# 1.) Introduction

In 1996 I presented at the Dąbrowski Congress on relativity and Dąbrowski. A recent post stimulated me to go back and have a look at this again. I am going to present the absolutely very briefest overview of theory first.

I see an analogy between the science and psychology of relative frames. Like physical frames, our psychological experience is unique to our frame of reference. Understanding others requires an appreciation for the relativity of various frames of reference. We cannot simply assume that others see the world as we do. It struck me that an appreciation of Dąbrowski's two basic types of perception, unilevelness and multilevelness, was helpful in this discussion and, as well, that an appreciation for frames of reference gives us a context to understand Dąbrowski better.

# 2.) Galilean Relatively (Galileo Galilei)

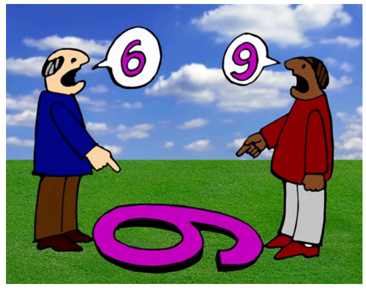
## Frame of reference

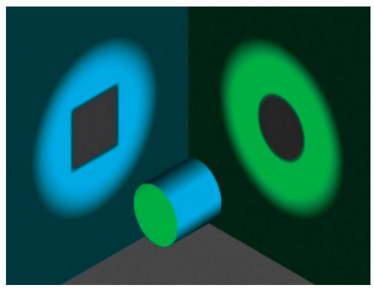
— A "frame of reference" is a standard relative to which motion and rest may be measured; any set of points or objects that are at rest relative to one another enables us, in principle, to describe the relative motions of bodies.

— The frame of reference is a point of view (POV): everything around you is relative to you.

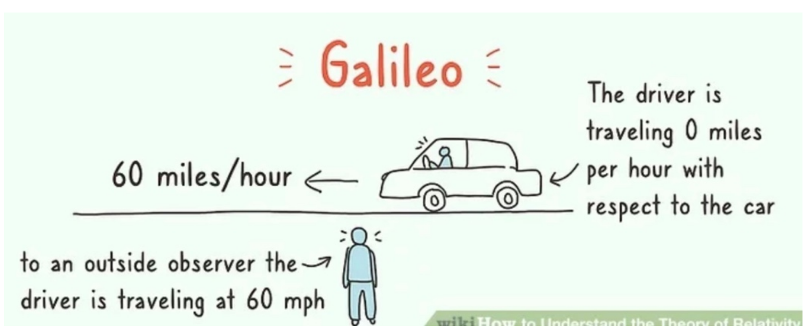
— Each person has their own frame of reference (POV). These views can be radically different.

— Think of a big picture frame enclosing us: only the things inside our “frame” can be used as a point of comparison or reference for any measurements.



— A frame of reference example: a driver in a car and an observer on the side of the road. The driver in the car sees the telephone poles along the side of the road moving by, but the driver feels stationary in the car. To an observer on the side of the road, the poles are stationary, and the car and driver are moving by. If you are traveling at 100 km/h, an observer on the side of the road will measure your speed at 100 km/h. If a car passes you at 110 km/h, the roadside observer will measure it at 110 km/h, but you will measure it as going 10 km/h.




## Relativity

— Relativity is the study of how different observers view the same reality.

## Aristotle

— In Aristotelian physics, if you drop a cannonball from the top of the mast of a moving ship, it will land directly below where it is dropped. Let's assume the ball takes two seconds to fall and during that time the ship has moved two feet forward. This means that the ball would land two feet **behind** the base of the mast.

## Galileo (1632)

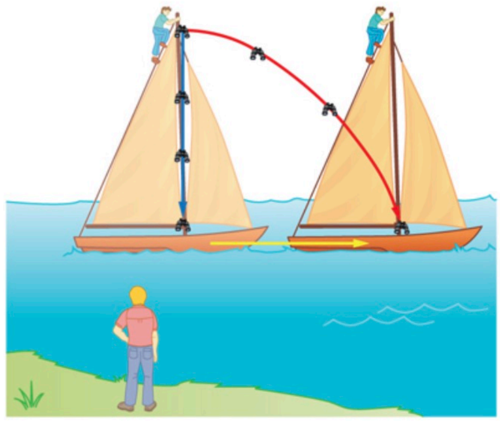
***Inertial frame***

— **Inertial frame** is a frame moving at a constant speed, or, being at rest (no acceleration). The lack of acceleration means no force is acting on a body or system of bodies. That means that the system's motion is determined entirely by its **inertia**.

***Galilean relativity***

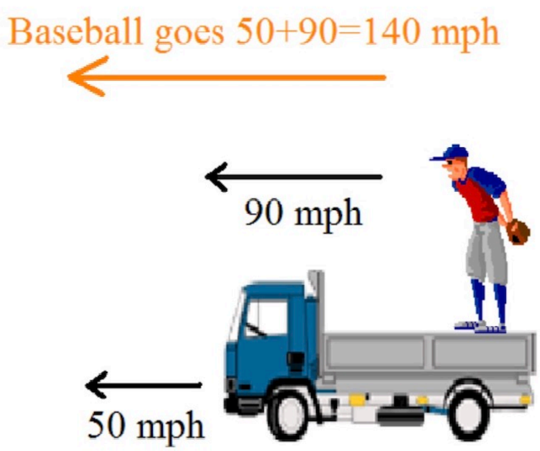
— Galilean relativity is the earliest formulation of the **classical theory of relativity**.
— Galileo formulated the principle of relativity in order to show that one cannot determine whether the earth revolves around the sun or the sun revolves around the earth.
— Galileo said if you drop the cannonball from the top of the mast and the ship is at rest, of course, the ball will land directly below at the base of the mast. Now, have the ship move forward at a uniform speed and observe what happens. Nothing changes – the ball (in this illustration, the binoculars) still falls at the base of the mast.

— Galileo realized that the ball (here binoculars) is moving along with the ship – they are in the same relative frame.
— To an observer on the ship, the binoculars fall straight down.
— The effects of continuous motion are the same as the effects of being at rest.
— The principle of relativity states that there is no physical way to differentiate between a body moving at a constant speed and an immobile body. An observer under a ship's deck cannot tell if the ship is moving or stationary.
— From the point of view of an observer on the shore, they will see the binoculars begin to fall, and as the boat moves forward, they will see a trajectory, and they will see the binoculars land at the base of the mast.



— Since we are in motion together with the Earth, and our natural tendency is to retain that motion, to us, the Earth appears to be at rest.

— Galilean relativity uses the "**addition of velocities**." For example, if someone is standing in the back of a truck going 50 mph and throws a baseball toward the front at 90 mph, the driver will measure the speed of the ball at 90 mph; however, a roadside observer will measure the speed of the ball at 140 mph. [As we will see, this does not apply to light.]




— The baseball has two speeds depending on who is observing: for the driver and pitcher – 90; and for an observer at the side of the road, 140.

— An observer in any inertial frame of reference cannot carry out any experiment that will detect the movement of the frame of reference. Thus, to say that an object is moving is almost meaningless; it can only be described as being in motion relative to something else. For example: imagine being on a red train. Looking out the window, you see a green train that appears to be moving. Based solely on this observation, it is impossible to tell which train is really moving (or, maybe both are moving). The same is true for someone on the green train you are observing.

***Galilean Invariance***

— Galilean Invariance says the fundamental laws of physics (and motion) are the same in all frames of reference that are moving with constant velocity with respect to one another (no acceleration).
— An object in a state of motion possesses an "inertia" that causes it to remain in that state of motion unless an external force acts on it.
— Galilean Invariance + Inertial Frame form the basis of Newton's Laws.

## Newton

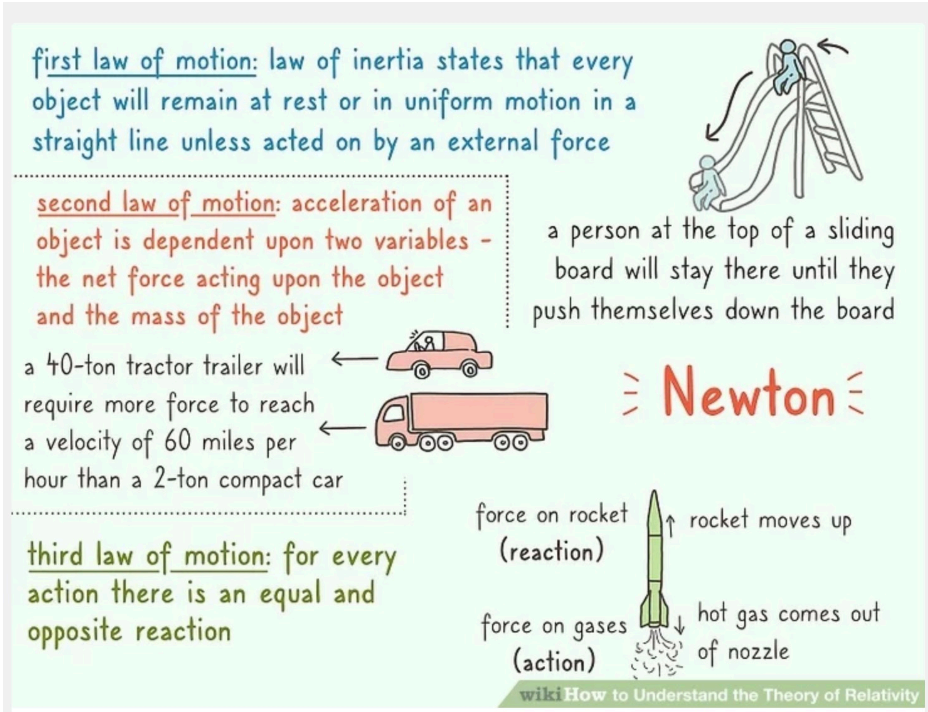
— Newton endorsed Galileo's relativity principle (law of inertia) but believed in a frame of absolute rest.

***Time is absolute.***

— There is no difference in time in different reference frames.

***Newton's three laws of motion***

— Newton's laws of motion (1687) dominated the scientific view of the physical universe for the next three centuries:
— In the **first law**, an object will not change its motion unless a force acts on it. [From Galileo]
— In the **second law**, the force on an object is equal to its mass times its acceleration (force = mass x acceleration).
— In the **third law**, when two objects interact, they apply forces to each other of equal magnitude and opposite direction. If an object pushes against another object, the second object pushes back just as hard.




# 3.) Special Relativity

## Einstein

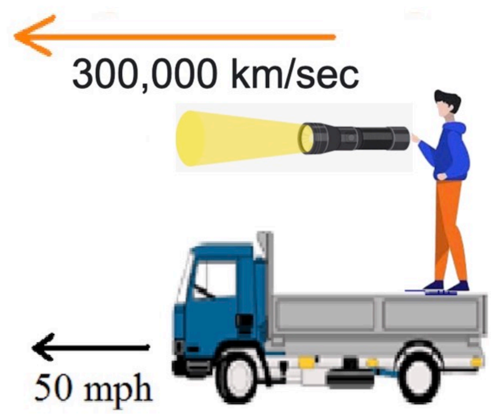
— Einstein formulated special relativity in **1905**.
— Special relativity is a subset of Einstein's broader and **subsequent** theory of general relativity.
— Special relativity applies only to inertial reference frames - it does not apply to non-inertial reference frames, frames that are in a state of acceleration.
— The "special" advance of special relativity combines the fact that the **speed of light is constant** and where you **ignore gravitational fields.**
— Observers in all reference frames perceive the same laws of nature. [Einstein added gravity when he formulated his theory of general relativity in 1915.]

***Special Relativity is comprised of two postulates:***

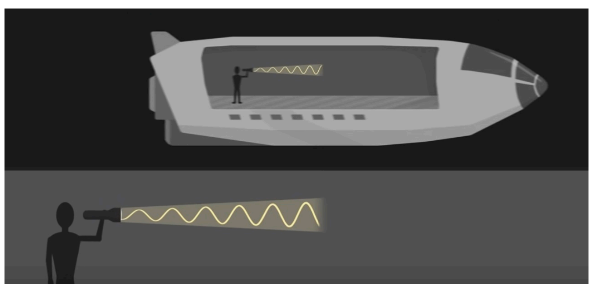
— 1). the laws of physics are the same in every inertial reference frame [Galileo]
— 2). the speed of light (c) is the same in every inertial reference frame.

***Postulate 2***

— Based upon postulate number two: If an observer at the side of the road shines a flashlight, this light will be measured at a speed of 299,792,458 m/s. If the driver of a car going 100 km/h shines a flashlight out the front window, both the driver and the observer on the side of the road will measure the speed of light at 299,792,458 m/s. [The speed of the car is not added in.]



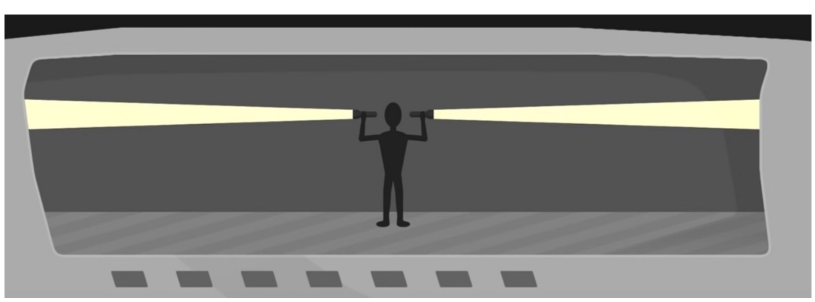

The speed of light measured by the driver and by the observer at the side of the road will be the same – 300,000 km/s. The speed of the vehicle is not added on.



The speed of light will be the same on the ground as on the speeding spaceship. (see Roussel, 2018)

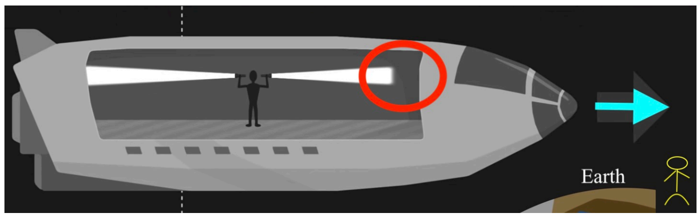
— Postulate 2 creates problems when you look at frames of reference that are moving very fast.

—An astronaut on a speeding spaceship turns on two flashlights simultaneously, one pointing to the front and one to the back. The astronaut will see the light hitting the back and the front simultaneously.



(see Roussel, 2018)

— However, as shown in the next illustration, to an observer on the earth watching, the light hits the back **before** it hits the front. This looks like a violation of the invariance of the speed of light. To explain this, Einstein deduced that for the astronaut, time is moving at a different rate compared to the observer on earth. Contradicting Newton, Einstein realized that **time must be relative to an observer's frame of reference**: time flows at different rates for different observers




(see Roussel, 2018)

— **Einstein's conclusion: time is relative**. There is no absolute time.

***Relativity of simultaneity [or simply simultaneity]***

— It is impossible to say in an absolute sense that two distinct events occur at the same time if those events are separated in space. If one reference frame assigns precisely the same time to two events that are at different points in space, a reference frame that is moving relative to the first will assign different times to the two events.

— Because light takes a finite time to traverse a distance in space, it is not possible to define simultaneity with respect to a universal clock shared by all observers. In fact, purely due to their locations in space, two observers may disagree about the order in which two spatially separated events occurred.

***Time Dilation***

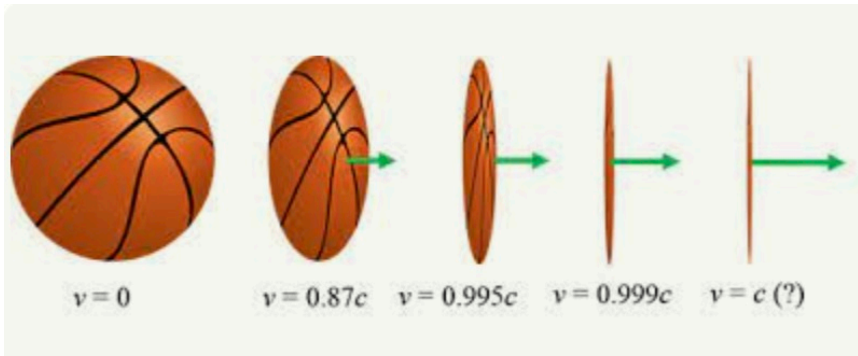
— The faster you move, the slower time passes. For example, for an airplane going around the earth: a clock from the plane will be a few billionths of a second behind a clock on the earth. Time for the observer on earth and an observer on a spacecraft will be different: time is relative to the framework. This factor is significant enough that it has to be taken into consideration for satellites and spacecraft orbiting the earth.

— In other words: When a frame of reference goes very fast (close to the speed of light) relative to a rest frame, its time slows down, as observed by someone in the rest frame. This relativistic effect is known as time dilation.

***Length Contraction***

— Because time is relative to the framework, length is also a relative measure. Thus, at faster speeds, objects and distances appear shorter.

— The space of a moving reference frame, and the objects in that space, become contracted in the direction of motion relative to the rest frame. This relativistic effect is known as length contraction.

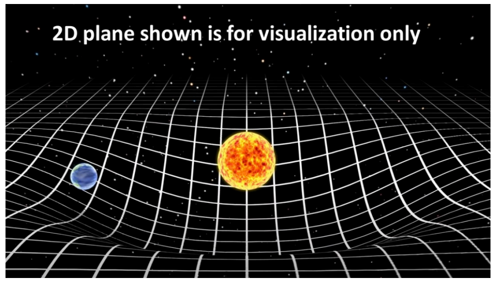



***Mass and energy are interchangeable***

— The mass is equivalent to an energy E/c2. In other words**, $E = mc^2$**.
— **$E = mc^2$** This formula means that under the right conditions, **energy and mass are interchangeable:** they are forms of the same thing. Again, under the right conditions, mass can become energy and vice versa. With sufficiently high energy, we can produce particles.
— John Wheeler: "It [special theory of relativity] united energy and momentum, knit electricity and magnetism more tightly together, showed that time is relative, provided a speed limit in nature, and, most dramatically, revealed the equivalence of mass and energy, giving the twentieth century its most famous formula, $E = mc^2$."

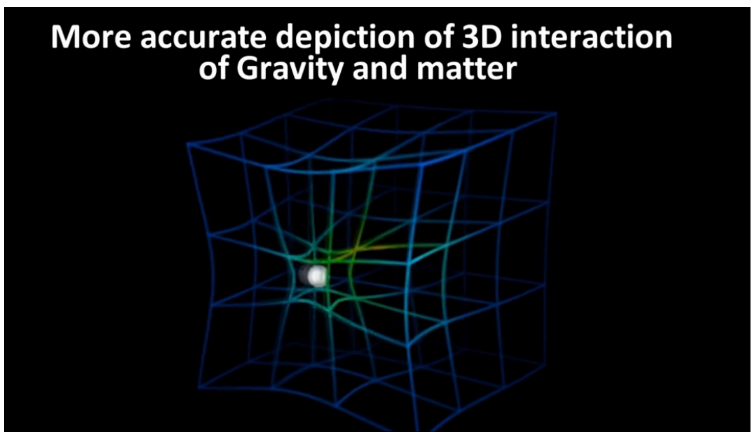
***Spacetime***

— In 1908, Minkowski, Einstein's math professor, developed **spacetime** in response to Einstein's 1905 paper on special relativity. He realized that the special theory of relativity could best be understood in a four-dimensional space, known as the "Minkowski **spacetime**," in which time and space are not separated entities but intermingled in four-dimensional spacetime.
—John Wheeler: "Minkowski's vision powerfully altered the way we look at the world around us. He showed that Einstein's theory unites not only space with time, but also the electric field with the magnetic field, and energy with momentum."
— Spacetime is really just a fabric we posit to describe how one thing affects another, and to express the limitations on such interactions. It's an emergent property of causal relationships. quantum mechanics forces us to revise our preconceptions about causation. (Ball)
— Spacetime is often depicted as **a flexible sheet**.




