Big Bang from Nothing

(Published in Dream 2047, monthly journal of Vigyan Prasar, March 2017)

http://www.vigyanprasar.gov.in/dream/dream2017/march2017/dream-march-2017-eng.pdf

There was absolutely nothing at the beginning of time and space; it was a complete void. Human imagination falters at the thought of such a void. Out of this unthinkable, all-pervading void arose a stir, a random quantum fluctuation, and time and space and all the matter and energy that is our Universe – this unfathomably beautiful ocean of existence – sprang into being. It was a creation *ex-nihilo* – out of nothing. This tiny fluctuation of the vacuum would ultimately turn into the Big Bang, creating the Universe of countless galaxies and stars, and in course of time, creatures capable of wondering at the mystery of their origin.

It is indeed strange and bizarre that nothingness would have such a wondrous creative potential latent in it. The idea that a void could convert itself into such a remarkable plenum of existence was first suggested by Edward Tryon, an American scientist in the journal *Nature* in 1973. It has long been known that every physical phenomenon in this Universe is guided by a set of conservation laws in which some particular physical quantities like electric charge or total energy or total momentum remain unchanged; we say these quantities are 'conserved'. Tryon in his paper 'Is the Universe a Vacuum Fluctuation?' pointed out that the sum of all the conserved charges for the whole Universe was consistent with being zero. Similarly, the total energy of the Universe also adds up to zero. It is because while the energy of all the matter ($E=mc^2$) is positive, the energy of the gravitational field through which they interact is negative.

That energy can be negative is in itself a strange idea, but strange ideas are what science takes sustenance from. Gravity is the strangest and the most bizarre of all the forces in nature. Every mass attracts every other mass, and thus has its own gravitational field over which the attractive force of its gravity acts and pulls at every other mass with a force, which is inversely proportional to the distance between them. The gravitational energy of the objects is zero, when they are at 'infinite' distance away.

When a body is brought near to another from far away under the attractive force of their gravity, the energy of the bodies is liberated rather than expended, i.e., they lose energy. They start with zero gravitational energy, and end up with negative energy. This is what is meant by saying that the energy of the gravitational field is negative. Any object, say a planet or a star, contain an infinite number of small masses put together, and thus has a definite amount of negative gravitational energy. In contrast, the mass-related energy of the body is always positive, being equal to the product of its mass and the square of the velocity of light ($= mc^2$).

What Tryon showed was that if the star is squeezed into a singularity, a point where the quantities that are used to measure its gravitational field tend to become infinite, its negative gravitational energy will continue to increase and then, at the singularity, its positive mass energy will exactly cancel the negative gravitational energy. Thus, the negative energy of the

Universe can be shown to cancel all the positive energy leading to a vacuum state equivalent to zero energy. This means it would take no energy to create the Universe. And thus the laws of physics are perfectly consistent with the creation of a Universe *ex-nihilo,* out of a void, and the Universe could emerge out of the void without violating the law of conservation of energy, a sacrosanct principle of physics. It was a random event which occurs purely governed by chance, guided by no laws, and, therefore, needing no lawmaker or God.

That the Universe has zero net energy could also be experimentally found from the rate of expansion of the Universe. The rate of cosmic expansion depends on the overall density of mass in the Universe, i.e., the amount of matter per unit volume. This quantity, denoted by the Greek letter omega (Ω), can be measured. The latest measurement reveals that it is close to unity. If it were less than unity, then the Universe would continue to expand forever and it would be 'open'; if it were more than unity, then the expansion of the Universe would come to a grinding halt, resulting in the collapse of all matter in a 'Big Crunch' as grand as the 'Big Bang' and the Universe would be 'closed'.

