Observer, Measurement, and Accessibility in Universal Modular Dynamics

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Abstract

We investigate the role of the observer, measurement, and accessibility within the framework of Universal Modular Dynamics (UMD), where physical structure is defined in terms of the density operator ρ, its modular generator $K = -\log \rho$, and the associated spectral distribution $p(k)$.

In contrast to conventional approaches, where the observer is treated as an external entity and measurement as a distinct process, we develop a structural interpretation in which both arise from the internal organization of the system.

We show that the observer can be represented as a localized, stable configuration of the spectral distribution, while measurement emerges as a consequence of limited accessibility to the full structure. In this framework, observable reality corresponds not to the complete structure, but to its accessible projection.

The analysis demonstrates that state reduction, information loss, and decoherence can be understood as manifestations of a single mechanism: the restriction of access to the full spectral organization.

These results provide a unified structural interpretation of observation and measurement, eliminating the need for additional postulates. They also suggest that classical reality arises as a stable, accessible description of an underlying, more complex structure.

The present work completes a sequence of studies in which structure, boundaries, and accessibility are successively derived within a common framework, and establishes observation as an intrinsic process through which structure becomes accessible to itself.

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1 Introduction

The problem of the observer and measurement occupies a central place in modern physics, particularly in quantum theory. Despite the success of the formalism, the interpretation of measurement remains conceptually unresolved.

In standard approaches, the observer is typically treated as an external entity, and measurement is introduced as a distinct process, separate from the underlying dynamics. This leads to a fundamental tension between unitary evolution and state reduction, giving rise to well-known conceptual difficulties, including the measurement problem and the role of collapse.

Within the framework of Universal Modular Dynamics (UMD), a different perspective becomes possible. In this approach, the fundamental object is the density operator ρ, and structure is defined in terms of its modular generator $K = -\log \rho$ and the associated spectral distribution $p(k)$. As shown in previous works, structural properties such as organization and boundaries can be derived from the spectral configuration itself.

This shift allows for a reconsideration of the role of the observer.

If structure is taken as primary, the observer cannot be regarded as external to the system. Instead, it must be understood as part of the same structural organization. This leads to the interpretation of the observer as a localized and stable configuration of the spectral distribution.

In this framework, measurement is no longer a separate act. It emerges as a consequence of limited accessibility to the full structure. Since any localized configuration has access only to a subset of $p(k)$, the observed description corresponds to a reduced version of the full structure.

Thus, measurement can be interpreted as a transition from the full structure to its accessible projection.

This leads to a fundamental shift in interpretation: observability is not an intrinsic property of the system, but a consequence of structural accessibility.

The aim of the present work is to formalize this idea. In particular, we investigate how the observer, measurement, and information can be derived within a unified structural framework, without introducing external procedures.

We show that limited accessibility naturally leads to effective descriptions, information loss, and the emergence of observable reality.

These results allow one to interpret observation as an intrinsic process through which structure becomes accessible to itself via localized configurations.

2 Problem Statement

Despite the formal success of quantum theory, the concepts of observer and measurement remain conceptually unresolved.

In standard formulations, measurement is introduced as a special process, distinct from the unitary evolution of the system. This leads to a fundamental separation between dynamics and observation, giving rise to several open questions:

- what determines the outcome of a measurement,
- how state reduction occurs,
- and what role the observer plays in this process.

These difficulties suggest that the conventional description may be incomplete at a conceptual level.

Within the framework of Universal Modular Dynamics (UMD), structure is defined in terms of the density operator ρ, its modular generator $K = -\log \rho$, and the spectral distribution $p(k)$. In this setting, structural properties such as organization and boundaries arise from the internal configuration of $p(k)$.

This allows one to reformulate the problem of observation.

If the observer is part of the same structure it describes, then it cannot have access to the full configuration. Instead, it interacts with a restricted subset of the structure.

This leads to the central question of the present work:

> What does it mean to observe within a structural theory where access to the full configuration is fundamentally limited?

More specifically, the following problems must be addressed:

- how to define the observer as a structural object,
- how measurement can arise without introducing external procedures,
- how limited accessibility affects the observed description,
- and how observable reality emerges from the full structure.

The core hypothesis is that observation is determined by accessibility:

$$\text{observation} \sim \text{access to a subset of } p(k). \tag{1}$$

In this framework, the observed description does not correspond to the full structure, but to its accessible projection.

