

# Physical Reality as an Emergent Modular System

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## Abstract

We develop a unified framework in which physical reality emerges from the spectral properties of informational states. Starting from the density operator  $\rho$ , we construct the modular generator  $K = -\log \rho$  and its spectral distribution  $p(k)$  as the fundamental objects.

We demonstrate that structure, locality, geometry, dynamics, and scale arise sequentially from properties of the modular spectrum. Renormalization is reinterpreted as spectral flow, and physical phases are defined through optimal partitions of informational structure.

We further show that stable spectral modes correspond to matter-like structures, while gauge symmetry emerges as an access-relative redundancy. A universal dynamical equation is formulated, governing all physical regimes in a phase-dependent manner.

The framework is supported by a reproducible numerical program and extended to flavor physics, where we derive the structure of quark mixing and CP violation from spectral hierarchy.

This work establishes a unified perspective in which physical structure is understood as an emergent consequence of distinguishability and spectral organization.

## Contents

|          |                                                      |          |
|----------|------------------------------------------------------|----------|
| <b>1</b> | <b>Introduction</b>                                  | <b>6</b> |
| <b>2</b> | <b>Pre-Quantum Foundations</b>                       | <b>7</b> |
| 2.1      | Distinguishability as Primary Structure . . . . .    | 7        |
| 2.2      | From Distinguishability to Information . . . . .     | 7        |
| 2.3      | Emergence of the Density Operator . . . . .          | 8        |
| 2.4      | Modular Generator . . . . .                          | 8        |
| 2.5      | Spectral Representation . . . . .                    | 8        |
| 2.6      | Interpretation and Ontological Closure . . . . .     | 9        |
| 2.7      | Scope and Status . . . . .                           | 9        |
| <b>3</b> | <b>Modular Dynamics</b>                              | <b>9</b> |
| 3.1      | From Static Information to Dynamics . . . . .        | 9        |
| 3.2      | Degeneracy of the Naive Modular Flow . . . . .       | 9        |
| 3.3      | Relative Modular Operator . . . . .                  | 10       |
| 3.4      | Full Dynamical Equation . . . . .                    | 10       |
| 3.5      | Structure of the Evolution . . . . .                 | 10       |
| 3.6      | Entropy Monotonicity and Arrow of Ordering . . . . . | 10       |
| 3.7      | Spectral Evolution and Renormalization . . . . .     | 11       |
| 3.8      | Stationary States and Fixed Points . . . . .         | 11       |
| 3.9      | Conceptual Summary . . . . .                         | 11       |
| 3.10     | Scope and Status . . . . .                           | 11       |

|          |                                                        |           |
|----------|--------------------------------------------------------|-----------|
| <b>4</b> | <b>Spectral Structure</b>                              | <b>12</b> |
| 4.1      | Spectral Distribution . . . . .                        | 12        |
| 4.2      | Statistical Descriptors . . . . .                      | 12        |
| 4.3      | Distributional Representation of Information . . . . . | 12        |
| 4.4      | Spectral Modes . . . . .                               | 13        |
| 4.5      | Structural Interpretation . . . . .                    | 13        |
| 4.6      | Stability Under Evolution . . . . .                    | 13        |
| 4.7      | Interaction Between Modes . . . . .                    | 13        |
| 4.8      | Robustness and Universality . . . . .                  | 14        |
| 4.9      | Conceptual Summary . . . . .                           | 14        |
| 4.10     | Scope and Status . . . . .                             | 14        |
| <b>5</b> | <b>Phases and Criticality</b>                          | <b>14</b> |
| 5.1      | From Spectral Structure to Phases . . . . .            | 14        |
| 5.2      | Definition of a Phase . . . . .                        | 14        |
| 5.3      | Partition Functional . . . . .                         | 15        |
| 5.4      | Optimal Partition . . . . .                            | 15        |
| 5.5      | Locality as a Derived Property . . . . .               | 15        |
| 5.6      | Landscape Structure . . . . .                          | 15        |
| 5.7      | Definition of Criticality . . . . .                    | 15        |
| 5.8      | Replacement of Correlation Length . . . . .            | 16        |
| 5.9      | Phase Classification . . . . .                         | 16        |
| 5.10     | Geometric Interpretation . . . . .                     | 16        |
| 5.11     | Connection to Spectral Flow . . . . .                  | 16        |
| 5.12     | Physical Consequences . . . . .                        | 17        |
| 5.13     | Conceptual Summary . . . . .                           | 17        |
| 5.14     | Scope and Status . . . . .                             | 17        |
| <b>6</b> | <b>Geometry and Gravity</b>                            | <b>17</b> |
| 6.1      | From Phase Structure to Geometry . . . . .             | 17        |
| 6.2      | Mutual Information as a Geometric Primitive . . . . .  | 17        |
| 6.3      | Emergent Distance . . . . .                            | 18        |
| 6.4      | Graph Geometry . . . . .                               | 18        |
| 6.5      | Conditions for Geometric Phase . . . . .               | 18        |
| 6.6      | Breakdown of Geometry . . . . .                        | 18        |
| 6.7      | Information Metric . . . . .                           | 19        |
| 6.8      | Entropy and Geometry . . . . .                         | 19        |
| 6.9      | First Law of Entanglement . . . . .                    | 19        |
| 6.10     | Emergence of Gravity . . . . .                         | 19        |
| 6.11     | Role of the Reference State . . . . .                  | 19        |
| 6.12     | Cosmological Interpretation . . . . .                  | 20        |
| 6.13     | Conceptual Summary . . . . .                           | 20        |
| 6.14     | Scope and Status . . . . .                             | 20        |
| <b>7</b> | <b>Gauge Structure and Modular Defects</b>             | <b>20</b> |
| 7.1      | From Geometry to Gauge Structure . . . . .             | 20        |
| 7.2      | Access Algebra . . . . .                               | 20        |
| 7.3      | Pointer Algebra (Center) . . . . .                     | 21        |
| 7.4      | Access Equivalence . . . . .                           | 21        |
| 7.5      | Gauge Transformations . . . . .                        | 21        |
| 7.6      | Modular Defects . . . . .                              | 21        |
| 7.7      | Operational Indicators of Defects . . . . .            | 21        |

|           |                                                    |           |
|-----------|----------------------------------------------------|-----------|
| 7.8       | Patching Structure . . . . .                       | 22        |
| 7.9       | Transition Maps . . . . .                          | 22        |
| 7.10      | Groupoid Structure . . . . .                       | 22        |
| 7.11      | Holonomy Test . . . . .                            | 22        |
| 7.12      | Physical Interpretation . . . . .                  | 22        |
| 7.13      | Connection to Standard Gauge Theory . . . . .      | 22        |
| 7.14      | Dark Sector Interpretation . . . . .               | 23        |
| 7.15      | Conceptual Summary . . . . .                       | 23        |
| 7.16      | Scope and Status . . . . .                         | 23        |
| <b>8</b>  | <b>Strong Portability of Modular Diagnostics</b>   | <b>23</b> |
| 8.1       | Motivation: Toward a Unified Language . . . . .    | 23        |
| 8.2       | Definition of Strong Portability . . . . .         | 23        |
| 8.3       | Unified Measurement Panel . . . . .                | 24        |
| 8.4       | SP Block: Spectral Profile . . . . .               | 24        |
| 8.5       | MC Block: Modular Commutator Diagnostics . . . . . | 24        |
| 8.6       | LP Block: Locality and Criticality . . . . .       | 24        |
| 8.7       | GS Block: Geometry and Stability . . . . .         | 25        |
| 8.8       | BR Block: Backreaction . . . . .                   | 25        |
| 8.9       | Universal Gates . . . . .                          | 25        |
| 8.10      | Validation Protocol . . . . .                      | 25        |
| 8.11      | Cross-Domain Application . . . . .                 | 26        |
| 8.12      | Portability Scorecard . . . . .                    | 26        |
| 8.13      | Mechanistic Invariants . . . . .                   | 26        |
| 8.14      | Failure Domains . . . . .                          | 26        |
| 8.15      | Conceptual Meaning . . . . .                       | 27        |
| 8.16      | Scope and Status . . . . .                         | 27        |
| <b>9</b>  | <b>Universal Equation</b>                          | <b>27</b> |
| 9.1       | From Modular Dynamics to a Unified Law . . . . .   | 27        |
| 9.2       | Phase-Dependent Structure . . . . .                | 27        |
| 9.3       | Universal Dynamical Equation . . . . .             | 27        |
| 9.4       | Components of the Equation . . . . .               | 28        |
| 9.5       | Interpretation of the Equation . . . . .           | 29        |
| 9.6       | Spectral Encoding of Physics . . . . .             | 29        |
| 9.7       | Fixed Points and Stability . . . . .               | 29        |
| 9.8       | Phase Transitions . . . . .                        | 29        |
| 9.9       | Relation to Known Physics . . . . .                | 29        |
| 9.10      | Flavor Sector as a Phase Realization . . . . .     | 30        |
| 9.11      | Conceptual Summary . . . . .                       | 30        |
| <b>10</b> | <b>Numerical Program and Empirical Validation</b>  | <b>30</b> |
| 10.1      | Role of Computation in UMD . . . . .               | 30        |
| 10.2      | Core Principles . . . . .                          | 30        |
| 10.3      | State Families . . . . .                           | 31        |
| 10.4      | Observable Set . . . . .                           | 31        |
| 10.5      | Step H: Spectral–Observable Relation . . . . .     | 31        |
| 10.6      | Extraction of the Running Exponent . . . . .       | 32        |
| 10.7      | Step M: Spectral Flow Law . . . . .                | 32        |
| 10.8      | Cross-Domain Validation . . . . .                  | 32        |
| 10.9      | Bootstrap Validation . . . . .                     | 32        |
| 10.10     | Criticality Detection . . . . .                    | 33        |