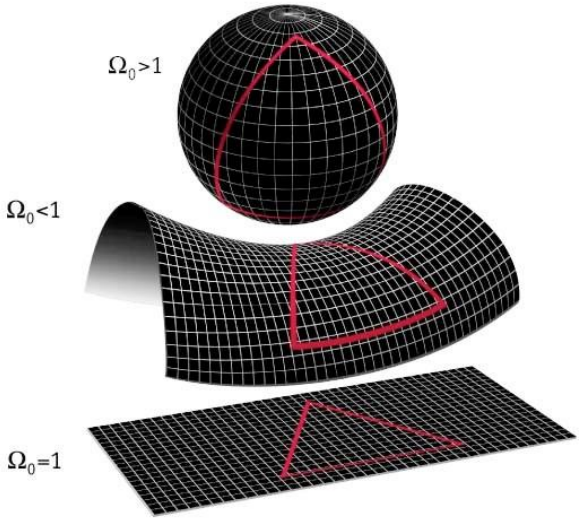
The first 300,000 years since the Big Bang was filled with radiation which was so hot that matter could then exist only in a dense state of 'plasma' consisting of protons and electrons at extremely high temperature. However, plasma is opaque to radiation, and even if it was possible to look as far back into the past towards the Big Bang, the surface of the 300,000-year-old Universe would permanently block our sight and we would not be able to 'see' anything earlier than that, since we can see only with the help of light. Therefore, the 300,000-year-old Universe is the earliest frame of reference for any measurement to be made.

At 300,000 years, the temperature of the incredibly hot Big-Bang Universe had dropped to only 3000 Kelvins[1] when electrons started combining with protons forming neutral atoms, mostly of hydrogen, and the Universe started becoming transparent to radiation. From then on, atoms would start absorbing and reemitting the photons that would be scattered by other particles of matter, making the Universe transparent to light. As the expansion continued unabated, cooling the Universe, the colour of radiation changed gradually - from yellow to orange to red to a deep red and then to the darkness of deep space.The Universe had expanded about 1,000 times since then and the wavelength of the photons has also stretched by the same factor. As temperature dropped ultimately to only 2.73 kelvins, the sea of photons would thus fade away slowly, changing from high-energy gamma radiation to the low-energy microwave radiation. This cosmic microwave background radiation was detected by Penzias and Wilson in 1964 with their radio telescope, which earned them a Nobel Prize.

The microwave background radiation is uniform and homogenous. Since our reference frame is the 300,000-year-old Universe, we can assume that matter and energy were distributed uniformly in that Universe. If we can take a picture of our 300,000-year-old Universe, we would be able to see all the nascent structures in that Universe – the small lumps of matter that were formed till that time arising from tiny perturbations in matter and energy in the very early Universe. These lumps would later evolve into galaxies, stars and planets that would define the large-scale structure of the Universe billions of years later. This would enable us to measure

[1] Kelvin scale temperature is obtained by deducting 273 from the corresponding Celsius scale temperature.

whether the Universe is open, closed or flat. If the universe was close, the lumps of matter would be close together making for higher density (Ω>1), while in an open universe they would be scattered farther away from each other and Ω would be less than 1. If the Universe was flat, Ω would be close to 1.



Three possible geometries of the Universe[2]