Thus, measurement is not an independent physical process, but a structural consequence of limited access.

The aim of this work is to formalize this perspective and to show how observer, measurement, and information can be derived from a unified structural framework.

Resolving this problem would eliminate the conceptual separation between dynamics and measurement, and establish observation as an intrinsic feature of structure itself.

3 Conceptual Background

In order to formalize the role of observer, measurement, and accessibility within a structural framework, it is necessary to clarify these concepts at a conceptual level.

In conventional approaches, these notions are often introduced operationally, without direct reference to the internal structure of the system. Within UMD, all elements of description must arise from a unified structural basis.

3.1 Observer as Structural Object

In standard interpretations, the observer is treated as an entity external to the system. However, in a structural theory such as UMD, such a separation is not consistent.

If physical reality is fully described by the spectral distribution $p(k)$, then the observer must be a part of this structure.

This leads to the following interpretation:

$$\text{observer} \sim \text{localized stable configuration of } p(k). \tag{2}$$

Such configurations are characterized by concentration of structural weight within a limited region, providing stability and persistence.

3.2 Measurement as Structural Process

Measurement is typically introduced as a special process involving state reduction. Within UMD, this notion is reformulated.

Since the observer has access only to a subset of the full structure, any interaction results in a reduced description.

Thus, measurement is not an external action, but a structural consequence of limited accessibility:

$$\text{measurement} \sim \text{reduction induced by accessibility}. \tag{3}$$

3.3 Information and Structure

In this framework, information is not treated as an abstract transferable quantity, but as a property of accessible structure.

The full distribution $p(k)$ contains more information than is available to any localized configuration. Therefore, a distinction arises between:

- total structural information,
- and accessible information.

This distinction is fundamental to understanding measurement and observation.

3.4 Accessibility

Accessibility is the central concept linking observer and structure.

A localized configuration has access only to a subset of the full distribution:

$$p_{\text{acc}}(k) \subset p(k). \tag{4}$$

This limitation is not imposed externally, but arises naturally from localization.

Thus, accessibility defines the effective domain within which observation is possible.

3.5 Observed Reality

Observed reality is determined by the accessible part of the structure.

Instead of the full distribution $p(k)$, the observer interacts with:

$$p_{\text{acc}}(k). \tag{5}$$

This implies that observed reality is a reduced description, corresponding to the accessible projection of the full structure.

3.6 Synthesis

The concepts introduced above form a unified scheme.

Observer, measurement, and information are not independent elements, but are connected through accessibility.

This leads to the general principle:

$$\text{observation} \sim \text{structurally limited accessibility}. \tag{6}$$

Thus, the problem of observation is reduced to the problem of access to structure, and measurement is understood as a consequence of this limitation.

3.7 Observer as Structural Object

In standard interpretations, the observer is treated as an entity external to the system. However, within a structural framework such as UMD, such a separation is not consistent.

If physical reality is fully described by the spectral distribution $p(k)$, then the observer must be part of this structure.

This leads to the interpretation:

$$\text{observer} \sim \text{localized stable configuration of } p(k). \tag{7}$$

Such configurations are characterized by concentration of structural weight within a limited region, ensuring stability and persistence.

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Measurement is typically introduced as a special process involving state reduction. Within UMD, this notion is reformulated.

Since the observer has access only to a subset of the full structure, any interaction results in a reduced description.

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$$\text{measurement} \sim \text{reduction induced by accessibility.} \tag{8}$$

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The full distribution $p(k)$ contains more information than is available to any localized configuration. Therefore, a distinction arises between:

- total structural information,
- and accessible information.

This distinction is fundamental for understanding measurement and observation.

3.10 Accessibility

Accessibility is the central concept linking observer and structure.

A localized configuration has access only to a subset of the full distribution:

$$p_{\text{acc}}(k) \subset p(k). \tag{9}$$

This limitation arises naturally from localization and does not require external constraints.

Thus, accessibility defines the effective domain within which observation is possible.

3.11 Observed Reality

Observed reality is determined by the accessible part of the structure.

Instead of the full distribution $p(k)$, the observer interacts with:

$$p_{\text{acc}}(k). \tag{10}$$

This implies that observed reality is a reduced description corresponding to the accessible projection of the full structure.

3.12 Synthesis

The concepts introduced above form a unified scheme.

Observer, measurement, and information are not independent elements, but are connected through accessibility.

