A Terminological Guide to Contemporary Cosmology

Based on Martin Rees' book *Just Six Numbers*.

Cosmological or ***Cosmology***: These terms refer to that branch of physical science that is concerned with the origin, nature, large-scale structure, development, and fate of the physical Universe. In philosophical of religion, *cosmological argument* refers to an argument for God's existence on the basis of the existence or beginning of the Universe.

Hot Big Bang: The cosmological theory or model of the Universe that has prevailed in the second half of the 20^{th} century. According to the classical hot big bang theory, the Universe came into existence rather abruptly between 15 to 20 billion years ago in a cosmic explosion from an extremely small, dense state. This compact, ultra-microscopic state or particle of pure energy exploded, generating a cosmic *expansion* that continues to this day. As the fireball cooled matter formed from energy and took the form of heavier particles, clouds of gas, and eventually stars, planets, and galaxies.

Cosmic Expansion: Although predicted by Einstein's theory of general relativity, in 1929 Edwin Hubble confirmed that the Universe is expanding. More specifically, he confirmed that observable galaxies were moving away from us. He extrapolated that observable galaxies were each moving away from each other. They are not rushing through empty space, but the space between galaxies is actually stretching. (An analogy to this is the movement of dots on the surface of a balloon that is inflated with air.) This picture when backwards implies that the Universe was at one time in the distant past much smaller and extremely dense, as all of its matter would have been compressed into an ultra-microscopic region. Ordinarily this picture is interpreted as implying a point of origin in a *singularity*, a point at which time and space were infinitely shrunk. Cosmic expansion provides support for big bang model of the Universe.

Nucleosynthesis: This refers to the production of *elements* under extremely high temperatures. *Big bang nucleosynthesis* is the process whereby the lightest chemical elements (hydrogen, helium, and lithium) were produced in the extreme temperatures that prevailed the first second after the big bang. Heavier elements (e.g., carbon, iron) are produced by similar thermonuclear processes in stars and strewn into space by a variety of processes, especially the death-explosion of massive stars (called a supernova). Nucleosynthesis provides further evidence for big bang cosmology. Stellar processes cannot account for all the elements in the Universe. Stars are formed in dense clouds of hydrogen gas in space, so stars do not explain the existence of hydrogen itself. And even though stars convert hydrogen to helium, there is too much helium in the Universe to have originated solely from stars. (Most stars actually convert helium into heavier elements, so the helium they produce is processed into elements other than helium). There must be or have been some other process that produced these chemical elements. Big bang cosmology can explain the origin of these elements.

Homogeneity*, *Isotropy*,** and ***Cosmic Irregularities: The Universe is *homogenous* in the sense that matter is evenly distributed throughout it when viewed on large scales. Similarly, our Universe exhibits a large-scale *isotropy*. It looks the same in all directions. It is symmetric. This is evidenced strikingly in the cosmic background radiation that pervades the cosmos, a left over relic from a time when the Universe was about 300,000 years old. The fact that the Universe is homogenous and isotropic implies a good deal of fine-tuning at the very beginning because any deviations from uniformity then would be exponentially increased as time passed and the Universe expanded. There are of course smaller-scale *irregularities* imposed on the over all smoothness of the Universe, and these give rise to more interesting structural features of the Universe, such as stars, galaxies, and galaxy clusters. These are much like waves or ripples on an otherwise smooth ocean surface. The size of the cosmic ripples is 10^{-5} (often referred to as Q). Q gives the Universe the requisite roughness to develop an interesting array of cosmic structures. Big Bang cosmology assumes but does not explain why the Universe started out in such a synchronized fashion, with a near perfect uniformity but just enough roughness to produce galaxies and other cosmic structures.

Flatness and ***Critical Density***: If the average mass-density of the Universe exceeds about five atoms per cubic meter, then the Universe has a density high enough to eventually halt its expansion (gravity will overcome expansion energy) and the Universe will collapse. Otherwise expansion energy will have the upper hand and U the universe will expand for eternity. *Critical density* refers to the mass-density that places the Universe on the border of eventual collapse and eternal expansion (and gives it a flat or Euclidean geometry). The ratio between the actual and critical density is called Omega. Full critical density is an Omega = 1.

Since most of the matter of the Universe is unseen (so called dark matter) it is difficult to determine what the actual density is. The matter that makes all the stars in the Universe (not just our galaxy, but every galaxy) contributes only a fiftieth of the critical density (roughly 1/10 of atom per cubic meter). Gases between galaxies contribute about as much. So dismantling all the visible matter in the cosmos would yield only 0.2 atoms per cubic meter, far less than is needed to exceed the critical density. There is also dark matter, but it probably does not contribute more than a fifth of the critical density. So the average density today is at least 0.3. But if omega today is at least 0.3, it must not have been too far off from 1 a second or two after the big bang. Deviations from unity or 1 would have been amplified during expansion. Thus if omega began much higher than 1, gravity would have quickly overcome expansion energy. If omega were much less than 1, expansion energy would have overcome gravity, which would have thrust omega toward zero. For instance, a beginning omega of .5 would have dropped to .25 after the universe expanded to a factor of two. So because omega is at least 0.3 today, it could not have been too far from 1 immediately after the big bang. The Universe likely has a flat geometry, but this flatness is an indication of an importance balance between expansion and gravity.

