Chapter 3

Quansistor as a Local Causal Information Compressor

Invariant-Based Compression Under Causal Constraints

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Abstract

This paper introduces the quansistor as a local causal information compressor: a mechanism that reduces operator-level information to invariant summaries while explicitly respecting locality and no-signalling constraints. Unlike classical compression, which operates on symbolic representations without regard to causal structure, quansistor compression acts directly on operators governing system evolution.

We formalize spectral compression as invariant reduction and show how such compression discards task-irrelevant operator detail while preserving structural information sufficient for verification, stability analysis, and auditability. The resulting compression is inherently local, causally confined, and cannot be exploited as a communication channel.

We analyze the implications of local causal compression for computation, verification, and storage, demonstrating how invariant-based records replace exhaustive execution histories. The quansistor framework provides a scalable and physically consistent foundation for audit-native and distributed computational architectures.

1 Motivation: Why Classical Compression Is Not Causally Aware

Compression is traditionally understood as a reduction in the length of a representation. Classical information theory treats compression as an encoding problem: data are transformed into shorter descriptions while preserving recoverability up to a specified fidelity.

While this paradigm has been extraordinarily successful, it is largely blind to causal structure. Classical compression schemes operate on symbols or bitstreams without regard to how information is generated, propagated, or constrained by physical or computational causality.

This chapter motivates the need for a notion of compression that is explicitly local and causally admissible.

1.1 Compression as Representation Reduction

In standard settings, compression is defined relative to:

- an encoding alphabet,

- a probability model or redundancy structure,
- a decoding procedure.

The compressed output is shorter because it exploits statistical regularities, not because it respects any notion of causal accessibility.

1.2 Causal Blindness of Classical Compression

Classical compression permits transformations that are informationally valid but physically implausible:

- global access to data assumed at compression time,
- instantaneous rearrangement of information,
- no distinction between local and nonlocal dependencies.

From a causal standpoint, such assumptions are unrealistic in distributed, physical, or large-scale systems.

1.3 Compression vs. Influence

Compression should not be confused with influence. A compressor that aggregates global information may implicitly assume nonlocal access, even if the output is later used locally.

In causally constrained systems, aggregation itself must respect locality and light-cone structure.

1.4 Why Causality Matters for Compression

In systems where:

- components are spatially separated,
- communication is delayed or unreliable,
- verification occurs post hoc,

compression mechanisms must ensure that no hidden signalling or illicit information flow is introduced.

This requirement is absent from classical compression theory.

1.5 The Need for Local Causal Compression

We therefore propose a refined notion:

> *A valid compression mechanism must operate locally, respect causal order, and reduce information only by discarding structure that is irrelevant to the intended task.*

This notion aligns compression with physical and computational reality.

1.6 Operator-Centric Perspective

In operator-first systems, the primary object is not a data stream but an operator defining admissible evolution. Compression, in this context, is not a shorter description of states, but a reduction of operator information to invariants.

This reframing prepares the ground for quansistors as causal compressors.

1.7 Roadmap

The next chapter formalizes locality and causality in the context of compression. Subsequent chapters introduce quansistors as operator-level compressors, analyze their causal safety, and compare them to classical and quantum models.

2 Locality, Causality, and the Meaning of Compression

Before introducing quansistors as causal compressors, we must clarify what *locality* and *causality* mean in the context of compression. Classical compression theory abstracts away from these notions; here they are essential.

2.1 Locality as Physical and Computational Constraint

Locality expresses the restriction that operations are performed using only information available within a bounded region of space, time, or system structure.

In physical systems, locality is enforced by spacetime separation. In distributed computational systems, locality corresponds to limited visibility, delayed communication, and partial knowledge.

A compression mechanism is local if:

- it operates only on data or operators accessible within a bounded region,
- it does not assume instantaneous access to remote information,
- it respects subsystem boundaries.

2.2 Causality and Temporal Order

Causality introduces an ordering constraint: information produced at an event can influence only events in its future causal cone. Any admissible compression process must respect this ordering.

In particular, a causally valid compressor must not:

- aggregate information from spacelike-separated regions instantaneously,
- depend on future events,
- implicitly encode nonlocal coordination.

2.3 Compression as Information Reduction

At an abstract level, compression reduces information by identifying and discarding redundancy. The critical question is which redundancies are discardable.