|           |                                                             |           |
|-----------|-------------------------------------------------------------|-----------|
| 10.11     | Near vs Far Observables . . . . .                           | 33        |
| 10.12     | Spectral Energy Distribution . . . . .                      | 33        |
| 10.13     | Correlation with Spectral Scale . . . . .                   | 33        |
| 10.14     | Failure Domains . . . . .                                   | 33        |
| 10.15     | Computational Pipeline . . . . .                            | 34        |
| 10.16     | Connection to Flavor Physics . . . . .                      | 34        |
| 10.17     | Summary . . . . .                                           | 34        |
| <b>11</b> | <b>Flavor Structure: CKM Mixing and CP Violation</b>        | <b>34</b> |
| 11.1      | Emergence of Flavor Mixing from Modular Structure . . . . . | 34        |
| 11.2      | Deterministic Construction of Modular Generators . . . . .  | 35        |
| 11.3      | Hierarchy of Mixing Angles . . . . .                        | 35        |
| 11.4      | Origin of CP Violation . . . . .                            | 35        |
| 11.5      | Physical Interpretation . . . . .                           | 36        |
| 11.6      | Summary . . . . .                                           | 36        |
| 11.7      | Comparison with Experimental Data (PDG) . . . . .           | 36        |
| 11.8      | Connection to the Higgs Sector . . . . .                    | 37        |
| 11.8.1    | Mass Generation as Spectral Formation . . . . .             | 37        |
| 11.8.2    | Yukawa Couplings as Modular Couplings . . . . .             | 37        |
| 11.8.3    | Unified Origin of Mass and Mixing . . . . .                 | 37        |
| 11.8.4    | Interpretation of the Higgs Field . . . . .                 | 38        |
| 11.8.5    | Geometric Picture . . . . .                                 | 38        |
| 11.8.6    | Key Result . . . . .                                        | 38        |
| 11.9      | Variational Origin of Yukawa Couplings . . . . .            | 38        |
| 11.9.1    | Variational Principle . . . . .                             | 38        |
| 11.9.2    | Emergence of Modular Generator . . . . .                    | 39        |
| 11.9.3    | Flavor Structure from Interaction Channels . . . . .        | 39        |
| 11.9.4    | Identification with Yukawa Structure . . . . .              | 39        |
| 11.9.5    | From $\lambda_{ij}$ to $C_{ij}$ . . . . .                   | 39        |
| 11.9.6    | Interpretation . . . . .                                    | 40        |
| 11.9.7    | Key Result . . . . .                                        | 40        |
| 11.10     | Discussion of Deviations . . . . .                          | 40        |
| <b>12</b> | <b>Discussion</b>                                           | <b>40</b> |
| 12.1      | Summary of Results . . . . .                                | 40        |
| 12.2      | Conceptual Shift . . . . .                                  | 41        |
| 12.3      | Unification Across Domains . . . . .                        | 41        |
| 12.4      | Role of Spectral Structure . . . . .                        | 42        |
| 12.5      | Interpretation of Renormalization . . . . .                 | 42        |
| 12.6      | Emergence of Geometry and Gravity . . . . .                 | 42        |
| 12.7      | Gauge Structure and Hidden Degrees of Freedom . . . . .     | 42        |
| 12.8      | Flavor Physics as Spectral Phenomenon . . . . .             | 43        |
| 12.9      | Operational Significance . . . . .                          | 43        |
| 12.10     | Limitations . . . . .                                       | 43        |
| 12.11     | Outlook . . . . .                                           | 43        |
| 12.12     | Final Perspective . . . . .                                 | 44        |
| <b>A</b>  | <b>Appendix A: Numerical Results</b>                        | <b>44</b> |
| A.1       | Overview . . . . .                                          | 44        |
| A.2       | Spectral Construction . . . . .                             | 44        |
| A.3       | CKM Extraction Procedure . . . . .                          | 44        |
| A.4       | Representative CKM Results . . . . .                        | 44        |

|          |                                         |           |
|----------|-----------------------------------------|-----------|
| A.5      | Mass Spectra . . . . .                  | 45        |
| A.6      | Mass–Mixing Relation . . . . .          | 45        |
| A.7      | CP Violation . . . . .                  | 45        |
| A.8      | Spectral Flow and Scaling . . . . .     | 45        |
| A.9      | Criticality Detection . . . . .         | 45        |
| A.10     | Robustness Tests . . . . .              | 46        |
| A.11     | Summary of Numerical Findings . . . . . | 46        |
| <b>B</b> | <b>Conclusion</b>                       | <b>46</b> |
| <b>C</b> | <b>Conclusion</b>                       | <b>47</b> |

# 1 Introduction

Modern theoretical physics is built upon two highly successful yet conceptually distinct frameworks: quantum theory and spacetime geometry. Quantum theory provides a probabilistic description of physical systems in terms of Hilbert spaces and operator algebras, while general relativity describes gravitation as the curvature of a differentiable spacetime manifold. Despite their empirical success, both frameworks rely on foundational structures that are introduced a priori and not derived within the theory itself.

This raises a fundamental question: what is the minimal ontological structure from which physical reality can be reconstructed?

In this work, we propose a shift from object-based ontology to an information-based formulation grounded in distinguishability. Instead of assuming the existence of spacetime, fields, or interactions, we begin with the notion that physical reality is fundamentally a structure of distinguishable states. This principle leads naturally to a representation of states by density operators  $\rho$ , which encode all physically accessible information in a basis-independent manner.

A key step in the construction is the introduction of the modular generator

$$K = -\log \rho, \tag{1}$$

which provides a logarithmic representation of informational content. The spectral properties of  $K$  define a global structure that captures the organization of information within the state. Rather than focusing on individual eigenvalues, we consider the spectral distribution as the primary object.

The central idea of this work is that physical structure emerges from this spectral organization. In particular, we demonstrate that a sequence of increasingly complex structures arises from the properties of the modular spectrum:

- spectral clustering defines internal structure,
- optimal partitions give rise to locality,
- correlation patterns induce geometric relations,
- modular evolution generates an intrinsic notion of dynamics,
- spectral statistics determine characteristic scales through renormalization.

This leads to a unified chain of emergence,

$$\rho \longrightarrow K \longrightarrow p(k) \longrightarrow \text{structure} \longrightarrow \text{locality} \longrightarrow \text{geometry} \longrightarrow \text{dynamics} \longrightarrow \text{scale}, \tag{2}$$

in which each level arises from the properties of the preceding one without introducing additional fundamental assumptions.

Within this framework, several core concepts of modern physics are reinterpreted. Renormalization is understood as spectral flow in the space of states rather than as a transformation of parameters. Geometry emerges from correlation structure rather than being postulated as a background. Gauge symmetry appears as an access-relative redundancy determined by the observable algebra. Criticality is characterized not by correlation length, but by instability of informational structure.

A central feature of the present approach is that it is not purely conceptual. The theory is accompanied by a computational program based on spectral observables, modular commutators, and partition diagnostics. This provides operational criteria for phase identification, criticality detection, and validation across multiple physical domains.

Furthermore, we extend the framework to flavor physics. We show that hierarchical structures in the modular spectrum naturally generate quark mass hierarchies and mixing patterns.

In particular, the Cabibbo–Kobayashi–Maskawa (CKM) matrix emerges as a manifestation of spectral misalignment between sectors, while CP violation arises from phase structure in modular dynamics.

The resulting framework defines a unified perspective in which physical reality is understood as an emergent manifestation of distinguishability and spectral organization. All structures—geometry, dynamics, matter, and interactions—are derived from a single primitive object, the density operator  $\rho$ , and its modular generator.

The structure of the paper is as follows. In Section 2 we establish the pre-quantum foundations based on distinguishability and derive the density operator formalism. Section 3 introduces modular dynamics and the universal evolution equation. Section 4 develops the spectral representation and statistical structure of information. Sections 5 and 6 establish the emergence of phase structure, locality, and geometry. Section 7 develops gauge structure and modular defects. Section 8 introduces strong portability as a unifying diagnostic framework. Section 9 formulates the universal dynamical equation. Section 10 presents the numerical program and validation results. Section 11 applies the framework to flavor physics and derives CKM structure and CP violation. We conclude with a discussion of conceptual implications and future directions.

## 2 Pre-Quantum Foundations

### 2.1 Distinguishability as Primary Structure

We begin by replacing the standard object-based ontology with a relational one. The fundamental notion is not that of an object, field, or spacetime point, but that of distinguishability between states.

Formally, we introduce a distinguishability structure

$$\Delta : \mathcal{S} \times \mathcal{S} \rightarrow \mathbb{R}_{\geq 0}, \quad (3)$$

satisfying

$$\Delta(x, x) = 0, \quad \Delta(x, y) = \Delta(y, x), \quad (4)$$

where  $\mathcal{S}$  denotes the set of admissible proto-states.

This structure encodes the operational principle that only differences between states have physical meaning. The question “what exists” is replaced by “what can be distinguished.”

### 2.2 From Distinguishability to Information

To obtain a quantitative description, distinguishability must be represented in a consistent and composable way. In particular, for composite systems, the distinguishability measure must satisfy compatibility under composition.

This requirement naturally leads to information-theoretic quantities. The most fundamental among them are divergences between states, such as the relative entropy

$$D(\rho \parallel \sigma) = \text{Tr}(\rho(\log \rho - \log \sigma)), \quad (5)$$

which provides a measure of distinguishability between probabilistic representations of states.

Thus, we adopt the principle:

*Distinguishability must admit a representation as an information measure.*

### 2.3 Emergence of the Density Operator

A quantitative representation of distinguishability requires the introduction of probabilities. However, classical probability distributions depend on a choice of basis and are therefore insufficient.

To achieve basis invariance, we are led to operator-valued representations. This requirement uniquely selects the density operator formalism.

A density operator  $\rho$  is a positive semidefinite operator acting on a Hilbert space  $\mathcal{H}$  such that

$$\rho \geq 0, \quad \text{Tr}(\rho) = 1. \quad (6)$$

The emergence of  $\rho$  can be understood as a consequence of three requirements:

- linearity of expectation values,
- positivity of probabilities,
- invariance under change of basis.

These conditions imply that states must be represented by positive operators. In this sense, quantum states are not postulated but derived.

### 2.4 Modular Generator

A central step in the construction is the transformation from multiplicative probabilities to additive quantities. This is achieved through the logarithmic map:

$$K = -\log \rho. \quad (7)$$

The operator  $K$  is referred to as the modular generator.

The logarithmic transformation plays a crucial role:

- it converts products into sums,
- it linearizes the informational structure,
- it enables a dynamical interpretation.

Thus, the transition

$$\rho \longrightarrow K \quad (8)$$

marks the passage from a static description to a generator of informational structure.

### 2.5 Spectral Representation

Let the density operator admit a spectral decomposition

$$\rho = \sum_i \lambda_i |\psi_i\rangle \langle \psi_i|, \quad \lambda_i > 0, \quad \sum_i \lambda_i = 1. \quad (9)$$

The modular generator is then diagonal in the same basis:

$$K = \sum_i k_i |\psi_i\rangle \langle \psi_i|, \quad k_i = -\log \lambda_i. \quad (10)$$

The eigenvalues  $\lambda_i$  encode the informational content of the state, while the quantities  $k_i$  represent additive information levels.

To obtain a global description, we introduce the spectral distribution

$$p(k) = \frac{1}{N} \sum_i \delta(k - k_i), \quad (11)$$

where  $N = \dim(\mathcal{H})$ .

This distribution serves as the primary structural object in the subsequent construction.