Fine-Tuning: Fine tuning generally refers to the unique values assigned to important cosmic numbers at the dawn of time, immediately after the big bang. These numbers and their significance are discussed by Rees. Among other things, the universe has just the right sort of ripples or roughness imposed on just the right sort of smoothness to produce a uniform universe that also has interesting cosmic structures like stars and galaxies. The universe also has just the right expansion rate to allow for the formation of stable stars. All of these are crucial to making the Universe a life conducive-system. Life requires a narrow range of chemical elements (such as carbon), and these elements depend on fundamental laws and initial conditions of the Universe having just the right sort of values and ratios to each other. Hence, more specifically, the fine-tuning of the Universe refers to that fact that the Universe's physical laws and initial conditions (at the big bang) are calibrated within a very narrow range so as to make the Universe conducive to life. This fine-tuning is *a priori* very unlikely.

Inflationary Cosmology: Developed in the last 30 years by scientists such as Guth and Linde, inflationary theories of the Universe are supplements to big bang cosmology (not alternatives).

Explanations of the classical hot big bang model often includes extrapolations back to a zero-point in the form of a singularity. This is understandable given that such an extrapolation seems implied by cosmic expansion. In fact, though, the original hot big bang model is really an account of what happened *after* a hypothesized bang, not necessarily an extrapolation to times earlier than this. It gives us a description of the way the Universe was immediately after its creation. This is because the *predictive* elements of the theory only take us back to right after the first second of the Universe's existence or perhaps at 10^{-35} second. (At 10^{-35} sec., the Universe was about 3 millimeters in radius). The microwave background radiation (part of the original theory) takes us back to 300,000 thousand years after the beginning, when the Universe was about 3000. Our knowledge of nucleosynthesis allows big bang extrapolations back to one second after the beginning when helium began to form. Big bang cosmology does not tell us about the conditions that prevailed prior to the first second or millisecond. Hence, the theory must assume and leave unexplained several important features to the Universe at that time.

Around 10^{-35} sec many of the crucial conditions that would determine the later structure of the Universe were determined. For instance, the expansion rate of the cosmos was imprinted at this time. The conditions that dictated the large-scale isotropy and small-scale irregularities of the cosmos were also imprinted at this time. In other words, big bang cosmology begins with an incredibly fine-tuned Universe and does not attempt to explain the mechanism involved in the very big bang itself.

Inflationary cosmology attempts to provide an explanation of the big bang itself. Inflationary theory postulates the emergence of the observable universe through an exponential rapid expansion phase from an unstable vacuum state. (A "vacuum" is the state of lowest possible energy density). More specifically, the universe emerges from a "false vacuum," a temporary vacuum with enormous energy density. Matter at high densities experiences negative pressure. If this negative pressure sufficiently outweighs the positive density, it can create a repulsive force. This repulsive gravitational field can drive an exponential expansion, like a balloon suddenly being filled with air at an incredible rate. Classical big bang cosmology and inflationary cosmology describe the same sort of Universe at all times after 10^{-35} seconds. However, unlike big bang cosmology that starts the Universe off at about 10^{-5} cubic meters in radius, inflationary theory begins at even early epoch of time when the Universe was around 10-52 cubic meters in radius. (Atomic radius is 10^{-10} meters) Inflationary theory also predicts some of the values involved in fine-tuning. For instance, inflation pushes the Universe toward flatness, and so explains why omega should be close to 1. It also explains why the Universe is isotropic but with sufficient irregularities to generate cosmic structures. Minor fluctuations in the vacuum are exponentially increased during expansion, leading to variations in density levels in certain regions of the Universe. These density perturbations form the seeds of galaxies.

Many Worlds Hypothesis: This is the view that our observable Universe is only one of many millions of other Universes. Guth, Rees, and many others argue that multiple universes are an implication of inflationary theory. The quantum processes that produce the observable Universe may also be responsible for producing millions of other Universes. The false vacuum may be like a pot of boiling water. When heated, a pot of water produces a whole host of bubbles through a percolation process. The false vacuum's unstable character may be like this. If it produces one universe, it produces many, perhaps an infinite number of them. In that case, our Universe is just one pocket universe from among an unlimited number of others. (Guth suggests that the false vacuum is eternal, i.e., has no beginning). This is a very important conclusion since it *may* reduce the surprising character of fine-tuning in our Universe. If there are millions of Universes, each with different values for the various crucial cosmic numbers, one of them is bound to throw up the values required for a life-producing Universe.