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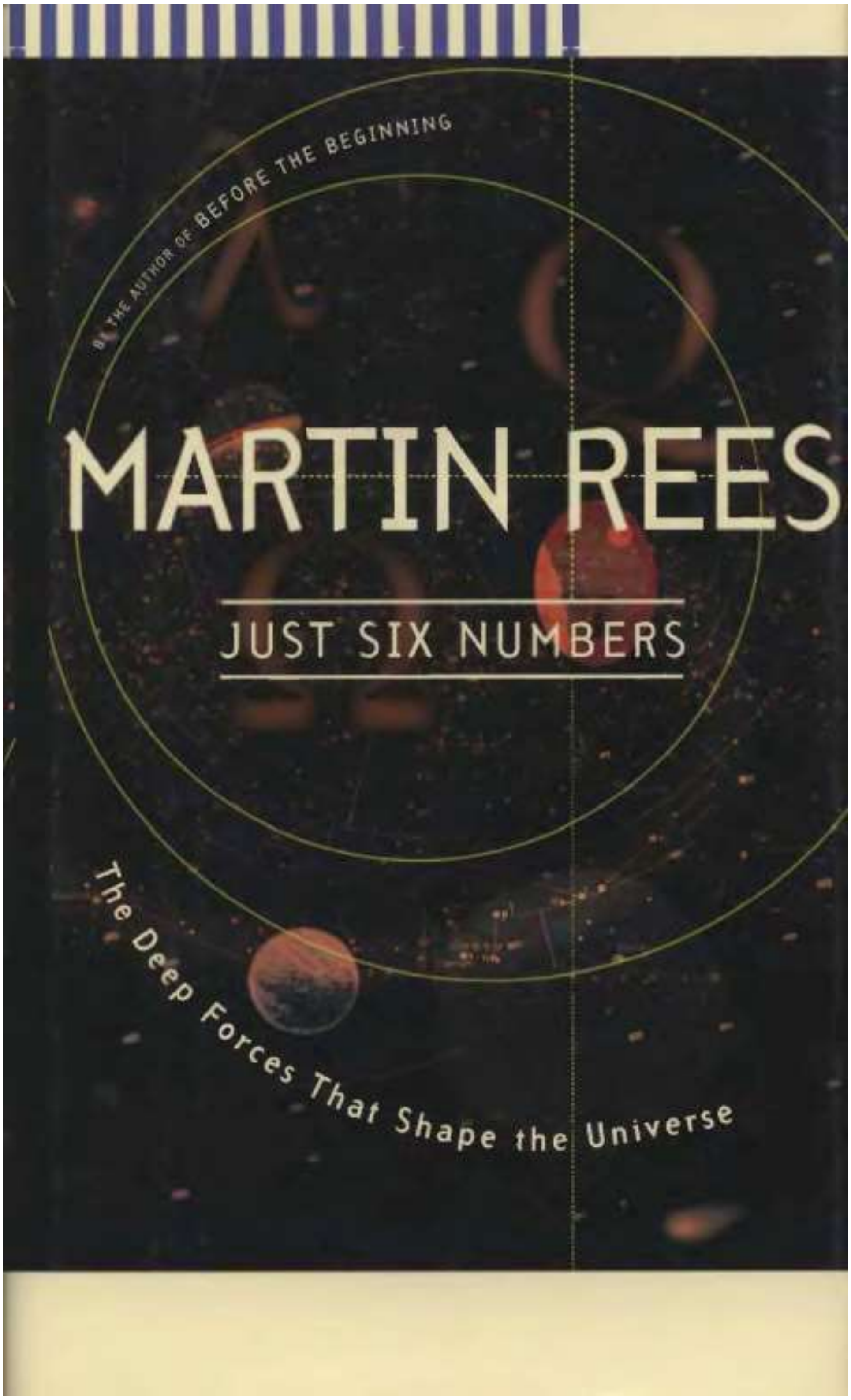
Just Six Numbers

