Space, Time, and Einstein: A Simple Explanation of Relativity

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You've seen him portrayed in films. You've seen the famous photo where he is whimsically sticking out his tongue. You've heard he's a genius. But what do you actually know about Albert Einstein's groundbreaking ideas?

These ideas, especially the Theory of Relativity, can give us a much better understanding of the world around us and of the whole universe. They even explain some of the most incredible things you may have ever heard or wondered about.

They have practical applications as well. For example, technologies that we use on a day-to-day basis, such as GPS location systems, depend on Einstein's Theory of Relativity.

The intricacies of Einstein's work are complex, but you don't need to be a physicist to understand the basics. Let's take it one step at a time.

We'll start by looking at the scientific developments that led up to Einstein's work. Then, we'll break down the concepts that Einstein introduced in his Special Theory of Relativity. Next, we'll explore how his General Theory of Relativity expanded on Special Relativity to include the effects of gravity. Finally, we'll explain General Relativity's limitations, the quest for a unified theory of the physical aspects of the universe, and the practical implications of all of this looking forward.

A. Earlier Work

1. Background

Let's start with a definition of a basic concept that will help us understand the whole idea of relativity. We call this concept an "inertial frame of reference." So, what exactly do we mean when we talk about an "inertial frame of reference"?

Inertial frames of reference are like stable platforms where motion is uniform.

Imagine you're in a car cruising smoothly down the road in a straight line at a constant velocity.

If you toss a ball up in the air, it will come back down to your hand just as it would if you were standing still on the ground. This happens because you, the ball, and the car are all moving together at the same speed and direction without any changes in acceleration. So, in this scenario, the car represents an inertial frame of reference.

Instead of using the term "inertial frame of reference" repeatedly, for simplicity, we will refer to it as a frame of reference from here on.

2. Early Concepts of Location and Motion

People once generally believed that they could locate everything from a single fixed point in space. They assumed this point was always completely at rest. Using our concept of a frame of reference, we could say that they believed that everything existed in only one, unique frame of reference.

3. **Galilean Relativity**

In the 17th century, Galileo studied how objects moved relative to each other and discovered that the laws of distance, rest, and motion remained consistent in different frames of reference. This means that the way objects move doesn't change based on where you're observing them from.

Galilean relativity does not provide a framework for dealing with changing acceleration or changing velocities, however.

4. **Newton’s Observation**

In 1687, Isaac Newton introduced his laws of motion and universal gravitation, which provided a new way to understand how things move and interact with each other.

The laws included the observation that when an object (for a modern interpretation, let’s say a car), moves forward past another object (again, for a modern interpretation, let’s say a tree), it appears to an observer standing by the tree that the tree is at rest and the car is moving past the tree.

On the other hand, from the point of view of an observer in the car, it appears that the tree is moving backward past the car.

Newton's laws showed that an object's motion and position are only meaningful when compared to another object's motion and position. This idea challenged the belief in a fixed state of rest and introduced the concept that motion is relative to a specific frame of reference.

Albert Einstein's Theory of Relativity later built upon and extended Newtonian mechanics to describe motion at high speeds and in gravitational fields more accurately.

5. **We also know that the speed of light is constant. Here's how we know that:**

Early Scientific Beliefs

Before 1887, scientists believed in a mysterious substance called the ether that filled space. They thought light waves traveled through this ether, and they expected the speed of light to change depending on Earth's motion through it.

The Michelson-Morley Experiment

In 1887 Albert Michelson and Edward Morley conducted an experiment that attempted to detect the motion of Earth through the hypothetical ether by observing any changes in the speed of light. They anticipated that they’d find that light’s speed differed in different directions due to Earth's motion through the ether. Michelson and Morley rotated the measuring device to measure the speed of light from different directions.

The result of the experiment surprised everyone. Michelson and Morley found that the speed of light remained constant in all directions, regardless of Earth's motion.

This discovery challenged the idea of the ether. Einstein took this groundbreaking result and built upon it. He realized that if the speed of light is constant for all observers, then time and space must be relative. This led him to propose his Special Theory of Relativity in 1905.

B. The Special Theory of Relativity

1. **The Laws of Physics, Including the Speed of Light, Are Relative from All Points of View**

   As we saw earlier, we can only measure the location and motion of something relative to the location and motion of something else. Additionally, the Michelson-Morley experiment proved that we can measure the speed of light and that it is that finite and must be constant*.