(see Roussel, 2020)

— These depictions are **misleading** as they are two-dimensional. A proper depiction would include a mass within a three-dimensional space with time as a fourth dimension. To understand this, you have to see the animation (see Roussel, 2020).




(see Roussel, 2020)

***What is moving?***

— Psychologically, many people feel as if they are in space moving through time. This is incorrect. Actually, **we, and our relative time, are moving through space together**.

***An event***

— Minkowski: An event must be described using four coordinates - its place in space (length, width, height) and the time it occurs.


# 4.) General Relativity

## Einstein

— Einstein (1916)
— Called general relativity because it is a generalization of special relativity.
— General relativity includes all reference frames, including those with acceleration.
— General relativity includes gravity.
— Summary: In special relativity, there is no gravity, and spacetime is flat; in general relativity, spacetime curves, and there is gravity.

***Gravity***

— The notebooks of Leonardo da Vinci show he used grains of sand poured out from a jar. to study the nature of gravity, and the equivalence between gravity and acceleration—well before Isaac Newton came up with his laws of motion, and centuries before Albert Einstein would demonstrate the equivalence principle with his general theory of relativity. Leonardo's model produced a value for the gravitational constant (G) to around 97 percent accuracy. What makes this finding even more astonishing is that Leonardo did all this without a means of accurate timekeeping and without the benefit of calculus, which Newton invented in order to develop his laws of motion and universal gravitation in the 1660s. (See Ouellette, 2023).
— At the present time, there is **no generally accepted explanation or theory of gravity**.
— **Gravity is not a force**; it is a consequence that emerges from the interaction of space and matter.
— Newton described the effects of gravity but didn't know how it worked.

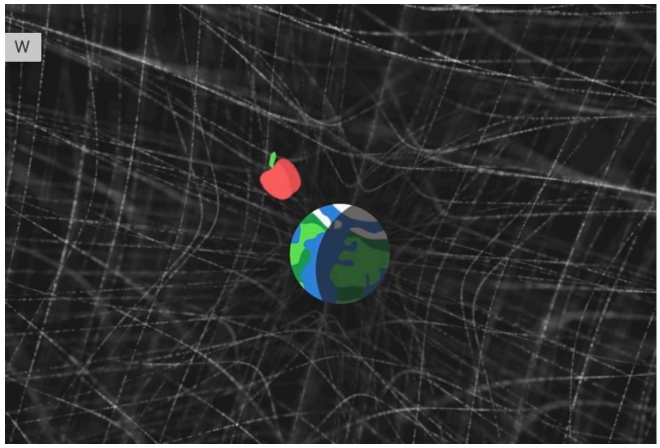
— Einstein proposed that objects with mass curve spacetime, resulting in other objects moving on or orbiting along those curves; this is what we experience as gravity.
— Einstein also linked gravity and acceleration: as mass acts upon space, space is curved, causing the mass to accelerate: gravity is a form of acceleration.
— Einstein predicted that gravitational waves ripple through the universe, but Einstein thought they would be too small to detect. In 2016, they were detected.
— The effect of mass on the curvature of spacetime has almost no effect on the movement of the objects until they are moving really fast. The curvature of spacetime is generally tiny; for example, the total stretching of space due to the Earth amounts to less than 1cm.
— In almost all cases, the vast majority of an object's movement is tied up in its forward movement through time. The curvature of spacetime is responsible for gravity. In spacetime, near heavy objects, the "future direction" points slightly down. So, anything that moves forward in time will find its trajectory pointing down slightly when near or passing heavy objects. This takes the form of downward acceleration. This acceleration (time pointing slightly down) is entirely responsible for the motion of the planets and every other everyday experience of gravity.

In flat space traveling forward in time has
no effect on your movement through space.

In curved space (e.g., near a large blue mass), parallel lines
can come together, and moving through time
leads to downward movement.

—Current thinking is split between gravity having a quantum property and gravity simply being an effect in the way that mass warps space-time. Notwithstanding these ideas, it could be that there is a quantum particle that contributes to the effect that matter is seen to always move towards the largest mass in its vicinity. [above from https://www.askamathematician.com/2010/12/q-why-does-curved-space-time-cause-gravity-a-better-answer/]

— A ball [mass] falling to Earth is affecting spacetime and, therefore, also affecting the motion of other bodies elsewhere.




(see Roussel, 2020)

***World lines***

— Events are joined by “**world lines**,” (from Minkowski). These are tracks through spacetime. These lines are depicted in the illustration above.

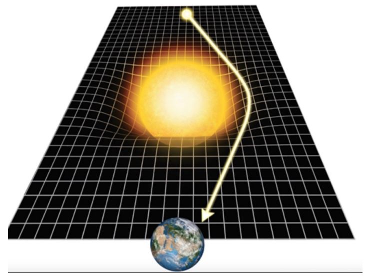
***Static time***

— A consequence of this new spacetime view is that motion through time, or motion of time: whichever way you choose to look at classical time, is replaced by **static time**, time that is just “there” in a frame of reference, the same way that space is there. A world line becomes a line on a map, a four-dimensional map on which the line traces a path through both space and time.”

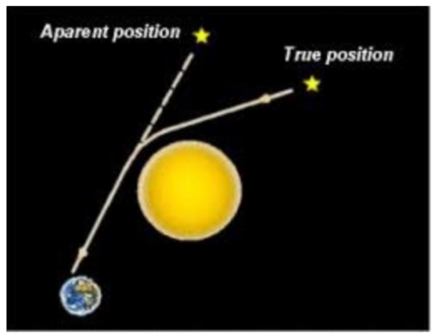
***Gravitational lensing***

— Gravitational lensing: If light travels through space and the space bends around a massive object like a star [when passing through a gravitational field], then, we should observe the light bend, and this is exactly what has been observed.

— Einstein dismissed the importance of gravitational lensing, initially doubted the reality of gravitational waves, and failed to anticipate the discovery of the expanding universe.



(gravitational lensing)

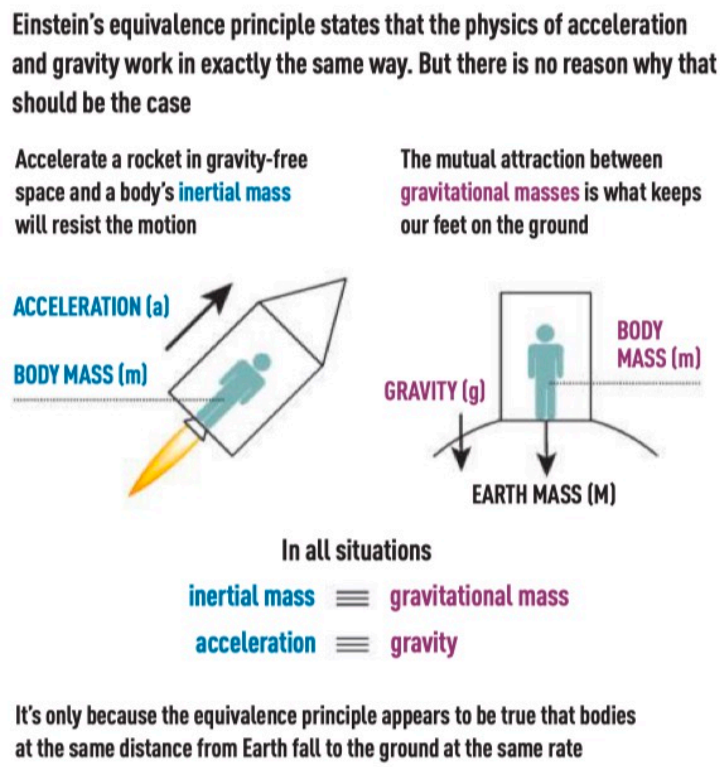



— John Wheeler: "**Space-time tells matter how to move, Matter tells space-time how to curve**." In other words, a bit of matter (or mass, or energy) moves in accordance with the dictates of the curved spacetime where it is located. At the same time, mass or energy is itself contributing to the curvature of spacetime everywhere. The greater the mass, the greater the curvature of space.

***Equivalence principle***

— The story goes that Einstein looked out the window and saw a window cleaner on a ladder. He imagined the man falling off and, in his imagination, realized that as the man fell, he would experience no forces: he would be in free fall in space. Einstein gave examples of a person in an elevator: if you are in an elevator sitting on the surface of the earth, you will feel a force pushing up on your feet of 9.81 metres per square second. If you drop a book, it will fall to the floor of the elevator. Imagine you are in a rocket ship going up at an acceleration of 9.81 metres per square second. You would have the same force pressing on your feet as you would in the elevator. Now, if you let go of the book, the floor of the rocket ship will rise up toward the book, eventually hitting it. From your position as an observer, you cannot tell the difference between these two scenarios: is the book falling toward the earth? Or is the rocket ship floor moving up towards it? This contradicts Newton, who said the force of gravity is pulling you down toward the earth. (see Veritasium, 2020).

— General relativity led to the **equivalence principle**. The local effects of gravity and of acceleration are equivalent. Gravitational and inertial mass our equivalent, therefore, the gravitational "force" as experienced locally while standing on a massive body (such as the Earth) is the same as the pseudo-force experienced by an observer in a non-inertial (accelerated) frame of reference.

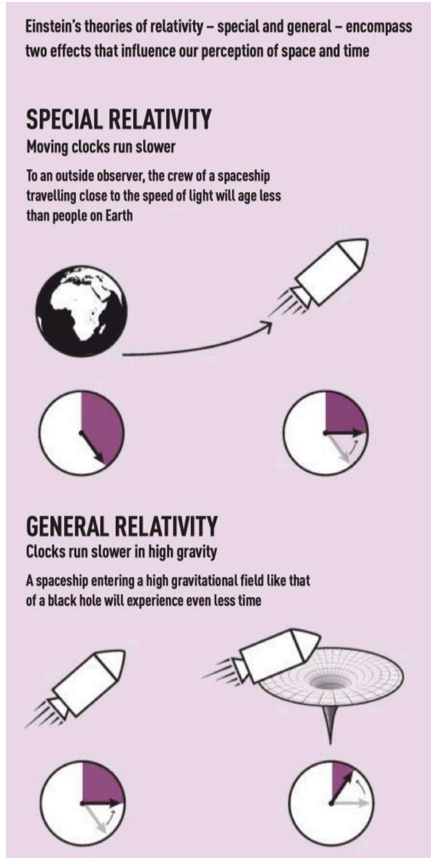



(Webb, 2021)

— The equivalence principle: "No experiment can be performed that could distinguish between a uniform gravitational field and an equivalent uniform acceleration."

***Gravity impacts time***

— Clocks run slower in higher gravity – a clock at sea level on Earth ticks slower than one at the summit of Mount Everest.



(Webb, 2021)

— **Gravity accelerates all objects equally** regardless of their masses or the materials from which they are made. In a vacuum (no air resistance), a bowling ball and a feather will fall at the same rate.

— The simplest classical system—the basic logical unit for computer science—is the two-state system. Sometimes it's called a bit. It can represent anything that has only two states: a coin that can show heads or tails, a switch that is on or off, or a tiny magnet that is constrained to point either north or south.

# 5.) Representations of reality.

— There are two main aspects to this, psychological and neurological.

— Likely, inter-individual differences are greater than recognized

***The epistemology of perception***

— There are many philosophical interpretations of how reality comes to be perceived.

— Perception is a central issue in epistemology, the theory of knowledge. At root, all our empirical knowledge is grounded in how we see, hear, touch, smell and taste the world around us.

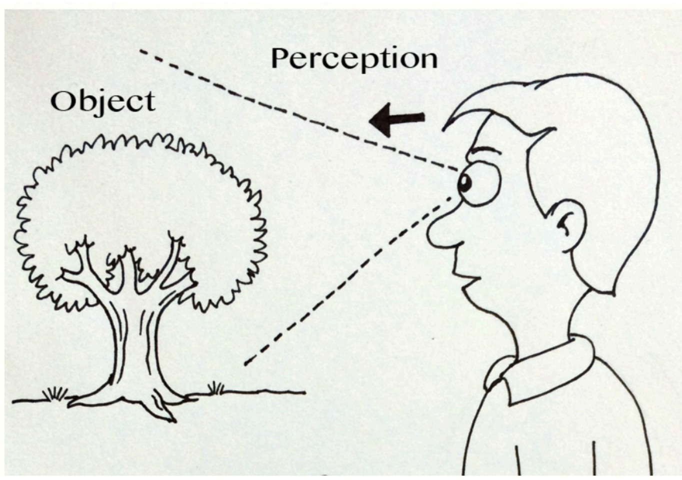
***Two levels of reality***

— It is often difficult to separate the **objective** (what actually is) from the **subjective** (what we think it is). Normally, we automatically assume that what we are experiencing is objective, but in reality, it's almost always subjective.

***Philosophical theories of perception***

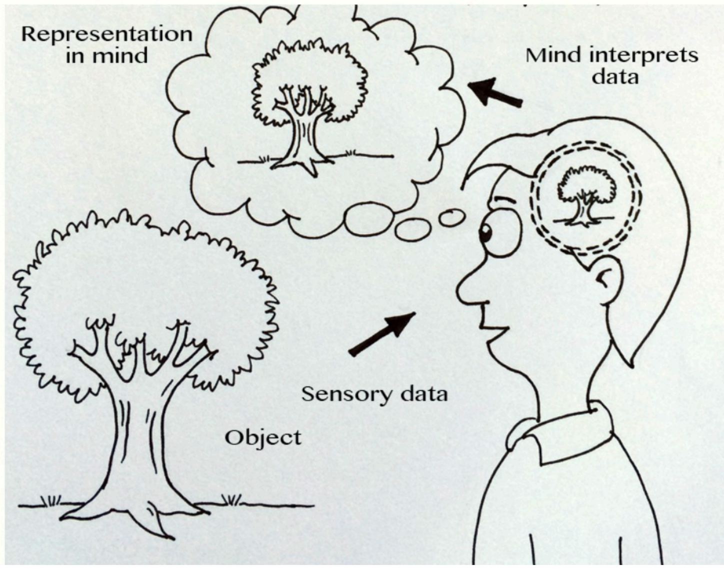
Direct realism ["naïve realism"]

— from Aristotle. Says that **objects exist independently of the mind** (or out in the world) **and we perceive them directly. Material objects are real**. When you see a red apple, your eyes acquire a tinge of red. When you taste a strawberry, your tongue acquires a little of the strawberry flavor.




Indirect realism ["representative realism" or representationalism]

— Second, indirect realism ["representative realism" or representationalism] says that objects exist independently of the mind (or out in the world) and that **we perceive them indirectly through our senses.**




Idealism

— A third view is idealism, originally derived from Socrates and Plato. (“Idealism” = “Ideas”) **Idealism says that without the mind there is no external world and that everything that exists are simply ideas. The material world is a construction** - a mere byproduct of a more important reality. Socrates, Plato, Augustine, Immanuel Kant, George Berkeley, and Hegel.

— Plato believed that there are actually two worlds (“realms”). The first is the “sensible” (sensible = perceived by our senses) imperfect world of appearances that we commonly take as being reality, but, more often than not, are simply illusions or shadows. It is the World of Becoming. We can have beliefs about the world we perceive through our senses but not knowledge. The prisoners in the cave accept the images on the wall of the cave as reality. Plato’s second, the intelligible world, is the perfect world of the spiritual and mental. It is the World of Being. It is eternal and universal and represents the Truth. These eternal Truths exist in one’s mind but can not be perceived in the physical world: Truth does not exist in the world we can grasp through our senses. Thus, we have knowledge of what we perceive in our mind, of our ideas and values, a higher form than the materialistic world around us. Plato’s approach is often referred to as Objective Idealism. The mind is the real Form of the World, and order exists before perception.

Early modern idealism

— Idealism became the dominant view in early modern philosophy, i.e., in rationalism (Descartes, Malebranche, Leibniz) and empiricism (Berkeley). Idealism derives from Descartes' mind-body dualism and his Platonist theory of ideas as "innate archetypes common to all rational beings." Accordingly, ideas are what is in our or

God's mind and what gives us access to the external world. George Berkeley advanced subjective idealism or empirical idealism: only minds and mental contents exist. Reality is our experience of things, and perception always dictates reality.

Modern idealism

— Modern idealism is a metaphysical philosophy that Immanuel Kant and Georg Wilhelm Friedrich Hegel advocated. Kant and Hegel held that universals are not real but are ideas in the minds of natural beings.

## Psychological

— Mental models are cognitively constructed representations, (conscious and/or unconscious) of the real or imagined world as it may or may not exist. They are influenced by individual cognitive factors (perceptual biases), and they are not necessarily accurate or complete.

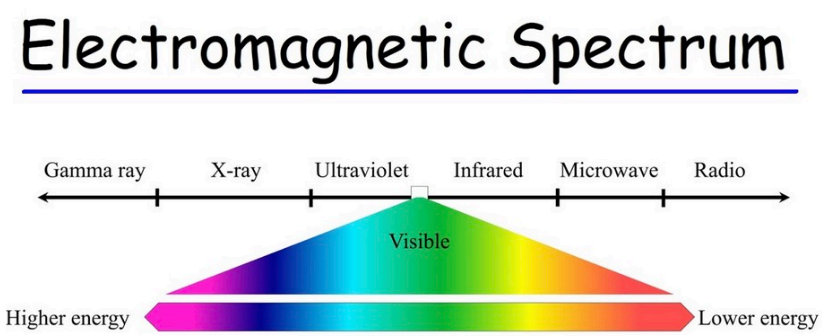
## Neurological

— We come to understand a mediated reality by how it is **represented by our senses**.

— Our senses operate in a very narrow band or window. For example, **visual perception** in humans is limited to visible light in the range of wavelengths between 370 and 730 nanometers of the electromagnetic spectrum.

— Without instrumentation, humans only visually perceive a tiny fraction of the reality around them.

— The same is true for hearing: humans are sensitive to sound frequencies between 20 Hz and 20,000 Hz. Dogs can hear from about 67 Hz up to 45,000 Hz.




— Examples of neurological continua that vary among individuals include the ability to perceive color. Some people are colorblind (there are seven different types). Another example that has been in the news lately is synesthesia.

— I don’t know how accurate this is, but it is interesting: https://www.youtube.com/watch?v=40ujKFD3z2g

# 6.) Quantum theory

## Differences between the classical and quantum

## Introduction to quantum

## Overview

## Aspects of quantum theory

***Schrödinger's wave equation***

***Scale***

***The double-slit experiment***

***Measurement***

***Wavefunction (Ball)***

***Wavefunction Collapse***

***Superposition***

***Principle of locality***

***Non-locality / Entanglement***

***Free Will***

***Information***

***The block universe***

***Heisenberg's uncertainty principle***

***Schrödinger's Cat***

***Quantum–classical transition.***

***Coherence***

***Decoherence***

***Quantum reconstruction***

***Ontic and epistemic interpretations***

***Einstein and quantum theory***

***Determinism/Superdeterminism***

***Summary of the Copenhagen interpretation***

***Arrow of time (Hossenfelder, 2022).***

***Photons***

***A photon's energy***

***Properties of a photon.***

***Pauli exclusion principle***

## Differences between the classical and quantum

The term classical physics refers to physics before the advent of quantum mechanics. Classical physics includes Newton's equations for the motion of particles, the Maxwell-Faraday theory of electromagnetic fields, and Einstein's general theory of relativity. But it is more than just specific theories of specific phenomena; it is a **set of principles and rules**—an underlying logic—that governs all phenomena for which quantum uncertainty is not important. Those **general rules are called classical mechanics.**

The job of classical mechanics is to **predict the future**.

