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1. Atomic Emptiness, the Double-Slit Experiment, and Wave-Particle Duality

Quantum physics can be both astonishing and intimidating for the uninitiated. It's a peculiar and seemingly illogical branch of science, even for physicists who work with it every day. Yet, this very science holds the key to answering some of the universe's most intriguing questions and has the potential to transform the world in the near future.

This branch of physics explores the behavior of the universe's smallest entities – subatomic particles. These particles can behave in completely unpredictable ways, exhibiting mysterious quantum effects.

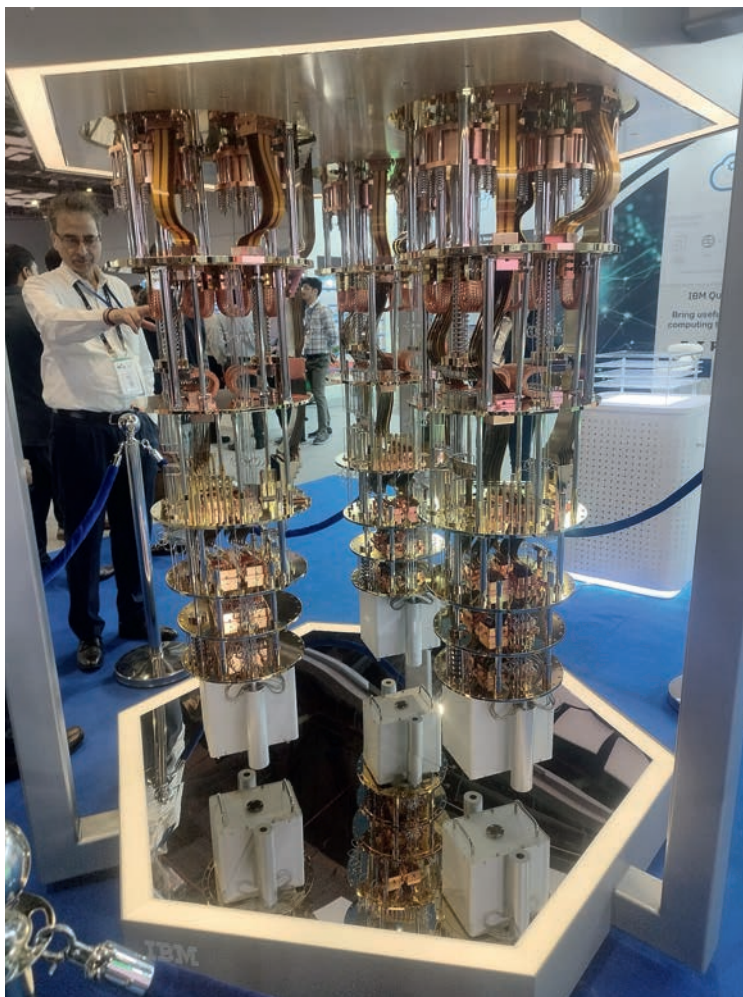
Although scientists don't fully understand the underlying processes, they have learned to harness the principles of quantum mechanics to develop cutting-edge technologies. Lasers, CT scanners, ultra-sensitive microscopes, phones, tablets, and advancements in telecommunications, robotics, and artificial intelligence are all made possible thanks to quantum effects.

In the near future, we can likely expect the creation of ultra-powerful machines – universal quantum computers, poetically referred to as the “Holy Grail” of modern physics.

Quantum physics is a relatively young science, with its core theories formulated only in the early 20th century. It encompasses several sub-disciplines, but the phenomena of quantum mechanics and quantum field theory play a fundamental role, characterized by uncertainty and randomness.

This inherent uncertainty and randomness give rise to numerous paradoxes and difficult-to-explain events in quantum physics, which continue to puzzle the brightest minds in the field. To grasp the general nature of quantum physics, it's

worth quoting Niels Bohr, one of its founding fathers: “Anyone who is not shocked by quantum theory has not understood it.”