The Deep Forces that Shape the Universe

By: Martin Rees



- Mathematical laws underpin the fabric of our universe – not just atoms, but galaxies, stars and people. The properties of atoms - their sizes and masses, how many different kinds there are, and the forces linking them together - determine the chemistry of our everyday world. The very existence of atoms depends on forces and particles deep inside them. The objects that astronomers study - planets, stars and galaxies – are controlled by the force of gravity. And everything takes place in the arena of an expanding universe, whose properties were imprinted into it at the time of the initial Big Bang. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p1]
- The cosmos is so vast because there is one crucially important huge number N in nature, equal to 1,000,000, 000,000,000,000,000,000,000,000,000,000. This number measures the strength of the electrical forces that hold atoms together, divided by the force of gravity between them. If N had a few less zeros, only a short-lived miniature universe could exist: no creatures could grow larger than insects, and there would be no time for biological evolution. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p2]
- Another number, Ɛ, whose value is 0.007, defines how firmly atomic nuclei bind together and how all the atoms on Earth were made. Its value controls the power from the Sun and, more sensitively, how stars transmute hydrogen into all the atoms of the periodic table. Carbon and oxygen are common, whereas gold and uranium are rare, because of what happens in the stars. If Ɛ were 0.006 or 0.008, we could not exist. . [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p2]
- The cosmic number Ω (omega) measures the amount of material in our universe - galaxies, diffuse gas, and 'dark matter'. Ω tells us the relative importance of gravity and expansion energy in the universe. If this ratio were too high relative to a particular 'critical' value, the universe would have collapsed long ago; had it been too low, no galaxies or stars would have formed. The initial expansion speed seems to have been finely tuned. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p2]
- Measuring the fourth number, λ (lambda), was the biggest scientific news of 1998. An unsuspected new force - a cosmic 'antigravity' - controls the expansion of our universe, even though it has no discernible effect on scales less than a billion light-years. It is destined to become ever more dominant over gravity and other forces as our universe becomes ever darker and emptier. Fortunately for us (and very surprisingly to theorists), λ is very small. Otherwise its effect would have stopped galaxies and stars from forming, and cosmic evolution would have been stifled before it could even begin. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p2-3]

- The seeds for all cosmic structures - stars, galaxies and clusters of galaxies - were all imprinted in the Big Bang. The fabric of our universe depends on one number, Q,, which represents the ratio of two fundamental energies and is about 1/100,000 in value. If Q were even smaller, the universe would be inert and structureless ; if Q were much larger, it would be a violent place, in which no stars or solar systems could survive, dominated by vast black holes. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p3]
- The sixth crucial number has been known for centuries, although it's now viewed in a new perspective. It is the number of spatial dimensions in our world, D, and equals three. Life couldn't exist if D were two or four. Time is a fourth dimension, but distinctively different from the others in that it has a built-in arrow: we 'move' only towards the future. Near black holes, space is so warped that light moves in circles, and time can stand still. Furthermore, close to the time of the Big Bang, and also on microscopic scales, space may reveal its deepest underlying structure of all: the vibrations and harmonies of objects called 'superstrings', in a ten-dimensional arena. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p3]
- We straddle the cosmos and the microworld - intermediate in size between the Sun, at a billion metres in diameter, and a molecule at a billionth of a metre. It is actually no coincidence that nature attains its maximum complexity on this intermediate scale: anything larger, if it were on a habitable planet, would be vulnerable to breakage or crushing by gravity. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p6-7]
- The size of the observable universe is, roughly, the distance travelled by light since the Big Bang, and so the present visible universe must be around ten billion light-years across. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p9]
- 'The most incomprehensible thing about the universe is that it is comprehensible' is one of Einstein's best-known aphorisms, expressing his amazement that the laws of physics, which our minds are somehow attuned to understand, apply not just here on Earth but also in the remotest galaxy. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p10]
- Space can't be indefinitely divided. The details are still mysterious, but most physicists suspect that there is some kind of granularity on a scale of 10^{-33} centimeters. This is twenty powers of ten smaller than an atomic nucleus: as big a decrease - as many frames in our 'zoom lens' depiction - as the increase in scale from an atomic nucleus to a major city. We then encounter a barrier: even if there were still tinier structures, they would transcend our concepts

of space and time. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p11]

- Only rather special planets could harbour life that in any way resembled what we have on Earth. Gravity must pull strongly enough to prevent their atmosphere from evaporating into space (as would have happened to an atmosphere on our Moon, if it ever had one). For water to exist on their surfaces, planets must be neither too hot nor too cold, and therefore the right distance from a long-lived and stable star. Their orbits must be stable (which they would not be if, for instance, their path was repeatedly crossed by a Jupiter-like planet in an eccentric orbit). The high 'hit rate' of the planet-seekers suggests that there are planets around a high proportion of Sun-like stars in our galaxy. Among these billions of candidates, it would be astonishing if there were not many planets resembling the young Earth. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p16]
- From the spectrum of the planet's light, we could infer what gases existed in its atmosphere. Our Earth's atmosphere is rich in oxygen; it didn't start out that way, but was transformed by primitive bacteria in its early history. The most interesting question, of course, is whether this may have happened elsewhere: even when a planet offers a propitious environment, what is the chance that simple organisms emerge and create a biosphere? [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p16-17]
- Any remote beings who could communicate with us would have some concepts of mathematics and logic that paralleled our own. And they would also share a knowledge of the basic particles and forces that govern our universe. Their habitat may be very different (and the biosphere even more different) from ours here on Earth; but they, and their planet, would be made of atoms just like those on Earth. For them, as for us, the most important particles would be protons and electrons: one electron orbiting a proton makes a hydrogen atom, and electric currents and radio transmitters involve streams of electrons. A proton is 1,836 times heavier than an electron, and the number 1,836 would have the same connotations to any 'intelligence' able and motivated to transmit radio signals. All the basic forces and natural laws would be the same. Indeed, this uniformity - without which our universe would be a far more baffling place - seems to extend to the remotest galaxies that astronomers can study. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p21]
- Clearly, alien beings wouldn't use metres, kilograms or seconds. But we could exchange information about the ratios of two masses (such as the ratio of