   Einstein concluded from these facts that the laws of physics and the speed of light are the same regardless of where you might happen to be, or how fast you happen to be moving relative to something else. That is, they are the same in every frame of reference.

   (*Strictly speaking, the speed of light is constant in a vacuum. This fact doesn't significantly affect the main ideas in our discussion, so we won't keep repeating it.)

2. **We know that nothing that has mass can travel faster than the speed of light. Here's how we know that:**

   First of all, what is mass? Mass is sometimes confused with weight, but it is not the same thing. An object's **mass** is simply the amount of matter that it contains, while **weight** is the force exerted on an object by gravity.

   An object's mass remains constant regardless of where it is. For example, the effect of gravity on the earth is eight times that on the moon. An object on the Moon **weighs** less than it does on Earth because of the moon's lower gravity, but that object still has the same **mass** as it does on Earth.

   Einstein proved that if something has any mass, it can't travel faster than the speed of light.

   To explain this in simpler terms, think of it this way. Objects that have mass have a resistance to changes in their motion. For example, it takes more effort to move a heavy box than it does to move a light one.

   As an object moves faster, it takes more energy to make it move even faster. While we will not go into the mathematics of Special Relativity, they show that as an object with mass accelerates toward the speed of light, the amount of energy required to overcome its resistance to speeding up approaches a limit that prevents the object from reaching or exceeding the speed of light. This makes it impossible to accelerate it further.

   Scientists have performed experiments that accelerated objects to velocities close to the speed of light using particle accelerators. Observations from these experiments show that the amount of energy needed to accelerate an object increases exponentially as they move faster.

   For example, the Large Hadron Collider (LHC), located at the European Organization for Nuclear Research (CERN), near Geneva, Switzerland, has accelerated objects to velocities up to 99.9999991% of the speed of light, but still cannot surpass it. This is not just a technological limitation of the Large Hadron Collider but is based on the observations showing that the amount of energy needed to move any faster increases exponentially with speed.

   Thus, the inability of anything that has mass to exceed the speed of light is a fundamental property of the universe as described by the Special Theory of Relativity.

3. **We also know that the passage of time itself can be determined only in relationship to the observer's frame of reference and motion. Here's how we know that:**

Background

Again, as we saw above, we can measure the location and motion of any point only relative to those of some other point, and the speed of light is constant in all frames of reference. Now we'll show that we can also measure time only relative to a specific frame of reference.

Einstein's "Thought Experiment"

A thought experiment is a mental exercise in which someone uses their imagination to explore what could happen under certain conditions, without physically being in that situation.

When he was a teenager, Einstein imagined that he was chasing a beam of light. He visualized what would happen if he caught up with the beam of light. He realized that this would lead to a situation that conflicted with the established notions of space and time.

Without getting into the details, the upshot of this mental exercise caused him to conclude that events that appear to happen at the same time from one point of view don't appear as if they occurred at the same time when they're observed from another point of view.

Ultimately, this realization contributed in a major way to the formulation of his Special Theory of Relativity.

Einstein's Explanation

In his popular work, *Relativity: The Special and General Theory*, Einstein used an analogy to explain how we can better understand the mental exercise mentioned above.

