

Towards a Non-linear Quantum Lambda Calculus

RIKIYA KASHIWAGI and ATSUSHI IGARASHI, Kyoto University, Japan

This paper presents a quantum extension of lambda calculus without linearity, reinterpreting contraction and weakening as logical operations on references to quantum states, rather than on the states themselves. We formally define the calculus with its operational semantics and conjecture that β -equal classical terms are contextually equivalent. This design enables the seamless integration of classical and quantum programming.

1 Introduction

The theoretical foundations of quantum programming languages have largely been built upon linear logic and its variants[1, 7, 8, 11, 12], reflecting the *No-Cloning* Theorem[14] and the *No-Deleting* Theorem[5] of quantum mechanics. Within this paradigm, variables representing quantum states are treated as linear resources that can be neither duplicated (contracted) nor discarded (weakened). While this linearity ensures the physical correctness, it creates a significant gap with the intuitions of classical, non-linear programming.

This paper proposes a quantum language designed as a direct extension of the ordinary, non-linear lambda calculus. Our central design principle is to ensure that ordinary equational reasoning of the (call-by-value) lambda calculus is sound in this extension; specifically, β -equivalent terms remain operationally indistinguishable in the quantum extension. This approach ensures any embedded classical program executes with its standard semantics, enabling seamless integration of classical and quantum programs.

A key consequence of enforcing this principle is that the quantum features of the language are cleanly isolated from the classical host. This quantum-native fragment, consisting of a set of unitary operations, forms a distinct module for expressing quantum control. This separation provides a natural framework that enables coexistence of the historically separate paradigms of ‘*Quantum Data, Classical Control*’[10] and ‘*Quantum Data, Quantum Control*’[4]. That means a programmer can compose the main logic in a higher-order classical style, while delegating complex quantum subroutines to specialized, domain-specific modules. The resulting language provides a familiar framework for classical programmers and, at the same time, introduces a structured and powerful abstraction for high-level quantum-classical programming.

2 Main idea

To build a quantum language on a non-linear foundation, a reinterpretation of the structural rules—contraction and weakening—is essential. In conventional linear type systems, contraction is viewed as data duplication and weakening as data deletion. This interpretation conflicts with the No-Cloning and No-Deleting theorems when the data is a quantum state.

Our approach reinterprets these rules using *reference-based semantics*. Contraction is not the physical copying of a quantum state, but merely the duplication of a reference to it. Similarly, weakening is simply the act of dropping a reference. As these are purely logical operations on references, they do not violate any physical laws. The physical instantiation of a quantum state occurs only when a unitary operator is applied to one of its duplicated references. Specifically, if the state is expressed as $\sum_i \alpha_i |i\rangle$, where $\{|i\rangle\}$ is a basis set, and a unitary U is applied, the operation transforms the state into the entangled state $\sum_i \alpha_i |i\rangle (U |i\rangle)$. This is similar to the ‘*Contraction as sharing*’ concept like in [1, 2], but it occurs not at the contraction step, but right before the application of a unitary.

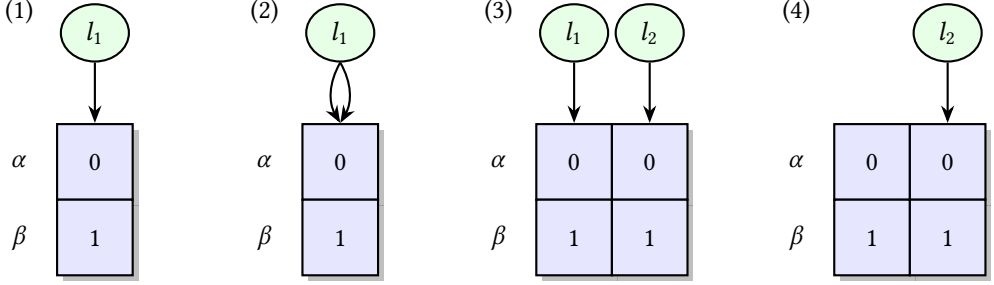


Fig. 1. Illustration of the internal states when $\pi_1 \circ \delta_I$ is applied to a qubit. The grids correspond to quantum states. The rows represent composite systems, and the columns represent superposition with the scalars on the left. From left to right: (1) l_1 refers to some qubit state. (2) Contraction duplicates a reference, not a state. (3) Applying an identity unitary to one of the duplicated references creates a distinct physical instance. (4) Weakening drops a reference.

