A Brief History of Time Study Guide

A Brief History of Time by Stephen Hawking

Contents

Plot Summary

Stephen W. Hawking writes about the history and present thinking of theoretical physicists in a manner the average person can understand. He begins with the earlier ways people understood the universe and moves to the present day, where many theories exist for specific pieces of the whole picture, but none of the theories cover the universe in its entirety.

Aristotle's thinking that everything is made up of only four elements and absolute position and time characterize the universe leads to Ptolemy's idea of heavenly spheres, both assuming the earth is at the center of the universe. Copernicus contributes the idea that the sun is the center, and Galileo concurs. Later observations with telescopes based on Galileo's early instrument reveal the true nature of the earth and the sun in relation to the universe, which grows much larger than the early conceptions. The earth indeed orbits the sun, but the sun orbits the galaxy, which is full of stars. Additionally, many other galaxies are observed with ever greater clarity. The importance of the earth dimishes with this view. It is not the center of the universe, and in fact occupies an insignificant spot within the whole.

Sir Isaac Newton generates the physics that predicts the movements of heavenly bodies accurately enough, and Albert Einstein brings forth the general theory of relativity, which implies that the universe started with a big bang from a singularity of infinite mass and curvature, a single point with no dimensions. Hawking works with black hole theory, among others, notably the combination of quantum mechanics and general relativity. Where general relativity describes the very large objects in the universe, quantum mechanics describes the very small and includes an uncertainty principle. Hawking suggests through the combination of the two theories that no singularity existed at the beginning of the universe because the universe may have had no beginning.

Physicists continue to seek a complete, unified theory of the universe, although this may not be possible to discover. The driving motivation is the thirst for knowledge, while another human motivation, the discomfort of uncertainty, resists the discovery of what may be taken as the mind of God. The author is fully aware of what scientific discovery means to the world's religions that cling to older models of the universe, and mentions this often. Earlier physicists also had problems with religions, so this is nothing new or anything to fear, as long as the science is reliable and the approach to bringing out the truth is handled gently. Hawking accomplishes this with his friendly tone and humor.

Introduction by Carl Sagan

Introduction by Carl Sagan Summary and Analysis

Carl Sagan writes the Introduction from Cornell University in Ithaca, New York. He begins with the observation that most adults do not concern themselves with understanding how the universe, which includes our planet earth, works. However, children do at a certain point before their curiosity about seemingly unanswerable questions melts away into the concerns of everyday life. Among these questions are: Why is there a universe at all? Why do we remember the past and not the future? What is the smallest piece of matter? Sagan hints that it might be possible for time to flow backwards, where effects happen before causes.

Adults often turn to religious concepts to explain away the fundamental questions of the universe, but these answers only reveal the limits of human understanding. They do not explain in clear terms just how the universe originated, but assume that the universe must have had a beginning. If the universe had a beginning, then it must have an end. All other things we normally experience have beginnings and ends, so the universe must be the same. Physicists of Stephen Hawking's caliber do not make these assumptions because the nature of the universe has been discovered to be more complex, where a beginning and an end are not necessarily true.

The basic questions common to very young children drive two groups of adults—philosophers and scientists. Philosophers try to understand the universe through disciplined logic contained in carefully constructed arguments. Scientists start with observations and mathematics, propose possible explanations, and may at some point land upon a single explanation that always makes sense and works mathematically.

Sagan recalls his witnessing of Stephen Hawking's official entrance into the Royal Society of London in 1974, one of the oldest scholarly organizations in existence. The highly respected physicist is already in a wheelchair due to Lou Gherig's disease, ASL (Amyotrophic Lateral Sclerosis). The disease affects his body, but not his mind. Sagan also mentions Hawking's attempts to understand the mind of God.

"And this makes all the more unexpected the conclusion of the effort, at least so far: a universe with no edge in space, no beginning or end in time, and nothing for a Creator to do" (p. x).

Chapter 1 Our Picture of the Universe

Chapter 1 Our Picture of the Universe Summary and Analysis

The nature of the universe has been looked at in many different ways throughout the ages. The older views may seem ridiculous today, such as the earth being a disk that sits on the back of a giant tortoise, but our present day ways of thinking may someday also seem ridiculous as we learn more. Physicists do not know everything about how the universe works even to this day.

Aristotle of the ancient Greeks (384-322 BC) thinks the earth is stationary, with the moon, sun, planets and stars revolving around it; however, the ancient Greeks are also aware the earth is a sphere. Ptolemy (second century AD) expands the earth-centric model to give fairly accurate predictions of planet positions, and the Christian church adopts this model because it gives room for the existence of heaven and hell outside the universe. Copernicus brings forth the sun-centric idea in 1514, where the earth and planets revolve around the sun. In 1609 Galileo uses his telescope and finds the moons of Jupiter, and Kepler proposes elliptical orbits for the planets. Newton, in 1687, publishes mathematical formulas that predict the movements of heavenly bodies based on his theory of gravity. He also believes the universe to be static (unmoving) and infinite (no center).

Prior to the 20th century, nearly every scientist believes either that the universe has always existed or that it was created at some time in the same state it is today. Some do argue against a static universe. From the religious side, St. Augustine expresses an idea that time was created along with the universe. It does not exist otherwise.

Edwin Hubble observes in 1929 that the universe is expanding, which gives support to the big bang theory. The big bang theory hypothesizes that the universe was at one time very small and infinitely dense, and then exploded outward in a big bang to become the universe we now observe. Physicists have known for some time that the universe is largely empty space, including the atoms that make up matter. A relatively huge distance separates the nucleus of an atom from its electrons. Take away all that empty space and what is left is a very small, compressed spot of, well, something. This is very hard to imagine, but it is what the big bang theory proposes was the state of the universe at its beginning. Perhaps more difficult to imagine is the absence of time, but as Hawking suggests, while the universe was compressed into its super dense spot form, time was of no consequence:

"Under such conditions all the laws of science, and therefore all ability to predict the future, would break down. If there were events earlier than this time, then they could not effect what happens in the present time. Their existence can be ignored because it would have no observational consequences" (pp. 8-9).

The principle is that without science, there can be no prediction, and with no predictive ability, time is meaningless. Hawking moves on to define scientific theory in a simplified manner. A scientific theory is a model of the universe with a set of rules. The mathematics that results from the model must accurately describe observations and reliably predict events within our universe, which goes without saying because all we know is the observable universe. Mystics, psychics, theologians and religious leaders may argue differently, but Hawking is not any of these. He is a theoretical physicist.

An example given of a too simple model is Aristotle's idea that everything is made up of only four elements: earth, air, fire and water. No predictions can be made from this model other than the most basic, such as throwing water on fire will put the fire out, or spread it out in the case of a kitchen grease fire. Conversely, Newton's theory of gravity predicts the movements of celestial bodies accurately enough to be of practical use.