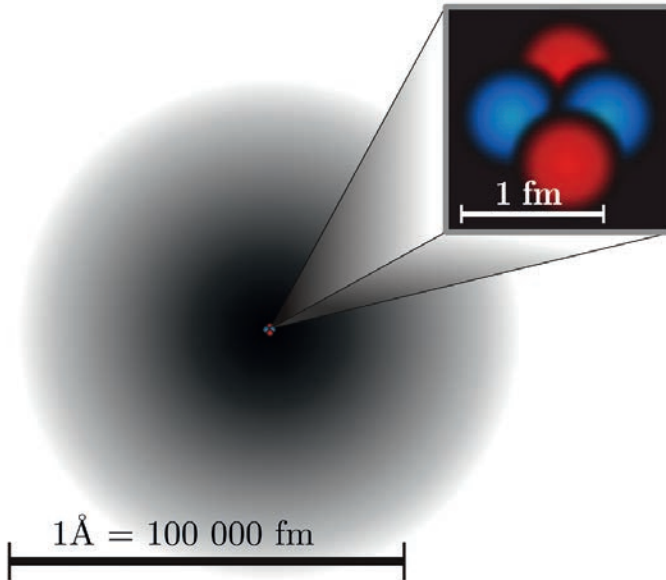


IBM Quantum Computer Demo at ITUWTS 2024, Delhi.
Photo by Dev Jadiya

Atomic Emptiness

It's difficult to imagine, but 99.999999999999% of an atom is empty space. The size of its nucleus is so small that it's measured in femtometers (a unit equal to one quadrillionth of

a meter). For instance, the diameter of a helium atom's nucleus is 1.67824 femtometers.



A schematic representation of a helium atom, with an electron cloud around it and a complex nucleus. Image: Murkt

This implies that our entire universe is almost 100% empty space, and only about 1% of all visible matter makes up the world around us. This scientific fact might make you reconsider how we perceive reality.

The space between an atom's nucleus and its orbiting electron cloud is virtually empty. As an analogy, if a hydrogen atom's nucleus were enlarged to the size of a basketball, its orbiting electron would be located 30 kilometers away, with the entire space between them being empty.

But if our bodies and the objects around us are mostly empty space, why can we touch them? This perceived "solidity" is created by forces of repulsion or attraction between atoms, similar to the forces between two magnets brought close together. Our hands and feet never actually touch anything; they only experience the force of repulsion, which creates the sensation of solidity.

It's hard to believe, but you're not actually touching the chair you're sitting on; you're hovering above it. This is because the atoms of your body and the chair are repelling each other. Our reality appears solid and tangible due to the all-pervading, oscillating ocean of energy around us, not because of anything truly substantial. Not only our bodies, but everything we see, feel, and interact with is essentially made of emptiness.

The Double-Slit Experiment

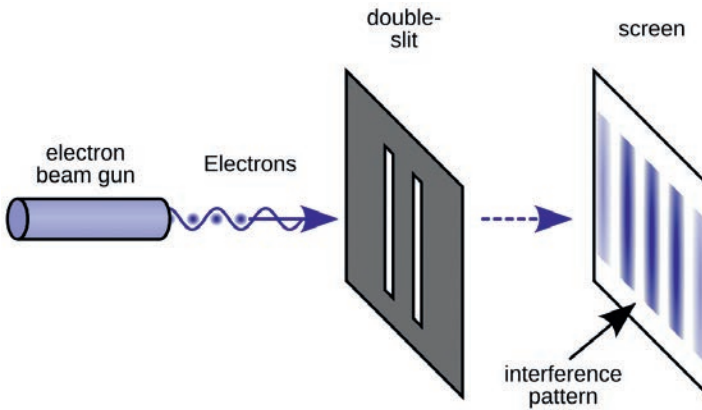
The most famous paradox in quantum physics is wave-particle duality, which describes how any micro-object, such as a photon or electron, can exhibit both the material properties of a particle with mass and the properties of a wave capable of propagating through space. Crucially, these properties change depending on whether there is, literally, an observer watching the quantum object.

This duality was first discovered in studies of light during an experiment conducted by English physicist Thomas Young in 1803. In 1923, French scientist Louis de Broglie hypothesized that not only light, but also elementary particles could possess wave-particle duality. In 1961, German physicist Claus Jönsson conducted an experiment similar to Young's double-slit experiment, but using beams of electrons.

This research confirmed the validity of quantum mechanics regarding the mixed wave-particle nature of elementary particles, and the experiment became one of the most astonishing in the history of science. Subsequently, the experiment has been repeated and verified in many laboratories worldwide, with consistent results.