This design has profound consequences for the language's equational theory. Consider a copy function $\delta \equiv \lambda x. \langle x, x \rangle$ and a projection $\pi_1 \equiv \lambda \langle x, y \rangle. x$. In our system, the equality $\pi_1 \circ \delta = \lambda x. x$ holds. This is because weakening (via π_1) is a logical dereference, not a physical act. In contrast, this identity fails in languages like QML[1] or Qunity[13], where weakening is interpreted as a partial trace. In those systems, the composition $\pi_1 \circ \delta$ induces decoherence, mapping a pure state to a mixed one.

However, this equational property is carefully constrained. If we define a copy function with inserting an identity unitary, $\delta_I \equiv \lambda x. \langle I x, x \rangle$, then $\pi_1 \circ \delta_I \neq \lambda x. x$. The application of the unitary I makes $I x$ a distinct physical instance from x ; for example, the input state $\alpha |0\rangle + \beta |1\rangle$ becomes the entangled state $\alpha |00\rangle + \beta |11\rangle$. The evaluation procedure for this case is illustrated in Fig. 1. We can only hope that the equational theory is sound with respect to operational equivalence for the classical fragment without unitaries like I .

3 The $\Lambda(\mathcal{U})$ calculus

3.1 Syntax

As outlined in the introduction, our language is designed as a direct extension of a non-linear lambda calculus denoted by Λ . Λ includes lambda terms, the unit and introductions and eliminations of products and sums. The key to our design is the isolation of quantum features from Λ , which is provided by a set \mathcal{U} of external unitary operations.

Definition 3.1 (The surface language $\Lambda(\mathcal{U})$). Given a set of terms \mathcal{U} , the language $\Lambda(\mathcal{U})$ is the set of terms defined by the following syntax:

$$M, N, P ::= * \mid x \mid \lambda x. M \mid M N \mid \langle M, N \rangle \mid \text{inj}_0 M \mid \text{inj}_1 M \mid \\ \text{let } \langle x, y \rangle = M \text{ in } N \mid \text{match } M [x \Rightarrow N \mid y \Rightarrow P] \mid \hat{U}$$

where $\hat{U} \in \mathcal{U}$.

From the perspective of the host language $\Lambda(\cdot)$, \hat{U} is treated as an opaque, first-class value. The language \mathcal{U} can represent any unitary transformation, ranging from a simple unitary gate to a complex subroutine that could be described by a domain-specific language, such as one based on the 'Quantum Data, Quantum Control' paradigm.

Example 3.2. The classical bit can be represented as $i \equiv \text{inj}_i *$ where $i = 0, 1$. A standard conditional expression if M then N else P can be written as a syntactic sugar for $\text{match } M [x \Rightarrow$

$N \mid y \Rightarrow P]$, where x and y are fresh variables. Using these notations, the logical NOT is $\text{not} \equiv \lambda x. \text{if } x \text{ then } 1 \text{ else } 0$, and the logical AND is $\text{and} \equiv \lambda x. \lambda y. \text{if } x \text{ then } y \text{ else } 0$.

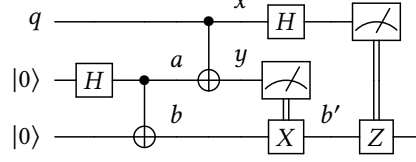
The quantum aspect of the language is captured by the \hat{U} term. Match expressions need special attention in this context. It behaves as usual only when the outermost of the scrutinee is evaluated to inl or inr . When it is evaluated to superposition of inl and inr , it performs a measurement to project one of them before that.

Example 3.3 (Quantum teleportation). Let \mathcal{U} be $\{H, \text{CNOT}, Z, X\}$ as the standard quantum gate set. The following program implements the quantum teleportation circuit on the right:

```

let ⟨a, b⟩ = CNOT ⟨H 0, 0⟩ in
let ⟨x, y⟩ = CNOT ⟨q, a⟩ in
let b' = if y then X b else b in
if H x then Z b' else b'

```



where $\text{let } x = M \text{ in } N$ is a syntactic sugar for $(\lambda x. N) M$.

It should be noted that the not function in Example 3.2 does not behave as the X gate (or the quantum NOT gate) when applied to a qubit, because the input is measured in the condition of the if expression, which collapses any superposition.

As a powerful example of this encapsulation of \mathcal{U} , a syntax inspired by pattern isomorphism[8] allows for the direct declaration of unitary operations as follows. Let \mathcal{U} be defined using the pattern isomorphism syntax. For instance, an X gate can be defined as $X \equiv \{0 \leftrightarrow 1 \mid 1 \leftrightarrow 0\}$.

3.2 Mathematical preliminaries for operational semantics

Our operational semantics relies on two key mathematical structures: ℓ^2 space to represent quantum states, and *finite distributions* to model probabilistic reduction.