proton and electron masses) or of two lengths, which are 'pure numbers' that don't depend on what units are used: the statement that one rod is ten times as long as another is true (or false) whether we measure lengths in feet or metres or some alien units. As Richard Feynman noted, he could tell extraterrestrials that he was 'seventeen billion hydrogen atoms high' and they should understand him. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p21-22]

- In the Sun and other stars like it, there is a balance between gravity, which pulls them together, and the pressure of their hot interior, which, if gravity didn't act, would make them fly apart. In our own Earth's atmosphere, the pressure at ground level, likewise, balances the weight of all the air above us. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p25]
- Gravity is important to us because we live on the heavy Earth. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p28]
- Gravitation is feebler than the forces governing the micro-world by the number N, about 10^{36}. What would happen if it weren't quite so weak? Imagine, for instance, a universe where gravity was 'only' 10^{30} rather than 10^{36} feebler than electric forces. Atoms and molecules would behave just as in our actual universe, but objects would not need to be so large before gravity became competitive with the other forces. The number of atoms needed to make a star (a gravitationally bound fusion reactor) would be a billion times less in this imagined universe. Planet masses would also be scaled down by a billion. Irrespective of whether these planets could retain steady orbits, the strength of gravity would stunt the evolutionary potential on them. In an imaginary strong-gravity world, even insects would need thick legs to support them, and no animals could get much larger. Gravity would crush anything as large as ourselves. Galaxies would form much more quickly in such a universe, and would be miniaturized. Instead of the stars being widely dispersed, they would be so densely packed that close encounters would be frequent. This would in itself preclude stable planetary systems, because the orbits would be disturbed by passing stars - something that (fortunately for our Earth) is unlikely to happen in our own Solar System. But what would preclude a complex ecosystem even more would be the limited time available for development. Heat would leak more quickly from these 'mini-stars': in this hypothetical strong-gravity world, stellar lifetimes would be a million times shorter. Instead of living for ten billion years, a typical star would live for about 10,000 years. A mini-Sun would burn faster, and would have exhausted its energy before even the first steps in organic evolution had got under way. Conditions for complex evolution would

undoubtedly be less favourable if (leaving everything else unchanged) gravity were stronger. There wouldn't be such a huge gulf as there is in our actual universe between the immense timespans of astronomical processes and the basic microphysical timescales for physical or chemical reactions. The converse, however, is that an even weaker gravity could allow even more elaborate and longer-lived structures to develop. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p30-31]

- Gravity is the organizing force for the cosmos. Paradoxically, the weaker gravity is (provided that it isn't actually zero), the grander and more complex can be its consequences. We have no theory that tells us the value of ? Ɲ. All we know is that nothing as complex as humankind could have emerged if ? Ɲ were much less than 1,000,000,000,000,000,000,000,000,000,000,000,000. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p31]
- A body that was a few times smaller, or a few times heavier, than a neutron star would trap all the light in its vicinity and become a black hole; the space around it would 'close up' on itself. If the Sun were squeezed down to a radius of three kilometres, it would become a black hole. Fortunately, Nature has done such experiments for us, because the cosmos is known to contain objects that have collapsed, 'puncturing' space and cutting themselves off from the external universe. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p35]
- Iron is only the twenty-sixth element in the periodic table, and at first sight the heavier atoms might seem a problem because it takes an input of energy to synthesize them. But intense heat in the collapse, and the blast wave that blows off the outer layers, together produce small traces of the elements in the rest of the periodic table, right up to uranium at number 92. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p45]
- Accounting for the proportions of the different atoms - and realizing that the Creator didn't need to turn ninety-two different knobs - is a triumph of astrophysics. Some details are still uncertain, but the essence depends on just one number: the strength of the force that binds together the particles (protons and neutrons) that make up an atomic nucleus. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p47]
- The nucleus of a helium atom weighs 99.3 per cent as much as the two protons and two neutrons that go to make it. The remaining 0.7 per cent is released mainly as heat. So the fuel that powers the Sun - the hydrogen gas in its core - converts 0.007 of its mass into energy when it fuses into helium. It is essentially this number, Ɛ, that determines how long stars can live. Further transmut-ations of helium all the way up to iron release only a further 0.001.

