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INTRODUCTION

A Journey through Gravity

Gravity. Such a familiar concept, present in every language and culture, yet one that scientists have struggled to understand for millennia. It is the overarching miracle connecting everything, everywhere, forever in the Universe. Universal in every sense. As humans, we may think of it as the hidden force that keeps us firmly planted on Earth, the reason why the Earth orbits the Sun, or the interaction that allowed the Milky Way and its hundreds of billions of stars to form. But that barely hints at its true significance. Gravity is the reason why the Universe itself can even exist and evolve. It elevates space and time from mere pieces of scenery into central actors in the unfolding drama of reality. As we embrace gravity, we can't help but also pit ourselves against it: leaping, floating, or flying as we pursue brief moments of freedom from its command. I, for one, have been chasing gravity my entire life—seeking, like so many scientists who have come before me, to unravel its deepest mysteries.

Imagine yourself alone in the cockpit of a small, single-engine aircraft, patiently waiting on the taxiway for the signal from air traffic control. Four simple words, "clear to take off," resonate like a magical password, unlocking a precise series of events that will achieve what would have been impossible just over 120 years ago: lifting and floating a one-ton object into midair. As the craft zooms down the runway, you are pressed back into the foam of your seat, accelerating horizontally to a speed of 100 to 200 km/h. Ironically, it is this horizontal speed that will allow the pressure under your wings to overcome the vertical pull of gravity and lift you skyward. As you rise to cruise altitude, even the slightest amount of turbulence shakes the small plane. For a moment, you feel like you are trapped inside a snow globe, existing at the mercy of some titanic, mischievous shaker—until you remember that a little tweak of the rudder, a gentle push on the trims, or a subtle twist of your ailerons is all you need to take control and surf gracefully on the airflow, simultaneously pushed upward by the pressure and pulled downward by gravity.

If soaring above the clouds is not for you, perhaps you would prefer to picture yourself submerged in the deep blue, mingling with thousands of coral reef fish a few dozen meters below the surface. As you contemplate the serenity of this underwater world, you are plunged into a silence broken only by the popping sounds of the vibrant coral reef and that of your own breath as you slowly inhale from your air tank and exhale small bubbles that shoot to the surface. With each breath, your body gently bobs up and down a few centimeters as the pressure of the air in your lungs tries to compensate for the force of gravity and the mass of the column of water that is pressing against every cell in your body.

Flying high in the air and diving deep under the sea are two of the most thrilling ways to defy gravity, at least here on Earth. But to achieve the ultimate feeling of weightlessness, nothing compares to floating in space, seemingly escaping gravity's clutches altogether. The feeling of freedom is no longer an illusion—there are no strings to pull or pressures to counteract. Observing Earth from orbit, you can savor the absolute freedom of free fall, a concept deeply engrained in our understanding of gravity, even while it remains a luxury that few have had the opportunity to enjoy.

In my life, I have experienced the joy of flying and diving and came within a hair's breadth of making it to outer space. But we don't need a fancy plane, scuba gear, or space shuttle to experiment with gravity. In fact, whether we are doing something as simple as dropping a ball, swinging in a hammock, or skipping a stone, we're all scientists conducting our own personal experiments and drawing our own conclusions about this universal yet mysterious phenomenon.

But what exactly is going on in those moments? What is gravity? It seems like such an innocent question, yet the answer always seems to be hidden behind abstruse laws of physics. Physical phenomena are often portrayed as a set of obscure fundamental rules—Archimedes' principle, Newton's inverse square law, Bernoulli's principle, and the like—that nature must unquestionably and rigidly obey. These laws are, of course, central to our understanding of the world and the structure of our reality. They have revealed how buoyancy allows boats to float, and how the difference in pressure caused by the motion of the air beneath their wings allows birds and planes to navigate the skies. They have enabled us to send a man, and hopefully soon a woman, to the Moon. Yet the presentation of these laws as being set in stone belies our scientific history. Far from being immutable and unchanging, our understanding and appreciation of these laws—what they mean, where they come from, and what lies behind them—is continuously unfolding before us.

Galileo Galilei, Johannes Kepler, Sir Isaac Newton, Albert Einstein, Stephen Hawking, Sir Roger Penrose, Andrea Ghez, and countless other brilliant scientists have each brought a new perspective to our understanding of gravity, but our journey is far from finished. Think of this book, then, as an invitation to join me in the quest to uncover the meaning of gravity, to grasp its connection with the structure of reality. Fortunately, for the most part we will not be undertaking this adventure alone. Instead, we will be guided by some of the greatest scientific minds of the past several centuries—that is, at least, until we reach the edge of the map, where we will take some exploratory steps into the unknown. Our journey will begin, however, in well-charted territory with a few trustworthy companions.

