Taxonomy of Noise in VQA

Variational Quantum Algorithms · Module 9 — Hardware Noise Models

Node 9.8

Position in Knowledge Graph

System: Variational Quantum Algorithms **Structural Domain:** Hardware Noise Models **Node:** 9.8

This is the **closing synthesis** of Module 9. The earlier nodes covered noise as individual objects: quantum channels (9.1), the depolarizing model (9.2), real hardware parameters (9.3), mitigation techniques (9.4-9.5), noise-adaptive ansatz design (9.6), and simulation modes (9.7).

This node steps back and organizes the whole landscape into a **taxonomy**: a structured map of the kinds of noise that affect VQAs, the kinds of damage they do, and the kinds of defenses that apply to each. The aim is to give a single chart that a practitioner can consult when diagnosing a noisy VQA — *"what kind of noise is killing me, and what do I do about it?"*

The taxonomy is organized along three axes:

1. **Where in the stack the noise lives** (physical, gate, circuit, classical post-processing).
2. **What kind of effect it has on the quantum state** (unital vs non-unital, Markovian vs non-Markovian, coherent vs incoherent).
3. **What it does to the VQA cost landscape** (shrinks, shifts, flattens, warps).

Each cell in the taxonomy has a characteristic signature, a set of mitigation techniques, and a connection to the thesis framing. At the end, I close the module with a summary of where the VQA literature stands on noise (2026) and where the open problems are.

Axis 1: Where The Noise Lives

Quantum computing has a layered architecture, and noise can enter at any layer. Knowing the layer tells you the characteristic timescale and the available countermeasures.

Layer 1 — Physical (sub-gate)

Examples. Thermal excitation, spontaneous emission, flux noise in superconducting qubits, laser phase noise for ion traps, atom loss for neutral atoms, nuclear spin coupling for silicon spins.

Timescale. Continuous during the circuit. Parameterized by T_1, T_2, T_ϕ (node 9.3).

Effect. Coherent and incoherent decay of the quantum state. The dominant source of decoherence in all current platforms.

Countermeasures. Hardware engineering (better qubits, better isolation, dynamical decoupling). Cannot be fixed at the circuit level; it's intrinsic to the physical layer.

Layer 2 — Gate (control-level)

Examples. Calibration drift, imperfect pulse shape, crosstalk between neighboring gates, leakage outside the computational subspace, finite control precision.

Timescale. Per-gate (nanoseconds to microseconds for superconducting, microseconds for ions).

Effect. Gate fidelity less than 1. Causes coherent errors (when control parameters are slightly wrong) and incoherent errors (when control parameters vary randomly).

Countermeasures. Recalibration (periodic benchmarking and correction), pulse shaping (DRAG pulses, Slepian pulses), randomized compiling (converting coherent to incoherent), gate-level Pauli twirling.

Layer 3 — Circuit (compilation-level)

Examples. SWAP overhead from routing, suboptimal layout, unnecessary gate count from poor decomposition, idle-time errors during synchronization.

Timescale. Circuit-level (microseconds to milliseconds).

Effect. Inflates the effective noise rate compared to the optimal circuit. Essentially a "compilation inefficiency" that translates to extra noise.

Countermeasures. Better compilation: noise-aware routing, native-gate ansätze, circuit optimization passes, ADAPT-style ansatz growth.

Layer 4 — Measurement (readout)

Examples. Readout confusion (measuring 0 when true state is 1), dispersive shift errors, thermal population.

Timescale. Measurement time (microseconds).

Effect. Biases the measurement outcome. Typically 1-5% on current hardware — larger than gate errors.

Countermeasures. Readout error correction (confusion matrix inversion, M3), repeated measurement, ancilla-based parity checks.

Layer 5 — Classical post-processing

Examples. Numerical precision in the classical optimizer, shot noise in expectation value estimation, optimizer instability, hyperparameter sensitivity.

Timescale. Classical loop iteration (milliseconds to seconds).

Effect. Adds noise to the effective cost function. Not a quantum noise per se, but functionally similar from the optimizer's perspective.

Countermeasures. More shots, better estimator (Bayesian posteriors, filters), optimizer improvements (Adam, adaptive learning rates), regularization.

Axis 2: What Kind Of Effect On The State

Within the quantum channel formalism, noise channels can be classified by several structural properties.

Unital vs Non-Unital

A channel is **unital** if $\mathcal{E}(I) = I$ — it preserves the maximally mixed state.

- **Unital examples:** depolarizing, Pauli noise, dephasing.
- **Non-unital examples:** amplitude damping (has a preferred state $|0\rangle$), thermal relaxation, measurement disturbance.