If you know everything about a system at some instant of time, and you also know the equations that govern how the system changes, then you can predict the future. That's what we mean when we say that **the classical laws of physics are deterministic**. **If we can say the same thing, but with the past and future reversed, then the same equations tell you everything about the past. Such a system is called reversible.**

The currently established laws of nature are deterministic with a random element from quantum mechanics. This means the future is fixed, except for occasional quantum events that we cannot influence. Chaos theory changes nothing about this. Chaotic laws are still deterministic; they are just difficult to predict, because what happens depends very sensitively on the initial conditions (Hossenfelder, 2022).

For the most part, there is really only one path, because quantum effects rarely manifest themselves macroscopically. What you do today follows from the state of the universe yesterday, which follows from the state of the universe last Wednesday, and so on, all the way back to the Big Bang (Hossenfelder, 2022).

A collection of objects—particles, fields, waves, or whatever—is called **a system**. A system that is either the entire universe or is so isolated from everything else that it behaves as if nothing else exists is a **closed system**.

**The collection of all states occupied by a system is its space of states,** or, more simply, its state-space. The state-space is not ordinary space; it's a mathematical set whose elements label the possible states of the system.

The next simplest system has a **state-space consisting of two point**s; in this case we have one abstract object and two possible states.

A system that changes with time is called **a dynamical system**. A dynamical system consists of more than a space of states. It also entails **a law of motion, or dynamical law.**

The variables describing a system are called its **degrees of freedom.** A coin has one degree of freedom, which we can denote by the greek letter sigma, $\Sigma$. Sigma has only two possible values; $\Sigma = 1$ and $\Sigma = -1$, respectively, for H and T.

All the basic **laws of classical mechanics are deterministic**.

It's not enough for a dynamical law to be deterministic; **it must also be reversible.**

If you reverse all the arrows, the resulting law is still deterministic. Another way, is to say the **laws are deterministic into the past as well as the future**.

There must be one arrow to tell you where you're going and one to tell you where you came from.

**The rule that dynamical laws must be deterministic and reversible is so central to classical physics**

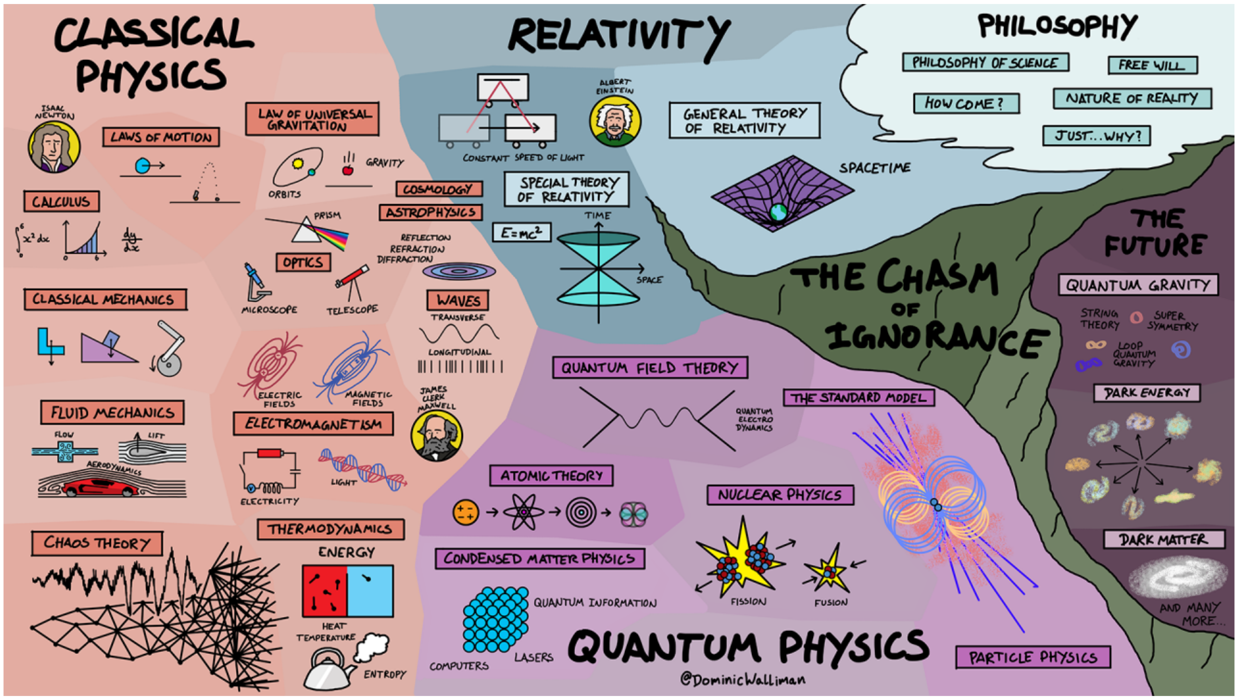
The **minus-first law is undoubtedly the most fundamental of all physical laws—the conservation of information**. **The conservation of information is simply the rule that every state has one arrow in and one arrow out. It ensures that you never lose track of where you started.**

There is no reason why you can't have a dynamical system with an **infinite number of states.**

In principle we cannot know the initial conditions with infinite precision. In most cases the
If a system is chaotic (most are), then it implies that however good the resolving power may be, the time over which the system is predictable is limited.

From: Susskind, L., & Friedman, A. (2014). Quantum mechanics: The theoretical minimum. Basic Books (AZ).

## Introduction



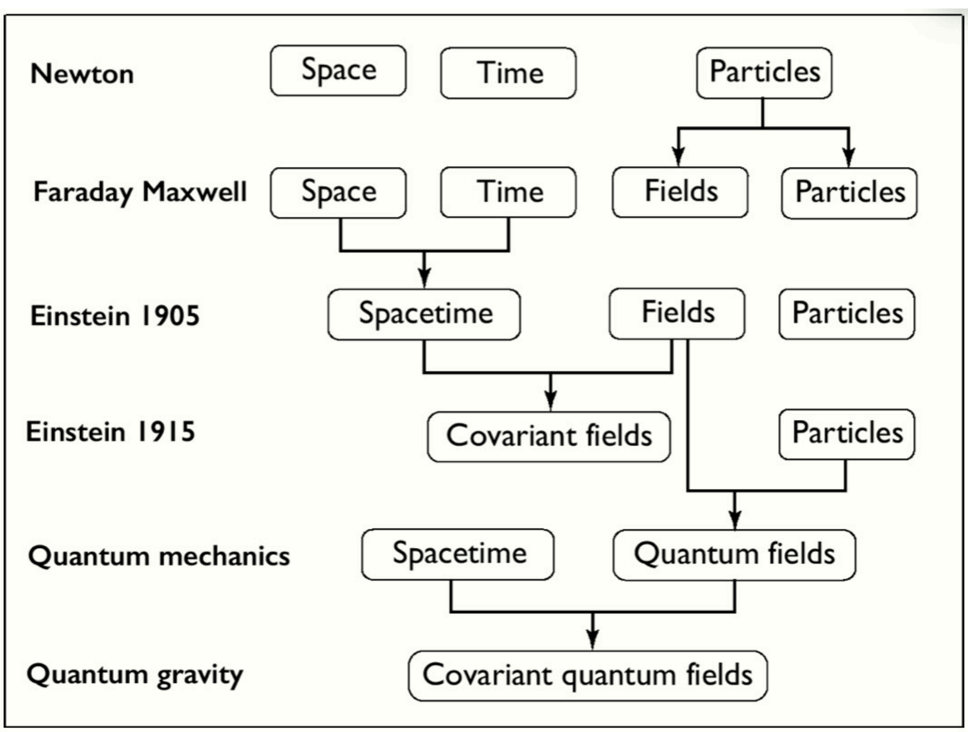
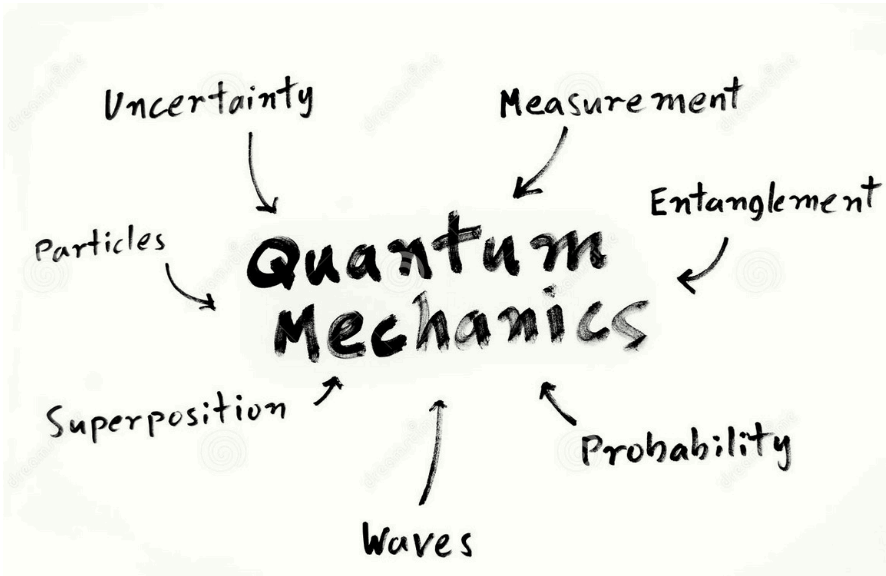




**Figure 7.8** What is the world made of? Of only one ingredient: covariant quantum fields.

Above (Rovelli, 2018)




— There are many different competing theories and interpretations and little consensus. In the quantum realm, theory is very nascent. Many important experiments have been conducted and carefully replicated. The mathematics of the experiments seem to be straightforward and understood. However, the results often contain implications that are at odds with our normal perceptions of the world and how it works. There are many different interpretations of what the results mean and how to reconcile them with our "old/normal" understanding of the world. Thus, many different theories have been suggested, some very odd. It will obviously take many more years of research before the theory-building can lead to explanations that achieve wide consensus.

— Of all of the books on the topic, I recommend beginning with **Ball (2020)**.

— This introduction lays the foundation for what follows and is taken from Ball (2020).

◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊

— The following claims are often made that **misrepresent** and **sensationalize** the topic.

—— Quantum objects can be both waves and particles. This is **waveparticle duality**.

—— Quantum objects can be in more than one state at once: they can be both here and there, say. This is called **superposition**.

—— Quantum objects can affect one another instantly over huge distances: so-called 'spooky action at a distance'. This is called **entanglement**.

—— You can't measure anything without disturbing it, so the human observer can't be excluded from the theory: it becomes unavoidably **subjective**.

—— Everything that can possibly happen does happen. There are two separate reasons for this claim. One is rooted in the (uncontroversial) theory called quantum electrodynamics that Feynman and others formulated. The other comes from the (extremely controversial) ‘**Many Worlds Interpretation**’ of quantum mechanics.

— Yet **quantum mechanics says none of these things.** In fact, Quantum mechanics doesn’t say anything about ‘how things are.’ It tells us what to expect when we conduct particular experiments. All of the ‘weird’ claims are nothing but interpretations laid on top of the theory.

— What is frequently described as the **weirdness of quantum physics** is not a true oddity of the quantum world but comes from our (understandably) contorted attempts to find pictures for visualizing it or stories to tell about it. Quantum physics defies intuition, but we do it an injustice by calling that circumstance ‘weird.’

◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊

## Overview

— Quantum mechanics works well mathematically.

— What has emerged most strongly from work on the fundamental aspects of quantum theory over the past decade or two is that it is not a theory about particles and waves, discreteness or uncertainty or fuzziness. **It is a theory about information.**

— Quantum mechanics is not really about the quantum. Even the term ‘quantum’ is something of a red herring, since the fact that the theory renders a description of the world granular and particulate (that is, **divided into discrete quanta**) rather than continuous and fluid is more a symptom than a cause of its underlying nature. If we were naming it today, we’d call it something else.

— Quantum mechanics was started by the German physicist **Max Planck** in 1900. He was studying how objects radiate heat. Warm objects emit radiation. If they are hot enough, some of that radiation is visible light: they become ‘red hot’, or with more heating, ‘white hot.’ Physicists described a special emitting object called a **black body** – it means that the object perfectly absorbs all radiation that falls on it. The energy of an **oscillator** can’t just have any value, but is restricted to chunks of a particular size (‘quanta’) proportional to the frequency of oscillation. (Oscillator: Anything that oscillates. A mass on a spring, a sound wave, light, an atom in a crystal lattice, etc.) In other words, if an oscillator has a frequency f, then its energy can only take values that are whole-number multiples of f, multiplied by some constant denoted h and now called **Planck’s constant**. This implies that each oscillator can only emit (and absorb) radiation in discrete packets with frequency f, as it moves between successive energy states.

— In 1905 Einstein proposed that quantization was a real effect, not just some sleight of hand to make the equations work. Atomic vibrations really do have this restriction. Moreover, he said, it applies also to the energy of light waves themselves: their energy is parcelled up into packets, called **photons**. The energy of each packet is equal to h times the light's frequency (how many wave oscillations it makes each second).

— Quantum mechanics is not really 'about' quanta: the chunking of energy is a fairly incidental (though initially unexpected and surprising) outcome of it.

— And it's not (as is often implied) that quantum works at small **scales** and classical at big ones. The significance of the size difference is not in terms of what objects do, but in terms of our perceptions. Because we haven't evolved to perceive quantum behaviour except in its limiting form of classical behaviour, we've had no grounds to develop an intuition for it.

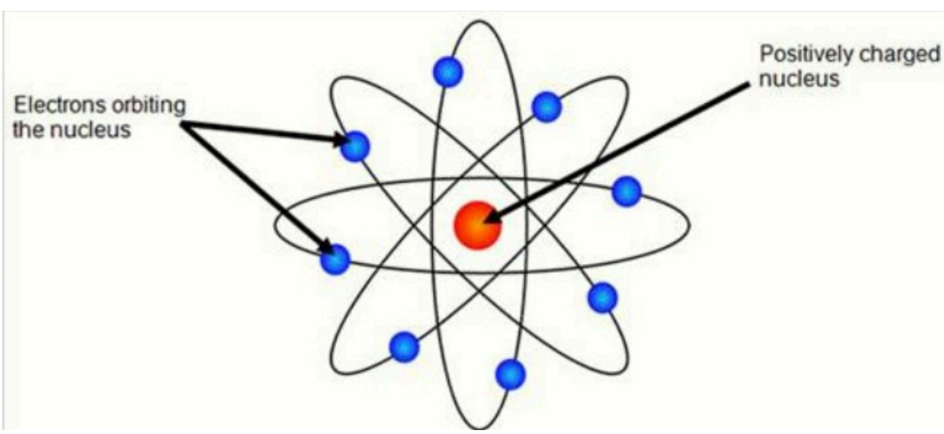
— The key **distinctions between classical mechanics and quantum mechanics**, in Susskind's view, are these: 1). Quantum physics has '**different abstractions**' – how objects are represented mathematically, and how those representations are logically related. Quantum abstractions are fundamentally different from classical ones. For example, we'll see that the idea of a state in quantum mechanics is conceptually very different from its classical counterpart. States are represented by different mathematical objects and have a different logical structure. 2). Quantum physics has a different relationship between the **state of a system** and the result of a measurement on that system. In the classical world, the relationship between the state of a system and the result of a measurement on that system is very straightforward. In fact, it's trivial. The labels that describe a state (the position and momentum of a particle, for example) are the same labels that characterize measurements of that state. To put it another way, one can perform an experiment to determine the state of a system. In the quantum world, this is not true. States and measurements are two different things, and the relationship between them is subtle and nonintuitive.

— Quantum objects are neither wave nor particle (but sometimes they might as well be)

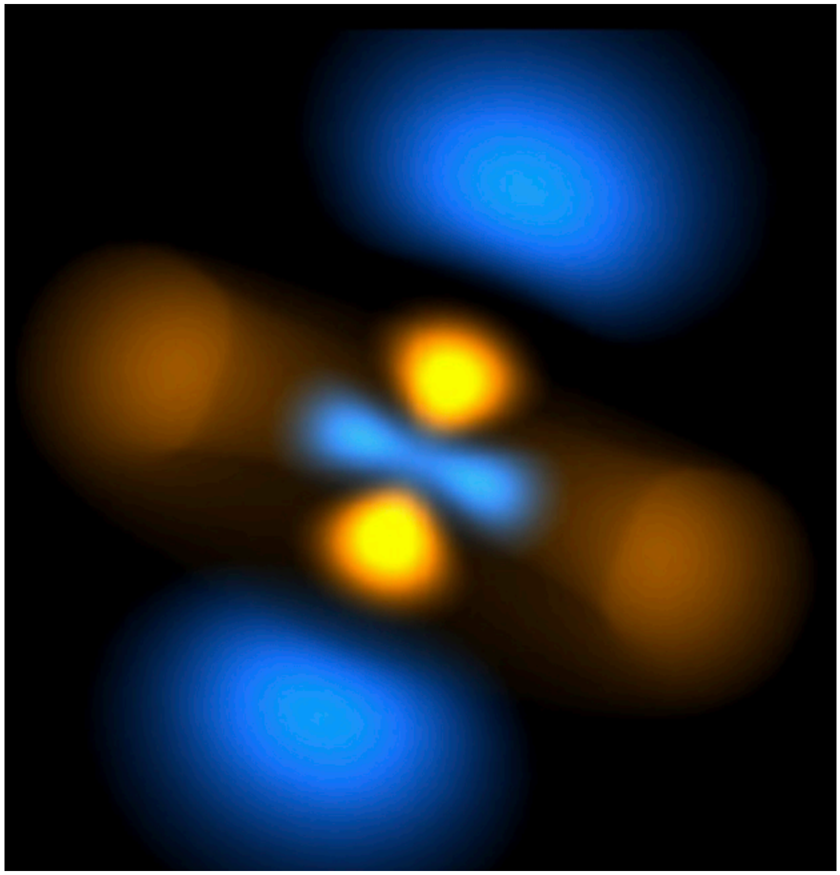
— The notion of **wave–particle duality** goes back to the earliest days of quantum mechanics, but it is as much an impediment as it is a crutch to our understanding.

— Quantum objects are not sometimes particles and sometimes waves, like a football fan changing her team allegiance according to last week's results. Quantum objects are what they are, and we have no reason to suppose that 'what they are' changes in any meaningful way depending on how we try to look at them. Rather, all we can say is that what we measure sometimes looks like what we would expect to see if we were measuring discrete little ball-like entities, while in other experiments it looks like the behaviour expected of waves of the same kind as those of sound travelling in air, or that wrinkle and swell on the sea surface. So the phrase 'wave–particle duality' doesn't really refer to quantum objects at all, but to the interpretation of experiments – which is to say, to our human-scale view of things.