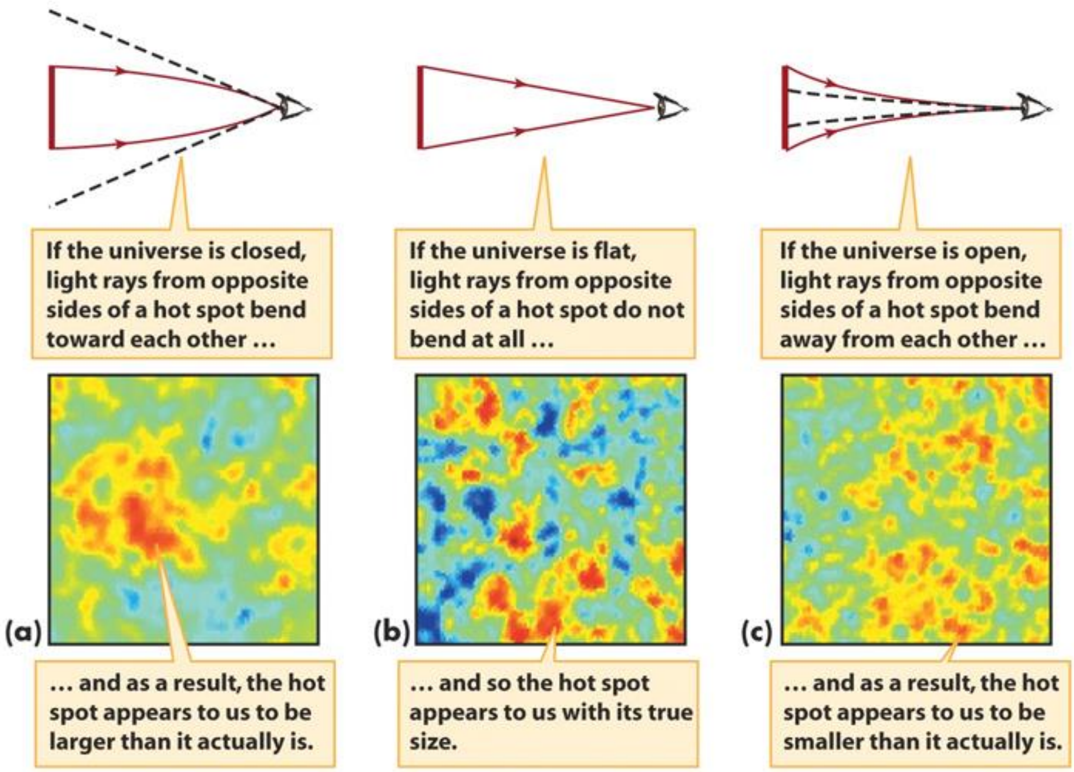
An arc on the surface of this Universe 300,000-year-old that subtends an angle of 1 degree at the earth would cover a distance of about 300,000 light years across. But here our assumption of one degree needs a qualification. The angle would actually be determined by the geometry of the surface of the Universe.

On a flat surface, light rays travel in straight lines and a triangle traced by them would consist of three straight lines enclosing 180 degrees, as we know from Euclidean geometry. But in a closed universe shaped like a sphere, such a triangle would include more than 180 degrees; light rays in such a Universe would converge when we look backwards in time. In an open universe shaped like a saddle, the three angles would enclose less than 180 degrees and light rays would curve outwards as we follow them backwards in time. Thus whether the angle covered by a distance on 300,000 light years on the surface of the a 300,000–year-old Universe would be exactly one degree, or more or less would depend on the geometry of this Universe.

To determine the geometry, an experiment was designed in 1997, and repeated in 2003, called BOOMERANG (**B**alloon **O**bservation **O**f **M**illimetric **E**xtragalactic **R**adiation **AN**d **G**eophysics). It mapped the 3 K microwave sky by circling over Antarctica at an altitude of 42 kilometres, to avoid any contamination by far hotter temperatures elsewhere on Earth. The high-altitude balloon, with the help of an onboard microwave radiometer, captured the image of a small part of the microwave sky, 'displaying hot and cold spots in the radiation pattern'. This pattern replicated the structure of the 300,000-year-old Universe, since that structure

[2] Source: http://timcooley.net

would have remained unaffected by the subsequent 'dynamical evolution' of the Universe. The image of the microwave sky was compared with the computer simulations of images for closed, open or flat Universe. The captured image showed an uncanny resemblance with the simulated image for a flat universe, indicating that its geometry is Euclidean, not curved. The BOOMERANG results were reported in 2000, after 50 million observations for each of 16 channels at four frequencies in the microwave radiometer, and indicated that the Universe was indeed flat.