Definition 3.4 (ℓ^2 space). Given a countable set X , the ℓ^2 space is defined as the set:

$$\ell^2(X) := \left\{ \psi : X \rightarrow \mathbb{C} \mid \|\psi\| := \sum_{x \in X} |\psi(x)|^2 < \infty \right\},$$

and inner product $\langle \psi, \phi \rangle = \sum_{x \in X} \overline{\psi(x)} \phi(x)$. It is known that $(\ell^2(X), \langle \cdot, \cdot \rangle)$ forms a Hilbert space.

Definition 3.5 (Finite distributions). The set of finite distributions over X is defined as:

$$\mathcal{D}(X) := \left\{ \mu : X \rightarrow [0, 1] \mid |\mu| := \sum_{x \in X} \mu(x) = 1, |\text{supp}(\mu)| < \infty \right\}.$$

Any element of $\ell^2(X)$ and $\mathcal{D}(X)$ can be written as linear combinations: $\psi = \sum_{x \in X} \psi(x) \delta_x$ and $\mu = \sum_{x \in X} \mu(x) \delta_x$ respectively, where δ_x is defined by $\delta_x(y) = 1$ if $y = x$ and 0 otherwise.

Next, we utilize two linear map constructions for ℓ^2 . The first is the functorial action of ℓ^2 , which lifts any function $f : X \rightarrow Y$ to a linear map $\ell^2(f) : \ell^2(X) \rightarrow \ell^2(Y)$ defined by $\ell^2(f)(\delta_x) := \delta_{f(x)}$. The second one extends a function $k : X \rightarrow \ell^2(Y)$ to a linear map $k^\sharp : \ell^2(X) \rightarrow \ell^2(Y)$ via linear extension: $k^\sharp(\sum_{x \in X} \alpha_x \delta_x) := \sum_{x \in X} \alpha_x k(x)$ only if the resulting sum converges for any input.

3.3 Operational semantics

This section defines the operational semantics, describing how the reference-based semantics from Section 2 is formalized. The state of a computation is captured by a *configuration*: a pair of a global store and the term being evaluated. Crucially, the store holds the physical quantum state, while the term operates only on locations (\mathcal{L})—references to that store. This separation allows contraction and weakening to be treated as logical operations on references, without directly affecting the

physical quantum state. Because a term is rewritten to contain these locations during execution, we must first define a distinct runtime language that extends the surface syntax with them.

Definition 3.6 (The runtime language $\Lambda_{\mathcal{L}}(\mathcal{U})$). Given a set of store locations \mathcal{L} , the runtime language is defined as $\Lambda_{\mathcal{L}}(\mathcal{U}) := \Lambda(\mathcal{U} \cup \mathcal{L})$. To simplify notation, M, N, P will also range over runtime terms. We will explicitly refer to surface terms when the distinction is significant.

Only first-order, or *basis values*, can be placed in the store and exist in a superposition. Values and basis values are given by the following syntax.

$$\begin{array}{ll} \text{Values} & V, W ::= l \mid * \mid \lambda x.M \mid \langle V, W \rangle \mid \text{inj}_0 V \mid \text{inj}_1 V \mid \hat{U} \\ \text{Basis values} & \hat{V}, \hat{W} ::= * \mid \langle \hat{V}, \hat{W} \rangle \mid \text{inj}_0 \hat{V} \mid \text{inj}_1 \hat{V} \end{array}$$

The set of all basis values is denoted by \mathcal{V}_0 .

A configuration $[\sigma, M]$ represents the state of a computation. The quantum store σ is a vector in a free Hilbert space over value stores (finite maps from locations \mathcal{L} to basis values \mathcal{V}_0), while M is the runtime term containing references to σ . Each value store in the support of σ must have the same domain; we can define $\text{dom}(\sigma)$ without ambiguity. Write C for the set of all configurations.

The operational semantics are defined by a call-by-value, small-step reduction relation (\longrightarrow). The key rules in Fig. 2 directly correspond to the four postulates of quantum mechanics[6].

State preparation (Q-PREP) It prepares a quantum state by taking a classical basis value \hat{V} and placing it into the store at a new location l .

Unitary Evolution (Q-EVOLVE) Applying a unitary \hat{U} to a reference l_1 transforms the entire quantum store σ according to the operator's interpretation. The location l_1 stays in the store, which reflects the 'Contraction as sharing' mechanism as illustrated in Fig. 1.

Measurement (Q-MEAS) The match expression performs a measurement on a referenced state, causing the computation to branch probabilistically and collapsing the quantum store.

Composite system (Q-DESTR) It destructs a pair stored at l_1 and creates new, distinct references l_2, l_3 to its components. It copies values at each value store, not meaning that the superpositions themselves are cloned.

