Astronomy is an observationally-led subject where chance discoveries play an important role. A whole range of such discoveries is continually made, from the trivial to the highly significant. What is generally needed is for luck to strike someone who is prepared, in the sense that they appreciate that something novel has been seen. “Chance favours the prepared mind” in the words of Pasteur (1854).

This is one definition of serendipitous discovery, first identified as such by Horace Walpole in a letter in 1754 to Horace Mann on discussing a Persian tale of three Princes of Serendip. We shall hear several more interpretations are outlined in these chapters, but I shall stick with the concept of a chance or unplanned discovery. In contrast with school laboratory science where the aim is to plan and carry out an experiment in controlled conditions, in general astronomers cannot do this and must rely on finding something or a situation which suits. Often, the possibilities afforded by a phenomenon are only appreciated later, after the surprise of the discovery has worn off.

A nice example is the discovery in 1979 of the volcanoes of Io by Voyager 1. This phenomenon was spotted by a navigational engineer, Linda Morabito, rather than one of the project scientists. Io turns out to be the most volcanically-active body in the Solar System.

‘Chance favours the prepared mind’ implies both an element of luck and a prior understanding of what is normal. Making successful discoveries in astronomy is not comparable to buying a lottery ticket and then sitting back but requires a deep familiarity with the Sky, the Universe, cosmic phenomena and/or physics. It does require both sides; you don’t make discoveries without making observations and you don’t identify them as such without knowing when something is new. As some examples from chemistry clearly demonstrate, some clumsiness, or at least a deviation from what would otherwise be the path of best practice, may also be needed (mercury was discovered to be a catalyst for synthetic indigo when a mercury thermometer was broken in the reaction vessel; Roberts 1989). It may not prove easy to build algorithms or robots to make serendipitous discoveries!

I am sure that chance plays a strong part in the way in which we learned the world as children. Playing is just that and we all start out with curiosity outweighing prejudice. Only later, alas, does prejudice come to dominate and become the enemy of discovery. It must have played an important role in the development of astronomy and science. It is possible of course to continue to make serendipitous (if not original) discoveries oneself, such as why the full moon always rises at sunset.

An illustration of how I define serendipity is shown in Figure 1. The axes of this 3-dimensional figure are luck, preparedness and aim. Pure serendipity lies just on the luck-

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1 see e.g. The Travels and Adventures of Serendipity, Merton & Barber 2006
Figure 1: Several active volcanoes can be seen in this NASA image of Io. This moon is tidally squeezed and heated by Jupiter, which leads to the eruptions. Since Io has little atmosphere the ejecta reach high altitudes before raining back.

preparedness plane, whereas the perfectly-planned, Kantian (Glashow 2002), experiment is just on the preparedness–aim plane. In reality many serendipitous discoveries have some aim (Archimedes was surely thinking about the problem of estimating the volume of an irregular object when he stepped in his bath), and I shall allow that. There just has to be a large unexpected element.

One way to categorize discoveries is through Discovery Space (Figure 2, Harwit 1982). New things are generally found when new parts of discovery space are explored. We need to go more than about 3 times deeper in that space to find new things. Discovery Space is multi-dimensional and not just in space and time but in spectral band (e.g. radio vs visible), spectral resolution (discerning different frequencies or colours), time resolution, polarization etc. A familiar analogy to a multi-dimensional space is provided by our senses; hearing is distinct from smell or sight and if we make them more acute we discover new things. Imagine having the sensitivity to smell of a dog, or the sensitivity to electrical activity of a shark!

Serendipity often involves an element of surprise, which implies an emotional quality to scientific work. Like a good joke which leads in one direction before jumping to another, so a serendipitous discovery – a Eureka, or even a ‘what the..’ moment can jump our train of thought to new directions. The way in which a serendipitous discovery turns our thoughts, either individually or collectively, into new directions is one of the major benefits of serendipity.

