The Grand Design – Stephen Hawking and Leonard Mlodinov
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Quantum theories can be formulated in many different ways, but what is probably the most intuitive description was given by Richard (Dick) Feynman, a colorful character who worked at the California Institute of Technology and played the bongo drums at a strip joint down the road. According to Feynman, a system has not just one history but every possible history. As we seek our answers, we will explain Feynman’s approach in detail, and employ it to explore the idea that the universe itself has no single history, nor even an independent existence. That seems like a radical idea, even to many physicists. Indeed, like many notions in today’s science, it appears to violate common sense. (28-33)

To deal with such paradoxes we shall adopt an approach that we call model-dependent realism. It is based on the idea that our brains interpret the input from our sensory organs by making a model of the world. When such a model is successful at explaining events, we tend to attribute to it, and to the elements and concepts that constitute it, the quality of reality or absolute truth. But there may be different ways in which one could model the same physical situation, with each employing different fundamental elements and concepts. If two such physical theories or models accurately predict the same events, one cannot be said to be more real than the other; rather, we are free to use whichever model is most convenient. (37-42)

M-theory is the only model that has all the properties we think the final theory ought to have, and it is the theory upon which much of our later discussion is based. M-theory is not a theory in the usual sense. It is a whole family of different theories, each of which is a good description of observations only in some range of physical situations. (46-49)

The different theories in the M-theory family may look very different, but they can all be regarded as aspects of the same underlying theory. They are versions of the theory that are applicable only in limited ranges—for example, when certain quantities such as energy are small. (52-54)

M-theory predicts that a great many universes were created out of nothing. Their creation does not require the intervention of some supernatural being or god. Rather, these multiple universes arise naturally from physical law. They are a prediction of science. Each universe has many possible histories and many possible states at later times, that is, at times like the present, long after their creation. Most of these states will be quite unlike the universe we observe and quite unsuitable for the existence of any form of life. Only a very few would allow creatures like us to exist. Thus our presence selects out from this vast array only those universes that are compatible with our existence. (57-62)

IN VIKING MYTHOLOGY, Skoll and Hati chase the sun and the moon. When the wolves catch either one, there is an eclipse. When this happens, the people on earth rush to rescue the sun or moon by making as much noise as they can in hopes of scaring off the wolves. There are similar myths in other cultures. (68-70)

Ignorance of nature’s ways led people in ancient times to invent gods to lord it over every aspect of human life. (86)

[…] with Thales of Miletus (ca. 624 BC– ca. 546 BC) about 2,600 years ago, that began to change. The idea arose that nature follows consistent principles that could be deciphered. And so began the long process of replacing the notion of the reign of gods with the concept of a universe that is governed by laws of nature, and created according to a blueprint we could someday learn to read. (90-92)

Thales is credited with the first prediction of a solar eclipse in 585 BC, though the great precision of his prediction was probably a lucky guess. He was a shadowy figure who left behind no writings of his own. (100-101)

Even as late as the sixteenth century, the great German astronomer Johannes Kepler (1571–1630) believed that planets had sense perception and consciously followed laws of movement that were grasped by their “mind.” (164-166)

The base ten number notation we find so convenient for arithmetic dates back only to around AD 700, when the Hindus took the first great strides toward making that subject a powerful tool. The abbreviations for plus and minus didn’t come until the fifteenth century. And neither the equal sign nor clocks that could measure times to the second existed before the sixteenth century. (169-171)

Aristotle built his physics upon principles that appealed to him intellectually. He suppressed facts he found unappealing and focused his efforts on the reasons things happen, with relatively little energy invested in detailing exactly what was happening. Aristotle did adjust his conclusions when their blatant disagreement with observation could not be ignored. But those adjustments were often ad hoc explanations that did little more than paste over the contradiction. In that manner, no matter how severely his theory deviated from actuality, he could always alter it just enough to seem to remove the conflict. For example, his theory of motion specified that heavy bodies fall with a constant speed that is proportional to their weight. To explain the fact that objects clearly pick up speed as they fall, he invented a new principle—that bodies proceed more jubilantly, and hence accelerate, when they come closer to their natural place of rest, a principle that today seems a more apt description of certain people than of inanimate objects. Though