From a causal perspective, redundancy is discardable only if:

- it is locally observable,
- its removal does not affect causally accessible queries,
- it does not introduce hidden dependencies.

This immediately rules out many global aggregation schemes.

2.4 Aggregation vs. Compression

It is important to distinguish compression from aggregation.

Aggregation combines information from multiple sources into a single summary. Compression reduces description length while preserving task-relevant content.

Aggregation is often nonlocal by default; compression need not be. A causal compression scheme must avoid aggregation that violates locality.

2.5 Formal Notion of Local Compression

We introduce the following definition.

Definition 2.1 (Local compressor)**.** A compression map $\mathcal{C}_R$ acting on a region R is local if its output depends only on information accessible within R and its causal past.

Such a compressor may produce outputs that are later compared or combined, but the compression step itself is causally confined.

2.6 Causal Consistency of Compressed Outputs

A compressed representation is causally consistent if it does not allow an observer to infer information about spacelike-separated regions without additional causal input.

This condition ensures that compression does not become an implicit signalling mechanism.

2.7 Observer-Dependent Compression

Compression is always relative to an observer or task. Different observers, restricted to different causal regions, may legitimately produce different compressed representations of the same global system.

This observer-dependence is not a flaw, but a reflection of causal constraints.

2.8 Compression Without Reconstruction

In causally constrained systems, the goal of compression is often not full reconstruction, but sufficiency for specific queries or verifications.

A compressed object is valid if it preserves answers to all queries that are causally accessible to the observer.

2.9 Preparation for Operator-Based Compression

The definitions introduced in this chapter prepare the ground for operator-level compression. By focusing on locality, causality, and sufficiency, we can define compression in terms of invariant reduction rather than symbol manipulation.

The next chapter introduces quansistors as local operators that perform exactly this form of causally admissible compression.

3 Quansistor as an Operator-Level Compressor

We now introduce the quansistor as a concrete realization of a local, causal information compressor. Unlike classical compressors, which act on symbol streams or state descriptions, a quansistor operates directly on operators that define admissible system evolution.

This chapter formalizes the quansistor as an operator-level compression map and clarifies why this operation constitutes compression rather than aggregation or communication.

3.1 Operator-Centric View of Compression

In an operator-first framework, the primary object is an operator A acting on a state space $\mathcal{H}$. The operator encodes constraints, dynamics, and allowed transformations.

Compression in this setting does not reduce a sequence of states, but reduces the informational content of the operator by discarding structure irrelevant to a given task.

3.2 Definition of a Quansistor

We define a quansistor as follows.

Definition 3.1 (Quansistor)**.** A quansistor is a localized operator-valued map

$$\mathcal{Q}_R : A_R \longrightarrow \mathcal{I}(A_R),$$

where A_R is an operator supported on a region R, and $\mathcal{I}(A_R)$ is a finite or compact family of spectral invariants sufficient for a specified class of queries.

The quansistor acts only on operator information accessible within its causal region.

3.3 Local Support and Causal Confinement

The locality of a quansistor is expressed by two constraints:

- *Spatial or structural locality*: $\mathcal{Q}_R$ depends only on operator components supported in R.
- *Causal locality*: $\mathcal{Q}_R$ depends only on information in the causal past of R.

These constraints ensure that quansistor operation cannot introduce hidden signalling channels.

3.4 Invariant Reduction as Compression

The output $\mathcal{I}(A_R)$ is strictly smaller, in informational content, than the full operator A_R. Multiple distinct operators may map to the same invariant set.

This many-to-one mapping is the defining feature of compression:

- fine-grained operator details are discarded,
- task-irrelevant distinctions are collapsed,
- only invariant structure is retained.

3.5 Why This Is Not Aggregation

Aggregation combines information from multiple regions into a global summary. Quansistor compression does not perform such combination.

Each quansistor:

- operates independently on its local operator,
- produces an invariant summary without accessing remote data,
- does not assume global synchronization.

Any later comparison or combination of invariant outputs occurs through explicit causal channels and is not part of the compression step.

3.6 Temporal Aspect of Quansistor Compression

Quansistor compression may be applied continuously or episodically as operators evolve. The compressed output reflects the operator structure accumulated up to that time.

Crucially, compression does not anticipate future evolution and therefore respects temporal causality.

3.7 Relation to Spectral Information

The invariant families produced by quansistors are typically spectral in nature:

- partial spectra,
- heat-kernel traces,
- resolvent statistics,
- gap and stability indicators.