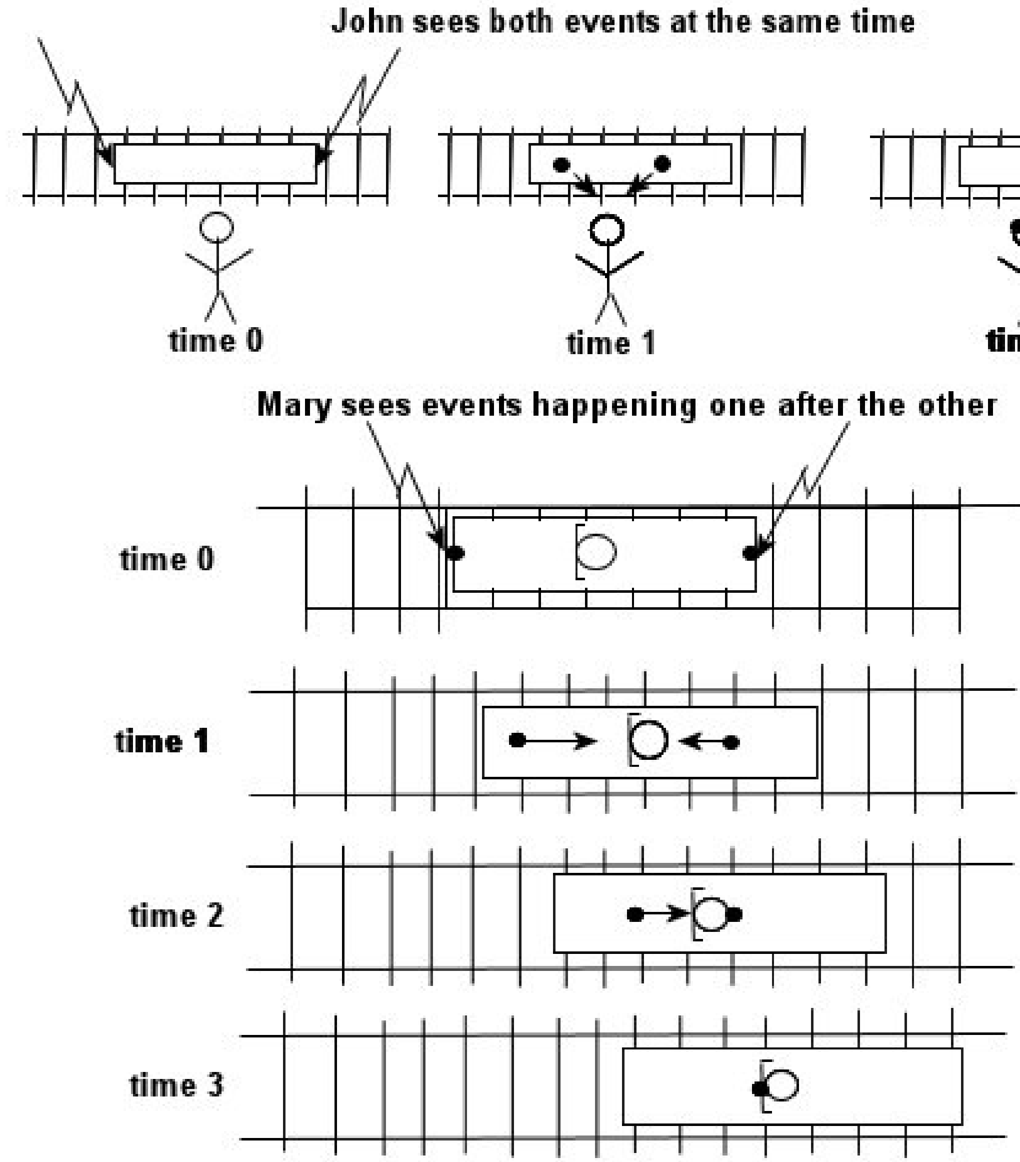
To express it in simple terms, imagine John standing on the ground as Mary passes him on a fast-moving train. Two bolts of lightning strike two points on the train (say, the front and back of the train) that are the same distance away from both Mary and John at the exact moment that Mary passes John.

From John's perspective, light from both bolts travels over the same distance to reach him, so since the speed of light is constant, he sees the flashes from both bolts at the same time. This leads him to conclude that the bolts struck simultaneously.

Mary, however, is moving toward the point where the lightning strikes the front of the train and away from the point where the lightning strikes the back of the train. From her point of view, the light from the back strike has to travel farther to reach her than the light from the front strike. Because the speed of light is constant, Mary will see the flash from the bolt that strikes the front first. Then she will see the flash from the bolt that strikes the back.

Thus, determining whether events happen at the same time depends on the viewpoint or frame of reference from which one observes them. Mary experiences a difference in how much time has passed between the two strikes compared to what John experiences.

Again, from Mary's perspective, the light from the back strike travels farther than that from the front strike. This demonstrates that positions and distances in space are relative and can change based on an observer's motion. It illustrates how the relativity of motion influences our understanding of space and challenges the traditional notion of fixed spatial dimensions.



(● = apparent positions of light pulses from the 2 lightning flashes)

Considering all of this together, we realize that neither time nor space remain absolute. They mutually influence each other. Thus, measurements of time and space depend on an observer's frame of reference and motion. The perspective from which we look at events decides whether they happen at the same time.

