BLACK HOLES | an essential component of our universe
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Black holes provide an important tool for probing and testing the fundamental laws of the universe. All objects exert an attractive gravitational force which depends on their mass. Now, imagine an object with a very large mass which is concentrated into such a small volume that the gravitational field generated is powerful enough to prevent anything from escaping its clutches – even light. This bizarre concept intrigues everyone, in particular physicists who theorise about the nature of matter, space and time, and astrophysicists who look for real black holes out in space. Their study brings together the big ideas in fundamental science: Einstein’s theory of gravity – *general relativity*; the theory of the very small – *quantum mechanics*; and the origin and evolution of the universe – *cosmology*.

**HISTORY**

The basic idea is quite old. In the late 18th century, John Michell at the University of Cambridge used Newton’s law of gravitation to calculate that the velocity needed to escape from the surface of a very massive star could exceed the speed of light. Any light emitted could never actually leave, thus creating a “dark star”.

It was not until 1916 that this idea re-emerged out of Einstein’s geometrical theory of gravity. This description regards the universe as having three dimensions of space and one of time – *spacetime*; gravity is thought of as the distortion of spacetime caused by the presence of matter. A Dutch physicist, Johannes Droste, and a German physicist, Karl Schwarzschild, independently found a spherical solution of Einstein’s complicated equations. It showed that a spherical mass like a star, when compressed beyond a certain critical radius, must collapse to an infinitely dense point called a *singularity*. Spacetime within the boundary of this radius, known as the *event horizon*, would be so curved – and gravity thus so strong – that nothing would ever come out again; it is, in effect, a (non-rotating) black hole (see diagram).

Such ideas were considered bizarre and of no practical value – until the 1960s and 1970s when there was a resurgence of interest. In 1963, a mathematician from New Zealand, Roy Kerr, produced a “beautiful” solution to Einstein’s equations in which the collapsed object was rotating – a *Kerr black hole*. This is particularly relevant because any real black holes existing in the universe would likely rotate. Later, it was shown that black holes could also have an electric charge – at least theoretically.

During the following decade, theorists in the US, the UK, and elsewhere set about understanding the properties of black holes – the term was coined in a lecture given in 1967 by the American physicist, John Wheeler. In Cambridge, the British physicist, Dennis Sciama, led and influenced a group of young researchers, including Stephen Hawking and Roger Penrose, who pioneered our understanding of black-hole phenomena.
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The first significant discovery about black holes was that they have just three simple properties: mass, spin and electric charge – the so-called “no-hair theorem”. However, the existence of incomprehensible singularities represented the breakdown of the laws of physics, and theorists looked for mathematical solutions that would avoid them. In 1965, Penrose proved that singularities could form when massive stars collapse, but later proposed that their mathematically “pathological” nature would always be hidden from us by the event horizon – the so-called “cosmic censorship” hypothesis.

BLACK HOLES TODAY
In the early 1970s, Hawking and others started to analyse the detailed mechanics of black holes – their thermodynamics. For example, they asked questions such as does a black hole have a temperature? What exactly happens when an object falls into a black hole: does the degree of disorder, or entropy, increase; and are the measurable physical characteristics – the information about the object – destroyed? Such issues became a huge area of heated discussion and research, and in more recent years have led to significant insights, with wide repercussions in both fundamental and applied physics.

BLACK HOLES IN THE UNIVERSE
In parallel, astronomers have found increasing evidence for black holes in the cosmos. Massive stars collapse into black holes at the ends of their lives, and most galaxies are thought to host supermassive black holes at their centres. The operation of instruments to study the radiation from the vicinity of black holes is providing insights into the evolution of stars, galaxies and even the universe itself (p10).

This booklet describes recent, remarkable discoveries made about black holes, and the UK role in them.

FALLING INTO A BLACK HOLE
If you were to fall towards a relatively small black hole, then you would feel the effects of tidal gravitational forces before reaching the event horizon, and your body would be stretched out until you were ripped apart – a process sometimes called spaghettification. However, if the black hole were large, you would not notice when you had crossed the event horizon, except that distant objects would look distorted because light would be bent. It would be too late to escape, and you would inevitably hurtle towards the singularity. An observer on the outside would not see this happening but would see your descent appear to slow down as you approached the event horizon and the light took longer to travel away. The light waves would also stretch out so that they reddened in colour. Eventually, all that would remain would be a dimming, reddened image of you frozen in time at the event horizon.
In 2011, UK astronomers were involved in finding the most massive stellar-mass black hole to date – IC 10 X-1 in the nearby galaxy IC 10, weighing in at a minimum of 23 to 33 solar masses.

**STELLAR BLACK HOLES**

Our galaxy may be teeming with black holes

Black holes have not yet been seen directly – only by the effect they have on matter nearby, for example, when they co-orbit with a star in a binary system. Material falling towards a black hole heats up to millions of degrees and radiates in the X-ray part of the electromagnetic spectrum.

