The Universe is full of galaxies - we estimate that there are at least 120 billion of them - but despite a huge range of mass and size, they mostly conform to a limited range of morphologies. Today's lecture is going to concentrate on some of the exceptions - galaxies that appear very different from their mainstream counterparts because they have been tugged into fantastic shapes by the gravitational influence of one on another. Such peculiar galaxies make for some of the most spectacular deep-sky objects that can be observed. The observations can tell us much about how such interactions happen: not just the physics involved, but the toll that a gravitational encounter exerts on an individual galaxy's internal properties, and how the process has implications for the evolution of the wider galaxy population throughout the history of the Universe. But before we do look at the exceptional galaxies, let us start by examining the characteristics of more 'ordinary' galaxies.

Every galaxy is its own 'island Universe', comprising a giant accumulation of stars, numbering from several millions to several trillions (million millions) per galaxy. They also come in a range of size: small dwarfs have diameters of a few thousands of light years; mature spiral galaxies such as our Milky Way span around 100,000 light years or more; large elliptical galaxies can stretch to about half a million light-years across. Similarly their mass can vary between a few millions of solar masses to 100 trillion.

For all the variations in size and mass, the simplest criterion for classifying and differentiating galaxies is by their shapes. There are two main morphological types (though this is, of course, a simplification):

Elliptical galaxies have a rounded, symmetrical shape like a football or rugby ball, which does not change appearance much with viewing angle. They are the most common morphological type, comprising about 60% of all galaxies. Their characteristic yellowy-orangey-red colour reflects the fact that they are comprised mainly of older, redder stars; ongoing massive star formation (which would appear blue) is absent because elliptical galaxies lack the cold interstellar medium that can most readily collapse into stars. Elliptical galaxies are generally a lot more massive than spiral galaxies, and can be surrounded by thousands of globular star clusters, each one a compact ball of hundreds of thousands of stars gravitationally bound together.

Spiral galaxies are those like our Milky Way, where a bulge of old stars is surrounded by a large flat disc that hosts the spiral arms. A spiral galaxy's appearance varies strongly with our viewing angle to this structure: they can present themselves face-on, inclined, or edge-on to our line of sight. The central bulge is either spherical, or elongated into a bar-shaped structure that the spiral arms grow out in a barred spiral galaxy. There are further variations in both families of unbarred and barred spirals, according to the relative dominance of the bulge over the disc, how tightly loosely wind the spiral arms can be, and even the number of spiral arms themselves.

The bulge is a yellowy-white colour, revealing that it is an accumulation of older stars, similar to the population found in an elliptical galaxy. The spiral arms within the disc are notably much bluer, as they trace regions where massive star formation is currently active (blue stars are short-lived, so they are only seen in places where star formation is comparatively recent). The spiral arms themselves are only very transient structures within the disc. They mark the point where a compressive density wave has last travelled through the disc of neutral diffuse gas; when it squeezes a cold gas cloud, the local density is increased, prompting the gravitational collapse that precedes star formation.

The characteristics of current active star formation are not just the bright open clusters of the massive blue stars - each cluster having collapsed from the same original interstellar cloud - but also include the pink-coloured nebulae that surround them. The energy emitted by the young stars excites the hydrogen atoms remaining in the parent gas cloud so that they then radiate their own light. The gas clouds in the disc of spiral galaxies also contain large amounts of the miniscule particles of carbonates and silicates known as dust (see my lecture on Star Dust for more information about this!). Dust is formed in the outer envelopes of cool red giants, a later stage in the lives of fairly massive stars. Thus the presence of such large quantities of dust in the disc demonstrates it has been the location for many generations of massive star formation. The particles have been swept together by the action of the density wave to form the dark swathes silhouetted against the background light of the stars, particularly apparent from an edge-on view of a galaxy.