Scientists have done tests with atomic clocks on fast-moving airplanes and satellites proving that the rate at which time passes **really does** change relative an observer's frame of reference and motion.

Another real-world example involves GPS systems. These systems depend on time signals sent by several satellites orbiting around the earth. If they failed to take into account time's relativity to the different frames of reference of Earth and the satellites, GPS locations would be too inaccurate to be useful.

These examples demonstrate that the relativity of time have observable effects on a small scale.

It is important to point out that we don't notice the effect of time's relativity at the speeds that we normally encounter in day-to-day life. It becomes quite significant, however, at speeds approaching the speed of light. We can use an imaginary scenario to visualize the profound nature of the relativity of time at a larger scale.

Imagine that we have two twins. Each one has a perfectly accurate clock that keeps track of the date and time. One of the twins stays on the ground, while the other travels at an extremely high speed by rocket to outer space and stays there for a long time. Each twin keeps her own clock with her.

The rate at which time passes is different for each twin depending on their frames of reference. Therefore, when the traveling twin returns to Earth, her clock shows a time and date that is much earlier than the other twin's clock, which remained on the ground.

This also affects the rate of their biological processes. In other words, the twins' biological aging will occur at different rates relative to each other.

As a result, in this hypothetical scenario, the twin who had stayed on Earth would have aged more than the one who had traveled to outer space!

4. Space-Time

So, in all frames of reference, the speed of light is constant, and the three dimensions of space and the dimension of time are relative. Time and space are so interrelated to each other that scientists see the universe as being four-dimensional, considering the three dimensions of space plus the dimension of time. They call this space-time.

How are space and time tied so tightly together in the concept of space-time? Start by thinking about it this way: no two objects or events can occupy the same point in both space and time. This makes sense when you think about the fact that you and I can't both occupy the exact same space at the same time.

While two things can be at the same point in space, they can't both be there at the same exact time. Likewise, two events can happen at exactly the same time, but only if they happen at different points in space.

As we showed above, even the idea that two things happened at the same time is not absolute. Whether or not they occurred simultaneously depends on your location, speed and direction of motion.

If you basically understand how these ideas fit together, you can say that you understand Einstein's Special Theory of Relativity.

Although Special Relativity explains much of what we can observe in the universe, it doesn't take gravity into account. In 1915, Einstein came up with his General Theory of Relativity, which does account for the effects of gravity.

C. **The General Theory of Relativity**

I have to admit that General Relativity is more complex than Special Relativity, but let's try to understand it. Again, we'll take it step by step.

1. **A New Explanation of Gravity**

Background: Newton's Law

Newton's law of gravity states that the force of gravity affects everything in the universe that has mass.

In simple terms, it means that any two objects with mass will attract each other with a force that depends on their masses and how far apart they are.

This law helps us understand why objects fall to the ground, why planets orbit around the sun, and many other things that relate to gravity.

Einstein's Dilemma

The problem that General Relativity attempts to deal with is that, prior to Einstein's work, people had interpreted Newton's law of gravity as implying that gravitational force travels instantaneously.

That conflicts with Special Relativity's prediction that nothing that has mass can travel faster than the speed of light. That prediction is now well-supported by evidence.

Einstein's Solution

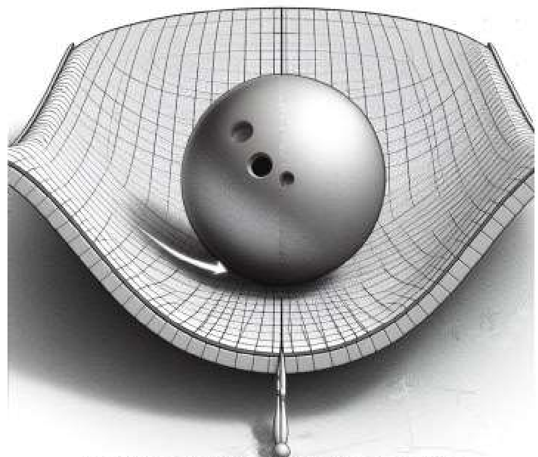
The General Theory of Relativity therefore proposes the revolutionary idea that gravity is not a force acting at a distance, as Newton's laws had proposed. Instead, General Relativity explains gravity as the result of objects following paths determined by a curvature of space-time around massive objects.

What do we mean by "a curvature of space-time"? Here is an analogy that may help you to visualize the idea.