The essence of the experiment is that a source emits a stream of electrons towards a screen or photographic plate. A barrier — a copper plate with two slits — is placed in the path of the electrons. For simplicity, imagine shooting small paintballs at

a screen instead of electrons, with the same copper plate with two slits placed between the screen and the “paintball gun.”



An illustration of the double-slit experiment. Image: NekoJaNekoJa

Before hitting the screen, the paintballs pass through the two slits. Logically, we should see two marks on the screen corresponding to the shape of the slits. However, in reality, a more complex pattern (interference) appears on the screen — multiple alternating bands from the impacts of the paintballs.

This occurs because, when passing through the slits, the electron-“paintballs” begin to behave not as particles, but as waves. Light particles (photons), atoms, and even molecules demonstrate the same behavior.

If we modify the experiment and launch the “paintballs” one at a time instead of a stream, the electron-paintball will still behave sometimes as a particle with mass and sometimes as a wave, passing through both slits simultaneously and leaving an interference pattern — an alternating pattern of bands — on the screen.

Now let’s consider the role of the observer, which makes this already puzzling story even more incredible. When the experiment was conducted without observation, the electrons immediately left an interference pattern on the screen.

But as soon as physicists tried to pinpoint which slit the electron passed through, the pattern changed dramatically and became “classical”: the electrons seemed unwilling to reveal their wave nature to the watchful eye of the observers. The scientists observed two bands on the screen, located directly opposite the two slits, without any alternating bands.

This phenomenon certainly seems mystical, but there’s another explanation: observing a system cannot be done without physically influencing it. To date, experts haven’t found a rigorous scientific explanation for why the presence of an observer determines the fate of the system and forces it to choose one of the possible states. Why does observing an electron make it a particle, while an unobserved and unmeasured electron can exhibit wave properties?

However, it has been experimentally proven that the determining factor in whether a particle behaves as a particle or a wave is observation.

2. The Quantum and Planck's Constant

Quantum theory and quantum mechanics — these concepts have become firmly embedded in our lives and are now familiar even to those not involved in science. It's not surprising, then, that even a schoolchild, repeatedly flipping a flash drive in futile attempts to insert it into a laptop's USB port, might wittily joke that the failures are due to the flash drive's "quantum superposition."

Quantum physics radically changes our understanding of the world, demonstrating that matter and physical fields aren't its sole foundation. New horizons are constantly opening before humanity, making it clear that we are all just particles of a vast quantum reality. Meanwhile, the solid edifice of Newtonian classical physics, which describes macroscopic objects, simply falls apart when applied to the subatomic microworld.

Most people have heard that quantum mechanics is full of paradoxes and bewilderingly strange phenomena that even the most brilliant physicists on the planet can't fully explain. Some are already familiar with "mystical" phenomena like quantum duality, the emptiness of atoms, the uncertainty principle, and many other enigmatic concepts.

However, it's important to understand that quantum physics, used to describe the smallest objects in the universe, is an incredibly complex, often illogical, and even absurd branch of science. As the eminent scientist and Nobel laureate Richard Feynman put it: "I think I can safely say that nobody understands quantum mechanics."

If the minds of brilliant scientists initially struggle to grasp quantum mechanics, what should non-specialists who are also interested in learning about this fascinating science

of the future do? If you're genuinely interested in quantum physics and want to learn more, it's best to start with its basic concepts.

The Quantum

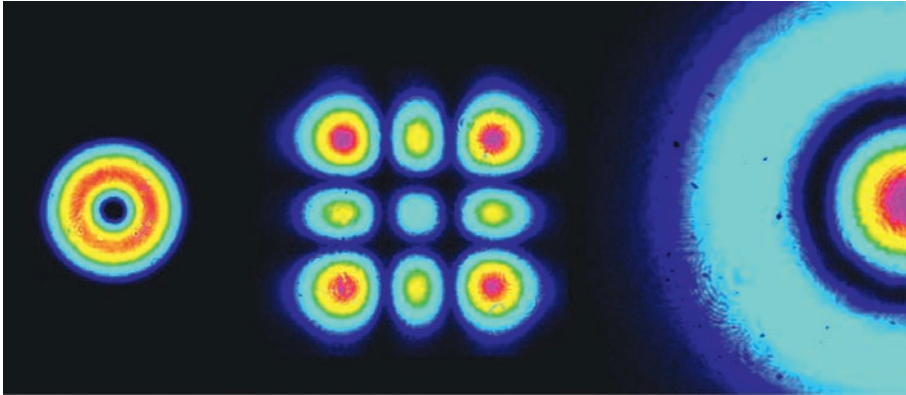
The term “quantum,” derived from the Latin “quantum” (meaning “how much”), is used to characterize the physical properties of a collection of particles, or a quantum system. It denotes an indivisible portion of a quantity in physics, such as energy or a field. It's important to note that this concept applies only to the micro-world: there can be a quantum of light or a quantum of the gravitational field, but not a quantum of earth or rain.