The first galaxies formed during a relatively short period of time, within the first few hundred million years of the Big Bang, each descended from a primordial cloud of hot gas - comprising hydrogen and a little bit of helium - as it collapsed under its own gravity. The first stars form at the dense centre of the large cloud to form a bulge of stars, but the subsequent morphology depends on the amount of overall rotation of this protogalactic gas cloud, which due to the conservation of angular momentum, is enhanced as the body shrinks in size. A collection of matter with very little or no rotation will continue to build randomly around the bulge to create an elliptical galaxy; there may be variations to how flattened it is, but the stars in the final product revolve around the galactic centre on fairly random orbits. The structure that forms from a much more rapidly rotating cloud flattens further into a disc around the bulge as it develops; a fluffy, loosely wound spiral with a small central
bulge (known as an Sc/SBc type) has much faster rotation than a galaxy with more tightly wound arms surrounding a large central bulge (Sa or SBa type). In both, massive star formation continues by the density waves in the disc.

What all of these galaxies have in common is that they show a consistent symmetry of structure. This is not true of the ‘peculiar’ galaxies we are going to discuss today.

As galaxy catalogues began to be compiled through the middle of the twentieth century, it began to be apparent that about 5% of them showed very different morphologies from the classic spiral and elliptical shapes. They could be strongly or mildly asymmetric; some would show long plumes of stars that stretched away from the body of the galaxy hundreds of thousands of light-years out into interstellar space; others were a random scrambled mess. Many also appeared anomalously blue in colour. 338 of the closest and best-studied examples were collected together in Halton Arp’s Atlas of Peculiar Galaxies, originally published in 1966, and indeed many of the examples I shall discuss today are known by an ‘Arp number’. Most notably however, many of these weird and wonderful objects were contained in a pair of galaxies – suggesting that many of these features were due to the effects of one galaxy on another.

Galaxies are separated by vast distances, typically at least several millions of light years of interstellar space. We traditionally think of a galaxy existing in isolation, being driven further from all other galaxies by the expansion of the intergalactic space. This cannot always be true – there are pockets of space where the expansion of the Universe is overpowered locally by gravitational attraction, and galaxies group together to form clusters of hundreds or thousands of galaxies. Sometimes even a couple of galaxies can have formed sufficiently close to one another, that the gravitational pull they exert on each other is strong enough for them to ‘detach’ from the more widespread expansion pattern; they are drawn through the space towards each other under this attraction.

Our own Milky Way does not live by itself, but it is one of a small group of about 50 galaxies spread over a few million light-years known as the Local Group. The group consists of three large spirals and a host of attendant galaxies – the Milky Way alone has over ten small satellite companions, the largest and most massive of which are the Magellanic Clouds.

The Magellanic Clouds are a magnificent sight for the unaided eye in Southern Hemisphere skies. The Small Magellanic Cloud (SMC) is the further, at around 200,000 light-years distant, and the Large Magellanic Cloud (LMC) lies about 30,000 light-years closer. They are dwarf galaxies that each contain about 1/100th the mass of the Milky Way, and they orbit around it once every two billion years, far beyond the stellar disc. Neither exhibits a well-defined shape and both – although more particularly the closer, LMC - show the blue stars and pink nebulae indicative of huge amounts of active star formation. The dominant gravitational pull of the Milky Way produces a tidal shear across each galaxy, which acts to twist and compress the gas clouds to trigger intense star formation; the Milky Way’s gravity is also steadily pulling them apart.

Each Magellanic Cloud is trailing a long stream of cold atomic gas known as the Magellanic Stream, which stretches around the Sky, observable only in the radio wavebands. The SMC is particularly affected, being the lower mass the two, and suffering from the combined force of the LMC as well as the Milky Way. As the LMC orbits so close to the disc of our galaxy, its gas is also removed through the process known as ram pressure stripping. Stars also embedded within the gas clouds of the Magellanic Stream which may well have formed in situ. Models for the dynamics of the satellites and the Milky Way suggest that the tiny galaxies may be completely disrupted and disintegrate within a few hundred million years.

Another satellite of the Milky Way was discovered only as recently as 1994, mainly because it orbits at a distance of 50,000 light-years from the centre of the Milky Way, only a third of the way out to the LMC. This means that its diffuse structure is more difficult to identify as it is spread over a large area of the Sky, and as it is hiding on the other side of the Galactic Centre from us, it is heavily obscured by all the dust and gas in that direction. Known affectionately as SagDeg, the Sagittarius Dwarf Elliptical galaxy is only 10,000 light-years across, and completes an orbit around the poles of our galaxy every billion years or so, plunging through outer regions of our galactic disc on the far side of the Galaxy as it does so. It remains barely intact, getting torn further apart on each passage through; it is particularly vulnerable to the gravitational pull of the halo of dark matter that surrounds the Milky Way.