This example is somewhat simplified. It doesn't attempt to depict the curvature of all four dimensions of space-time (the three dimensions of space plus the dimension of time). Instead, it utilizes only a 3D model, but it should still help you to understand the concept of space-time curvature and how gravity arises from that curvature.

First, imagine space-time as a giant trampoline.

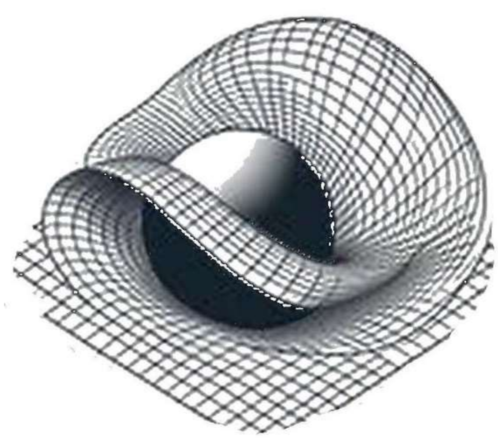
When you place a heavy bowling ball (representing a massive object like a star) in the center of the trampoline, it creates a deep dent in the trampoline's surface. Lighter objects, like marbles (representing smaller objects), will roll toward the bowling ball due to the curvature in the fabric caused by the bowling ball's mass.



Bowling ball bending trampoline
(3D visualization created using AI)

Now, picture this trampoline as not just a flat surface but as a three-dimensional fabric that curves in all directions around massive objects. Just as the bowling ball bends the trampoline, massive objects bend space-time around them. This bending effect is what we experience as gravity – the bending of space-time by mass.

The image below shows a hypothetical model that illustrates this concept, at least in 3D. (Of course, it's not physically possible to actually draw an illustration of 4D space-time.)



Portion of Space-time
Bending Around a Massive Object
(3D visualization created using AI)

When you roll a marble near the bowling ball on the trampoline, it follows a curved path due to the dent created by the heavy ball. Similarly, planets and light from distant stars follow curved paths around massive objects like the sun due to the curvature of space-time caused by the mass of objects like the sun.

The idea that we live in a curved a 4D space-time might still sound far-fetched to some. It's fairly obvious that space has three dimensions and time has one dimension. Still, I myself find it hard to actually visualize something that has four dimensions. Scientists have found, however, that General Relativity's predictions agree better with actual observations than those of Newton's law of gravity.

There is proof of this. In the 19th century, scientists noted that Mercury's orbit did not precisely match the predictions of Newtonian gravity. General Relativity, however, accurately explains this discrepancy, highlighting how its predictions better align with the actual observations of Mercury's orbit.

In addition, careful scientific observations have shown that light rays really do bend around the sun and other massive objects.

Although scientists had accepted Newton's law of gravitation as established fact since 1687, this radical change overturned it.

2. **Gravity Also Affects the Passage of Time**

In the Special Relativity section above, we showed that the rate at which time passes is not absolute. It depends on the frame of reference and motion of the observer. General Relativity shows that, in addition to that, the presence of gravity also affects the passage of time. Clocks located closer to a gravitational source, like Earth's surface, will experience a slower passage of time compared to clocks at higher altitudes, such as orbiting satellites. So, GPS systems must also take this gravitational effect into account in order to provide accurate locations.

In 1976, experiments with time signals sent to and from the Viking 1 Mars lander provided evidence of this effect. More recent experiments using precisely accurate atomic clocks have measured the amount of change that gravity has on the passage of time. They showed that the amount of difference is exactly what General Relativity predicts.

3. **Matter and Energy are Interchangeable**

The new explanation of gravity leads to an even more incredible conclusion: matter and energy are actually two sides of the same coin. We can transform each one into the other.

To understand how this can be so, let's go back to the trampoline analogy. The heavy bowling ball placed on the stretched fabric causes a dent in the fabric. This dent represents, in a simplified 3D model, how mass curves space-time, creating what we experience as gravity.

Now, think of this dent in space-time as a source of energy. When a smaller object interacts with this curved space-time it moves along the curvature toward the more massive object. This is similar to what happens when our bowling ball's mass causes a dent, or curvature, on the surface of the trampoline.

A marble on a trampoline rolls down toward the bowling ball along the curve caused by the dent. This releases energy, as the marble rolls down the dent and picks up speed. In general, the amount of energy released is proportional to the mass of an object as it moves toward the massive object along the curvature caused by the massive object.