This leads to the general principle:

$$\text{observation} \sim \text{structurally limited accessibility.} \tag{11}$$

Thus, the problem of observation is reduced to the problem of access to structure, and measurement is understood as a consequence of this limitation.

4 Structural Representation

To formalize the concepts introduced in the previous section, we express observer, measurement, and accessibility in terms of the spectral structure defined by the distribution $p(k)$.

Within UMD, all physical structure is encoded in $p(k)$, allowing any subsystem to be represented as a configuration within this distribution.

4.1 Observer as Localized Distribution

The observer is represented as a localized region of the spectral distribution:

$$p_{\mathrm{loc}}(k) \subset p(k). \tag{12}$$

This region is characterized by concentration of structural weight and relative stability under perturbations.

Thus, the observer is not an external entity, but a subsystem defined by localization within the full structure.

4.2 Decomposition of Structure

The full distribution may be decomposed as:

$$p(k) = p_{\mathrm{loc}}(k) + p_{\mathrm{env}}(k), \tag{13}$$

where:

- $p_{\mathrm{loc}}(k)$ corresponds to the observer,
- $p_{\mathrm{env}}(k)$ corresponds to the environment.

This decomposition is not fundamental, but emerges from the degree of localization and interaction.

4.3 Accessibility Mapping

Due to localization, the observer has access only to a subset of the full structure. This is formalized by a mapping:

$$\mathcal{A} : p(k) \longrightarrow p_{\mathrm{acc}}(k), \tag{14}$$

where $p_{\mathrm{acc}}(k)$ denotes the accessible part of the distribution.

This mapping represents the restriction of structure imposed by localization.

4.4 Measurement as Reduction

Measurement is interpreted as the application of the accessibility mapping:

$$p(k) \longrightarrow p_{\mathrm{acc}}(k). \tag{15}$$

This transition results in a reduced description of the system.

Thus, measurement is not a separate process, but a consequence of accessibility.

4.5 Information Loss

The reduction from $p(k)$ to $p_{\mathrm{acc}}(k)$ leads to loss of information, which may be quantified as:

$$\Delta I = I[p(k)] - I[p_{\mathrm{acc}}(k)]. \tag{16}$$

This loss reflects the impossibility of reconstructing the full structure from accessible data.

4.6 Observed Reality

Observed reality corresponds to the accessible distribution:

$$\text{reality} \sim p_{\text{acc}}(k). \tag{17}$$

Thus, the observed description is a projection of the full structure.

4.7 Dynamics of Accessibility

Under structural evolution,

$$p(k) \to p(k, \lambda), \tag{18}$$

the accessible region also evolves:

$$p_{\text{acc}}(k) \to p_{\text{acc}}(k, \lambda). \tag{19}$$

This leads to a dynamical description of observation.

4.8 Synthesis

The structural representation establishes the following correspondences:

$$\begin{aligned} \text{observer} &\sim p_{\text{loc}}(k), \\ \text{measurement} &\sim \mathcal{A}(p(k)), \\ \text{reality} &\sim p_{\text{acc}}(k). \end{aligned} \tag{20}$$

These relations provide a unified formal description of observation and measurement as intrinsic features of structure.

5 Analysis

Using the structural representation developed in the previous section, we now analyze the mechanisms through which observation and measurement arise.

The central goal is to explain how limited accessibility leads to observable phenomena such as state reduction, information loss, and classical behavior.

5.1 Accessibility and Measurement

Since the observer is represented by a localized configuration $p_{\text{loc}}(k)$, it has access only to a subset of the full structure.

Thus, any interaction is effectively described by the mapping:

$$p(k) \longrightarrow p_{\text{acc}}(k). \tag{21}$$

Measurement is therefore identified with the restriction of structure induced by accessibility.

5.2 Emergence of Reduction

In standard quantum theory, state reduction is introduced as a separate postulate.

Within UMD, reduction arises naturally as a consequence of the transition:

$$p(k) \longrightarrow p_{\text{acc}}(k). \tag{22}$$

This transition removes inaccessible components, resulting in a reduced and stable description.

Thus, state reduction is not fundamental, but emergent.

5.3 Information Loss Mechanism

The difference between the full and accessible structures leads to loss of information:

$$\Delta I = I[p(k)] - I[p_{\mathrm{acc}}(k)]. \tag{23}$$

This loss is intrinsic and reflects the impossibility of reconstructing the full structure from accessible data.