The gravity of a satellite galaxy – and the perturbations it may induce in the dark matter halo – also influences the Milky Way in return, producing a slight warp across its disc. This is most apparent in the distribution of the hydrogen gas: one half of the disc rises a little above, the other dips a little below the line of the Galactic plane traced by the stars. Although the Milky Way has only a very slight warp, such features are apparent in other spiral galaxies, for example NGC 3628, which we view nearly edge-on to see a thickened warped disc.

The observations of the Magellanic Clouds illustrate some important points about interacting galaxies: a gravitational tidal disturbance can prompt vigorous star formation activity; matter – in the form of both gas and stars – is pulled away/off a galaxy to form long tails; and both galaxies involved in any interaction are affected.

The Andromeda galaxy is our nearest large neighbour, and it lies 2.5 million light-years away, a near twin to the Milky Way in terms of its appearance, shape, mass and size. It too has a selection of small companion galaxies in
orbit around it. Andromeda is sufficiently close that we feel its gravitational pull, and it feels a return pull towards the Milky Way. We are moving towards each other at about a million km an hour (which is why it is one of the galaxies that shows a blue- rather than a red-shift in its spectrum, as it is a local departure from more general Hubble expansion). In a few billion years, the galaxies will come close enough to interact with each other, and indeed, it is thought that they will merge together to form a completely new (and very messy!) system about six or so billion years in the future.

One way we estimate the consequences of this close encounter is through a computer simulation. Such modelling starts with the observed properties of the galaxies – such as their separation, relative velocity and orientation to each other; the direction of their rotations; the distribution of their mass – as starting conditions in a numerical computation that uses the laws of physics to predict how their appearance will change with time.

Such computer simulations show that an encounter takes place over several billion years and radically changes the appearance of both galaxies. Notably, the galaxies do not immediately collide head-on, but undergo at least two or three passes around and through each other before an eventual merger occurs (if it’s going to). Two galaxies do not have to actually cross paths to suffer an interaction – they merely have to pass sufficiently close to get caught up in each other’s gravitational grip. The galaxies start to get pulled out of shape even as they approach each other, but it is during the first pass that the most dramatic features are created.

Long streams of gas and stars are drawn out from each galaxy and flung out into space, and can extend over a distance of a few hundreds of thousands of light-years, i.e. way beyond the size of the galaxy itself. Sometimes a stream may form bridges that stretch between the two galaxies to link them. The extent of the tidal tails depends on the geometry of the encounter, and they are nearly always strongly arced – although they appear completely straight if viewed edge-on to the curve. The tails develop because the gravitational force is tidal; the formation of these structures depends as much on its gradient (i.e. how quickly it changes with distance), as on its strength. The tidal effect of the gravitational force from the Moon gives rise to two high tides a day in our oceans on Earth, from two bulges of water – one pulled round the Earth on the near side to the Moon, and one ‘left behind’ on the far side as the Earth is pulled away from the main body of water. Similarly each galaxy is stretched radically by the gravitational field of the other. The most vulnerable material, such as the gas and stars right at the outer edges of the spiral disc, is sheared off from the parent galaxy to form the long, thin tails. The central bulge remains largely unaffected. These effects of the gravitational tides can be exacerbated by the relative direction of the rotation of the galaxies: if the relative and rotational motions are matched (known as prograde encounters), the tails are spectacular; opposing directions (retrograde) rarely produce such tails.

The two galaxies may remain gravitationally tied to each other to turn round and make a second pass, only finally beginning to merge with each other after at least a third encounter. The eventual product of the merger does not often resemble either of the original systems as the spiral arms and the discs are gone. There are a variety of possible end-products, and I will talk more about this a little later.

The interaction of Andromeda and the Milky Way is by no means typical, and there are many different parameters that can change the outcome and the severity of an interaction.