When Einstein ran the numbers, he found that the amount of energy released can be expressed in the now famous equation:

$$E=mc^2$$

Where **E** is the amount of energy released, **m** is the object's mass, and **c** is the speed of light.

Einstein's derivation of this equation involves complex mathematics that we will not delve into here. We can discuss the equation's meaning and significance, however.

The equation implies that matter and energy are interchangeable forms of the same underlying concept. One can convert matter to energy and vice versa. In words, it says that the amount of energy released when you convert matter to energy equals the matter's mass multiplied by the speed of light squared.

What is the role of the speed of light in the equation? The equation uses the speed of light because converting matter to energy creates what scientists call pure energy. Pure energy travels at the speed of light, approximately 186,000 miles per second.

Why is the speed of light squared in the equation? The equation mainly squares the speed of light because energy is exponentially related to speed when converting matter to energy. Squaring the speed of light also keeps the units of measure equivalent on both sides of the equation.

The square of the speed of light is a huge number. This shows that an immense amount of energy is bound up within matter. The practical implication of this is the terrific amount of energy produced by nuclear reactions.

Thus, General Relativity's new explanation of gravity, which better explains actual observations than Newton's law of gravity, implies that we can convert matter and energy to each other using the conversion equation $E=mc^2$.

We can sum up the key ideas of the General Theory of Relativity with four statements:

1. Gravity is the result of objects following paths determined by a curvature of space-time.
2. The presence of gravity affects the passage of time.
3. We can convert matter to energy, and vice versa.
4. The amount of energy released when we convert matter to energy is enormous because of the huge conversion factor, the speed of light squared.

The General Theory of Relativity has enormously significant effects in the real world. To cite two of the most notable examples, it provides a more accurate description of gravity than did Newton's law, and it underlies the process and the tremendous power of nuclear reactions.

D. Limitations of General Relativity

Although General Relativity does a great job of describing how the universe behaves on a large scale, it falls short when it comes to understanding what happens among tiny subatomic particles.

Enter Quantum Mechanics, another major theory in physics.

Quantum Mechanics is like the detective of the subatomic world, explaining how particles and forces interact at that tiny level. It covers a lot of ground that General Relativity doesn't touch.

Now, here's the catch: Quantum Mechanics and General Relativity don't always get along. It's kind of like trying to mix oil and water—they just don't blend together smoothly.

Despite their differences, both theories succeed exceptionally well in their own ways. General Relativity focuses on big things like gravity and the connection between space and time, while Quantum Mechanics zooms in on the behavior of particles at the subatomic level. Together, they paint a clearer picture of how the universe works, even if they sometimes seem to speak in different languages

E. Future Developments

For decades, scientists have regarded reconciling General Relativity with Quantum Mechanics as the most important goal of physics. If we could do this, we would have a complete, unified theory that explains all of the physical aspects of the universe. This could provide deeper insights into space-time, particles, and their interactions.

Although scientists have done much theoretical work, they have not yet found a way to unify these two fundamentally different theories. On one hand, General Relativity breaks down when it tries to explain the behavior of matter and forces at the microscopic scale of subatomic particles. On the other hand, while scientists have been exploring many approaches, no one has yet found a definitive way to explain gravity using Quantum Mechanics.

Experimental tests attempting to accomplish this unification are challenging due to the extreme conditions required to observe such experiments' effects.

If scientists were successful in developing a unified theory, it could have significant practical implications for ordinary people. We must be careful when speculating on what a unified theory might lead to, however. Scientific advances have often led to unexpected results.

Some have suggested that such a theory could lead to the development of technologies that would revolutionize computing, communication, and sensing.

In any case, a theory that unifies General Relativity with Quantum Mechanics could very well reshape our entire understanding of the universe.

F. Conclusion

The Theory of Relativity completely redefines everything we once thought we knew about time, space, gravity, matter, and energy.

The results are both astonishing and terrifying. Scientific progress, including this theory, presents humanity with the dual potential for great advancements and significant harm. Science can only show us how things work and what is possible.

It is our responsibility as humans to grapple with the ethical dimensions of applying this knowledge. Only we, collectively and individually, can decide when, how, and why we harness these discoveries. Our task is to ensure that wisdom and compassion guide how we use new knowledge.