<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. What are the essential questions of cosmology?</td>
<td></td>
</tr>
<tr>
<td>2. What was the view of the universe in 200BC?</td>
<td></td>
</tr>
<tr>
<td>3. What did Kepler discover?</td>
<td></td>
</tr>
<tr>
<td>4. What did Newton’s law of gravity predict?</td>
<td></td>
</tr>
<tr>
<td>5. What did Einstein’s theory of General Relativity say that distance and time depended on?</td>
<td></td>
</tr>
<tr>
<td>6. What did it say about time and space?</td>
<td></td>
</tr>
<tr>
<td>7. What did General Relativity say about the speed of light?</td>
<td></td>
</tr>
<tr>
<td>8. What does it say that mass does to spacetime?</td>
<td></td>
</tr>
<tr>
<td>9. What did Schwarzschild show that General Relativity predicted?</td>
<td></td>
</tr>
<tr>
<td>10. What did Einstein discover that his theory said about a static universe?</td>
<td></td>
</tr>
<tr>
<td>11. What do the terms isotropic and homogeneous mean?</td>
<td></td>
</tr>
</tbody>
</table>
12. What are the three possible geometries of the universe and what do they mean?

13. What is the modern estimate for the age of the universe?

14. What is cosmic background radiation?

15. What theory did Alan Guth suggest?

16. What was predicted to be evidence of the irregularities in the early universe.

17. What missions found these irregularities?

18. What did the WMAP mission tell us about the geometry of the universe?

19. What did the efforts to measure the slowing of the expansion of the universe reveal?

20. What does this suggest?

21. How much of the matter that makes up critical density is matter, and how much is dark energy?

22. What theory of modern physics has remained elusive?
Introduction to Cosmology

A brief history of the universe from the Big Bang to black holes

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Prologue

Cosmology is the branch of science concerned with the study of the universe or cosmos. It is probably the oldest of the sciences, as the questions posed by cosmologists have been pondered through the ages. How big is the universe? How old is it? How did it come into being? At the same time, cosmology ranks among the most modern and dynamic of the physical sciences, as astounding advances in both theory and experiment change our view of the universe.

In this paper, a brief history of cosmology is presented, from the observation of the planetary orbits in the 17th century to the discovery of the expanding universe in 1929. The theories underlying these discoveries are outlined, from Newton’s universal law of gravity to Einstein’s general theory of relativity. The modern view of the origins of our universe (the Big Bang model) is presented, and recent modifications of the model outlined. In conclusion, dramatic new astronomical observations that have once again revolutionized our view of the universe are discussed.

I  Early cosmology

The earliest records of rational attempts to describe the motion of the stars and planets date back to classical antiquity. By 200 BC, the accepted view of the universe was that of an exact sphere, with the distant stars and planets executing perfect circular motions about the earth. Although much of Greek scholarship was lost during the Dark Ages, this view of the universe merged with Christian theology, and survived up to the 16th century AD.

Cosmology underwent a major paradigm shift during the European Renaissance, when it was first suggested that the planets revolve around the sun rather than the earth (the Copernican hypothesis). With the invention of the telescope, support for the Copernican view was provided by the astronomical observations of scientists such as Tycho Brahe, Galileo and Kepler - despite the objections of the Church. In particular, Kepler discovered that the motion of the planets about the sun could be neatly described in terms of well-known mathematical curves or orbits. However, the nature of the force responsible for this planetary motion remained a mystery.

II  Newtonian cosmology

In 1687, Isaac Newton published a number of universal laws that described all known motion, the culmination of his life’s work. In particular, Newton postulated a law of gravity that predicted an attractive force between any two bodies due to their mass (the amount of matter in each body). This law successfully accounted for the known motion of falling bodies (terrestrial gravity). Even better, the same law accurately predicted the Keplerian orbits of the planets about the sun (celestial gravity). In this manner, Newton gave the first physical explanation for both terrestrial and celestial gravity, showing them to be of common origin.

III  The theory of relativity

Newton’s laws of motion and gravity dominated physics for over two hundred years. However, a great upheaval occurred in 1905 with the advent of Einstein’s Special Theory of Relativity. Dispensing
with the concept of absolute motion, the new theory predicted that quantities such as distance and time were not absolute, but depended on the relative motion of observers (and that three-dimensional space and time were not independent, but components of the four-dimensional quantity spacetime). Relativity also predicted a dependence of mass on motion, a relation that implied that mass was simply a form of energy ($E = mc^2$). Most dramatically, special relativity postulated that the speed of light was a universal constant for all observers, and represented a natural limit for physical speed. Relativity gained acceptance quite quickly over the next few years, as scientists became convinced by the simplicity and completeness of the theory, and by supporting evidence. (Nowadays, the dependence of mass, distance and time on motion, and the constancy of the speed of light, are routinely verified in experiments in high-energy particle accelerators).