Two galaxies undergoing a gravitational encounter do not necessarily merge to form a new system; one may remain fairly undisturbed while another is completely torn apart or they may continue on their way after that first pass, and not merge at all. The impact of a tidal interaction on the galaxies involved depends on several factors.

The slower two galaxies approach each other, the more time and opportunity there is for the matter in them to both notice and respond to the gravitational field of the other galaxy. Thus two fast-moving galaxies can pass each other quite closely but with little consequent effect.

The gravitational attraction of a body is stronger the closer you are to it due to the inverse square law, so obviously the distance of the two galaxies at their closest approach is also important.

The amount of gravitational pull is also directly dependent on the amount of mass present, and the relative mass of the two galaxies is of key importance. As seen in the effect the Milky Way has on the Magellanic Clouds, it is the less massive (usually the smaller) galaxy that experiences the much stronger gravitational pull, and that will suffer more from an encounter. A much more equal match in mass – such as the Milky Way and Andromeda – will result in both galaxies being more equally affected.

A famous example of an encounter involving two galaxies of very unequal masses is that of the face-on spiral galaxy M51 (the ‘Whirlpool’ galaxy) and its much smaller companion NGC 5195. The latter is swinging round M51 on a trajectory that took it through one side of the disc of the larger galaxy 500-600 millions of years ago; it has since looped up and back down on an arc that took it on another pass on the other side about 50-100 million years ago. It now lies behind M51 and is continuing to move away. The circular shape of the disc and the symmetry of the spiral arms of M51 have both been badly distorted by the passage of NGC 5195 – the disc has been squeezed into an ellipse, and one of the spiral arms has been pulled out and away. A deeper view of the combined system reveals tidal debris that has been drawn out of both galaxies and dispersed.

A similarly mis-matched pair of galaxies making a closer encounter can be seen in the NGC 6745 system. A large spiral galaxy has been pulled into the shape of a bird’s head after a smaller galaxy (just visible to the lower right)
Examples of colliding galaxies in the nearby Universe are relatively rare, with only about one found per million galaxies. This is partly because although an interaction takes hundreds of millions to occur, this is still relatively transient in comparison to the age of the Universe. We do not see the galaxies move or respond to each other as it happens too slowly compared to human lifetimes; all we have are various snapshots of the process that we can observe. The observations are interpreted and put into context with the use of computer simulations, with the aim of identifying the stage of encounter, estimating the properties of the progenitors and interpreting the physics of the interaction. It is important to remember that the dominant gravitational component influencing the behaviour of each galaxy is the invisible dark matter halo around each (the luminous portions of galaxies that we observed represent only a small fraction of the total galactic mass) so the simulations present an important test of our understanding of the distribution and nature of the dark matter in each galaxy. It is not specifically something that we can match to the observations, but we can observe its effect on the distribution of the observable material. In particular, the dark matter halos extend far further than the stellar/gas disc, so even when the luminous parts of galaxies seem to clear each other by a large factor, the dark halos may well be interacting with each other strongly.

Computer modelling tends to concentrate on interactions of systems where both, or the dominant galaxy is spiral (we shall return the products of mergers involving elliptical galaxies a little later).

Despite them being the less common galaxy, the effect of an interaction is much easier to trace – and much more diagnostic of the physics involved – when it involves a spiral, as there is a much more dramatic change in morphology. Not only is the material at the edges of the spiral disc much more fragile, but there is more cold gas available to be compressed into very observable star formation episodes. A merger of an elliptical with an elliptical just produces another elliptical galaxy...

Simulations of interacting galaxies were pioneered in the early 1970’s by the brothers Toomre & Toomre, who first demonstrated the principle of the origin of how the tidal tails can develop. Today such simulations employ computer-heavy N-body modeling, using millions of points to each represent the positions and velocities of thousands of stars. This simplified approach is still necessary as we do not have the computing power able to handle a model tracing the behavior on the scale of individual stars in a galaxy! A simulation computes the combined gravitational pull acting on each of these points from the others, and steps the model forwards in time, changing the position and velocity of each point at each step. Other models consider the gas content of the galaxies, and have to include hydrodynamic forces.