It plays a central role in determining the outcome of measurement.

5.4 Emergence of Classicality

Classical behavior emerges from the stability of the accessible structure.

Suppression of inaccessible contributions leads to effective reduction of complexity, producing stable and reproducible outcomes.

Thus, classical reality is interpreted as a stabilized accessible configuration.

5.5 Decoherence as Structural Effect

Decoherence may be understood as the loss of phase information associated with inaccessible components of the structure.

Since the observer cannot access the full distribution, interference effects are effectively suppressed.

This leads to a transition from coherent to mixed descriptions.

Thus, decoherence is not an additional mechanism, but a direct consequence of limited accessibility.

5.6 Observer Dependence

Different observers correspond to different localized configurations and therefore have different access to the structure.

As a result:

- different observers may obtain different descriptions,
- measurement outcomes depend on the structure of the observer,
- observed reality is relative to accessibility.

However, this relativity is structurally determined and not arbitrary.

5.7 Dynamics of Observation

Under structural evolution,

$$p(k) \to p(k, \lambda), \tag{24}$$

the accessible region evolves:

$$p_{\mathrm{acc}}(k) \to p_{\mathrm{acc}}(k, \lambda). \tag{25}$$

Thus, observation is inherently dynamical.

Changes in accessibility lead to changes in observed reality.

5.8 Main Result

The analysis leads to the following conclusion:

$$\text{observation} \sim \text{dynamical restriction of structure.} \tag{26}$$

State reduction, information loss, and decoherence are all manifestations of a single mechanism: limited accessibility to the full structure.

This provides a unified explanation of measurement within the UMD framework, without the need for additional postulates.

6 Physical Interpretation

The results obtained in the previous section allow for a direct physical interpretation of observation, measurement, and information within the UMD framework.

The central conclusion is that these concepts do not require external definition. Instead, they arise as consequences of the internal structural organization.

6.1 Observation as Internal Process

Observation is not an interaction between independent systems.

Since the observer is a localized configuration within the same structure, observation corresponds to an internal process:

$$\text{observation} \sim \text{interaction of structural regions.} \tag{27}$$

This eliminates the need for an external observer.

6.2 Reality as Accessible Structure

Observed reality is not the full structure $p(k)$, but its accessible part:

$$\text{reality} \sim p_{\text{acc}}(k). \tag{28}$$

Thus, what is perceived as physical reality is a reduced description determined by accessibility.

6.3 Measurement as Stabilization

Measurement corresponds to the selection of stable configurations within the accessible structure.

Through interaction, certain configurations become stable, while others are suppressed. The observed outcome corresponds to one of these stable configurations.

Thus:

$$\text{measurement} \sim \text{stabilization of accessible configurations.} \tag{29}$$

6.4 Classical Reality

Classical behavior arises from stability and suppression.

Due to limited accessibility, interference between inaccessible components is effectively removed, leading to stable and reproducible outcomes.

Thus, classical reality emerges as:

- a reduced description,
- stabilized by accessibility,
- and reinforced by suppression of inaccessible structure.

6.5 Relativity of Observation

Different observers correspond to different localized configurations and therefore have different accessible domains.

As a result, observed reality is relative to the observer:

$$\text{reality} \sim p_{\text{acc}}^{(i)}(k). \tag{30}$$

However, this relativity is not arbitrary, but determined by the underlying structure.

6.6 Information as Structural Quantity

Information is interpreted as a property of accessible structure.

- Increasing accessibility corresponds to gaining information,
- decreasing accessibility corresponds to information loss,
- measurement corresponds to reconfiguration of accessible information.

Thus, information is directly tied to structural accessibility.

6.7 Unified Picture

The analysis leads to a unified interpretation:

$$\begin{aligned} \text{observer} &\sim p_{\text{loc}}(k), \\ \text{measurement} &\sim \mathcal{A}(p(k)), \\ \text{reality} &\sim p_{\text{acc}}(k). \end{aligned} \tag{31}$$

These relations provide a coherent description of observation as an intrinsic structural process.

6.8 Synthesis

The physical interpretation can be summarized as follows:

$$\text{observability} \sim \text{structurally limited accessibility}. \tag{32}$$

Thus, the properties of observed reality are determined not only by the structure itself, but by the domain of its accessibility.