Special relativity revolutionized the Newtonian view of time, distance and motion. It also raised questions concerning Newton’s universal law of gravity - if nothing could travel faster than the speed of light, how did Newton’s force of gravity act instantaneously on the planets over immense astronomical distances? In 1915, Einstein published a new theory of relativity that incorporated the effects of gravity. The new theory, Einstein’s General Theory of Relativity, was nothing less than a new theory of gravity. A central prediction of general relativity was that space and time were affected by the presence of mass. General relativity postulated that the density of matter in a given location (i.e. the amount of mass per unit volume) would cause spacetime itself to curve, causing other mass to move along spacetime curves. Thus, Einstein replaced Newton’s force of gravity with a view of gravity as a curvature of space and time, a view forms the foundation of the modern understanding of gravity.

One of the first solutions of the equations of general relativity led to the startling prediction of black holes. In 1917, Karl Schwarzschild demonstrated that relativity predicted that if a large enough amount of matter was concentrated in a minute region of space, the curvature of spacetime could be so extreme that light might never escape from the region. Indeed, the Schwarzschild solution implied a critical radius for any massive object, below which light could not escape from the surface of the object. Many years later, it was shown that black holes are often formed at the end of the life of a star and there is now strong evidence that our universe contains a great many black holes. Indeed, it seems nearly all galaxies (including our own) have a supermassive black hole at their centre.

IV Relativistic cosmology
Soon after publishing his new theory of gravity, Einstein applied general relativity to the study of the entire cosmos. He quickly discovered that relativity predicted a universe that was not static but dynamic - either expanding or contracting. No astronomical evidence to support this strange prediction existed, and Einstein concluded relativity must be incomplete. Assuming a static universe, Einstein postulated that the attractive pull of gravity on the mass in the universe must be balanced by some repulsive effect – perhaps an inbuilt tendency of empty space to expand. Einstein introduced a new term (the cosmological constant) representing this repulsive effect to the equations of general relativity, adjusting the term carefully so that the theory predicted a static universe. (Later, Einstein was to declare the introduction of this term his greatest blunder).

Other scientists began to apply general relativity to the study of the universe, without the introduction of the rather artificial cosmological constant. In
particular, the Russian mathematician Alexander Friedmann obtained a family of solutions to the original equations of general relativity, assuming only that the universe is *isotropic* (the same in every direction) and *homogeneous* (of constant density of matter at large scales). The Friedmann solutions predicted an expanding universe, with only three possible geometries and fates, depending on the total density of matter in the universe. Above a certain density of matter, the attractive pull of gravity would eventually overcome the expansion of the universe, resulting in gravitational collapse (*closed universe* geometry). Below this critical density of matter, the expansion would overcome the effects of gravity and expand forever (*open universe*). In between these possibilities was the case of a universe exactly balanced between expansion and the pull of gravity (*flat universe*).

**V The expanding universe**

The great debate between a static and expanding universe was not resolved for a decade. Then in 1929, astronomical observation showed that remote galaxies were rushing away from the earth at a speed proportional to their distance (*Hubble’s Law*). This linear relation (see figure 1) represented unequivocal experimental evidence of the expanding universe predicted by Friedmann, and marked the second great paradigm shift in cosmology.

An exciting application of Hubble’s Law was an estimate of cosmic age, since the slope of the expansion graph (the *Hubble constant*) could in principle yield a value for the age of the universe. Unfortunately, this estimate was in conflict with the known age of stars for many years – it was later realised that the fault lay in the calculation of astronomical distances on the Hubble graph.

**VI The origin of the universe**

With the expansion of the universe established experimentally, scientists began to speculate about its origins. It was realised that if the volume of the universe was continually increasing as time progressed, the density of matter in the universe must be continually decreasing. Working backwards, theorists such as Lemaitre and Gamow postulated that the present universe emanated from a tiny, infinitely dense and infinitely hot fireball billions of years ago, expanding and cooling ever since – a postulate now known as the *Big Bang* model of the evolution of the universe. (An alternative model, the *steady-state* universe, was proposed for some years, but eventually found to be at variance with astronomical evidence).

