our DNA. Were the magnetic field to disappear, as is the case on Mars, it could be terminal for our species.

Pascal and Perier had shown that there is a vacuum beyond the Earth, meaning that there is no air. There is little or no gas out in space, but there is certainly a very important something in the form of the Earth's magnetic field.

Gravitational fields and the inverse square law

Gravity is the most familiar force but it is actually rather feeble: it is easy to pick up an apple, defeating the gravitational pull of the entire planet. Our muscular strength comes from the much more powerful electrical forces, which give us shape and form. However, the attractions and repulsions from positive and negative charges within matter annul one another, whereas the gravitational attraction from each and every atom in a large body adds up. Gravity rules once an object is larger than about 500 km in diameter.

Caring nothing for direction, pulling in all three dimensions the same, gravity makes spherical bodies. This is the case for the Sun, the bumps and valleys on the Earth being mere ripples on the surface caused by geological action, and its oblateness being due to its spinning around once each day.

For extremely large bodies the effects of gravity accumulate to exert a powerful pull. The Sun, no more than a thumbnail in size as viewed from the Earth, can entrap us and the planets in a cosmic waltz around the vastness of space hundreds of millions of kilometres distant. How is this influence spread throughout space?

It was Isaac Newton who had the seminal insight that gravity's pull between two bodies diminishes as the square of the distance between them increases. This 'inverse square law' of gravity's weakening with distance is critical for the structure of the universe

and also possibly for the development of physical science. We are trapped on Earth that orbits the Sun; the small but relatively nearby Moon gives a gravitational tug that determines the tides, but the remote galaxies of stars don't measurably affect this. Tides, eclipses, and the flight of spacecraft can be determined without needing to take account of those distant masses. Had the force of gravity been independent of distance it would have been those remote galaxies that ruled, and the Earth would have been unable to condense under its own gravity. Had it fallen in direct proportion to distance it is possible that we could have inhabited a planetary earth but arguable whether the rules of gravity would have been determined; the ability to ignore all but two bodies, with small perturbations from a third, is what has enabled computations to be made and the basic rules to have been determined.

how so?

The inverse square law of force is not unique to gravity: the same occurs for the electrical forces between two charged particles. Given the number of possibilities that might have been, it is intriguing that both the electric and gravitational forces exhibit the same inverse square behaviour. The reason is intimately due to the three-dimensional nature of space and the fact that gravity fills all of it, as do electrical fields at least in the vicinity of a single charge.

? ha!

A massive body, such as the Earth or Sun, somehow sends out its gravitational tentacles into space in all directions uniformly. The Earth's orbit around the Sun is nearly circular. Imagine the Sun at the centre of a ball whose diameter is the same as that of the Earth's orbit. The gravitational tug on our planet is the same at all points on the surface of the imaginary ball. If we now imagined ourselves transported to an orbit that was double that of the Earth's, the surface of the imaginary ball would be four times greater as the area increases with the square of the distance. Newton realized that if the force of gravity were likened to tentacles spreading out from the source in all directions symmetrically, then the intensity at any distance would be spread light with respect to the speed of source or observer is a result, in part, of distances contracting as in Lorentz and Fitzgerald's formula but this was not due to any ether acting on the rod. For Einstein the contractions are an intrinsic property of space itself. Distances and time intervals as recorded by observers at different speeds take on different measures; what is space for one observer is a mix of space and time for another. These ideas, which are the basis of Einstein's theory of relativity, formed a completely new world view.

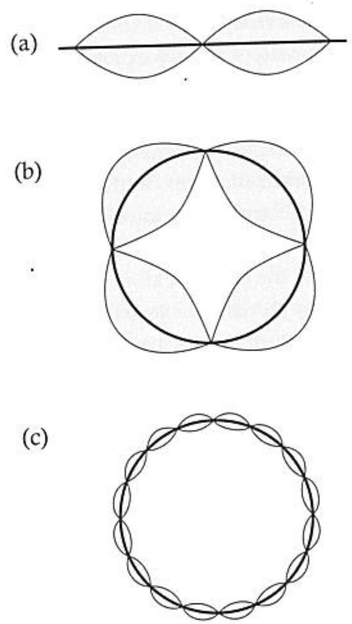
Which does however imply that the L-F ether has not been falsified, it was just replaced with an equivalent concept called "space".

Chapter 5
Travelling on a light beam

Michelson and Morley's experiment showed that the Earth does not measurably move relative to the ether. Lorentz and Fitzgerald had proposed that the ether distorts the measuring apparatus so as to mask the motion, but Albert Einstein realized that there was a more radical explanation: there is no ether at all!

The fact that the velocity of light is independent of the speed both of the source and of the receiver was an enigma, though it is not clear to what extent Einstein was aware of this result (see page 68). In any event he had begun to muse about the symmetry of things with respect to motion. If there is no ether there is no absolute space and hence no absolute motion: only relative motion has physical meaning.

Einstein knew that light is electromagnetic radiation whose properties are described by Maxwell's equations. He thought about how this radiation would appear to two observers who were moving relative to one another. Specifically he made a series of 'thought experiments', more usually referred to by their German analogue 'gedankenexperiment', which involves imagining a situation according to the laws of physics.



8. **Electron waves in the Bohr atomic model**

What are these waves and how do they relate to the uncertainty principle that we met above? Such questions have plagued science ever since the birth of quantum theory. Einstein and Bohr, among others, argued at length about the meaning of quantum theory, so forgive me if I do not profess to have the answers. Here is how I try to come to terms with it; if you prefer some other then please proceed with that as there is no agreed wisdom as to any 'official' explanation.