These quantities are robust under representation changes and align with the spectral conception of information.

3.8 Compression Without State Materialization

A key advantage of operator-level compression is that it does not require explicit enumeration of system states.

Quansistors operate on operator descriptions directly, avoiding the exponential cost of state-space traversal.

3.9 Task-Relative Sufficiency

The choice of invariant family $\mathcal{I}$ determines what information is preserved. A quansistor is correct if $\mathcal{I}(A_R)$ is sufficient for the intended task, such as verification, stability assessment, or regime detection.

Compression is therefore relative to purpose, not absolute.

3.10 Transition

We have defined quansistors as operator-level compressors that reduce information locally and causally by mapping operators to invariant summaries.

The next chapter examines the nature of spectral compression in detail and formalizes how invariant reduction achieves compression without violating causality.

4 Spectral Compression and Invariant Reduction

Having defined the quansistor as an operator-level compressor, we now analyze the mechanism by which compression is achieved. The central idea is *spectral compression*: a reduction of operator information to invariant structures derived from its spectrum.

This chapter formalizes invariant reduction and clarifies when such reduction is lossy or lossless with respect to a given class of queries.

4.1 From Operators to Spectral Objects

Let A_R be an operator supported on a region R. By the spectral theorem, A_R admits a decomposition in terms of its spectral measure μ_{A_R}.

Rather than retaining A_R in full detail, a quansistor extracts a finite or compact representation $\mathcal{I}(A_R)$ constructed from μ_{A_R} or functions thereof.

This mapping

$$A_R \longrightarrow \mathcal{I}(A_R)$$

is the essence of spectral compression.

4.2 Invariant Families

An invariant family $\mathcal{I}$ is a collection of functionals on operators satisfying invariance under admissible transformations (e.g., unitary conjugation).

Typical invariant families include:

- truncated or coarse-grained spectra,
- heat-kernel traces $\mathrm{Tr}(e^{-tA_R})$ for selected t,
- resolvent-based statistics,
- spectral gaps and band structure indicators,
- asymptotic eigenvalue counting functions.

Each family captures a different aspect of operator structure.

4.3 Invariant Reduction as Information Loss

Invariant reduction is inherently many-to-one: distinct operators may share the same invariant values. This loss of distinction is precisely what makes compression possible.

From an informational standpoint:

- discarded details are those not visible to the chosen invariant probes,

- retained information corresponds to stable, task-relevant structure.

Compression is therefore intentional and controlled.

4.4 Lossless vs. Lossy Spectral Compression

Spectral compression is *lossless* relative to a query class $\mathcal{Q}$ if all answers to queries in $\mathcal{Q}$ depend only on $\mathcal{I}(A_R)$.

It is *lossy* if some queries require access to finer operator detail.

This distinction is relative, not absolute: the same invariant family may be lossless for one task and lossy for another.

4.5 Granularity and Resolution

The degree of compression is controlled by the granularity of the invariant family:

- coarse invariants yield strong compression but large equivalence classes,
- fine invariants yield weaker compression but higher discriminative power.

Choosing granularity is a design decision informed by task requirements and resource constraints.

4.6 Robustness Under Perturbations

Spectral invariants are typically stable under small perturbations of the operator. This robustness makes spectral compression well-suited for noisy, approximate, or physical systems.

In contrast, state-based representations often exhibit extreme sensitivity to small changes.

4.7 Temporal Accumulation of Spectral Information

As operators evolve over time, spectral invariants may change slowly or remain stable over extended intervals. Quansistor compression naturally tracks such temporal structure without storing full evolution histories.

This supports long-term monitoring and regime detection.

4.8 Compression Without Reconstruction

A key feature of spectral compression is that it does not aim at

5 Causal Safety and No-Signalling Guarantees

Having established quansistors as operator-level compressors based on spectral invariant reduction, we now address a critical question: can such compression mechanisms be exploited as communication channels, potentially violating causal constraints?

In this chapter, we show that quansistor-based spectral compression is causally safe and intrinsically satisfies no-signalling guarantees.

5.1 What Would Constitute Signalling

A signalling mechanism from region A to region B requires the following:

- a controllable local intervention at A,
- a distinguishable effect on local observables at B,
- absence of any mediating causal propagation.

If any of these conditions fails, signalling is impossible.