Appearance of hot spots in BOOMERANG experiment depending on the specific structure of the Universe [3]

The results of the BOOMERANG experiment are extremely important to explain the creation of the Universe, because unlike an open or a closed Universe, a flat universe would not require any energy that already existed somewhere to create it. Thus quantum fluctuations alone would suffice to create such a flat universe from nothing, as postulated by Tryon.

When Hubble's observations about the expanding Universe had pointed towards the Big Bang origin of the Universe, physicists faced an insurmountable problem. If we wind the cosmic clock backwards, we arrive at the beginning of the Universe when all matter and energy of the Universe were concentrated at a point from whence the Universe sprang into existence. But, then, concentration of all matter and energy at a point would imply a state of infinite compression, and space (along with time, since there can be no space without time) would disappear at such a state, as it would have been compressed infinitely so as to disappear

[3] Source: http://ircamera.as.arizona.edu

completely. This state is known as a space-time singularity. Because all laws of physics are framed in terms of space and time, there cannot be any law of physics at this point when space-time itself ceases to exist. Thus all laws of physics would break down at a singularity. How then could one explain the origin of the Universe? Yet Big Bang was an established reality, tested by experiments, which could not be easily explained away. Actually Big Bang did not happen at a point in space; rather space, along with time, itself came into existence with the Big Bang.

Scientists could not find a convincing way of resolving this difficulty. As long as this mystery was not resolved, there was still the scope to invoke an all-powerful God to trigger the creation event. To understand how the problem was solved by physicists in the 1980s, we have to redirect our focus away from the grand world of stars and galaxies into the microscopic world of fundamental particles – and follow the laws that guide their behaviour, i.e. the laws of quantum mechanics.

At the turn of the 20th century, two remarkable developments had revolutionized our comprehension of the physical world. One of course was the theory of relativity, but equally remarkable was the discovery of the laws of quantum mechanics in the 1920s, which recognized probability as a fundamental feature of the atomic reality which governs all processes, even the existence of matter.

Quantum theory started with investigating the nature of propagation of light. Till then, it was held that light was propagated in the form of a continuous wave. In an ultimate break from classical physics, quantum theory proved not only that light was emitted and absorbed in a discontinuous manner, it was also propagated in a discontinuous manner, in small packets of energy called photons or quanta. Eight years later, in 1913, Neils Bohr applied these ideas to build up his model of the hydrogen atom, which, with astonishing simplicity, could successfully explain the radiation of spectral lines by atoms. Quantum mechanics had indeed come to stay!

But the new theory threw up more problems than it solved, as science always does. Discreteness is a property associated with particles, not with waves. We can visualise streams of particles, and if light consisted of streams of photons, each with a definite amount of energy (= Plank constant h multiplied by the frequency of light), then light should always behave as particles. But it was also a well-established experimental fact that light did behave as if consisting of waves, as evident from the experiments on interference of two beams of light derived from the same source, or from experiments on polarisation, i.e., cutting out some of the vibrations in the waves. They could only be explained in terms of the wave theory. A wave is a spread out thing in space while a particle, like the photon, is a localised thing. How can something which is spread out be localised at the same time? These two concepts were apparently irreconcilable.

Failure of this theory to explain the wave properties of light would open up a whole new dimension about what physical reality, and that reality turned out to be far stranger than fiction. So strange was it that even Einstein, whose theories played a crucial role in establishing the nature of this reality, refused stubbornly to accept its implications, by saying that God did not play dice with the world.

Classical physics taught us that particles and waves are separate entities; together they constitute the physical reality. Quantum physics told us that in the micro-world of atoms and electrons, there was no such thing as a particle or a wave; that it depended entirely on our observation and interpretation whether an electron would behave as a particle or as a wave. Classical physics made us believe that we were independent observers in a world where the particles and waves played their respective roles to be observed and interpreted by us. Quantum physics told us that we were no longer the 'outside' observers in this Universe. We are, in fact, participators in Nature's scheme of things, and being participators, we also determine the course of events. In the world of quantum mechanics, no event is an event unless it is observed. The act of observation itself interferes with the course of the event being observed and thus determines it. Thus, just as light, which is an electromagnetic wave, can behave also as streams of particles, so also a particle like electron, which exhibits the particle properties by possessing charge and mass, can also behave as a wave. How either will actually behave, however, depends on what observation we decide to make on them.