— In 1924 **Louis de Broglie** proposed that quantum particles – then still envisaged as tiny lumps of stuff – might display wave-like properties.
— If light waves can be particle-like, de Broglie said then might not the entities we've previously considered as particles (such as electrons) be wavy?
— Building on Max Planck's quantum hypothesis in which energy was considered to be grainy rather than smooth, **Bohr** proposed that the electrons have quantized energies, so that they can't fritter it away gradually. They must remain in a **fixed orbit** unless kicked into another one with a different 'allowed' energy either by absorbing or radiating a quantum of light with the right amount of energy. Each orbit, Bohr argued, has only a finite capacity to accommodate electrons. So if all the orbits of lower energy than that of a given electron are already full, there's no way the electron can lose some of its energy and jump down into them.
— Electrons confined to particular orbits around the nucleus would have to have particular wavelengths – and thus frequencies and energies – so that a whole number of oscillations would fit long the orbital path, forming '**standing waves**' rather like the waves in a skipping rope tied to a tree at one end and shaken (except that we can't answer the question 'waves of what?').
— It turns out that the resulting **wavefunctions** don't correspond to electrons circulating the nucleus like planets, but have considerably **more complicated shapes called orbitals**. Some orbitals are diffuse spheres, perhaps with a concentric shell shape. Others have rather complex dumb-bell-or doughnut-shaped regions where the amplitude is large. These shapes can explain the geometries with which atoms join together in molecules.




The old traditional "Solar system" model proposed by Bohr in 1913.



See https://daugerresearch.com/orbitals/index.shtml

## Aspects of quantum theory

### ***Schrödinger's wave equation***

— Here are some representative descriptions.

— The Schrodinger wave equation is a mathematical expression describing the energy and position of the electron in space and time, taking into account the **matter wave** nature of the electron inside an atom.

— Matter waves are very small particles in motion having a wave nature – dual nature of particle and wave. Any variable property that makes up the matter waves is a wave function of the matter-wave.

— The Schrödinger equation gives the evolution over time of a wave function, the quantum-mechanical characterization of an isolated physical system.

— Schrodinger equation gives us a detailed account of the form of the wave functions or probability waves that control the motion of some smaller particles. The equation also describes how these waves are influenced by external factors. Moreover, the equation makes use of the energy conservation concept that offers details about the behaviour of an electron that is attached to the nucleus.

— In quantum theory, the state of a system is described by what's known as its wave function, which determines the probabilities of different outcomes when events take place. The Schrödinger equation governs how the wave function changes with time. For example, it governs the process of quantum tunnelling, which in turn underlies important physical effects such as how the Sun generates energy via nuclear fusion, photosynthesis in plants, and flash memories you use to store data in computer USB flash drives (Ellis, 2020)

— We will be discussing the wave equation throughout this essay.

— See (Schrödinger equation, 2023).

***Scale***

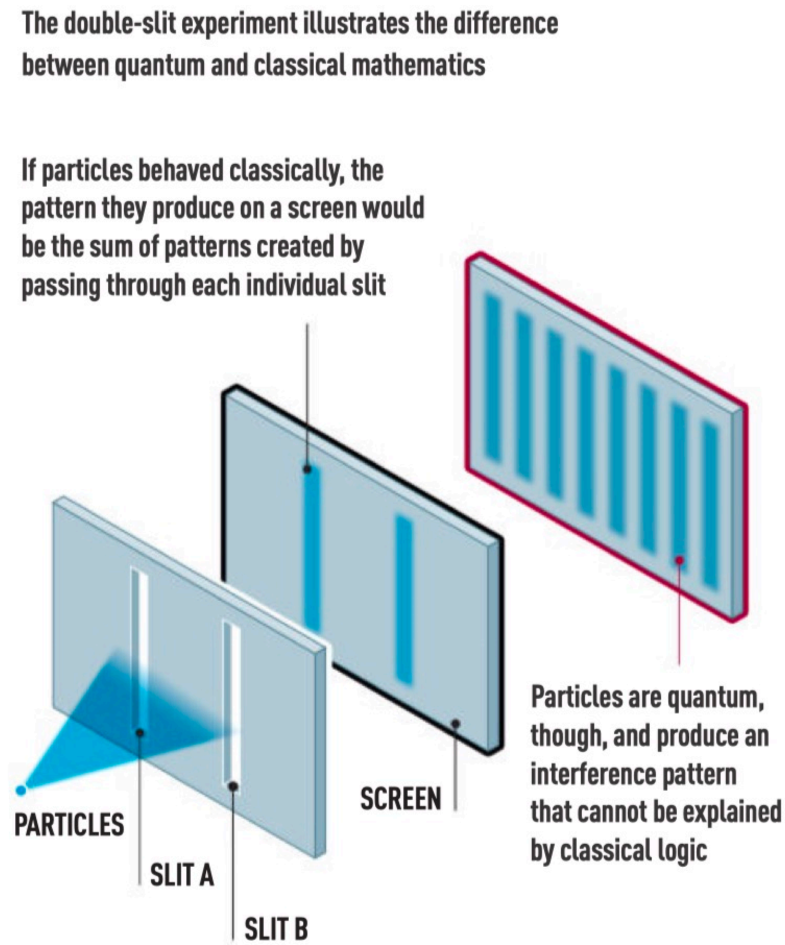
— Scale. It is a common misconception that quantum properties only apply to atomic-scale physics. **Every object in the universe (from atoms to stars) operates according to quantum physics**. In many situations, such as throwing a baseball, quantum physics leads to the same result as classical physics. In such situations, we use classical physics instead of quantum physics because the mathematics is easier and the principles are more intuitive. The laws of quantum physics are still operating in a baseball thrown across the field, but their operation is not obvious, so we say the system is non-quantum.

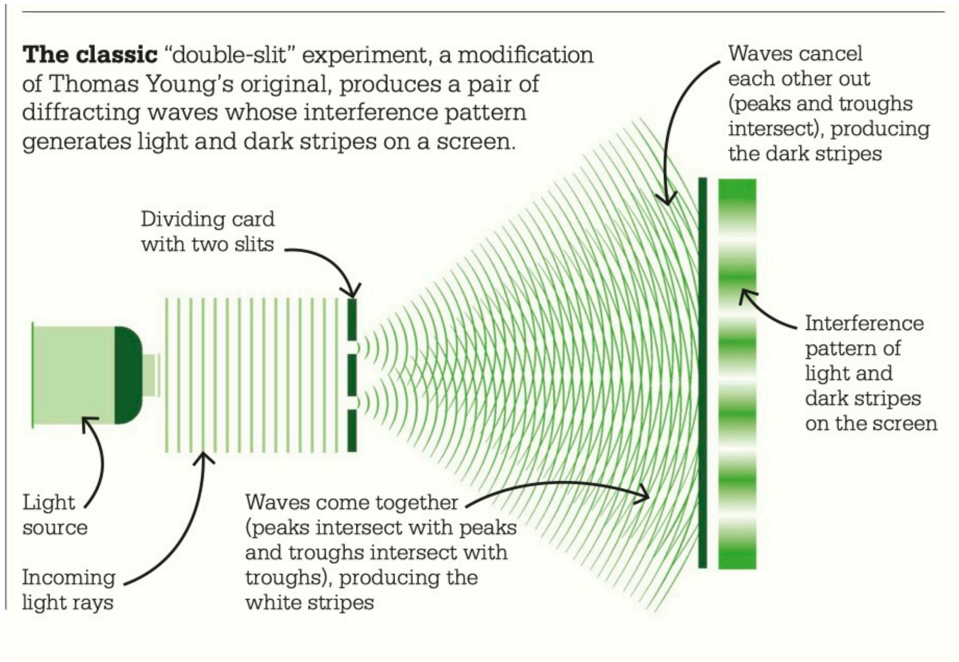
— Often in the physical and biological sciences we make observations on a **macroscopic scale** that we try to understand in terms of processes at smaller scales: how atoms, molecules or cells are moving and interacting. And this is a valid and productive way to conduct science. We can meaningfully say that my coffee cup and the view out of my window are – and indeed I am – somehow generated by processes and effects operating at smaller scales. This **hierarchy is sequential**: the properties and principles at one scale emerge from those operating at the level below. The solidity, brittleness and opacity of the coffee cup can be understood in terms of the atoms and molecules that make up its fabric, congregated in vast numbers. But quantum mechanics disturbs this hierarchy. In Bohr's view, quantum experiments like the double slits can't be considered in terms of macroscopic outcomes resulting from underlying microscopic processes. **We have to regard the macroscopic process itself as an irreducible phenomenon, inexplicable in terms of more fundamental, smaller-scale 'causes.'** Ball

— It's not obvious why any of the properties that things have at the everyday scale should remain meaningful properties at the microscopic scale. Some don't. Electrons don't have a colour, nor do they really have a definable size. But they do have other familiar properties: mass, velocity, energy and electric charge. By the same token, some properties appear at the microscale that don't have any significance (at least in our daily experience) in the macroworld. Ball

***The double-slit experiment***

— This experiment was first performed by Thomas Young in 1801, as a demonstration of the wave behavior of visible light. There are many variations of this famous experiment and several major conclusions arising from it. I will provide several references to it, but I will not discuss it in detail (Ananthaswamy, 2019; Double-slit experiment, 2022, December 22; Hossenfelder, 2021, October 30).






— "a beam of light illuminates a plate with two parallel slits cut into it. The light that passes through the slits hits a screen, creating stripes of light and darkness as a result of the interference between the two light waves that went through the slits. This interference is proof that light is not just a classical particle, as Isaac Newton had argued, but also a wave. The weirdness of the quantum version is that interference happens even if you just send one photon through the double-slit setup. That is, it does if you measure the effects at a screen beyond the slits – then you measure a classical interference pattern, just as if the light were a wave. Measure at either of the slits, meanwhile, and you see a blip that indicates the photon passing through one slit or the other a particle, in other words" (Brooks, 2020, p. 13).

— It is arguably the central experiment in quantum mechanics. And no one truly understands it. The so-called quantum double-slit experiment is delightfully simple to explain. It's also simple to see what the results are. What **we don't understand is how to interpret those outcomes in terms of underlying processes**: in terms of things doing stuff. (Ball)

— For two interfering light waves, **constructive interference** will increase the brightness whereas **destructive interference** will produce darkness. (Ball)

— Imagine creating two wave sources by passing a single train of waves through two small slit-like gaps in a wall, spaced close together. As the waves pass through the slits, they will radiate on the far side like ripples from a stone dropped into a pond. Where these ripples overlap, there is a regular pattern of constructive and destructive interference. If these are light waves, then a screen on the far side of the slits receives a stripy pattern of light and dark bands, called interference fringes. This is an example of **diffraction**: the spreading and interference of light passing through gaps or bouncing off arrays of objects. (Ball)

— **The interference pattern is strictly a wave phenomenon**. (Ball)

— So long as we don't try to figure out which slit they go through, they will behave as if they go through both at once. But if we try to pin down which slit they pass through, they only go through one. **The mere act of making the measurement – even if we can be pretty sure that the measurement shouldn't obstruct or influence the electron's path appears to turn a wave into a particle.** (Ball)

— **Bohr: There is no quantum world.** There is only an abstract quantum physical description. It is wrong to think that the task of physics is to find out ***how*** nature is. Physics concerns what we can say ***about*** nature. (Ball)

— This is the central tenet of the so-called **Copenhagen Interpretation** of quantum mechanics, developed by Bohr and his colleagues in the Danish capital during the mid-1920s. It's an interpretation that **doesn't so much tell us 'what is happening', but rather, proscribes what we can legitimately ask about it.** (Ball)

***Measurement***

— **Everything that seems strange about quantum mechanics comes down to measurement. If we measure, the quantum system behaves one way. If we don't, the system does something else. Different ways of looking (measurement) can elicit apparently mutually contradictory answers.** If we look at a system one way, we see this; but if we look at the same system another way, we see not merely that but not this. The object went through one slit; no, it went through both. (Ball)

— **It seems to be the fact of detection, not the method, that makes the difference**. It's not easy to see how any physical theory working at the level of known interactions between particles can account for that. (Ball)

— According to the Copenhagen Interpretation, this '**observer effect**' is precisely what we should expect, given the mathematical structure of quantum mechanics. It's only strange if we insist on asking about physical causes rather than just predicting results. But quantum mechanics (said Bohr) can make no claim to tell us about such causes. This is commonly called **an instrumentalist view: crudely, it says quantum theory offers only prescriptions, not descriptions**. (Ball)

— Today, most scientists would accept that our reliance on sensory data puts us at one remove from any *Ding an sich* [a thing as it is in itself], not mediated through perception by the senses or conceptualization, and therefore unknowable.]: **all our minds can do is to use those data to construct its own image of the world, which is inevitably an approximation and idealization of what is really 'out there.'** (Ball)

— Bohr, influenced by Kant's ideas, went further. He said that **the world revealed by experience – which is to say, by measurements – is the only reality** worthy of the name. (Ball)

— The **Copenhagen Interpretation claims that the act of measurement actively constructs the reality that is measured.** We must abandon the notion of an objective, preexisting reality and accept that measurement and observation bring specific realities into being from a palette of possibility. (Ball)

— The '**measurement problem'** is another of the commonly misunderstood notions in quantum physics. **It's often interpreted as meaning that we can't investigate anything without disturbing it, and that as a result science becomes wholly subjective. Neither clause is accurate.** (Ball)

— **In Bohr's view, quantum experiments like the double slits can't be considered in terms of macroscopic outcomes resulting from underlying microscopic processes. We have to regard the macroscopic process itself as an irreducible phenomenon, inexplicable in terms of more fundamental, smaller-scale 'causes.'** (Ball)

— In the double-slit experiment, say, our instinct is to regard the phenomena as the motions of electrons and photons along particular trajectories, or wave-like interference between them, ... Bohr asserted that instead **the entire experiment is the phenomenon that we must understand. … instead of trying to figure out what has made the difference to the outcome in terms of 'where the particle went', we should be asking 'Why does it matter how we look?'** (Ball)

— **Wheeler**: In actuality it is wrong to talk of the 'route' of the photon. For a proper way of speaking … it makes no sense to talk of the phenomenon until it has been brought to a close by an irreversible act of amplification [that is, a measurement on a classical instrument]: '**No elementary phenomenon is a phenomenon until it is a registered (observed) phenomenon.**' (Ball)

— In the view of Bohr and Wheeler, **there are no fundamental quantum phenomena about which we have any right to speak until we measure them.** (Ball)

— [More experiments were done] all show that indeed it makes no difference when we intervene, so long as we do so before a measurement is made. Nature always seems to 'know' our intentions. (Ball)

— **Classically, if two states start off being different, and both experience the same influences, they stay different**. Say I throw two identical tennis balls up into the air at the same angle but at different speeds. The slower one will always fall to the ground sooner and nearer than the other, and at a time and place that is wholly predictable. This seems obvious – in essence, it's saying that systems don't change their state for 'no reason.' **This principle is not quite the same for quantum systems, because they are governed by probability and are prone to**

**randomness. ...of all the things that could happen, one of them must happen**. (Ball)

***Wavefunction (Ball)***

— Wave equations stipulate what the amplitude of the wave is in different parts of space. For a water wave, the amplitude is simply how high the water surface is. For a sound wave, it means how strongly the air is compressed in the peaks of the wave, and how severely it is 'stretched' or rarefied in the troughs. But what is the 'amplitude' of an electron wave? **The wave in Schrödinger's equation isn't a wave of electron charge density. In fact it's not a wave that corresponds to any concrete physical property. It is just a mathematical abstraction – for which reason it is not really a wave at all, but is called a wavefunction.**

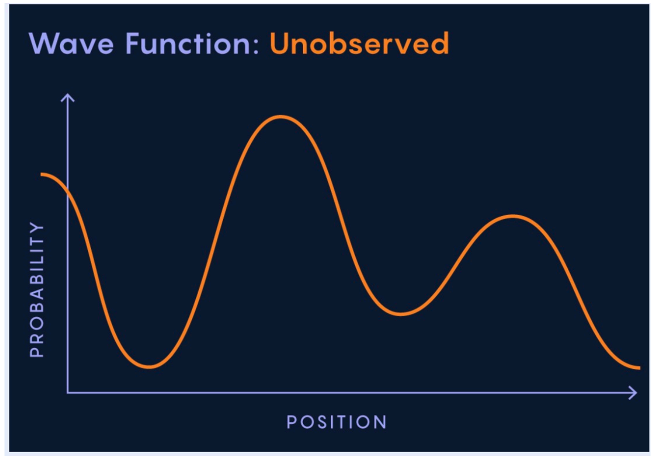
— **Max Born argued that the amplitude of the wavefunction squared (amplitude×amplitude) indicates a probability**. The Schrödinger equation, then, is an expression for finding out how an abstract entity called a wavefunction is distributed in space and how it evolves in time. And – here's the really important thing – **this wavefunction contains all the information one can possibly access about the corresponding quantum particle.** In each case, what you get from this operation is not exactly the momentum, or energy, or whatever, that you'd measure in an experiment; it's **the average value** you'd expect to get from many such measurements.

— Instead of particles and trajectories, we have wavefunctions. Instead of definite predictions, we have probabilities. Instead of stories, we have maths.

— In this view, electrons confined in space – around the nucleus of an atom, say – are like a swarm of bees indistinctly glimpsed as they hover around a hive. At any instant each bee is somewhere, but it's only by making a measurement that you find out where. But that's not the right way to think about **a wavefunction – for it says nothing about where the electron is.** I just told you, though, that the wavefunction says all we can know about the electron. If so, we have to accept that, as far as quantum mechanics (and therefore current science) is concerned, there simply is no 'where the electron is.'

— **The wavefunction is not a description of the entity we call an electron. It is a prescription for what to expect when we make measurements on that entity.**

— **The wavefunction tells us nothing about where the electron is until we make a measurement**.