The later stages in a star's life are therefore relatively brief. (They are even briefer because, in the hottest stellar cores, extra energy drains away invisibly in neutrinos.) The amount of energy released when simple atoms undergo nuclear fusion depends on the strength of the force that 'glues' together the ingredients in an atomic nucleus. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p47-48]

- Without nuclear energy, the sun would deflate within about ten million years, as Kelvin realized a century ago. Because the force only acts at short range, it becomes less effective in the larger and heavier nuclei: this is why the nuclei heavier than iron become less tightly bound rather than more so. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p48]
- A helium nucleus contains two protons, but it also contains two neutrons. Rather than the four particles being assembled in one go, a helium nucleus is built up in stages, via deuterium (heavy hydrogen), which comprises a proton plus a neutron. If the nuclear 'glue' were weaker, so that Ɛ were 0.006 rather than 0.007, a proton could not be bonded to a neutron and deuterium would not be stable. Then the path to helium formation would be closed off. We would have a simple universe composed of hydrogen, whose atom consists of one proton orbited by a single electron, and no chemistry. Stars could still form in such a universe (if everything else were kept unchanged) but they would have no nuclear fuel. They would deflate and cool, ending up as dead remnants. There would be no explosions to spray the debris back into space so that new stars could form from it, and no elements would exist that could ever form rocky planets. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p49]
- At first sight, one might have guessed from this reasoning that an even stronger nuclear force would have been advantageous for life, by making nuclear fusion more efficient. But we couldn't have existed if Ɛ had been more than 0.008, because no hydrogen would have survived from the Big Bang. In our actual universe, two protons repel each other so strongly that the nuclear 'strong interaction' force can't bind them together without the aid of one or two neutrons (which add to the nuclear 'glue', but, being uncharged, exert no extra electrical repulsion). If 8 were to have been 0.008, then two protons would have been able to bind directly together. This would have happened readily in the early universe, so that no hydrogen would remain to provide the fuel in ordinary stars, and water could never have existed. So any universe with complex chemistry requires Ɛ to be in the range 0.006-0.008. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p49]

- The English theorist Fred Hoyle stumbled on the most famous instance of 'fine tuning' when he was calculating exactly how carbon and oxygen were synthesized in stars. Carbon (with six protons and six neutrons in its nucleus) is made by combining three helium nuclei. There is negligible chance of all three coming together simultaneously, and so the process happens via an intermediate stage where two helium nuclei combine into beryllium (four protons and four neutrons) before combining with another helium nucleus to form carbon. Hoyle confronted the problem that this beryllium nucleus is unstable: it would decay so quickly that there seemed little chance of a third helium nucleus coming along and sticking to it before it decayed. So how could carbon ever arise? It turned out that a special feature of the carbon nucleus, namely the presence of a 'resonance' with a very particular energy, enhances the chance that beryllium will grab another helium nucleus in the brief interval before it decays. Hoyle actually predicted that this resonance would exist; he urged his experimental colleagues to measure it, and was vindicated. This seeming 'accident' of nuclear physics allows carbon to be built up, but no similar effect enhances the next stage in the process, whereby carbon captures another helium nucleus and turns into oxygen. The crucial 'resonance' is very sensitive to the nuclear force. Even a shift by four per cent would severely deplete the amount of carbon that could be made. Hoyle therefore argued that our existence would have been jeopardized by even a few percentage points' change in Ɛ. [Livio et al. (Nature, 340,281 1989) have computed just how sensitive the carbon production is to changes in the nuclear physics.] [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p50]
- Irrespective of how the elements were made, a change in E would affect the length of the periodic table. A weaker nuclear force would shift the most tightly bound nucleus (which is now iron, number 26) lower down the periodic table and reduce below ninety-two the number of stable atoms. This would lead to an impoverished chemistry. Conversely, a larger Ɛ could enhance the stability of heavy atoms. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p50]
- The actual mix of elements would depend on Ɛ, but what is remarkable is that no carbon-based biosphere could exist if this number had been 0.006 or 0.008 rather than 0.007. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p51]
- The expansion almost certainly began between ten and fifteen billion years ago, twelve or thirteen billion being the best guess. There are two reasons for this persistent uncertainty in the age of our universe. The exact distances to galaxies are (unlike their recession speeds) still somewhat inexact; also, the

estimate depends on how much faster (or slower) the expansion might have been in the past. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p59]