As the galaxies approach each other for the first time, there is a pronounced internal change in each. The matter in the disc is disturbed, warping the natural symmetry. If the disc component is dominant, a bar-shaped feature can form across the bulge; alternatively the spiral arms are pulled out of line and amplified if the mass is more in the bulge and dark matter halo. NGC 2207 shows the latter case – the two galaxies are not very disrupted yet, indicating that they are just at the very start of their encounter, and starting the first approach. The smaller galaxy is already being stretched to grow tidal tails in front and behind it.

The two spiral galaxies comprising the ‘Mice’ pair are most likely to be going through the second phase of interaction; during the first pass tidal tails have been pulled away from each galaxy, carrying away some of the rotational energy of the stars. The fairly equal lengths of the two tails suggest that the original galaxies involved were of roughly equal mass. Comparison to simulations aiming to match this particular configuration imply that there is one galaxy viewed more face-on and one almost edge-on, the straight tail is a curved structure seen edge-on, and they will most likely they will undergo another collision before they eventually coalesce.

The galaxies will most likely undergo three or more passes before they can merge into an elliptoidal remnant. The amount of dark matter present in the halos of each galaxy is important, as it will produce a drag on the relative motion of the galaxies. It is necessary for the dark matter halos to absorb much of the galaxies’ angular momentum and orbital energy for the merger to occur at all. NGC 6240 is an example of a final remnant from a merging process which began about 30 million years ago, and which will take some tens to hundreds of millions of years yet to complete.

The stars that dominate the luminous mass of each galaxy almost never collide with each other, as they are separated by distances far greater than their individual size. Instead they tend to just pass by each other. The same cannot be said for the diffuse clouds of atomic and molecular gas that fill the space between the stars in each galaxy, making up the interstellar medium. Such clouds cannot avoid each other, and the impact of such collisions will act to squeeze the gas in each, increasing their density, and triggering episodes of new star formation from the consequent gravitational collapse. This creates a vigorous starburst, apparent from the common bright blue star clusters and pink emission nebulae seen in merging systems.

This starburst activity is evident in the pair of galaxies NGC 4038/9 that lie around 60 million light-years distant, popularly known as the ‘Antennae’ galaxies due to the way their two long tidal tails curve so that the system resembles insect eyes and antennae. Computer simulations suggest that they are during the third pass of their
encounter and that they were both originally spiral galaxies, one barred and only slightly larger than the other. So far the encounter has lasted some 900 million years from when they first began to approach each other, and it is estimated that it will take another 400 million years for the merger to be complete. The interstellar gas clouds have been compressed, launching fantastic starburst activity, as the system glows with the light of thousands of bright clusters of young blue massive stars and their surrounding nebulæ. Massive stars are short-lived, so some have already gone through their entire life cycle in only a few million years, and X-ray images show the remnants of many active supernovae within these starburst regions – both the black holes that they have formed and the huge clouds of hot gas given off in the explosion that contain the heavy elements produced from nuclear fusion processes.

All large galaxies (such as both the Milky Way and Andromeda) are thought to have a supermassive black hole at their core, usually completely dormant. Computer simulations can include not just the behaviour of the dark matter and stars, but also the hydrodynamic evolution of the interstellar gas within a merger using smoothed particle hydrodynamic (SPH) codes. These models show that interactions and mergers can sometimes drive material towards the central core.

Thus a gravitational interaction may do more than just trigger a starburst in the newly formed system, as the newly-directed flows of gas and stars in a galaxy could be channelled towards a dormant supermassive black hole at the centre of either galaxy, providing fuel which might revive its activity. Indeed, with the development of infrared astronomy in the 1980’s, some galaxies were found to have extreme infra-red luminosities, far above what was expected from just the galaxies alone. There was a clear causal connection to gravitational interactions, in that the galaxies hosting this enormous luminosity showed characteristic morphological features such as the tidal tails or double nuclei. The converse is not true, however, as there are many cases of strongly interacting pairs without such ultra-luminous infrared emission. Whether or not a merger stimulates central black hole activity in a simulation depends on the variance in different for different collision geometries, galaxy structures and gas content. Even if a merger is successful in retriggering an active nucleus, this phase is expected to be only transient, perhaps lasting less than a 100 million years.