The first black-hole candidate, discovered in 1964, was a powerful X-ray source 6000 light years away – Cygnus X-1. Astronomers, including Paul Murdin and Louise Webster at the Royal Greenwich Observatory, realised the X-ray emitter had to be the massive companion of a blue supergiant star pinpointed in the same location. Measuring the disturbance of the supergiant's motion (using the Doppler effect*) by the gravitational pull of its unseen partner revealed that this body had to have a mass of at least eight times that of the Sun. Furthermore, measurements of the rapid X-ray flickering suggested that the emitting material was concentrated in a relatively small volume. (This is because the timing of the flickering depends on the coordinated communication between different areas in the material, which even travelling at the speed of light, takes a definite amount of time to cross a certain distance.) Calculations had shown that the only other compact object it could have been – the dense stellar core composed of neutrons left over from a supernova explosion – cannot exceed three solar masses before collapsing further into a singularity, and so Cygnus X-1 seemed most likely to be a stellar-sized black hole.

So far, about 50 candidate X-ray-emitting binaries containing black holes have been identified in our galaxy, the Milky Way. It has been estimated that 100 million black holes could exist in the Milky Way including many single ones that do not have a binary partner to unmask them.

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**THE LIFE OF A BLACK-HOLE BINARY**

It is thought that such black holes form when a star of initially tens of solar masses has used up all its fuel. It implodes under its own gravity to form a black hole whose birth is heralded by a burst of neutrinos* and possibly gamma-rays. If part of a binary system, the black hole starts to feed on gas sucked from the companion star. This material accretes into a disc whirling around the event horizon. Friction heats up the flowing material, creating a viscous plasma of charged particles that spiral down to the black hole, releasing X-rays. The accreting material then builds up again in the disc and the process is repeated. In this way,
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**ACCRETION**
Astronomers are still trying to unravel the intricacies of how these processes work. By matching X-ray data to theoretical models, Chris Done at Durham University studies the ebb and flow of accretion. Such studies provide a fine probe of black-hole behaviour. It is possible to distinguish between a black hole and a neutron star in an accreting binary. A neutron star has a solid surface so that when matter falls on it, all the energy is radiated into space; however, a black hole has an event horizon through which material and most of the energy disappear. Done was able to show that this produced differences in how their X-ray spectra and luminosity varied over time with the rate of accretion. She also measured the maximum temperature in the accretion disc. This marks a point at three times the radius of the event horizon for a static black hole, where gravity is so strong that matter cannot orbit the black hole fast enough to avoid falling straight in – the so-called *last stable orbit*. The temperature therefore gives an indication of the size-scale of black holes, which was shown to correlate with the luminosity and accretion rate.

**RADIO MEASUREMENTS**
Rob Fender at the University of Southampton carried out simultaneous observations of X-ray and radio emissions to understand how the accretion flow and jet formation are coupled. Radio emissions give information about the rate and amount of material flowing out in the jets, and are likely to provide a lot more information about black holes in the future. He and his colleagues are also looking for telltale evidence of single black holes wandering around in dense dust clouds in our galaxy.

**JUMBO STELLAR BLACK HOLES**
Stellar-sized black holes have also been found outside the Milky Way in other galaxies. The X-ray source, LMC X-3 in the Large Magellanic Cloud, provides one of the best examples of a black hole. To find black holes further afield, the black hole’s partner has to be massive and thus very luminous. Paul Crowther at the University of Sheffield, who looks for bright X-ray binaries containing 20-solar-mass star companions, recently found a massive stellar black hole in the galaxy, NGC 300, 7 million light years away. X-ray and optical observations revealed that the black hole weighed in at more than 15 times the mass of the Sun, while its closely orbiting partner was even more massive, at 20 solar masses. Such stars will also end up as black holes.

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* The Doppler effect: the wavelength of emitted light shifts towards the blue (shorter wavelengths) or red side (longer wavelengths) of the spectrum, depending on whether the object is moving towards us or away from us.
* Neutrinos are elementary particles with hardly any mass that are liberated in stellar nuclear reactions.
* Elements emit or absorb energy at particular wavelengths to give a characteristic spectrum of emission or absorption lines.

Black holes produce two jets of charged particles which emit radio waves.
SUPERMASSIVE BLACK HOLES

Giant black holes with masses of millions or billions of stars probably exist at the centres of most galaxies

In the 1960s, astronomers discovered some mysterious, powerfully luminous objects with hydrogen emission lines that were strongly shifted towards the red end of the spectrum indicating they were billions of light years away.* The lines were also broadened by the Doppler effect, which means that they contained material moving at velocities of thousands of kilometres a second. Furthermore, their brightness varied over weeks or months, and this showed that the mass was contained in a volume of the size of the solar system or less (using the same arguments as for stellar black holes on p6). Donald Lynden-Bell, when at the Royal Greenwich Observatory (now at Cambridge), proposed that the only explanation for such activity was that these “quasi-stellar” objects, or quasars, must contain massive black holes. Martin Rees at Cambridge and his students extended the work, showing how matter spiralling into the black holes releases so much energy that it outshines the host galaxy, and even powers luminous radio emission.