- The best evidence that everything really emerged from a dense 'beginning' is that intergalactic space isn't completely cold. This warmth is an 'afterglow of creation'. It manifests itself as microwaves, the kind of radiation that generates heat in a microwave oven but very much less intense. The first detection of the 'cosmic microwave background', back in 1965, was the most important advance in cosmology since the discovery of the expansion of the universe. Later measurements confirmed that these microwaves have a very distinctive property: their intensity at different wavelengths, when plotted on a graph, traces out what physicists call a 'black body' or 'thermal' curve. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p65]
- The present average temperature of the universe is 2.728 degrees above absolute zero. This is, of course, exceedingly cool (around -270°C); but there's a well-defined sense in which intergalactic space still contains a lot of heat. Every cubic metre contains 412 million quanta of radiation, or photons: in comparison, the average density of atoms in the universe is only about 0.2 per cubic metre. This latter number is less precisely known, because we are unsure how many atoms may be in diffuse gas or 'dark' matter, but there seem to be about two billion photons for every atom in the universe. During the expansion of the universe, the density of atoms and of photons both decrease. But the decrease is the same for both, and so the ratio of photons to atoms stays the same. Because this ratio of 'heat' to 'matter' is so large, the early universe is often referred to as a 'hot' Big Bang. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p66]
- The standard Big Bang theory simply postulates that everything was set up with just enough energy to go on expanding. An answer to why it is expanding at all must be sought in the still earlier stages, where we don't have such direct evidence nor such a confident understanding of the physics. The name 'Big Bang' was introduced in the 1950s by the celebrated Cambridge theorist Fred Hoyle. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p67]
- the steady-state theory fell from favour as soon as evidence emerged that the universe was actually different in the past. Though it turned out wrong, the steady-state theory was a 'good' theory in that it made very clear-cut and testable predictions; it was a genuine stimulus to the subject, goading observers to push their techniques to the limit. Hoyle himself never became fully reconciled to the Big Bang, although he adopted a compromise picture

that sceptical colleagues called a 'Steady Bang' . [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p68]

- The ratio of the actual density to the critical density is a crucial number. Cosmologists denote it by the Greek letter a (omega). The fate of the universe depends on whether or not exceeds one. At first sight our estimate of the actual average concentration of atoms in space seems to imply that fl is only 1/25 (or 0.041, portending perpetual expansion, by a wide margin. But we should not jump too soon to that conclusion. We've come to realize in the last twenty years that there's a lot more in the universe than we actually see, such unseen material consisting mainly of 'dark stuff' of unknown nature. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p73]
- The cumulative evidence for dark matter is now almost uncontestable. The way stars and galaxies are moving suggest that something invisible must be exerting a gravitational pull on them. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p74]
- Our bodies each contain nearly 10^{29} atoms. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p80]
- It's embarrassing that more than ninety per cent of the universe remains unaccounted for - even worse when we realize that the dark matter could be made up of entities with masses ranged from 10^{-33} grams (neutrinos) up to 10^{39} gm (heavy black holes), an uncertainty of more than seventy powers of ten. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p82]
- There are 10^{78} atoms within our observable universe[Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p84]
- Our universe contains atoms and not antiatoms because of a slight 'favouritism' that prevailed at some very early stage. This implies, of course, that a proton (or its constituent quarks) can sometimes appear or disappear without the same thing happening to an antiproton. There is a contrast here with net electrical charge: this is exactly conserved, so that if our universe started off uncharged, there would always be an exact cancellation between positive and negative charges. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p86]
- In this perspective, it looks surprising that our universe was initiated with a very finely-tuned impetus, almost exactly enough to balance the decelerating tendency of gravity. It's like sitting at the bottom of a well and throwing a stone up so that it just comes to a halt exactly at the top - the required precision is astonishing: at one second after the Big Bang, Ω cannot have

differed from unity by more than one part in a million billion (one in 10^{15})n order that the universe should now, after ten billion years, be still expanding and with a value of Ω that has certainly not departed wildly from unity. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p88]