Aristotle’s theories often had little predictive value, his approach to science dominated Western thought for nearly two thousand years. (173-181)

[…] in 1277 Bishop Tempier of Paris, acting on the instructions of Pope John XXI, published a list of 219 errors or heresies that were to be condemned. Among the heresies was the idea that nature follows laws, because this conflicts with God’s omnipotence. Interestingly, Pope John was killed by the effects of the law of gravity a few months later when the roof of his palace fell in on him. (184-186)

Galileo did uncover a great many laws, and advocated the important principles that observation is the basis of science and that the purpose of science is to research the quantitative relationships that exist between physical phenomena. But the person who first explicitly and rigorously formulated the concept of laws of nature as we understand them was René Descartes. (189-192)

If nature is governed by laws, three questions arise: 1. What is the origin of the laws? 2. Are there any exceptions to the laws, i.e., miracles? 3. Is there only one set of possible laws? (230-231)

[…] employing God as a response to the first question merely substitutes one mystery for another. (234-235)

It is Laplace who is usually credited with first clearly postulating scientific determinism: Given the state of the universe at one time, a complete set of laws fully determines both the future and the past. This would exclude the possibility of miracles or an active role for God. The scientific determinism that Laplace formulated is the modern scientist’s answer to question two. (245-247)

Many, however, while accepting that scientific determinism governs physical processes, would make an exception for human behavior because they believe we have free will. (251-252)

Do people have free will? If we have free will, where in the evolutionary tree did it develop? Do blue-green algae or bacteria have free will, or is their behavior automatic and within the realm of scientific law? Is it only multicelled organisms that have free will, or only mammals? (256-258)

Though we feel that we can choose what we do, our understanding of the molecular basis of biology shows that biological processes are governed by the laws of physics and chemistry and therefore are as determined as the orbits of the planets. (261-263)

[…] we are no more than biological machines and that free will is just an illusion. (267)

Because it is so impractical to use the underlying physical laws to predict human behavior, we adopt what is called an effective theory.

In physics, an effective theory is a framework created to model certain observed phenomena without describing in detail all of the underlying processes. (271-273)

In the case of people, since we cannot solve the equations that determine our behavior, we use the effective theory that people have free will. (277-278)

FEW YEARS AGO the city council of Monza, Italy, barred pet owners from keeping goldfish in curved goldfish bowls. The measure’s sponsor explained the measure in part by saying that it is cruel to keep a fish in a bowl with curved sides because, gazing out, the fish would have a distorted view of reality. (295-297)

[…] modeldependent realism: the idea that a physical theory or world picture is a model (generally of a mathematical nature) and a set of rules that connect the elements of the model to observations. This provides a framework with which to interpret modern science. (337-339)

[…] according to the principles of quantum physics, which is an accurate description of nature, a particle has neither a definite position nor a definite velocity unless and until those quantities are measured by an observer. It is therefore not correct to say that a measurement gives a certain result because the quantity being measured had that value at the time of the measurement. In fact, in some cases individual objects don’t even have an independent existence but rather exist only as part of an ensemble of many. And if a theory called the holographic principle proves correct, we and our four-dimensional world may be shadows on the boundary of a larger, five-dimensional space-time. (347-352)

According to model-dependent realism, it is pointless to ask whether a model is real, only whether it agrees with observation. If there are two models that both agree with observation, like the goldfish’s picture and ours, then one cannot say that one is more real than another. (365-367)

In vision, one’s brain receives a series of signals down the optic nerve. Those signals do not constitute the sort of image you would accept on your television. There is a blind spot where the optic nerve attaches to the retina, and the only part of your field of vision with good resolution is a narrow area of about 1 degree of visual angle around the retina’s center, an area the width of your thumb when held at arm’s length. And so the raw data sent to the brain are like a badly pixilated picture with a hole in it. Fortunately, the human brain processes that data, combining the input from both eyes, filling in gaps on the assumption that the visual properties of neighboring locations are similar and interpolating. Moreover, it reads a two-dimensional array of data from the retina and creates from it the impression of three-dimensional space. The brain, in other words, builds a mental picture or model. (374-380)

