Where am I?

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Part of getting to grips with life is to find out were we are in the world, in relation to our family and our ancestors, in relation to the community we live in and society at large. It takes many years to do so. This piece is about where in the world we are physically or, more specifically, where in the universe are we? It has taken many centuries to find out.

If you'd asked the question 300 years ago, '*where in the world am I*?' you wouldn't have got a very precise answer. If you lived in Britain then you'd have known the parish you were in and where it was in relation to the rest of Britain but you couldn't have run your fingers over a globe and appreciated where you were in relation to all the land and seas that we now know comprise the world. They weren't known about in Britain. You couldn't even have found accurate figures for your latitude and longitude.

Latitude and longitude denote exactly where you are on the globe relative to everything else. The chair I am in, the chair you are in, has a specific latitude and longitude defining a place not shared by anyone else. Ok, there's also height above sea level but it's not often that's needed to distinguish exactly where you are. I'll concentrate on latitude and longitude. What difference do latitude and longitude make? Latitude makes a big difference to climate, for the higher the latitude the lower the Sun is in the sky all day, for much of the world. That makes it quite easy to find latitude. You just need an instrument such as a sextant (not invented 300 years ago) that will let you measure how high in the sky the Sun is at midday (say) and a simple calculation lets you work out your latitude from the result. You need to know the date, but that's not usually a problem.

What difference does living at different longitudes but the same latitude make? Because of the Earth's rotation, the Sun, planets and stars seem to constantly rotate above us. At different longitudes, the stars in a given direction, such as due south or directly overhead, at a given time of the night are different. To find longitude, then, you need to watch the stars, know a precise direction and read an accurate clock. The story of how our ancestors cracked the problem of finding accurate longitudes in the 18^{th} century is quite intriguing and the stuff of several books. Nowadays we use GPS to find out where we are in the world: job done.

Ok, you know where you are on the world but you look at the sky in the day time and at night and you see the Sun and some planets and, if you're away from the city, you see myriads of stars. Where are we, in the bigger picture? It's not obvious. The world is big but the universe is bigger. How much bigger? 300 years ago the answer would have come back that the Sun is at the centre; we and the planets orbit around and the fixed stars are points of light a long way away. There was no accurate knowledge of the size of the solar system nor really any concept that the stars are spread over a vast amount of space. Thanks to Galileo, Kepler and others, the astronomical telescope was a century old 300 years ago but in terms of providing an answer to where we are in the cosmos, not much progress had been made. The history of science tends to highlight 'great discoveries' but in reality progress in many fields takes centuries. You may be surprised to learn that we have only become fairly sure over the past couple of decades of where we are in the universe and what the universe is like on a large scale. We are alive at a very privileged time.

Let me cut to the chase. Many stars seem dotted around the sky at random. Are we in a special place in the universe or just somewhere at random? The answer is that we are quite clearly in a very special place in the universe. We are at a place where life is sustainable. As I say in another piece accompanying this course, most of the Universe is unfit for life to survive. Putting numbers to this statement, perhaps only somewhere between 1 part in 10^{20} to 1 part in 10^{40} of the universe is habitable. That's a very small fraction indeed. So here we are in a special place. However, the Universe is utterly huge and there are indeed a huge number of special places we could be in. Is there anything particularly special about where the Earth is, among all these possible special places? The answer seems to be 'no'.

We are in orbit around a star, our Sun. It's a very common kind of star. Indeed, one of our nearest neighbours, α-Centauri, is a very similar star. Our Sun isn't the brightest of stars. We wouldn't see a similar star 100 light years away with our naked eye but we do see a good many stars that are more than 100 light years away, because they are much brighter than our Sun. It's not the dullest of stars either. Bright stars burn up very quickly but the Sun has lived long enough, about 4.6 billion years, for us to evolve on Earth. Dull stars last many billions of years but have a very narrow zone around them where the temperature is high enough to sustain life as we know it. The Sun has a broader zone, and of course the Earth is within it. We are about 8 light minutes from the Sun, which doesn't sound much but it is 150 million km.

Going round the Sun with us, each at their own speed, are 7 other planets with well over a hundred moons between them, tens of thousands of asteroids, millions of comets, or potential comets, and plenty of 'stuff' in between. We have found planets around many other stars but not 8 planets. There's a good reason for this. They may be there but we haven't yet got the technology to detect them because they are so far away. Even the nearest stars are over 250,000 times as far away as our Sun and the rest of the stars are of course further. Our planetary solar system stretches out to about six-and-a-half light hours from the Sun. There's more beyond this in the solar system but no planets. What we now think of as the solar system used to be considered more or less the whole sensible universe. Our planetary system is clearly tiny on the scale of the typical distance between the stars around us.