- We have already noted that any complex cosmos must incorporate a 'large number' Ɲ reflecting the weakness of gravity, and must also have a value of Ɛ that allows nuclear and chemical processes to take place. But these conditions, though necessary, are not sufficient. Only a universe with a 'finely tuned' expansion rate can provide the arena for these processes to unfold. So Ω must be added to our list of crucial numbers. It had to be tuned amazingly close to unity in the early universe. If expansion was too fast, gravity could never pull regions together to make stars or galaxies; if the initial impetus were insufficient, a premature Big Crunch would quench evolution when it had barely begun. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p88-89]
- Cosmologists react to this 'tuning' in different ways. The most common reaction seems, at first sight, perverse. This is to argue that because our early universe was set up with Ω very close to unity, there must be some deep reason why it is exactly one; in other words, because the 'tuning' is very precise, it must be absolutely perfect. This odd-looking style of reasoning has actually served well in other contexts; for instance, we know that in a hydrogen atom, the positive electric charge on the proton is cancelled by the negative charge on the orbiting electron, to immense precision - better than one part in 10^{21}. No measurement can, however, tell us that the net charge on an atom is exactly zero: there is always some margin of error. So-called 'grand unified theories', which interrelate electrical forces with nuclear forces, have, within the last twenty years, suggested a deep reason why the cancellation is exact. However, most physicists even fifty years ago would have guessed that the cancellation was exact, even though there weren't then any convincing arguments. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p88-89]
- Einstein's equations then allowed a static universe where, for a suitable value of λ, a cosmic repulsion exactly balanced gravity. This universe was finite but unbounded: any light beam that you transmitted would eventually return and hit the back of your head.This so-called 'Einstein universe' became no more than a curiosity after 1929. Astronomers had by then realized that our galaxy was just one of many, and that distant galaxies were receding from us: the universe wasn't static, but was expanding. Einstein thereafter lost interest in λ. Indeed, George Gamow's autobiography My World Line recalls

a conversation in which Einstein, three years before his death,rated λ as his 'biggest blunder', because if he hadn't introduced it, his equations would have obligated the conclusion that our universe would be expanding (or contracting). He could then maybe have predicted the expansion before Edwin Hubble discovered it. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p96-97]

- If λ isn't zero, we are confronted with the problem of why it has the value we observe - one smaller, by very many powers of ten, than what seems its 'natural' value. Our present cosmic environment would be very little different if it were even smaller (though the long-range forecast, discussed below, would be somewhat altered). However, a much higher value of λ would have had catastrophic consequences: instead of becoming competitive with gravity only after galaxies have formed, a higher-valued A would have overwhelmed gravity earlier on, during the higher-density stages. If λ started to dominate before galaxies had condensed out from the expanding universe, or if it provided a repulsion strong enough to disrupt them, then there would be no galaxies. Our existence requires that λ should not have been too large. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p99]
- But what about the long-range future? What would happen if we came back when the universe was ten times older - a hundred billion rather than ten billion years old? My favoured guess (before there was much relevant evidence) used to be that the expansion would by then have halted and been succeeded by recollapse to a Big Crunch in which everything experienced the same fate as an astronaut who falls inside a black hole. Our universe would then have a finite timespan for its continued existence, as well as being bounded in space. But this scenario requires Ω to exceed unity in value, contrary to the evidence that has mounted up in recent years. Dark matter assuredly exists, but there does not seem to be enough to yield the full 'critical density': Ω seems to be less than unity. Furthermore, an extra cosmic repulsion, described by λ, may actually be speeding-up the expansion of our universe. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p100]
- Eventually, black holes will also decay. The surface of a hole is made slightly fuzzy by quantum effects, and it consequently radiates. In our present universe, this effect is too slow to be interesting unless mini-holes the size of atoms actually exist. The timescale is 10^{66} years for the total decay of a stellar-mass hole; and a hole weighing as much as a billion suns would erode away in 10^{93} years. Eventually, after 10^{100} years have passed, the only surviving vestige of our Local Group of galaxies would be just a swarm of

dark matter and a few electrons and positrons. All galaxies beyond our Local Group would undergo the same internal decay, and would move further from us. But the speed with which they disperse depends crucially on the value of λ. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p101]

