Quantum Physics, Philosophy and the Universe

Irreducible Epistemic Limits and the Emergence of Classical Determinism

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The universe is causally connected at all scales, but at microscopic scales the total causal network is fundamentally inaccessible. These irreducible epistemic limits are themselves ontological features of reality. Classical determinism emerges gradually as systems increase in scale, making the inaccessible fraction of causal information negligible.

1 Full disclosure: the ideas expressed in this paper are entirely of the author's, while the wording was partly formatted by AI (CHATGPT-4).

Determinism and cause/effect

This is an important distinction, and one that is often blurred in philosophy. Many people use "determinism" and "cause and effect" as if they were synonymous, but they are not.

Cause and effect

Cause and effect is simply the idea that events have causes. If event A influences event B, then A is a cause of B.

Examples:

- Strike a match → it lights.
- Push a ball → it rolls.
- A photon hits a solar cell → an electron is ejected.

Notice that this says nothing about whether the outcome was inevitable. It only says that there is a causal relationship.

Determinism

Determinism is a much stronger claim. It says that: Given the complete state of the universe at one instant, together with the laws of nature, there is exactly one possible future.

In symbols,

Initial State + Laws → One and only one future.

Nothing could have happened differently.

An analogy

Imagine dropping a marble into a machine. The marble activates gears. Perhaps one of three doors opens depending on a genuinely random quantum event. There is still cause and effect:

Drop marble
→ gears move
→ detector fires
→ Door 2 opens.

Everything has a cause. But the exact door was not predetermined.

Now consider a deterministic machine for which the quantum detector is replaced with ordinary gears.

Drop marble
→ gears move
→ Door 2 opens.

Every time.

Not only is there causation, but there was never any possibility of Door 1 or Door 3.

Quantum mechanics

On the other hand, modern quantum mechanics is interesting because nearly everyone agrees it is causal. For example: An unstable nucleus decays because of its quantum state. But standard quantum mechanics says the exact moment of decay is not fixed in advance. The decay has a cause (the unstable nucleus), but not a predetermined time.

Thus, Cause: yes ; Determinism: no

Radioactive decay

Take Uranium-238. Every atom is identical. One atom decays today. Another survives another million years. The cause is the unstable nucleus. But nothing in standard quantum mechanics specifies exactly which atom decays first.

So, Cause: Yes; Predetermined: No.

Lightning

Suppose lightning strikes a tree. The causes include

- cloud charge,
- electric field,
- humidity,
- ionization of air.

Yet the exact microscopic path taken by the discharge depends on countless quantum and thermal fluctuations. There are causes, but not necessarily a uniquely predetermined outcome.

Classical mechanics

Classical Newtonian mechanics is both causal and deterministic.

If you knew every position and every velocity, then, in principle, you could calculate the entire future forever. That is why classical physics became identified with determinism. But determinism came from the mathematical form of Newton's equations, not from the mere existence of causes.

Why philosophers confuse them

Historically, before quantum mechanics, nearly every successful physical theory was deterministic. So philosophers began assuming causation = determinism. Quantum mechanics broke that connection. Now we have a theory that is extraordinarily successful experimentally while appearing to be causal but not deterministic (at least in its standard interpretation).

Hidden variables

Some interpretations try to recover determinism. For example, David Bohm's interpretation[1] says:

- particles always have definite positions,
- hidden variables determine everything.

So Bohmian mechanics is: Cause, yes; Determinism, yes.

A useful summary is:

Cause and effect	Determinism
Every event has causes.	Every event is uniquely fixed by the past.
Allows multiple possible outcomes.	Allows only one possible outcome.
Compatible with probabilistic laws.	Requires the future to be completely determined.
"A influences B."	"A guarantees B."

The key insight is that **causation is about influence**, whereas **determinism is about inevitability**. You can have causal processes that produce genuinely probabilistic outcomes. Quantum mechanics, in its standard interpretation, is the leading example: events arise through lawful causal interactions, yet the specific outcome is described only by probabilities rather than being uniquely fixed by the prior state. This distinction is why many philosophers and physicists today reject the old assumption that accepting cause and effect automatically commits one to a deterministic universe.

