AI-Driven Discovery of Physics-Native Quantum Information Units
Version 1.1 — December 2025

Abstract

This document presents Version 1.1 of the research concept proposing that quantum information units may naturally emerge from the symmetry, degeneracy, or low-energy structure of physical Hamiltonians.

The goal is to explore whether modern AI systems can identify such physics-native information units, potentially reducing the overhead associated with conventional, engineered qubits. This version strengthens the conceptual motivation, provides examples of relevant Hamiltonians, adds related work context, and expands the system architecture description.

1. Introduction

Contemporary qubit designs rely on engineered logical abstractions that impose large physical-to-logical overheads. Recent improvements in error-correcting codes and decoding strategies suggest that these overheads may reflect not intrinsic physical limitations, but rather a mismatch between the abstractions we impose and the information-preserving structures present in the underlying physics.

Motivated by Feynman's original intuition—that computation should follow the natural structure of quantum mechanics—this work explores whether stable, low-noise information-bearing subspaces can be discovered using AI-assisted analysis of Hamiltonian landscapes.

2. Conceptual Motivation

The central question is whether nature offers information encodings that differ from the qubit model. Rather than defining computational units a priori, we examine whether physics-native encodings arise from:

- symmetry-protected subspaces
- degenerate manifolds
- conserved quantities
- low-energy basins shaped by the Hamiltonian

These structures may exhibit stability without relying on heavy error correction, and could serve as alternative information units aligned with the system's physical dynamics.

3.Mathematically Elegant vs. Physically Natural Representations

In many areas of quantum computing, the mathematical representation of computation is valued for its elegance: clean tensor products, well-defined gate sets, and compact algebraic descriptions. However, physical systems do not necessarily organize information according to our preferred mathematical structures.

A circuit may look “beautiful” on paper — composed of symmetric patterns of Hadamard, phase, and controlled operations — yet remain physically fragile because the underlying interactions break these imposed symmetries. Conversely, a physically stable structure may appear mathematically irregular or cumbersome, but derives its resilience precisely from the native dynamics of the Hamiltonian.

This tension suggests that mathematical elegance is not a reliable proxy for physical suitability. Physics may preserve information in subspaces that do not resemble qubits, that lack clean algebraic decompositions, or that arise from accidental or non-obvious symmetries. Such structures are often overlooked because they do not match the engineered abstractions commonly used in qubit architectures.

Identifying these physically natural encodings — even when they do not align with standard quantum gate formalisms — may be essential if we wish to develop quantum information units that are stable for reasons intrinsic to the system, rather than enforced through heavy error correction.

4. Example Hamiltonians

To ground the idea, Version 1.1 introduces three illustrative Hamiltonians:

1. Transverse Field Ising Model:

$H = -J \Sigma \sigma^z{}_i \sigma^z{}_{i+1} - h \Sigma \sigma^x{}_i$

Known for symmetry-breaking and stable subspace behavior.

2. Kitaev Chain:

Supports Majorana zero modes and topological degeneracy, a candidate for physics-native encoding.

3. Heisenberg XXZ Model:

Exhibits conservation laws and symmetry structures that influence stability.

These examples serve as potential landscapes for AI-assisted discovery of stable subspaces.

5. System Architecture

The proposed pipeline consists of:

5.1 Hamiltonian Library

A structured set of analytic and synthetic Hamiltonians chosen for their symmetry and noise-relevant properties.

5.2 AI Discovery Engine

Neural architectures trained to detect approximate symmetries, conserved quantities, and low-decoherence regions.

5.3 Dynamics Simulator

Time evolution tools that assess stability under realistic noise models.

5.4 Stability Scoring

Metrics comparing candidate subspaces with standard qubits, emphasizing error resilience.

5.5 Realization Filter

A mapping from candidate encodings to feasible physical platforms (superconducting, trapped ions, photonics, etc.).

6. Related Work

This work aligns with emerging research in:

• quantum optimal control

• variational subspace discovery

• symmetry-protected quantum information (SPT phases)

• AI-assisted Hamiltonian learning

• topological computation

These areas suggest that alternative information encodings may be physically meaningful and computationally useful.

7. Limitations

This work remains conceptual. Key limitations include:

• absence of numerical results (future work)

• no guarantee that discovered subspaces will outperform qubits

• uncertainties in physical realizability

• potentially high computational cost in large Hamiltonian spaces

Nonetheless, the conceptual framework motivates further exploration.

8. Discussion and Outlook

If physics-native information units exist and can be systematically identified, the implications may include:

• reduced qubit overhead

• architectures aligned with underlying physical structure

• new pathways for error resilience

• a return to Feynman's intuition about computation following physics

Future work will extend the Hamiltonian library, develop prototype AI models, and perform stability tests.

References

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