Nothing can be proven, according to Hawking, because all scientific theories must predict the same results forever or be abandoned. Just one different result, assuming the experiment is conducted correctly, disproves the theory—and nobody can know the results of all future experiments or all future observations. What a scientific theory can earn is confidence that the same results will always be obtained, and this is the way it works in the practical world of scientists. New theories are commonly based on older theories. Hawking points out that Einstein based his more accurate theory of gravity on Newton's, which is evidence for the validity of Einstein's theory.

When describing the universe, scientists tend to break the problem up into smaller, more manageable chunks. Hawking thinks this technique might never come up with a universally accurate overall model. He brings up the two primary theories in use today: relativity, which works well for large-scale objects in the universe measured in miles, and quantum mechanics, which works well for very small objects like microelectronic circuits. The two theories contradict each other, and so neither can be correct for all cases within a single universe. Hawking seeks the theory which will be correct for all cases, the complete unified theory, but he has no practical purpose for doing so. The desire for new knowledge motivates his quest for the complete unified theory.

Chapter 2 Space and Time

Chapter 2 Space and Time Summary and Analysis

Galileo and Newton change the Aristotelian approach to science. Galileo actually conducts experiments to test theory, while Aristotle believes everything can be determined through pure thought. Newton uses Galileo's measurements to work out his laws of motion. From these efforts come Newton's laws of how gravity works, and so humanity advances toward a better understanding of the universe.

Aristotle thinks that objects have absolute position within absolute space, but this turns out not to be true. Another of his concepts, shared by Newton, is that time is also absolute. These interpretations of the universe work in a commonsense way while dealing with everyday objects or very large objects like planets, but as objects approach the speed of light, the ideas fall apart.

Light travels at the speed of 186,000 miles per second. The speed of light is the c (constant) in Einstein's relativity formula, E = mc squared (Energy equals mass multiplied by the speed of light times itself). The speed of light is considered a constant because the speed is the same no matter from what position it is observed or how fast the observers are moving. But if the observers' velocity comes close to the speed of light, their mass increases to infinity. This is why nothing can move faster than the speed of light, according to the theory of relativity.

Another implication of the theory of relativity is that time is not absolute:

"We must accept that time is not completely separate from and independent of space, but is combined with it to form an object called space-time" (p. 23).

Within three-dimensional space, a location on the surface of the earth is defined by its longitude, latitude and altitude above or below sea level. Time adds another coordinate, and thus another dimension. The universe becomes four-dimensional.

In a four-dimensional universe, objects always move in straight lines, but due to the influences of mass and energy, light bends and so we see objects moving along curved paths. Hawking uses the surface of the earth and an airplane to explain how this works. The shortest path between two distant cities is a straight line, but because the earth has curvature, the flight path has curvature as well.

If time is relative, then "time should appear to run slower near a massive body like the earth" (p. 32). This is tested in 1962 by mounting two very accurate clocks on a water tower, one at the top and the other at the bottom. The bottom clock runs slower. This principle is very important for a GPS (Global Positioning System), as the calculations must take into consideration how time speeds up for satellites orbiting the earth, while time on the ground runs slower. Otherwise the calculated position will be far off the actual position.

The universe is more dynamic than once thought. Time and space are variables within equations, not fixed constants. The only constant in the universe is the speed of light, according to the theory of relativity, and all this comes together into a view that the universe has a beginning, possibly an end, and is expanding.

Chapter 3 The Expanding Universe

Chapter 3 The Expanding Universe Summary and Analysis

When looking into the sky on a clear night, most of the stars visible to the naked eye are a few hundred light years away. A light year is the distance light travels in an earth year at its constant velocity of 186,000 miles per second—5.88 trillion miles. Our sun is about 8 light minutes away, and the closest star is 4 light years distant. Most of the points of light are stars in our own galaxy, but some are galaxies or clusters of galaxies containing many more stars, and to our eyes the galaxies appear as single points of light.

Edwin Hubble discovers these galaxies in 1924, and by analyzing the light emitting from them, determines that all the galaxies are moving away from the earth, or that is how it seems. The earth is not likely the center of the universe, so the observation that all galaxies moving away must be the same no matter where the observation is made in the universe. In effect, the universe is expanding and looks the same from any point within.

In 1922 Alexander Friedmann makes the assumption that the universe looks the same, but in 1965 Arno Penzias and Robert Wilson accidentally stumble upon the proof of the assumption. They measure microwaves and observe that microwave radiation is constant no matter where they point their instruments and no matter what the position of the earth.

The question then becomes, is the universe expanding in a way that will go on forever or not? If the expansion has enough velocity, it will go on forever. If not, the universe will eventually stop expanding and collapse on itself due to gravity. Hawking compares this to a rocket that does not have enough energy to break out of the earth's gravity. The rocket will fall back to earth, but if it does break the gravity and shoots on out into space, it will continue moving away.

Over the decades between 1920 and 1960, physicists try to explain what is happening. Some avoid a conclusion arising from the idea of an expanding universe, the big bang. Others accept the big bang. In 1965, Roger Penrose brings forth the idea that a star can collapse on itself and become a thing of infinite mass and infinite curvature of space-time, but with zero surface area and zero volume—a black hole. This black hole is also known as a singularity. If black holes exist, then the singularity the led up to the big bang might have existed too, thereby explaining why the universe is expanding.

Hawking embraces Penrose's ideas and develops his Ph.D. thesis around them. He reverses the direction of time in the theorem and realizes that the theorem explains both gravitational collapse into a black hole and the expansion of the universe. In 1970 he and Penrose publish a paper on this subject with the arguments based on Einstein's generally theory of relativity. The paper is well-received, and the big bang theory becomes accepted. But relativity does not explain how a singularity, something that has zero volume and zero surface area, becomes a big bang. Hawking needs to include quantum mechanics, which can provide this explanation.

Chapter 4 The Uncertainty Principle

Chapter 4 The Uncertainty Principle Summary and Analysis

In 1900, Max Plank proposes the idea that electromagnetic radiation, which includes visible light, X rays, gamma rays and other forms of radiation travelling in waves, is emitted in packets called quanta. In 1926, Werner Heisenberg develops the uncertainty principle, where the position and speed of atomic particles cannot be measured without disturbing the position and speed of the particles. In effect, the universe cannot be deterministic, completely predictable, if the present state of the universe cannot be determined accurately. Heisenberg and Erwin Shrodinger then bring out a reformulation of standard mechanics that they call quantum mechanics.

In quantum mechanics, predictions consist of a number of possibilities. Each possibility has a probability of occurring for any given event, and so chance plays a part in the universe. Einstein's objection is often quoted: "God does not play dice." However, quantum mechanics explains the behavior of atomic particles well enough that the development of microelectronics, and thus the very small computers in use today, depend upon the theory.