This semantics imposes a meta-level constraint on \hat{U} . Specifically, the *interpretation* $\llbracket \hat{U} \rrbracket_{\mathcal{U}} : \mathcal{V}_0 \rightarrow \ell^2(\mathcal{V}_0)$ must satisfy the following condition: if $U = \llbracket \hat{U} \rrbracket_{\mathcal{U}}$, then $(U|_{\text{dom}(U)})^\#$ is unitary.

Definition 3.7 (Small-step reduction). Given a set of partial functions $\llbracket \hat{U} \rrbracket_{\mathcal{U}}$ for $\hat{U} \in \mathcal{U}$, the reduction relation $\longrightarrow \subseteq C \times \mathcal{D}(C)$ is the smallest relation closed under the classical rules (Appendix A.1) and the quantum rules (Fig. 2). The relation is then extended to all evaluation contexts E via the standard congruence rule: if $[\sigma, M] \longrightarrow \mu$, then $[\sigma, E[M]] \longrightarrow \sum_{[\sigma', M'] \in \text{supp}(\mu)} \mu([\sigma', M']) \delta_{[\sigma', E[M']]}$. The definition of evaluation contexts is given in Appendix A.1.

A key property to the physical realizability of the semantics is norm preservation, which guarantees that the norm of the quantum state does not change during reduction.

Theorem 3.8 (Norm preservation). *If $[\sigma, M] \longrightarrow \mu$, then for all $[\sigma', M'] \in \text{supp}(\mu)$, $\|\sigma'\| = \|\sigma\|$.*

Since a single reduction step can yield a distribution of configurations, the *multi-step reduction* (\longrightarrow^*) is not a simple reflexive and transitive closure. Instead, it is defined inductively to compose these probabilistic outcomes, akin to a monadic bind.

Definition 3.9 (Multi-step reduction). The multi-step reduction relation $\longrightarrow^* \subseteq C \times \mathcal{D}(C)$ is the smallest relation satisfying:

- $[\sigma, M] \longrightarrow^* \delta_{[\sigma, M]}$ for all $[\sigma, M] \in C$.

$$\begin{array}{c}
\text{197} \quad \frac{f(\rho) = \rho \cup \{(l_2, \hat{V}), (l_3, \hat{W})\} \text{ where } \rho(l_1) = \langle \hat{V}, \hat{W} \rangle \quad l_2, l_3 \notin \text{dom}(\sigma)}{\text{200} \quad [\sigma, \text{let } \langle x, y \rangle = l_1 \text{ in } M] \longrightarrow \delta_{[\ell^2(f)(\sigma), M[l_2/x, l_3/y]]}} \text{ Q-DESTR} \\
\text{201} \quad \frac{\begin{array}{l} |\alpha_0|^2 + |\alpha_1|^2 = 1 \quad \|\sigma_0\| = \|\sigma_1\| \quad f_0(\rho) = \rho \cup \{(l_2, \hat{V})\} \text{ where } \rho(l_1) = \text{inj}_0 \hat{V} \\ \text{202} \quad f_1(\rho) = \rho \cup \{(l_3, \hat{W})\} \text{ where } \rho(l_1) = \text{inj}_1 \hat{W} \quad l_2 \notin \text{dom}(\sigma_0) \quad l_3 \notin \text{dom}(\sigma_1) \end{array}}{\text{203} \quad \begin{array}{l} [\alpha_0 \sigma_0 + \alpha_1 \sigma_1, \text{match } l_1 [y \Rightarrow M \mid z \Rightarrow N]] \\ \text{204} \quad \longrightarrow |\alpha_0|^2 \delta_{[\ell^2(f_0)(\sigma_0), M[l_2/y]]} + |\alpha_1|^2 \delta_{[\ell^2(f_1)(\sigma_1), N[l_3/z]]} \end{array}} \text{ Q-MEAS} \\
\text{205} \quad \frac{\begin{array}{l} f(\rho) = \rho \cup \{(l, \hat{V})\} \\ \text{206} \quad l \notin \text{dom}(\sigma) \end{array}}{\text{207} \quad [\sigma, \hat{U} \hat{V}] \longrightarrow \delta_{[\ell^2(f)(\sigma), \hat{U} l]}} \text{ Q-PREP} \quad \frac{\begin{array}{l} f(\rho) = \sum_{\hat{V}} \llbracket \hat{U} \rrbracket u(\rho(l_1))(\hat{V}) \delta_{\rho \cup \{(l_2, \hat{V})\}} \\ \text{208} \quad l_2 \notin \text{dom}(\sigma) \end{array}}{\text{209} \quad [\sigma, \hat{U} l_1] \longrightarrow \delta_{[f^\#(\sigma), l_2]}} \text{ Q-EVOLVE}
\end{array}$$

Fig. 2. Quantum reduction rules

- If $[\sigma, M] \longrightarrow \mu$ and for all $[\sigma', M'] \in \text{supp}(\mu)$, $[\sigma', M'] \longrightarrow^* \nu_{\sigma', M'}$, then $[\sigma, M] \longrightarrow \sum_{[\sigma', M'] \in \text{supp}(\mu)} \mu([\sigma', M']) \nu_{\sigma', M'}$.