— Before measurement, then, the system is fully described by a wavefunction from which one can calculate the various probabilities of the different possible measurement outcomes. Let's say that the system is in a superposition of possible states A, B and C. Then, according to quantum mechanics, the wavefunction can do nothing except continue evolving in its unitary way, preserving these three possible states. (Ball)

***Wavefunction Collapse***

— John von Neumann was one of the first to make **wavefunction collapse** an 'official' component of quantum mechanics, incorporating it into his 1932 textbook on the subject. (Ball)

— Wigner hypothesized that collapse stems from conscious intervention in the quantum system – that it is produced by our own minds. Does collapse spread over the planet with the news of the result? Which observer 'decides' when wavefunction collapse occurs? There are all kinds of other problems with this idea. What, for example, constitutes a conscious observation? (Ball)

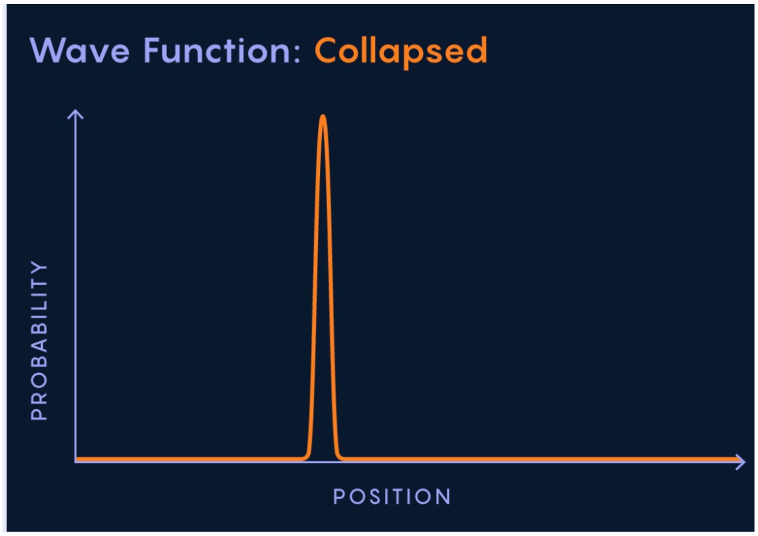
— John Wheeler offered an extraordinary view of cosmic evolution that depends on consciousness-induced collapse of the wavefunction. (Ball)

— Could it be that only when we register quantum events – the interactions of countless particles in the past – do they become actual events? Bohr insisted that quantum and classical are fundamentally different realms of experience, and papered over the divide with the word 'complementarity'. (Ball)

— in **QBism** quantum mechanics is used to describe everything external to the observer. It's then perfectly permissible to speak of superpositions of macroscopic states or objects: Schrödinger's cat, and so forth. Rather, it asserts that there are no things that can be meaningfully spoken of beyond the self. It doesn't deny the existence of anything outside of that subjective experience, but it denies us knowledge of it. (Ball)

— in QBism there are no objective states. Rather, according to Chris Fuchs, 'quantum states represent observers' personal information, expectations and degrees of belief.'– which is to say, it interprets the theory without pronouncing on what lies beyond it. It claims only that such an objective world exists, and that quantum mechanics is the framework that we need to make sense of it. QBism, then, embraces the notorious 'observer effect' in quantum mechanics in a particularly subtle way. (Ball)

— But measurement does something else. It '**collapses**' (Heisenberg's original word was 'reduces') these possible states A, B and C, expressed in the wavefunction, to just one. (Ball)




— There is nothing in the Schrödinger equation that allows or accounts for wavefunction collapse. (Ball)

— The fundamental mathematical **machinery of quantum mechanics is unitary**: the Schrödinger equation which describes how a wavefunction evolves through time prescribes that this evolution is only and always unitary. Yet every experiment ever performed on a quantum system which sets out to directly measure some property of the system induces what we are forced to call '**collapse of the wavefunction**': it gives a unique answer. And this is necessarily **a non-unitary process**, and therefore inconsistent with what wavefunctions seem able, in theory, to do. (Ball)

— To Bohr, wavefunction collapse was virtually emblematic of the distinction between the unitary quantum world and the everyday reality in which we make observations and measurements. **Measurements must be classical by definition: they require some big apparatus with which humans can interact.** From our perspective the world is made up of phenomena things happen – and a phenomenon only exists when it has been measured. **Wavefunction collapse is simply a name we give to the process by which we turn quantum states into observed phenomena.** Wavefunction collapse is then a generator of knowledge: it is not so much a process that gives us the answers, but is the process by which answers are created. (Ball)

— "When the **particle is measured or disturbed in some way, its wave function collapses and it snaps into a single state and a definite position**. This collapse can be triggered by any interaction of a quantum object with its environment – a rogue vibration, for example, or a heat fluctuation" (Brooks, 2020, p. 14).

— Each time you measure a quantum object, you “collapse” its wave function, causing the range of possible characteristics encoded in the maths to **condense into a particular momentum or position** (but not both because that would violate the quantum uncertainty principle).

— “What is that quantum object doing before you measure it? Does it have all those properties simultaneously? Or none of them? And when you measured it, forcing it to adopt a definite guise, what actually happened?” (Brooks, 2020, p. 38).

— It seems clear that the quantum reality humans perceive [Not the reality that exists] is observer-dependent. **Different people can construe different versions of reality at any one time, with no way of saying which is right.**

— Many popular science writers propagate the misconception that a quantum state (and, therefore, reality itself) is determined by conscious observers: i.e. if there is no observer, a tree falling in the forest will make no noise: the moon will not exist if no one is observing it. However, wavefunction collapse is not driven by measurement (conscious observers) alone. In fact, **every interaction a quantum particle makes can collapse its state.**

— “Quantum theory isn’t a description of physical reality itself, but just an operational framework that allows us to make predictions about it. “It’s sort of a bit like a user interface” (Brooks, 2020, p. 38).

— At the present time, there is **no suitable explanation for the collapse of the wavefunction**.

***Superposition***

— Superposition refers to a situation in which **a measurement on a quantum object could produce two or more possible outcomes, but we don’t know which it will be, only their relative probabilities.** (Ball)

— Superposition two (or more) quantum states can be added together (“superposed”), and the result will be another valid quantum state; conversely, **every quantum state can be represented as a sum of two or more other distinct states**.

—— In simple terms, **superposition is the ability of a quantum system to be in multiple states at the same time until it is measured**.

***Principle of locality***

— Superposition: that the properties of a particle are localized on that particle, and what happens here can’t affect what happens there without some way of transmitting the effects across the intervening space. this **locality is just what quantum entanglement undermines** (Ball)

— Superposition that “for an action at one point to have an influence at another point, something in the space between the points, such as a field, must mediate the action.” In view of the theory of relativity, the speed at which such an action, interaction, or influence can be transmitted between distant points in space **cannot exceed the speed of light.** This formulation is also known as "Einstein locality" or "local relativistic causality."

***Non-locality / Entanglement***

— Entanglement is indeed a real attribute of quantum objects, as numerous careful experiments since the 1970s have demonstrated. … The main thing you need to know about entanglement is this: **it tells us that a quantum object may have properties that are not entirely located on that object**. (Ball)

— In quantum mechanics, the moment you make a measurement, probabilities change, instantaneously and everywhere. This update of the wave function is **nonlocal**. It is, as Einstein put it, a "spooky action at a distance." it turns out that in that process of measurement, **no information is submitted faster than the speed of light**… so it's not as though there's something concretely wrong with the theory. It just feels wrong (Hossenfelder, 2022).

— Quantum events don't appear to have an explanation as such – one in which definable causes lead to specific effects – but **only a probability of occurrence**. This is what Einstein found unreasonable. … It looks as though the particle has just decided its spin orientation on a whim, in the instant, but actually that orientation was fixed all along – yet hidden from view. … This obscured property that allegedly renders quantum mechanics deterministic became known as **a hidden variable**. (Ball)

— In the **Einstein, Podolsky and Rosen (EPR) experiment**, two particles are produced in a way that makes their quantum states interrelated – entangled, as we'd now say. Because of this correlation between their properties, a measurement made on one of them would provide instant information about the other one too. And that's the problem. … Think of a pair of gloves: one left-handed, the other right-handed. If we were to post one at random to Alice in Aberdeen and the other to Bob in Beijing, then the moment Alice opened the parcel and found the left glove (say), she'd know that Bob's glove is right-handed. (Ball)

— Quantum entanglement imposes the correlation between the values for the two particles in the EPR experiment. So now if Alice measures one photon (say) and finds it has a vertical polarization, she has elicited that polarization by making the measurement. … Yet Bob's photon must then have a horizontal polarization, and this too has seemingly been imposed by Alice's measurement. And there seems no avoiding the conclusion that it must happen the instant Alice makes her measurement. …that's impossible, the authors said, because Einstein's theory of special relativity forbids any signal to travel faster than light. **If Bohr was right that quantum objects don't have properties at all until they are measured, the EPR experiment contains an**

**impossible effect: what Einstein called ‘spooky action at a distance**’. This was the **EPR paradox**. (Ball)

— The measurement is the phenomenon, and quantum mechanics predicts the outcome reliably. … Bell’s proposal involved making repeated measurements on pairs of entangled particles. … **Hidden variables**, remember, fix matters so that the particles have definite states all along, although we don’t know which is which until we measure them. … The key is that a hidden-variables picture and a quantum-mechanical picture give different predictions of how the strength of correlation depends on the angle between the orientation of Bob’s magnets and Alice’s. …Every single time, the observed correlation statistics have turned out to match what quantum mechanics predicts, and to rule out Einstein’s hidden variables. …There is no ‘spooky action at a distance’ … The mystery of the EPR experiment, says David Mermin, is that ‘it presents us with a set of correlations for which there is simply no explanation.’ (Ball)

— Contrary to what Einstein thought … that is not really ‘action’, it is not ‘spooky’, and it doesn’t exactly involve ‘distance’. Neither does it violate special relativity. … What relativity says is that events at one place may not exert a causal influence on events at another place faster than the time it takes for light to pass between them. By causal I mean that Alice does something and it determines what Bob sees. … Einstein and his colleagues made the perfectly reasonable assumption of locality: that the properties of a particle are localized on that particle, and what happens here can’t affect what happens there without some way of transmitting the effects across the intervening space. … But this locality is just what quantum entanglement undermines – which is why ‘spooky action at a distance’ is precisely the wrong way to look at it. … In quantum mechanics, **properties can be non-local**. … What in fact we’re dealing with here is another kind of quantum superposition. We’ve seen that superposition refers to a situation in which a measurement on a quantum object could produce two or more possible outcomes, but we don’t know which it will be, only their relative probabilities. Entanglement is that same idea applied to two or more particles: a superposition of the state in which particle A has spin up and B spin down, say, and the state with the opposite configuration. Although the particles are separated, they must be described by a single wavefunction. We can’t untangle that wavefunction into some combination of two single-particle wavefunctions. (Ball)

— These experiments, incidentally, show us something else important about quantum effects like entanglement: they **persist over macroscopically large distances.** … Spacetime is the four-dimensional fabric described by Einstein’s theory of general relativity, in which it is revealed to have a particular shape. It’s this shape that defines the force of gravity: mass makes spacetime curve, and the resulting motions of objects in that curved arena make manifest the force of gravity. … Some researchers now suspect that spacetime is actually made from the interconnections created by quantum entanglement. Others think there is more to it than that. … **Kochen and Specker** pointed out that the outcomes of quantum measurements may depend on their context … It means that **if you look at a quantum object through different windows, you see different things**. … But in quantum mechanics, even when you ask the same question ('How many black and white balls are there?'), the answer you get may depend on how the measurement is done. … Like Bell's theorem, the Kochen–Specker theorem says something about what hidden variables – hypothetical concealed factors that fix the properties of quantum objects irrespective of whether they are measured or not … **hidden variables, are local: they apply specifically to this or that object, just as the properties of macroscopic objects do.** (Ball)

— You can never say 'this system has such and such properties', but only that it has those properties in a particular experimental context. Alter that context and you alter the overall hidden-variables description. (Ball)

— It's long been suspected that quantum non-locality and contextuality are somehow related. … Dagomir Kaszlikowski suggested that indeed they are ultimately expressions of the same thing: different facets of a more fundamental '**quantum essence**', for want of a better term. … This **essence**, whatever it is, defies any local realist description of the quantum world: one in which objects have specific, well defined features that are intrinsic to the object itself. You simply can't say as we're accustomed to do in the macroscopic world – 'this thing here is like so, regardless of anything else.' (Ball)

— Kaszlikowski showed that non-locality and contextuality seem to be mutually exclusive: a system can exhibit one feature or the other, but never both at the same time. … That's to say, 'quantumness' can enable a system to exceed the hidden-variables correlations in a Bell-type experiment, or it can enable the system to show a stronger dependence on context of measurement than a hidden-variables model can accommodate. But it can't do both at the same time. … Kaszlikowski and colleagues call this behaviour **monogamy**. (Ball)

— **In quantum mechanics, properties can be non-local.** Only if we accept Einstein's assumption of locality do we need to tell the story in terms of a measurement on particle A 'influencing' the spin of particle B. Quantum non-locality is the alternative to that view. (Ball)

— What in fact we're dealing with here is another kind of **quantum superposition**. (Ball)

— Entanglement is that same idea applied to two or more particles: a superposition of the state in which particle A has spin up and B spin down, say, and the state with the opposite configuration. Although the particles are separated, they must be described by a single wavefunction. We can't untangle that wavefunction into some combination of two single particle wavefunctions. Quantum mechanics is able to embrace such a notion without batting an eyelid; we can simply write down the maths. The problem is in visualizing what it means. (Ball)

— Non-locality, entanglement and superposition appear not just to allow objects to become interconnected in a way that pays no heed to spatial separation but also seems to do odd things to time, such as producing an illusion (or perhaps more than that?) of backwards causation, or allowing superpositions of the causal ordering of two events (so that which came first is indeterminate; see here). It could be that the causal structure of the universe is a more fundamental concept than both of these theories. (Ball)

— Elementary particles of the same kind are identical. (Vaidman, 2021).

— The essence of an object is the **massively entangled quantum state** of its particles and not the particles themselves. One quantum state of a set of elementary particles might be a cat and another state of the same particles might be a small table. An object is a spatial pattern of such a quantum state. (Vaidman, 2021).

— Clearly, we cannot now write down an exact wave function of a cat. We know, to a reasonable approximation, the wave function of the elementary particles that constitute a nucleon [collective term for protons and neutrons]. The wave function of the electrons and the nucleons that together make up an atom is known with even better precision. The wave functions of molecules (i.e. the wave functions of the ions and electrons out of which molecules are built) are well studied. A lot is known about biological cells, and physicists are making progress in the quantum representation of biological systems. Out of cells we construct various tissues and then the whole body of a cat or a table. (Vaidman, 2021).

— "Two particles could have their wave functions tied together or entangled, so intimately that any action you performed on one seemed to influence the other instantaneously – no matter how far apart they were. (Brooks, 2020, p. 22).

— Non-locality flies in the face of Einstein's special theory of relativity, which states that no physical influence can travel faster than the speed of light.

— John Stewart Bell did experiments that proved entanglement. In the years since experiments have vindicated quantum mechanics again and again.

— At the present time, there is no suitable explanation for entanglement.

— Today, many different experiments show that Einstein's local and realistic universe likely does not exist and that a quantum interpretation of Nature is correct.

— Schrödinger: (Entanglement is) ... "the characteristic trait of quantum mechanics that enforces its entire departure from classical lines of thought" In other words: it is the phenomenon that definitively separates the quantum and classical worlds: it is the characteristic trait of quantum mechanics.

— Non-locality lets influences seem to propagate across space instantaneously while forbidding us from actually sending any meaningful information (indeed, from sending anything at all) that fast. (Ball)
— See (Ash, 2021)

***Free will***

— Sean Carroll and Carlo Rovelli suggest that we should interpret free will as an emergent property of a system. A pepped-up version of this argument was recently put forward by Philip Ball. It relies on using causal relations between macroscopic concepts—so also emergent properties—to define free will (Hossenfelder, 2022).
— You will still feel as if you have free will, but you will know that really you're running a sophisticated computation on your neural processor (Hossenfelder, 2022).
— Summary: According to the currently established laws of nature, the future is determined by the past, except for occasional quantum events that we cannot influence. Whether you take that to mean that free will does not exist depends on your definition of free will (Hossenfelder, 2022).

***Information***

— It looks more logical to frame quantum mechanics as a set of rules about **information**: what is and isn't permissible when it comes to sharing, copying, transmitting and reading it. What distinguishes the quantum world of entanglement and non-locality from the everyday world where such things can't be found is a kind of **information-sharing between quantum systems** that allows us to find out about one of them by looking at the other. Non-locality is a baffling concept when we think in terms of particles with certain properties located in space, but is perhaps less so when we consider what it means to have knowledge of a quantum system. (Ball)

***The block universe***

— "In its marriage of space and time, Einstein's great theory fatally undermines the concept of "now." What is happening "now" in a particular location depends on where you are and how fast you're moving, so two different observers may see different things at the same time in the exact same spot. This makes "now" an illusion. **Time doesn't really pass at all**, and our perception that it does is due to our limited perspective on the world. **In reality, past, present, and future form a single, ever-existing block**" (Brooks, 2020, p. 32).
— According to the currently established laws of nature, the future, the present, and the past all exist in the same way. That's because, regardless of exactly what you mean by exist, there is nothing in these laws that distinguishes one moment of time from any other. The past, therefore, exists in just the same way as the present.

***Heisenberg's uncertainty principle***

— It is impossible to know both the position and momentum of a particle at the same time.

— In a word, **classical reality is what we would call real. … An object that adheres to quantum rules doesn't have a reality that can be pinned down**. Its properties are characterized by a probabilistic wave function that essentially says: if you make a measurement, here is what you might find.

— Heisenberg articulated this with his famous Uncertainty Principle. … The Uncertainty Principle actually is rather technical, and it's not surprising that non-specialists may miss its message. … Quantum objects may in principle have a number of observable properties, but we can't gather them all (Copenhagenists might in fact say 'elicit them') in a single go, because they can't all exist at once. … And by gathering some we may scramble the values of others. … So the Uncertainty Principle was purely a mathematical deduction. (Ball)

— As we get better at measuring p, we find that there's a limit to how precisely we can at the same time pin down q. … A more rigorous statement of the situation, however, is that if Heisenberg's speed is known to within a certain degree of accuracy, his position is undefined with a scope defined by the uncertainty relationship above. He can only be said to have a position at all to within these bounds. … There are various ways of deriving it, but perhaps the most instructive makes reference to Heisenberg's own mathematical formulation of quantum mechanics, called **matrix mechanics.** This was a rival to Schrödinger's 'wave mechanics' (Ball)

— The imprecision in our ability to measure two properties at once, Heisenberg suggested, comes from the smallness and delicacy of a quantum particle. … It is virtually impossible to make a measurement on such an object without disturbing and altering what we're trying to measure. … **The restriction on precise knowledge of both speed (more properly, momentum) and position is an intrinsic property of quantum particles**, not a consequence of the limitations of experiments. … It comes from the idea that quantum particles can show both a wave-like nature, spread out in space, and a localized particle nature. To get a good probability of finding the particle in a small region of space from a wave-like probability distribution, we can combine waves of different wavelengths such that they interfere constructively (here) in just that region but destructively everywhere else. This localized wave is called a **wave packet**. (Ball)

— But the wavelength determines the particle's momentum. So the more waves there are, the more possibilities there are for a measurement of momentum. … The **'disturbance' view implies that the particle being observed really does have some precisely defined position and momentum, but that we simply can't measure these things accurately without changing them**. … So if the maths says that we can't measure some observable quantity with more than a certain degree of precision, that quantity simply does not exist with greater precision. That is the difference between ***uncertainty*** ('I'm not sure what it is') and ***unknowability*** ('It is only to this degree'). … Rather, what the theory can tell you depends on what exactly you want to know and how you intend to find out about it. It suggests that 'quantum uncertainty' isn't a sort of resolution limit, like the point at which objects in a microscope look blurry, but is to some degree chosen by the experimenter. … This fits well with the emerging view of quantum theory as, at root, a theory about information and how to access it. (Ball)

— The properties of quantum objects don't have to be contained within the objects (Ball)

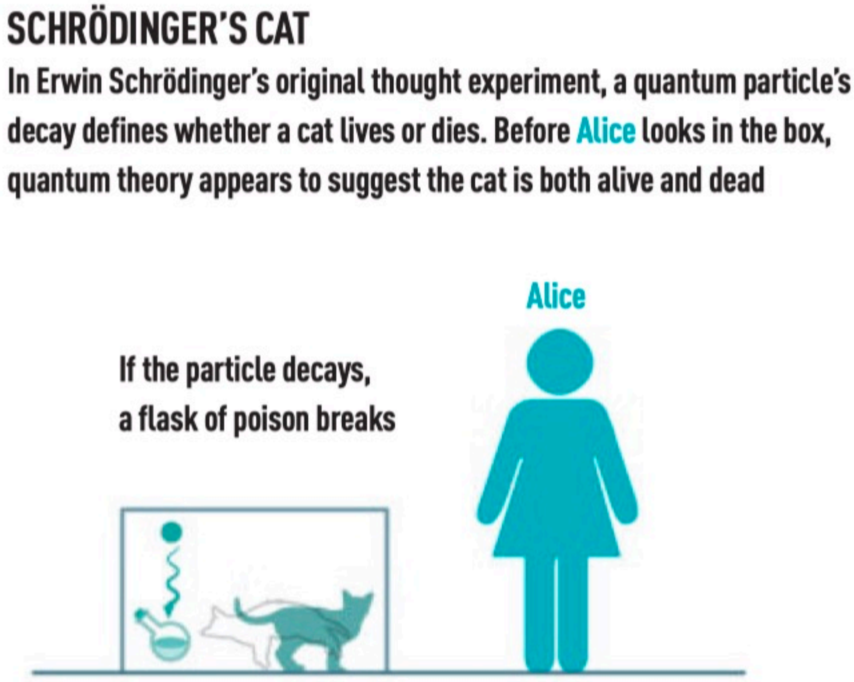
***Schrödinger's Cat***

— Schrödinger's aim was to demonstrate the paradox created if we try to divide the world into classical and quantum parts. What happens when the two can't be so neatly separated? (Ball)

— Schrödinger tried to illustrate the **absurdity** of the Copenhagen interpretation by suggesting that you place a cat and something that could kill the cat (a radioactive atom) in a box. The radioactive decay is probabilistic, so in the cat's reality, it is in quantum superposition [Paul Dirac's principle], suggesting that it is both alive and dead at the same time. Ironically this illustration has become extremely popular.