A consequence of quantum mechanics is that sometimes waves behave like particles and particles like waves. This can be demonstrated through simple experiments with light and electrons which reveal how both waves and particles behave the same way. Yet the wave-like interference of atomic particles has led to a better understanding of the atom.

At one time the atom was thought of as being similar to the solar system, but now the idea is less definite due to the uncertainty of the position and velocities of particles. This has the most impact on the way electrons are envisioned, especially in complex atoms and even more complex molecules. Theoretically, quantum mechanics can explain and predict everything in the universe, but the math becomes too lengthy and at the time of Hawking's book publication cannot be done, even with computers.

The theory of quantum mechanics better describes the small world of atoms. The general theory of relativity best describes very large objects in space, as the gravity force is relatively weak. However, with black holes and the big bang, gravity is very strong, so quantum mechanics should better describe these singularities. Somehow these two theories need to be unified in order to accurately describe both the very small and the very large.

Chapter 5 Elementary Particles and the Forces of Nature

Chapter 5 Elementary Particles and the Forces of Nature Summary and Analysis

People before the 20th century maintained relatively simple views of the universe. Today physicists have continually discovered the higher and higher complexities, where the elements number far more than four, and atoms are made of many kinds of particles.

Einstein observes Brownian motion—the movement of dust particles suspended in water—and proposes that the movement of atoms causes the Brownian motion. He publishes the idea in a 1905 paper. In 1911, Ernest Rutherford demonstrates that an atom is made up of electrons orbiting a nucleus made up of protons, and in 1932, James Chadwick discoveres the neutron. The model of the atom consisting of electrons, protons and neutrons persists until the 1960s, when Murray Gell-Mann determines that atomic particles are make up of sub-atomic particles he calls quarks.

Three quarks make up either a proton or neutron. In reality quarks have no color, as they are very much smaller than the smallest wavelength of light and thereby cannot reflect color, but physicists think of them as coming in three colors: red, green and blue. Both the proton and neutron are made up of three quarks, one of each color. Quarks also come in at six varieties: up, down, strange, charmed, bottom and top. A proton has two up quarks and one down quark; a neutron has two down quarks and one up quark. Physicists can produce the other varieties of quarks in experiments, but they do not exist for long and decay into regular protons and neutrons.

Particle energy is measured in electron volts, the energy that an electron gains from an electrical field of one volt. The way physicists determine that the sub-atomic particles exist is first through mathematical theory, then by shooting atomic particles at each other in a large, circular tube known as a particle accelerator. Here the shooting particles have millions of electron volts, and the high energy collisions break the atomic particles into their sub-atomic particles.

Quantum physics describes a particular quality of particles—that everything in the universe behaves like both a wave and a particle, and this suggests that everything can be described in terms of particles. One of these terms is spin, or what the particle looks like from different directions. A particle with spin 0 is like a dot, identical in all directions. A particle with a spin of 1 is like an arrow and does look different from different directions, such as how the central ace symbol on the Ace of Spades appears differently as the card is spun around. The Queen of Hearts looks differently until it is spun only half way around, and this quality is spin 2. Spin ½ is odd in that it takes two full spins before it looks the same, an idea that no card in the deck can illustrate. The importance of spin ½ is that this is the kind of particle that makes up all the matter in the universe. Spins 0, 1 and 2 have to do with the forces between matter particles.

Matter particles follow the exclusion principle, an important concept that Wolfgang Pauli brings to physics in 1925. The exclusion principle simply states that two matter particles cannot be in the same place at the same velocity at the same time. If two cars try to defy the exclusion principle on the freeway, the result is a bad accident. So, matter particles can collide with each other, just as cars can, and also have the same limitation on where they can be. In 1928, Paul Dirac comes up with the math to explain matter particles, and the math brings with it another idea: antimatter. In 1932, the antimatter particle of the electron, the positron, is discovered in physical reality.

The mathematics of particle physics includes virtual particles, those that have no mass and therefore can never be detected in a particle accelerator. However, the virtual particles are manifested by their effects on matter particles. These virtual particles carry force and have spins of 0, 1 and 2. Virtual particles also disobey the exclusion principle exclusively. An unlimited number of virtual particles can be exchanged between matter particles, and since the virtual particles do not have mass, they can crowd into the same place at the same velocity at the same time. The virtualization of particles may be a magic trick in particle physics, but it keeps the understanding on the particle level rather than resorting to some other explanation of force.

Force-carrying virtual particles are categorized into four groups: gravitons, photons, bosons, and gluons. Hawking points out that the grouping may be arbitrary—force-carrying particles could be the same particle at different states.

Gravitons (spin 2) carry gravitational force, the weakest of the four forces but also universal among matter particles. Gravity influences all matter particles. Gravity acts over long distances and is always attractive.

Photons (spin 1) carry electromagnetic force, which is much stronger across short distances than gravity. This type of virtual particle is not the same as a photon of light, which is a matter particle. Electromagnetic force is either positive or negative, with opposites attracting and the same charge repelling. The electromagnetic attraction between a proton and an electron keeps the electron orbiting the nucleus of an atom.

Bosons (spin 1) carry the weak nuclear force, while gluons (spin 1) carry the strong nuclear force. The weak nuclear force causes radioactivity and has an effect on all matter particles. The strong nuclear force holds the quarks together in protons and neutrons.

GUTs (Grand Unification Theories) try to bring the various virtual particles together as one entity, but the theories do not include gravity. As such, they cannot unify general relativity and quantum mechanics, only photons, bosons and gluons. The neglect of gravity is also significant in that the force does have a major impact on the universe and may be able to overcome the other forces. This is how a star collapses into a black hole, according to the general theory of relativity.

Chapter 6 Black Holes

Chapter 6 Black Holes Summary and Analysis

A black hole is the result of a large star using up all of its hydrogen fuel and collapsing inward from the huge force of gravity. The gravity force is so strong that nothing can escape, including light. The point at which nothing can escape the gravity is called the event horizon. Conversely, anything passing the event horizon becomes sucked into the black hole and is torn apart by the strong gravity.

Central to the idea of a black hole is the theory of light. Newtonian theory proposes that light is made of particles, and quantum mechanics verifies that light is truly a particle, but also behaves as a wave. In fact all matter particles behave like waves. This is important because gravity only acts upon matter particles, of which light is made up—photons.

Not all stars can become black holes. The Chandrasekhar limit, determined by Subrahmanyan Chandrasekhar in the late 1920s, is the smallest mass a star can have in order for it to produce a black hole. This size is about one and a half times the mass of the sun. Suns below the limit can produce white dwarfs and neutron stars, both bodies of tremendous mass. The neutron stars, also called pulsars, out-mass the white dwarfs. Black holes out-mass them all and are similar to the singularity that existed before the big bang.