Practical significance. Unital noise has no "preferred direction" in state space — it symmetrically shrinks expectation values. Non-unital noise *biases* the state toward a specific fixed point, which means it can *move the minimum* of the VQA cost landscape, not just shrink its amplitude. This is a more insidious kind of error, because the optimizer converges to the wrong answer.

Markovian vs Non-Markovian

A noise process is **Markovian** if the error at each step depends only on the current state (no memory). It is **non-Markovian** if there's memory — the error depends on the history.

- **Markovian examples:** depolarizing channels (applied per gate), random Pauli noise.
- **Non-Markovian examples:** low-frequency flux noise, 1/f noise, crosstalk between distant gates via a shared bath.

Practical significance. Markovian noise accumulates predictably (multiplicatively per gate). Non-Markovian noise is harder — it can cause correlated errors that break standard analysis. Most VQA theory assumes Markovian; real hardware is often not.

Coherent vs Incoherent

Coherent errors are unitary but wrong — e.g., a Z rotation by 1.01π instead of π. They preserve the purity of the state; the state evolves to a slightly wrong pure state.

Incoherent errors are mixing operations — they increase the state's entropy. Decoherence, depolarizing noise, amplitude damping.

Practical significance. Coherent errors are *more damaging per error rate* because they can constructively interfere over many gates, compounding in a correlated way. Incoherent errors average out (variance scales as $\sqrt{L}$). So a 1% coherent error can do more damage than a 1% incoherent error over a deep circuit.

Countermeasure. *Randomized compiling* converts coherent errors to incoherent by randomly conjugating each gate with a random Pauli. It's essentially free and recommended for VQAs on coherent-error-dominated hardware.

Axis 3: What It Does To The VQA Cost Landscape

This is the VQA-specific axis — what the noise does to the optimizer's experience of the landscape.

Shrinks The Contrast

The most common effect: depolarizing-like noise shrinks the amplitude of all Pauli expectation values uniformly. The cost landscape is compressed toward a constant, but its *shape* (location of minima, directions of gradients) is unchanged.

Signature. Cost values all closer to the noiseless average $\mathrm{Tr}(H)/d$; minimum unchanged in parameter space; gradients scaled down.

Impact on VQA. Reduces signal-to-noise ratio; optimizer still finds the right answer but needs more shots. Mitigable via ZNE or CDR.

Shifts The Minimum

Non-unital noise (amplitude damping, thermal population) biases the state toward a specific fixed point, which shifts the cost function's minimum in parameter space. The optimizer converges, but to the wrong place.

Signature. Noisy minimum is at different parameters than noiseless minimum; even with infinite shots, the optimizer converges to a biased answer.

Impact on VQA. Systematic bias that cannot be removed by averaging. Requires either PEC (unbiased mitigation) or symmetry verification (if a symmetry is broken by the noise).

Flattens The Landscape

Depolarizing noise at high rate or over deep circuits causes the entire landscape to become flat — the exponential decay of contrast reaches the shot noise floor everywhere. This is the **noise-induced barren plateau** (Wang 2021).

Signature. Gradient variance is indistinguishable from shot noise; optimization stalls; no parameter update direction is reliable.

Impact on VQA. Training fails. No amount of shots helps (shot noise floor is the problem). Only defense is shallower circuits or noise reduction at the hardware level.

Warps The Landscape

Coherent errors and correlated noise can introduce *wrong* features into the landscape — spurious minima, new saddle points, distorted gradient directions.

Signature. Hard to detect; the optimizer converges but the convergence point is wrong in a non-obvious way. Validation against a known answer reveals the issue.

Impact on VQA. Insidious. Testing on a known-answer benchmark (small H_2 or a Clifford-reducible problem) is essential to catch this.

The Full Taxonomy Table

Putting it all together:

Noise type	Layer	Unital?	Markov?	Cost effect	Mitigation
Depolarizing	Gate	Yes	Yes	Shrinks	ZNE, CDR
Amplitude damping	Physical/Gate	**No**	~Yes	Shifts + shrinks	PEC, symmetry verification
Dephasing	Physical	Yes	Yes (approx)	Shrinks Z contrast	DD, ZNE
Coherent (cal drift)	Gate	Yes	Yes	Warps	Recalibration, randomized compiling
Crosstalk	Gate	Varies	**No**	Warps	Scheduling, DD, isolation
Leakage	Gate	**No**	Varies	Warps	Leakage-reducing pulses, filtering
Readout	Measurement	N/A	Yes	Bias observations	Confusion matrix inversion
1/f flux noise	Physical	Yes	**No**	Shrinks + warps	DD, hardware engineering
Shot noise	Classical	N/A	Yes	Flattens	More shots, Bayesian filter
Calibration drift	Control	Varies	**No**	Warps over time	Periodic recalibration, adaptive control

Reading the table. Each row is a distinct noise source. The columns tell you how it behaves and what to do about it. The "Mitigation" column points at specific techniques.