Definition 3.10 (Termination). A surface term M is said to *terminate*, denoted $M \Downarrow$, if there exists $\mu : \mathcal{V} \rightarrow [0, 1]$ such that $[\delta_0, M] \longrightarrow \mu$, and for every $[\sigma, M'] \in \text{supp}(\mu)$, M' is a closed value.

3.4 Preservation of Classical Reasoning

As mentioned in Section 1, the central design principle of our language is that the quantum extension preserves the behavior of the classical fragment. This guarantee is essential for programmers and compilers, as it ensures that classical reasoning and standard optimizations remain valid. To formalize this, we first define contextual equivalence, which states that two terms are equivalent if their observable behaviors are identical in any context. A context $C[\cdot]$ is defined as a closed term with a single hole $[\cdot]$ in it.

Definition 3.11 (Contextual equivalence). For $M, N \in \Lambda$, $M \approx N \Leftrightarrow_{\text{def}} \forall C[\cdot] \in \Lambda(\mathcal{U}). C[M] \Downarrow \Leftrightarrow C[N] \Downarrow$.

We conjecture that, as far as the classical fragment is concerned, the classical β_V -equivalence is sound with respect to the contextual equivalence. Here, $\longleftrightarrow_{\Lambda}^*$ denotes the congruence closure of the classical reduction relation defined in Appendix A.1.

Conjecture 3.12 (Preservation of β -equivalence). For all $M, N \in \Lambda$, if $M \longleftrightarrow_{\Lambda}^* N$ then $M \approx N$.

4 Discussion

This paper establishes a non-linear calculus that reinterprets structural rules as reference operations, preserving key classical identities like $\pi_1 \circ \delta = \lambda x.x$. The central conjecture, crucial for justifying classical reasoning, remains that full β_V -equivalence is preserved by quantum contextual equivalence. A proof may require adapting bisimulation techniques, such as those in [3, 9], to our quantum semantics. It should be noted that η_V -equivalence for *match* does not hold in general because measurement induces probabilistic branching, e.g., $\text{match } x [y \Rightarrow \text{inj}_0 y \mid z \Rightarrow \text{inj}_1 z] \not\approx x$.

A second point concerns resource management. Our high-level semantics, where new store locations imply new qubits, is a deliberate abstraction for a clear operational model. For a practical implementation, we should introduce a compiler layer responsible for explicit resource management, such as garbage collection or qubit reuse.