Note that discovery doesn’t always make you famous. Stigler’s law of eponyms states that “no scientific discovery is named after its original discover” and indeed Stigler did
Figure 2: Serendipitous discoveries combine luck (or chance), preparedness and aim. Conventional school science is usually concentrated on the preparedness, aim plane and totally new things are found on the preparedness, luck plane. There is usually, however, some aim to the observations, which is why I have tried through shading to make the region have volume.

I have spent much of my career in X-ray astronomy, which had a serendipitous beginning. Indeed, X-rays were discovered serendipitously by Roëntgen in 1895. We are all familiar with X-rays for their property of being easily absorbed by the bones of our body. The astronomical X-rays mostly observed by astronomers are even more easily absorbed and can only travel a few inches in air. Consequently, X-ray astronomy must be carried out above the Earth’s atmosphere from high-altitude balloon, rocket or satellite. Solar X-rays were discovered in the 1950s (see Friedman 1990) but it was estimated that it would be impossible to detect the X-rays from other stars using the equipment of the
time. Riccardo Giacconi proposed to NASA using a sounding rocket to look for solar X-rays reflected from the Moon. In a short rocket flight on 18 June 1962 he and his team discovered diffuse X-ray emission from around the Sky and a peak of emission in a direction which did not point at the Moon. They had found Sco X-1 and the X-ray Background (XRB). We now know that the first is due to matter from a normal star falling onto an orbiting neutron star; the XRB is due to matter falling into distant supermassive black holes.

Unexpected discoveries are routinely made in astronomy, even sometimes by amateurs. The NASA website Astronomy Picture of the Day, which is one of the first things I log into each day, has most of them and can certainly be appreciated by everyone. A recent example, Comet Holmes, first discovered in 1872, flared up by a factor of 500,000 last November and was first spotted by J.A. Henriquez Santana in Tenerife as a naked-eye object in the constellation of Perseus. Why it flared up is still a mystery, although the list of possible reasons is growing. It is unlikely to have been due to a collision with something else since it probably did the same abrupt brightening when it was discovered. It must have an inherently unstable core; presumably it briefly had much stronger ‘volcanoes’ than Io. Such events in the Sky must have been familiar to the Chinese and Korean court astronomers who watched the Sky as a way to predict the future of both the Emperor and the State. Some of the events they witnessed were supernovae, which mark the collapse and subsequent explosion of stars. One such led to the expanding supernova remnant known as the Crab Nebula (it doesn’t really look like a Crab, but then the constellation

Figure 3: A schematic representation of some parts of discovery space. The axes could represent the volume of space surveyed, the brightness level down to which the observations are sensitive and the epoch of the observations. Alternatively they could be spatial resolution or contrast level, or ability to discern rapid variations.
Figure 4: The Crab nebula, which is about 6000 light years away. It is the remnant of a massive star seen to explode in 1054. High energy electrons from the pulsar near the centre create the blue glow.

of Cancer doesn’t either). We now know that the solid remnant of the collapsed star is a neutron star spinning at 30 times a second. Neutron stars were predicted to exist in the 1930s soon after neutrons were discovered in Cambridge. They have the mass of the Sun but a radius of just 15 km, which is smaller than London. Long suspected to be the power source of the nebula, the object was not identified as such until after pulsars were serendipitously discovered by Jocelyn Bell, Anthony Hewish and others in 1967.

They were looking for the flickering of so-called radio stars, due to the solar wind, in order to determine how small they are (the effect of turbulence in our atmosphere on the visible light from stars which are pointlike makes them twinkle, whereas planets which are extended do not). They built an array of aerals sensitive to variations of a second or less. Jocelyn Bell discovered ‘scruff’ every sidereal day on the pen recorder charts within which she found 1.3 s pulses. Little Green Men as the responsible agent were ruled out when several more pulsars were found. They are rapidly spinning, highly magnetized neutron stars of which the Crab pulsar is just one, which played a key role in developing the theory of how they operate since the nebula acts as a calorimeter for the power radiated.