Another important pillar of the Quantum Theory is Heisenberg's 'Uncertainty Principle' which sounded the death-knell of the principle of scientific determinism. A particle is associated with certain pairs of properties, e.g., position and momentum, energy and time, etc., which according to classical physics could be accurately determined. By knowing the position and momentum of the particle precisely at any given instant, it is possible, according to classical physics, to predict its entire future course. But a particle is not simply a particle in quantum mechanics; it is only one description of the reality, the other being its wave properties. The uncertainty principle only measures the extent to which these complementary descriptions overlap.

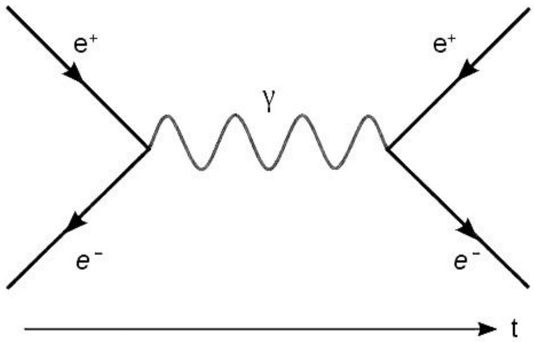
Position and momentum (= mass*velocity) are fundamental properties of a particle. But a particle is also a wave, and a wave cannot be reduced to a point; it always shall have a spread, and this spread therefore measures the uncertainty in the position of the particle. Similarly, momentum of the wave depends on the wavelength, and the spread in wavelength also determines the uncertainty in the momentum.

The interesting thing is that the length of the region the particle occupies and the spread in its associated wavelength are not independent, but are inversely related to each other; the more we want to localise the particle by confining it to smaller and smaller regions, the higher will be the spread in wavelength. In other words, the more certain we want to be about the position of the particle, the more uncertain we shall be about its momentum and *vice versa*. The Uncertainty Principle says that the product of the uncertainties is limited by the Plank's constant h. The energy possessed by a particle and the time interval during which it possesses that energy also exhibit an identical relationship of uncertainty.

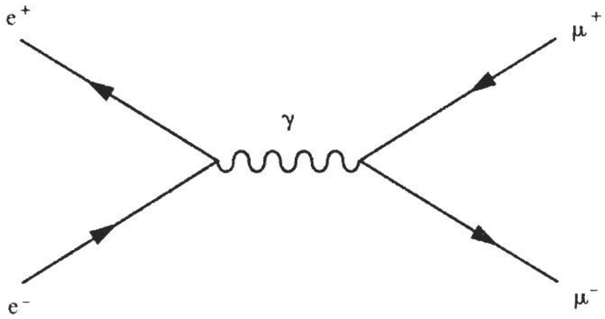
The consequence of this is startling – it means that during an infinitesimally small interval of time, an atomic event can possess unusually large amount of energy without violating the principle of conservation of energy. Since energy and matter are basically the same, therefore this amount of energy can be large enough to allow for the spontaneous creation of quantum particles (e.g., an electron) and its antiparticle (positron), which are equal in all respects except for the electric charge. The two charges exactly cancel each other and conform to the law of conservation of charges. Particles created from photons are called virtual particles, which do not have any real existence as they exist only for the brief time interval allowed by the uncertainty relation and then annihilate each other, liberating the energy that has gone into their making before any human device could register their presence.

