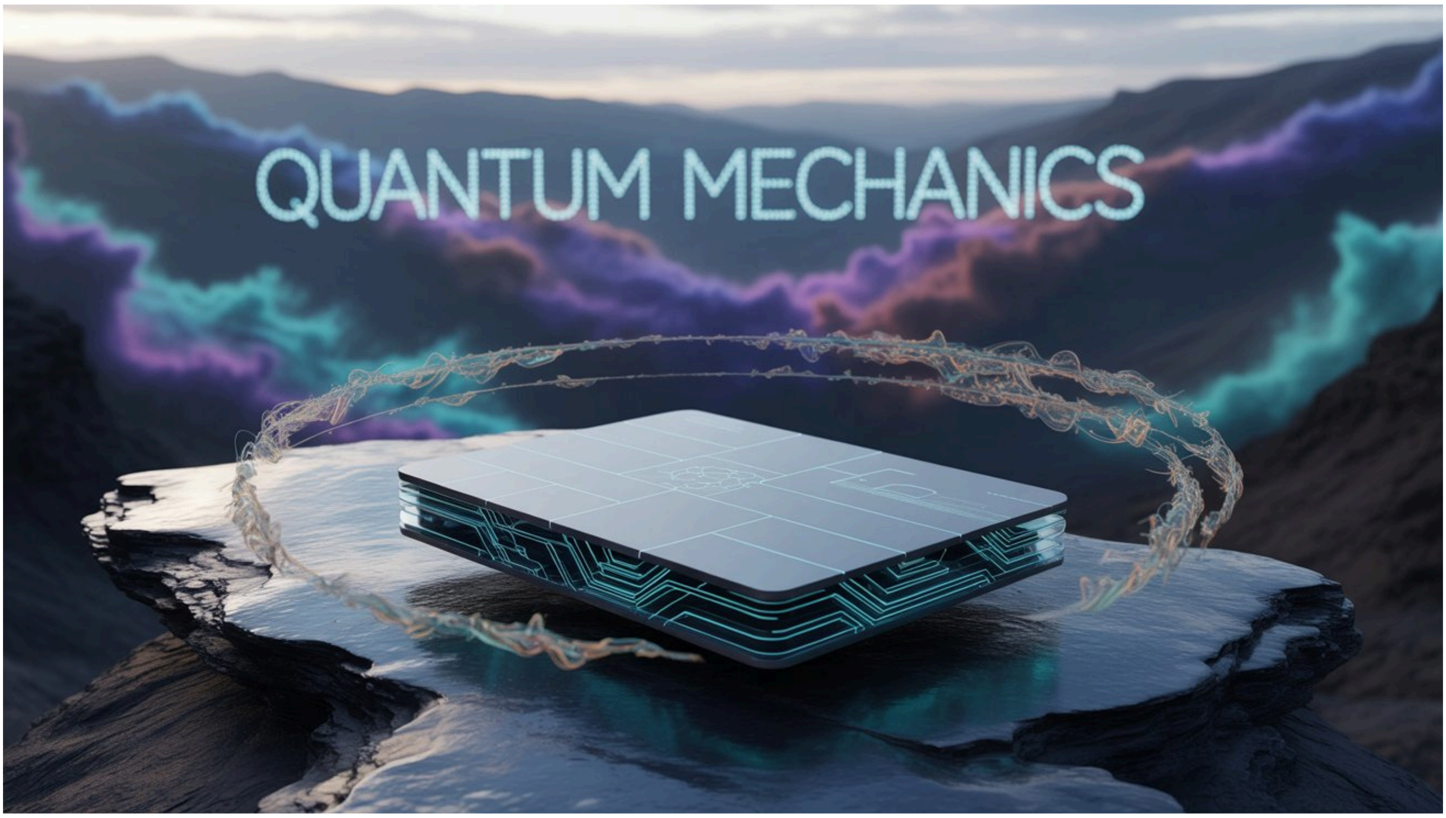
From Physics to Qubits: The Postulates of Quantum Mechanics Explained for Everyone

By Eva Andrés



A Mystery Turned into Technology

At the beginning of the 20th century, a handful of physicists began to discover that, in the microscopic world, the rules we knew no longer applied. Electrons behaved both as waves and particles at the same time. Atoms seemed to act capriciously, jumping from one state to another without warning. A reality that appeared to mock classical logic.