- After (say) 100 billion years, we would be able to see out as far as 100 billion light-years; objects that are now far beyond our present horizon, because their light hasn't yet had time to reach us, would come into view. But if λ isn't zero, the cosmic repulsion will push galaxies away from each other at an accelerating rate. They will fade from view even faster because their redshifts increase rather than diminish. Our range of vision will be bounded by a horizon that is rather like an inside-out version of the horizon around a black hole. When things fall into a black hole, they accelerate, getting more and more redshifted and fading from view as they approach the hole's 'surface'. A galaxy in a λ dominated universe would accelerate away from us, moving ever closer to the speed of light as it approaches the horizon. At late times, we will not see any further than we do now. All galaxies (except Andromeda and the other small galaxies gravitationally bound into our own Local Group) would be fated to disappear from view. Their distant future lies beyond our horizon, as inaccessible to us as the events inside a black hole. Extragalactic space will become exponentially emptier as the aeons advance. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p101-102]
- the temperature contrasts are also immense: the stars have blazing surfaces (and still hotter centres), but the dark sky is close to the 'absolute zero' of temperature -warmed to just 2.7 degrees by the microwave afterglow from the Big Bang . [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p103]
- The most conspicuous structures in the cosmos - stars, galaxies, and clusters of galaxies - are all held together by gravity. We can express how tightly they are bound together - or, equivalently, how much energy would be needed to break up and disperse them - as a proportion of their total 'restmass energy' (mc^2). for the biggest structures in our universe - clusters and superclusters - the answer is about one part in a hundred thousand. This is a pure number - a ratio of two energies - and we call it Q. The fact that Qis so small (of the order of means that gravity is actually quite weak in galaxies and clusters. Newton's theory is therefore good enough for describing how the stars move within a galaxy, and how each galaxy traces out an orbit under the gravitational influence of all the other galaxies and the dark matter within a cluster. The smallness of Q also means that we can validly treat our universe

as approximately homogeneous, just as we'd regard a globe as smooth and round if the height of the waves or ripples on its surface were only 1/100,000 of its radius (equivalent to only 60 metres for a globe the size of the Earth). [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p106]

- The ripples would have been imprinted very early on, before the universe 'knew' about galaxies and clusters; there would be nothing special about these sizes (or, indeed, about any dimensions that seemed significant in our present universe). The simplest guess would be that nothing in the early universe favours one scale rather than another, so that the ripples are the same on every scale. The degree of initial 'roughness' was somehow established when our entire universe was of microscopic size: how this could have happened. The number Q is crucial for determining the 'texture' of structure in our universe, which would be very different if its value were either much larger or much smaller.[Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p106]
- The formation of galaxies, clusters and superclusters obviously requires the universe to contain enough dark matter and enough atoms. The value of **Ω** must not be too low: in a universe that contained radiation and very little else, gravity could never overwhelm pressure. And λ mustn't be so high that the cosmic repulsion overwhelms gravity before galaxies have formed. There must also be enough ordinary atoms, initially in diffuse gas, to form all of the stars in all of the galaxies. But we've seen that something else is needed as well, namely initial irregularities to 'seed' the growth of structure. The number Q measures the amplitude of these irregularities or 'ripples'. Why Q is about 10^{-5} is still a mystery. But its value is crucial: were it much smaller, or much bigger, the 'texture' of the universe would be quite different, and less conducive to the emergence of life forms.[Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p114-115]
- If Q were smaller than 10^{-5} but the other cosmic numbers were unchanged, aggregations in the dark matter would take longer to develop and would be smaller and looser. The resultant galaxies would be anaemic structures, in which star formation would be slow and inefficient, and 'processed' material would be blown out of the galaxy rather than being recycled into new stars that could form planetary systems. If Q were smaller than 10^{-6}, gas would never condense into gravitationally bound structures at all, and such a universe would remain forever dark and featureless, even if its initial 'mix' of atoms, dark matter and radiation were the same as in our own . On the other hand, a universe where Q were substantially larger than 10^{-5}-where the initial 'ripples' were replaced by large-amplitude waves - would be a turbulent and

violent place. Regions far bigger than galaxies would condense early in its history. They wouldn't fragment into stars but would instead collapse into vast black holes, each much heavier than an entire cluster of galaxies in our universe. Any surviving gas would get so hot that it would emit intense X-rays and gamma rays. Galaxies (even if they managed to form) would be much more tightly bound than the actual galaxies in our universe. Stars would be packed too close together and buffeted too frequently to retain stable planetary systems. (For similar reasons, solar systems are not able to exist very close to the centre of our own galaxy, where the stars are in a close-packed swarm compared with our less-central locality). [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p115]

- The fact that Q is 1/100,000 incidentally also makes our universe much easier for cosmologists to understand than would be the case if Q were larger. A small guarantees that the structures are all small compared with the horizon, and so our field of view is large enough to encompass many independent patches each big enough to be a fair sample. If Q were much bigger, superclusters would themselves be clustered into structures that stretched up to the scale of the horizon (rather than, as in our universe, being restricted to about one per cent of that scale). It would then make no sense to talk about the average 'smoothed-out' properties of our observable universe, and we wouldn't even be able to define numbers such as Ω . [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p115-116]
- The smallness of Q, without which cosmologists would have made no progress, seemed until recently a gratifying contingency. Only now are we coming to realize that this isn't just a convenience for cosmologists, but that life couldn't have evolved if our universe didn't have this simplifying feature. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p116]
- Many crucial features of our universe could have been imprinted when the cosmic clock was reading 10^{-35} seconds, or even less. In these contexts, each factor of ten on the cosmic clock in the age of the universe - each extra zero after the decimal point - is likely to be equally eventful and should count equally. The leap back from 10^{-14} seconds to 10^{-35} seconds is then bigger (in that it spans more factors of ten) than the timespan between the three minute threshold when helium was formed (about 200 seconds after the Big Bang) and the present time (3×10^{17} seconds, or ten billion years). In this perspective, there is plenty of action at even earlier stages. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books