With their realization that gravity must be a universal force, acting on everything and accelerating everyone in the same way, regardless of their mass, Galileo, Kepler, and Newton provided the first crucial piece of the puzzle. This insight was made possible by a new perspective on what it means to *be free*, a perspective that discarded centuries of Aristotelian dogma and radically transformed the concept of *inertia*.

This new perspective was brought to light in 1632, with the publication of Italian astronomer and physicist Galileo Galilei's *Dialogue Concerning the Two Chief World Systems* (*Dialogo sopra i due massimi sistemi del mondo*). In the dialogue, Galileo championed a new Copernican revolution, one that went beyond merely denying that the Earth occupied a special place in the solar system, by further dismissing the idea that *any* person or object could ever hold a privileged position with respect to the laws of nature.

To make this argument, Galileo considered the world through the eyes of a sailor confined to the main cabin below the decks of a moving ship. Unable to see the world outside, the sailor was entertained by watching the motion of "some flies and butterflies" with whom she shared the cabin. Galileo realized that the sailor would not be able to tell whether the ship was at rest or in motion at constant speed, at least not from observing these small flying animals. Why? Because if the ship moves at constant speed, so does everything on board, including the air in which the flies and butterflies flutter about. The sailor, trapped below deck, can only observe the motion of the flying creatures relative to the inside of the ship's cabin. Galileo used this thought experiment, which highlighted the importance of *relative* motion, to explain how the Earth could rotate without us being able to feel it. Moreover, once we recognize that we cannot tell the difference between the lower deck of a ship at rest and that of one in uniform motion, we can infer that the laws of physics should be the same for any observer moving at constant velocity, no matter the speed.

It is precisely this notion of "Galilean relativity"—the realization that the laws of nature are the same regardless of who describes them—that is enshrined in Newton's first law of motion, which holds that every object will remain at rest or in uniform motion in a straight line unless compelled to change its state by the action of an external force.[1] Newton realized that *being free* is the privilege to carry on undisturbed, pursuing our journey at the same velocity, uniformly. Building on the work

1. This idea replaced the Aristotelian notion of *inertia*—the desire to slow down and come to a state of absolute rest. In contrast to Aristotle, who thought that forces were necessary to maintain velocity, Newton realized that *forces* lead to *acceleration* (change in velocity). In our everyday lives, friction with the air and the ground acts as a force, naturally slowing us down (deceleration or negative acceleration). However, in outer space, where there is no air and no friction, objects can be free and maintain a uniform velocity.

of Kepler, who developed the laws of planetary motion, this insight would later lead to Newton's 1687 law of universal gravitation, also known as Newton's inverse square law. According to this law, the force of gravity exerted between any two massive particles (that is, particles having mass) is a *universal* and *instantaneous* force, whose intensity decays as the square of the distance between the two particles.

Newton's law, as many of us have been taught, describes how an object, when dropped, is inexorably attracted by the mass of the Earth. But the universal nature of gravity extends far beyond this simple phenomenon. It applies to everything and everyone, no matter the object, no matter the separation. In 1798, Henry Cavendish was among the first to test it formally in a laboratory, and more than three centuries after its discovery, Newton's inverse square law has been scrutinized with impeccable precision, from distances smaller than a tenth of the width of human hair to separations that extend billions of kilometers. In fact, Newton's law of universal gravitation is so fundamental that it can still be used to predict how gravity has governed most of the evolution of our Universe, from the gravitational collapse of dark matter to the formation of clusters of galaxies and the creation of the solar system.

Centuries passed before observational evidence began to cast a sliver of doubt on Newton's law of gravity. However, in retrospect, the idea that gravitational attraction between any two objects happens *instantaneously* should have raised a red flag. According to Newton's simple law, if two particles were to appear, they would be *immediately* attracted to one another without any delay. No matter what your views on attraction may be, we all know that this phenomenon cannot be immediate. Even when it comes to love at first sight, you first need to "see" the other person (that is, to "communicate," even if not verbally) for attraction to take place. Newton himself, in a letter to Richard Bentley, expressed his discomfort with the concept of an instantaneous law: "Tis unconceivable that inanimate brute matter should (without the mediation of something else which is not material) operate upon & affect other matter without mutual contact; as it must if gravitation in the sense of Epicurus be essential & inherent in it. And this is the reason why I desired you would not ascribe {innate} gravity to me" [1].

Our own journey will begin two centuries later, when American scientists Albert Michelson and Edward Morley revealed the results of their infamous "failed experiment," ushering in a new scientific revolution. Shortly thereafter, Einstein introduced new ideas of relativity into our understanding of gravity: first putting forward the notion of special relativity, which supplanted the kinematics of Galileo, and then unveiling gravity as we understand it today through the theory of general relativity. Guided by these theories, we will uncover an entirely new structure of physics and understanding of our Universe in which gravity is fundamentally identified with the very fabric of space and time, entwined and unified.