Werner Israel calculates that non-spinning black holes are perfectly spherical in 1967. In 1970, Brandon Carter takes the first steps to describe spinning black holes. They bulge in the middle due to the spin, which all spinning celestial bodies do. But all this so far is mathematical theory. The observed evidence for black holes consists of their affects, not directly seeing them. They are, after all, black against a black background.

A fairly certain example of a black hole is the star system Cygnus X-1. It consists of a visible star orbiting a black hole, and the reason scientists think so is that a white dwarf or pulsar could not have enough gravitational pull to create the effect. The only thing with more gravity is a black hole. The way our galaxy spins and jets of materials are other observed indications that black holes exist.

Small black holes might have existed during the early stages of the universe. This is conjecture, as is the creation of a black hole by the explosion of a very large hydrogen bomb. We would not want to test this idea of creating a little black hole, as it would destroy the entire world in a very short amount of time. Nobody would be left to earn a Nobel prize in physics, and so the effort is pointless.

Chapter 7 Black Holes Ain't So Black

Chapter 7 Black Holes Ain't So Black Summary and Analysis

While it is true that a black hole has extremely powerful gravity that disallows any particles to escape from its influence, the event horizon does, theoretically, allow for a certain amount of radiation. This thinking takes into account the behavior of matter particles and virtual particles as they fall into the event horizon. Some of the particles match up with their anti-particles, some cause the emission of other particles.

An implication of this possibility for radiation is that black holes might be detected by observing the low-level radiation. Gamma ray detection is currently done on a regular basis, and some researchers have attempted to find black hole gamma radiation, but so far the attempts have not been successful. The reason physicists want to detect black holes is that finding them in concentrations around our galaxy would explain certain gravitational influences that cannot be accounted for by the known mass of the universe. Something else must be out there that we cannot see—dark or black matter.

That something else might be black holes left over from the early period of the big bang. The speculation is that these black holes have clumped around galaxies due to gravitational pulls, rather than being distributed more uniformly throughout the universe. With an estimated 300 black holes per cubic light year of space, possibly clumped around our galaxy, one of them may someday be found via its gamma radiation.

Chapter 8 The Origin and Fate of the Universe

Chapter 8 The Origin and Fate of the Universe Summary and Analysis

If only Einstein's general theory of relativity is used, the universe must have a beginning in the big bang and an end either in a big crunch back to a singularity or into many black hole singularities. However, if quantum mechanics is used—especially the uncertainty principle which states that the whereabouts of a particle can never be determined, only the probability of its whereabouts—then several mysteries of the observed universe are explained and a startling conclusion results: the universe has always existed and always will, and so there is no need for a creator God.

Hawking points out that mathematics is only useful for describing what we observe in the known universe. Regarding the origination of the universe, the mathematical problem which exists is our not having observed the origination itself, so the math has to run backwards in time. Real time is described in math through real (rational) numbers, and so is not useful for the math needed to infer what the universe was like shortly after the big bang. Imaginary numbers, which are bona fide math concepts, can be used to run time backwards.

Before Hawking and his associates develop the math that incorporates quantum mechanics, the universe is thought to have started very hot and then cooled to its present state. This goes along with the idea of an expanding universe, and taken together, the theories explain much of why the universe is the way it is. However, this leaves four questions unanswered:

What caused the early universe to be extremely hot?

Why is the universe consistently uniform from the grand vision of it?

Why did the universe not collapse back on itself shortly after the big bang?

Why do stars and galaxies exist, the local irregularities within the grand regularity?

"'We see the universe the way it is because we exist'" (p. 124). This quote is a simple statement of the anthropic principle. A weak form of the anthropic principle holds that intelligent beings will see the universe in a certain way, but will not see anything outside of the cosmic neighborhood. A strong form holds that the universe has to be the way it is, otherwise intelligent beings would not exist to observe it. The strong anthropic principle also implies that many other kinds of universes can exist, but only the kinds that support intelligent beings can ever be observed. Hawking finds these ideas not useful in that they introduce unnecessary complexities.

Hawking works to find a fairly simple combination of the general theory of relativity and quantum mechanics to describe how the universe works. The complete unification theory has not been fully worked out, but what Hawking has so far uses Euclidean space-time to reach the conclusion that the universe is finite in extent but has no edge, similar to the surface of a sphere. By this model, the universe needs no initial singularity or big bang. Black holes release their matter back into space and eventually evaporate. Therefore, the universe was never extremely hot, could not have collapsed back on itself, has always been uniform on a grand scale, and has always had stars and galaxies. There was no beginning and there cannot be an end—the idea of a creator God becomes meaningless. Hawking is aware that this model of the universe does not have any fans in Vatican City.

Chapter 9 The Arrow of Time

Chapter 9 The Arrow of Time Summary and Analysis

With the attempt to unify quantum gravity with general relativity, the use of imaginary numbers leads to imaginary time, or time that can easily go forward into the future like real time, or backwards into the past. However, this also violates the second law of thermodynamics which states in any closed system, disorder always increases over time. The amount of disorder in a system is called its entropy. Therefore, movement back through time is not possible without violating the second law of thermodynamics.

Another vector of time is human memory. We remember the past, not the future, and the direction of the psychological arrow coincides with the direction of the thermodynamic arrow. However, a cosmological arrow of time involves the expansion phase of the universe and the contraction phase. Hawking first thinks that time might indeed run backward in the contraction phase. This indicates that intelligent life is only possible during the expansion phase of the universe. If time runs backwards during the contraction phase, life as we know it could not develop because the second law of thermodynamics, something that allows for metabolism, would reverse too. The closed systems would lose entropy and gain order.

A colleague of Hawking's points out that time does not necessarily run backward during the contraction phase, and one of his students develops a more complex model that shows the thermodynamic arrow will not reverse during the contraction phase. Hawking admits to his mistake, but allows that when the universe has lost all order, life will be impossible. He concludes that life is only possible during the expansion phase of the universe because there will be no strong thermodynamic arrow of time during the contraction phase.

Chapter 10 The Unification of Physics

Chapter 10 The Unification of Physics Summary and Analysis

Physicists are good at solving small problems regarding the nature of the universe, but nobody has come up with a single theory that explains everything or predicts reliably in all cases. This is why so many theories have been developed and why they sometimes contradict each other in astonishing ways. From one viewpoint, the universe must have had a beginning and will likely have an end. From another, the universe may have always existed and always will. Black holes may be completely black or there might be radiation from the event horizon. On top of this all, quantum mechanics introduces the uncertainty principle. We may never be able to predict everything reliably as a consequence.

Hawking brings out three possibilities: Someday physicists will discover a complete unified theory; no complete unified theory is possible, only an infinite number of smaller, more focused theories; no theory of the universe is possible at all—events happen randomly and for no purpose.