The fundamental idea of quantum physics is the study of very small particles that behave according to special laws. These laws are radically different from those we are accustomed to in the macro-world. In classical physics, all objects have specific properties, such as rigidity or elasticity. But because particles in quantum physics can behave like waves, pass through walls, and even add and subtract from each other, the laws of classical physics don't apply. Indeed, the principles underlying quantum theory are so contrary to common sense that even the most brilliant minds have tried their best to give them a rational explanation, but their attempts have not been successful.

Returning to quanta, the concept emerged in physics in 1900 thanks to the work of German physicist Max Planck. He was attempting to theoretically describe the radiation emitted by heated bodies, known as “black body” radiation. Like many crucial discoveries, the discovery of the quantum was, to some extent, an accident.

Interestingly, neither Planck nor, slightly later, Einstein, initially grasped the significance of their discoveries or accepted quantum theory. There was a good reason for this: the new

theory violated the laws of classical physics. Nevertheless, Einstein later became the first physicist to declare that Planck's discovery of portions of light radiation (later called Planck's constant) would require a revision of existing laws of physics.

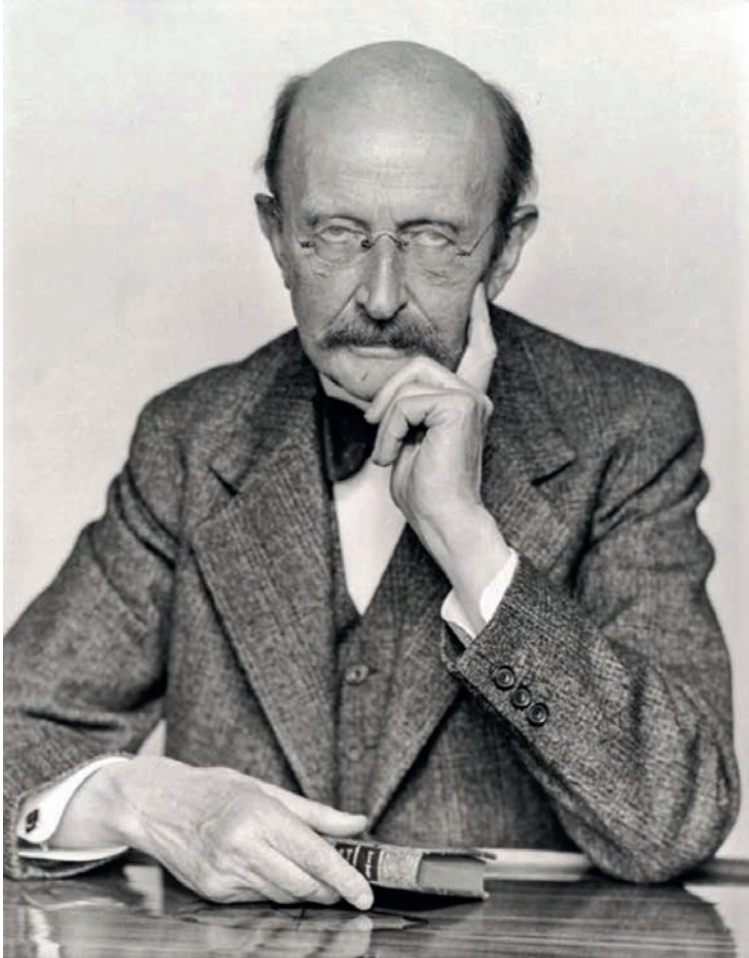


The quantum of electromagnetic radiation (light) is a photon. An image of photon beams is taken using a photosensitive CCD sensor. A CCD (charge-coupled device) is a device that converts the energy of optical radiation into an electrical signal. Image: Egor Kovlakov / LMSU

Through his research, Max Planck truly revolutionized physics. He discovered that atoms emit energy not continuously, but discretely — in distinct portions he called quanta. A quantum is the minimum amount of energy emitted or absorbed by a body.