Interestingly the pulsar was suspected to be the energy source before (it was known as Baade’s star). I’ve heard stories that the occasional lay observer saw the object twinkling (their eyes may have been particularly sensitive to variations). X-ray data of the Crab taken just before the Cambridge radio discovery of pulsars was later found to show pulses but, and this is important, was not analysed in a way that revealed the pulses at the time (Fishman et al 1969). How many important discoveries are lying in someone’s archive or
Figure 5: Gamma-ray light curve of the soft gamma-ray repeater SGR1806 from December 2004. The spike near t=0 is saturated. Note the oscillations in the decay phase which caused the Earth’s magnetic field to oscillate.

hard disk?

Sometimes, supernovae mark the formation of a black hole, which can produce intense, brief, gamma-ray emitting jets seen as a gamma-ray burst (GRB). Observations of GRB have been dominated by serendipitous discoveries from the very start when seen by US military (Vela) satellites in 1967 and announced in 1972. Some are observed right across the Universe and are the brightest things in the Universe during their brief life. Some GRB are different and are due to quakes on neutron stars with superstrong magnetic fields, one thousand times stronger than those of a typical radio pulsar and several thousand million million times stronger than the Earth’s magnetic field in a room. Such objects are called magnetars and a recent outburst on 27 December 2004 from SGR 1806 gave the strongest event ever observed at any wavelength. For the first 2 tenths of a second the (mostly gamma-ray) energy flux on Earth received from this object, which is about 30,000 light years away, exceeded that of a Full Moon. It was then intrinsically one thousand times brighter than the 100 billion stars in our Milky Way galaxy! It saturated all gamma-ray detectors and some of the best measurements of its maximum brightness came from a Russian satellite instrument which was in Earth’s shadow and saw the emission reflected from the Moon. The decay phase of the event consisted of 5 sec pulsations which were even detected as oscillations in Earth’s magnetic field (the gamma-rays ionized the upper atmosphere which in turn affected the magnetic field). If astrologers wanted to have a scientific basis for their ‘predictions’ they would take up gamma-ray astronomy. If the event had been much closer then it could have profoundly affected us all – in a very negative manner.

The time domain is the least explored one in astronomy and continues to be rich in discoveries. It is likely to be opened up further over the next decade with telescopes mapping the visible Sky every few days such as PanStarrs, LSST, Lofar, Gaia, SKA etc. Such instruments will produce vast amounts of data (many Terabytes) every day
so analysing the data will be a serious challenge. This is becoming an issue with the enormous facilities now coming on line in many subjects. The Large Hadron Collider is an example from physics. So much data is produced that most has to be eliminated immediately. How to optimize such enormous data gathering exercises for serendipitous discoveries is unclear.

Sometimes the object or effect was predicted earlier, but considered too faint or difficult to be seen. This was the case with both neutron stars and black holes which are so tiny that it seemed reasonable to assume that they would be unobservable. What was required was for the emission to be stimulated (as in a laser) for the pulsar or highly beamed by relativistic outflow for the GRB. Any scientific paper written predicting their observational detection well before they were discovered would rightly have been rejected!

The discovery of the black hole at the Galactic Centre is a further example of this. While not exactly a serendipitous discovery, it was made possible by the lucky, and still unexplained occurrence of suitable markers (the He stars) in that place. Two teams, one led by Genzel in Munich the other by Ghez in Los Angeles, have seen and followed the motion of individual bright stars orbiting the central black hole. One star has now been seen over the past 15 years to complete one whole orbit. The precision with which this elliptical orbit has been measured leaves us in no doubt that the central 4 million solar masses of our Galaxy is extremely compact and can only be a black hole.