Regarding the third possibility, Hawking argues that randomness must exist to a certain degree due to the uncertainty principle, but that a level of prediction can be made regardless, albeit the predictive power is limited. The second possibility is what physicists have experienced so far, but that does not negate the first possibility. Physicists still seek out a complete unified theory.

A fairly recent attempt at finding the complete unified theory is string theory. Rather than particles being the very basic building blocks of matter and energy, string theory proposes that strings of vibrating energy are the basic building blocks. One of the striking things that comes out of this theory is the existence of more than one time dimension and three special dimensions—the four dimensions of our familiar world. The theory implies that many other dimensions exist, but are too subtle for humans to detect. Hawking points out several problems with string theory, but he acknowledges that the idea is still too new to fully abandon.

If the complete unified theory is ever discovered, the impact on human knowledge will be significant. A major area of intellectual inquiry will have come to an end, and the insights this brings will be taught as established human knowledge. Meanwhile, the search goes on. Hawking speculates that the search may be over by the end of the 20th century, a speculation that has turned out to be untrue. However, who knows what breakthroughs are happening but have not yet been published for peer review? Hawking also points out that the discovery of the complete unified theory would only be the first step toward "a complete understanding of the events around us, and of our own existence" (p. 169).

Chapter 11 Conclusion

Chapter 11 Conclusion Summary and Analysis

Stephen Hawking recaps the major points that he makes in earlier chapters. People are naturally curious about the universe and why we are here, why the universe bothers to exist. Some may be satisfied with an idea like a huge turtle holding up a disk-shaped world, but that idea does not explain what we observe—nobody falls over the edge of the world, which is, in truth, spherical. Theoretical physicists seek better explanations than old mythology.

The early ideas that the universe is deterministic fall apart with the uncertainty principle of quantum mechanics. The general theory of relativity supports the idea of a beginning to the universe, the expansion of the universe, and its eventual collapse back into a singularity or a scattering of black holes. Combining the two theories makes an entirely different overview, one that has no singularities, beginning or end. This view of the universe has no boundaries either and a few more dimensions. The newest idea at the time of Hawking's writing is string theory, which expands the notion of more dimensions, but we cannot detect them.

If science does discover a complete theory of the universe, then humans will have come to "know the mind of God" (p. 175). However, the question of why the universe exists at all remains unanswered. Addressing the question why was at one time the job of philosophers, but now science moves too quickly for philosophers to keep up.

Another way to put this is that science can only address the question of how. Mathematics is the language of describing how things work in the universe, and good mathematics predicts what will happen given any set of circumstances, at least most of the time. Our scientific ability to predict has a few holes in it, but it has worked well enough to travel in space and build amazing technologies. Gravity works, whether through a particle or a string. That detail—particle or string— may not be important as people address the question of why.

Physics may someday describe how God's mind works. Why God's mind works the way it does will remain one of the great mysteries.

Albert Einstein

Albert Einstein Summary and Analysis

Hawking often refers to Einstein's general theory of relativity and the famous equation that energy equals mass times the speed of light squared. He brings out details of Einstein's life that are not commonly known.

For example, Einstein becomes a pacifist after he witnesses the tremendous waste of human life during World War I. He demonstrates against the war and encourages his fellow native Germans to resist conscription into the army. He advocates peaceful coexistence after the war and, being of Jewish descent, joins the Zionist movement. Later, when the Nazis take over Germany, Einstein decides to stay in the United States rather than returning to his homeland, even though this means losing all his assets to the German government.

The German people seem not to care about the loss of Einstein, and ironically he encourages the United States to research and develop the atomic bomb even though he is a pacifist. Offsetting this, he also pushes for international control of nuclear weapons, as he understands the full consequences of nuclear war.

In 1952, he is asked to be the president of Israel, but refuses. Although half of his life has been centered around politics and the other half around physics, Einstein prefers the permanence of a good mathematical formula over the fleeting nature of politics.

Galileo Galilei

Galileo Galilei Summary and Analysis

The author considers Galileo the founder of modern physics. This founding comes with a price—the Roman Catholic Church does not like the idea that science might contradict the Bible.

Galileo believes, as Copernicus, that the planets orbit the sun, and he writes to this effect. The Church sees this weakening of doctrine as a direct weakening of the Church in its fight against Protestantism and commands Galileo to stop writing about Copernican theory, which he does. Later, when one of Galileo's friends becomes pope, Galileo is allowed to write a book about both Aristotelian and Copernican theories as long as it passes the Church censors. The book is published in 1632, and later the pope wishes that it had not been. The pope orders Galileo to the Inquisition, where he is sentenced to house arrest for the rest of his life.

Galileo uses his house-arrest time to write another forbidden work. It is smuggled out of Italy to Holland, where it is published under the title Two New Sciences in 1638, and thereby Galileo becomes the founder of modern physics.

Isaac Newton

Isaac Newton Summary and Analysis

If Einstein is the social conscious of physics and Galileo its underground proponent, Isaac Newton is the pugilist of physics. He fights continually while involved with academia, physics and his ownership of calculus, the underlying math of modern physics. He has an uncanny ability to gain positions of authority over his enemies, then attempts to punish them with what might be considered glee. Newton has a bad habit of writing, under the names of his friends, in support of his own articles and criticizing others. His friends do not go unrewarded. Newton appoints them to a committee, supposedly impartial, to investigate the claims of his worst enemy.

Newton's authoritarian side finds a comfortable place as Warden of the Royal Mint. In this position he can prosecute counterfeiters to his heart's delight, even to the point of sending them to the gallows.

Regardless of his character flaws, Newton does publish perhaps the most influential book in physics: Principia Mathematica.

Characters

Stephen Hawking

Hawking is the author of the book and an esteemed theoretical physicist. As such, most of the book is about his thinking based on the theories of others and theories that he has developed. His personal life comes through a bit when he mentions his disability, but more importantly he adds passages about his professional life, which includes being a consultant to the Vatican regarding the nature of the universe and giving lectures around the globe.

Black holes, the results of collapsing stars, occupy his attention, along with trying to formulate a complete unified theory of the universe. Black holes involve singularities that have infinite mass and curvature. A common feature is the event horizon, a point where nothing can escape the black hole, so if something does cross the event horizon, it can never return. Hawking radiation is named after the author because of his work regarding how some radiation may be emitted from the event horizon. An ironic part of his search for a complete unified theory is that one view eliminates the initial singularity of the universe and implies that black holes return their matter to the universe.

Hawking seems little upset that one part of his work might contradict another. The point is to discover new knowledge, not to be right all the time. One passage in the book expresses his ease of admitting being wrong, as opposed to other physicists who try to avoid such an admission. Hawking is an approachable professor and scientist.