Quasars are now regarded as the most luminous members of a class of galaxies that have a central compact region powered by a supermassive black hole, which spews out vast amounts of radiation at all wavelengths. These are known as active galactic nuclei (AGN). They account for about 1% of all galaxies. Hundreds of AGN have been identified, with solar masses from a million to several billion, and they are some of the most studied objects in astrophysics.

In principle, galactic black holes behave no differently from their more diminutive stellar counterparts, showing the same dramatic phenomena. They have a mass, a spin, and an accretion disc fed by material from the surrounding galactic gas, dust and stars. The processes of accretion flow and energy emission are thought to be similar but occur on much longer timescales, which may not be easily observable. Studies of stellar black holes thus provide useful data that can be extrapolated to their larger cousins.

One aspect that had seemed different was that AGNs had not

COMPUTER SIMULATIONS

An important aspect of research into black holes is to simulate their behaviour on a computer. Teams using the UK Astrophysical Fluid Facility (UKAFF), headed by Andrew King at the University of Leicester, have simulated the X-ray outbursts that occur during accretion, and also how the gas that fills galaxy clusters is kept hot by jets of hot gas ejected from supermassive black holes within the clusters.

At the same time, an international team involving Ian Hawke at the University of Southampton is carrying out fully relativistic simulations to explore the extreme physics and violent dynamics of the core collapse of a supernova that leads to the birth of a black hole.
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Black holes

revealed the periodic outbursts of X-ray emissions, typical of stellar black holes, which result from the cyclic build-up and release of material in the accretion disc. However in 2008, Martin Ward, together with Chris Done and colleagues at Durham, found evidence of such varying emission close to the black hole of an AGN. Such data help in understanding the complex accretion processes.

Black-hole spin

Andy Fabian at Cambridge is also studying how the energy is released in the accretion flow. The X-rays generated by the infall of gas onto the black hole is re-radiated by the surrounding gas, to give a characteristic spectrum. This reveals broadened iron emission lines (as for stellar black holes) due to the Doppler shift resulting from the gas orbiting the black hole. The emission lines are further skewed towards the red side of the spectrum due to the intense gravitational field (p5). Fabian showed how the profile of these lines can probe the movement of material that is very close to the event horizon, thus determining the spin of the black hole and accreting material. James Reeves at Keele University has also been measuring the spin and radii of supermassive black holes, with a view to determining how they grow and whether they acquire their spin simply through accretion or through the collision and merging of black holes. Understanding these processes will also throw light on another feature of AGN that is associated with spin – narrow twin jets of radio-emitting material extending 10 million light years at close to the speed of light. About 10% of AGN emit such jets, which are probably charged particles such as electrons.

Redshift: the expansion of the universe means that all galaxies are moving away from us. As they do so, their light becomes stretched out and shifted towards the red end of the spectrum. More distant galaxies are receding faster, and as the light takes longer to reach us, we are also looking back at them at an earlier stage of their evolution.

The Black Hole in the Milky Way

The Milky Way almost certainly harbours a massive black hole. For 16 years, astronomers monitored individual stars whizzing around a bright radio source called Sagittarius A* (SgrA*) at the centre of the galaxy. Using Kepler’s laws of motion, they were able to determine the mass of the central object to be about 4 million solar masses crushed into a volume 44 million kilometres across. The only known physical object that could have these parameters is a black hole. Furthermore, nearby clouds of ionised material have been detected, with bright gamma-ray and X-ray fluorescence probably caused by a flare-up of activity from SgrA* some 350 years ago. Such outbursts may be part of the black hole’s life-cycle. Astronomers recently spotted a cloud of gas, with a mass of about three times that of Earth, set to pass close to SgrA* in 2013. It may feed matter into the black hole’s accretion disc, powering a sudden surge in energy output. Observatories will be looking out for a flare-up in X-ray activity in this location.
Supermassive black holes play an intimate role in the evolution of galaxies and the universe

One of the key mysteries is why AGN, in particular the luminous quasars, are mostly observed at an epoch when the universe was only a few billion years old. Nearby galaxies – and therefore galaxies as we see them in recent times – are quiescent. They show no sign of black-hole “feeding” and few signs of the star formation seen in the high-redshift active galaxies, which depends on the availability of large amounts of gas and dust. How does the power of the AGN get turned off?