## 2.6 Interpretation and Ontological Closure

The sequence

$$\text{distinguishability} \longrightarrow \rho \longrightarrow K \longrightarrow p(k) \quad (12)$$

defines the foundational layer of the theory.

Each step follows from the previous one without introducing additional primitives. In particular:

- $\rho$  encodes distinguishability in a basis-independent form,
- $K$  provides a logarithmic representation of information,
- $p(k)$  captures the global spectral structure.

This establishes an informationally closed framework in which all subsequent physical structures will be derived from properties of the spectral distribution and its evolution.

## 2.7 Scope and Status

At this stage, the construction is purely informational. No assumptions about spacetime, geometry, or dynamics have been introduced.

The objects  $(\rho, K, p(k))$  define a complete representation of the state at the informational level. In the following sections, we will show how physical structure emerges from this representation through modular dynamics and spectral organization.

# 3 Modular Dynamics

## 3.1 From Static Information to Dynamics

In the previous section, we established that the density operator  $\rho$  and its logarithmic transform

$$K = -\log \rho \quad (13)$$

arise naturally from the requirement of representing distinguishability.

We now address the central question: how does a state evolve in the space of distinguishability?

Unlike conventional approaches, we do not assume an external time parameter. Instead, we introduce an ordering parameter  $\lambda$  that parametrizes the evolution of informational structure:

$$\rho \longrightarrow \rho(\lambda). \quad (14)$$

The parameter  $\lambda$  is not interpreted as physical time, but as an intrinsic ordering variable in state space.

## 3.2 Degeneracy of the Naive Modular Flow

A natural candidate for dynamics is the modular commutator

$$\frac{d\rho}{d\lambda} = -i[K, \rho]. \quad (15)$$

However, since  $K = -\log \rho$  is a function of  $\rho$ , it commutes with  $\rho$ :

$$[K, \rho] = 0. \quad (16)$$

This implies that the naive modular flow is trivial.

*Nontrivial dynamics requires an extension of the modular generator.*

### 3.3 Relative Modular Operator

To resolve this degeneracy, we introduce a reference state  $\sigma$  and define the relative modular generator

$$K_{\rho|\sigma} = -\log \rho + \log \sigma. \quad (17)$$

In general,

$$[K_{\rho|\sigma}, \rho] \neq 0, \quad (18)$$

which produces nontrivial evolution.

The reference state  $\sigma$  encodes macroscopic constraints and defines a phase-dependent notion of equilibrium.

### 3.4 Full Dynamical Equation

We define the evolution of the state by the equation

$$\frac{d\rho}{d\lambda} = -i[K_{\rho|\sigma}, \rho] + \mathcal{D}[\rho], \quad (19)$$

where  $\mathcal{D}[\rho]$  is a dissipative term.

We take  $\mathcal{D}[\rho]$  in the Gorini–Kossakowski–Sudarshan–Lindblad (GKSL) form:

$$\mathcal{D}[\rho] = \sum_{\alpha} \gamma_{\alpha} \left( L_{\alpha} \rho L_{\alpha}^{\dagger} - \frac{1}{2} \{ L_{\alpha}^{\dagger} L_{\alpha}, \rho \} \right), \quad \gamma_{\alpha} \geq 0. \quad (20)$$

This ensures:

- complete positivity,
- trace preservation,
- physical consistency of the evolution.

### 3.5 Structure of the Evolution

The dynamical equation naturally decomposes into two parts:

$$\frac{d\rho}{d\lambda} = \underbrace{-i[K_{\rho|\sigma}, \rho]}_{\text{coherent flow}} + \underbrace{\mathcal{D}[\rho]}_{\text{dissipative flow}}. \quad (21)$$

The coherent term generates internal informational motion, while the dissipative term governs redistribution of spectral weight.

A key property is that the commutator term is isospectral: it preserves the eigenvalues of  $\rho$ , while the dissipator modifies them.

### 3.6 Entropy Monotonicity and Arrow of Ordering

The GKSL evolution satisfies a monotonicity property for the relative entropy:

$$\frac{d}{d\lambda} D(\rho(\lambda) \parallel \sigma) \leq 0. \quad (22)$$

This establishes a preferred direction of evolution.

*The parameter  $\lambda$  defines an informational arrow of ordering.*

Thus, irreversibility arises as a consequence of informational structure rather than as a fundamental assumption.

### 3.7 Spectral Evolution and Renormalization

Under the evolution  $\rho(\lambda)$ , the modular generator becomes

$$K(\lambda) = -\log \rho(\lambda), \quad (23)$$

and the spectral distribution evolves accordingly:

$$p(k; \lambda). \quad (24)$$

The commutator term preserves the spectrum, while the dissipator induces spectral drift:

$$\frac{d\lambda_i}{d\lambda} = \langle \psi_i | \mathcal{D}[\rho] | \psi_i \rangle. \quad (25)$$

This leads to the interpretation:

*Renormalization group flow is spectral evolution of the state.*

Scale is therefore identified with informational level rather than geometric size.

### 3.8 Stationary States and Fixed Points

A stationary state  $\rho_*$  satisfies

$$\frac{d\rho}{d\lambda} = 0, \quad (26)$$

which implies

$$[K_{\rho|\sigma}, \rho] = 0, \quad \mathcal{D}[\rho] = 0. \quad (27)$$

Such states correspond to fixed points of the spectral flow and define equilibrium configurations.

### 3.9 Conceptual Summary

We summarize the logical chain established in this section:

$$\text{distinguishability} \longrightarrow \rho \longrightarrow K_{\rho|\sigma} \longrightarrow \text{dynamics}. \quad (28)$$

This formulation implies a fundamental shift:

- no background spacetime is assumed,
- no fundamental time parameter is required,
- no external Hamiltonian is postulated.

Instead, dynamics arises as evolution in the space of distinguishability, governed by modular structure.

### 3.10 Scope and Status

The dynamical law introduced here provides a complete and self-contained description of evolution at the informational level.

In the following sections, we will show how this dynamics gives rise to phase structure, locality, geometry, and ultimately physical observables.

## 4 Spectral Structure

### 4.1 Spectral Distribution

Given a density operator  $\rho$ , we define the modular generator

$$K = -\log \rho, \quad (29)$$

with eigenvalues  $\{k_i\}$ .

Rather than treating these eigenvalues individually, we introduce the spectral distribution

$$p(k) = \frac{1}{N} \sum_i \delta(k - k_i), \quad (30)$$

where  $N = \dim(\mathcal{H})$ .

This distribution encodes the global structure of informational content associated with the state. It provides a representation that is invariant under basis transformations and robust under perturbations.

### 4.2 Statistical Descriptors

The distribution  $p(k)$  can be characterized by standard statistical quantities:

$$\mu_K = \frac{1}{N} \sum_i k_i, \quad (31)$$

$$\text{Var}(K) = \frac{1}{N} \sum_i (k_i - \mu_K)^2. \quad (32)$$

In addition, quantile-based descriptors provide robust measures of spectral structure. For  $\alpha \in (0, 1)$ , the quantile  $q_\alpha$  is defined by

$$\int_{-\infty}^{q_\alpha} p(k) dk = \alpha. \quad (33)$$

A key observable is the spectral width

$$\Delta K = q_{0.9} - q_{0.1}, \quad (34)$$

which captures large-scale variation in the distribution.

These descriptors encode:

- global scale ( $\mu_K$ ),
- fluctuations ( $\text{Var}(K)$ ),
- tail structure (quantiles).

### 4.3 Distributional Representation of Information

The distribution  $p(k)$  provides a global representation of informational structure. Unlike the operator  $\rho$ , which depends on a full matrix representation,  $p(k)$  captures only the spectral content.

This leads to an equivalence relation:

$$\rho_1 \sim \rho_2 \iff p_1(k) = p_2(k). \quad (35)$$

All observables depending only on  $p(k)$  are invariant within this class.

This motivates the interpretation:

*Physical structure is encoded at the level of spectral distributions.*

#### 4.4 Spectral Modes

A generic spectral distribution is not uniform. It typically exhibits structure in the form of clusters or regions of enhanced density.

We define a spectral cluster as a subset of eigenvalues

$$C_\alpha = \{k_i \mid k_i \in \text{region of enhanced density}\}. \quad (36)$$

A spectral mode is defined as a cluster satisfying:

- persistence under perturbations  $\rho \rightarrow \rho + \delta\rho$ ,
- smooth variation of statistical descriptors,
- separation from other clusters by regions of lower density.

Each mode defines a partial distribution

$$p_\alpha(k) = \frac{1}{|C_\alpha|} \sum_{k_i \in C_\alpha} \delta(k - k_i). \quad (37)$$

#### 4.5 Structural Interpretation

Spectral modes provide a natural notion of internal structure. Instead of assigning structure externally, we identify:

$$\text{structure} \equiv \text{stable spectral mode}. \quad (38)$$

This definition is purely internal and does not rely on spatial or dynamical assumptions. Multiple modes induce a hierarchical organization:

- microscopic level: individual eigenvalues,
- mesoscopic level: spectral modes,
- macroscopic level: full distribution  $p(k)$ .

#### 4.6 Stability Under Evolution

Under modular evolution  $\rho(\lambda)$ , the distribution evolves as  $p(k; \lambda)$ .

A spectral mode  $C_\alpha$  is dynamically stable if

$$C_\alpha(\lambda_1) \approx C_\alpha(\lambda_2) \quad (39)$$

over a finite range of  $\lambda$ .

This stability defines persistent structures in the system.

#### 4.7 Interaction Between Modes

Spectral modes are not independent. Their interaction is encoded in the evolution of the distribution.

This interaction manifests as:

- merging or splitting of clusters,
- transfer of spectral weight,
- changes in relative prominence.

These processes define mechanisms of structural reorganization.

## 4.8 Robustness and Universality

A key property of the spectral representation is robustness. Small perturbations of the state induce small deformations of  $p(k)$ .

Statistical descriptors such as  $\mu_K$ ,  $\text{Var}(K)$ , and  $\Delta K$  remain stable under such perturbations.

This implies that spectral structure is a universal feature, independent of microscopic details.

## 4.9 Conceptual Summary

We summarize the key result of this section:

$$\rho \longrightarrow K \longrightarrow p(k) \longrightarrow \text{structure.} \quad (40)$$

This establishes the first nontrivial step in the chain of emergence: internal structure arises directly from spectral organization.

## 4.10 Scope and Status

At this stage, structure has been defined purely in spectral terms. No notion of space, locality, or geometry has been introduced.

In the following section, we show how relations between spectral modes give rise to locality and phase structure.

# 5 Phases and Criticality

## 5.1 From Spectral Structure to Phases

In the previous section, we established that internal structure emerges from the spectral distribution  $p(k)$  in the form of stable spectral modes.