This gave rise to the quantum theory of light, formulated by Planck in 1900 and substantiated in 1905 by Albert Einstein in his work on the photoelectric effect, for which he received the Nobel Prize in 1921.

According to the theory, the energy of a quantum (E) is equal to the frequency of the atom's radiation (ν) multiplied by Planck's constant (h), expressed as $E = h\nu$. The coefficient h (the elementary quantum of action) is a fundamental quantity in quantum theory and appears in all formulas and equations of quantum mechanics.



Max Planck (1858 – 1947) was a German theoretical physicist.
Photo: Hugo Erfurth

Therefore, the higher the frequency of an electromagnetic wave (the number of its oscillations), the more energy a single quantum carries, and all electromagnetic interactions are exchanges of quanta of corresponding energy. Thanks to understanding the discrete or “quantized” nature of this exchange at energy levels, humanity has managed to harness the energy of the atom and unlock incredible prospects for creating new technologies. This is the immense significance of Planck’s quantum theory.

3. Three Myths About Quantum Mechanics

Schrödinger's Cat

Quantum mechanics, which governs the world of atoms and particles, certainly has a mystical aura. Unlike other branches of physics, this theory is so strange that it contradicts our intuitive understanding of the world. But that's precisely what makes it so intriguing and fascinating.

Perhaps this is why discussions about quantum mechanics often lead to persistent myths and misconceptions, not only in casual conversations on internet forums, but also in science fiction and even the mass media.

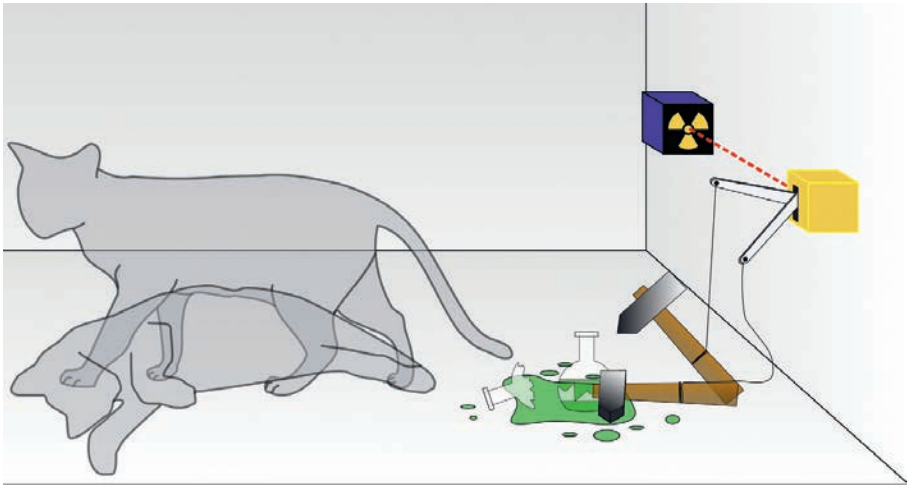
Erwin Schrödinger, one of the founders of quantum mechanics, could hardly have imagined that his thought experiment would become an internet meme in the 21st century. Yet, Schrödinger's cat, symbolizing a certain ambiguity, has become not just a meme but a veritable pop culture icon.

The meaning of the meme, featuring the unfortunate cat sitting in a box with a switch, lies in its ambiguity and absurdity from the standpoint of common sense. As a result of a random event — the radioactive decay of an atom — the switch in the box might activate, killing the cat. Or it might not. Thus, the unfortunate cat exists in a superposition — in multiple states. It can be both alive and dead simultaneously, but until we open the box, we won't know for sure.

However, in reality, no one ever put a poor cat in a box with a switch, or even in a steel safe, which is what Schrödinger actually mentioned. Furthermore, to be completely accurate, it was a female cat (German: die Katze), not a male.