The uncertainty relation thus implies that energy can be created out of nothing for extremely short time periods and virtual particles can go in and out of reality spontaneously. It allows virtual particles – ‘virtual’ because they cannot be observed directly, they pop in and out of existence quantum mechanically – to carry almost infinite amounts of energy, provided they last for infinitesimally short intervals of time before disappearing again. They can be created out of nothing carrying ever larger amounts of energy and disappear again into nothing in ever shorter intervals of time. The process is a random one, and thus a vacuum randomly fluctuates between being and nothingness, between form and emptiness, though in the end they cancel each other out. Only if enough energy is supplied to this vacuum from an external source, these virtual particles in the vacuum would become real.

Thus vacuum, or empty space, in reality is not empty, but rather a plenum where matter and energy are being created and destroyed continually in a superb cosmic dance. These ideas of the relativistic quantum field theory were conclusively proved in experiments conducted at CERN, Geneva, in the giant superconducting super-collider accelerator machine where collisions between matter (made up of particles) and anti-matter (made up of anti-particles) provided the energy necessary to bring the virtual particles fluctuating in vacuum into real existence .



An electron and a positron annihilate each other producing energy in the form of gamma radiation (left), and an electron-positron pair pops out of energy as virtual particles (right)



An electron and a positron annihilate each other producing energy in the form of gamma radiation (left), and another particle-antiparticle pair of muons as virtual particles (right)

But the problem is who supplied the extra energy to one virtual Universe to create this real Universe? The answer is gravity, the oldest known and perhaps the least understood physical phenomenon. The reason that real particles cannot spring into existence out of empty space is that our space today is flat in which a light ray is constrained to travel ordinarily in a straight line, and for such a space, the law of conservation of energy dominates, forbidding such 'real' creations. But at the beginning of space and time, when no law including the law of energy conservation existed, creation of 'real' particles by a random quantum fluctuation of the vacuum was a distinct possibility if space was extremely curved, like a sphere. In the first such mathematical model of the Universe developed in 1978, it was shown that a fluctuation could produce a few particles and then the mutual gravitational interaction between them would cause space to become curved, leading to a cascade of more particles and more curvature of space and this would result in an expanding Universe starting from a hot Big Bang.

But the problem still remained. As soon as the Universe containing as much matter as it actually contains starts expanding soon after its creation, the enormous gravitational pull between all the matter confined within a volume as small as an atomic nucleus would force it to collapse upon itself, creating a new singularity in which everything would disappear instantaneously. There has to be a mechanism to expand this nascent Universe, during the split second of its virtual existence, incredibly rapidly so that its size increased manifolds before gravity could start working. The puzzle was solved finally by Alan Guth and Alex Vilenkin, by suggesting a mechanism of 'inflation'. In 1983, Vilenkin had constructed a model and a mechanism for a Universe in which a 'nothing', a 'void', could randomly convert itself into geometry of space-time from which a Big Bang would result. Thus space-time could come into existence out of absolutely nothing and could just as well disappear into nothing.

It is now possible for us, imperfect human beings, to look into and explain the Genesis without invoking the all-knowing intelligence of an omnipotent God. From the frothing sea of vacuum, the structure of space-time came into existence as a random event at zero time. We recall that the quantum effects become dominant when the numbers, dimensions, time are of the order of Planck's Constant ($\sim 10^{-27}$) or smaller. The earliest time the calculations of relativistic quantum gravity has so far probed into is 10^{-43} second (10million trillion trillion trillionth of a second) after Genesis. This is known as the 'Planck time'. The temperature of the Universe was an enormous 10^{32} kelvins, and its size of the order of Planck length, which is 1.6×10^{-35} metre. It was at this stage that gravity started asserting itself, twisting and warping the structure of space-time upon which the future events will take place. It was a microscopic and empty Universe – just a point upon a timeless, spaceless, perfectly symmetrical vacuum. Human imagination stumbles to grasp such a state of non-being.

The symmetry would soon break and a billionth of a second later, the cosmic cast of all matter would appear in the form of quarks, leptons and gluons, which would eventually form the atoms and molecules and stars and galaxies. The primeval void would ultimately evolve into the present cosmos. Emptiness would take form.