We now address a central question:

*How do distinct physical regimes arise from a single underlying dynamics?*

The answer is given by phase structure. In contrast to conventional approaches, phases are not introduced via external parameters or symmetry breaking, but arise from the organization of information within the state.

## 5.2 Definition of a Phase

We define a phase as a triple

$$F = (P^*, \mathcal{A}_F, \mathcal{Z}_F), \quad (41)$$

where:

- $P^*$  is the optimal partition of the system,
- $\mathcal{A}_F$  is the accessible algebra of observables,
- $\mathcal{Z}_F$  is the center (pointer algebra).

This definition is entirely internal and does not rely on spacetime, fields, or symmetry groups.

### 5.3 Partition Functional

To determine  $P^*$ , we introduce the functional

$$J_\eta(P; \rho) = D(\rho \| \rho_P) + \eta \Omega(P), \quad (42)$$

where:

- $\rho_P = \bigotimes_{X \in P} \rho_X$  is the factorized state,
- $\Omega(P)$  penalizes complexity,
- $\eta > 0$  controls the balance between accuracy and simplicity.

The first term measures residual correlations, while the second enforces structural simplicity.

### 5.4 Optimal Partition

The optimal partition is defined as

$$P^* = \arg \min_P J_\eta(P; \rho). \quad (43)$$

This partition identifies subsystems that are maximally independent in the information-theoretic sense.

### 5.5 Locality as a Derived Property

We define the locality measure

$$T_P(\rho) = D(\rho \| \rho_P). \quad (44)$$

Interpretation:

- small  $T_P \Rightarrow$  weak correlations (localized structure),
- large  $T_P \Rightarrow$  strong correlations (nonlocal structure).

Thus:

*Locality is not fundamental; it is an emergent property of optimal partitioning.*

### 5.6 Landscape Structure

The functional  $J_\eta(P; \rho)$  defines a landscape over partitions.

We introduce two key quantities:

- $\Delta$  — the gap between the best and competing partitions,
- $\Gamma$  — the switching rate between near-optimal partitions.

These quantities characterize the stability of the informational organization.

### 5.7 Definition of Criticality

We define criticality by the condition

$$\text{Criticality} \equiv (\Delta \rightarrow 0) \wedge (\Gamma > 0). \quad (45)$$

Interpretation:

- $\Delta \rightarrow 0$  implies a flat landscape,
- $\Gamma > 0$  implies active competition between structures.

Thus:

*Criticality corresponds to instability of informational organization.*

## 5.8 Replacement of Correlation Length

In conventional theories, criticality is associated with divergence of correlation length.

In the present framework:

- no background geometry is assumed,
- correlation length is not fundamental.

Instead:

*Criticality is defined by the structure of the partition landscape.*

## 5.9 Phase Classification

We identify three primary regimes:

- **Localized phase:** stable  $P^*$ ,  $\Delta \gg 0$ ,  $\Gamma \approx 0$ ,
- **Critical phase:**  $\Delta \rightarrow 0$ ,  $\Gamma > 0$ ,
- **Non-geometric phase:** no stable partition exists.

Each regime corresponds to a qualitatively distinct organization of information.

## 5.10 Geometric Interpretation

When a unique optimal partition exists:

- subsystem structure is stable,
- distances derived from correlations are well-defined,
- geometry emerges.

When multiple partitions compete:

- subsystem structure fluctuates,
- distances become ambiguous,
- geometry becomes unstable.

Thus:

$$\text{Criticality} \Rightarrow \text{instability of geometry.} \quad (46)$$

## 5.11 Connection to Spectral Flow

Phase transitions correspond to structural changes in the spectral distribution  $p(k; \lambda)$ .

In particular, criticality is associated with:

$$\beta_q \approx 0, \quad \frac{d^2 k(q)}{d\lambda^2} \neq 0, \quad (47)$$

where  $\beta_q = \frac{dk(q)}{d\lambda}$  is the spectral flow.

This links phase structure directly to modular dynamics.

## 5.12 Physical Consequences

This framework predicts:

- phase transitions without reference to symmetry breaking,
- absence of fundamental correlation length,
- dynamical switching between competing structures,
- emergence and breakdown of geometry as phase phenomena.

## 5.13 Conceptual Summary

We summarize the key result:

$$\text{Phases} = \text{stable regimes of informational organization.} \quad (48)$$

and

$$\text{Criticality} = \text{flatness} + \text{switching.} \quad (49)$$

This provides a universal definition of phase structure independent of spacetime or fields.

## 5.14 Scope and Status

At this stage, phase structure has been defined purely in terms of information and spectral organization.

In the next section, we show how stable phases give rise to emergent geometry and gravitational dynamics.

# 6 Geometry and Gravity

## 6.1 From Phase Structure to Geometry

In the previous section, we established that physical regimes correspond to distinct phases of informational organization.

We now address the next fundamental question:

*When does a geometric description emerge from a purely informational framework?*

The key principle is that geometry is not fundamental. It arises only in phases where the organization of correlations is sufficiently stable.

## 6.2 Mutual Information as a Geometric Primitive

Let  $X$  and  $Y$  be subsystems defined by the optimal partition  $P^*$ .

We define the mutual information:

$$I(X : Y) = S(\rho_X) + S(\rho_Y) - S(\rho_{XY}), \quad (50)$$

where  $S(\rho) = -\text{Tr}(\rho \log \rho)$  is the von Neumann entropy.

Interpretation:

- large  $I(X : Y) \Rightarrow$  strong correlation,
- small  $I(X : Y) \Rightarrow$  weak correlation.

### 6.3 Emergent Distance

We define an effective distance:

$$d(X, Y) = \frac{1}{(I(X : Y) + \varepsilon)^\nu}, \quad (51)$$

where  $\varepsilon > 0$  is a regularization parameter and  $\nu > 0$  controls scaling.

Thus:

*Distance is an inverse function of correlations.*

### 6.4 Graph Geometry

The set of subsystems  $X \in P^*$  defines a weighted graph:

$$G = (V, E), \quad (52)$$

where:

- vertices correspond to subsystems,
- edges are weighted by  $d(X, Y)$ .

Distances between arbitrary nodes are defined via shortest paths:

$$d_\rho(X, Y) = \min_{\gamma: X \rightarrow Y} \sum_{(i,j) \in \gamma} d(i, j). \quad (53)$$

### 6.5 Conditions for Geometric Phase

A geometric description is valid only if:

- the optimal partition  $P^*$  is stable,
- correlations vary smoothly,
- geometric observables are robust under perturbations.

We define a stability measure  $S_{\text{geo}}$  characterizing fluctuations of distances.

Thus:

*Geometry exists only in stable phases.*

### 6.6 Breakdown of Geometry

In critical regimes:

- multiple partitions compete,
- subsystem structure fluctuates,
- distances become ambiguous.

Therefore:

$$\text{Criticality} \Rightarrow \text{breakdown of geometry}. \quad (54)$$

## 6.7 Information Metric

Consider a parametric family of states  $\rho(\theta)$ .

We define the information metric:

$$g_{\mu\nu} = \frac{\partial^2}{\partial\theta^\mu \partial\theta^\nu} D(\rho(\theta) \parallel \rho(\theta_0)). \quad (55)$$

Interpretation:

- the metric is derived from distinguishability,
- geometry is a second-order structure in state space.

## 6.8 Entropy and Geometry

Entropy plays a central role:

$$S(\rho) = -\text{Tr}(\rho \log \rho). \quad (56)$$

Changes in entropy encode geometric deformations:

$$\delta S \sim \delta(\text{geometry}). \quad (57)$$

## 6.9 First Law of Entanglement

For small perturbations:

$$\delta S = \delta\langle K \rangle, \quad (58)$$

where  $K = -\log \rho$  is the modular generator.

This relation is purely information-theoretic.

## 6.10 Emergence of Gravity

The relation

$$\delta S = \delta\langle K \rangle \quad (59)$$

has profound consequences.

In geometric regimes:

- entropy variation corresponds to energy variation,
- modular generator acts as an effective Hamiltonian,
- local perturbations induce geometric response.

This leads to equations analogous to gravitational dynamics.

Thus:

*Gravity emerges as an entropic response of informational structure.*

## 6.11 Role of the Reference State

The reference state  $\sigma$  defines equilibrium.

Deviations from  $\sigma$  generate effective forces:

$$K_{\rho|\sigma} = -\log \rho + \log \sigma. \quad (60)$$

Interpretation:

- $\sigma$  encodes macroscopic constraints,
- deviations correspond to dynamical excitations.

## 6.12 Cosmological Interpretation

In near-equilibrium regimes:

- entropy approaches extremal values,
- effective constant terms emerge.

These can be interpreted as:

- emergent cosmological constant,
- large-scale equilibrium structure.

## 6.13 Conceptual Summary

We summarize the main results:

$$\text{Geometry} = \text{correlation structure}, \quad (61)$$

$$\text{Metric} = \text{distinguishability}, \quad (62)$$

$$\text{Gravity} = \text{entropic response}. \quad (63)$$

## 6.14 Scope and Status

At this stage, geometry and gravity have been derived as emergent phenomena from informational structure.

No spacetime manifold, metric tensor, or gravitational action was assumed.

In the next section, we extend this framework to gauge structure and modular defects.

# 7 Gauge Structure and Modular Defects

## 7.1 From Geometry to Gauge Structure

In the previous section, we showed that geometry emerges from correlation structure in stable phases.

We now extend this framework to describe gauge structure.

The central idea is:

*Gauge symmetry is not fundamental, but arises as a redundancy in the accessible description of the system.*

## 7.2 Access Algebra

Given a phase  $F = (P^*, \mathcal{A}_F, \mathcal{Z}_F)$ , we define the access algebra:

$$\mathcal{A}_F = \bigvee_{X \in P^*} \mathcal{B}(\mathcal{H}_X), \quad (64)$$

where  $\mathcal{B}(\mathcal{H}_X)$  denotes the algebra of observables on subsystem  $X$ .

Interpretation:

- $\mathcal{A}_F$  defines what can be measured,
- it determines the operational content of the theory.

### 7.3 Pointer Algebra (Center)

We define the center:

$$\mathcal{Z}_F = \{Z \in \mathcal{A}_F \mid [Z, A] = 0 \quad \forall A \in \mathcal{A}_F\}. \quad (65)$$

Interpretation:

- $\mathcal{Z}_F$  encodes classical observables,
- it defines superselection sectors.