At the purest level one just has to accept the uncertainty principle and its implications. However, it is always more comforting when we can form a mental model with properties that the theory has, as then we can develop intuition about its behaviour and implications. The position and momentum uncertainty does have

an analogue that we are familiar with. Draw lots of dots to form a wave with a fixed wavelength; then if we identify position as the location of a given dot in the wave, and momentum as the wavelength; this is an analogue of the uncertainty principle at work. According to quantum mechanics, the higher the momentum so the shorter is the wavelength. Suppose I know the position precisely; then all I have is a single dot and it is impossible to know what the wavelength will be; it could be anything you want. If I have a few dots forming the beginning of the wave, then I will begin to see if the wavelength is small or large, and only after I have a complete wavelength will I be able to say with absolute certainty what its value is. However, the price of this certainty in knowing the wavelength is giving up knowledge of position to any better precision than the length of the wave. Mathematically this is realized by Fourier analysis – the representation of any curve, or even an abrupt spike, as a superposition of waves with different wavelengths. A singular spike at a precise location is equivalent to a sum over an infinite set of waves of all wavelengths.

One sees here that it is an oxymoron to define the position of a wave; it only becomes a known wave when one measures over its full wavelength. If this at least opens your mind to accept that there are familiar concepts for which position and another quality cannot both be meaningfully defined with precision, then one is beginning to appreciate the nature of the quantum world. The fact that waves have these properties makes them very useful as mental models of what is happening. However, in my opinion that is all that they are: mental models.

A seething vacuum

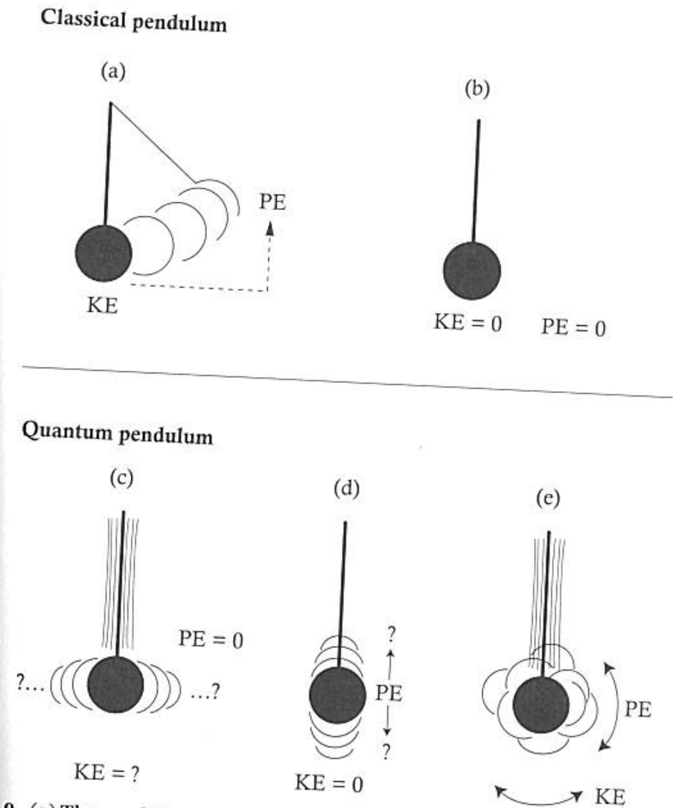
Imagine a region of vacuum, for example a cubic metre of outer space with all of the hydrogen and other particles removed. Can it really be devoid of matter and energy? In the quantum universe the answer is no.

Iaving the precise information that there is no particle at each and every point implies knowing nothing about motion and hence of energy. You may remove all matter and mass, but quantum uncertainty says there exists energy: energy cannot also be zero. To assert that there is a void, containing nothing of these, violates the uncertainty principle. There is a minimum amount known as zero point energy, but that is the best you can do. It is possible to visualize this by considering a pendulum consisting of just a few atoms.

The precise speed of a particle can only be determined if its position is unknown. This implies that a small cluster of molecules suspended by a thread of atoms and swinging like a pendulum could never come completely to rest, hanging vertically, with the ball of molecules stationary at the lowest height, or 'zero point'. Instead, quantum uncertainty implies that it must wobble slightly around this position. This phenomenon is called zero point motion.

As it swings under the influence of gravity, the higher above the zero point the molecules are, so the greater is their potential energy. At the top of the swing the potential energy of a macroscopic pendulum is at its maximum, the kinetic energy being zero; conversely, at its lowest point the potential energy is zero and the kinetic energy is maximal. Things are more subtle for a 'nanoscopic' quantum pendulum. If we minimize the potential energy by restricting the pendulum's ball to be at height zero, its state of motion and hence kinetic energy become indeterminate. Conversely, minimize the kinetic energy by having the pendulum at rest, and its height above zero becomes unknown. Quantum mechanics implies that there is a minimum sum of kinetic and potential energies that can be achieved: both cannot simultaneously be zero. This minimum amount is the zero point energy of the atomic assembly.

For a macroscopic pendulum, such as in an antique clock, this zero point energy is too small to notice. However, for clusters of



9. **(a) The pendulum starts high up at rest: its potential energy (PE) is big and its Kinetic energy (KE) is zero. Gravitational force swings it downwards; at the lowest point where it has no PE, it will have its maximum KE. Throughout the swing the sum of PE + KE is a constant. (b) It is possible to hang the pendulum vertically and at rest. The PE is zero as is the KE. The total energy is therefore zero. (c) For a quantum pendulum we cannot have PE and KE simultaneously zero. Hanging at the lowest point with PE = 0, the motion is indeterminate, and so the KE is unknowable. This is 'zero point motion'. (d) Alternatively, if the pendulum is at rest with KE = 0 its position and hence PE are undetermined. (e) There is a minimum sum possible for PE + KE known as the zero point energy**

principle?