7 Conclusion

In this work, we have investigated the role of observer, measurement, and accessibility within the framework of Universal Modular Dynamics (UMD), where physical structure is defined in terms of the density operator ρ, its modular generator $K = -\log \rho$, and the associated spectral distribution $p(k)$.

In contrast to conventional approaches, where the observer is treated as an external entity and measurement as a distinct process, we have shown that both can be derived as consequences of internal structural organization.

The observer is identified as a localized and stable configuration of the spectral distribution, possessing access only to a restricted subset of the full structure. As a result, observation is inherently associated with limited accessibility.

This leads to a reinterpretation of measurement as a structural reduction induced by restricted access. State reduction, information loss, and decoherence are not independent processes, but manifestations of a single underlying mechanism.

A central result of this work is that observed reality does not correspond to the full structure, but to its accessible projection:

$$\text{reality} \sim p_{\text{acc}}(k). \tag{33}$$

Thus, the properties of the observed world are determined not only by the structure itself, but by the domain of its accessibility.

This perspective eliminates the conceptual separation between dynamics and measurement, and establishes observation as an intrinsic process through which structure becomes accessible to itself.

The present work completes a sequential structural program:

$$\text{Structure} \longrightarrow \text{Boundaries} \longrightarrow \text{Accessibility}. \tag{34}$$

Within this unified framework, fundamental physical notions — including observer, measurement, information, and reality — are derived as consequences of structural organization, rather than introduced as independent postulates.

These results provide a coherent foundation for interpreting quantum measurement and observable phenomena, and suggest that accessibility plays a fundamental role in the emergence of physical reality.

A Structural Definitions and Notation

This appendix summarizes the structural definitions and notation used throughout the paper. The purpose is to provide a clear and consistent interpretation of all quantities within the UMD framework.

A.1 Full Structure

The full structure of the system is described by the spectral distribution:

$$p(k), \tag{35}$$

where k denotes spectral values of the modular generator $K = -\log \rho$.

The distribution $p(k)$ encodes the complete structural information of the system.

A.2 Localization

A localized structure is defined as a concentration of the distribution within a restricted region:

$$p_{\text{loc}}(k) \subset p(k). \tag{36}$$

Localization characterizes stable subsystems within the full structure.

A.3 Observer

The observer is defined as a localized and stable configuration:

$$\text{observer} \sim p_{\text{loc}}(k). \tag{37}$$

Thus, the observer is not external, but part of the structure.

A.4 Decomposition of Structure

The full structure may be decomposed into:

$$p(k) = p_{\text{loc}}(k) + p_{\text{env}}(k), \tag{38}$$

where $p_{\text{env}}(k)$ represents the environment.

This decomposition arises from localization and is not fundamental.

A.5 Accessibility

Accessibility is defined as the subset of structure available to the observer:

$$p_{\text{acc}}(k) \subset p(k). \tag{39}$$

It reflects the limitation imposed by localization.

A.6 Accessibility Mapping

The restriction of structure is represented by a mapping:

$$\mathcal{A} : p(k) \longrightarrow p_{\text{acc}}(k). \tag{40}$$

This mapping encodes the limitation of access.

A.7 Measurement

Measurement is defined as the application of the accessibility mapping:

$$\text{measurement} \sim \mathcal{A}(p(k)). \tag{41}$$

Thus, measurement is a structural reduction rather than an external process.

A.8 Information Loss

The loss of information due to restricted access is given by:

$$\Delta I = I[p(k)] - I[p_{\text{acc}}(k)], \tag{42}$$

where $I[\cdot]$ denotes a suitable measure of structural information.

A.9 Observed Reality

Observed reality is defined as the accessible structure:

$$\text{reality} \sim p_{\text{acc}}(k). \tag{43}$$

This implies that reality corresponds to a reduced description of the full structure.

A.10 Dynamics

Under structural evolution:

$$p(k) \to p(k, \lambda), \tag{44}$$

the accessible structure evolves accordingly:

$$p_{\text{acc}}(k) \to p_{\text{acc}}(k, \lambda). \tag{45}$$

This leads to a dynamical description of observation.

A.11 Summary

The key relations of the framework are:

$$\begin{aligned} \text{observer} &\sim p_{\text{loc}}(k), \\ \text{measurement} &\sim \mathcal{A}(p(k)), \\ \text{reality} &\sim p_{\text{acc}}(k). \end{aligned} \tag{46}$$

These definitions provide a unified structural basis for describing observation, measurement, and information within UMD.

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