It is said that the electron was discovered in 1897 by British physicist J. J. Thomson at the Cavendish Laboratory at Cambridge University. He was experimenting with currents of electricity inside empty glass tubes, a phenomenon known as cathode rays. His experiments led him to the bold conclusion that the mysterious rays were composed of minuscule “corpuscles” that were material constituents of atoms, which were then thought to be the indivisible fundamental unit of matter. (391-395)

A model is a good model if it: 1. Is elegant 2. Contains few arbitrary or adjustable elements 3. Agrees with and explains all existing observations 4. Makes detailed predictions about future observations that can disprove or falsify the model if they are not borne out. (420-422)

To paraphrase Einstein, a theory should be as simple as possible, but not simpler. (435)

There seems to be no single mathematical model or theory that can describe every aspect of the universe. Instead, as mentioned in the opening chapter, there seems to be the network of theories called M-theory. Each theory in the M-theory network is good at describing phenomena within a certain range. Wherever their ranges overlap, the various theories in the network agree, so they can all be said to be parts of the same theory. But no single theory within the network can describe every aspect of the universe— all the forces of nature, the particles that feel those forces, and the framework of space and time in which it all plays out. (480-484)

Quantum physics tells us that nothing is ever located at a definite point because if it were, the uncertainty in momentum would have to be infinite. In fact, according to quantum physics, each particle has some probability of being found anywhere in the universe. So even if the chances of finding a given electron within the double-slit apparatus are very high, there will always be some chance that it could be found instead on the far side of the star Alpha Centauri (587-590)

But quantum physics agrees with observation. It has never failed a test, and it has been tested more than any other theory in science. (606-607)

Imagine a simple process in which a particle begins at some location A and moves freely. In the Newtonian model that particle will follow a straight line. After a certain precise time passes, we will find the particle at some precise location B along that line. In Feynman’s model a quantum particle samples every path connecting A and B, collecting a number called a phase for each path. That phase represents the position in the cycle of a wave, that is, whether the wave is at a crest or trough or some precise position in between. Feynman’s mathematical prescription for calculating that phase showed that when you add together the waves from all the paths you get the “probability amplitude” that the particle, starting at A, will reach B. The square of that probability amplitude then gives the correct probability that the particle will reach B. (631-636)

[…] for a general system, the probability of any observation is constructed from all the possible histories that could have led to that observation. Because of that his method is called the “sum over histories” or “alternative histories” formulation of quantum physics. (657-659)

Quantum physics tells us that no matter how thorough our observation of the present, the (unobserved) past, like the future, is indefinite and exists only as a spectrum of possibilities. The universe, according to quantum physics, has no single past, or history. (687-688)

The fact that the past takes no definite form means that observations you make on a system in the present affect its past. (688-689)

[…] the Bible tells the story of Joshua praying for the sun and moon to stop in their trajectories so he would have extra daylight to finish fighting the Amorites in Canaan. According to the book of Joshua, the sun stood still for about a day. Today we know that that would have meant that the earth stopped rotating. (713-715)

Faraday had little formal education. He had been born into a poor blacksmith’s family near London and left school at age thirteen to work as an errand boy and bookbinder in a bookshop. There, over the years, he learned science by reading the books he was supposed to care for, and by performing simple and cheap experiments in his spare time. Eventually he obtained work as an assistant in the laboratory of the great chemist Sir Humphry Davy. Faraday would stay on for the remaining forty-five years of his life and, after Davy’s death, succeed him. Faraday had trouble with mathematics and never learned much of it, so it was a struggle for him to conceive a theoretical picture of the odd electromagnetic phenomena he observed in his laboratory. (730-735)

Einstein’s work showed that, like the concept of rest, time cannot be absolute, as Newton thought. In other words, it is not possible to assign to every event a time with which every observer will agree. Instead, all observers have their own measures of time, and the times measured by two observers who are moving relative to each other will not agree. (820-822)