What are CAs with prop comparable to uncertainty

a few atoms and molecules this minimum energy is comparable to the total energies of these groups of particles themselves. The zero point energy is then manifested by motion, for example of the atoms within molecules and of the individual molecules within the bulk cluster. Thus while the motion of molecules in a substance gives rise to what we call temperature, the higher the temperature so the more agitated their motions, the quantum theory implies that there will remain an intrinsic zero point energy even as one approaches the absolute zero of temperature; this is −273 degrees Celsius, which is 0 K, zero degrees Kelvin. One implication is that it is impossible to achieve absolute zero of temperature where everything is both frozen in position and without momentum and energy.

The remarkable thing is that this applies to a finite size of space, even if there is no matter in it. The consequence is that a finite region of empty space, 'empty' in the sense of having all matter removed, will be filled with energy. All finite volumes of whatever size are subject to fluctuations in energy. For macroscopic volumes the effect is too small to notice, but for very small volumes the energy fluctuations are big.

link to dark energy?

As two pieces of light can cancel to zero due to their wave-like character, so can zero turn to two counterbalancing somethings. The Void may have no electromagnetic fields on the average, but fluctuations driven by the zero point phenomenon are always present with the result that there is no such thing as literally empty space. In the modern perspective, the vacuum is the state where the amount of energy is the minimum possible; it is the state from which no more energy can be removed. In scientific jargon this state of vacuum is called the 'ground state'. Latent within the laws of nature are excited states, with energy densities corresponding to one, two, or even billions of material particles or radiation. You can remove all of these real particles until you reach the ground state, but the quantum fluctuations will still survive. The quantum vacuum is like a medium, and from what we know

about the ground states in macroscopic collective systems, further surprises can be expected for the properties of the quantum vacuum, as we shall see in Chapter 8.

First we need to be convinced that zero point energy is real and not some artefact of mathematics. A physical consequence was suggested in 1948 by Hendrik Casimir and, after years of attempts, was finally demonstrated experimentally in 1996.

What does this look like as a pattern?

The Void is a quantum sea of zero point waves, with all possible wavelengths, from those that are smaller even than the atomic scale up to those whose size is truly cosmic. Now put two metal plates, slightly separated and parallel to one another, into the vacuum. A subtle but measurable attractive force starts to pull them towards one another. There is of course a mutual gravitational attraction of the one for the other, but that is trifling on the scale of the 'Casimir effect', which arises from the way that the plates have disturbed the waves filling the quantum vacuum.

Disturbance of pattern?

The metals conduct electricity and this affects any electromagnetic waves in the zero point energy of the Void. Quantum theory implies that between the plates only waves that have an exact integer number of wavelengths can exist. Like a violin string vibrating between its fixed ends giving a tone and harmonics, only those waves that are in 'tune' with the gap between the plates can 'vibrate', whereas outside the plates all possible wavelengths can still exist. Consequently there are some waves 'missing' between the plates, which means that there is less pressure exerted on the inside of the plates than on their outward faces, leading to an overall force pressing inwards. Quantum mechanics predicts how large this force should be. Its magnitude is proportional to Planck's quantum, h (as it is a quantum effect), the velocity of electromagnetic waves, c, and inversely proportional to the distance d between the plates to the fourth power, d^4. This implies that the force vanishes as the plates become far apart, which makes sense as for infinite separation we are back with the infinite void for which there can be no effect. Conversely, the force will be larger when the two plates are very close; in such circumstances it is possible to measure it, verifying both its magnitude and variation with the distance of separation.

The force has been measured, the effect confirmed, and the concept of zero point energy in the Void established. The Casimir effect demonstrates that a *change* in the zero point energy is a real measurable quantity, even though the zero point energy itself is not available. The amount of zero point energy is actually infinite and some misinterpretations of the theory have led to suggestions in tracts such as *Infinite Energy* (*sic*) magazine that this is a source of power that has been overlooked by science until tapped by workers in cold fusion and the like. Zero point energy is not like this. It is the minimum energy that a system, or the vacuum, can have.

The zero point motion of electromagnetic fields is ever present in the vacuum. The zero point energy of the vacuum cannot be extracted or used as power; the vacuum is as low as it gets. Yet the effects of zero point motion can be felt by particles passing through the vacuum.

An electron in flight wobbles slightly as it feels the zero point motion of the vacuum electromagnetic fields. To reveal this we need some measurable reference and an electron trapped within a hydrogen atom is enough to show that the vacuum is far from empty. The electron in hydrogen is moving at a speed of about 1 per cent of the speed of light. The spectrum of hydrogen reveals the energy changes as electrons jump between different orbits in the atoms. The differences in energies between the various levels are manifested as the energy of the light that appears in the spectral lines.

Techniques that had been developed in radar during the Second World War enabled post-war physicists to measure the energies of the spectrum, and by inference of the electrons, to an accuracy of better than one part per million. This led to the discovery of the 'Lamb shift', named after Willis Lamb who first measured it in 1947; this subtle shift relative to what quantum mechanics expected if the vacuum were truly empty agrees perfectly with calculations that include the effects of fluctuations in an effervescing quantum vacuum.

While quantum mechanics makes precise statements about phenomena on subatomic length scales, it does so while ignoring the effects of gravity. No one has successfully combined the two great pillars of twentieth-century physics – quantum mechanics and general relativity – to make a mathematically consistent and experimentally tested unified theory. In practice scientists sidestep this as the two theories are each flawless in their respective arenas. Yet in the first 10^{-43} s of the Big Bang, the universe was so small and gravity so all embracing that a theory of quantum gravity would rule. Establishing what this is remains one of the major unsolved challenges in mathematical physics. However, we can appreciate the profound implications it will have for some of the problems that we need to answer. For example, our experience is that the dimensions of space and time are somehow different, at least in our ability to travel through them and to receive or process information. While this subtle difference is true as perceived by our macroscopic senses, and to our description of natural phenomena down to the scale of atoms and beyond, when in those first moments our universe was compressed into a distance scale of about 10^{-35} m, a quantum theory of gravity would intertwine space and time inextricably. In quantum gravity, space and time must somehow be 'the same'.