### 7.4 Access Equivalence

Two states are operationally equivalent if:

$$\rho \sim_F \rho' \iff \text{Tr}(\rho A) = \text{Tr}(\rho' A) \quad \forall A \in \mathcal{A}_F. \quad (66)$$

Thus:

*Gauge equivalence is indistinguishability under accessible observables.*

### 7.5 Gauge Transformations

A unitary transformation  $U$  is a gauge transformation if:

$$U \mathcal{A}_F U^\dagger = \mathcal{A}_F, \quad U \mathcal{Z}_F U^\dagger = \mathcal{Z}_F. \quad (67)$$

In the strongest form:

$$U Z U^\dagger = Z \quad \forall Z \in \mathcal{Z}_F. \quad (68)$$

Interpretation:

- gauge transformations preserve all observable content,
- they act only on inaccessible degrees of freedom.

### 7.6 Modular Defects

We introduce a central concept:

*A modular defect is a region where the access structure  $(\mathcal{A}_F, \mathcal{Z}_F)$  cannot be defined globally and consistently.*

### 7.7 Operational Indicators of Defects

Defects are detected through:

- partition instability (high switching rate  $\Gamma$ ),
- landscape flatness ( $\Delta \rightarrow 0$ ),
- variation in  $\dim \mathcal{Z}_F$ ,
- breakdown of coherence suppression.

Thus:

$$\text{Defect} = \text{instability of information structure.} \quad (69)$$

## 7.8 Patching Structure

In defect regions, a global description is impossible.

We introduce patches  $\{U_\alpha\}$  such that:

- each patch has its own  $(\mathcal{A}_F^{(\alpha)}, \mathcal{Z}_F^{(\alpha)})$ ,
- descriptions are locally consistent.

## 7.9 Transition Maps

On overlaps  $U_\alpha \cap U_\beta$ , we define maps:

$$\phi_{\alpha\beta} : \mathcal{A}_F^{(\alpha)} \rightarrow \mathcal{A}_F^{(\beta)}, \quad (70)$$

which preserve expectation values.

## 7.10 Groupoid Structure

Unlike global symmetry groups, these maps compose only when domains match.

Thus, the gauge structure forms a *groupoid* rather than a group:

$$\phi_{\beta\gamma} \circ \phi_{\alpha\beta} \text{ defined only if compatible.} \quad (71)$$

Interpretation:

*Gauge symmetry is local and relational, not global.*

## 7.11 Holonomy Test

To detect nontrivial gauge structure, consider a loop:

$$\Phi_{\text{loop}} = \phi_{\gamma\alpha} \circ \phi_{\beta\gamma} \circ \phi_{\alpha\beta}. \quad (72)$$

If:

$$\Phi_{\text{loop}} \neq \text{Id}, \quad (73)$$

the gauge structure is nontrivial.

Interpretation:

*Holonomy signals modular defects.*

## 7.12 Physical Interpretation

We summarize:

- gauge symmetry is emergent,
- it reflects observational limitations,
- defects correspond to breakdown of global structure.

## 7.13 Connection to Standard Gauge Theory

In conventional theories:

- gauge symmetry is postulated,
- groups are introduced a priori.

In the present framework:

- gauge symmetry emerges from access structure,
- groupoid replaces global symmetry group.

### 7.14 Dark Sector Interpretation

We define the commutant:

$$\mathcal{A}'_F = \{X \mid [X, A] = 0 \ \forall A \in \mathcal{A}_F\}. \quad (74)$$

Interpretation:

- $\mathcal{A}'_F$  contains inaccessible degrees of freedom,
- it represents hidden structure of the system.

Thus:

$$\text{Dark sector} = \text{information inaccessible to } \mathcal{A}_F.$$

### 7.15 Conceptual Summary

We summarize the key results:

$$\text{Gauge} = \text{access-relative redundancy}, \quad (75)$$

$$\text{Defects} = \text{instability of access structure}, \quad (76)$$

$$\text{Gauge structure} = \text{groupoid of patches}. \quad (77)$$

### 7.16 Scope and Status

Gauge structure has been derived as an emergent phenomenon from informational organization.

No symmetry group or gauge principle was assumed.

In the next section, we introduce the principle of strong portability and the universal diagnostic framework.

## 8 Strong Portability of Modular Diagnostics

### 8.1 Motivation: Toward a Unified Language

A central challenge in theoretical physics is not only to unify equations, but to unify descriptions across domains.

Different areas—quantum systems, geometry, gravity, and renormalization—use distinct primitives and methods.

We impose a stronger requirement:

$$A \text{ unified theory must provide a transportable diagnostic framework.}$$

This leads to the concept of *strong portability*.

### 8.2 Definition of Strong Portability

Strong portability is the property that a single diagnostic panel, defined in terms of  $(\rho, K)$ , can be applied across multiple physical domains without retuning.

The only allowed adaptations are:

- choice of flow parameter  $\lambda$ ,
- choice of visible subsystem  $\rho_{\text{vis}}$ .

No structural modification of diagnostics is permitted.

### 8.3 Unified Measurement Panel

We define a universal diagnostic structure:

$$\mathcal{F} = \text{SP} \cup \text{MC} \cup \text{LP} \cup \text{GS} \cup \text{BR}. \quad (78)$$

Each block captures a distinct aspect of the system.

### 8.4 SP Block: Spectral Profile

We define spectral coordinates:

$$k(q) = -\log \lambda_q(\rho_{\text{vis}}), \quad (79)$$

where  $\lambda_q$  denotes the  $q$ -quantile of the spectrum.

Derived quantities include:

- spectral differences  $\Delta k$ ,
- curvature measures,
- distributional asymmetry.

Interpretation:

*The spectrum encodes scale structure.*

### 8.5 MC Block: Modular Commutator Diagnostics

We define the observable:

$$b_L(\rho; O) = \frac{\|[K, O]\|}{\|K\| \|O\|}. \quad (80)$$

Empirically, we observe scaling behavior:

$$b_L \sim k(q)^\nu, \quad (81)$$

where  $\nu$  is a running exponent.

Interpretation:

- probes non-classical structure,
- directly measurable,
- connects spectral structure to observables.

### 8.6 LP Block: Locality and Criticality

We define:

$$T_P(\rho) = D(\rho \| \rho_P). \quad (82)$$

Criticality is detected by:

$$(\Delta \rightarrow 0) \wedge (\Gamma > 0). \quad (83)$$

Interpretation:

*This block captures phase structure and transitions.*

## 8.7 GS Block: Geometry and Stability

We compute correlation-based distances:

$$d_\rho(i, j), \tag{84}$$

and define stability:

$$S_{\text{geo}} = \text{Var}_{\text{seeds}}(d_{\text{nn}}). \tag{85}$$

Interpretation:

- geometry is valid only when stable,
- instability signals breakdown of geometric phase.

## 8.8 BR Block: Backreaction

We consider relations of the form:

$$\Delta d \sim \alpha_1 \Delta k + \alpha_2 \Delta S. \tag{86}$$

Interpretation:

*Backreaction links spectral dynamics to geometry.*

## 8.9 Universal Gates

All diagnostics are subject to strict validation gates:

- G1: numerical stability,
- G2: fit quality,
- G3: geometry stability,
- G4: labeling validity,
- G5: domain validity.

Failure implies abstention, not adjustment.

## 8.10 Validation Protocol

We define a universal validation scheme:

- seed-block cross-validation,
- observable perturbations,
- parameter robustness.

Two core tasks:

- prediction of  $S_{\text{geo}}$ ,
- classification of phases (L/C/N).

### 8.11 Cross-Domain Application

The same diagnostics apply across:

- open quantum systems,
- information geometry,
- emergent geometry,
- renormalization group flows.

Key result:

*The same observables characterize all domains.*

### 8.12 Portability Scorecard

We define:

- PASS (Strong): full agreement,
- PASS (Weak): partial consistency,
- FAIL: instability or out-of-domain.

Interpretation:

- prevents overinterpretation,
- enforces domain awareness.

### 8.13 Mechanistic Invariants

Strong portability requires:

- stable relation between  $b_L$  and  $k(q)$ ,
- separation of coherent and dissipative dynamics,
- reproducible phase classification.

### 8.14 Failure Domains

The framework explicitly identifies invalid regimes:

- random pure states,
- unstable partitions,
- insufficient sampling.

Key rule:

*Outside domain  $\Rightarrow$  no claims.*

## 8.15 Conceptual Meaning

Strong portability implies:

- a single language for all physics,
- different theories correspond to different regimes,
- unification is operational, not formal.

Thus:

$$\text{Physics} = \text{portable diagnostics on } (\rho, K). \quad (87)$$

## 8.16 Scope and Status

The framework provides a universal diagnostic structure linking theory and computation.

In the next section, we combine these elements into a single universal dynamical equation.

# 9 Universal Equation

## 9.1 From Modular Dynamics to a Unified Law

We now combine the previous structures into a single dynamical equation.

The guiding principle is:

*All physical phenomena arise as phase-dependent realizations of modular dynamics.*

Thus, instead of multiple fundamental theories, we postulate a single universal evolution law for the state  $\rho$ .

## 9.2 Phase-Dependent Structure

Each physical regime is characterized by a phase:

$$F = (P^*, A_F, Z_F), \quad (88)$$

where:

- $P^*$  is the optimal partition,
- $A_F$  is the accessible algebra,
- $Z_F$  is the center (pointer algebra).

This structure determines:

- observable content,
- classical sector,
- correlation structure.

## 9.3 Universal Dynamical Equation

We define the universal equation:

$$\frac{d\rho}{d\lambda} = -i [K_{\rho|\sigma_F}, \rho] + D_{\text{ent}}^{(F)}[\rho] + D_{\text{class}}^{(F)}[\rho] + F_{\text{phase}}^{(F)}[\rho]. \quad (89)$$

This equation is valid across all domains.

## 9.4 Components of the Equation

### (1) Coherent Modular Flow

$$-i [K_{\rho|\sigma_F}, \rho] \quad (90)$$

with

$$K_{\rho|\sigma_F} = -\log \rho + \log \sigma_F. \quad (91)$$

Interpretation:

- generates internal informational dynamics,
- preserves the spectrum (isospectral flow),
- encodes distinguishability gradients.

### (2) Entropic Dissipator

$$D_{\text{ent}}^{(F)}[\rho] = \sum_{\alpha} \gamma_{\alpha}^{(F)} \left( L_{\alpha} \rho L_{\alpha}^{\dagger} - \frac{1}{2} \{L_{\alpha}^{\dagger} L_{\alpha}, \rho\} \right), \quad \gamma_{\alpha}^{(F)} \geq 0. \quad (92)$$

Properties:

- completely positive,
- trace-preserving,
- generates entropy production.

Interpretation:

*Dissipation is the source of spectral flow (RG dynamics).*

### (3) Classicalization Channel

$$D_{\text{class}}^{(F)}[\rho] = \kappa_F (P_{Z_F}(\rho) - \rho), \quad (93)$$

where

$$P_{Z_F}(\rho) = \sum_{\mu} P_{\mu} \rho P_{\mu}. \quad (94)$$

Interpretation:

- suppresses off-diagonal coherences,
- drives emergence of classical observables,
- defines superselection sectors.

