Foundational Statement — Physics-Native Hamiltonian Discovery

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1. Foundational Statement — Physics-Native Hamiltonian Discovery

This project is based on the hypothesis that meaningful quantum-information structures do not have to be imposed from the outside, but can *emerge* from the internal structure of physical Hamiltonians.

Instead of starting from engineered logical qubits, we start from the Hamiltonian

$$H = \sum_i c_i P_i$$

where the P_i are Pauli strings and the c_i are real coefficients.

By scanning ensembles of such Hamiltonians, diagonalising them, and analysing their spectra and eigenvectors, the project treats degeneracy patterns and structured eigenstates as *physical evidence* of underlying information-bearing subspaces.

Working hypothesis (informal statement)

For a broad class of Hamiltonians H, the spectrum contains systematically recurring near-degenerate manifolds whose eigenvectors exhibit stable, low-entropy structure.
These structures behave as physics-native information units.

In other words: instead of forcing the physics to fit our qubit abstraction, we ask what *information units the physics itself prefers*.

2. Degeneracy Patterns as Systematic Signatures

A central object in this programme is the **degeneracy pattern** of a Hamiltonian: clusters of eigenvalues that are exactly or nearly equal, together with the structure of their associated eigenvectors.

In each experiment (v0.1–v0.5), the workflow is:

- generate a Hamiltonian H as a random (or structured) sum of Pauli strings
- compute the full set of eigenvalues $\{E_k\}$ and eigenvectors $|\psi_k\rangle$
- identify pairs (or manifolds) with
  $|E_i - E_j| < \varepsilon$ (near-degeneracy)
- analyse the dominant computational-basis amplitudes of the corresponding eigenstates.

Across many seeds and Hamiltonians, the project repeatedly observes:

- eigenstates dominated by a *small* set of basis states (low-entropy structure)
- mirrored amplitude patterns between partner states in a degenerate pair
- recurring motifs (e.g. complementary bitstrings) across different seeds and runs.

These **degeneracy-plus-structure patterns** are treated as *signatures* of physics-native subspaces: they show where the Hamiltonian itself "wants" to store coherent information.

3. Iterative Hamiltonian Search as a Physical Probe

The repeated scanning over seeds and Hamiltonians (v0.1 → v0.5 → …) is not just a numerical trick; it functions as an **experimental probe** of the underlying principle.

Each experiment answers three questions:

1. **Existence**
   Do near-degenerate manifolds appear in this Hamiltonian at all?
2. **Structure**
   Are the associated eigenstates random-looking, or do they have a simple, interpretable pattern in the computational basis?
3. **Consistency**
   Do similar patterns reappear across different seeds, Hamiltonian families, or system sizes?

If the working hypothesis is correct, then:

- degeneracies should not be rare accidents,
- structured subspaces should appear repeatedly,
- and their characteristics (symmetry, locality, support patterns) should be recognisable across many different runs.

In that sense, the **algorithm is a microscope**: it reveals where the Hamiltonian hides robust, low-dimensional structure.

4. Local vs Backend Execution (Classical vs IBM Heron)

The project now has two complementary execution modes:

1. **Local classical execution**
   - Diagonalisation done on a classical machine.
   - Full access to all eigenvalues and eigenvectors.
   - Ideal for scanning many seeds and building statistical intuition.
2. **Backend execution (e.g. IBM Heron)**
   - Selected Hamiltonians are mapped to actual hardware experiments.
   - Circuits prepare approximate eigenstates or probe subspaces.
   - Measurements test whether the candidate physics-native subspace remains stable under realistic noise.

The **agreement** between local simulations and backend-based experiments becomes a crucial consistency check:

- If a candidate subspace looks clean and structured locally *and* retains its character under hardware noise,
  then it is a much stronger candidate for a usable physics-native information unit.

In later versions (v0.5, v0.6+), backend experiments will be integrated systematically as a second stage after local discovery.

5. Positioning and Uniqueness Relative to Existing Work

From a research-landscape perspective, this project sits at the intersection of:

- quantum error-correction and fault tolerance
- Hamiltonian complexity and many-body physics
- AI-assisted pattern discovery in high-dimensional spaces.

What appears to be **distinctive** here is the combination of:

- treating degeneracy and eigenvector structure as *primary* objects for defining information units,
- running systematic Hamiltonian scans as an experimental routine (v0.x series),
- and framing the whole effort around the search for a **compact physical law** for structure emergence—
  an analogue of “$E = mc^2$” but for information-bearing subspaces in Hilbert space.

Many groups work on better codes, better decoders, and better devices.
This programme asks a slightly different question:

Are we already *too far away* from the physics when we define qubits?
And can we instead let the Hamiltonians tell us what the natural information units are?

That framing—and the concrete v0.x pipeline you are building around it—gives the project a clear and recognisable identity.

6. Outlook for Future Versions (v0.6, v0.7, ...)

Going forward, each new version can be anchored in the same conceptual spine:

- **v0.6** — add perturbation tests and basic stability metrics
  - slightly deform H and track how degeneracies and subspaces move
  - quantify how “rigid” or “fragile” each candidate information unit is.

- **v0.7** — integrate AI-based structure discovery
  - cluster eigenstates by support patterns, symmetries, or localisation
  - let the AI propose families of "native encodings" that recur across many Hamiltonians.
- **v0.8 and beyond** — move toward an effective law
  - summarise the statistics of degeneracies and subspace structures
  - attempt to express them in a compact relation linking spectrum, symmetry, and information-bearing capacity.

Each Friday-whitepaper can then:

1. restate the foundational hypothesis (Section 1),
2. present the new degeneracy patterns and signatures (Section 2–3),
3. show how local and backend results compare (Section 4),
4. clarify how this version fits into the broader research landscape (Section 5),
5. and close with a short roadmap/outlook (Section 6).