The complementary uncertainty between motion, momentum, and energy, and location in space and time, suggests that in quantum gravity there are fluctuations occurring in the fabric of space and time themselves. If we were to measure distances that are as small compared to a proton as that proton is to a human, or to record time scales as short as 10^{-43} seconds, we would find that Newton's matrix had evaporated into a space-time foam. I cannot imagine what this would be like, but science fiction writers love it.

There is general agreement that the quantum vacuum is where everything that we now know came from, even the matrix of space and time. As we shall see, the seething vacuum offers profound implications for comprehending the nature of Creation from the Void.

The infinite sea

The stability of matter and the periodic regularity in Mendeleev's table of the atomic elements are ultimately due to the fact that electrons obey a fundamental rule of quantum mechanics known as the exclusion principle: no two electrons in some collection can occupy the same quantum energy state. When Paul Dirac first realized that quantum theory implied that electrons can have positively charged 'anti'-electron counterparts known as positrons, he used this exclusion principle to make a model of the vacuum that would naturally give rise to such unusual entities. He proposed that we regard the vacuum as being far from empty: for Dirac it was filled with an infinite number of electrons whose individual energies occupy all values from negatively infinite up to some maximum value. Such a deep, calm sea is everywhere and unnoticeable so long as nothing disturbs it. We call this normal state the ground state, which is our base level relative to which all energies are defined: Dirac's 'sea level' defines the zero of energy.

is mass interpretation of energy? [illegible]

Einstein's famous equation $E = mc^2$ can be rearranged to read $m = E/c^2$, which says that mass can be produced from energy. An electron and its antimatter twin, the positron, have the same mc^2

and equal but opposite signs of electric charge. So if the energy E exceeds $2mc^2$ it is possible for an electron and a positron to emerge. The energy fluctuations in the vacuum can spontaneously turn into electrons and positrons but constrained by the uncertainty principle to last only for a brief moment of less than $\hbar/2mc^2$, which amounts to a mere 10^{-21} s. This time is so small that light would have been able to travel only across about one thousandth the span of a hydrogen atom. Such 'virtual' particles cannot be seen any more than can the deviation from energy conservation that these fluctuations amount to. However, the implication that the vacuum is filled with virtual particles can be detected by careful and precise measurements.

An electrically charged particle, such as an electron or an ion, is surrounded by a virtual cloud of electrons and positrons. It is also surrounded by all other varieties of charged particles and their antiparticles; the heavier they are, the more nugatory is their fluctuation, and so it is the electron and positron, being the lightest, that are the dominant players. One effect of these clouds is to modify the strength of the electrical forces between two charged objects. The finer the microscope with which we look, the more we become sensitive to the effects of these virtual clouds in the vacuum. As an electron and positron pair fluctuate into and out of their virtual existence within only one thousandth part of an atomic radius, they can influence the force between the proton and remote electron in a hydrogen atom, which gives a small modification to the inverse square law of force, and also affect the magnetism of particles like the electron in calculable ways that agree with the data to a precision of better than one part in a hundred billion.

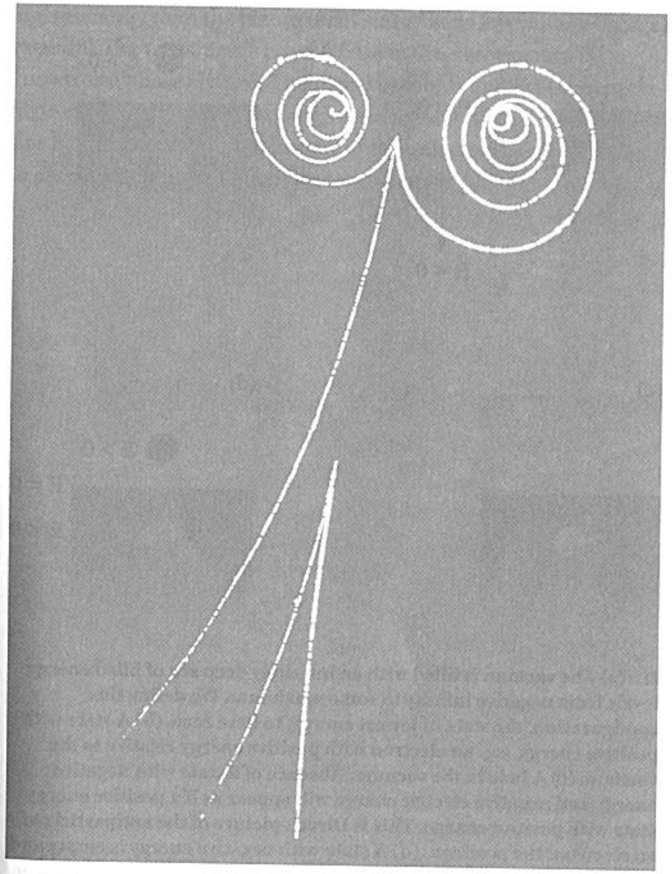
In Dirac's interpretation of the vacuum as an infinitely deep sea filled with electrons, if one electron in this sea were missing, it would leave a hole. The absence of a negatively charged electron with energy that is negative relative to sea level will appear as a positively charged particle with positive energy, namely with all the attributes of a positron. Fluctuations in the surface of the sea, in accord with the zero point energy phenomenon described earlier, could momentarily elevate an electron leaving a hole, appearing as a virtual electron–positron pair.