Question: Are there unknown factors that can produce different outcomes? The answer depends on **why** there are multiple possible outcomes. We identify two very different possibilities.

1. Unknown factors (epistemic uncertainty)

This is the classical view. Suppose I roll a die. There are countless factors I don't know:

- the exact force of my throw,
- the angle,
- air currents,
- the friction of the table,
- tiny imperfections in the die.

Because we don't know these variables, we say there are six possible outcomes.

But a strict determinist would say: If you knew every one of those variables exactly, only one outcome was ever possible. So the multiple outcomes are merely due to our ignorance. This is called epistemic uncertainty (uncertainty due to lack of knowledge)

2. Genuine indeterminacy (ontological uncertainty)

Quantum mechanics introduces a different possibility.

Imagine a radioactive atom. Even if you know everything that can possibly be known about the atom:

- its quantum state,
- its energy,
- its surroundings,

Standard quantum mechanics still does not predict exactly when it will decay. It predicts only probabilities.

For example,

- 30% chance within one hour,
- 70% chance it survives the hour.

There are no additional hidden variables in the standard interpretation. The multiple outcomes are not because we lack information. They are because nature itself does not determine a unique outcome in advance. This is called ontological indeterminacy. So there are two very different meanings of "possible outcomes"

Determinist:

There is only one real outcome. The others merely reflect what we don't know.

Indeterminist:

Several outcomes are genuinely possible until one actually occurs. Cause and effect itself does not decide between them.

This is the important point.

Suppose we press a button. The button causes a quantum device to emit a photon. The photon reaches a beam splitter. It has a 50% probability of going left and 50% probability of going right. The chain:

Button → Device → Photon → Detector

This is entirely causal.

The question is whether the final branch was

- predetermined by hidden information (determinism), or
- genuinely not fixed until the interaction occurred (indeterminism).

Cause and effect alone doesn't answer that question.

This distinction also relates to a point we've made in earlier discussions. We've argued that an electron is continually interacting with the rest of the universe, so its behavior is influenced by an enormous number of changing interactions[2]. That view is compatible with **causality**, because the electron's evolution is always being affected by its environment. The remaining question is whether those countless influences are sufficient to determine one unique future (determinism), or whether, even after accounting for all of them, nature still permits more than one possible outcome. That is precisely where the philosophical and physical debate lies.

Suppose an electron is moving through space. As it can be pointed out, it is interacting with:

- trillions upon trillions of photons,
- electromagnetic fields,
- gravitational fields from every mass in the universe,
- neutrinos,
- vacuum fluctuations (if these are taken as physically real),
- nearby nuclei,
- distant galaxies (through gravity).

Each interaction has

- a strength,
- a direction,
- a time dependence,
- interference with all the others.

The number of variables is effectively astronomical.

Now ask:

Can any experiment determine all of these interactions simultaneously?

Probably not.

In fact, one could argue that no conceivable experiment could, because the act of measuring one interaction changes the conditions for the next, and much of the universe is permanently outside our observational reach (for example, beyond our cosmological horizon).

That is a much stronger claim than simply saying, "we don't know."

It says there are principled limits on what can ever be known. However, there is still another step to take before concluding that determinism is false. A determinist would respond: The electron still has a unique trajectory. We simply cannot discover it. In other words,

Reality → completely determined

Knowledge → permanently incomplete.

That position is logically consistent. A determinism that can never, even in principle, be distinguished from indeterminism is not a scientifically useful hypothesis. That is a powerful philosophical point. It echoes ideas associated with philosophers such as Karl Popper[3], who argued that scientific theories should be distinguishable by possible observations.

We would rephrase this argument in this way: Every event has causes, but the totality of those causes is embedded in an unimaginably complex network of interactions extending throughout the universe. Because no observer can ever isolate or measure all of those interactions, **the complete causal state is permanently inaccessible**. Consequently, whether the universe is deterministic or not becomes an empirically undecidable question. Determinism may remain a metaphysical possibility, but it no longer functions as a scientific explanation.

Notice that this conclusion is slightly different from saying: Epistemic shielding **is** ontological indeterminacy.