5.2 Locality of the Compression Operation

Quansistor compression acts on an operator A_R supported in region R and depends only on information accessible within R and its causal past.

Formally, for spacelike-separated regions R_A and R_B, the compression map $\mathcal{Q}_{R_A}$ has no access to operator components supported in R_B.

This excludes direct nonlocal influence at the compression stage.

5.3 Invariance of Remote Local Statistics

Let $\mathcal{Q}_{R_A}$ be a quansistor acting in region A. For any observable O_B localized in a spacelike-separated region B, we require:

$$\langle O_B \rangle = \langle O_B \rangle_{\mathcal{Q}_{R_A}}.$$

That is, the act of compression at A leaves all local expectation values at B unchanged.

This condition is the operational core of no-signalling.

5.4 Absence of Controllable Global Updates

Spectral invariants produced by a quansistor summarize operator structure, but they cannot be arbitrarily or selectively rewritten by local choice.

Changing a spectral invariant requires:

- modification of operator structure,
- propagation of effects through causal interaction,
- or explicit reconfiguration of constraints.

None of these processes occur instantaneously or without causal mediation.

5.5 Compression Outputs Are Not Signals

The outputs of quansistor compression are invariant summaries. They lack:

- an encoding alphabet,
- tunable parameters accessible at a single site,
- immediate remote observability.

Without these elements, no signalling protocol can be constructed.

5.6 Correlation Without Communication

Spectral invariants may encode correlations across subsystems, but these correlations are revealed only through:

- causal aggregation of local outputs,
- post hoc comparison,
- explicit communication channels.

This mirrors the role of classical communication in revealing entanglement correlations.

5.7 Compression Does Not Amplify Influence

A potential concern is whether compression could amplify subtle influences into detectable signals. Spectral compression does not amplify influence; it discards information.

Any influence present in the compressed output must already be present in the operator structure and must propagate causally.

5.8 Formal No-Signalling Guarantee

We summarize the argument as follows:

> *Quansistor-based spectral compression satisfies no-signalling because local compression operations cannot induce controllable changes in remote local observables outside the future light cone.*

This guarantee holds independently of the strength or scope of operator-level correlations.

5.9 Compatibility with Relativistic Constraints

Because quansistor compression respects locality of access, temporal ordering, and absence of instantaneous global updates, it is fully compatible with relativistic causality.

No superluminal information transfer is introduced at any stage.

5.10 Transition

With causal safety established, we now turn to practical implications. The next chapter examines how local causal compression via quansistors impacts computation, verification, and storage architectures.

6 Implications for Computation, Verification, and Storage

Having established quansistors as local, causal, and non-signalling information compressors, we now examine the concrete implications of this framework for computation, verification, and storage. The emphasis is on architectural consequences rather than implementation details.

6.1 Computation as Operator Evolution

In quansistor-based systems, computation is understood as the evolution of operators under local updates rather than as a sequence of explicit state transitions.

This perspective yields several advantages:

- execution order becomes less critical,
- intermediate states need not be materialized,
- correctness is judged by invariant outcomes.

Computation is therefore defined by structural consistency rather than by exact procedural replay.

6.2 Deterministic Replay Without Full Histories

Traditional deterministic replay relies on recording every nondeterministic event. This approach becomes infeasible at scale.

With quansistor compression, replay is replaced by invariant regeneration:

- given the same initial operator conditions,
- and the same admissible local updates,
- the same spectral invariants must result.

Verification focuses on invariant agreement, not on reproducing full execution paths.

6.3 Verification by Invariant Matching

Verification becomes a structural problem:

> *Did the system evolve an operator consistent with the declared invariant family?*

This can be answered without access to internal states, logs, or proprietary implementation details. Only invariant summaries need to be exposed.

6.4 Auditability Without Log Explosion

Audit systems based on quansistor compression store:

- compact invariant commitments,
- metadata describing invariant families,
- optional witnesses for recomputation.

This replaces massive log storage with stable, low-volume audit artifacts that remain meaningful long after execution.

6.5 Storage of Meaning Rather Than History

Classical storage preserves execution history. Quansistor-based storage preserves meaningful structure.

Invariant records answer questions such as:

- Was the system stable?
- Did it enter a forbidden regime?
- Did it satisfy declared constraints?

They intentionally discard incidental detail.