— **Quantum physics is not replaced by another sort of physics at large scales. It actually gives rise to classical physics.** Our everyday, common-sense reality is, in this view, simply what quantum mechanics looks like when you're six feet tall. You might say that it is **quantum all the way up**. (Ball)

— Schrödinger's cat forces us to rethink the question of what distinguishes quantum from classical behaviour. Why should we accept Bohr's insistence that they're fundamentally different things unless we can specify what that difference is? (Ball)





***Quantum–classical transition.***

— The quantum–classical transition is then like an ocean crossing between two continents: drawing a border somewhere in the open sea is an arbitrary exercise, but the continents are undeniably distinct. **The land of the quantum, said Schrödinger, is random and unpredictable, yet the classical realm is orderly and deterministic because it depends only on statistical regularities among that atomic-scale chaos.** (Ball)

***Coherence***

— **The classical world is defined by certainties – either this or that – while the quantum world is (until a classical measurement impinges on it) no more than a tapestry of probabilities**, with individual measurement outcomes determined by chance. At the root of the distinction, though, lies the fact that quantum objects have a wave nature – which is to say, **the Schrödinger equation tells us that they should be described as if they were waves, albeit waves of a peculiar, abstract sort that are indicative only of probabilities.** (Ball)

— It is this waviness that gives rise to distinctly quantum phenomena like interference, superposition and entanglement. These behaviours become possible when there is a well-defined relationship between the quantum 'waves': in effect, when they are in step. This co-ordination is called **coherence**. (Ball)

— Quantum coherence is essentially what permits 'quantumness.' (Ball)

— If the quantum wavefunctions of two states are not coherent, they cannot interfere, nor can they maintain a superposition. A loss of coherence (**decoherence**) therefore destroys these fundamentally quantum properties, and the states behave more like distinct classical systems. Macroscopic, classical objects don't display quantum interference or exist in superpositions of states because their wavefunctions are not coherent. (Ball)

— If a quantum system in a superposed state interacts with another particle, the two become linked into a composite superposition. That, we saw earlier, is exactly what entanglement is: a superposed state of two particles, whose interaction has turned them into a single quantum entity. It's no different for a quantum particle off which, say, a photon of light bounces: the photon and the particle may then become entangled. Likewise if the particle bumps into an air molecule, the interaction places the two entities in an entangled state. This is, in fact, the only thing that can happen in such an interaction, according to quantum mechanics. You might say that, as a result, the quantumness – the coherence – spreads a little further. (Ball)

***Decoherence***

— **Decoherence** is what destroys the possibility of observing macroscopic superpositions – including Schrödinger's live/dead cat. (Ball)

— The environment [will] disperse the quantum coherence. This happens with extraordinary efficiency – it's probably the most efficient process known to science. And it is very clear why size matters here: there is simply more interaction with the environment, and therefore faster decoherence, for larger objects. (Ball)

— Einstein's question about the moon. Yes, it is there when no one observes it – because the environment is already, and without cease, 'measuring' it. All of the photons of sunlight that bounce off the moon are agents of decoherence, and more than adequate to fix its position in space and give it a sharp outline. The universe is always looking. (Ball)

— Hierarchy of quantum states. There are states corresponding to the outcomes of measurements, and then there are superpositions of these. The former survive a decohering measurement, the latter don't. (Ball)

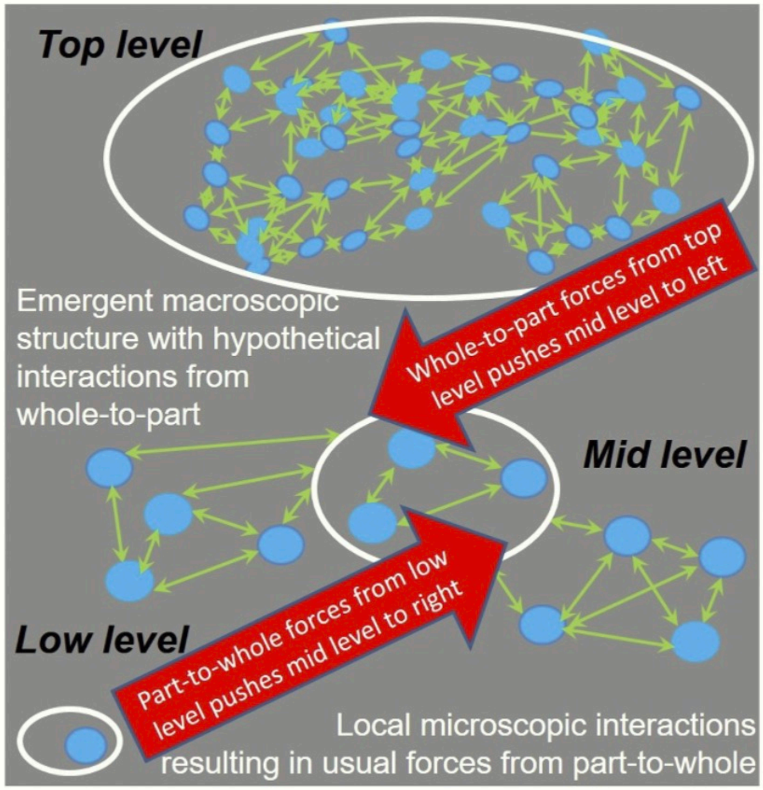



**Fig. 1.** Overdetermination. Part-to-whole forces from low level to midlevel push particles to the right while hypothetical whole-to-part forces from top level to midlevel push the same particles in the opposite direction, to the left.

(Aharonov, Cohen, & Tollaksen, 2018).

***Quantum reconstruction***

— Wheeler's proposition that if we really understood the central point of quantum theory, we ought to be able to state it in one simple sentence. (Ball)

— The **reconstructionists** are a diverse bunch of physicists, mathematicians and philosophers. (Ball)

— The programme of reconstruction typically seeks to identify some fundamental quantum axioms (Ball)

— The key **difference between classical and quantum mechanics is that the first calculates trajectories of objects while the second calculates probabilities** (expressed as a wave equation). Its probabilistic character doesn't make quantum mechanics unique in itself: coin tossing is about probability too, but you don't need quantum mechanics to explain it. **What makes quantum theory so puzzling is that sometimes what we observe seems to force us to speak as though the quantum coins were both heads and tails at once.** (Ball)

— Reformulating quantum mechanics as an abstract 'generalized probability theory' linking inputs (possible states of a system) to outputs (measurement of some property) (Ball)

— Jeffrey Bub: Quantum mechanics is 'fundamentally a theory about the representation and manipulation of information, not a theory about the mechanics of nonclassical waves or particles.' (Ball)

— If you describe a system using a kind of algebra in which the various terms in the equations commute – crudely meaning (here) that the answers you get don't depend on the order in which you perform the calculations – then what you see is classical behaviour. But if the algebra of your equations doesn't commute – if the order matters then you get a quantum-type theory. this is where the uncertainty principle comes from: the fact that in quantum mechanics some quantities do not commute. Bub believes that non-commutativity is what distinguishes quantum from classical mechanics. This property, he says, is a feature of the way information is fundamentally structured in our universe. (Ball)

— Clifton, Bub and Halvorson:

—— 1. You can't transmit information faster than light between two objects by making a measurement on one of them (the condition imposed by special relativity, and called no-signalling).

—— 2. You can't deduce or copy perfectly the information in an unknown quantum state (this is more or less the no-cloning rule).

—— 3. There is no unconditionally secure bit commitment. (Ball)

— If we make these three basic stipulations about quantum information, from them we can deduce a great many of the behaviours, such as superposition, entanglement, uncertainty and non-locality, at the heart of quantum theory. We don't get the full theory, but we get its essence. And these three principles in turn are related to the fact that quantum mechanics is a non-commutative kind of algebra. (Ball)

***Ontic and epistemic interpretations***

— **Ontic interpretation**: those who think that the wavefunction is an element of reality, that it describes reality as it is follow the **ontic interpretation**, from the term ontology, which in philosophy means the stuff that makes up reality. People who follow the ontic school would say that even though the wavefunction does not describe something palpable, like the particle's position or its momentum, its absolute square represents the probability of measuring this or that physical property: the superpositions that it does describe are a part of reality.

—— Hidden-variables models and the de Broglie/Bohm interpretation, take the view that quantum objects have objective properties – which means in turn that wavefunctions are 'real' entities

—— God does not play dice it only looks that way because we don't (and perhaps can't) know everything.

— **Epistemic interpretation**: those who think that the wavefunction is **not an element of reality**: they see a mathematical construct that allows us to make sense of what we find in experiments. This way of thinking is called the epistemic interpretation, from the term epistemology in philosophy. In this view, measurements taken as objects and detectors interact and people read the results; this describes what we can know about the world. The rules of quantum physics are fantastic at describing the results of these measurements. There is no need to attribute any kind of reality to the wavefunction.

—— The **Copenhagen Interpretation is epistemic**, insisting that it's not physically meaningful to look for any layer of reality beneath what we can measure. God plays dice only in an epistemic picture.

***Einstein and quantum theory***

— In a 1935 paper, Einstein, Boris Podolsky, and Nathan Rosen [the EPR paper] introduced a thought experiment to argue that quantum mechanics was not a complete physical theory. Known today as the "**EPR paradox**," the thought experiment was meant to demonstrate the innate conceptual difficulties of quantum theory. It said that the result of a measurement of one particle of an entangled quantum system can have an instantaneous effect on another particle, regardless of the distance between the two parts. [see https://www.aps.org/publications/apsnews/200511/history.cfm]

— John Wheeler: "Einstein, the most brilliant, creative physicist of the twentieth century, clung tenaciously to the view that nature at its core is deterministic, not probabilistic. 'God is subtle, but He's not malicious,' as he put it in the famous statement. Einstein's philosophical stance will no doubt reverberate through physics for as long as there are unanswered questions about the laws that govern the very small and the very energetic."

— Einstein "He [God] does not play dice with the universe." [Ultimately, this is a misleading characterization.]

—— How Einstein ever got tagged as anti-quantum is almost as big a mystery as quantum mechanics itself. The very notion of quanta—of discrete units of energy—was his brainchild in 1905, and for a decade and a half, he stood practically alone in its defense. Einstein came up with most of what physicists now recognize as the essential features of quantum physics, such as light's peculiar ability to act as both particle and wave, and it was his thinking about wave physics that Erwin Schrödinger built on to develop the most widely used formulation of quantum theory in the 1920s. Nor was Einstein anti-randomness. In 1916 he showed that when atoms emit photons, the timing and direction of emission are random (Musser, 2015).

—— Quantum phenomena are random, but quantum theory is not. The Schrödinger equation is 100 percent deterministic. It describes a particle or system of particles using a so-called wave function, which expresses particles' wave nature and accounts for the undulating patterns that collections of particles can form. The equation predicts what happens to the wave function at every moment with complete certainty (Musser, 2015).

—— The determinism of the Schrödinger equation is the determinism of the wave function, and the wave function is not directly observable, as the positions and velocities of particles are. Instead, the wave function specifies the quantities that can be observed and the likelihood of each eventuality. The theory leaves open what exactly the wave function is and whether it should be taken literally as a real wave out there in the world (Musser, 2015).

—— Werner Heisenberg, another early pioneer of quantum theory, envisioned the wave function as a haze of potential existence. If it fails to pinpoint unequivocally where a particle is located, that is because the particle is not, in fact, located anywhere. Only when you observe the particle does it materialize somewhere. The wave function might have been spread out over a huge region of space, but at the instant, the observation is made, it abruptly collapses to a narrow spike at a single position, and the particle pops up there. Bohr himself never accepted wave function collapse.

—— Einstein was definitely anti–Copenhagen interpretation. He recoiled from the idea that the act of measurement should cause a break in the continuous evolution of a physical system, and that was the context in which he began to complain about divine dice rolling. conventional wisdom is wrong that Einstein repudiated the randomness of quantum physics. He was trying to explain the randomness, not to explain it away (Musser, 2015).

—— Conventional wisdom is wrong that Einstein repudiated the randomness of quantum physics. He was trying to explain the randomness, not to explain it away (Musser, 2015).

—— Einstein believed this "spooky action at a distance" was nonsense. His own special theory of relativity held that nothing could travel faster than light, so there was no way for two particles to communicate with each other instantaneously from opposite sides of the universe. He refused to accept quantum mechanics as a fundamental theory of nature.

— It seems clear that the current understanding of the details of classical physics will have to be tweaked as advances take place to better understand quantum phenomena and when a theory connecting classical and quantum physics unfolds. Thus far, no suitable theory exists.

***Determinism/Superdeterminism***

— Overdetermination occurs when a single-observed effect is determined by multiple causes, any one of which alone would be sufficient to account for ("determine") the effect. That is, there are more causes present than are necessary to cause the effect.

— As mentioned above: The Schrödinger equation is 100 percent deterministic. The equation predicts what happens to the wave function at every moment with complete certainty (Musser, 2015).

— Superdeterminism is a radical hidden-variables theory proposed by John Bell. He is renowned for a 1964 theorem, now named after him, that dramatically exposes the nonlocality of quantum mechanics (Horgan, 2022).

— Bell said the puzzle of nonlocality vanishes if you assume that "the world is superdeterministic, with not just inanimate nature running on behind-the-scenes clockwork, but with our behavior, including our belief that we are free to choose to do one experiment rather than another, absolutely predetermined." (Horgan, 2022).

— Hossenfelder notes that superdeterminism eliminates the apparent randomness of quantum mechanics. "In quantum mechanics," she explains, "we can only predict probabilities for measurement outcomes, rather than the measurement outcomes themselves. The outcomes are not determined, so quantum mechanics is indeterministic. Superdeterminism returns us to determinism." "The reason we can't predict the outcome of a quantum measurement," she explains, "is that we are missing information," that is, hidden variables. Superdeterminism gets rid of the measurement problem and nonlocality as well as randomness. Hidden variables determine in advance how physicists carry out the experiments; physicists might think they are choosing one option over another, but they aren't. Hossenfelder calls free will "logically incoherent nonsense." Hossenfelder predicts that physicists might be able to confirm superdeterminism experimentally. "At some point it'll just become obvious that measurement outcomes are actually much more predictable than quantum mechanics says. Indeed, maybe someone already has the data, they just haven't analyzed it the right way." (Horgan, 2022).

— Einstein also believed that specific causes must have specific, nonrandom effects, and he doubted the existence of free will. He once wrote, "If the moon, in the act of completing its eternal way around the earth, were gifted with self-consciousness, it would feel thoroughly convinced that it was traveling its way of its own accord." (Horgan, 2022).

***Summary of the Copenhagen interpretation***

— In the interpretation proposed by Niels Bohr… the wave function just shouldn't be considered real.

— The Copenhagen Interpretation is sometimes said to be the 'orthodox' vision of quantum mechanics. This isn't really true. (Ball)

— In 1926 and 1927, Werner Heisenberg and Niels Bohr were also struggling with the meaning of the Schrödinger wave equation. Eventually, they developed the Copenhagen interpretation for understanding quantum mechanics. It remains the predominantly accepted interpretation today.

— Quantum theory suggests that the world is made of little discrete bits. However, that is not what quantum mechanics says; if anything, it is the opposite: the universe is made of waves, but when you solve the equation for the waves, you find that the waves take certain discrete (but still probabilistic) shapes, and that's where the word Quantum comes from.

"Textbook" or "Copenhagen" interpretation

— When nobody is looking:

—— Systems are described by wave functions

—— Wave functions obey the Schrödinger equation

— When somebody measures:

——Wave function collapses to a particular value

—— Probability of measuring x is the wave function squared

— Today's textbook picture of quantum mechanics clearly has huge issues to resolve:

——1. The Measurement Problem. What do you mean, "look at" or "observe"? When does it happen? Is consciousness somehow involved? Far too vague to be part of fundamental physics.

—— 2 The Reality Problem. What is the wave function? Does it represent reality? Is it the only part of reality? Or does it just characterize our ignorance about the situation? Does reality exist outside of our perceptions?

— Quantum particles exist in all possible states at the same time. When an observation is made, the wave function collapses, and we see the reality of the state. The collapse can also occur whenever systems interact or when radioactive decay occurs. The collapse describes the change from a system with many possible quantum states (superposition) to only one of those possible states: the determination of which end state prevails is random.

— Schrodinger’s Cat illustrates that quantum mechanics deals with probabilities and that all possibilities remain probable until an observation is made, making the situation real. The cat is alive with 100% probability when the lid is closed. If the half-life of the radioactive decay is 10 minutes, then after 10 minutes, the chance that the decay has occurred and the cat is dead is 50%. At this moment, we cannot see into the box, the wave function has not collapsed, and the cat can be considered both alive and dead in terms of probabilities. When we open the lid, the wave function collapses to reveal either a live cat or a dead cat.

— When the actual position of an electron is determined, and it is plotted in a position, the wave function is said to collapse. The collapse means when the electron is 100% in one position.

— Heisenberg’s uncertainty principle: it is impossible to know both the position and momentum of a particle at the same time

— The interpretation describes the observer’s role: all possible probabilities of the wave function remain valid until an observation reveals reality.

— In the Copenhagen interpretation, the wave function is not considered real (it is seen as a type of knowledge: a mathematical description).

***Plasma***

— In physics we can run our models backward in time, and so, starting with the present state of the universe—expansion with matter clumped in galaxies—we can go back in time and deduce that the matter must have been squeezed together. It must once have been a hot and almost entirely smooth soup of elementary particles, called a plasma.

— Three states of matter: solid, liquid, gaseous; but there is also a fourth state of matter. The term plasma refers to a gas that is at least partially ionized. So there are high temperatures. Because of the ionization the gas is conductive and depending on the density of the plasma the movement of the plasma determines the structure of the magnetic field (this is the case near the surface of the sun) or the magnetic field determines the movement of a thin plasma.

— About 99% of the visible matter in the universe is plasma. On Earth, we observe plasma states, for example, during electrical discharges.