It is possible to make these virtual fluctuations visible by supplying energy to the atom. If a photon with energy greater than $2mc^2$ irradiates an atom, it is most likely that it will ionize that atom. However, it is possible that a virtual electron and positron are bubbling within the atom's electric field as the photon hits. In such a case the photon may eject them out of the atom, leaving the atom behind undisturbed. This phenomenon, known as 'pair creation', can be photographed in a bubble chamber leading to beautiful and enigmatic artwork as in Fig. 10. The two virtual particles thus become real.

For Dirac, such antiparticles are holes left in the infinitely deep sea that is the vacuum. This picture also resolves what would otherwise be a paradox. If the vacuum were truly empty, then what would encode the laws of nature, the properties of matter, such that all electrons and positrons created 'out of the vacuum' have identical properties, with specific masses rather than emerging with a random continuum of possibilities? Protons and quarks and similar particles also satisfy the exclusion principle and fill an infinitely deep sea. It is the infinitely deep storehouse of the Dirac sea that provides us with the particles that we can materialize.

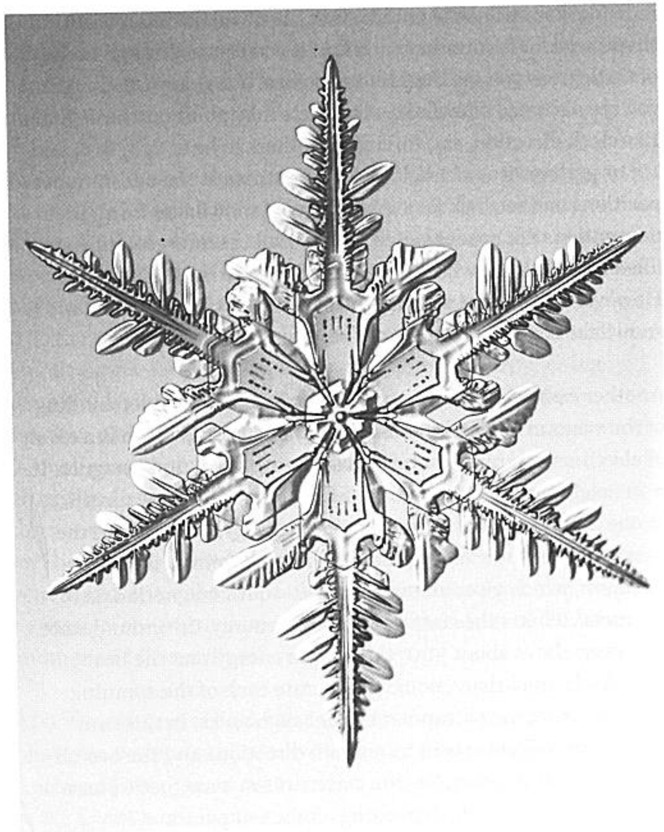
In this interpretation, the vacuum is a medium. It has profound connections with phenomena that occur in 'real' media, such as solids and liquids where vast numbers of atoms or particles organize themselves into different 'phases'. Thus the quantum vacuum is like the configuration with the lowest possible energy, the 'ground state', of a many-body system. We will see more of this in the next chapter. The implications are profound, including the

Does the vacuum



10. Pair creation

possibility that the nature of the vacuum has not always been the same throughout the history of the universe. It also raises an interesting possibility: that one could *add* something to the vacuum and yet *lower* its energy. In such a case one would have created a new state of vacuum; the previous vacuum, which has



12. **The six-fold symmetry of a snowflake**

So we now have a new perspective on the ancient philosophers' question of whether nature allows a vacuum. The answer is, depending on your point of view, either 'no' (in that the void is actually filled with an infinite sea of particles together with quantum fluctuations) or 'yes; there are many different types of vacuum' (i.e. depending on how the medium that is the quantum

vacuum is organized). The received wisdom in physics tends to be in the latter camp. We will learn more about this after seeing how patterns and form can emerge as the quantum vacuum moves from one organized state to another.

Phase changes and vacuum

Many physical systems do not show the fundamental symmetries of the forces that build them. Electromagnetic forces don't care about left or right yet biological molecules have mirror images that are inert or even fatal while their originals are food or beneficial.

Balance a perfectly engineered cylindrically shaped pencil on its point. Turn around: it looks the same. This invariance when one rotates is known as a symmetry, in this case rotational symmetry. Balanced on its tip the pencil is metastable as the force of gravity will pull it to ground if it is displaced from the vertical by the slightest amount. The gravitational force is rotationally symmetric, which implies that when the pencil falls to the ground, no particular direction is preferred over another. Do the experiment thousands of times and the collection will show the pencils have fallen to all points of the compass, in accord with the rotational symmetry. However, on any individual experiment you cannot tell in which direction the pencil will fall; having fallen, perhaps to the north, the 'ground state' will have broken the rotational symmetry. Roulette is another example. Play long enough and all the numbers will win with equal likelihood; this guarantees that the house wins as the zero is theirs. But on any individual play it is your inability to predict with certainty where the ball will fall that is the source of the gamble.

as is the void?

In the example of the pencil, the state in which the symmetry is broken is more stable than the symmetric state in which the pencil was precariously balanced on its tip. In general, the laws that govern a system have some symmetry but if there is a more stable state that spoils it, the symmetry is 'spontaneously broken', or 'hidden'. So it was with a snowflake and water or with magnetism of iron.