The Big Bang model has been found to successfully account for many features of the observable universe including its age, rate of expansion, and elemental composition. Modern estimates of the age of the universe (14.7 billion years) obtained from the slope of the expansion graph are in good agreement with the age of the oldest stars estimated by astronomical observation. Detailed calculations of the formation of elementary matter after the Bang, by the process of nucleosynthesis, led to a prediction that our universe is composed of roughly 75% Hydrogen and 25% Helium - a prediction in good accord with observation. Most striking of all, the Big Bang model predicted an unexpected feature of the present universe: the existence of *cosmic background radiation*, remnants of radiation left over from the primordial Bang. The detection of the cosmic background radiation in 1965, of the exact temperature and wavelength predicted, was a spectacular triumph for the Big Bang model.

Despite these successes, the Big Bang model is far from complete. The most
serious failure of the model is known as the *singularity problem*: while a consistent model of the evolution of the universe after the Bang is given, little information concerning the Bang itself is offered. This shortcoming arises from a breakdown in the equations of general relativity at time zero. Nowadays, this breakdown is attributed to the fact that general relativity does not incorporate quantum effects, effects that are expected to be significant at times extremely close to the Bang. Other problems concerning the description of early universe by the Big Bang model have emerged. In the *horizon problem*, it has been demonstrated that the model cannot account for the large-scale homogeneity of the universe. Indeed, calculations imply that information would have had to travel faster than the speed of light in the early universe in order to achieve the present cosmic homogeneity!

Another riddle is the *flatness problem*; it has been shown that for the universe to have evolved to its present state, the geometry of the early universe must have been precisely flat, to an unbelievable degree of precision. Why should the density of matter in the early universe have been so finely tuned?

**VII Inflation**

The above theoretical problems dogged the big bang model for many years. Finally, an important modification of the model occurred in the 1980s, with the suggestion by Alan Guth of *cosmic inflation*. Arising from considerations of particle physics, inflation theory postulated that the very early universe initially underwent an extremely short, intense burst of accelerated expansion, followed by the much slower expansion that we now observe. Inflation theory provided a modified big bang model that neatly circumvented many of the big bang riddles. For the case of the *horizon problem*, the sheer speed of inflation provided a simple mechanism for all components of the cosmos to have been in thermal equilibrium in the early universe. For the case of the *flatness problem*, inflation predicted that a flat geometry for the universe was not only likely, but in fact inevitable. Most exciting of all, modified inflation theories gave the first detailed model of galaxy formation in the early universe; the theories suggested that tiny perturbations in the homogeneity of the early universe predicted by quantum theory were inflated to macroscopic size during inflation, resulting in the large-scale galaxies and supergalaxies of matter observed today. Intriguingly, it was predicted that evidence of these irregularities in the early universe might still be detectable today as minute variations in the cosmic microwave background.

Highly successful at overcoming many of the big bang riddles in theory, the inflation model of the big bang suffered from a lack of experimental evidence for some years. However, fascinating support has been offered by recent astronomical measurements. In 1992, minute irregularities in the cosmic microwave background were indeed detected by the COBE satellite telescope – and the distribution of these ripples matched the distribution predicted by inflation. In 2002, much better resolution of these irregularities was provided by the WMAP satellite telescope, giving strong support for both inflation theory and the prediction of quantum perturbations in the early universe. Further, the WMAP data yielded conclusive evidence that the geometry of the universe is not open or closed, but precisely flat – just as predicted by inflation.

**VIII The accelerating universe**

With the evidence above, one might have hoped for a definitive picture of the origin of the universe. However, another dramatic discovery has been made that has shaken modern cosmology to its
foundations. In 1998, painstaking efforts to measure an expected slowing of the expanding universe (due to gravity) resulted in the astonishing discovery that the universe is in fact speeding up! This discovery, the acceleration of the universe, marks the third great paradigm shift in cosmology. While an accelerating universe is not in conflict with general relativity or inflation theory, it suggests the existence of a mysterious phenomenon (dark energy) that acts to overcome gravitation effects at the largest cosmological scales. Hence, the equations of general relativity have been reconsidered once more, with a new term introduced in order to account for the phenomenon (in a manner uncannily reminiscent of Einstein’s cosmological constant).

It should be noted that the postulate of dark energy is also supported by the observation that the geometry of the present universe is exactly flat (section VII). This observation implies that the density of matter in the present universe lies at at the critical value – yet estimates of the total density of all known matter gives an answer that is only 30% of critical density. It is now thought that the remaining 70% arises from dark energy.

At the time of writing, the physical nature and origin of dark energy remains the subject of much debate. The most popular theory is that dark energy is a quantum vacuum energy – an energy that arises from the appearance of quantum particles of matter and anti-matter that materialize momentarily out of the cosmic vacuum, only to recombine and disappear almost immediately. However, such theories are highly speculative, and scientists wait with bated breath for the latest evidence from satellite telescopes.