Thus, quantum mechanics was born—a theory so strange that even Einstein doubted it. Yet, as decades went by, it proved to be the most accurate description we have of nature at the subatomic level.

Today, more than a hundred years later, those very rules that once seemed incomprehensible still pose new enigmas. Quantum physics has transformed our daily lives with technologies such as lasers, MRI scanners, and semiconductors. We have experimentally demonstrated astonishing phenomena like quantum entanglement, confirmed time and again, which challenges our classical intuition about space and time.

And yet, despite these advances—and despite quantum mechanics being the most experimentally confirmed theory in the history of science—we still do not have all the answers. We continue to search for a "theory of everything" that unifies Einstein's relativity with quantum theory and explains the deepest mysteries of the universe.

Along the way, however, it is worth pausing to recall the essentials: the four fundamental postulates of quantum mechanics. Let's explore them together and discover how they are reflected in quantum computing.

Postulate I: Quantum State

"Any quantum system is described by a vector in a Hilbert space."

In everyday language: everything we can know about a quantum system is condensed into a kind of "mathematical arrow" called the wave function, state, or simply ket. It is usually written as $|\psi\rangle$.

This vector lives in a very special mathematical space called Hilbert space, which can have finite or infinite dimensions. It contains all the possible states of a quantum system.

You can picture it as a complete map of all the versions that system could take. Each point in that space represents one possibility, and the quantum state is the combination that tells us where the system lies in that sea of options.

As long as we don't measure our system, the quantum state vector remains in Hilbert space, in a state of indefiniteness. It is not in a single state but rather in a superposition of basis states—that is, a linear combination of them.

Think of Schrödinger's famous thought experiment: until we open the box, we don't know whether the cat is alive or dead, because in fact its state is a mixture of both possibilities. Only when we look (that is, measure) does reality "decide."

That superposition captures all the information we have about the system… until we choose to look. Only then does the state collapse into one of the possible options.

And what are those basis states? They are the fundamental building blocks of Hilbert space: the "pure" positions that, when combined, allow us to describe any quantum state.

In Schrödinger's cat case, we can imagine that the state "alive" is represented by the ket $|0\rangle$ and the state "dead" by the ket $|1\rangle$. As long as we don't open the box (measure), the cat's state would be represented as:

$|\psi\rangle = a|0\rangle + b|1\rangle$ where $|a|^2 + |b|^2 = 1$.

The values $|a|^2$ and $|b|^2$ represent the probabilities of each option, and as probabilities they must add up to 1. This is known as Born's rule.