You may cry foul at this point arguing that this is not really a failure of symmetry, but more a result of one's imprecision in balancing the pencil: 'The pencil dropped because it was not perfectly upright.' This is true, but suppose that it had been balanced on a perfectly engineered point. Even then the atoms in the tip are in random motion, due to the temperature, heat, manifested in their kinetic energy. This randomness means that the direction of toppling is random. You might agree but suggest that we do the experiment at temperatures approaching absolute zero of temperature, −273°C, where the kinetic energy tends to vanish. Your gedankenexperiment supposes the tip to be engineered from perfectly spherical molecules, the pivotal one being frozen in place at absolute zero temperature where thermal motion has ceased. The catch is that the quantum laws take over. If motion has vanished, then position is unknown and the point of balance is itself randomized. If the point were precisely known at some instant, motion would be undetermined and the resulting imbalance unpredictable. It seems that here, and in general, the quantum fabric of nature enables high-energy metastability to choose a state of lower energy where the symmetry is spontaneously broken. Thus melting ice, or heating magnetized metal, causes the symmetry to return, but when allowed to cool again, the symmetry is broken with no memory of what happened before.

The rule is that raising the temperature causes structure and complexity to melt away giving a 'simpler' system. Water is bland; ice crystals are beautiful.

The universe today is cold; the various forces and patterns of matter are structures frozen into the fabric of the vacuum. We are far from the extreme heat in the aftermath of the Big Bang, but if

we were to heat everything up, the patterns and structures would disappear. Atoms and the patterns of Mendeleev's table have meaning only at temperatures below about 10,000°; above this temperature atoms are ionized into a plasma of electrons and nuclear particles as in the Sun. At even hotter temperatures, the patterns enshrined in the Standard Model of particles and forces, where the electron is in a family of leptons, with families of quarks and disparate forces, do not survive the heat. Already at energies above 100 GeV, which if ubiquitous would correspond to temperatures exceeding 10^{15} degrees, the electromagnetic force and the weak force that controls beta-radioactivity melt into a symmetric sameness. Theories that describe matter and forces as we see them in the cold imply that all these structures will melt away in the heat. According to theory, the pattern of particles and forces that we are governed by may be randomly frozen accidental remnants of symmetry breaking when the universe 'froze' at a temperature of about 10^{17} degrees. We are like the pencil that landed pointing north, or the roulette wheel where the ball landed in the slot that enabled life to arise. Had the ball landed elsewhere, such that the mass of the electron were greater, or the weak force weaker, then we would have been losers in the lottery and life would not have occurred.

Here I have come full circle back to my starting conundrum. If the spontaneous symmetry breaking had made other parameters and forces, we would not have been here to know it. This has given rise to the radical idea that there may be many vacua, multiplicities of universes, of which ours is the one where by chance the dials were set just right.

An example here is of magnetized metal: heat it, destroying the magnetism, and cool it again. In one part the atomic magnets become frozen together pointing in one direction, while in another part of the metal they lock in another direction. This phenomenon is known as 'magnetic domains'. Could this be a model of the universe? Theorists have built mathematical models of the Big [illegible] different species [illegible] Evolutionary rules...

Bang, which have to agree with what we know and exhibit the 'true' symmetry in the early hot epoch. A general feature seems to be that such models imply that when cooling occurs from the initial symmetric state, there is a 'landscape' of possible solutions. When you view the entire landscape, you see on the average the original symmetry: like the orientations of the fallen pencil at all points of the compass, there are all possible masses and forces that are consistent with the original symmetry. What is true hereabouts, and in the billions of light years accessible to us, might be different elsewhere.

[illegible] which ones survive. Note that we may have some [illegible] ESS (or a balance [illegible] not stable).

Changing forces in the vacuum

The effervescence of the vacuum disturbs passing electrons and hence also the forces that one charged particle exerts on another. While the inverse square law of the electrostatic force is natural for electric fields that uniformly spread out through three-dimensional space, precision data show subtle deviations from this. Moving at 1 per cent of the speed of light, the effects of relativity are measurable. The stretching and interweaving of space and time distorts the simple inverse square behaviour giving subtle additional effects that grow more rapidly than the inverse square when two charges approach one another. Most familiar as magnetism, these are the immediate manifestations of relativity. When two charges get even closer, separated by distances smaller than an atom's length, the quantum vacuum further distorts these forces.

As mentioned before, forces are transmitted by particles that carry energy and momentum from one body to another. In the case of the electromagnetic force it is the exchange of photons that does the job. If the photons travel directly from one charged particle to another without disturbance, the inverse square law of force arises; however, when a photon's flight is interrupted by the quantum vacuum, such that it fluctuates into a virtual electron positron en route, the strength of the force is subtly changed.

In effect the negative and positive charges of the virtual electron and positron act like a blanket around the naked charge that spawned the force. Measurements at CERN show that if two charges approach within distances that are some 100 millionth the radius of a hydrogen atom, a thousand times smaller even than the size of its nucleus, the electromagnetic force appears effectively some 10 per cent stronger. Calculations suggest that the strength increases even further at yet smaller distances, though it has not been possible to test this experimentally yet. Modern ideas are that the 'true' strength of the electromagnetic force is perhaps some three times stronger than we perceive in macroscopic measurements. When the electrostatic force causes a comb to attract a piece of paper at a range of a few millimetres, or even when the proton ensnares an electron at atom's length, the force has been enfeebled by the charges of the virtual fields latent within the intervening vacuum. Only at the minutest distances, where only the most singular fluctuations can intervene, is the true electromagnetic strength to be revealed.

This discovery has given a dramatic change to our view of forces. Within a nucleus there are other forces at work, known as the weak and strong, their names testifying to their strengths as perceived relative to that of the electromagnetic force. The strong force is responsible for holding the positively charged members of the nucleus, the protons, in a tight grip even while their mutual electrical repulsion ('like charges repel') is trying to drive them apart. Within the protons and neutrons themselves, the strong force confines the quarks in permanent imprisonment. One manifestation of the weak force is beta-radioactivity where the nucleus of one atomic element can transmute into another. As the electromagnetic force is carried by photons, so is the strong force between the quarks carried by gluons, while the weak force is transmitted by electrically charged *W* bosons or by electrically neutral *Z* bosons. These different particles are affected by the vacuum in different ways. For example, gluons are blind to electrons, positrons, and photons, but have to force their way through the clouds of quarks and antiquarks, and even other gluons that lurk within the quantum vacuum. The W and Z by contrast feel both charged particles and also the nearly massless electrically neutral particles known as neutrinos and antineutrinos.