Albert Einstein

The author refers to Einstein often and his famous equation, energy equals mass times the speed of light squared. Einstein contributes much to physics, but his general theory of relativity carries the most importance for the author. This theory leads to the idea of black holes developing from stars that have consumed all their nuclear fuel (hydrogen). If a star has a mass one and one half times that of the sun, the gravity of the star overcomes all other forces and it shrinks down to a singularity, a black hole.

Another implication of Einstein's relativity theory is that time runs slower while an observer is closer to a large mass than when farther away. This phenomenon has been demonstrated through experiments and is incorporated into GPS technology.

Of importance to the origination of the universe, the general theory of relativity enables the theory of the big bang. The universe starts from an infinitely massive and curved point with no dimensions, the first singularity.

Hawking gives Einstein a few pages toward the end of the book. Einstein is as political as he is scientific. He is asked to be the president of Israel in 1952. His time in pre-Nazi Germany is full of resentment from others for his passive political stance. When the

Nazis take over Germany, Einstein stays in the United States and loses all his assets in Germany. He urges the United States to develop nuclear weapons, but also wants them to be under international control.

Max Planck

Max Planck introduces the idea that light is emitted in packets that he calls quanta. This idea leads to quantum mechanics, a theory that explains how very small particles, such as electrons, behave. A critically important part of the theory is the uncertainty principle, where the position and velocity of any given particle could be a number of possibilities, and that probability plays a part in how the universe works. Hawking combines quantum mechanics with relativity and proposes a very different view for the origination of the universe: the universe may have always existed, and may do so forever.

A significant irony runs through Hawking's use of Planck's and other's contributions to quantum mechanics. The physics theory that arises contradicts black holes, one of Hawking's primary studies and sources of fame. But, either the universe starts with a big bang or it never starts because it has always been. Hawking does not seem to care which way it goes, just that it all makes mathematical sense.

What starts with Planck ends with Hawking's conclusion at the end of his theoretical treatise. The author proposes that someday humanity may understand the mind of God, and the uncertainty principle may be one of the most important steps in that direction.

Sir Isaac Newton

Newton formulates several laws of physics that still hold to this day. The law of gravity is the most famous, and the tale about Newton coming up with the idea from an apple falling may have some truth to it. Another important law is the second law of thermodynamics. This introduces the concept of entropy in any closed system, where movement is from the organized to the disorganized. General relativity and quantum gravity make Newton's law of gravity less important while Hawking attempts to unify physics, yet the author finds the second law of thermodynamics useful for sifting through other theories.

Aristotle

Aristotle is the first purely theoretic scientist. He believes that all knowledge is available through thinking. Hawking uses Aristotle's thinking to describe how the ancients viewed the world and the universe. The views have since been discredited, but they started millennia ago and were common world views for most of that time.

Ptolemy

Ptolemy's view of the universe proposes spheres with the sun in the middle. Each heavenly body has its own sphere, while an outer sphere holds the fixed stars. The Roman Catholic church supported this view, as it leaves room for heaven and hell outside the sphere of the fixed stars.

Nicholas Copernicus

Copernicus first proposes that the earth orbits the sun, not the other way around. Possibly out of fear that his ideas will cause the church to brand him a heretic, Copernicus circulates his ideas anonymously. Nobody takes him seriously.

Galileo Galilei

Galileo, famous for his experiments with gravity, also believes the earth orbits the sun. People do take him seriously, but he runs into trouble with the Roman Catholic Church. The Church sentences Galileo to permanent house arrest, but he writes a book which is smuggled out of Italy and published in Holland. The book becomes the foundation of modern physics.

Edwin Hubble

Hubble discovers the first galaxies outside our own. He also figures out a way to determine their distances using light spectrum shift. This leads to his observation that all the galaxies are moving away from each other—the universe is expanding. Hawking takes this observation and argues how the expansion may one day stop, after which the universe may contract back to one or a number of singularities.

Murray Gell-Mann

Gell-Mann is the physicist who discoveres that electrons, protons and neutrons are made up of smaller particles he calls quarks. He wins the Nobel prize in 1969 due to his work with quarks. Hawking uses Gell-Mann's discovery as a springboard into a discussion of sub-atomic particles.

Objects/Places

CERN

CERN is the world's largest particle physics laboratory. It is home to the largest particle accelerator, an underground circular device with a diameter of two kilometers.

Particles

Particles are what particle physicists study. A molecule is a particle of a compound, an atom a particle of an element. Electrons, protons and neutrons make up atoms, and quarks make up the components of an atom. Virtual particles carry forces, such as gravity and atomic forces.

The Universe

The universe is what physicists study on both the very large and the very small scales. The concept of the size of the universe has improved over the past few centuries. It is much larger than previously envisioned. The complexity of its structure is also better understood, but not completely.

The Solar System

The solar system is home to earth. It consists of planets that orbit the sun according to the laws of gravity.

Strings

Strings are linear or circular bits of vibrating energy which might be the fundamental building blocks of the universe, according to string theory.

Mathematics

Mathematics is the language of science, with calculus being an important branch for physics. This is why engineering students are required to learn calculus.

Theory

Theory in physics consists of mathematical equations. The math should predict actual events in the universe, or else it is not worthwhile. No single theory covers everything yet, but some work well enough to be practical for specific situations.

Dimension

A dimension is a property of a universe. Our universe has four dimensions: height, width and depth (or longitude, latitude and elevation; or x, y and z coordinates), and time. Some theories in physics propose other dimensions as well.

Time

Time is one of the dimensions of our universe. If big bang theory is right, time begins shortly after the big bang when the dimension becomes significant. According to the general theory of relativity, time is relative to position in regards to a massive body. This characteristic of time is incorporated into GPS systems.

Big Bang

The big bang, an idea that comes out of the general theory of relativity, is the beginning singularity, or a point that is infinitely massive and has infinite curvature. Something causes the singularity to expand outward, thus creating the universe.

Singularity

A singularity is a point of infinite mass and infinite curvature. The singularity before the big bang has these characteristics, as do black holes.

Black Hole

A black hole is a star of a certain mass that burns away all its nuclear fusion fuel and collapses on itself due to very strong gravitational force. The result is a singularity.

Uncertainty Principle

The uncertainty principle of quantum mechanics states that the position and velocity of any particle at any time is not absolutely predictable. This gives rise to ideas that the universe has no boundaries and may have always existed.

Anthropic Principle

The anthropic principle involves a human looking at the universe and asserting that it must be the way it is, otherwise no humans would exist to look at the universe.

Themes

Uncertainty

The human race's search for knowledge begins with uncertainty. All kinds of superstitions arise to explain what cannot at the time be explained. A hunger exists for a clear, concise explanation, whether it be gods with human personalities or mathematical formulas that explain everything observed. Uncertainty is uncomfortable for several reasons.