Key observations: - Non-unital and non-Markovian noise are the hardest cases. - Depolarizing is the best-case scenario — everything else is worse. - Classical-layer "noise" (shot noise, drift) is a major factor in practice.

The VQA Noise Hierarchy

On current (2026) hardware, the noise sources rank roughly as follows, in order of total impact on VQAs:

1. **Two-qubit gate errors.** By far the dominant source. 0.1%-1% per gate. All mitigation efforts focus here first.
2. **Readout errors.** Second-biggest. 1%-5% per qubit. Cheap to fix, always apply readout mitigation.
3. **Single-qubit gate errors.** 0.01%-0.1%. Smaller but accumulate over many gates.
4. **Decoherence during idle.** T2 effects. Mitigable via DD and smart scheduling.
5. **Crosstalk.** Usually smaller than direct gate errors but can be correlated and insidious.
6. **Coherent errors / calibration drift.** Slow-varying. Recalibration handles it.
7. **Leakage.** Usually $< 0.1\%$ on mature platforms. Reduced by careful pulse design.

This hierarchy is *specific to superconducting hardware in 2026.* Trapped ions have different rankings (less readout error, more laser noise). Neutral atoms add atom loss. The taxonomy is platform-dependent but the axes are universal.

Where The Field Stands (2026)

A summary of the state of noise + VQA research as of 2026:

1. Theory is mature for depolarizing noise. Wang 2021's plateau theorem, Ragone-style bounds, and ZNE theory give a comprehensive picture for the depolarizing case.

2. Non-unital noise is less well-understood. Analytical results for amplitude damping are scattered. Most theoretical work still uses depolarizing as a stand-in.

3. Mitigation is well-developed but has hit a shot-complexity wall. ZNE, PEC, CDR, symmetry verification are all established. The open question is how to extend them without exponential shot blow-up.

4. Hardware fidelities are improving but slowly. Two-qubit gate fidelities have gone from 99% (2018) to 99.9% (2026) on the best platforms — a factor of 10. This gives a factor-10 increase in usable depth. Steady but not transformational progress.

5. Circuit-level mitigation is well-established. Noise-aware compilation, ADAPT-VQE, and HEA are in every production VQA stack.

6. Open frontiers: - Non-Markovian noise modeling — how to treat it in VQA theory. - **Adaptive mitigation** — auto-selecting techniques based on circuit properties. - **Noise-aware optimizer design** — optimizers that know about mitigation cost. - **Error-corrected VQAs** — using minimal error correction (a few logical qubits) inside VQAs. - **Noise-tailored ansätze** — designing ansätze that are specifically resistant to the dominant noise types.

The field has matured from "we don't know how noise affects VQAs" (2017) to "we have a comprehensive taxonomy and standard tools" (2026). The remaining questions are about *how much* mitigation and adaptation can push the NISQ-era depth, and when fault-tolerance will take over.

Thesis Framing

From the thesis perspective:

1. **Noise is a perturbation of the objective generator, not of the optimizer dynamics.** The optimizer (HOPSO or otherwise) operates on whatever noisy cost function it's given; the noise lives in the evaluation of the objective. Separating these cleanly is architecturally important.
2. **Mitigation is a classical side-computation attached to the objective generator.** Not part of the quantum dynamics. This matches HOPSO's abstraction of the optimizer-objective boundary.
3. **Noise-adaptive ansatz design is a modification of the objective generator's functional form.** Changing the ansatz changes what function $C(\boldsymbol{\theta})$ the optimizer sees. This is a form of dynamical restriction that complements regularization.
4. **Adaptive noise handling (monitoring hardware drift and reconfiguring) is the natural extension.** This is what Module 10 takes up explicitly: the closed-loop adaptive VQA that uses feedback control at the outer level.

The thesis claim from this module: **noise is a solvable problem at the depths current hardware allows, provided you use the full toolkit (adaptation + mitigation + hardware tuning) and choose the right optimizer for the noisy landscape**.