Rather, it says: The universe may be ontologically deterministic, but it is ontologically opaque to observers. That distinction matters philosophically.

Now, there is an interesting possibility that aligns even more closely with this thinking. One could argue that information accessibility is itself an ontological feature of the universe. In that view, the universe is not merely hiding information from us accidentally; it is structured so that certain information is fundamentally inaccessible. **The unknowability is then not just a limitation of human observers but a property of reality itself**. This doesn't prove indeterminism, but it does mean that the ontology of the universe includes irreducible epistemic limits.

This is where the ideas about the continual interactions of an electron become especially interesting. We're not simply saying, "we don't know enough." We're saying that the web of interactions is so vast and so fundamentally inaccessible that the distinction between a deterministic universe and an indeterministic one may itself be forever beyond empirical resolution. That is a subtle and defensible philosophical position, and it shifts the debate from *"Is nature deterministic?"* to *"Can determinism ever be more than a metaphysical assumption?"*

Consider the following: The ontology of the universe includes irreducible epistemic limits. At large distances, however, classical physics rules. So one would have to come up with a sliding ruler: very small distances we get indeterminacy; as we get to larger distances, determinacy. The obvious question is, where do we draw the line?

Perhaps this is arguably the hardest conceptual problem in the foundations of quantum mechanics: if the microscopic world is indeterministic (or irreducibly unknowable) and the macroscopic world appears deterministic, where does one become the other?

There are several possibilities.

1. There is no sharp line (my view of the mainstream)

This is the view adopted by most physicists today.

There isn't a boundary like

- below 1 µm → quantum,
- above 1 µm → classical.

Instead, there is a continuous transition.

As systems become larger,

- the number of particles increases,
- interactions with the environment explode,
- coherence is lost,
- quantum interference becomes effectively impossible to observe.

Classical behavior emerges gradually.

This is the idea behind decoherence.

So the "sliding ruler" is continuous rather than abrupt

2. There is a real boundary

Some physicists have proposed that there is an objective transition.

For example, Roger Penrose[4] has argued that gravity may trigger an objective collapse of the wavefunction once mass distributions become sufficiently different. Then there really would be a dividing line. The difficulty is that no experiment has yet established such a boundary.

Imagine defining an "epistemic accessibility" parameter.

At atomic scales:

- enormous environmental influence,
- impossible to isolate every interaction,
- irreducible uncertainty.

At molecular scales:

- somewhat less relative uncertainty.

At human scales:

- billions of microscopic uncertainties average out,
- deterministic laws become extraordinarily accurate.

So perhaps what changes isn't ontology itself, but the degree to which causal information is recoverable.

An intriguing possibility

We could almost define something like

$$P(L) = \frac{accessible\ causal\ information}{total\ causal\ information}$$

where L is the characteristic length scale.

Then

- at atomic scales, $P(L)$ is very small;
- at planetary scales, $P(L)$approaches one.

Notice what this says. It doesn't say reality becomes deterministic. It says our ability to describe it deterministically increases with scale. That is a subtle but important distinction.

Where do we draw the line?

Perhaps we shouldn't.

One lesson of twentieth-century physics is that nature often resists sharp boundaries.

Examples include:

- There is no precise boundary between liquid and gas above the critical point.

- There is no exact boundary between classical and relativistic mechanics; relativity smoothly approaches Newtonian mechanics as $v/c \to 0$.
- There is no exact boundary between wave and particle descriptions.

So it wouldn't be surprising if there were no unique boundary between indeterminacy and determinacy.

Instead, determinism might be an emergent approximation, becoming progressively better as the number of interacting degrees of freedom increases and microscopic fluctuations average out.

"At large distances, classical physics rules." We can modify this to: At large scales, classical physics becomes an extraordinarily accurate effective theory. That wording is more consistent with modern physics. Even macroscopic objects are fundamentally quantum systems. We describe them classically not because they cease to be quantum, but because quantum effects become vanishingly small relative to the scales we observe. Thus, classical determinism may itself be an emergent consequence of a universe whose ontology includes **irreducible epistemic limits** at the microscopic level. That formulation captures the philosophical intuition while remaining compatible with what we currently know about quantum theory.

References:

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