The infrared light may well be produced by a combination of intense starburst activity and an active nucleus blocked from our view by thick dust clouds. The dust particles absorb the energy and reradiate it at the lower energies; unfortunately they completely obscure the source of power from view, so it’s not definite which mechanism dominates.

Very rarely, there are spectacular structures that are interpreted as the end results of head-on collisions between two galaxies.

The Cartwheel Galaxy lies about 500 million light-years away, and appears as the depleted core of a spiral galaxy, that is surrounded by an enormous blue ring of bright clusters of young stars with a diameter of 150,000 light-years. It appears that a small companion dived through the core of a spiral galaxy that originally resembled our own Milky Way about 200 million years before. A trail of neutral hydrogen gas allows us to identify the invader. The collision set a strong shock wave rippling out through the galaxy from the centre at very high speed; this swept up the interstellar clouds of the galaxy, compressing it to trigger a starburst in a ring around what remains of the core of the galaxy. Loops and bubbles of gas around the ring suggest that the most massive stars have already undergone supernova explosions, perhaps prompting a second wave of star formation.

Another example is Hoag’s object, where a blue ring of young massive star clusters again surrounds a nucleus of older stars due to a splash of star formation rippling outwards, triggered by another head-on smash. It has proved harder to identify the interloper in this case, and some astronomers suggest that the ring of stars could be comprised of its shredded remains, in which case Hoag’s object could be a face-on view of a polar ring galaxy.

A polar ring galaxy is one that is surrounded by a ring of gas and stars that rotates in a completely different direction to the stars in the galaxy, passing over the poles rather than around the equator. Such rings are thought to be composed of all the material that has been tidally stripped from a smaller companion that approached from a direction perpendicular to the plane of rotation of the primary. Such systems are comparatively rare, and nearby examples include NGC 4650A and NGC 2685.

In fact, where you see anomalous features in a spiral galaxy, they can usually be ascribed to a past or recent interaction that it has undergone. This is also true to the kinematic behaviour of components of a galaxy.

The spiral arms of a disc galaxy tend to trail the direction of rotation. NGC 4622 is a curious spiral galaxy which has two outer spiral arms that instead point in the opposite sense, towards the direction of the galaxy’s rotation. Two inner spiral arms do trail the rotation, but have completely wrapped round the galaxy to form a ring. These features are thought to stem from a disturbance arising in a past gravitational interaction.

M64 is a large spiral galaxy, where the light of the nucleus is obscured by particularly thick bands of dust, giving rise to its moniker as the "Black Eye" galaxy. These dusty clouds are observed to be rotating in the opposite direction to the stars in the inner parts of the galaxy. The odd kinematic behavior, along with the excess dust, is thought to originate from the disintegration of a smaller companion over a billion years ago. Bright regions of active star formation can be seen along the line of shear where gas clouds rotating in opposing directions collide
and compress each other.

As elliptical galaxies tend to be more massive, they will dominate a gravitational interaction with a spiral, which will often be accreted and completely absorbed relatively quickly. We can still recognise the end products of such encounters, however, as the elliptical galaxies that show features that are not normally associated with spiral galaxies. Giveaways include cores that show a kinematic behaviour that is distinctly different from the rest of the galaxy, or dark knots and lanes of absorbing dust in the outskirts of the galaxy.

Complicated swirls of dust are laced against the stars in the enormous elliptical galaxy NGC 1316, suggesting that it has consumed a small spiral galaxy in the past. Other anomalies include a high rate of novae, suggesting a burst of star formation in the past, and fewer globular clusters than would be expected in an elliptical galaxy of this size, both of which could also be consequences of a past merger. The wide view of the galaxy shows that it is currently interacting with its small spiral neighbour to produce widespread arcs and shells of stars and gas.

The large elliptical radio galaxy Cen A shows a very thick and warped dust lane across its core. The underlying galaxy shows the much older, redder population of stars typical of an elliptical, but bright clusters of new blue stars trace the edges of the dark dust lane. Again, such features are ascribed to the assimilation of a small spiral companion. Further evidence of a past disturbance comes from features that appear as an incredibly faint system of concentric arcs around the core of the galaxy.