Well away from streetlights and the general glow surrounding a town you will see that the stars are not all dotted at random over the sky but there is a band of stars, the Milky Way, that reaches high up above the horizon. The Milky Way is a galaxy, an aggregation of stars all influenced by the gravity of the other stars in the group. It's not as easy to obtain a picture of our galaxy as it is of our solar system because the galaxy contains a lot of dust and we can't see across it. The problem is not unlike trying to find the outline of a wood when you're inside it. '*Can't see the wood for the trees*' is the expression. We can look using dust-penetrating infra-red and use other techniques to build up a picture of the Milky Way. It's a spiral galaxy, probably a 'barred spiral', of the kind we can see aplenty through decent telescopes in directions of clear view. The part of the Milky Way that contains stars (there is thought to be more to it, but that's another story) is 100,000 light years across and some 1000 light years thick. Broadly speaking, seen side on it has roughly a discus-like shape, with a central bulge, the whole rotating around in space. If we could we see it from outside (impossible of course because we'd have to travel tens of thousands of light years to do so) then there would be four or five coarse spiral arms cutting a radius. The Sun and ourselves are in one of these spiral arms (near the edge of the Orion arm) about 25,000 light years from the centre.

The Milky Way is spinning, not as a whole like a solid discus but each star at its own speed depending on the total gravitational force it experiences from the rest of the Milky Way. We're orbiting the centre once in about 240 million years. Over the lifetime of the Sun and

Earth, that's close to 20 orbits. Accompanying us in our galaxy are more than a hundred, thousand, million stars (10^{11}) and huge volumes of interstellar dust within some of which new stars are being born. In the middle of the central bulge (in the direction of the constellation of Sagittarius) is an enormous black hole of several million solar masses. We can't see it directly but we can, in the infra-red, see close-in stars orbiting it and deduce where it is and what its mass is. The Milky Way galaxy is huge. Within the Milky Way there are thousands of millions of stars similar to our Sun – that's a lot – and we are nowhere special, apart from being in a habitable place.

For much of the nineteenth century, the Milky Way was the whole universe. We now know it is but a dot in the visible Universe. Being in it, it looms large to us. More than 99.9% of our night sky starlight comes from the Milky Way. Out of the plane of the Milky Way disk we can see a long way, a very long way as it turns out. Deducing how far away objects are isn't easy in astronomy. After all, our standard of length is the metre, which you can hold between outstretched hands. Even to find that the Milky Way is 100,000 light years (10^{21} m) across takes a good bit of deduction. When measuring distances beyond the Milky Way astronomers tend to use the unit of the parsec (defined in the course). A parsec (abbreviated pc) is 3.26 light years. In the great scheme of things it's hardly worth changing the units but in the interests of joining the astronomers, we'll use parsecs from now on. The Milky Way is about 30,000 pc across. Is there structure in the universe beyond the scale of the Milky Way? The answer is 'yes', plenty.

The Milky Way is part of the local group of galaxies. This group contains just two other spiral galaxies (the Andromeda galaxy, our 'sister' galaxy of comparable size, and the smaller Triangulum galaxy) and some 40 other galaxies, mainly classified as irregular or dwarf, or both. Our local galaxies are all in motion relative to each other at speeds of less than 100 km s^{-1}, quite leisurely by astronomical standards. One or two small ones are being pulled apart by the tidal forces from the Milky Way.

The local collection of galaxies spans about 3 Mpc (million parsecs), about 100 times the diameter of the Milky Way. Galaxies are therefore a lot closer together relative to their own size than stars are relative to their size. To give a figure I didn't give earlier, our nearest stars are a distance away about 25 million times the diameter of our Sun. Using the Sun as a measure, only Mercury and Venus are within 100 solar diameters and hence the solar system is comparatively less populated than our local group of galaxies.

Our local group, though, is an outpost of the Virgo cluster of galaxies, centred about 15 Mpc away. Galactic clusters are the largest aggregations whose structure is mainly controlled by their own gravity. Galaxies in a cluster move through space relative to each other in response to the gravitation of the rest of the cluster. There has been time since the origin of stars and galaxies for the galaxies in a cluster to make several orbits of the cluster and hence for the cluster to acquire some identity. The next level up from a cluster is known as a supercluster and there has not been time since their formation for all the galaxies in a supercluster to cross the supercluster, or make one orbit of it.