On a personal level, the discomfort seems to be an instinct. Certain physicists do not want to believe their own studies due to discomfort. On a political level, the effects of power come into play. At various point in history, the Roman Catholic Church has wanted science to accord with their own Biblical explanations in order to retain power, especially when Protestantism threatens to take away church membership. During these times, physicists could be suppressed, as in Galileo's situation.

However, the clear practicality of quantum mechanics requires belief in the uncertainty principle. Entire corporate empires depend upon the truth of the uncertainly principle, as do militaries, television viewers, and literally everyone who uses anything electronic in the world. Uncertainty is, from the quantum mechanics view, an established fact of life.

The irony of this is that the uncertainty principle may one day change dramatically the idea of God. If God has not created the universe because it has always existed, and if God cannot be shown to intervene in the universe, then what is God? Hawking does not go so far as to propose that God does not exist. He only demonstrates that physics has no need for God to explain how the universe works.

Thirst for Knowledge

The thirst for knowledge is closely related to the discomfort of uncertainty. Stephen Hawking has a natural thirst for knowledge about the nature of the universe. He seems less interested in the nature of God, or thinks that nature is simply irrelevant when it comes to physics. Yet he mentions God regularly, most notably while addressing possibilities which go against Roman Catholic Church doctrine. Fear of the Church does not extinguish his thirst for knowledge, nor does it stop Galileo from laying the foundation of modern physics. The author feels a strong association with Galileo, possibly hinting at some sort of spiritual connection that physics can never describe.

Hawking mentions many people in the book, people who discover new things or attempt different approaches to a problem. If the discovery or attempt brings on the wrath of politicians, church leaders or the general public, the discoverers gain a certain level of heroism. They tell the truth as they understand it and take whatever punishment follows. The thirst for knowledge sometimes requires the courage of a lion, or perhaps that of a fool, or perhaps that of pure faith. Newton was the lion, Galileo the fool, and Einstein the childlike faithful physicist. At the end of the conflicts, truth should, and so far has, won out.

But what can be known if all scientific theories cannot be proven? If everything is uncertain, what can be known for certain? Hawking appeals to good sense. If something has happened all the time in the past, then it is within reasonable certainty that it will happen all the time in the future. However, something different might happen, and when it does, it becomes time to rethink the problem, or in the case of physics, the math. We can be certain that falling off a cliff into rocks will either kill or maim, no doubt about it. But if something odd happens in a particle accelerator, physicists must rethink. This might extend into rethinking the whole nature of the universe. For Hawking, the thirst for knowledge overpowers the need for certainty.

Persistance

The discovery of a good overall theory of the universe may not be possible, yet Hawking and many others still persist in chasing that knowledge. The author has hope that such a theory will be discovered sometime soon, but so far this has not happened, or if it has, the theory is still too far down in the cauldron of theoretical physics to have percolated up to general scientific knowledge. Nobody can predict everything that happens with one theory, only bits and pieces here and there for specific purposes.

Sometimes an informed guess must be used or a trick played with the mathematics which has outrageous implications if the equations are worked all the way through. Some of the equations are simply too cumbersome for even computers to complete. Yet the physicist keep on trying, keep on eliminating ridiculous infinities, keep on balancing string theory equations. Just because the going is rough now does not mean the desired destination cannot be found—this only means that the going is rough. Yet humans have their limitations. If something looks too difficult, the natural tendency is to abandon the quest and go on to something else.

Persistence has a life bigger than any individual or any group of people. One generation of physicists might abandon something like string theory, but then another generation comes along and picks up the theory with fresh ideas. This may be the way a complete unified theory of the universe finally comes into being, and humanity may come to an understanding of God's mind. The author does not mention it, but understanding God's mind is only one part. Understanding the human heart is another and outside the realm of physics. Both thirsts for knowledge involve uncertainty and persistence, and both may be beyond human understanding. Yet people keep on trying because, as with Stephen Hawking, the thirst for knowledge overpowers the need for certainty.

Style

Perspective

Stephen W. Hawking (January 8, 1942 -) is a world-famous theoretical physicist. He holds a top professorship at the University of Cambridge and a fellowship with Gonville and Caius College. He is most noted for his work with quantum gravity and black holes, suggesting that black holes emit radiation at their event horizons. This theoretical phenomenon is now called Hawking radiation.

Early on in his career, Hawking contracted ALS (amyotrophic lateral sclerosis—Lou Gehrig's disease), an illness that greatly reduces the ability to move and talk, but not to think. Nevertheless, he lectures for his students and gives talks throughout the world. His views are important enough that the Vatican listens to his counsel. Whether the Catholic Church is willing to modify its doctrine to drop a creationist God is another matter. Hawking's blending of quantum mechanics with the general theory of relativity, although not a perfect overall theory of the universe, does suggest that the universe has always existed, and so no creator is necessary.

The author's loyalty to mathematical reasoning and his ability to explain the implications of various theories set him apart from others who speak in math terms unintelligible to the average person, who doggishly defend their mistakes, and who may support an undeserving theory for ulterior motives. Hawking freely uses humor in both his writing and lectures, which brings the man closer to the reader and audience.

A Brief History of Time is written for the masses, for liberal arts students, for politicians and for religious leaders. Some beliefs may not be supported by the evidence of the physical world. Other beliefs may be wrong-headed in their implications regarding human survival, such as nuclear war. Writers of science fiction should understand that some science is outdated, thus reducing the credibility of their fiction. The general population should have an understanding of their world and universe, if for no other reason than to appreciate microelectronics. Hawking makes this all possible through the book, which is a huge best-seller.

Tone

Hawking's editor warns him not to use very many mathematical equations in his work, as each equation presented cuts readership in half. The author accommodates this request and only gives one equation, Einstein's energy equals mass times the speed of light squared. The author's use of prose, to describe how theories work and what they mean regarding the nature of the universe, generates a conversational style sprinkled with humor and analogy. He occasionally takes side trips from the main idea, which he usually builds to and brings home toward the end of each chapter. The chapters flow from one to another, completing a very large scope within a relatively short book, as a brief history should be.

The lack of pedantry and condescension brings the subject matter closer to the non-mathematician. Some prior knowledge is assumed, but this is easily researched by a simple dictionary lookup or Web search. Most readers with only high school physics will be able to pick up the few unexplained ideas. An apparent weak area, the discussion of string theory, is due to the timeframe in which Hawking writes. The theory is not well developed in the late 1980s.

Most editors frown on the use of the exclamation point, but the editor of this book lets them pass. This is a part of Hawking's personality, his enthusiasm about how the universe works and how it might work. A slang term for the exclamation point is the astonisher, and the author is truly astonished that physics is not so simple, that black holes might shine a little on some level, and that infinitesimal strings of energy might better explain reality. Exclamation points also lend a sense of hominess to the prose, as if it is written in letter form to a friend.