— Hydrogen is the most abundant element in the cosmos. The universe consists roughly of about 75% hydrogen and about 25% helium. All elements heavier than helium make up less than 1% of the mass. Nevertheless, these elements are important, without them there would be no solid planets and, of course, no life.

— Throughout the universe, hydrogen is mostly found in the atomic and plasma states, with properties quite distinct from those of molecular hydrogen.

***Arrow of time (Hossenfelder, 2022).***

— Useful energy=free energy. Free energy is the counterweight of entropy. As entropy increases, free energy decreases, and change becomes impossible.
— When pieces of a broken window fall to the ground, their momentum disperses in tiny ripples in the ground and shock waves in the air, but it is incredibly unlikely that ripples in the ground and the air would ever synchronize in just the right way to catapult the broken glass back into the right position. Sure, it’s possible mathematically, but in practice it’s so unlikely, we never see it happening.
— Suppose you want to prepare the batter to bake a cake. You put flour into a bowl, add sugar, a pinch of salt, and maybe some vanilla extract. Then you put butter on top, break a few eggs, and pour in some milk. You begin mixing the ingredients, and they quickly turn into a smooth, featureless substance. Once that has happened, the batter won’t change anymore. If you keep on mixing, you will still move molecules from one side of the bowl to the other, but on average the batter remains the same. Everything is as mixed up as it can be, and that’s it. Basically, our universe will end up like this too: as mixed up as it can be, with no more change, on average. In physics, we call a state that doesn’t change on average—like the fully mixed batter—an **equilibrium state.** Equilibrium states have reached maximum entropy; they have no free energy left.
— The equilibrium state is the state you are likely to reach, and the state you are likely to reach is the state of highest entropy—that’s just how entropy is defined. The second law of thermodynamics, hence, is almost tautological. It merely says that a system is most likely to do the most likely thing, which is to increase its entropy.
— The past-hypothesis says that the universe started out in a state of low entropy a state that was very unlikely—and that entropy has gone up ever since. It will continue to increase until the universe has reached the most likely state, in which nothing more will change, on average (See Past hypothesis, 2022).
— The past-hypothesis is a necessary assumption for our theories to describe what we observe.
— This is why the universe has a direction forward in time, the **arrow of time** it’s the direction of entropy increase; it points one way and not the other. This entropy increase is not a property of the evolution laws. The evolution laws are time-reversible. It’s just that in one direction the evolution law brings us from an unlikely to a likely state, and that transition is likely to happen. In the other direction, the law goes from a likely to an unlikely state—and that (almost) never happens.

— **Entropy** is formally a statement about the possible configurations of a system that leave some **macroscopic** properties unchanged. For the cake batter, for example, you can ask how many ways there are to place the molecules (of sugar, flour, eggs, and so on) in a bowl so you get a smooth batter. Each such specific arrangement of the molecules is called a **microstate** of the system. A microstate is the full information about the configuration: for example, the position and velocity of all those single molecules.

— The smooth batter, on the other hand, is what we call a **macrostate**. It's the average that doesn't change.

— **Dualism**: that the human mind is more than a complicated biological machine.

— **Emergent properties** and objects can be derived from or reduced to something else. **Fundamental** is the opposite of emergent. A fundamental property or object cannot be derived from or reduced to anything else. **The more fundamental layers are the deeper ones, whereas the emergent ones are higher levels**.

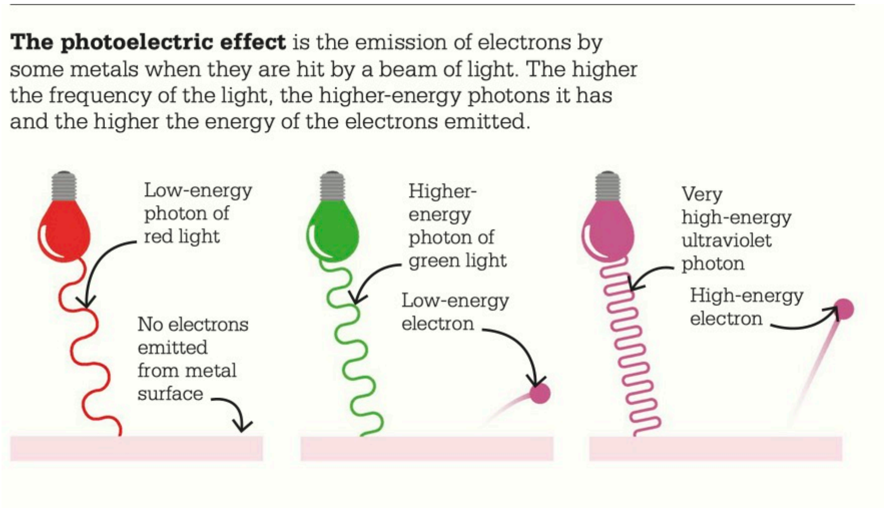
— The only fundamental theories we currently know of—the currently deepest level—are the standard model of particle physics and Einstein's general relativity, which describes gravitation.

— In summary, according to the best current evidence, the world is **reductionist**: the behavior of large composite objects derives from the behavior of their constituents, but we have no idea why the laws of nature are that way.

***Photons***

— [Do not confuse photon and proton]

— In 1905, Einstein described the **photoelectric effect** and proposed that light is made of discrete particle-like quanta.



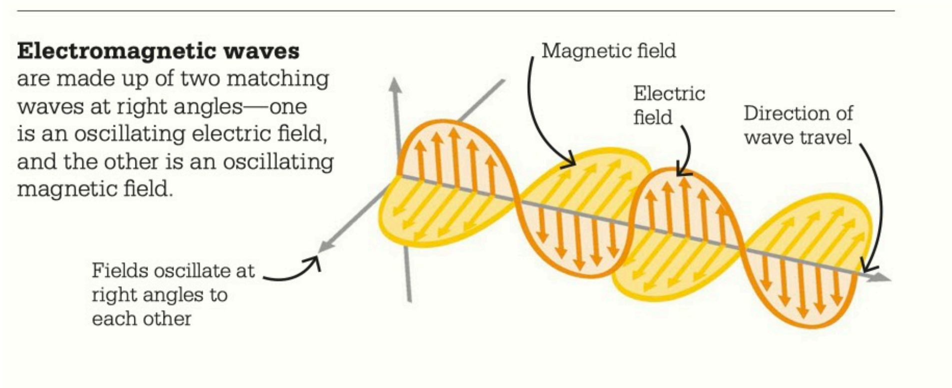
— Einstein’s idea of particle-like quanta flew in the face of hundreds of experiments showing that light was like a ripple spreading on a lake or pond. The only plausible explanation was that, somehow, light must be both a wave and a stream of particles.
— In 1923, Louis de Broglie proposed that, just as light waves could behave like particles, the fundamental particles of matter could behave like waves. This is perhaps the most fundamental statement of quantum theory, known as waveparticle duality.
— In1926, Gilbert Lewis coined the term “**photon**” in a letter to Nature.
— Bohr’s Group created the Copenhagen interpretation: a collection of views about the meaning of quantum mechanics developed during 1925–1927
— A photon is a quantum object; it can be seen as part wave and part particle.
— Thus, the quantum world is “both wave and particle.” As we will see, measurement causes it to be one or the other.
— A photon has no charge, no resting mass, and travels at the speed of light.
— As shown by **Maxwell, photons are just electric fields traveling through space**.
— Schrödinger proposed a new idea underlying the world. Schrödinger’s wave equation encodes all the possible behaviors for a quantum system, but with certainties giving way to probabilities. Picture the simple case of an atom flying through space. If you know its wave function, you can use Schrödinger’s equation to work out the probability of finding the atom at any location you want. But you can’t tell where it is without measuring it. If you were to measure an identical particle again in exactly the same way, you would quite possibly find it somewhere different, according to the probabilities of different positions encoded in the wave function.
— The consensus became and remains that the **waves associated with quantum particles are totally abstract things: not “real,”** unlike any waves anyone has ever seen or had ever imagined.
— **In this view, the wave function is merely a probability distribution**, a statistical summary of what large numbers of measurements would tell you about the properties of the particle.
— **Quantum uncertainty does not allow you to break the laws of physics**. Conservation laws are fundamental, universal laws of physics that hold everywhere and cannot be broken. The conservation of mass/energy states that matter/energy cannot be created or destroyed but only transformed from one state into another. The conservation of momentum states that the total momentum of a system is constant. Momentum cannot be created or destroyed. If a tiny pebble suddenly transformed into a large duck, it would definitely break the law of conservation of mass/energy, as matter would have been created out of nothing. If a rock sitting motionless suddenly shot in the air with no external force applied, it would break the law of conservation of momentum as momentum would have been created out of nothing. The conservation laws of physics and the statistical nature of quantum theory keep the universe ticking

forward in a very predictable way despite the uncertainty present in single particles. [https://www.wtamu.edu/~cbaird/sq/2013/08/23/how-does-quantum-theory-allow-a-rock-to-turn-suddenly-into-a-duck/]

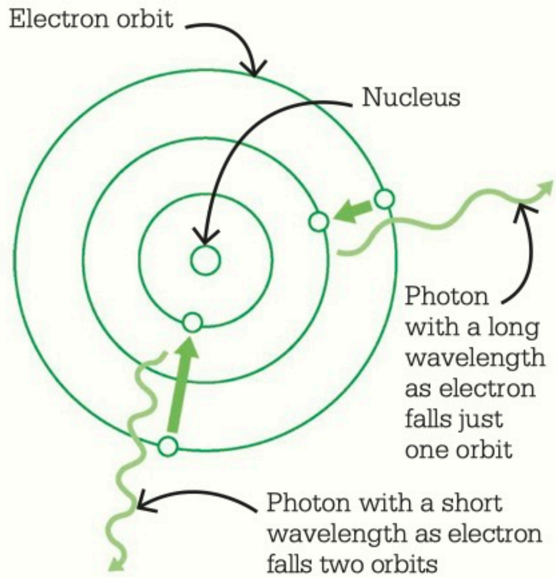
— This is the major difference between classical physics which is precise, versus quantum physics, which is probabilistic in nature. Quantum mechanics replaced the hard certainties of classical physics with wave functions and probabilities.

—— **At the present time, there is no suitable explanation for how classical physics and quantum physics interact**: what is the interface, and how does one state shift to the other?

— All electromagnetic radiation (EMR) is light, but we can only see a small portion of this radiation: the portion we call visible light.




— The energy of each photon is inversely proportional to the wavelength of the associated EM wave. **Being a wave allows it to carry momentum, and therefore energy, without having mass. The shorter the wavelength, the more energetic the photon is; the longer the wavelength, the less energetic the photon.**




**The wavelength of light** that an atom emits depends on how much energy an electron loses in falling from one orbit to another. The further it falls, the shorter the wavelength of the light and the higher its energy.

— A wave transports momentum via its wave motion and not by physically transporting an object with mass.

— **All massless particles/waves travel at the speed of light in a vacuum**. This includes gravitational waves, which propagate changes in the gravitational field, light waves, which propagate changes in the electromagnetic field; and gluons, which propagate changes in the strong nuclear force field. In fact, the phrase "speed of light" can be misleading as it seems to make light look special. A better name would be "the universal speed limit" or "the speed of massless particles."

***A photon's energy***

— A photon contains energy that cannot be divided. This energy is stored as an oscillating electric field. These fields may oscillate at almost any frequency. These packets of energy can be transmitted over vast distances with no decay in energy or speed.

— According to theory, a photon has energy and momentum but no mass. $E = hf = hc/\lambda$. Here h = 6.626*10-34 joule-seconds: a universal constant called Planck's constant.

— Planck's constant specifies how much the energy of a photon increases when the frequency of its electromagnetic wave increases by 1

— Photons are easily created and destroyed.

— Light dissipates by being absorbed by materials and then converted to heat and other forms of energy.

—— When photons encounter matter, they may be absorbed and transfer their energy to the atoms and molecules.

—— Creation and destruction of photons must conserve energy and momentum.

—— An atom consists of a nucleus and electrons, which “circle” the nucleus at different distances from it. The further an electron is from the nucleus, the more energy it has. If an electron moves closer to the nucleus, it loses energy, which is emitted as photons.

—— When an electron absorbs energy, it jumps to a higher orbital. This is called an excited state. An electron in an excited state can release energy, and 'fall back' to a lower state. When it does, the electron releases a photon of electromagnetic energy. The energy contained in that photon corresponds to the difference between the two states the electron moves between. [The lowest energy level an electron can occupy is called the ground state. Higher orbitals represent higher excitation states. The higher the excitation state, the more energy the electron contains. …When the electron returns to the ground state, it can no longer release energy but can absorb quanta of energy and move up to excitation states (higher orbitals). The number of movements an electron can make depends on the number of excitation states available. In the case of one ground state plus one excitation state, there is only one possible state change. The electron can absorb one quantum of energy and jump up to the excitation state. From that excitation state, the electron can then drop back down, releasing a photon with a fixed amount of energy based on the energy lost by the electron when it fell to the lower orbital] (see Bohr model, 2023).

—— The wavelength of light [photons] an atom emits depends on how much energy an electron loses in falling from one orbit to another. The further it falls, the shorter the wavelength of the light [photons] and the higher its energy.

—— Electrons reside inside atoms in different energy levels. When we excite electrons by, for example, in the case of a bulb, heating the tungsten atoms, we elevate them to higher energy levels. However, nature seeks stability; electrons abhor climbing to higher levels. To achieve stability, electrons descend back to their original or even lower levels. When an electron makes this downward leap, the atom emits a photon. As millions and billions of electrons simultaneously descend to lower levels, the tungsten unleashes a massive torrent of photons.

—— This is quite worthwhile: https://www.youtube.com/watch?v=EOHYT5q5lhQ

***Properties of a photon.***

— A single photon carries the following properties:

—— Wavelength – This is the spatial distance between the peaks of the photon's wave.

—— Frequency – This is the number of times that the wave reaches a peak in a unit of time at a fixed location. The human perception of the color of light is very closely related to the light's frequency. Therefore, the word “frequency” can loosely be used interchangeably with the word “color.”
—— Wavevector – This is the photon's direction of propagation, as well as the number of wave peaks that exist in a unit length.
—— Period – This is the time between two peaks of the photon's wave at a fixed location.
—— Speed – This is the rate at which the photon travels through space, which is always 299,792, 458 meters per second.
—— Position – This is the physical location of the photon in space. Although the position of an individual photon is not well defined and contains intrinsic uncertainty while it exists, a photon does carry some degree of location information, thus enabling us to record images in a digital camera based on where the photons hit the sensor.
—— Wave Phase – This is the relative location of the wave peaks of two different photons, and is important in properly describing interference effects.
—— Momentum – This is a motional property that describes light's ability to collide with other objects and get them moving.
—— Spin – This is a quantum property that loosely resembles the type of spinning we see in everyday life. The spin of a photon is also called its polarization state and represents an intrinsic angular momentum.
—— A Quantized Electromagnetic field – A photon is a quantized ripple in the overall electromagnetic field. As such, photons are able to interact with an electric charge. Particles with electric charge can create photons, destroy photons, and scatter photons. Also, photons can exert forces on charged particles. Furthermore, photons obey the principles and equations of quantum field theory.
—— Kinetic Energy – This is the energy of the light due to its motion. Note that because a photon has no mass, its kinetic energy equals its total energy. The energy of light allows it to create a gravitational field according to General Relativity.
— Information: if we combine many photons into a beam of light, we can encode information, such as images in the pattern of the photons. Each of the photon's properties listed above can be exploited to carry information. For instance, human eyes, conventional cameras, and traditional space telescopes extract photon position and frequency (color) information from a group of photons in order to form images. Radio antennas vary the frequency (FM) or the photon count (AM) along the length of the radio waves that they create in order to encode information.
— Photons act like waves while traveling and act like particles when interacting with matter. For example, in the context of starlight, the light travels through space for millions of years, acting like a wave and then acts like a collection of particles when

hitting a photon detector, like a telescope, or an eye. Each photon, therefore, collapses from mostly wave-like to mostly particle-like upon being detected.

— Photons are a type of bosons, meaning that many photons can overlap in the exact same quantum state. Millions of photons can all exist at the same location in space, going in the same direction, with the same polarization, the same frequency, etc. Coherent beams such as laser beams and radar beams are composed of many photons all in the same state. The number of photons in a light beam is more an indication of the beam's brightness than of the beam's width.

— Photons do not obey the Pauli exclusion principle. This means photons can exist in the same state, such as in laser beams.

***Pauli exclusion principle***

— In quantum mechanics, the Pauli exclusion principle states that two or more identical particles cannot occupy the same quantum state within a quantum system simultaneously (see Pauli exclusion principle, 2022).

# 7). Glossary

Action at a distance. The concept of two, separated systems exerting physical effects on each other. In modem physics direct action at a distance is replaced by field theory in which separated systems interact only by stimulating influences to propagate through a field which extends across the space between them. For example, the moon's motion, acting through the intermediary of its gravitational field, raises the ocean tides.

Causality. The relationship between cause and effect. In classical physics, an effect is restricted merely to follow a cause. In relativistic physics causal connections are additionally limited by the finite speed of light. Events which cannot be connected by influences travelling at the speed of light or less are causally independent. One cannot affect the other.

Concordance model. Describes the universe on large scales. It includes all known types of matter in a classical approximation, and adds dark matter and dark energy. It uses the mathematical framework of general relativity. The concordance model is both deterministic and local. The concordance model is also known as ΛCMD (where Λ is the cosmological constant and CDM stands for “cold dark matter”).

Conservation of momentum. A fundamental law of both classical and quantum physics, which requires the total momentum of an isolated system to remain constant, whatever internal changes may occur in the system. In classical Newtonian mechanics, momentum is defined as mass x velocity.

Copenhagen interpretation. The interpretation of quantum mechanics associated with the name of Niels Bohr and his research school in Copenhagen during the 1930s. The Copenhagen interpretation is usually accepted to be the conventional viewpoint in spite of the continuing challenge to its position.

Determinism, deterministic. A theory is deterministic if any given initial condition allows one to deduce the state of the system for all later times. Classical chaos is deterministic, and so is general relativity. The opposite of nondeterministic.

Effective model. An effective model is an approximate description of a system at a desired level of resolution. All effective models are emergent. They are not merely emergent, however. They discard information deemed irrelevant for the purposes at hand.

Einstein-Podolsky-Rosen experiment. (EPR paradox). A thought experiment devised by Einstein and colleagues in 1935 designed to expose the pecularities of quantum mechanics as interpreted by Bohr. The experiment consisted of measurements performed simultaneously on two quantum systems that at one time interacted and then are moved far apart.

Electrodynamics.The theory that treats electromagnetic fields together with their sources - electric charges, currents, and magnets. Electrodynamics takes into account the motion of the sources, the propagation of the fields and the interaction between sources and fields.

Emergent. An object, property, or law is emergent if it cannot be found or defined on the level of constituents and their behavior. If the emergent object, property, or law can be derived from the behavior and properties of the constituents, it is weakly emergent. If it cannot be so derived, it is strongly emergent. There are no known examples of strong emergence in nature.

Evolution law. The evolution law is applied to the initial state of a system and allows us to calculate the state of the system at any later time. If the evolution law is time-reversible, we can also use it to calculate the state at any earlier time. All currently known evolution laws in the foundations of physics are differential equations.

Faster-than-light signalling. Hypothetical mechanism involving physical effects propagating faster than light, thereby enabling events to be causally connected that would otherwise be regarded as physically independent according to the theory of relativity.