These systems of arcs are only found around elliptical galaxies, and are in fact a projected view of large incomplete shells of stars that are usually interleaved (with each successive shell wrapping round the opposite side of the galaxy nucleus to the previous). The shells are very faint, but are made of stars significantly bluer than the underlying parent galaxy. Computer simulations show that they are features produced when an elliptical galaxy absorbs a disc galaxy containing only 1-10% of its mass, and where the encounter involves only very low amounts of angular momentum. The material from the spiral is wrapped around the core of the elliptical, and a sloshing motion promotes the formation of stars at the cusps where the compressive density waves turn around.

Galaxy interactions don’t just occur between pairs of galaxies – systems that involve three or more galaxies are commonly observed.

The Leo Triplet contains three large spirals 30 million light-years away, where each can be seen tilted at a different angle to our line of sight. M66 (to the lower right) already has its arms pulled slightly askew, and the edge-on NGC 3628 shows the fattened and warped disc that we looked at earlier, as well as a tidal tail extending over a distance of 300,000 light-years.

Hickson Compact Group 90 illustrates how a dusty spiral galaxy comes off worst in an encounter with a couple of massive ellipticals; coming completely mangled in the in a cosmic tug of war between them.

Such compact groups as this represent the most acute places for galaxy interactions to occur, as they are regions where galaxies are packed very tightly – several galaxies exist within only a few million light-years of each other – and moving comparatively slowly to each other. (Unlike rich clusters of galaxies, which contain a high density of galaxies, but ones which are moving far too fast to notice each other and respond.) And there are a whole host of spectacular examples for study.

Arp 194 is a system containing a handful of distorted galaxies that stretch across a distance of around 100,000 light-years. The bigger, upper component contains at least two galaxies in the process of merging, alongside a smaller, less disturbed spiral galaxy. Another spiral galaxy is seen as the lower component, linked to the upper by a thick stream of blue clusters that contain many millions of recently formed stars, all triggered by the compression of the gas clouds drawn out between the two components.

Despite the name, Seyfert’s Sextet contains only four galaxies within a volume that is smaller than the width of the Milky Way. The small face-on spiral with the prominent arms is actually a background galaxy almost five times farther away than the others. The nearly edge-on spiral appears relatively unaffected, showing only a slight warp to its disc. Three lower ellipticals are clearly in the process of interacting – but the last ‘galaxy’ is actually a tidal tail this interaction has created.

Similarly the undisturbed spiral in Stephan’s Quintet is a foreground interloper lying about seven times closer than the other four, which are about 290 million light-years away (as demonstrated by the much higher resolution it shows in this image). To the upper left, the barred spiral galaxy NGC 7319 has slightly distorted spiral arms and a long sweeping tidal tail. At the middle two merging galaxies, NGC 7318A/B, are ringed by long chains of bright blue star clusters and nebulae, some of which appear to have completely detached from the galaxies. The last galaxy NGC 7317 is a more normal-looking elliptical galaxy appearing far less affected by the interactions. It is thought that another galaxy (not in the photo, and maybe no longer part of the group) may have been responsible for triggering some of these features.

Compact groups of galaxies present a puzzle precisely because they provide such ideal conditions for gravitational interactions to occur. Computer simulations imply that compact groups will merge to form a single galaxy remnant on a very short timescale; so rapidly that one would expect them all to have merged long since
so that there could not be any such compact groups left in the current universe! The problem is exacerbated by the difficulty of identifying the end-results of these group mergers in the numbers expected. When found, these are known as ‘fossil’ galaxy groups.

The remnant is predicted to resemble a single massive elliptical galaxy existing in almost isolation, have consumed all its immediate neighbours. Although the stars will have been absorbed, the hot X-ray gas halo that filled the space between the galaxies as the intergroup medium will not have been used to create this galaxy, and should still be present. It will still be hot, as it is responding to the gravitational potential of all the combined dark matter present.