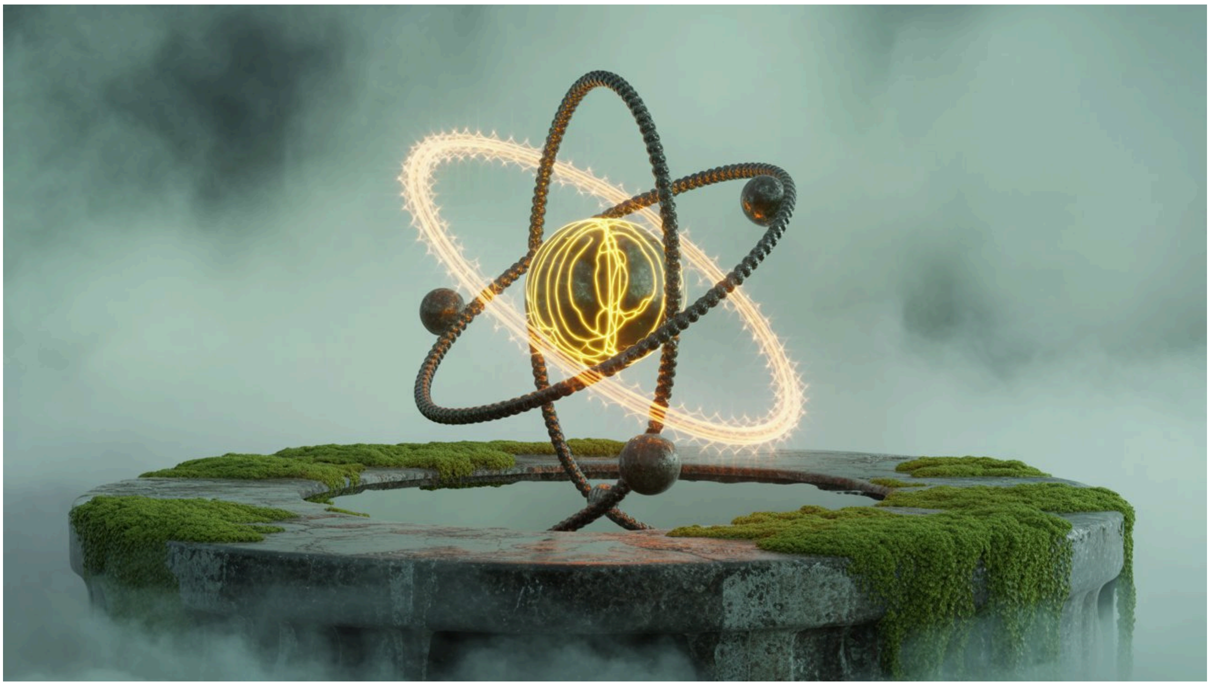
And here lies the big difference with classical computing: while a classical bit can only explore one option at a time, a qubit can span many possibilities in parallel. It's like trying all the keys to a door at once.

Postulate II: Observables

"Every physical quantity is represented by a Hermitian operator, and its eigenvalues correspond to the possible results of a measurement."

In quantum mechanics, what we can measure —the position of a particle, its velocity, its energy— is called an observable. Each observable is represented by a very special mathematical operator, a Hermitian operator. The reason is simple: its possible outcomes, called eigenvalues, are always real numbers—results that make physical sense.

In short, this postulate teaches us a central lesson of quantum physics: our knowledge is limited to what we can measure.



And this is where the debate begins. Einstein resisted the idea that reality could depend on an observation. He would ask: "Do you really believe the Moon ceases to exist if no one looks at it?" For him, quantum systems had to possess well-defined properties even when no one was measuring them.

To preserve this vision of an "objective" reality, Einstein and other physicists proposed the existence of hidden variables: unknown details that would determine the true state of the system, even before it was observed.

In 1964, physicist John Bell formulated a set of mathematical inequalities—the famous Bell's inequalities—to test this hypothesis. If they held, hidden variables existed; if they were violated, quantum mechanics was right: results are not determined until the moment of measurement.

The experiments were decisive. Time and again, from the 1980s to the most recent in 2012 with Alain Aspect's work, Bell's inequalities were violated. This means that local hidden variables do not exist: quantum reality is neither objective nor deterministic in the classical sense, but intrinsically dependent on the act of measurement.

This discovery was so fundamental that in 2022 the Nobel Prize in Physics was awarded to Aspect, John F. Clauser, and Anton Zeilinger for their experimental demonstrations of the non-existence of hidden variables.

In quantum computing, this is reflected at the end of an algorithm: we measure the qubits and obtain an outcome $|0\rangle$ or $|1\rangle$. But that outcome only emerges at the moment of observation.

Postulate III: Quantum Measurement

"The outcome of a measurement is, by nature, random. Knowledge can only be accessed through probabilities."

Niels Bohr used to say: "Anyone who is not shocked by quantum theory has not understood it." And this postulate is probably the main reason why.

It tells us that the result of a measurement is intrinsically random. We cannot access absolute certainties—only probabilities.