Calculations show that while the strength of the electromagnetic force grows as the shielding effects of the vacuum are removed at short distances, the different response of the gluons to the vacuum cause the strength of the 'strong' force to be enfeebled in the analogous circumstances. Experiment has confirmed this. The strong binding forces that grip an atomic nucleus, giving it stability, are thus a result of the vacuum strengthening the gluons' grip at distances of 10^{-15} m. The masses of protons, neutrons, and ultimately of all bulk matter are effectively due to the gluonic vacuum acting over nuclear dimensions. This is surprising, but true. The successful comparisons between data and the calculations, which assume that the quantum vacuum plays an essential role, are too much to be mere accidents. Furthermore, they provide a tantalizing hint that, were it not for the effects of the vacuum, the strengths of all these forces would probably be the same. If true, this implies a profound unity to the forces of nature at source, and that the multitude of disparate phenomena that occur at macroscopic distances, such as our daily experiences, are controlled by the quantum vacuum within which we exist.

To experience the forces and nature at distances so small that the intervention of the vacuum is nugatory requires the study of collisions among particles at exceedingly high energies. Such conditions were commonplace in the early universe where the extreme heat would be manifested by high kinetic energies of the particles. The theory of the forces and the vacuum embodied in the 'Standard Model' of particle physics implies that in the early universe, initially the vacuum state had a symmetric phase where these forces exhibited essentially the same strengths and were in effect unified. As the universe cooled, phase transitions occurred

and the symmetric vacuum state was replaced by increasingly asymmetric states. Thus what we now call the strong force separated from the electro-weak, which is the name given to the still unified electromagnetic and weak forces, at a temperature above 10^{28} degrees, which would have occurred around 10^{-34} seconds after the Big Bang.

The separation of the electro-weak into what we now recognize as electromagnetic and weak took place at much lower temperatures, around 10^{15} degrees, which is accessible in experiments at CERN and has been studied in detail. The breaking of this symmetry is rather different from the phase change that had earlier led to the emergence of a separate strong interaction. The 'weak' force appears weak because it is a short-range force, extending over distances smaller than the extent of a proton and hence quite unlike the infinite range of the electromagnetic force. It is its short range that means that its effects at longer range appear feeble even though, close in, its natural strength, essentially the same as that of the electromagnetic force, is revealed. So why is the reach of the weak force so tiny? The answer has to do with the nature of its carriers, the W and Z bosons: whereas the photon is massless, the W and Z are very massive, approaching 100 times the mass of a proton. It is only when the energies of collisions, or temperatures in the universe, are so large as to make the energy locked into the mc^2 of these bosons trifling by comparison, that the unity of the forces is revealed. This brings us to the frontier of current research into the nature of the vacuum, which is concerned with the nature of mass and the Higgs vacuum.

The Higgs vacuum

The weak force, then, appears feeble because of its limited reach. Compared to the scale of around 10^{-31} m where the forces are unified and the different effects of the quantum vacuum are nugatory, the 10^{-18} m range of the weak force is so large as to be effectively infinite. In energy terms, whereas the photon has no

So we have a picture of the universe erupting as a quantum fluctuation in the vacuum, which somehow is exceedingly hot and expanded rapidly. This picture would have led to vast amounts of matter and antimatter being produced symmetrically, yet there is no evidence for antimatter surviving in bulk today. It is generally believed that there has to be some asymmetry between protons and antiprotons. The origin of this is still being sought but it may be another example of spontaneous symmetry breaking as the universe went through a phase change.

Inflation

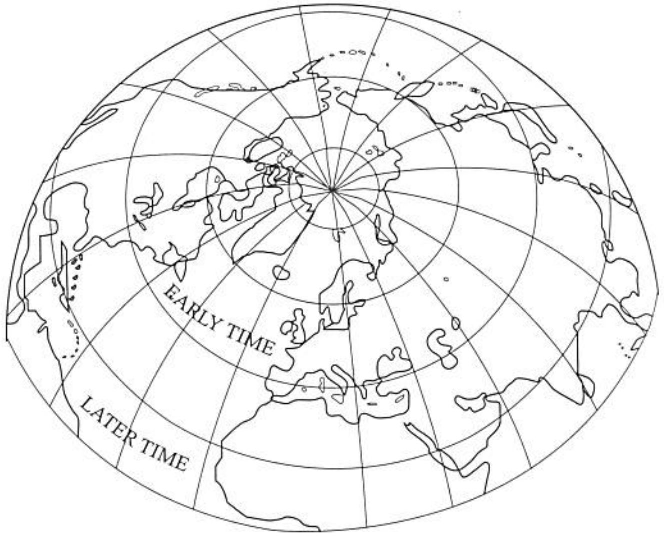
Problems remain with this scenario including the question of where all the thermal energy came from. Furthermore, from experience with phase changes in condensed-matter physics we know that they are never completely smooth. For example, when hot metal cools to make a magnet, the magnetism varies from one region to another, forming 'domains' of distinct magnetism. There are defects, non-uniformities throughout the metal. The same ought to have happened throughout the universe when it underwent phase transitions, giving phenomena such as walls of energy, cosmic strings, call them what you will. In any event, there has been no clear sighting of any such bizarre entities. Also, theory suggests that such a sequence of events would have led to the universe's evolution being so fast that its lifetime would have been little more than some tens of thousands rather than the present tens of billions of years. A possible solution to these paradoxes came with the idea of Alan Guth and Paul Steinhardt who proposed that the universe is a domain in some bigger omniverse. In this theory, known as inflation, our universe is the result of an enormous swelling of a single one of these microscopic 'domains'. At first sight this seems impossible as it requires matter spontaneously to fly apart, which ought not to happen when there is a universal gravitational attraction at work. However, in general relativity not just the mass energy and momentum but also the

pressure contribute and if the pressure were negative, and dominant over the matter and thermal energies, the result could be a rapid expansion, a sort of 'anti-gravity' effect.