At the centre of the Virgo cluster is a huge elliptical galaxy (M87) containing over a hundred times the mass of our Milky Way. Near the centre are lots of other elliptical galaxies. Very roughly the Virgo cluster is spherical with some extending protuberances stretching out over what is called the Virgo Supercluster, or Local Supercluster. We're in a protuberance, which is why we see much of the cluster in the direction of the constellation of Virgo. In the Virgo cluster itself there are about 80 elliptical and lenticular galaxies, 120 spirals, 900 dwarfs and probably lots more small irregular galaxies in addition that are simply too small to spot because of the vast distances involved.

If galaxies are clustered, there must be spaces between the clusters and there are. The spaces are known as voids. Voids come in sizes ranging from a couple of Mpc to as big as 75 Mpc across. Voids are therefore enormous volumes of space, usually pretty spherical in shape, where there are few if any galaxies. Superclusters are not the largest features seen in the Universe. On the largest of scales, galactic clusters and superclusters are seen to be distributed in great walls and filaments. The Virgo Supercluster is part of the Centaurus wall, a huge flattish structure seen almost edge on that is 100 Mpc long. The wall has voids within it and clusters within it, several much richer and more massive than the Virgo cluster.

This brings us to the appearance of the Universe on the largest scale. As astronomers were able to look at ever increasing volumes of space in recent decades, it almost seemed that the larger the scale we probed the universe, the larger the structures we saw. We now believe that this process does come to a halt at sizes of about 200 Mpc. On scales bigger than this, the universe looks much the same in general appearance wherever we look. Galaxies in the universe are distributed a bit like the matter in a sponge. There are huge stretches of galactic clusters in walls and filaments, surrounding large voids but also having smaller voids within the walls. The smaller voids effectively connect the larger ones together so the analogy with a sponge-like structure is better than one with a foam-like structure, for foam consists of separate, isolated, cells. The detail is being uncovered as you read this. There are some amazing pictures on the web drawn from surveys involving the location in space of over a million galaxies. You wouldn't have seen much of what is now shown had you looked in the year 2000.

So how big is the Universe? The 'Big Bang' theory of cosmology is now so well established, or at least its main features are, that it's known as the *concordance theory*. This theory of the origin and evolution of the universe predicts that the universe extends beyond what we can see in practice and what we could see even if we had perfect observing instruments. In other words, the universe as a whole is bigger, much bigger, than the observable universe. Our universe, both the seen and unseen part, began some 13.7 billion years ago. It is this boundary in time that limits the observable universe, not a boundary in space. The universe is not infinite but even in principle we can't see further than light could have travelled in 13.7 billion years, and for various reasons we can see less far. The concordance theory describes a universe that has inflated to a much greater size but the size of the universe that is in principal visible to us is 14,300 Mpc. That's greater than 13.7 billion light years because the most distant objects we could see are not now at the position where we see them. Never minding the technical detail, 14,300 Mpc is an absolutely enormous size.

So, *where am I*? Sitting in a chair occupying about 1 m^2 of the Earth, you can reflect that there are a million square metres in a square km and about 500 million square km over the surface of the Earth. The Earth is no small ball. It takes light about $1/24^{th}$ of a second to cross the diameter of the Earth, about 8 minutes to reach the Sun and 6½ hours to reach Neptune, the outermost planet, so the solar system is big by terrestrial standards. So big, in fact, that no viable technology we know could get a person to Neptune alive. Stepping out to take the bigger view, the solar system is scarcely a pin-prick on the scale of stellar distances. The distance to the unreachable Neptune is about 0.2 milliparsecs. Think of the size of our galaxy, about 30,000 pc across with us 7.6 kpc from the centre. Think of the distance to the centre of our neighbourhood galactic cluster in Virgo of 15 Mpc and then on out to the fabric of the universe at large, stretching over thousands of Mpc. Finally, reflect that the volumes of space involved increase as the cube of the distances. Carl Sagan put it: ‘Once we overcome our fear of being tiny, we find ourselves on the threshold of a vast and awesome Universe that utterly dwarfs – in time, in space, and in potential – the tiny anthropocentric proscenium of our ancestors’.

Sitting in your chair contemplating yourself in relation to the size of the universe the word *insignificant* might come to mind, if not *insignificant* to the power of ten! Are you sitting in just another spot on just another planet orbiting just another star in just another galaxy? Maybe in physical terms, ‘yes’. Yet, you have a brain that can look out on the universe and marvel at its size, its complexity, its simplicity, its beauty; its workings. What fraction of the universe is occupied by such brains? An exceedingly small fraction to be sure, say 1 part in 10^{60} for the sake of a plausible number, for we like numbers. That makes your chair a very, very special place indeed in the universe.

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