References

- [1] T. Altenkirch and J. Grattage. 2005. A Functional Quantum Programming Language. In *20th Annual IEEE Symposium on Logic in Computer Science (LICS' 05)*. IEEE, Chicago, IL, USA, 249–258. doi:10.1109/LICS.2005.1
- [2] Pablo Arrighi and Gilles Dowek. 2004. Operational Semantics for Formal Tensorial Calculus. In *Proceedings of the International Workshop on Quantum Programming Languages*. 21–38.
- [3] Ugo Dal Lago, Davide Sangiorgi, and Michele Alberti. 2014. On Coinductive Equivalences for Higher-Order Probabilistic Functional Programs. In *Proceedings of the 41st ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages (POPL '14)*. Association for Computing Machinery, New York, NY, USA, 297–308. doi:10.1145/2535838.2535872
- [4] Alejandro Díaz-Caro. 2022. A Quick Overview on the Quantum Control Approach to the Lambda Calculus. *Electronic Proceedings in Theoretical Computer Science* 357 (April 2022), 1–17. doi:10.4204/EPTCS.357.1 arXiv:2204.03885 [cs]
- [5] Arun Kumar Pati and Samuel L. Braunstein. 2000. Impossibility of Deleting an Unknown Quantum State. *Nature* 404, 6774 (March 2000), 164–165. doi:10.1038/404130b0
- [6] Michael A. Nielsen and Isaac L. Chuang. 2010. Quantum Computation and Quantum Information: 10th Anniversary Edition. <https://www.cambridge.org/highereducation/books/quantum-computation-and-quantum-information/01E10196D0A682A6AEFFEA52D53BE9AE>. doi:10.1017/CBO9780511976667
- [7] Neil J. Ross. 2017. *Algebraic and Logical Methods in Quantum Computation*. Ph.D. Dissertation. arXiv. arXiv:1510.02198 [quant-ph]
- [8] Amr Sabry, Benoît Valiron, and Juliana Kaizer Vizzotto. 2018. From Symmetric Pattern-Matching to Quantum Control. In *Foundations of Software Science and Computation Structures*, Christel Baier and Ugo Dal Lago (Eds.). Springer International Publishing, Cham, 348–364. doi:10.1007/978-3-319-89366-2_19
- [9] Davide Sangiorgi and Valeria Vignudelli. 2019. Environmental Bisimulations for Probabilistic Higher-order Languages. *ACM Trans. Program. Lang. Syst.* 41, 4 (Oct. 2019), 22:1–22:64. doi:10.1145/3350618
- [10] Peter Selinger. 2004. Towards a Quantum Programming Language. *Mathematical Structures in Computer Science* 14, 4 (Aug. 2004), 527–586. doi:10.1017/S0960129504004256
- [11] Peter Selinger and Benoît Valiron. 2009. Quantum Lambda Calculus. In *Semantic Techniques in Quantum Computation*. Cambridge University Press, 135–172. doi:10.1017/CBO9781139193313.005
- [12] André van Tonder. 2004. A Lambda Calculus for Quantum Computation. *SIAM J. Comput.* 33, 5 (Jan. 2004), 1109–1135. doi:10.1137/S0097539703432165
- [13] Finn Voichick, Liyi Li, Robert Rand, and Michael Hicks. 2023. Qunity: A Unified Language for Quantum and Classical Computing. *Proceedings of the ACM on Programming Languages* 7, POPL (Jan. 2023), 921–951. doi:10.1145/3571225
- [14] W. K. Wootters and W. H. Zurek. 1982. A Single Quantum Cannot Be Cloned. *Nature* 299, 5886 (Oct. 1982), 802–803. doi:10.1038/299802a0

A Operational semantics

A.1 Full definitions of operational semantics

The remaining part of the single-step reduction relation (Definition 3.7) is the classical β_V -reduction rules, given in Fig. 3. These rules are standard for call-by-value lambda calculus. They are promoted to the full reduction relation \longrightarrow by $[\sigma, M] \longrightarrow \delta_{[\sigma, M']}$ if $M \longrightarrow_{\Lambda} M'$.

$$\begin{aligned}
 (\lambda x.M) V &\longrightarrow_{\Lambda} M[V/x] \quad \beta\text{-LAM} & \text{let } \langle x, y \rangle = \langle V, W \rangle \text{ in } M &\longrightarrow_{\Lambda} M[V/x, W/y] \quad \beta\text{-PAIR} \\
 \text{match inj}_0 V [x \Rightarrow M \mid y \Rightarrow N] &\longrightarrow_{\Lambda} M[V/x] \quad \beta\text{-INJ}_0 \\
 \text{match inj}_1 V [x \Rightarrow M \mid y \Rightarrow N] &\longrightarrow_{\Lambda} N[V/y] \quad \beta\text{-INJ}_1
 \end{aligned}$$

Fig. 3. Classical reduction rules

The relation \longrightarrow is defined by the rules in Fig. 2 and Fig. 3, together with the congruence rule induced by the evaluation contexts. They are defined as:

$$\begin{aligned}
 E ::= & [\cdot] \mid E M \mid V E \mid \langle E, M \rangle \mid \langle V, E \rangle \mid \text{inj}_0 E \mid \text{inj}_1 E \mid \\
 & \text{let } \langle x, y \rangle = E \text{ in } M \mid \text{match } E [x \Rightarrow M \mid y \Rightarrow N]
 \end{aligned}$$

A.2 Proof of norm preservation

Lemma A.1 (Linearity of norm). $\|\sum_i \alpha_i \psi_i\| = \sqrt{\sum_i |\alpha_i|^2 \|\psi_i\|^2}$ if $\langle \psi_i, \psi_j \rangle = 0$ for all $i \neq j$.

Lemma A.2. For all injection $f : X \rightarrow Y$ and $\psi \in \ell^2(X)$, $\|\ell^2(f)(\psi)\| = \|\psi\|$.

PROOF. Let g be a left inverse of f , then

$$\|\ell^2(f)(\psi)\| = \left\| \sum_{x \in X} \psi(x) \delta_{f(x)} \right\| = \sum_{y \in f(X)} |\psi(g(y))|^2 = \sum_{x \in X} |\psi(x)|^2 = \|\psi\|. \quad (1)$$

□

Lemma A.3. For all isometry $f : \ell^2(X) \rightarrow \ell^2(Y)$ and $\psi \in \ell^2(X)$, $\|f(\psi)\| = \|\psi\|$.