What Alan Guth had noticed was that if the true vacuum contains a Higgs field, there is the possibility that a region of the universe could have been in the unstable or 'false' vacuum. (The false vacuum is akin to the state of the pencil balanced on its point and the true vacuum is the pencil fallen to the table.) Recall that adding the Higgs field to the false vacuum will *lower* the energy. In the false vacuum the total energy is proportional to the volume, and it requires work to increase that volume. Due to the lower energy state in the Higgs vacuum, the natural tendency will be for such a volume to contract, and with respect to the true Higgs vacuum the false vacuum state will be one in which the pressure is effectively negative. So if a fluctuation occurs in a region of false vacuum, the gravitational effect of the negative pressure can overwhelm that of the matter, leading to an expansion. As the universe makes the transition from the false to the Higgs vacuum in this picture, it is possible that a huge inflation can occur in a remarkably short time.

There are examples in condensed-matter physics of supercooled systems. This is where the system remains in the 'wrong' phase such as when water stays liquid below the nominal freezing point. A similar thing could have happened with the vacuum of the universe. A fluctuation occurs in the false vacuum and continues; only later does the universe make the transition to the true vacuum. It has been calculated that in such circumstances a region of space could double in size every 10^{-34} seconds!

After the period of inflation, the transition to the true vacuum releases energy, like the emission of latent heat when water freezes. This energy produced the particles of matter that would



14. The history of the universe in space and imaginary time

Hawking and Hartle have suggested that time might not be a simple linear flow but has another dimension, which they call 'imaginary time'. Suppose that we represent the universe with one spatial dimension, and time plus imaginary time as the surface of a sphere. We can identify points on this ball by their latitude and longitude, much as we do on the surface of the Earth. In Hawking and Hartle's picture, the lines of latitude are the coordinates of time, and the longitude is what they call 'imaginary time'. The Big Bang is then at the north pole and the Crunch at the south pole. Each line of latitude corresponds to a particular time, for example 40 degrees north might represent 'today'.

Now look at the region near the north pole. As we approach time zero, the grid for imaginary time becomes condensed, much as

approaching the north pole makes all lines of longitude converge. There is nothing singular about the pole; the fact that all lines of longitude converge there is just an 'accident' of how we chose to draw the grid. On our globe you can imagine travelling around the Arctic and, apart from being cold, it is no different from travelling anywhere else on the surface. We could have layered the globe with lines radiating out from London and homing in on the Antipodes if we had wished.

Possibly Hawking and Hartle's imaginary time is just that – imaginary. Or maybe this is a mathematically consistent theory that is just beyond imagination. It is the modern example of the problem that has plagued three millennia of thinkers: our minds have developed a view of the world based on our macroscopic sense of time and three space dimensions. We describe matter and energy within this mental construct. Paradoxes about the 'start' of the universe arise when we are restricted to this mental picture. Yet 14 billion years ago space and time were so warped and fluctuating that the 'reality' would have been far beyond our conceptual ability. The Big Bang created space and time. Before it ('before' of course only having meaning in the sense of our familiar mental matrix) there was no yesterday.

It is possible to imagine that what we call the Big Bang was when the compact universe emerged from the era of quantum gravity, which is when time took over from imaginary time. Questions about where everything came from, how it all 'began', are sidestepped; the universe in this picture has no beginning, no end: it just is. Do you feel that this is the answer to the question of the ages, that the paradox of creation has been resolved? I am not convinced; imaginary time is, for me at least, unimaginable. We may have given a name to the big question but that is not the same as understanding the answer. Why the universe is, and in what, remain enigmas.

Could the ability to resolve the [illegible] dark energy [illegible] (i.e. interpret the same [illegible] w/ less [illegible]) [illegible]

If multiple universes have erupted as quantum fluctuations, such that our bubble happens to have won the lottery where the laws, dimensions, and forces are just right for us to have evolved, this still begs the question of who, what, where were encoded the quantum rules that enable all this. Was Anaxagoras right: the universe emerged as order out of chaos, the ur-matter is the quantum void? Or perhaps Hawking and Hartle's conception of a universe that has no beginning or end, and simply exists, is the answer, such that Thales, who insisted that something cannot come from nothing, is right. The paradox of creation is thus an as yet unresolved mystery about the nature of space and time.

In the 3,000 years since the philosophers of ancient Greece first contemplated the mystery of creation, the emergence of something from nothing, the scientific method has revealed truths that they could not have imagined. The quantum void, infinitely deep and filled with particles, which can take on different forms, and the possibility of quantum fluctuation lay outside their philosophy. They were unaware that positive energy within matter can be counterbalanced by the negative sink of the all-pervading gravitational field such that the total energy of the universe is potentially nothing; when combined with quantum uncertainty, this allows the possibility that everything is indeed some quantum fluctuation living on borrowed time. Everything may thus be a quantum fluctuation out of nothing.

But if this is so, I am still confronted with the enigma of what encoded the quantum possibility into the Void. In Genesis some God said, 'let there be light,' but for the Rigveda, gods are creations of human imagination, invoked to explain what lay beyond understanding: 'the Gods came afterwards . . . who then knows whence all has arisen?' As science discovers answers, it exposes deeper questions whose answers are for the future. In

the meantime, I leave you with a poetic interpretation from the Rigveda:

> The non-existent was not; the existent was not
> Darkness was hidden by darkness
> That which became was enveloped by The Void.