One effect of gravity is to bend light. This was first measured for the Sun during a total solar eclipse by Cambridge astronomer Arthur Eddington in 1919 and as it matched Einstein’s predictions it is what made Einstein famous. Further examples were lacking for almost 60 years during which time few people considered the effect from an observational point of view. Then in 1979 a double quasar\footnote{A quasar is an accreting massive black hole producing so much radiation that it outshines its host galaxy.} was discovered by Walsh, Carswell and Weymann, who were making routine measurements of the properties of a large sample of quasars. Two of the quasars were separated by 6 arcsec and were found to have identical spectra. So identical that at first they didn’t think that the telescope operator had actually moved the telescope. What they had discovered was light being deflected above and below a massive galaxy along the line of sight. When things are exactly lined up the background source appears as a ring (an Einstein ring) around the lensing galaxy, but in a more typical case such as the double quasar where things are slightly mismatched then the image appears as two separate objects (a third one occurs at the centre but is often absorbed by dust in the lensing galaxy). Both images of the double quasar vary with what we now know is the same pattern yet shifted in time by 430 days, which is the difference in light travel time along the two paths. Gravitational lensing has now become (and remains) something of an astronomical industry. More dramatic examples were found in clusters of galaxies in the 1980s. Again these were found serendipitously. They had certainly been seen earlier (and can be seen in published images) but not noticed as such.

One of my own serendipitous discoveries is of ripples in the hot gas at the centre of a cluster. To observe the gas requires X-rays and the image was taken with the Chandra X-ray telescope. The ripples correspond to quasi-spherical ripples in the pressure of the gas.
Figure 6: A double Einstein ring caused by gravitational lensing. Three galaxies lie almost exactly in a line, with the nearest one bending the light from the more distant ones into two rings of light.

Figure 7: The large fluffy objects are galaxies in a rich cluster, the total mass of which is gravitationally bending the light from distant galaxies into many arcs. In essence the whole cluster core, several hundred thousand light years across, acts as a giant telescope.

They are strong sound waves created by the action of gas accreting into the supermassive black hole at the centre of the central galaxy of the cluster. There are several notable properties of these sound waves, the first is that they carry lots of energy to large radii, in essence they enable the central black hole to have a significant influence on gas over intergalactic distances, the second is that they have a very low frequency of one ripple per 10 million years! It corresponds to a B flat about 57 octaves below middle C. The main response of the UK media to our press release on this was just the B flat!

As my final example I return to our Galaxy to discuss the case of extrasolar planets, which were long sought for but only found orbiting normal stars in 1995 by Mayor and Queloz. (Curiously, 3 planetary-mass objects were found orbiting a pulsar in 1991.) The problem lay in everyone’s expectations which supposed that other solar systems would
Figure 8: Chandra X-ray image of the centre of the Perseus cluster of galaxies. The X-rays are produced by hot gas lying between the galaxies. Jets squirting from close to a massive black hole at the centre blow a sequence of bubbles in the gas which create sound waves seen as ripples in the gas.

resemble our own. In our own Solar system the most massive planet, Jupiter, orbits far out every 12 years creating a very tiny response in our Sun which would be difficult to measure in other stars. In the first extrasolar system found, it was a Jupiter-mass planet in a 4 day orbit! Being so close means that its effect on the star is much larger than if it were in a 12 year orbit, swinging that star about at 60 rather than 12.5 m per sec. Such ‘hot jupiters’ give a much larger signal than anyone had expected. Now hundreds have been found, not all with such extreme orbits, but nevertheless few of them actually resembling our own (many of much more highly eccentric orbits than found in our Solar System). 55 Cancri is the nearest one with 5 planets.