PROOF. For all $x, x' \in X$, $\langle f(\delta_x), f(\delta_{x'}) \rangle = \langle \delta_x, \delta_{x'} \rangle = 0$ holds because f is an isometry. Then, by Lemma A.1,

$$\|f(\psi)\| = \left\| \sum_{x \in X} \psi(x) f(\delta_x) \right\| = \sqrt{\sum_{x \in X} |\psi(x)|^2 \|f(\delta_x)\|^2}.$$

As $\|f(\delta_x)\| = \sqrt{\langle f(\delta_x), f(\delta_x) \rangle} = \|\delta_x\| = 1$, we have $\|f(\psi)\| = \sqrt{\sum_{x \in X} |\psi(x)|^2} = \|\psi\|$. □

Theorem 3.8 (Norm preservation). If $[\sigma, M] \rightarrow \mu$, then for all $[\sigma', M'] \in \text{supp}(\mu)$, $\|\sigma'\| = \|\sigma\|$.

PROOF. By induction on the derivation of $[\sigma, M] \rightarrow \mu$. We only show the cases for the quantum rules; the other cases are immediate.

- Case Q-DESTR: Since the function f adds new entries l_2 and l_3 to ρ , it is injective; hence by Lemma A.2, $\|\ell^2(f)(\sigma)\| = \|\sigma\|$.
- Case Q-PREP: The same reasoning as in Case Q-DESTR.
- Case Q-MEAS: Similar argument to the Case Q-DESTR, f_0 and f_1 are injective. For each basis ρ_i in σ_i ($i = 0, 1$), $\rho_0 \neq \rho_1$ holds because they differ at least on the values stored in l_1 ; thus, $\langle \sigma_0, \sigma_1 \rangle = 0$.

$$\begin{aligned} \|\alpha_0 \sigma_0 + \alpha_1 \sigma_1\| &= \sqrt{|\alpha_0|^2 \|\sigma_0\|^2 + |\alpha_1|^2 \|\sigma_1\|^2} && \text{(by Lemma A.1)} \\ &= \sqrt{(|\alpha_0|^2 + |\alpha_1|^2) \|\sigma_0\|^2} && (\|\sigma_0\| = \|\sigma_1\|) \\ &= \|\sigma_0\| && (|\alpha_0|^2 + |\alpha_1|^2 = 1) \\ &= \|\ell^2(f_0)(\sigma_0)\| && \text{(by Lemma A.2)} \end{aligned}$$

Similarly, $\|\alpha_0 \sigma_0 + \alpha_1 \sigma_1\| = \|\ell^2(f_1)(\sigma_1)\|$.

- Case Q-EVOLVE: As $(\llbracket \hat{U} \rrbracket_{\mathcal{U}})^{\#}$ is a unitary, $\|\llbracket \hat{U} \rrbracket_{\mathcal{U}}(\rho(l_1))\|^2 = 1$; hence, $\|f(\rho)\| = 1$ for any basis ρ in σ . For all basis ρ, ρ' in σ ,

$$\langle f(\rho), f(\rho') \rangle = \sum_{\hat{V}} \overline{\llbracket \hat{U} \rrbracket_{\mathcal{U}}(\rho(l_1))(\hat{V})} \llbracket \hat{U} \rrbracket_{\mathcal{U}}(\rho'(l_1))(\hat{V}) = \langle \delta_{\rho}, \delta_{\rho'} \rangle.$$

As $f^{\#}(\delta_{\rho}) = f(\rho)$ by definition, $\langle f^{\#}(\delta_{\rho}), f^{\#}(\delta_{\rho'}) \rangle = \langle \delta_{\rho}, \delta_{\rho'} \rangle$ holds, which means $f^{\#}$ is an isometry. Thus, by Lemma A.3, $\|f(\sigma)\| = \|\sigma\|$. □