Fundamental. A law, property, or object is fundamental if it cannot be derived from anything else. Fundamental is the opposite of emergent.

General relativity. Albert Einstein’s theory of gravity, according to which gravity is the effect of a curved space-time. General relativity is classical, local, and deterministic. It is currently fundamental, but because of its incompatibility with quantum field theory, widely believed to be emergent from a more fundamental theory yet to be found.

Heisenberg's uncertainty principle. After Werner Heisenberg, this is a mathematical formula that describes an irreducible level of uncertainty that is always present (for quantum reasons) in certain pairs of dynamical quantities when they are measured together, e.g. the position and momentum of a particle.

Initial condition / initial state. Complete information about the state of a system at one particular moment in time, to which the evolution law is then applied. The state of the system in the initial condition is called the initial state.

Infinite regress. Philosophically unpalatable outcome of an argument in which each step depends logically on a succeeding step, continuing in an unending sequence.

Irreversible process. In some physical systems, e.g., the swinging pendulum, the processes of interest can also occur in reverse. In others, e.g., the diffusion of two different gases into each other, the process is irreversible.

Locality. A physical restriction on the way in which events can causally influence each other. In a general context, locality refers to the idea that events can only influence other events in their immediate vicinity. It also has a more restrictive meaning. If all physical effects are assumed to propagate no faster than light, two spatially separated events that occur simultaneously cannot be causally connected. Hence an event can only be instantaneously connected to another if it is at the same spatial location. Local, locality. A theory is local if information transfer in this theory obeys the speed-of-light limit and if information, to go from one point to another, has to pass through all closed surfaces dividing these points. I want to warn the reader that physicists use several different definitions of local; this is only one of them, sometimes more specifically referred to as Einstein local. If you have heard that quantum mechanics is nonlocal, this was using a different notion of locality. In the definition used here, quantum mechanics is local, and so are the standard model of particle physics and the concordance model.

Lorentz invariance. A mathematical concept connected with the symmetry properties of theories. It relates the values of physical quantities observed in one frame of reference to those observed in another in a way consistent with the principles of the special theory of relativity. A theory must possess Lorentz invariance if it is to comply with the special theory.

Non-deterministic. A theory in which the later state of a system cannot be deduced from the initial state by the evolution law. It is the opposite of deterministic. A non-deterministic theory is also not time-reversible, but the opposite is not necessarily the case (a deterministic theory might not be time-reversible).

Non-locality. The hypothetical circumstances in which locality fails. Some quantum processes have non-local flavour in that spatially separated events can be correlated, but usually this is assumed not to violate the more restrictive definition of locality concerning instantaneous causal connection between spatially separated events. A theory in which spatially separated places can exchange information instantaneously. None of the currently known fundamental theories have this property. It is the opposite of local.

Planck's constant. A universal constant of nature, denoted h, which quantifies the scale at which the quantum effects are important. It is present in all mathematical descriptions of quantum systems, and may appear in a variety of contexts, e.g. as the ratio of the energy of a photon to the frequency of the light wave.

Quantum field theory. The quantum theory applied to fields, such as the electromagnetic field. Quantum field theory forms the basis for current understanding of high-energy particle physics and the fundamental forces that control subatomic matter. A more complicated version of quantum mechanics in which particles interact by means of other particles. Like quantum mechanics, quantum field theory is local but non-deterministic and not time-reversible.

Quantum mechanics. The theory by which we describe the behavior of particles (this includes light, which is made of particles called photons). Quantum mechanics is local but non-deterministic and not time-reversible.

Quantum potential. Mode of description of quantum systems favoured by Bohm, Hiley and co-workers in which the erratic and unpredictable fluctuations associated with quantum behaviour are regarded as a consequence of a 'potential' field analogous to, for example, the gravitational potential.

Reductionism. The practice of seeking better explanations by deriving an already known theory from a simpler theory. The theory that can be derived is then said to be reducible and the theory that it can be derived from is considered more fundamental. If the fundamental theory describes nature on shorter distances than the reducible theory, one often specifically speaks of ontological reductionism, whereas in the general case, one speaks of theory reductionism. Theory reductionism does not necessarily entail ontological reductionism, though historically they have gone hand in hand.

Relativity, theory of. The currently accepted description of space, time and motion, and a cornerstone of twentieth-century physics. The 'special' theory, first published by Einstein in 1905, introduced unusual ideas such as time dilation and the equivalence of mass (m) and energy (E = mc2). A key result of the special theory is that no material body, physical influence, or signal can exceed the speed of light (c). The later (1915) 'general' theory included the effects of gravitation on spacetime structure.

Schrodinger's cat paradox. A paradox arising from a thought experiment in which a quantum process is used to put a cat into an apparent superposition of live and dead states.

Schrodinger's equation. An equation, similar to that for a conventional wave, which describes the behaviour of the quantum wave function.

Standard model of particle physics. The standard model describes the properties and behavior of all the experimentally confirmed particles and forces, except gravity, which is described by general relativity. It is a type of quantum field theory and therefore both local and non-deterministic. The standard model is currently fundamental.

State function. Abstract mathematical object that encodes all the physical information needed to give the most complete available physical description of a quantum system. In many cases, the state function can be represented as a wave function obeying Schrodinger's equation.

Time-reversible, time-reversibility. An evolution law is time-reversible if it maps one initial state to exactly one state at any other time. In this case, one can use the evolution law both forward and backward in time. The theory of general relativity is time-reversible in the absence of singularities. Quantum field theories are time-reversible except for the measurement process. A time-reversible theory is also deterministic, but a deterministic theory is not necessarily time-reversible.

Two-slit experiment. An experiment first performed by Thomas Young in which light falls on two nearby narrow slits in a screen and produces an interference pattern on an image screen, thereby demonstrating the wave nature of light.

Virtual particles. The Heisenberg uncertainty principle permits particles to appear and disappear again spontaneously, having survived for only very short durations. These fleeting entities are called 'virtual' to distinguish them from the more familiar, long-lived, 'real' particles.

Wave function. A mathematical description of the state of a quantum system. In simple cases, the behaviour of the wave function is described by Schrodinger's equation.

Wave function, collapse or reduction of. The process that occurs when a measurement is made of a quantum system, whereby the wave function abruptly and discontinuously alters its structure. The significance of this 'collapse' is contentious.

Wave packet. Sometimes the wave function of a quantum system is concentrated in a narrow region of space. This configuration, which implies that the particle being described is relatively localized, is called a wave packet.

Zero point energy. An irreducible quantity of energy which, according to quantum mechanics, always resides in a system that is confined in some way. Its existence can be regarded as a consequence of Heisenberg's uncertainty principle.

# 8.) References/Readings

Action at a distance. (2022, December 12). In Wikipedia. https://en.wikipedia.org/wiki/Action_at_a_distance

Admin. (2011, November 22). Difference between general relativity and special relativity. Compare the Difference Between Similar Terms. https://www.differencebetween.com/difference-between-general-relativity-and-vs-special-relativity/

Aharonov, Y., Cohen, E., & Tollaksen, J. (2018). Completely top–down hierarchical structure in quantum mechanics. *Proceedings of the National Academy of Sciences, 115*(46), 11730–11735. https://doi.org/10.1073/pnas.1807554115

Al-Khalili, J. (2011). *Black holes, Wormholes and time machines* (2nd ed.). CRC Press.

Al-Khalili, J. (2012). *Quantum: A guide for the perplexed*. Weidenfeld & Nicolson.

Al-Khalili, J. (2020). *The world according to physics*. Princeton University Press.

Al-Khalili, J. (2022). *The joy of science*. Princeton University Press.

Albert, D. Z. (1994). *Quantum mechanics and experience*. Harvard University Press.

Ananthaswamy, A. (2019). *Through two doors at once: The elegant experiment that captures the Enigma of our quantum reality.* National Geographic Books.

Andrews, J. (2010). *The economist book of isms*. Profile Books.

Ash, A. (2021, July 30). Quantum Entanglement Explained - How does it really work? *YouTube*. https://www.youtube.com/watch?v=unb_yoj1Usk

Bais, S. (2007). *Very special relativity: An illustrated guide*. Harvard University Press.

Ball, P. (2020). *Beyond weird: Why everything you thought you knew about quantum physics is different?* University of Chicago Press.

Bardon, A. (2013). *A brief history of the philosophy of time*. Oxford University Press.

Bergson, H. (2001). *Time and free will: An essay on the immediate data of consciousness*. Courier Corporation.

Bohr model. (2023, January 9). In *Wikipedia*. https://en.wikipedia.org/wiki/Bohr_model

Bolles, E. B. (2004). *Einstein defiant: Genius versus genius in the quantum revolution*. Joseph Henry Press.

Born, M. (2012). *Einstein's theory of relativity*. Courier Corporation.

Brooks, M. (Ed.). (2020). *New Scientist Essential Guide: Quantum Physics*, #5, New Scientist.

Buonomano, D. (2017). *Your brain is a time machine: The neuroscience and physics of time*. W. W. Norton & Company.

Canales, J. (2015). *The physicist and the philosopher: Einstein, Bergson, and the debate that changed our understanding of time*. Princeton University Press.

Carroll, S. (2004). *Spacetime and geometry: An introduction to general relativity*. Addison-Wesley.

Carroll, S. (2019). *Something deeply hidden: Quantum worlds and the emergence of Spacetime.* Penguin.

Copenhagen interpretation. (2022, December 7). In *Wikipedia*. https://en.wikipedia.org/wiki/Copenhagen_interpretation

Cosmic distance ladder. (2022, October 2). In *Wikipedia*. https://en.wikipedia.org/wiki/Cosmic_distance_ladder

Darrigol, O. (2021). *Relativity principles and theories from Galileo to Einstein*. Oxford University Press.

Davies, P. (2022). *What's eating the universe?: And other cosmic questions*. University of Chicago Press.

Davies, P. C., & Brown, J. R. (1993). *The ghost in the atom: A discussion of the mysteries of quantum physics.* Cambridge University Press.

Double-slit experiment. (2022, December 22). In *Wikipedia*. https://en.wikipedia.org/wiki/Double-slit_experiment

Elementary particle. (2023, January 19). In *Wikipedia*. https://en.wikipedia.org/wiki/Elementary_particle

Ellis, G. (2020, June 8). Here's why so many physicists are wrong about free will. Aeon. https://aeon.co/essays/heres-why-so-many-physicists-are-wrong-about-free-will

Eternalism (philosophy of time). (2022, December 10). In *Wikipedia*. https://en.wikipedia.org/wiki/Eternalism_(philosophy_of_time)

Equivalence principle. (2022, November 22). In *Wikipedia*. https://en.wikipedia.org/wiki/Equivalence_principle

Feynman, R. P. (1985). *QED: The strange theory of light and matter*. Princeton Book Company Publishers.

Galison, P. (2004). *Einstein's clocks and Poincare's maps: Empires of time*. National Geographic Books.

Gates, S. J., & Pelletier, C. (2019). *Proving Einstein right: The daring expeditions that changed how we look at the universe*. PublicAffairs.

General relativity. (2023, January 26). In Wikipedia. https://en.wikipedia.org/wiki/General_relativity

Greene, B. (2004). *The fabric of the Cosmos: Space, time, and the texture of reality*. Knopf.

Growing block universe. (2022, November 24). In *Wikipedia*. https://en.wikipedia.org/wiki/Growing_block_universe

Halpern, P. (2015). *Einstein's dice and Schrodinger's cat: How two great minds battled quantum randomness to create a unified theory of physics*. Basic Books.

Halpern, P. (2017). *The quantum labyrinth: How Richard Feynman and John Wheeler revolutionized time and reality*. Basic Books.

Heisenberg. (2022, December 25). In *Wikipedia*. https://en.wikipedia.org/wiki/Werner_Heisenberg

Horgan, J. (2022, March 10). Does quantum mechanics rule out free will? Scientific American. https://www.scientificamerican.com/article/does-quantum-mechanics-rule-out-free-will/

Hossenfelder, S. (2021, October 30). The delayed choice quantum eraser, Debunked. *YouTube*. https://www.youtube.com/watch?v=RQv5CVELG3U&t=14s

Hossenfelder, S. (2022). *Existential physics: A scientist's guide to life's biggest questions*. National Geographic Books.

Koltko-Rivera, M. E. (2004). The psychology of worldviews. *Review of General Psychology, 8*(1), 3–58. https://doi.org/10.1037/1089-2680.8.1.3

Kwok, S. (2017). *Our place in the universe: Understanding fundamental astronomy from ancient discoveries*. Springer.

Kwok, S. (2021). *Our place in the universe - II: The scientific approach to discovery*. Springer.

Length contraction. (2022, December 3). In *Wikipedia*. https://en.wikipedia.org/wiki/Length_contraction

McMahon, D. (2008). *Quantum field theory demystified*. McGraw Hill Professional.

McMahon, D., & Alsing, P. M. (2006). *Relativity demystified*. McGraw Hill Professional.

Mereology. (2022, November 25). In *Wikipedia*. https://en.wikipedia.org/wiki/Mereology

Musser, G. (2015, September). Is the Cosmos Random? *Scientific American, 313*(3), 88-93.

Ni, J. (2014). *Principles of physics: From quantum field theory to classical mechanics.* World Scientific Publishing Company.

Ouellette, F. (2023, February 10). Leonardo noted link between gravity and acceleration centuries before Einstein. Ars Technica. https://arstechnica.com/science/2023/02/leonardo-noted-link-between-gravity-and-acceleration-centuries-before-einstein/

Outer space. (2023, January 27). In *Wikipedia*. https://en.wikipedia.org/wiki/Outer_space

Pauli exclusion principle. (2022, November 17). In *Wikipedia*. https://en.wikipedia.org/wiki/Pauli_exclusion_principle

Parsons, P. (2018). *The beginning and the end of everything: From the Big Bang to the end of the universe*. Michael O'Mara Books.

Past hypothesis. (2022, November 15). In *Wikipedia*. https://en.wikipedia.org/wiki/Past_hypothesis

Penrose, R. (2017). *Fashion, faith, and fantasy in the new physics of the universe*. Princeton University Press.

Penrose, R., & Longair, M. (1999). *The large, the small and the human mind.* Cambridge University Press.

Penrose, S. R., & Hameroff, S. (2017). *Consciousness and the universe: Quantum physics, evolution, brain & mind*. Science Publishers.

Periodic table. (2023, January 23). In *Wikipedia*. https://en.wikipedia.org/wiki/Periodic_table

Petkov, V. (2021). *Seven fundamental concepts in Spacetime physics*. Springer.

Principle of locality. (2022, October 19). In *Wikipedia*. https://en.wikipedia.org/wiki/Principle_of_locality

Quantum contextuality. (2022, October 26). In *Wikipedia*. https://en.wikipedia.org/wiki/Quantum_contextuality

Quantum entanglement. (2023, January 8). In *Wikipedia*. https://en.wikipedia.org/wiki/Quantum_entanglement

Quantum field theory. (2022, December 23). In *Wikipedia*. https://en.wikipedia.org/wiki/Quantum_field_theory

Quantum superposition. (2022, December 5). In *Wikipedia*. https://en.wikipedia.org/wiki/Quantum_superposition

Randall, L. (2009). *Warped passages: Unraveling the mysteries of the universe's hidden dimensions.* HarperCollins.

Relational frame theory. (2022, October 7). In Wikipedia. https://en.wikipedia.org/wiki/Relational_frame_theory

Relativity of simultaneity. (2023, January 4). In *Wikipedia*. https://en.wikipedia.org/wiki/Relativity_of_simultaneity

Retrocausality. (2022, October 22). In *Wikipedia*. https://en.wikipedia.org/wiki/Retrocausality

Robinson, A. (2015). *Einstein: A hundred years of relativity*. Princeton University Press.

Roussel, A. (2018, November 8). We all move at the Speed of Light. *YouTube*. https://www.youtube.com/watch?v=au0QJYISe4c

Roussel, A. (2020, September 3). A new way to visualize General Relativity. *YouTube*. https://www.youtube.com/watch?v=wrwgIjBUYVc&t=604s

Rovelli, C. (2018). R*eality is not what it seems: The journey to quantum gravity.* National Geographic Books.

Rovelli, C. (2021). *Helgoland: Making sense of the quantum revolution*. Penguin.

Russell, B. (2009). *ABC of relativity*. Taylor & Francis.

Schiller, C. (2021). *Motion Mountain: The Adventure of Physics Volume IV, The Quantum of Change*. Thirty-first edition. https://www.motionmountain.net/motionmountain-volume4.pdf

Schrödinger equation. (2023, February 5). In *Wikipedia*. https://en.wikipedia.org/wiki/Schr%C3%B6dinger_equation

Sheehy, S. (2023). *The matter of everything: How curiosity, physics, and improbable experiments changed the world*. National Geographic Books.

Sire, J. W. (2009). *The universe next door: A basic worldview catalog*. IVP Academic.

Smith, R. (2020). *Quantum physics for beginners: Discover the secrets of quantum physics in a simple and comprehensive way*. Independently Published.

Smolin, L. (2019). *Einstein's unfinished revolution: The search for what lies beyond the quantum.* Penguin Press.

Spacetime. (2022, December 2). In *Wikipedia*. https://en.wikipedia.org/wiki/Spacetime

Stein, V. (2022, February 1). Einstein's theory of special relativity. *Space.com*. https://www.space.com/36273-theory-special-relativity.html

Synesthesia. (2023, January 13). In *Wikipedia*. https://en.wikipedia.org/wiki/Synesthesia

Taylor, E. F. & Wheeler, J. A., (1992). *Spacetime physics*. Macmillan.

Terrell rotation. (2022, November 8). In *Wikipedia*. https://en.wikipedia.org/wiki/Terrell_rotation

Theory of relativity. (2022, December 13). In *Wikipedia*. https://en.wikipedia.org/wiki/Theory_of_relativity

Time dilation. (2022, November 27). In *Wikipedia*. https://en.wikipedia.org/wiki/Time_dilation

Unger, R. M., & Smolin, L. (2015). *The singular universe and the reality of time*. Cambridge University Press.

Vaidman, L. (2021 Fall Edition) "Many-Worlds Interpretation of Quantum Mechanics," The Stanford Encyclopedia of Philosophy, Edward N. Zalta (ed.), https://plato.stanford.edu/archives/fall2021/entries/qm-manyworlds.

Veritasium. (2020, October 9). Why Gravity is NOT a Force. *YouTube*. https://www.youtube.com/watch?v=XRr1kaXKBsU&t=540s

Wave function collapse. (2022, December 7). In *Wikipedia*. https://en.wikipedia.org/wiki/Wave_function_collapse

Wheeler John Archibald. (2022, November 20). In *Wikiquote*. https://en.wikiquote.org/w/index.php?title=John_Archibald_Wheeler&oldid=3195786.

Wheeler, J. A. (2010). *Geons, black holes, and quantum foam: A life in physics*. W. W. Norton & Company.

Webb, R. (Ed.). (2021). New Scientist Essential Guide: Einstein's universe relativity and the cosmos it built, #10, New Scientist.

Wilczek, F. (2021). *Fundamentals: Ten keys to reality*. National Geographic Books.

Wolfson, R. (2003). *Simply Einstein: Relativity demystified*. W. W. Norton & Company.

Wüthrich, C., Bihan, B. L., & Huggett, N. (2021). *Philosophy beyond Spacetime: Implications from quantum gravity.* Oxford University Press.

Zee, A. (2013). *Einstein's gravity in a nutshell*. Princeton University Press.