Time's Arrow and Quantum Reality: A Unification

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Introduction

Two of the most difficult puzzles in the foundations of physics:
(1) what explains the arrow of time?
(2) why is the world quantum mechanical?
In this talk, we propose a unified solution to these problems.

1 The Arrow of Time

What explains the arrow of time?

- Can physics explain the arrow of time? (Focus: the entropic arrow of time)
- Obstacle: fundamental equations do not include an arrow. (Some caveats)
- Standard answers:
  —Past Hypothesis (PH): the universe started in a low-entropy state.
  —Statistical Postulate (SP): uniform probability distribution given PH.
- Macrostate: a macroscopic description of the physical system (in terms of volume, density, pressure).
- Microstate: a microscopic description of the physical system (in terms of positions and velocities of the particles or the wave function of the system).
- Each macrostate is compatible with / multiply-realizable by many microstates.
- Entropy measures "how many" microstates are compatible with a given macrostate.
- Philosophical surprises:

  (1) Nomic vagueness: a fundamental law of physics includes vague terms.

  Reason: PH macrostate has a vague boundary. Arbitrary to choose a precise boundary. No microscopic traceability. (Borderline cases, emergent phenomena)

  (2) Imprecise probabilities: objective probabilities can be imprecise.

  Reason: PH macrostate has a vague boundary; the SP probability distribution over microstates compatible with the PH macrostate will be slightly different given different precisifications of the macrostate.

Quest for Precision: To justify the choice of a precise initial condition and probability.

2 The Quantum Mystery

$$\boxed{\text{Why is the world quantum mechanical?}}$$

Illustration of the puzzle: the double-slit experiment.

- Standard answer: the wave function.
- The wave function is postulated in our best quantum theories.
- The wave function remains after we solve the measurement problem!
- The wave function is mysterious:

  —Ridiculously high-dimensional.

  —Complex numbers.

  —Unlike the ordinary ontology of particles and fields.
- How to interpret the wave function?

  1) Ontological Interpretation: the wave function is a new physical field on a high-dimensional fundamental space.

  Problems: radical ontology; empirical incoherence; challenges for emergence; symmetries unexplained. (Also a problem for Humean supervenience.)

  2) Nomological Interpretation: the wave function is on par with laws of nature and determining how things move.

  Problem: the wave function is not simple enough.

Quest for Simplicity: To find a simple quantum state that is empirically adequate.

3 A Unified Theory

We offer a new perspective on time's arrow in a quantum universe that will solve both problems.

3.1 The Intuitive Idea

Standard answers (in a toy model):

- Past Hypothesis: in the beginning, the wave (function) belongs to the low-entropy macrostate $M_0 = \{\Psi_1, \Psi_2, \Psi_3\}$
- Statistical Postulate: each wave is equally likely (1/3 probability).
- Problems:

  (1) Not simple: an individual wave (Ψ_2) is quite complicated and too informative.

  (2) Not precise: the macrostate M_0 could be replaced by slightly different sets of microstates.

New solution:

- Heuristic: to make something simpler, we can start by making it less detailed and more coarse-grained.
- E.g. a macroscopic description of the gas in a box is less detailed and much simpler than a microscopic description (an individual wave).
- Can we coarse-grain the microscopic wave?
- We will use the PH macrostate to get a coarse-grained wave.
- Given the initial macrostate $M_0 = \{\Psi_1, \Psi_2, \Psi_3\}$, there is a natural choice: taking the "average."
- The coarse-grained wave is sufficient to determine the motion of microscopic particles and fields. (Empirical equivalence)

The Initial Projection Hypothesis (IPH): The universe is initially a density matrix $W_0 = 1/3(\Psi_1) + 1/3(\Psi_2) + 1/3(\Psi_3)$. [This is a version for the toy model.]

- W_0 is a more coarse-grained and less detailed state.
- We can rewrite the fundamental equations in terms of W_0.
- W_0 is the initial microstate: it enters into the fundamental equations, directly guides Bohmian particles, undergoes GRW collapses, or determines a field on physical space.
- W_0 is the initial macrostate: it corresponds to the PH macrostate.

Payoffs:

(1) The initial quantum state is simple.

—Intuitively: the coarse-grained state W_0 washes out the differences among the wave functions and contains less information.

—Details: PH is sufficiently simple to be a law $\longrightarrow$ PH subspace is simple $\longrightarrow$ the projection onto the PH subspace is simple $\longrightarrow$ the "coarse-grained wave" is simple enough to be nomological.

—<u>The first quest is finished!</u>

—New theory: ontology consists in particles / fields in physical space; laws include a simple quantum state.

—Good news for Humeans: reconciliation of Humean supervenience and quantum mechanics.

(2) We can justify a precise initial macrostate (no need for probabilities).

—W_0 corresponds to the low-entropy macrostate, but it also determines the microscopic facts. It has <u>microscopic traceability.</u>

—The precision in the macrostate is no longer arbitrary or gratuitous.

—Accuracy condition: microscopic histories.

—No more nomic vagueness or imprecise probabilities.

—<u>The second quest is finished!</u>

—Moreover, the initial quantum state is nomologically necessary.

—Interesting news for Everettians: the world is strongly deterministic.

Upshot: we have obtained a unified solution to both puzzles.

A list of payoffs:

Time's arrow; quantum mystery; fundamentality of space-time; Humean supervenience; narratability and Lorentz invariance; nomic vagueness; imprecise probabilities; strong determinism; unification of quantum mechanical and statistical mechanical probabilities; unification of universe-level and subsystem-level descriptions.

3.2 Technical Details (omitted in the talk; for the experts):

- PH and SP cast in terms of quantum mechanics in Hilbert space...

  —Past Hypothesis: the initial wave function of the universe is chosen from a low-dimensional subspace $\mathscr{H}_{PH}$, which corresponds to a low-entropy macrostate.

  —Statistical Postulate: uniform probability distribution on $\mathscr{H}_{PH}$, i.e. normalized surface area measure on the unit ball of wave functions in $\mathscr{H}_{PH}$.

- The Past Hypothesis subspace $\mathscr{H}_{PH}$ is compatible with many wave functions.

Crucial observation: we can use PH to determine a natural quantum state.

- Density Matrix Realism: the quantum state is objective and represented by a density matrix. (More coarse-grained than wave functions.)

- **Initial Projection Hypothesis (IPH):** the initial quantum state is a special density matrix W_0—the normalized projection onto the Past Hypothesis subspace

$$W_0 = \frac{\mathbb{I}_{PH}}{\dim \mathscr{H}_{PH}}, \tag{IPH}$$

  where $\mathbb{I}_{PH}$ is the projection operator onto the PH subspace ($\mathscr{H}_{PH}$), and "dim" counts the dimension of the PH subspace. W_t evolves by the von Neumann equation.

- The normalized projection is an impure density matrix. It can be decomposed (non-uniquely) as:

$$W_V = \int_{\mathscr{S}_V} |\psi\rangle \langle\psi| \, \mu(d\psi) \tag{IPH'}$$

- New equations in terms of an objective density matrix: W-Bohm, W-GRW, W-Everett.

- IPH with an objective W is empirically equivalent to PH+SP with an objective Ψ.

- W_0 is as simple as PH. W_0 can be nomological just as the Hamiltonian function in classical mechanics.

- W_0 is fixed by the theory. IPH chooses a unique state. (A justified choice.)

- The choice of W_0 in IPH can be maximally precise, as it has a microscopic trace because of the new W equations.

- Papers on arXiv: **1712.01666**, **1901.08053**, **1810.07010**.