Epilogue
A handful of key astronomical observations underpin our current view of the cosmos. The observation of the expanding universe in 1929 (Hubble’s Law) concurred with the predictions of the general theory of relativity. The detection of the cosmic background radiation in 1965 offered unequivocal support for the Big Bang model of the origin of the universe implied by relativity. The discovery of minute variations in the cosmic background radiation in 1992 and 2002 offered strong support for the inflationary Big Bang model, and for the conjecture of quantum perturbations in the early universe. These measurements also offered strong evidence that the geometry of our universe is flat. Finally, an unexpected discovery, the accelerated expansion of the universe, has prompted theoreticians to postulate the existence of dark energy, a quantum vacuum energy that acts to overcome the contraction of gravity.

However, a great flaw lies in our view of the early universe, since all known models fail as the origin of the timeline is approached. It has long been suggested that this flaw is the result of a fundamental shortcoming of the theory of relativity - the irreconcilability of general relativity with quantum theory. Uniquely among modern theories of physics, a quantum formulation of general relativity (quantum gravity) has proved elusive - yet quantum effects are expected to be highly significant at times extremely close to time zero. It is accepted that a complete theory of the evolution of the universe will not be possible until the development of a successful quantum theory of gravity. In this respect, cosmology resembles another branch of physics, the study of the elementary particles.

The outstanding problem in particle physics today is the inclusion of gravity in a single, unified quantum theory of all the fundamental interactions. Particle physicists have long suggested that the four fundamental forces of nature (the gravitational, electromagnetic, weak nuclear and strong nuclear forces) are separate, low-energy manifestations of what was once a single force at times close
to the Big Bang. It is postulated that as the universe expanded and cooled, this single force gradually broke down into the four separate interactions observed today (by the process of spontaneous symmetry breaking). A detailed quantum theory that describes the electromagnetic and weak nuclear forces in terms of a single force (the electroweak interaction) was developed in the 1970s and dramatically verified by high-energy experiments in particle accelerators a decade later. More ambitious quantum theories that incorporate the strong nuclear force (Grand Unified Theories) have been developed, and some experimental support for these models has emerged. However, unification theories that seek to unify the force of gravity with all the other forces (Theories of Everything) remain elusive, as the gravitational interaction lacks a quantum formulation.

Hence, cosmology and particle physics pose the same great challenge: a reconciliation of general relativity and quantum theory, the two great pillars of modern theoretical physics. A successful reconciliation, the development of a quantum theory of gravity, will shed much light on the nature of the elementary particles and their interactions, and on the origins of our universe …
A Theory of Everything?
Some physicists believe string theory
may unify the forces of nature
by Brian Greene

The fundamental particles of the universe that physicists have identified—electrons, neutrinos, quarks, and so on—are the "letters" of all matter. Just like their linguistic counterparts, they appear to have no further internal substructure. String theory proclaims otherwise. According to string theory, if we could examine these particles with even greater precision—a precision many orders of magnitude beyond our present technological capacity—we would find that each is not pointlike but instead consists of a tiny, one-dimensional loop. Like an infinitely thin rubber band, each particle contains a vibrating, oscillating, dancing filament that physicists have named a string.

In the figure at right, we illustrate this essential idea of string theory by starting with an ordinary piece of matter, an apple, and repeatedly magnifying its structure to reveal its ingredients on ever smaller scales. String theory adds the new microscopic layer of a vibrating loop to the previously known progression from atoms through protons, neutrons, electrons, and quarks.

Although it is by no means obvious, this simple replacement of point-particle material constituents with strings resolves the incompatibility between quantum mechanics and general relativity (which, as currently formulated, cannot both be right). String theory thereby unravels the central Gordian knot of contemporary theoretical physics. This is a tremendous achievement, but it is only part of the reason string theory has generated such excitement.

Field of dreams

In Einstein's day, the strong and weak forces had not yet been discovered, but he found the existence of even two distinct forces—gravity and electromagnetism—deeply troubling. Einstein did not accept that nature is founded on such an extravagant design. This launched his 30-year voyage in search of the so-called unified field theory that he hoped would show that these two forces are really manifestations of one grand underlying principle. This quixotic quest isolated Einstein from the mainstream of physics, which, understandably, was far more excited about delving into the newly emerging framework of quantum mechanics. He wrote to a friend in the early 1940s, "I have become a lonely old chap who is mainly known because he doesn't wear socks and who is exhibited as a curiosity on special occasions."