$$\begin{array}{c}
\frac{l \in \text{dom}(\Sigma)}{\Sigma \mid \Gamma \vdash l : \Sigma(l)} \text{Loc} \quad \frac{}{\Sigma \mid \Gamma \vdash * : \top} \top\text{-I} \quad \frac{}{\Sigma \mid \Gamma, x : A \vdash x : A} \pi_1 \quad \frac{\Sigma \mid \Gamma \vdash x : A}{\Sigma \mid \Gamma, y : B \vdash x : A} \pi_2 \\
\\
\frac{\Sigma \mid \Gamma, x : A \vdash M : B}{\Sigma \mid \Gamma \vdash \lambda x. M : A \rightarrow B} \rightarrow\text{-I} \quad \frac{\Sigma \mid \Gamma \vdash M : A \rightarrow B \quad \Sigma \mid \Gamma \vdash N : A}{\Sigma \mid \Gamma \vdash M N : B} \rightarrow\text{-E} \\
\\
\frac{\Sigma \mid \Gamma \vdash M : A \quad \Sigma \mid \Gamma \vdash N : B}{\Sigma \mid \Gamma \vdash \langle M, N \rangle : A \otimes B} \otimes\text{-I} \quad \frac{\Sigma \mid \Gamma \vdash M : A}{\Sigma \mid \Gamma \vdash \text{inj}_0 M : A \oplus B} \oplus_0\text{-I} \\
\\
\frac{\Sigma \mid \Gamma \vdash M : B}{\Sigma \mid \Gamma \vdash \text{inj}_1 M : A \oplus B} \oplus_1\text{-I} \quad \frac{\vdash_{\mathcal{U}} \hat{U} : \hat{A} \rightarrow \hat{B}}{\Sigma \mid \Gamma \vdash \hat{U} : \hat{A} \rightarrow \hat{B}} \text{Op} \\
\\
\frac{\Sigma \mid \Gamma \vdash M : A \otimes B \quad \Sigma \mid \Gamma, x : A, y : B \vdash N : C}{\Sigma \mid \Gamma \vdash \text{let } \langle x, y \rangle = M \text{ in } N : C} \otimes\text{-E} \\
\\
\frac{\Sigma \mid \Gamma \vdash M : A \oplus B \quad \Sigma \mid \Gamma, x : A \vdash N : C \quad \Sigma \mid \Gamma, y : B \vdash P : C}{\Sigma \mid \Gamma \vdash \text{match } M [x \Rightarrow N \mid y \Rightarrow P] : C} \oplus\text{-E}
\end{array}$$

Fig. 4. Typing rules

B Type system

We present the simple type system of $\Lambda(\mathcal{U})$ calculus. Syntax of types and typing context is given as follows.

Types	$A, B, C ::=$	$\top \mid A \otimes B \mid A \oplus B \mid A \rightarrow B$
Basis types	$\hat{A}, \hat{B} ::=$	$\top \mid \hat{A} \otimes \hat{B} \mid \hat{A} \oplus \hat{B}$
Typing context	$\Gamma ::=$	$\epsilon \mid \Gamma, x : A$

The types include the unit type \top , product types $A \otimes B$, sum types $A \oplus B$, and function types $A \rightarrow B$. \otimes and \oplus indicate that they are tensor product and direct sum of Hilbert spaces when interpreted as superpositions. Crucially, there is no distinction between classical and quantum types in this system. For instance, the type of both classical bit and qubit are represented as the same $\top \oplus \top$.

Typing judgements are defined on the runtime terms, which means they include typing rules for store locations. In order to map locations to their types, we introduce the notion of store typing.

Definition B.1 (Store typing). A store typing Σ is a finite mapping from locations to basis types. A store σ is well-typed under Σ , denoted $\Sigma \vdash \sigma$, if for every $l \in \text{dom}(\Sigma)$, $\vdash \sigma(l) : \Sigma(l)$ holds.

Similar to the definition of the reduction relation, we impose an assumption for \mathcal{U} : for each \hat{U} , there exists a typing judgement of the form: $\vdash_{\mathcal{U}} \hat{U} : \hat{A} \rightarrow \hat{B}$.

Definition B.2 (Typing judgments). Given a set of external typing judgements $\vdash_{\mathcal{U}} \hat{U} : \hat{A} \rightarrow \hat{B}$ for $\hat{U} \in \mathcal{U}$, A typing judgment is of the form $\Sigma \mid \Gamma \vdash M : A$. The typing rules are given in Fig. 4.

The standard type safety properties are expressed as follows.

Theorem B.3 (Subject reduction). *If $\Sigma \mid \Gamma \vdash M : A$, $[\sigma, M] \rightarrow [\sigma', M']$ and $\Sigma \vdash \sigma$, then there exists Σ' such that $\Sigma' \mid \Gamma \vdash M' : A$ and $\vdash \sigma' : \Sigma'$.*

Theorem B.4 (Progress). *If $\Sigma \mid \Gamma \vdash M : A$, then either M is a value or there exists μ such that $[\sigma, M] \rightarrow \mu$ for any σ with $\Sigma \vdash \sigma$.*

393
394
395
396
397
398
399
400
401
402
403
404
405
406
407
408
409
410
411
412
413
414
415
416
417
418
419
420
421
422
423
424
425
426
427
428
429
430
431
432
433
434
435
436
437
438
439
440
441