.

## 8 Conclusion

We have presented QPL, a relations-first quantum programming language that compiles directly to measurement-based quantum computing without gate decomposition. Our key insight is that entanglement and measurement—the primitives of MBQC—can serve as the foundation of a quantum programming language, providing a more direct path to photonic and fault-tolerant quantum hardware.

**Contributions:**

1. **Language design:** We introduced `QuantumRelation` and `ask()` as first-class abstractions, making entanglement and contextual measurement explicit primitives rather than derived concepts.
2. **Operational semantics:** We formalized QPL’s semantics through state representation, entanglement operations, and contextual measurement, grounded in quantum information theory.
3. **MBQC compilation:** We demonstrated that QPL relations naturally map to cluster states and measurement patterns, enabling direct compilation to MBQC without gate decomposition.
4. **Implementation:** We implemented and validated a complete MBQC compiler through four stages: 2-qubit foundations (Stage 0), n-qubit generalization (Stage 1), graph extraction (Stage 2), and pattern generation with adaptive corrections (Stage 3)—totaling 2,555 lines of code and 47 tests with 100% physics correctness including teleportation fidelity of 1.0.
5. **Research directions:** We outlined future work on tensor networks for scalable simulation, photonic backend integration, quantum type systems, and fault-tolerant compilation.



### Why this matters:

Gate-based quantum computing is not how quantum mechanics fundamentally operates, nor is it how emerging quantum hardware (photonic systems, surface codes) natively computes. MBQC is both more fundamental (measurement is asking questions of entangled systems) and more practical (photonic quantum computers operate via MBQC) than gates.

QPL demonstrates that relations-first programming is viable: entanglement and measurement can be primitives, not derived operations. This opens new possibilities for quantum algorithm design, hardware compilation, and formal verification.

### Open questions:

- Can tensor networks enable simulation of 100+ qubit QPL programs?
- Do relations-first programs compile to more efficient MBQC patterns than gate-based programs?
- Can type systems enforce quantum constraints (no-cloning, entanglement tracking) at compile time?
- Will QPL simplify fault-tolerant quantum programming by abstracting surface codes?

We do not yet know all the answers. But QPL Stages 0-3 prove the direction is viable: a complete working compiler from relations to MBQC patterns demonstrates that this paradigm can be implemented and validated.

**Collaboration:** QPL is open source (<https://github.com/dcoldeira/quantum-process-language>). We welcome collaboration from researchers in quantum programming languages, MBQC theory, photonic quantum computing, and categorical quantum mechanics. This work represents the foundation of a research program extending through PhD-level investigation.

**The path forward:** Gates are a constraint we inherited from classical computing. Measurement-based quantum computing reveals a different paradigm: computation as asking questions of entangled systems. QPL programs this paradigm directly.

Relations first. Measurements as questions. MBQC as the compilation target.

Let's see how far this goes.

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