Today, more than a century has passed since Einstein's breakthroughs, and general relativity stands stronger than ever. Gravity has been exhaustively tested, including in some of the most extreme environments, and the evidence unfailingly accords with Einstein's predictions. The very force within gravity has been detected thanks to gravitational waves. At the same time, we have also learned much more about the quantum nature of our world through atomic, nuclear, and particle physics, quantum chemistry, and the numerous technological advances of the electronic and computer age. With these advances, new ideas and theories constantly bubble up in our effort to make sense of the world in which we live. And yet, to date, none has surpassed Einstein's theory of general relativity, despite the obvious need for new physics. For there is one thing that, from the very beginning, general relativity itself has been forthright about: there is a point where the theory must fail, where a brand-new layer of physics waits to be unveiled. From this failure comes the opportunity to probe and appreciate nature on an even deeper level.

As we continue on our journey, we shall see how gravity, viewed from a more modern perspective, can also be thought of as the manifestation of a fundamental particle—the graviton—much like electromagnetism is the manifestation of the photon, the fundamental particle of light. In the very same way that we can "see" *light* as electromagnetic waves propagate through space and time, we can now "hear" gravitational waves (or *glight*, as we shall call it here) as they disturb the very fabric of spacetime. We have now observed gravitational waves through many different instruments, and the reality of glight has become unquestionable. Their detection offers an unparalleled opportunity to decipher the many mysteries that our Universe is still hiding. What is the origin of the Universe? What are the dark components of the Universe that explain its structure and evolution but cannot be directly detected with our instruments? What is our fate? These profound questions are begging for answers. And who wouldn't want to follow that trail?

Eventually our journey will take us to the edge of the map. While Einstein's theory of general relativity has provided natural and elegant answers to some of the most perplexing questions about the nature of gravity, it also has raised several puzzles with which we continue to grapple. How is it that the contributions of known particles that we understand so well in our underground particle accelerators affect the Universe in ways we cannot even start to comprehend?

As we attempt to reconcile the evolution of our Universe with the fundamental quantum nature of the world, we will be forced to reconsider gravity on an even deeper level. What if, on large cosmological scales, gravity behaves differently than predicted by general relativity? What if gravity, long assumed to be massless, in fact has mass? This idea is almost as old as general relativity itself and has been explored by some of the greatest scientists of the past century. Until recently, all attempts to make sense of this idea have failed dramatically. Yet far from being the end, this is where the most exciting part of our journey will begin as I guide you through new pathways that my colleagues and I have recently uncovered in our quest to grapple with gravity.

These paths previously looked so unpromising that their exploration was considered not only impractical or dangerous but simply unthinkable. Today, however, it seems that they may lead us to an entirely new way to think about gravity. And while these new theories may not provide final answers to all of our questions, by exploring gravity as it might be, even if not in our own reality, we may come to appreciate nature for all that it has to offer.

Gravity is one of the first physical phenomena of which we are aware, and we possess a near universal desire to probe its limits. As babies, we repeatedly push toys off the table, watching them tumble to the ground (and watching our exasperated parents retrieve them). As children, we jump tirelessly on the trampoline, seeing how high we can soar before being pulled back down to our terrestrial home. As old friends, we skip stones at the beach, observing the beauty of the cascading ripples. In every instance, we both play with and try to counteract this tenacious phenomenon. Its constant pull is the source of so much stress in our lives, but rather than hiding from it we all learn to embrace it.

As we fall through the curvature of spacetime as freely as we fall through our lives, we soon realize that, while being free and straight, our journey through space and time is far from straightforward. Certainly, our journey would not be complete without its share of obstacles and falls. Embracing them and appreciating the beauty of falling is essential if we are to make progress in our never-ending quest. All theories of gravity developed so far have experienced the virtue of failure. Daring to fail means appreciating each fall not as an embarrassing epilogue but rather as an opportunity for a more fundamental understanding of nature.

Think of this journey, then, as a celebration of gravity's mysteries and of science itself—complete with its doubts and failures, yes, but also with the incredible thrill of discovery. This is not just my quest, nor that of my colleagues. It is not the discovery of Einstein or Newton alone. It is our *shared* adventure, yours as much as that of the great scientists who paved the way. It is a journey that began thousands of years ago, and one that may never end. Along the way, however, we hope to gain knowledge that will enrich the lives of future generations and civilizations, allowing them to pursue their own destiny, to surf between new layers of reality, and to interact with the all-encompassing fabric of the Universe.

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Note: Page numbers in *italics* indicate figures.