Closing Module 9

Module 9 has traversed the noise landscape:

- **9.1:** Quantum channels and CPTP maps — the formal language.
- **9.2:** Depolarizing noise — the workhorse model and its implications.
- **9.3:** Gate errors and coherence times — the physical parameters.
- **9.4:** Mitigation techniques — the post-processing toolkit.
- **9.5:** Zero-noise extrapolation — the dominant mitigation in depth.
- **9.6:** Noise-adaptive ansatz design — the pre-processing complement.
- **9.7:** Simulation modes — how to model all this classically.
- **9.8 (this node):** Taxonomy — the full chart and the state of the field.

The arc: from abstract formalism → to physical reality → to defensive techniques → to a unified map. Each step adds structure that the previous lacked.

This module is the *practical* companion to Modules 7 (control theory) and 10 (adaptive deployment). Those modules tell you how to *design* a VQA for noise; this module tells you what the noise *is*.

Structural Role

This node is the **synthesis and closing** of Module 9. It organizes the module's content into a three-axis taxonomy, provides a summary table, ranks noise sources by impact, and sketches the state of the field in 2026.

It is the capstone reference node for VQA practitioners who need to quickly diagnose noise issues and select countermeasures.

Relations to Other Concepts

- **Nielsen-Chuang** — the formal channel language.
- **Wang et al. (2021)** — noise-induced plateau theorem.

- **Cai et al. (2023)** — comprehensive review of quantum error mitigation.
- **Module 9.1-9.7** — the components being synthesized.
- **Module 10** — the next step, where adaptive control handles drift and time-varying noise.

Worked Example — Diagnosing A Failing VQA

Scenario. You're running a 12-qubit VQE for a molecule. You know the noiseless answer (from exact diagonalization): ground state energy $E_0 = -7.88$ Hartree. Your noisy VQA converges to -7.72, off by 0.16 Hartree (way too much).

Diagnosis workflow:

Step 1. Apply readout error correction. New result: -7.79. Improvement 0.07; readout was a significant contributor.

Step 2. Apply symmetry verification on electron count. New result: -7.81. Improvement 0.02; non-unital (amplitude-damping-like) errors were shifting the minimum.

Step 3. Apply ZNE with linear fit. New result: -7.85. Improvement 0.04; depolarizing-like errors were shrinking contrast.

Step 4. Switch to noise-aware qubit selection (best 12 qubits on the device). New result: -7.87. Improvement 0.02; heterogeneous fidelity was inflating effective noise.

Step 5. Apply DD during idle periods. New result: -7.875. Improvement 0.005.

Remaining error: 0.005 Hartree. Possibly unmitigable or requires deeper techniques (PEC, CDR).

Diagnosis summary. - Main source: readout error (44% of total bias). - Second: depolarizing contrast loss (25%). - Third: non-unital shift (12%). - Fourth: heterogeneous fidelity (12%). - Fifth: idle errors (3%).

Each source is attacked by a different mitigation. The taxonomy directs which tool to use for which problem.

Visualization

Pending. A treemap or Sankey diagram showing the five-layer stack (physical, gate, circuit, measurement, classical), with noise sources in each layer sized by their typical contribution to VQA error. Arrows connecting each source to its mitigation technique. Caption: "The noise taxonomy at a glance."

Exercises

1. For each noise type in the taxonomy table, identify whether it can shift the VQA minimum (non-unital) or just shrink contrast (unital).
2. (Conceptual) Why is a 1% coherent error typically more damaging than a 1% incoherent error for a deep VQA? Quantify using a circuit of depth 100.
3. (VQA, project-scale) Design a noise diagnostic pipeline: given a noisy VQA result, determine the dominant error source by applying mitigation layers one at a time and measuring the improvement. Output the diagnosis as a table.

Research Extensions

- **Non-Markovian noise for VQAs** — extending the theory to time-correlated errors.
- **Adaptive mitigation selection** — auto-picking the right mitigation per circuit.

- **Error-correction-aware VQAs** — running VQAs on partially error-corrected circuits.
- **Noise-tailored ansatz families** — ansätze specifically designed to resist the dominant error type on the target hardware.
- **Unified VQA noise simulator** — simulating all noise axes simultaneously with controllable knobs.

Cross-links to Other Courses

- **Module 9.1-9.7** — all the components of the taxonomy.
- **Module 7 (Control-Theoretic View)** — the design side.
- **Module 10 (Adaptive Control Systems)** — the deployment endpoint.
- **Module 6 (Optimization Dynamics)** — the optimizer's interaction with noise.
- **Quantum Error Correction** — the long-term answer beyond NISQ.

Variational Quantum Algorithms · Module 9 — Hardware Noise Models · Node 9.8
Concepts: quantum-noise, decoherence, quantum-channels, optimization-landscape
Prerequisites: 9.1, 9.2, 9.3, 9.4, 9.5, 9.6, 9.7

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