This phenomenon is known as the collapse of the wavefunction. Before measurement, the system exists in a cloud of possibilities; by measuring, we force the system to "choose" a definite outcome. Observing is not passive—it is intervention.

Let's see an example.
A qubit on the equator of the Bloch sphere is in perfect superposition between $|0\rangle$ and $|1\rangle$. If we measure it in the Z basis:

- there is a 50% probability of obtaining $|0\rangle$,
- and a 50% probability of obtaining $|1\rangle$.

The result is random. But once measured, the superposition is lost: the qubit becomes fixed in the observed state.

This introduces two key ideas:

1. We don't always get the most probable outcome. Even if a state has a 90% probability, the 10% event can still happen.
2. That is why quantum algorithms are run many times. By repeating the same circuit hundreds or thousands of times (so-called shots), we reduce uncertainty and recover the true probability distribution encoded in the wavefunction.

In practice, we often work with expectation values. If we measure an observable $\hat{A}$ many times, the average result is written as:

$$\langle \hat{A} \rangle = \langle \psi | \hat{A} | \psi \rangle$$

This expectation value is not the most probable outcome, but the statistical average of all possible results, weighted by their probabilities.

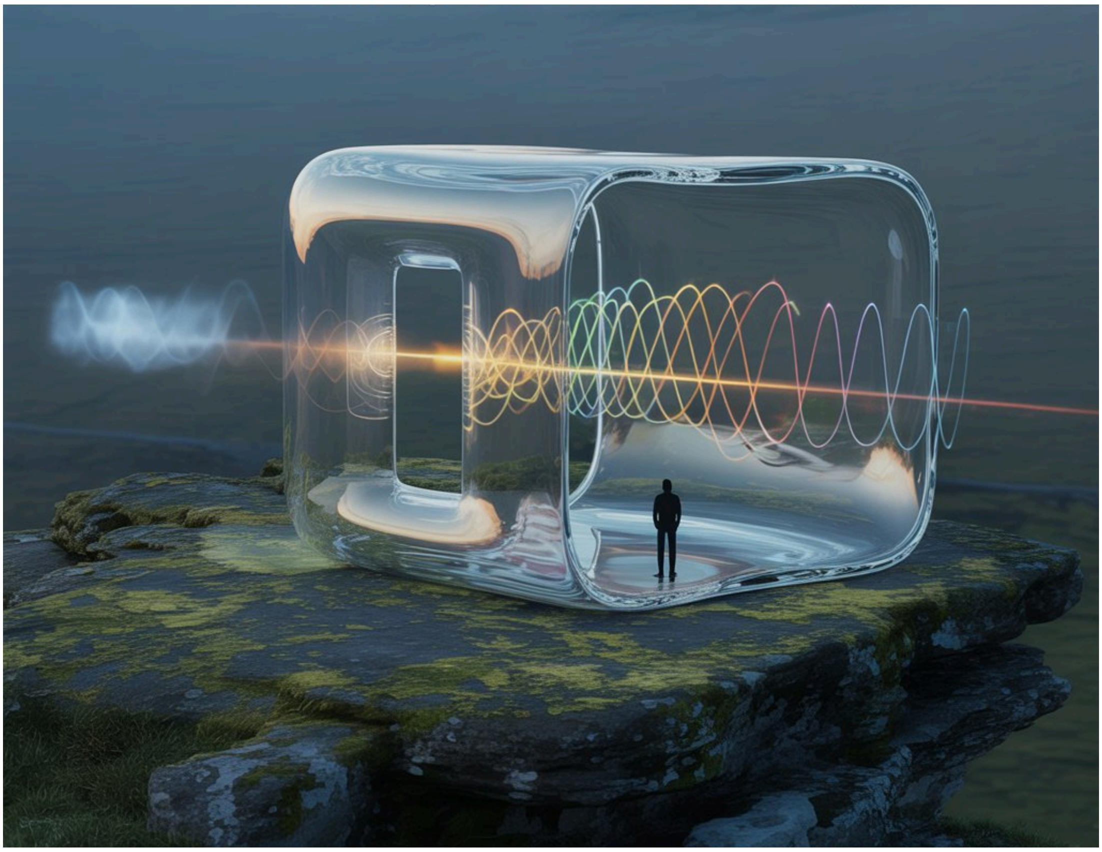
Every time we measure a quantum system, we gain information... but we also lose something: the ability to predict other properties with certainty. That is the hidden cost of wavefunction collapse.