### (4) Phase Correction Term

$$F_{\text{phase}}^{(F)}[\rho] \quad (95)$$

Interpretation:

- effective contributions specific to a phase,
- includes emergent interactions,
- encodes low-energy phenomenology.

## 9.5 Interpretation of the Equation

The key conceptual statement is:

*One equation — multiple physical regimes.*

- Quantum mechanics:  $D_{\text{ent}} = 0$ ,  $D_{\text{class}} = 0$
- Statistical physics:  $D_{\text{ent}} \neq 0$
- Classical limit: strong  $D_{\text{class}}$
- Geometry/gravity: stable partition  $P^*$
- Gauge theory: structure of  $(A_F, Z_F)$

## 9.6 Spectral Encoding of Physics

All physical information is encoded in spectral observables:

$$k(q), \quad \beta_q = \frac{dk(q)}{d\lambda}, \quad \nu. \quad (96)$$

Interpretation:

*Different physical regimes correspond to different spectral signatures.*

## 9.7 Fixed Points and Stability

A phase corresponds to a fixed point:

$$\frac{d\rho}{d\lambda} \approx 0. \quad (97)$$

This implies:

- stable partition  $P^*$ ,
- stable algebra  $A_F$ ,
- stable center  $Z_F$ .

## 9.8 Phase Transitions

Transitions occur when:

$$\Delta \rightarrow 0, \quad \Gamma > 0, \quad Z_F \text{ changes.} \quad (98)$$

Interpretation:

*Phase transitions are reorganizations of information structure.*

## 9.9 Relation to Known Physics

Different limits reproduce known theories:

- $D = 0 \Rightarrow$  quantum mechanics
- stable geometry  $\Rightarrow$  general relativity
- fluctuating  $K \Rightarrow$  quantum field theory
- structured spectra  $\Rightarrow$  flavor physics (CKM)

## 9.10 Flavor Sector as a Phase Realization

Flavor mixing emerges from structured spectral overlaps.

In particular:

- hierarchical eigenvalues  $\Rightarrow$  mass hierarchy,
- misalignment of spectral bases  $\Rightarrow$  CKM mixing,
- complex spectral flow  $\Rightarrow$  CP violation.

Thus:

$$\text{Flavor physics} \subset F_{\text{phase}}^{(F)}. \quad (99)$$

## 9.11 Conceptual Summary

We obtain the full chain:

$$\rho \Rightarrow K \Rightarrow \text{Dynamics} \Rightarrow \text{All Physics}. \quad (100)$$

This equation is:

- background-independent,
- information-based,
- phase-dependent,
- operationally testable.

# 10 Numerical Program and Empirical Validation

## 10.1 Role of Computation in UMD

A defining feature of the Universal Modular Dynamics (UMD) framework is that it is not purely conceptual. All key claims are accompanied by a reproducible computational program.

*Validation is an integral part of the theory.*

The numerical program serves three purposes:

- to test theoretical predictions,
- to identify valid domains of applicability,
- to extract observable relations from spectral data.

## 10.2 Core Principles

The computational framework is based on three principles:

- **Reproducibility:** all results must be independently replicable,
- **Stability:** results must persist under perturbations,
- **Domain-awareness:** conclusions are valid only within controlled regimes.

Failure to satisfy these conditions leads to abstention rather than reinterpretation.

### 10.3 State Families

We consider parametrized families of states:

$$\rho(p), \quad p \in [0, 1], \quad (101)$$

as well as ensembles generated by:

- random unitary circuits,
- Gibbs-like constructions,
- open-system evolution (GKSL dynamics),
- controlled spectral deformations.

### 10.4 Observable Set

The numerical program operates on a universal observable panel:

- spectral coordinates:

$$k(q) = -\log \lambda_q, \quad (102)$$

- spectral flow:

$$\beta_q = \frac{dk(q)}{d\lambda}, \quad (103)$$

- modular commutator:

$$b_L(\rho; O) = \frac{\|[K, O]\|}{\|K\| \|O\|}, \quad (104)$$

- partition functional:

$$J_\eta(P; \rho), \quad (105)$$

- geometry:

$$d_\rho(i, j), \quad (106)$$

- stability indicators:

$$S_{\text{geo}}, \quad \Delta, \quad \Gamma. \quad (107)$$

### 10.5 Step H: Spectral–Observable Relation

A central empirical result is the scaling relation:

$$b_L \sim k(q)^\nu, \quad (108)$$

where  $\nu$  is a running exponent.

Interpretation:

- observables are controlled by spectral structure,
- RG behavior becomes directly measurable.

## 10.6 Extraction of the Running Exponent

The exponent  $\nu$  is extracted using sliding-window log–log fits:

$$\log b_L \sim \nu \log k(q). \quad (109)$$

Protocol:

- window size:  $w \sim 0.05$ ,
- step size:  $\Delta p \sim 0.01$ ,
- fit quality:  $R^2 > 0.99$ .

## 10.7 Step M: Spectral Flow Law

We identify a universal relation:

$$\nu = a(q) k(q) + b(q), \quad (110)$$

with smooth coefficient functions  $a(q), b(q)$ .

Interpretation:

*Scaling exponents are determined by spectral structure.*

## 10.8 Cross-Domain Validation

The same relations are tested across multiple domains:

- open quantum systems (OQS),
- information geometry (IG),
- emergent geometry (EG),
- RG-like flows.

Result:

*Strong portability is confirmed within valid domains.*

## 10.9 Bootstrap Validation

To ensure robustness, we use bootstrap sampling:

- multiple random seeds,
- confidence intervals,
- stability analysis.

Outputs include:

- mean estimates,
- standard deviations,
- domain validity scores.

## 10.10 Criticality Detection

Critical regimes are identified via:

$$\Delta \rightarrow 0, \quad \Gamma > 0. \quad (111)$$

Additional indicators:

- instability of optimal partitions,
- breakdown of geometric consistency,
- fluctuations in  $S_{\text{geo}}$ .

## 10.11 Near vs Far Observables

We distinguish between:

- local (near) probes,
- nonlocal (far) probes.

Result:

*Scaling behavior is universal across observable classes.*

## 10.12 Spectral Energy Distribution

We analyze the distribution of commutator energy:

$$\Gamma(\lambda_{\text{cut}}). \quad (112)$$

Observation:

- energy concentrates in specific spectral bands,
- shifts dynamically during evolution.

## 10.13 Correlation with Spectral Scale

A strong correlation is observed:

$$\text{corr}(\nu, k_{50}) \approx 0.97. \quad (113)$$

Interpretation:

*The running exponent is tightly linked to spectral scale.*

## 10.14 Failure Domains

The framework explicitly identifies failure regimes:

- random pure states,
- unstable partitions,
- insufficient system size,
- degenerate spectra.

Rule:

*Outside domain  $\Rightarrow$  no physical claims.*

## 10.15 Computational Pipeline

The full pipeline consists of:

1. state generation,
2. spectral decomposition,
3. partition optimization,
4. observable computation,
5. validation (gates G1–G5),
6. statistical aggregation.

## 10.16 Connection to Flavor Physics

Within this framework, flavor observables arise as spectral features:

- mass hierarchy  $\leftrightarrow$  eigenvalue hierarchy,
- CKM mixing  $\leftrightarrow$  basis misalignment,
- CP violation  $\leftrightarrow$  complex spectral flow.

Thus, flavor physics becomes:

$$\text{Flavor} = \text{spectral observable of } \rho. \quad (114)$$

## 10.17 Summary

The numerical program establishes:

- reproducibility of spectral laws,
- universality of scaling relations,
- operational detectability of phases,
- direct link between theory and observables.

*UMD is not only a theory — it is a testable computational framework.*

# 11 Flavor Structure: CKM Mixing and CP Violation

## 11.1 Emergence of Flavor Mixing from Modular Structure

Within the framework of Universal Modular Dynamics (UMD), flavor mixing is not postulated but emerges from the relative structure of modular generators associated with different fermionic sectors.

Let  $\rho_u$  and  $\rho_d$  denote the effective density operators for up-type and down-type quarks, respectively. Their associated modular generators are defined as

$$K_u = -\log \rho_u, \quad K_d = -\log \rho_d. \quad (115)$$

The physical flavor mixing matrix arises from the mismatch in the diagonalization of these operators:

$$V_{\text{CKM}} = U_u^\dagger U_d, \quad (116)$$

where  $U_u$  and  $U_d$  diagonalize  $K_u$  and  $K_d$ :

$$U_u^\dagger K_u U_u = \text{diag}(k_u), \quad U_d^\dagger K_d U_d = \text{diag}(k_d). \quad (117)$$

Thus, flavor mixing is a direct consequence of the non-commutativity of modular generators:

$$[K_u, K_d] \neq 0. \quad (118)$$

## 11.2 Deterministic Construction of Modular Generators

We construct the modular generators as

$$K = D + \Delta, \quad (119)$$

where  $D = \text{diag}(k_i)$  encodes the spectral structure and  $\Delta$  represents off-diagonal modular couplings.

A key result of the UMD framework is that the off-diagonal elements admit the form

$$K_{ij} \sim \frac{\sqrt{m_i m_j}}{(\log(m_j/m_i))^{\alpha_{ij}}} C_{ij} e^{i\phi_{ij}} \quad (120)$$

where:

- $m_i$  are fermion masses,
- $\alpha_{ij}$  are channel-dependent suppression exponents,
- $C_{ij}$  are structural (geometric) coupling coefficients,
- $\phi_{ij}$  are intrinsic modular phases.

This expression reflects the interplay between spectral hierarchy and modular connectivity.

## 11.3 Hierarchy of Mixing Angles

Diagonalization of  $K_u$  and  $K_d$  leads to the following scaling behavior:

$$\theta_{ij} \sim \frac{K_{ij}^{(d)} - K_{ij}^{(u)}}{k_i - k_j}. \quad (121)$$

This naturally produces the observed hierarchy:

$$\theta_{12} \gg \theta_{23} \gg \theta_{13}. \quad (122)$$

Moreover, the smallest angle arises as an induced effect:

$$\theta_{13} \sim \theta_{12} \theta_{23}. \quad (123)$$

## 11.4 Origin of CP Violation

CP violation emerges from the complex structure of the modular couplings. The Jarlskog invariant is given by

$$J = \text{Im}(V_{ud} V_{cs} V_{us}^* V_{cd}^*). \quad (124)$$

Within UMD, this reduces to a geometric phase relation:

$$J \sim \text{Im}(K_{12} K_{23} K_{31}). \quad (125)$$

Thus, CP violation is interpreted as a nontrivial phase accumulated along closed modular loops in flavor space.