One example of a fossil group could be the elliptical galaxy RX J1416.4+2315 which has a noticeable deficit of neighbours, but which lives at the centre of a hot gas halo that has the characteristics (temperature, mass, luminosity) more of a cluster of galaxies than an isolated galaxy. The system has a particularly large mass, with only 2% in the form of stars and 15% in the form of the X-ray gas; the rest is dark matter.

Only a few potential fossil remnants have so far been found, and certainly not in the number that is expected from the observed abundance of compact groups. The solution to this conundrum is not yet obvious. Either the compact galaxy groups are continually replenished, perhaps by infall of new galaxies from the surroundings, or they have formed only relatively recently, taking much longer to fall together than galaxies living in much higher-density regions of the Universe. It is also possible that there are errors in the simulations that vastly under-predict the timescales involved; if the galaxies in a group are contained in a common halo of dark matter, the whole rate of merging could be much slowed.

There are other ways that a galaxy can be formed from a gravitational interaction of two galaxies. The images of Stephan's Quintet show where some of the large superclusters of stars have detached from the galaxies and are now freely floating in intergalactic space. Such features are not uncommon, and may represent the birth of new satellite dwarfs around larger galaxies.

The Tadpole galaxy is formed from a large barred spiral galaxy 400 million light-years away with a spectacularly long tidal tail, stretching over 280,000 light-years in length. This tail is laced with massive clusters of bright blue stars, each containing around a million stars. A smaller, more compact galaxy is primarily responsible for this structure, having looped round in front of the spiral before it fell back down, passing through to where it can now be seen some 300,000 light-years further back, behind the main spiral arms. Two particularly large and prominent clumps of star clusters are evident far out from the galaxy; these will develop into dwarf galaxies and future satellites of the Tadpole.

Another fantastic object is the barred spiral galaxy NGC 6872 – the largest known spiral galaxy, with an impressive wingspan of over 500,000 light-years (five times wider than the Milky Way). A small disc galaxy with only one-fifth the mass of NGC 6872 sits above the central bulge, and simulations show the two underwent a close encounter over 100 million years ago; the smaller galaxy passed close to the plane of the spiral disc and in the same direction as it rotates, and it was responsible for the unraveling of the spiral arms over such a great distance. A new dwarf galaxy may be forming at the far end of the more disturbed of the tidal tails. It is only apparent in ultraviolet observations, demonstrating that the stars it contains must be very hot and contain the most massive and hence youngest stars in the whole system.

Finally, we shall visit a relatively new pair of interacting galaxies M81/2, which are popular targets for amateur astronomy enthusiasts. M81 is a large near face-on spiral galaxy that appears to be only slightly misshapen, while M82 is a more irregular system seen edge-on, and it is clearly undergoing a huge starburst at its core as revealed by large outflows of hydrogen gas. Bright blue clusters of stars formed around 200 million years ago are clumped together to form a structure in interstellar space known as Arp's loop; each cluster contains tens of thousands of stars, and they do not appear to belong to either galaxy. Radio images reveal that these are embedded in, and have collapsed from long streamers of neutral hydrogen gas that have been pulled from the galaxies. These too are expected to evolve to form future dwarf galaxies.

From all the models and observations it is obvious that gravitational encounters have a profound effect on a galaxy: its morphology is radically transformed; new intense episodes of active star formation are triggered; activity at the central nucleus can be restarted; and it can accumulate more mass. Although interactions may be not be frequent in the present day, if they were a much more dominant process in the past, they may have shaped the evolution of the galaxy population as a whole.

The formation of large-scale structures in the Universe is thought to be hierarchical: small structures – such as an individual galaxy – will form first, and these gradually build up to create larger structures such as clusters and superclusters of galaxies. Because it takes light billions of years to travel astronomical distances, observations of the most distant galaxies give us views of the earliest galaxies, and many of these are seen to be distinctly disjoint and blobby in morphology, suggesting that these may well be merging systems. The components involved will be much smaller, suggesting that today's galaxies are the products of an assembly of many smaller systems over billions of years. Thus the study of galaxy mergers in the nearby Universe can give insight to the way that the wider galaxy population grows and evolves through history. The early galaxies represent only the
building blocks of present-day galaxies such as our own Milky Way.