A classic example: imagine using a laser to determine the position of an electron. The very photons we shine on it to measure it can knock it slightly, altering its momentum. In trying to measure its position precisely, we have disturbed its motion. As a result, we can no longer know both quantities with exact accuracy.

This tension—knowing one thing at the expense of another—is no accident: it is precisely what Heisenberg's uncertainty principle expresses.

In the quantum world, we can't have it all. Knowing a particle's position precisely means giving up precise knowledge of its momentum (mass times velocity), and vice versa. Nature forces us to accept a fundamental limit to knowledge: measuring always means sacrificing part of the information.

Thus, the third postulate reminds us that quantum mechanics is not made of certainties, but of probabilistic structures. And that when we observe, we are not just looking at the world—we are forcing it to make a choice.



Postulate IV: Time Evolution

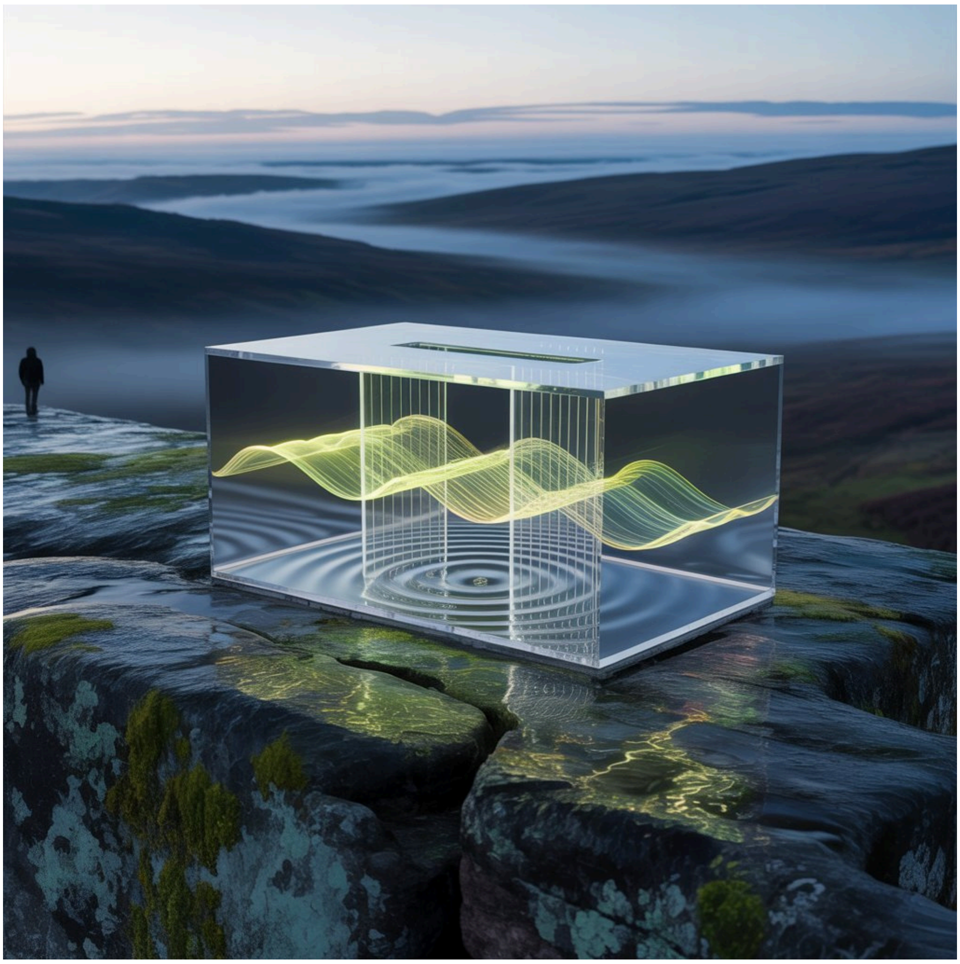
"The evolution of a quantum system is unitary and deterministic... until we measure it."