Einstein was simply ahead of his time. More than half a century later, his dream of a unified theory has become the Holy Grail of modern physics. And a sizeable part of the physics and mathematics community is becoming increasingly convinced that string theory may provide the answer. From one principle—that everything at its most microscopic level consists of combinations of vibrating strands—string theory provides a single explanatory framework capable of encompassing all forces and all matter.

String theory proclaims, for instance, that the observed particle properties—that is, the different masses and other properties of both the fundamental particles and the force particles associated with the four forces of nature (the strong and weak nuclear forces, electromagnetism, and gravity)—are a reflection of the various ways in which a string can vibrate. Just as the strings on a violin or on a piano have resonant frequencies at which they prefer to vibrate—patterns that our ears sense as various musical notes and their higher harmonics—the same holds true for the loops of string theory. But rather than producing musical notes, each of the preferred mass and force charges are determined by the string's oscillatory pattern. The electron is a string vibrating one way, the up-quark is a string vibrating another way, and so on.

Far from being a collection of chaotic experimental facts, particle properties in string theory are the manifestation of one and the same physical feature: the resonant patterns of vibration—the music, so to speak—of fundamental loops of string. The same idea applies to the forces of nature as well. Force particles are also associated with particular patterns of string vibration and hence everything, all matter and all forces, is unified under the same rubric of microscopic string oscillations—the "notes" that strings can play.

A theory to end theories

For the first time in the history of physics we therefore have a framework with the capacity to explain every fundamental feature upon which the universe is constructed. For this reason string theory is sometimes described as possibly being the "theory of everything" (T.O.E.) or the "ultimate" or "final" theory. These
Grandiose descriptive terms are meant to signify the deepest possible theory of physics—a theory that underlies all others, one that does not require or even allow for a deeper explanatory base.

In practice, many string theorists take a more down-to-earth approach and think of a T.O.E. in the more limited sense of a theory that can explain the properties of the fundamental particles and the properties of the forces by which they interact and influence one another. A staunch reductionist would claim that this is no limitation at all, and that in principle absolutely everything, from the big bang to daydreams, can be described in terms of underlying microscopic physical processes involving the fundamental constituents of matter. If you understand everything about the ingredients, the reductionist argues, you understand everything.

The reductionist philosophy easily ignites heated debate. Many find it fatuous and downright repugnant to claim that the wonders of life and the universe are mere reflections of microscopic particles engaged in a pointless dance fully choreographed by the laws of physics. Is it really the case that feelings of joy, sorrow, or boredom are nothing but chemical reactions in the brain—reactions between molecules and atoms that, even more microscopically, are reactions between some of the fundamental particles, which are really just vibrating strings?

In response to this line of criticism, Nobel laureate Steven Weinberg cautions in *Dreams of a Final Theory*:

At the other end of the spectrum are the opponents of reductionism who are appalled by what they feel to be the bleakness of modern science. To whatever extent they and their world can be reduced to a matter of particles or fields and their interactions, they feel diminished by that knowledge....I would not try to answer these critics with a pep talk about the beauties of modern science. The reductionist worldview is chilling and impersonal. It has to be accepted as it is, not because we like it, but because that is the way the world works.

Some agree with this stark view, some don't.

Others have tried to argue that developments such as chaos theory tell us that new kinds of laws come into play when the level of complexity of a system increases. Understanding the behavior of an electron or quark is one thing; using this knowledge to understand the behavior of a tornado is quite another. On this point, most agree. But opinions diverge on whether the diverse and often unexpected phenomena that can occur in systems more complex than individual particles truly represent new physical principles at work, or whether the principles involved are derivative, relying, albeit in a terribly complicated way, on the physical principles governing the enormously large number of elementary constituents.

My own feeling is that they do not represent new and independent laws of physics. Although it would be hard to explain the properties of a tornado in terms of the physics of electrons and quarks, I see this as a matter of calculational impasse, not an indicator of the need for new physical laws. But again, there are some who disagree with this view.

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**A fresh start for science**

What is largely beyond question, and is of primary importance to the journey described in my book *The Elegant Universe*, is that even if one accepts the debatable reasoning of the staunch reductionist, principle is one thing and practice quite another. Almost everyone agrees that finding the T.O.E. would in no way mean that psychology, biology, geology, chemistry, or even physics had been solved or in some sense subsumed. The universe is such a wonderfully rich and complex place that the discovery of the final theory, in the sense we are describing here, would not spell the end of science.

Quite the contrary: The discovery of the T.O.E.—the ultimate explanation of the universe at its most microscopic level, a theory that does not rely on any deeper explanation—would provide the firmest foundation on which to build our understanding of the world. Its discovery would mark a beginning, not an end. The ultimate theory would provide an unshakable pillar of coherence forever assuring us that the universe is a comprehensible place.