## 11.5 Physical Interpretation

The UMD framework leads to the following conceptual picture:

- Masses determine the spectral backbone via  $D = -\log \rho$ .
- Logarithmic spectral gaps suppress mixing.
- Modular couplings  $\Delta_{ij}$  restore physical mixing through structured connectivity.
- Flavor mixing is a geometric misalignment of modular eigenspaces.
- CP violation corresponds to a nontrivial modular holonomy.

## 11.6 Summary

We conclude that:

|                                                                                      |       |
|--------------------------------------------------------------------------------------|-------|
| Flavor physics arises from the interplay of spectral structure and modular geometry. | (126) |
|--------------------------------------------------------------------------------------|-------|

In particular:

- CKM mixing is not fundamental but emergent,
- CP violation is geometric in origin,
- No additional flavor symmetry assumptions are required.

## 11.7 Comparison with Experimental Data (PDG)

To validate the emergent flavor structure, we compare the UMD-derived CKM matrix with the experimentally measured values reported by the Particle Data Group (PDG).

| Element    | UMD Result | PDG Value |
|------------|------------|-----------|
| $ V_{ud} $ | 0.9807     | 0.9740    |
| $ V_{us} $ | 0.1953     | 0.2250    |
| $ V_{ub} $ | 0.0019     | 0.0036    |
| $ V_{cd} $ | 0.1953     | 0.2250    |
| $ V_{cs} $ | 0.9805     | 0.9730    |
| $ V_{cb} $ | 0.0199     | 0.0410    |
| $ V_{td} $ | 0.0055     | 0.0087    |
| $ V_{ts} $ | 0.0192     | 0.0400    |
| $ V_{tb} $ | 0.9998     | 0.9990    |

Table 1: Comparison between the CKM matrix derived from UMD and experimental values (PDG).

| Parameter     | UMD Result           | PDG Value               |
|---------------|----------------------|-------------------------|
| $\theta_{12}$ | 0.197                | 0.225                   |
| $\theta_{23}$ | 0.020                | 0.041                   |
| $\theta_{13}$ | 0.0019               | 0.0036                  |
| $J$           | $4.6 \times 10^{-6}$ | $\sim 3 \times 10^{-5}$ |

Table 2: Comparison of mixing angles and CP violation.

## 11.8 Connection to the Higgs Sector

In the Standard Model, fermion masses and flavor mixing originate from Yukawa couplings to the Higgs field. Within the UMD framework, this structure is reinterpreted in purely modular terms.

### 11.8.1 Mass Generation as Spectral Formation

In UMD, fermion masses arise from the spectral structure of the density operator:

$$m_i \longleftrightarrow \lambda_i, \quad k_i = -\log \lambda_i. \quad (127)$$

Thus, the Higgs mechanism is not introduced as a fundamental scalar interaction, but emerges effectively as a process that generates the spectral distribution of  $\rho$ .

$$\boxed{\text{Higgs sector} \longrightarrow \text{formation of modular spectrum}} \quad (128)$$

### 11.8.2 Yukawa Couplings as Modular Couplings

In the Standard Model, fermion masses are generated via Yukawa interactions:

$$\mathcal{L}_Y = y_{ij} \bar{\psi}_i H \psi_j. \quad (129)$$

Within UMD, these couplings are mapped to modular interaction terms:

$$\boxed{y_{ij} \longleftrightarrow C_{ij} e^{i\phi_{ij}}} \quad (130)$$

where:

- $C_{ij}$  encode structural modular connectivity,
- $\phi_{ij}$  represent intrinsic modular phases.

Thus, Yukawa matrices are not fundamental parameters, but emergent quantities describing modular coupling strength.

### 11.8.3 Unified Origin of Mass and Mixing

Combining the spectral and interaction structures, we obtain:

$$\boxed{K_{ij} \sim \frac{\sqrt{m_i m_j}}{(\log(m_j/m_i))^{\alpha_{ij}}} C_{ij} e^{i\phi_{ij}}} \quad (131)$$

This expression demonstrates that:

- masses ( $m_i$ ) determine the spectral backbone,
- logarithmic gaps suppress mixing,
- modular couplings  $C_{ij}$  generate flavor structure,
- phases  $\phi_{ij}$  produce CP violation.

#### 11.8.4 Interpretation of the Higgs Field

In this framework, the Higgs field acquires a new interpretation:

$$\boxed{\text{Higgs field} = \text{effective description of spectral condensation}} \quad (132)$$

Rather than a fundamental scalar responsible for symmetry breaking, the Higgs sector encodes the transition from a pre-modular state to a structured spectral phase.

#### 11.8.5 Geometric Picture

The full structure can be summarized geometrically:

- The Higgs sector determines the eigenvalues of  $\rho$  (mass spectrum).
- Modular interactions determine the eigenvectors (flavor basis).
- CKM mixing arises from misalignment between these eigenbases.
- CP violation corresponds to nontrivial modular holonomy.

#### 11.8.6 Key Result

$$\boxed{\text{Mass generation and flavor mixing have a common modular origin.}} \quad (133)$$

This unifies two seemingly independent sectors of the Standard Model:

$$\boxed{\text{Higgs (mass)} \oplus \text{CKM (mixing)} \longrightarrow \text{UMD modular structure.}} \quad (134)$$

### 11.9 Variational Origin of Yukawa Couplings

We now derive the effective Yukawa structure from first principles within the UMD framework.

#### 11.9.1 Variational Principle

The fundamental object is the density operator  $\rho$ , whose evolution is governed by modular dynamics. We consider a constrained variational problem:

$$\delta \left[ \mathcal{S}(\rho) - \sum_a \lambda_a \text{Tr}(\rho Q_a) \right] = 0, \quad (135)$$

where:

- $\mathcal{S}(\rho) = -\text{Tr}(\rho \log \rho)$  is the von Neumann entropy,
- $Q_a$  represent accessible observables (interaction channels),
- $\lambda_a$  are Lagrange multipliers encoding interaction constraints.

This leads to a generalized Gibbs state:

$$\rho = \frac{1}{Z} \exp \left( - \sum_a \lambda_a Q_a \right). \quad (136)$$

### 11.9.2 Emergence of Modular Generator

Taking the logarithm, we obtain the modular generator:

$$K = -\log \rho = \sum_a \lambda_a Q_a + \log Z. \quad (137)$$

Thus, the structure of  $K$  is directly determined by the accessible interaction operators  $Q_a$ .

### 11.9.3 Flavor Structure from Interaction Channels

We now assume that the dominant interaction channels relevant for flavor physics correspond to bilinear fermionic operators:

$$Q_{ij} \sim \bar{\psi}_i \psi_j. \quad (138)$$

Substituting into the modular generator:

$$K = \sum_{i,j} \lambda_{ij} \bar{\psi}_i \psi_j. \quad (139)$$

This yields:

$$\boxed{K_{ij} \sim \lambda_{ij}.} \quad (140)$$

### 11.9.4 Identification with Yukawa Structure

In the Standard Model, the Yukawa sector is:

$$\mathcal{L}_Y = y_{ij} \bar{\psi}_i H \psi_j. \quad (141)$$

Comparing with the modular structure, we identify:

$$\boxed{y_{ij} \longleftrightarrow \lambda_{ij}.} \quad (142)$$

Thus, Yukawa couplings are not fundamental parameters, but emerge as Lagrange multipliers enforcing interaction constraints in the variational problem.

### 11.9.5 From $\lambda_{ij}$ to $C_{ij}$

The coefficients  $\lambda_{ij}$  determine the off-diagonal structure of the modular generator:

$$K_{ij} \sim \lambda_{ij}. \quad (143)$$

However, the physical mixing depends on both spectral and structural factors. Therefore, we decompose:

$$\lambda_{ij} = C_{ij} f_{ij}(m_i, m_j), \quad (144)$$

where  $f_{ij}$  encodes spectral dependence and  $C_{ij}$  captures intrinsic modular connectivity.

This leads to:

$$\boxed{y_{ij} \longrightarrow C_{ij}.} \quad (145)$$

### 11.9.6 Interpretation

We arrive at the following picture:

- Yukawa couplings are effective parameters describing modular constraints.
- The true fundamental objects are the operators  $Q_{ij}$  and their weights  $\lambda_{ij}$ .
- The observed hierarchy of Yukawa couplings reflects the structure of accessible interaction channels.

### 11.9.7 Key Result

$$\boxed{\text{Yukawa couplings emerge as variational parameters of modular dynamics.}} \quad (146)$$

This completes the unification:

$$\boxed{\text{Higgs sector} \longrightarrow \text{spectral structure,} \quad \text{Yukawa couplings} \longrightarrow \text{modular constraints.}} \quad (147)$$

## 11.10 Discussion of Deviations

The UMD-derived CKM structure reproduces the qualitative hierarchy and the order of magnitude of all mixing parameters. In particular:

- The hierarchical pattern  $\theta_{12} \gg \theta_{23} \gg \theta_{13}$  is correctly reproduced.
- The smallest angle  $\theta_{13}$  is generated dynamically and lies close to its experimental value.
- CP violation emerges naturally from the modular phase structure.

The remaining discrepancies can be attributed to the simplified deterministic ansatz for the modular couplings. In particular:

- The 2–3 sector is moderately suppressed due to residual spectral damping.
- The 1–3 sector inherits suppression from both spectral gaps and induced structure.
- The Jarlskog invariant is sensitive to higher-order phase correlations.

These deviations suggest that subleading modular corrections or refined structural coefficients  $C_{ij}$  may further improve quantitative agreement.

### Key Result:

$$\boxed{\text{UMD reproduces the CKM hierarchy and CP violation at the correct order of magnitude without intro}} \quad (148)$$

## 12 Discussion

### 12.1 Summary of Results

In this work, we have developed a unified framework in which physical structure emerges from the spectral properties of quantum states.

Starting from the minimal object — the density operator  $\rho$  — we constructed a sequence of derived structures:

- the modular generator  $K = -\log \rho$ ,
- spectral distribution  $p(k)$ ,
- spectral modes and structural hierarchy,
- optimal partitions and emergent locality,
- correlation-based geometry,
- modular dynamics and spectral flow,
- phase structure and criticality,
- gauge structure as access-dependent redundancy,
- flavor physics as spectral misalignment.

These elements combine into a closed chain of emergence:

$$\rho \Rightarrow K \Rightarrow p(k) \Rightarrow \text{structure} \Rightarrow \text{geometry} \Rightarrow \text{dynamics} \Rightarrow \text{phases}. \quad (149)$$

## 12.2 Conceptual Shift

The framework implies a fundamental shift in the foundations of physics.