Physicist Erwin Schrödinger captured it with an inspiring thought: "The task is not to see what no one has yet seen, but to think what nobody has yet thought about that which everybody sees."

This postulate tells us that the evolution of a quantum system is unitary and deterministic**...** until we measure it.

- Deterministic, because if we know the initial state of a system and its Hamiltonian (the equation that encodes its energy and dynamics), we can precisely calculate what its state will be at any future moment.
- Reversible, because this evolution does not lose information: it can be "rewound" backwards without anything being destroyed.

All of this is described by the famous Schrödinger equation, which governs how quantum states change over time.



What Does "Unitary" Mean?

A unitary transformation is a mathematical operation that satisfies three key conditions:

1. It preserves the size of the quantum state. The "length" of the vector $|\psi\rangle$ remains constant.
2. It is reversible. There exists an inverse operation that exactly undoes the evolution.
3. It preserves total probability. No possibility disappears or is created from nothing: the system evolves without losing information.

This is one of the most beautiful aspects of quantum theory: as long as we don't measure, the evolution is so perfect that nothing is lost.

What Happens When We Measure?

Here lies the paradox: deterministic evolution breaks the moment we measure. At that instant, the system "jumps" to one of the possible basis states in a random process called wavefunction collapse. This jump is neither unitary nor reversible: once collapsed, there is no going back.

Application in Quantum Computing

In quantum computers, this postulate is fundamental. Quantum algorithms are built as sequences of unitary gates that transform qubits step by step.

A simple example is the Hadamard gate, which converts $|0\rangle$ into a superposition of $|0\rangle$ and $|1\rangle$. All quantum operations work this way: they maintain coherent and reversible evolution until the final measurement.

That is why, in quantum programming, the golden rule is clear: don't measure until the end. Measuring too early destroys the superposition prematurely.

The Real World: Decoherence and Noise

The fourth postulate assumes a closed quantum system, completely isolated from its environment: no interactions with external particles, radiation, thermal noise, etc. But real quantum systems are never perfectly isolated. They interact with their surroundings, causing decoherence: the gradual loss of their delicate quantum nature. The "quantumness" (superposition, entanglement) is lost as the system mixes with the classical world.

The current challenge in quantum computing is to delay decoherence as long as possible. Research focuses on:

- Quantum error correction codes
- Noise-resistant quantum gates
- Extreme isolation techniques for qubits

The goal is to keep the system "closed" long enough to complete useful calculations before environmental interactions ruin it.

Quantum Life Beyond the Laboratory

Although we often imagine quantum mechanics in ultra-cold, isolated labs, nature has been playing with it for billions of years.

- **Efficient Photosynthesis**
  In plants and bacteria, light energy is transported through quantum superpositions in photosynthetic complexes. Remarkably, even amid thermal noise, these superpositions last long enough (femtoseconds) to make transport more efficient. Here, the environment does not destroy coherence—it guides it.
- **Migratory Birds and the Magnetic Field**
  Some birds seem to navigate using chemical reactions in proteins called

cryptochromes. There, entangled electron spins act as a quantum compass sensitive to Earth's magnetic field—a natural quantum GPS in flight!

- **Natural Superconductivity**
  In materials like superconductors or superfluids, electrons form collective quantum states that maintain macroscopic coherence at low temperatures (Cooper pairs).

These examples remind us that quantum coherence is not just a technological challenge: it is a strategy that nature has mastered, even in seemingly hostile environments.