2000, p120]

- Their distinctive consequences in our low-energy world are vestigial: for instance, protons, the main ingredient of all stars and planets, would very slowly decay - an effect that could be important in the remote future but is insignificant now. Everything, however, would have been hotter than degrees for the first seconds. Perhaps the early universe was the only place where the requisite temperature for unifying the forces could even be reached. This 'experiment' shut down more than ten billion years ago, but did it leave fossils behind, just as most of the helium in the universe survives from the first few minutes? It seems that it did: indeed, the favouritism of matter over antimatter may have been imprinted at this ultra-early stage. Even more important, the vast scale of the universe, and the fact that it is expanding at all, may be determined by what happened in those brief initial instants. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p123]
- Cosmologists sometimes claim that the universe can arise 'from nothing'. But they should watch their language, especially when addressing philosophers. We've realized ever since Einstein that empty space can have a structure such that it can be warped and distorted. Even if shrunk to a 'point', it is latent with particles and forces - still a far richer construct than the philosopher's 'nothing'. Theorists may, some day, be able to write down fundamental equations governing physical reality. But physics can never explain what 'breathes fire' into the equations, and actualizes them in a real cosmos. The fundamental question of 'Why is there something rather than nothing?' remains the province of philosophers. And even they may be wiser to respond, with Ludwig Wittgenstein, that 'whereof one cannot speak, one must be silent'. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p131]
- Paley's argument that the inverse-square law is especially benign now seems one of his more robust ones: there is no scope for natural selection of a favoured law of force, and nothing could react back on the universe to change it. Paley was writing more than a century before atoms were realized to consist of electrons orbiting a positively charged nucleus; otherwise, he could have bolstered his case by noting that, for similar reasons, atoms would be impossible in a universe ruled by an inverse-cube law because there would be no stable orbits for electrons. There is therefore a problem with more than three spatial dimensions. Could we then live in a world where there were less than three? The best argument here is a very simple one: there are inherent limitations on complex structures in 'flatland' (or, indeed, on any two-dimensional surface). It is impossible to have a complicated network without

the wires crossing; nor can an object have a channel through it (a digestive tract, for instance) without dividing into two. And the scope is still more constricted in a one-dimensional 'lineland'. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p136]

- The basic quantum of energy is measured by Planck's constant (a number named after the great physicist Max Planck, who pioneered the idea of quantization a century ago). Up to a point, we can probe ever-finer detail by using more and more energetic quanta, associated with ever-shorter wavelengths. But there is a limit. This limit arises when the requisite quanta are such extreme concentrations of energy that they collapse into black holes. This happens at the 'Planck length', which is about 10^{19} times smaller than a proton; quanta with this tiny wavelength each carry as much energy as the rest-mass of 10^{19} protons. Light takes about 10^{-43} seconds to traverse this distance, and this 'Planck time' is the shortest time interval that can ever be measured. So even space and time are subject to quantum effects. because gravity is so weak, these effects come in on a far smaller scale than in ordinary atoms, when the controlling forces are electrical. (This is a consequence of the vastness of our first cosmic number, N.) decide which came first) when the time interval between them is less than the Planck time. These scales are smaller than atoms by just as much as atoms are smaller than stars. There is no prospect of any direct measurements in this domain: it would require particles with energies a million billion times higher than can be produced in the laboratory. [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p141-142]
- Our everyday world, plainly moulded by subatomic forces, also owes its existence to our universe's well tuned expansion rate, the processes of galaxy formation, the forging of carbon and oxygen in ancient stars, and so forth. A few basic physical laws set the 'rules'; our emergence from a simple Big Bang was sensitive to six 'cosmic numbers'. Had these numbers not been 'well tuned', the gradual unfolding of layer upon layer of complexity would have been quenched. Are there an infinity of other universes that are 'badly tuned', and therefore sterile? Is our entire universe an 'oasis' in a multiverse? Or should we seek other reasons for the providential values of our six numbers? [Martin Rees: ***Just Six Numbers (The Deep Forces that Shape the Universe)***, Basic Books 2000, p161]
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