[…] if general relativity were not taken into account in GPS satellite navigation systems, errors in global positions would accumulate at a rate of about ten kilometers each day! (866-867)

[…] in quantum field theories the force fields are pictured as being made of various elementary particles called bosons, which are force-carrying particles that fly back and forth between matter particles, transmitting the forces. The matter particles are called fermions. Electrons and quarks are examples of fermions. The photon, or particle of light, is an example of a boson. It is the boson that transmits the electromagnetic force. What happens is that a matter particle, such as an electron, emits a boson, or force particle, and recoils from it, much as a cannon recoils after firing a cannonball. The force particle then collides with another matter particle and is absorbed, changing the motion of that particle. According to QED, all the interactions between charged particles—particles that feel the electromagnetic force—are described in terms of the exchange of photons. (891-897)

It may have proved difficult to meld the strong force with the electromagnetic and weak forces, but those problems are nothing compared with the problem of merging gravity with the other three, or even of creating a stand-alone quantum theory of gravity. The reason a quantum theory of gravity has proven so hard to create has to do with the Heisenberg uncertainty principle (971-974)

According to the Old Testament, God created Adam and Eve only six days into creation. Bishop Ussher, primate of all Ireland from 1625 to 1656, placed the origin of the world even more precisely, at nine in the morning on October 27, 4004 BC. We take a different view: that humans are a recent creation but that the universe itself began much earlier, about 13.7 billion years ago. (1074-1077)

[…] once we add the effects of quantum theory to the theory of relativity, in extreme cases warpage can occur to such a great extent that time behaves like another dimension of space. (1187-88)

In the early universe—when the universe was small enough to be governed by both general relativity and quantum theory—there were effectively four dimensions of space and none of time. That means that when we speak of the “beginning” of the universe, we are skirting the subtle issue that as we look backward toward the very early universe, time as we know it does not exist! We must accept that our usual ideas of space and time do not apply to the very early universe. (1188-1191)

The realization that time can behave like another direction of space means one can get rid of the problem of time having a beginning, in a similar way in which we got rid of the edge of the world. Suppose the beginning of the universe was like the South Pole of the earth, with degrees of latitude playing the role of time. As one moves north, the circles of constant latitude, representing the size of the universe, would expand. The universe would start as a point at the South Pole, but the South Pole is much like any other point. To ask what happened before the beginning of the universe would become a meaningless question, because there is nothing south of the South Pole. In this picture space-time has no boundary—the same laws of nature hold at the South Pole as in other places. In an analogous manner, when one combines the general theory of relativity with quantum theory, the question of what happened before the beginning of the universe is rendered meaningless. This idea that histories should be closed surfaces without boundary is called the noboundary condition. (1193-1200)

The realization that time behaves like space presents a new alternative. It removes the age-old objection to the universe having a beginning, but also means that the beginning of the universe was governed by the laws of science and doesn't need to be set in motion by some god. (1201-1203)

We are the product of quantum fluctuations in the very early universe. (1232)

We create history by our observation, rather than history creating us. (1246)

Seasonal weather patterns on earth are determined mainly by the tilt of the earth's axis of rotation relative to the plane of its orbit around the sun. During winter in the Northern Hemisphere, for example, the North Pole is tilted away from the sun. The fact that the earth is closest to the sun at that time—only 91.5 million miles away, as opposed to around 94.5 million miles away from the sun in early July—has a negligible effect on the temperature compared with the effect of its tilt. But on planets with a large orbital eccentricity, the varying distance from the sun plays a much larger role. On Mercury, for example, with a 20 percent eccentricity, the temperature is over 200 degrees Fahrenheit warmer at the planet's closest approach to the sun (perihelion) than when it is at its farthest from the sun (aphelion). In fact, if the eccentricity of the earth's orbit were near one, our oceans would boil when we reached our nearest point to the sun, and freeze over when we reached our farthest (1315-1322)