The fact is that this was a thought experiment proposed by Schrödinger in 1935 during a discussion about the physical

meaning of the wave function, which characterizes the state of a quantum system. The physicist used it to illustrate the incompleteness of quantum mechanics when transitioning from subatomic systems to macroscopic ones — a process physicists call decoherence.



Schrödinger's cat thought experiment: a cat, a flask of poison, and a radioactive source connected to a Geiger counter are placed in a sealed box. As illustrated, the quantum description uses a superposition of an alive cat and one that has died. Image: Dhatfield

In the cat experiment, the wave function of the system, or simply the “probability wave,” represents an abstract cloud of numerous particles, each with a “hidden” coordinate. In essence, the wave function expresses that both the live and dead cat are, excuse the expression, mixed or smeared in equal proportions.

However, we cannot assume that in superposition, reality is actually “smeared” in space according to the wave function. Therefore, while the modern meme doesn't reflect the true meaning of the experiment, it accurately captures the absurdity that Schrödinger was pointing out.

Going further, it's worth noting that the cat's superposition arising in the experiment cannot be applied to large systems

like cats or humans. The quantum coherence of the trillions of atoms making up a cat is extremely short-lived. However, this doesn't mean that quantum coherence is impossible in biological systems in principle.

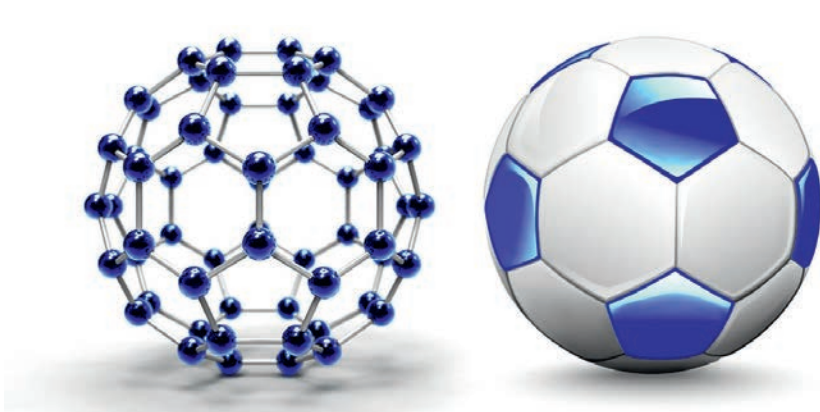


A life-size cat figure in the garden of Huttenstrasse 9, Zurich, where Erwin Schrödinger lived from 1921 to 1926. Depending on the light conditions, the figure appears to be either a live cat or a dead one.

Photo: Koogid

Scientists have long known that even large molecules can exist in superposition, meaning they can be in different places simultaneously as “probability waves.” A famous experiment by Austrian physicist Anton Zeilinger (2022 Nobel laureate in physics) demonstrated quantum superposition with large car-

bon-60 molecules (also known as fullerenes or “buckyballs”) back in 1999.



Fullerenes are molecular compounds in the form of symmetrical polyhedra with an even number of carbon atoms. The most common molecule, C_{60} , consists of sixty carbon atoms and looks like a soccer ball, hence its name, buckyball. C_{60} has been found in planetary nebulae and several types of stars. Illustration: Eva Sarett

Currently, such experiments are being conducted with truly gigantic molecules. For example, in 2019, an international team of researchers from Austria, Germany, Switzerland, and China conducted an unprecedented experiment, placing a molecule consisting of 2,000 atoms into a state of quantum superposition. From the perspective of classical physics, such a state is impossible. Moreover, scientists don't intend to stop there and plan to significantly increase the mass of objects in future experiments.

Quantum Entanglement and the Principle of Nonlocality

The next misconception is related to perhaps the “spookiest” phenomenon in quantum physics: quantum entanglement. In the simplest terms, it's a quantum property that links

two different particles. Even if one is on Earth and the other is at the opposite end of the universe, measuring one automatically and instantly reveals the state of the other.

Albert Einstein called this phenomenon “spooky action at a distance” because interaction between objects separated by vast distances cannot propagate faster than the speed of light.

The world around us is traditionally local, and we all know that to change the properties of a specific object, it must interact with another object. But in the phenomenon of quantum entanglement, the opposite principle — nonlocality —



David Mermin and Reinhold Bertlmann showing their socks at the conference Quantum [Un]Speakables II, Vienna 2014. Photo: Bertlmann

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