6.6 Privacy and Intellectual Property Protection

Because invariant summaries do not expose internal state, they support:

- privacy-preserving verification,
- protection of proprietary algorithms,
- selective disclosure of system behavior.

Verification and confidentiality are no longer in direct conflict.

6.7 Scalability in Distributed Systems

In distributed environments, quansistor compression scales naturally:

- each node compresses locally,
- invariant outputs are small and stable,
- global reasoning occurs only when needed.

This avoids centralized bottlenecks and reduces communication overhead.

6.8 Long-Term Preservation and Reinterpretation

Invariant-based records remain interpretable even as system implementations change. Future observers can re-evaluate invariant data under new models or standards.

This property is essential for scientific reproducibility and long-lived infrastructure.

6.9 Interaction with Classical Storage and Communication

Quansistor compression complements, rather than replaces, classical storage and communication:

- classical channels carry control and data,
- invariant records provide structural guarantees.

Separating these roles simplifies system design.

6.10 Architectural Summary

Systems built around quansistor compression:

- treat operators as first-class computational objects,
- use invariants as canonical records,

- decouple verification from execution history.

This architectural shift enables scalable, auditable, and causally safe computation.

6.11 Transition

The final chapter addresses the limits of this approach, trade-offs in invariant selection, and open research problems. These considerations define the practical scope of quansistor-based causal compression.

7 Limits, Trade-offs, and Open Problems

This final chapter delineates the limits of quansistor-based local causal compression, clarifies the trade-offs inherent in invariant reduction, and identifies open problems for future research. The aim is to precisely define the scope of applicability of the framework developed in this paper.

7.1 Fundamental Limits of Local Causal Compression

Quansistor compression is constrained by both locality and causality. As a result, it cannot:

- access or summarize information outside its causal region,
- capture global structure instantaneously,
- preserve all operator details while remaining compact.

These limits are not shortcomings, but direct consequences of respecting causal structure.

7.2 Information Loss as a Design Feature

Invariant reduction necessarily collapses distinctions between operators. This loss of information is intentional and task-driven.

The central design question is not how to avoid loss, but:

> *Which distinctions are worth preserving for a given purpose?*

Poor invariant selection may discard information relevant to future queries, while overly rich invariant sets reduce compression benefits.

7.3 Trade-offs in Invariant Selection

Choosing an invariant family involves balancing:

- compression ratio versus discriminative power,
- robustness versus sensitivity,
- computational cost versus informational richness.

No single invariant family is optimal for all tasks. Adaptive or layered invariant schemes may be required in practice.

7.4 Non-Uniqueness and Invariant Collisions

Distinct operators may share identical invariant summaries. From the informational perspective adopted here, such operators are equivalent with respect to the chosen task.

However, in adversarial or high-assurance settings, invariant collisions must be anticipated and mitigated by:

- enlarging invariant families,
- combining independent spectral probes,
- incorporating temporal or multi-scale invariants.

7.5 Finite-Time and Approximate Observations

In real systems, invariants are computed or measured approximately and over finite time windows. This introduces uncertainty and estimation error.

These limitations reflect epistemic constraints, not violations of the underlying causal framework. The theory remains valid under approximation.

7.6 What Quansistor Compression Does Not Do

It is important to state explicitly what quansistor compression does not provide:

- it is not a communication channel,
- it does not enable remote control,
- it does not replace classical data transport,
- it does not reconstruct full system histories.

Any system exhibiting such behavior necessarily includes additional mechanisms beyond quansistor compression.

7.7 Open Problems

Several open questions remain and define directions for further research:

- How can invariant families be optimized automatically for specific tasks?
- What formal bounds can be placed on invariant collision probability?
- How do quansistor compressors compose across hierarchical systems?
- Can invariant-based compression be integrated with learning systems?
- What are optimal probing strategies under strict causal constraints?

Addressing these questions will require contributions from operator theory, distributed systems, and information theory.

7.8 Broader Perspective

Local causal compression reframes the role of information in computation. Rather than treating information as a transferable commodity, it treats information as a structural property of admissible evolution.

This perspective aligns compression with physical law and distributed reality.

7.9 Conclusion

Quansistors, understood as local causal information compressors, provide a coherent framework for reducing information to invariant structure without violating causality.

By explicitly respecting locality, no-signalling, and task-relative sufficiency, this approach enables scalable computation, verifiable execution, and meaningful storage in complex systems.

This concludes the analysis of quansistor-based local causal compression.