[…] in 1992 came the first confirmed observation of a planet orbiting a star other than our sun. We now know of hundreds of such planets, and few doubt that there exist countless others among the many billions of stars in our universe. That makes the coincidences of our planetary conditions—the single sun, the lucky combination of earth-sun distance and solar mass—far less remarkable, and far less compelling as evidence that the earth was carefully designed just to please us human beings. (1334-1337)

The first step occurs when older stars start to accumulate helium, which is produced when two hydrogen nuclei collide and fuse with each other. This fusion is how stars create the energy that warms us. Two helium atoms can in turn collide to form beryllium, an atom whose nucleus contains four protons. Once beryllium is formed, it could in principle fuse with a third helium nucleus to form carbon. But that doesn't happen, because the isotope of beryllium that is formed decays almost immediately back into helium nuclei. The situation changes when a star starts to run out of hydrogen. When that happens the star's core collapses until its central temperature rises to about 100 million degrees Kelvin. Under those conditions, nuclei encounter each other so often that some beryllium nuclei collide with a helium nucleus before they have had a chance to decay. Beryllium can then fuse with helium to form an isotope of carbon that is stable. But that carbon is still a long way from forming ordered aggregates of chemical compounds of the type that can enjoy a glass of Bordeaux, juggle flaming bowling pins, or ask questions about the universe. For beings such as humans to exist, the carbon must be moved from inside the star to friendlier neighborhoods. That, as we’ve said, is accomplished when the star, at the end of its life cycle, explodes as a supernova, expelling carbon and other heavy elements that later condense into a planet. (1391-1400)

Today we can create computer models that tell us how the rate of the triple alpha reaction depends upon the strength of the fundamental forces of nature. Such calculations show that a change of as little as 0.5 percent in the strength of the strong nuclear force, or 4 percent in the electric force, would destroy either nearly all carbon or all oxygen in every star, and hence the possibility of life as we know it. (1410-1413)

[…] if the other nuclear force, the weak force, were much weaker, in the early universe all the hydrogen in the cosmos would have turned to helium, and hence there would be no normal stars; if it were much stronger, exploding supernovas would not eject their outer envelopes, and hence would fail to seed interstellar space with the heavy elements planets require to foster life. If protons were 0.2 percent heavier, they would decay into neutrons, destabilizing atoms. If the sum of the masses of the types of quark that make up a proton were changed by as little as 10 percent, there would be far fewer of the stable atomic nuclei of which we are made; in fact, the summed quark masses seem roughly optimized for the existence of the largest number of stable nuclei. (1417-1423)

The turning point in the scientific rejection of a human-centered universe was the Copernican model of the solar system, in which the earth no longer held a central position. (1466-1467)

[…] our universe seems to be one of many, each with different laws. That multiverse idea is not a notion invented to account for the miracle of fine-tuning. It is a consequence of the no-boundary condition as well as many other theories of modern cosmology. But if it is true, then the strong anthropic principle can be considered effectively equivalent to the weak one, putting the fine-tunings of physical law on the same footing as the environmental factors, for it means that our cosmic habitat—now the entire observable universe—is only one of many, just as our solar system is one of many. That means that in the same way that the environmental coincidences of our solar system were rendered unremarkable by the realization that billions of such systems exist, the fine-tunings in the laws of nature can be explained by the existence of multiple universes. (1476-1482)

[…] just as Darwin and Wallace explained how the apparently miraculous design of living forms could appear without intervention by a supreme being, the multiverse concept can explain the fine-tuning of physical law without the need for a benevolent creator who made the universe for our benefit. (1483-1485)

[…] any complex being has free will—not as a fundamental feature, but as an effective theory, an admission of our inability to do the calculations that would enable us to predict its actions. (1573-1574)

M-theory is the unified theory Einstein was hoping to find. The fact that we human beings—who are ourselves mere collections of fundamental particles of nature—have been able to come this close to an understanding of the laws governing us and our universe is a great triumph. But perhaps the true miracle is that abstract considerations of logic lead to a unique theory that predicts and describes a vast universe full of the amazing variety that we see. If the theory is confirmed by observation, it will be the successful conclusion of a search going back more than 3,000 years. (1605-1609)