This leads me to an area of research in astronomy which relies solely on serendipity, namely the search for extraterrestrial intelligence. What are the chances of detecting another intelligent civilization? Drake’s equation gives us some idea. The number of civilizations, \( N \), in the Galaxy with which we can communicate is given by

\[
N = R f_p n f_i f_e f_c L,
\]

where \( R \) is the rate with which stars are being formed (about 1 per year), \( f_p \) is the fractions of stars which have planets, \( n \) is the number of those planets which are habitable and \( f_i, f_e \) and \( f_c \) are the fractions of those planets on which life, intelligence and communicable civilizations occur. \( L \) is the lifetime in years of a communicable civilization. The detection of extrasolar planets has pinned down one of the very uncertain numbers, \( f_p \), (to say 10% or more). Even then the optimist will find that \( N \sim 0.001 - 0.01L \). A key unknown is the length of time a technologically aware civilization lasts, \( L \). Ours is only just over 100 years old and we need them to last millions of years for \( N \) to be in the
Figure 9: Velocity of the star 51 Peg along our line of sight (courtesy of G. Marcy). It oscillates by about 55 m/s due to a Jupiter-mass planet orbiting it every 4 days.

1000s or more. If they do last that long then we are most likely to find a civilization in the middle of its run, not just near the start as we are. Therefore we will be dealing with civilizations which are hundreds of thousands to millions of years more technologically advanced than our own.

If so, then what will they look like and how will they communicate? Would our present methods seems as absurd for interstellar communication as smoke signals would do across continents? Should we look for highly directed radio signals, which is where the effort has gone so far, or maybe for flashes of X-rays or gamma-rays, as I suggested 30 years ago (Fabian 1977)? Won’t any intelligent civilization be looking for serendipitous flashes in the night?

It is clear that astronomy is rich in serendipitous discovery and phenomena. Harwit predicted that such discoveries would soon slow down as most things were discovered. His argument was based on the assumption that the phenomena have equal weight but given that they are not I foresee such discoveries continuing on well into the future. Several of my examples have been drawn from the past few months and years and even then I had a wide range of discoveries to choose from. In many areas, astronomy is still in an exploratory discovery phase. Cosmology too is equally rich, as is discussed by Simon Singh. In the near future we can expect surprises from neutrino and gravitational wave astronomy. We may yet find that dark matter, which comprises 21% of the Universe,
comes in 42 different varieties.

Does it not then make sense to tailor our research funding, both for the hardware – the telescopes – and for the modes of working, to take this into account? This leads to a current dilemma. Facilities (and people) are increasingly expensive. Funding agencies using public funds want value for money so are most likely to fund projects and telescopes and teams where a successful outcome is predicted. This tends to mean looking into areas close to where we know, rather than stepping out into the unknown. In the case of serendipitous discovery there is little that can be predicted with certainty, we can only argue on the basis of past success. It means stepping out boldly in discovery space.

This situation contrasts with laboratory physics where experiments are mostly controlled and conditions predictable. This is not to say that serendipitous discovery is then absent, as is discussed by Richard Friend, but when a new facility costs millions to billions of pounds then it is generally the clearest defined case with predictable outcomes which wins the money. The situation with respect to astronomy has become polarized by an emphasis on fundamental physics in some quarters. In that view, how a galaxy works is of less interest than the more fundamental issue of whether there are or are not other dimensions to space, for example. Astronomy is often tied up in the messy complexity of everything, whereas the ‘fundamentalists’ want to study the (assumed) much cleaner basis of it all.

My own view on this is that since fundamental physics has not made significant discoveries since 1979 (Smolin 2007) then a direct approach on the fundamental problems may not be the best. If there are other dimensions, they could as well emerge from some serendipitous astronomical discovery. When looking at the night sky with the naked eye, averted vision is often best, and an averted, rather than directly focused approach to
discoveries can often pay off best. We have to keep observing the Universe in all its detail – general astronomical observatories of all wavebands are the way to go.

This ‘fundamentalist’ debate is not settled (e.g. White 2007) and will continue to play out over the next decade. It is ironic that our telescopes are remembered mostly for the serendipitous discoveries they made (Keck Fig, 10, HST) and not for the issues for which the original science case was made, yet we put most of our efforts into the known science aspects of the science case for a new telescope. Rather like the common view of democracy, or peer review, this common approach is highly flawed but is however the best available.

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