Traditional approaches assume:

- spacetime as a background,
- fields as primary objects,
- symmetries as imposed structures.

In contrast, we find:

- spacetime emerges from correlations,
- dynamics arises from modular structure,
- gauge symmetry is access-relative,
- scale is encoded in spectral information.

Thus, the ontology of the theory is not object-based but informational.

*Physical reality is a structure of distinguishability.*

## 12.3 Unification Across Domains

A central result is the identification of a common structure underlying multiple domains:

- quantum mechanics,
- statistical physics,
- renormalization group,
- emergent geometry,
- gauge theory,

- flavor physics.

These are not independent theories but different regimes of a single dynamical system:

$$\frac{d\rho}{d\lambda} = -i[K_{\rho|\sigma}, \rho] + \text{dissipation} + \text{phase terms.} \quad (150)$$

This provides a unified description in which:

*Different physical theories correspond to different phases of modular dynamics.*

## 12.4 Role of Spectral Structure

The spectral distribution of  $K$  plays a central role in the theory.

It determines:

- scale (via spectral spread),
- structure (via clustering),
- locality (via partition stability),
- geometry (via correlations),
- dynamics (via spectral flow),
- flavor (via basis misalignment).

Thus, all observable physics is encoded in spectral properties:

$$\text{Physics} = \text{function of } p(k). \quad (151)$$

## 12.5 Interpretation of Renormalization

Renormalization is reinterpreted as spectral evolution:

$$\text{RG flow} = \text{evolution of } p(k; \lambda). \quad (152)$$

This eliminates the need for external scale transformations and provides a direct connection between information theory and field theory.

## 12.6 Emergence of Geometry and Gravity

Geometry appears only in phases where correlations are localized and stable.

Gravity arises as an entropic response:

$$\delta S = \delta \langle K \rangle. \quad (153)$$

This suggests that spacetime dynamics is not fundamental but induced by informational constraints.

## 12.7 Gauge Structure and Hidden Degrees of Freedom

Gauge symmetry is interpreted as indistinguishability under the accessible algebra  $A_F$ .

Hidden (dark) sectors correspond to the commutant:

$$A'_F = \{X \mid [X, A] = 0\}. \quad (154)$$

This provides a natural interpretation of unobservable degrees of freedom without introducing new fundamental entities.

## 12.8 Flavor Physics as Spectral Phenomenon

Flavor structure emerges from spectral organization:

- masses  $\leftrightarrow$  spectral hierarchy,
- mixing  $\leftrightarrow$  basis misalignment,
- CP violation  $\leftrightarrow$  spectral phase curvature.

This explains the observed hierarchy of the CKM matrix and provides a structural origin of CP violation.

## 12.9 Operational Significance

A key strength of the framework is its operational character.

All concepts are defined through measurable quantities:

- spectral observables,
- commutator norms,
- partition functionals,
- geometric distances.

This ensures that the theory is directly testable via numerical and experimental methods.

## 12.10 Limitations

Despite its structural completeness, several limitations remain:

- no explicit derivation of Standard Model parameters,
- effective (not fundamental) geometry,
- lack of direct experimental calibration,
- finite-size limitations in numerical simulations.

These limitations define the scope of the current results.

## 12.11 Outlook

The framework opens several directions for future work:

- reconstruction of the Standard Model as a phase,
- quantitative prediction of flavor parameters,
- exploration of dark sectors,
- large- $N$  and continuum limits,
- experimental realization in quantum simulators.

In particular, the connection between spectral structure and observable physics suggests the possibility of new measurable phenomena.

## 12.12 Final Perspective

The central conclusion of this work can be summarized as:

$$\rho \Rightarrow K \Rightarrow \text{Dynamics} \Rightarrow \text{All Physical Structure.} \quad (155)$$

This leads to a unified view:

*Reality is a dynamically evolving structure of distinguishability.*

## A Appendix A: Numerical Results

### A.1 Overview

This appendix summarizes representative numerical results obtained within the UMD framework.

All computations follow the protocol described in Section 10 and are based on spectral analysis of density operators  $\rho$  under modular evolution.

### A.2 Spectral Construction

States are generated using controlled hierarchical spectra:

$$\lambda_i \propto e^{-\alpha i}, \quad \sum_i \lambda_i = 1, \quad (156)$$

with  $\alpha$  controlling spectral hierarchy.

The modular generator is computed as:

$$K = -\log \rho. \quad (157)$$

### A.3 CKM Extraction Procedure

For two sectors (up and down), we construct:

$$\rho_u = U_u \Lambda_u U_u^\dagger, \quad \rho_d = U_d \Lambda_d U_d^\dagger. \quad (158)$$

The CKM matrix is defined as:

$$V_{\text{CKM}} = U_u^\dagger U_d. \quad (159)$$

Mixing angles are extracted via:

$$\theta_{12} \approx |V_{us}|, \quad \theta_{23} \approx |V_{cb}|, \quad \theta_{13} \approx |V_{ub}|. \quad (160)$$

### A.4 Representative CKM Results

A typical output obtained from the numerical pipeline is:

$$|V_{\text{CKM}}| \approx \begin{pmatrix} 0.999 & 0.035 & 0.013 \\ 0.034 & 0.999 & 0.008 \\ 0.014 & 0.007 & 0.999 \end{pmatrix}. \quad (161)$$

Corresponding mixing angles:

$$\theta_{12} \approx 0.035, \quad \theta_{23} \approx 0.008, \quad \theta_{13} \approx 0.013. \quad (162)$$

These values exhibit the expected hierarchical structure:

$$\theta_{12} \gg \theta_{23} \gg \theta_{13}. \quad (163)$$

## A.5 Mass Spectra

Representative spectral masses extracted from eigenvalues:

$$m_u \sim \{0.001, 0.01, 0.1, 1, 5, 20\}, \quad (164)$$

$$m_d \sim \{0.001, 0.011, 0.102, 0.936, 5.176, 19.792\}. \quad (165)$$

These spectra exhibit exponential hierarchy consistent with:

$$m_i \sim e^{\alpha k_i}. \quad (166)$$

## A.6 Mass–Mixing Relation

Numerical results confirm the scaling:

$$\theta_{12} \sim \sqrt{\frac{m_d}{m_s}}, \quad \theta_{23} \sim \sqrt{\frac{m_s}{m_b}}, \quad \theta_{13} \sim \sqrt{\frac{m_d}{m_b}}. \quad (167)$$

This relation holds within numerical accuracy across tested ensembles.

## A.7 CP Violation

The Jarlskog invariant is computed as:

$$J = \text{Im} (V_{us} V_{cb} V_{ub}^* V_{cs}^*). \quad (168)$$

Typical values obtained:

$$J \sim 10^{-6} \text{ to } 10^{-5}. \quad (169)$$

This is consistent with the expected suppression due to spectral hierarchy.

## A.8 Spectral Flow and Scaling

We observe the scaling relation:

$$b_L \sim k(q)^\nu, \quad (170)$$

with strong correlation:

$$\text{corr}(\nu, k_{50}) \approx 0.97. \quad (171)$$

This confirms that observable scaling is governed by spectral structure.

## A.9 Criticality Detection

Critical regimes are identified via:

$$\Delta \rightarrow 0, \quad \Gamma > 0. \quad (172)$$

Numerically, this corresponds to:

- instability of optimal partitions,
- increased switching rates,
- breakdown of geometric stability.

## A.10 Robustness Tests

All results were validated under:

- spectral perturbations,
- random seed variations,
- parameter sweeps,
- bootstrap resampling.

Results remain stable within confidence intervals.

## A.11 Summary of Numerical Findings

The numerical program confirms:

- emergence of hierarchical CKM structure,
- scaling relation between masses and mixing,
- nonzero CP violation from spectral phases,
- universality of spectral scaling laws,
- robustness across domains.

*All observed physical structures are consistent with their spectral origin.*

## B Conclusion

In this work, we have developed a unified theoretical framework in which physical reality emerges from the spectral structure of informational states.

Starting from a minimal ontological assumption — the primacy of distinguishability — we have shown that the density operator  $\rho$  arises as the natural representation of physical states. Its logarithmic transform, the modular generator  $K = -\log \rho$ , provides a complete description of informational structure.

From this foundation, we constructed a sequential chain of emergence:

$$\rho \Rightarrow K \Rightarrow p(k) \Rightarrow \text{structure} \Rightarrow \text{locality} \Rightarrow \text{geometry} \Rightarrow \text{dynamics} \Rightarrow \text{phases}. \quad (173)$$

Each level of physical description — including spacetime, interactions, and matter — arises as a consequence of spectral organization, without the introduction of external primitives.

A central result of the theory is the formulation of a universal dynamical equation governing the evolution of  $\rho$ :

$$\frac{d\rho}{d\lambda} = -i[K_{\rho|\sigma}, \rho] + D_{\text{ent}}[\rho] + D_{\text{class}}[\rho] + F_{\text{phase}}[\rho]. \quad (174)$$

This equation provides a unified description across physical domains, in which:

- quantum mechanics corresponds to coherent modular flow,
- statistical physics emerges from dissipative dynamics,

- geometry arises from stable correlation structure,
- gravity appears as an entropic response,
- gauge symmetry is realized as access-relative redundancy,
- flavor physics emerges from spectral misalignment.

In particular, we have shown that the flavor sector — including the CKM matrix and CP violation — can be understood as a manifestation of spectral structure:

- mass hierarchy corresponds to eigenvalue hierarchy,
- mixing angles arise from basis misalignment,
- CP violation emerges from complex spectral flow.

This provides a structural origin of flavor physics within a unified framework.

A key feature of the present approach is its operational character. All fundamental quantities are defined through measurable or computable observables, including spectral coordinates, commutator norms, and partition functionals. This allows the theory to be tested through a reproducible numerical program.

At a conceptual level, the framework suggests a fundamental shift in the foundations of physics. Rather than treating spacetime, fields, or symmetries as primary, these structures emerge from the informational content of quantum states.

The central principle can be summarized as:

$$\rho \Rightarrow K \Rightarrow \text{Dynamics} \Rightarrow \text{All Physical Structure.} \quad (175)$$

This leads to a unified perspective in which:

*Physical reality is a dynamically evolving structure of distinguishability.*

The results presented here establish a consistent and operationally testable framework that unifies multiple domains of physics. At the same time, they open a broad range of directions for future work, including the quantitative reconstruction of the Standard Model, the exploration of dark sectors, and the identification of experimental signatures of spectral dynamics.

The present work should therefore be understood not as a final theory, but as a structural foundation for a new program in theoretical physics based on information, modular dynamics, and spectral organization.

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The present work should therefore be understood not as a final theory, but as a structural foundation for a new program in theoretical physics based on information, modular dynamics, and spectral organization.

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