Structure

A Brief History of Time follows a logical framework of chapters leading to conclusion. Personalities who shaped classical physics and modern physics enter into the narrative, and three of them receive special attention at the end: Albert Einstein, Galileo Galilei and Isaac Newton. The logical progression of the chapters keeps the reader from losing place and falling behind, although some sections may require multiple readings. This is not surprising in a compressed format and reflects that what is obvious to an expert in a field may not be so to a layperson. Usually a full reading of the chapter helps give perspective on where Hawking is going in his thought process.

Those who have experienced a Hawking lecture, perhaps in a video or in person, will recognize his thinking style. He approaches a subject as if on vacation—side trips to visit something along the road are common. However, the visit is always interesting and related to the main idea in some manner. Often his personal opinion about the likeliness of a theory being true goes beyond mathematics to the practical. The two-dimensional dog is an example. Certainly a dog-like creature is impossible in two dimensions, and that observation appeals to common wisdom, but this does not mean that two-dimensional creatures are impossible. They are simply improbable from our point of view, living in four dimensions. The same can be said about the many dimensions suggested by string theory.

Hawking often revisits ideas along his thinking trip and expands on them, fleshing out what had been served in skeletal form. Apparent contradictions fall away as the reader comes to understand that different theories give rise to different possibilities. The universe can be thought of in several ways. Physics has no one answer to it all, and revisiting different theories helps to keep this perspective. To use another metaphor, Hawking moulds the reader's concepts of the universe, but desires that they should remain elastic upon finishing the book, not set in bronze. The framework of the book contains this elasticity, clay within a cage.

An unfortunate feature of a book is the inability to raise one's hand in class and ask a question. The sometimes rambling, sometimes elastic style that Hawking uses within a strong framework begs for questions all along the way, some of which he anticipates. A frequently-asked-question appendix could be helpful, but perhaps the idea is to leave the reader with curiosity strong enough to continue learning about physics and the nature of the universe in which we live. Toward this end, the structure performs admirably.

Quotes

"A well-known scientist (some say it was Bertrand Russell) once gave a public lecture on astronomy. He described how the earth orbits around the sun and how the sun, in turn, orbits around the center of a vast collection of starts called our galaxy. At the end of the lecture, a little old lady at the back of the room got up and said: 'What you have told us is rubbish. The world is really a flat plate supported on the back of a giant tortoise.' The scientist gave a superior smile before replying, 'What is the tortoise standing on?' 'You're very clever, young man, very clever,' said the old lady. 'But it's turtles all the way down!'" (p. 1).

"Ptolemy's model provided a reasonable, accurate system for predicting the positions of heavenly bodies in the sky. . . . It was adopted by the Christian church as the picture of the universe that was in accordance with Scripture, for it had the great advantage that it left lots of room outside the sphere of fixed stars for heaven and hell" (p. 3).

"As we shall see, the concept of time has no meaning before the beginning of the universe. This was first pointed out by St. Augustine. When asked: What did God do before he created the universe? Augustine didn't reply: He was preparing Hell for people who asked such questions. Instead, he said that time was a property of the universe that God created, and that time did not exist before the beginning of the universe" (p. 8).

"Newton was very worried by this lack of absolute position, or absolute space, as it was called, because it did not accord with his idea of an absolute God. In fact, he refused to accept lack of absolute space, even though it was implied by his laws" (p. 18).

"We have seen in this chapter [3] how, in less than half a century, man's view of the universe, formed over millennia, has been transformed" (p. 50).

"Einstein's general theory of relativity seems to govern the large-scale structure of the universe. It is what is called classical theory; that is, it does not take account of the uncertainty principle of quantum mechanics, as it should for consistency with other theories" (pp. 60-61).

"The event horizon, the boundary of the region of space-time from which it is not possible to escape, acts rather like a one-way membrane around the black hole: objects, such as unwary astronauts, can fall through the event horizon into the black hole, but nothing can ever get out of the black hole through the event horizon. . . . One could well say of the event horizon what the poet Dante said of the entrance to Hell: 'All hope abandon, ye who enter here'" (p. 89).

". . . the physicist John Wheeler once calculated that if one took all the heavy water in all the oceans of the world, one could build a hydrogen bomb that would compress matter at the center so much that a black hole would be created. (Of course, there would be no one left to observe it!)" (p. 96).

"If Euclidean space-time stretches back to infinite imaginary time, or else starts at a singularity in imaginary time, we have the same problem as in the classical theory of specifying the initial state of the universe: God may know how the universe began, but we cannot give any particular reason for thinking it began one way rather than another. On the other hand, the quantum theory of gravity has opened up a new possibility, in which there would be no boundary to space-time and so there would be no singularity at which the laws of science broke down and no edge of space-time at which one would have to appeal to God or some new law to set the boundary conditions of space-time. One could say: 'The boundary condition of the universe is that it has no boundary.' The universe would be completely self-contained and not affected by anything outside itself. It would neither be created nor destroyed. It would just BE" (p. 136).

"What should you do when you find you have made a mistake like that? Some people never admit that they are wrong and continue to find new, and often mutually inconsistent, arguments to support their case—as Eddington did in opposing black hole theory. Others claim to have never really supported the incorrect view in the first place, or if they did, it was only to show that it was inconsistent. It seems to me much better and less confusing if you admit in print that you were wrong" (p. 151).

"String theory has a curious history. It was originally invented in the late 1960s in an attempt to find a theory to describe the strong force. . . . In 1984 interest in strings suddenly revived . . . it might be able to explain the types of particles that we observe" (pp. 160-162).

"A complete, consistent, unified theory is only the first step: our goal is a complete understanding of the events around us, and of our own existence" (p. 169).

"We find ourselves in a bewildering world. We want to make sense of what we see around us and to ask: What is the nature of the universe? What is our place in it and where did it and we come from? Why is it the way it is?" (p. 171).

"However, if we do discover a complete theory, it should in time be understandable in broad principle by everyone, not just a few scientists. Then we shall all, philosophers, scientists, and just ordinary people, be able to take part in the discussion of the question of why it is that we and the universe exist. If we find the answer to that, it would be the ultimate triumph of human reason—for then we would know the mind of God" (p. 175).

Topics for Discussion

Characterize Stephen Hawking's personality as he reveals it in the book.

Of what importance is the uncertainty principle in quantum mechanics?

Investigate string theory and create a timeline of the major events in its history.

How might radiation be emitted from the event horizon of a black hole?

Why is the Vatican interested in what Stephen Hawking has to say about the nature of the universe?

What is entropy?

Why can a scientific theory never be proven?

What is a virtual particle?

What is a quark?

What are the roles of mathematics in physics?

Compare and contrast a theoretical physicist and an experimental physicist.

Why is the statement, "before the big bang" meaningless from the perspective of the general theory of relativity?