Observations about 10 years ago revealed that there was a close relation between the mass of the black hole and the combined mass of the stars in the central part of the host galaxy, the bulge. This suggested that the black hole, although tiny compared with the galactic bulge, somehow controlled its activity, in particular the formation of new stars from galactic gas and dust. In pioneering work, Joe Silk of the University of Oxford and Martin Rees, followed by Andy Fabian, and later Andrew King of the University of Leicester, showed that the likely explanation was that when the black hole reaches a certain size, the radiation emitted by its accretion disc blows the gas and dust out of the host galaxy, in effect starving the supermassive black holes. The symbiotic relationship between black holes and their host galaxies is a major area of study for UK astronomers, which they hope to tease out with the next generation of international observatories (p12).

Waking the dead

Sleeping black holes may be re-awakened from time to time when an orbiting star approaches rather closely, causing a tidal disruption that rips the star apart. Andy Lawrence of the Royal Observatory Edinburgh and Martin Ward, together with colleagues elsewhere, have been looking for transient flare-ups in nearby galaxies that might be evidence of such events, and think they have already found examples. Astronomers, including Andrew Levan at the University of Warwick and Niall Tanvir at the University of Leicester, recently identified a bright X-ray and gamma-ray burst from an AGN 3.8 billion light years away that probably resulted from a star being ripped apart when it wandered too close to the central black hole. When two host galaxies merge, their supermassive black holes are also thought to spring back into life and embark on a feeding frenzy.

Origins and evolution

How supermassive black holes formed in the first place is still a mystery. One scenario is that the progenitors were the black holes created from the
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When galaxies collide, their black holes start to gorge themselves on the incoming gas and dust.

**DO INTERMEDIATE BLACK HOLES EXIST?**

A major puzzle in explaining black-hole formation is that there is no definite evidence for mid-sized holes of between 100 and 100 000 solar masses that should exist if supermassive black holes form from smaller ones. One set of candidates are the rare “ultraluminous X-ray” (ULX) sources most often found in star-forming galaxies. Tim Roberts at Durham has observed that whilst most of them are unexpectedly bright X-ray binaries, with some being distant background quasars, there are one or two ULXs that may be intermediate black holes. In 2009, a group of astronomers led by Sean Farrell at Leicester found a “hyperluminous” source, HLX-1, on the edge of the distant galaxy, ESO 243-49, which demonstrated typical variable black-hole behaviour, and could be best explained by a black hole of about 10 000 solar masses. Farrell thinks that HLX-1 is the central black hole of a low-mass dwarf galaxy that “fell into” ESO 243-49, and had most of its stars and gas stripped away. Astronomers have suggested that the best place to look for intermediate-mass black holes is in old globular clusters – mature but congested conurbations of tightly bound stars orbiting a galaxy. They contain some of the first massive stars to form during galactic evolution, which, in the overcrowded stellar environment, could have collapsed and merged into a large central black hole. Tom Maccarone at the University of Southampton hopes to identify such candidates from their radio emissions.

![These images from the SDSS catalogue (p13) show galaxies that host two of the largest black holes identified so far. The brightest galaxy in each image is respectively NGC3842 (top) and NGC4889 (bottom).](image)

![Record supermassive black holes
In 2011, two supermassive black holes were discovered by a team at the University of California, Berkeley, each about 10 billion solar masses and “sleeping” quietly at the centres of NGC 3842 and NGC 4889 – giant elliptical galaxies, 300 million light years away. These ancient monsters are 2500 times as massive as the black hole at the centre of the Milky Way and five times larger than the orbit of Pluto.](image)
The UK has made a major contribution to the study of black holes through both instrument development and research results. The astrophysical environments of black holes are studied at all wavelengths across the electromagnetic spectrum. Huge advances have been made thanks to state-of-the-art ground-based and space observatories. Furthermore, direct observations of black holes are expected to become available in the next few years with the advent of gravitational-wave astronomy.

**X-RAY SPACE MISSIONS**

The signature X-ray emissions from a black-hole environment are detected by dedicated telescopes orbiting in space (X-rays do not penetrate the atmosphere). Major breakthroughs have been made with observatories launched by the European Space Agency (ESA), NASA and the Japanese space agency (JAXA). Data from XMM-Newton (ESA) and Chandra (NASA), both launched in 1999, allowed researchers to map accretion processes and tease out the symbiotic relationship between the growth of black holes and galaxy evolution (p10). The joint Japanese-US mission, Suzaku, launched in 2005, has been able to probe the spectroscopic iron lines associated with material moving close to the event horizon, while the Rossi X-ray Timing Explorer (RXTE) can follow the fast-changing variations of emissions that characterise black-hole behaviour.

**FUTURE X-RAY MISSIONS**

In 2012, NASA will launch the Nuclear Spectroscopic Telescope Array (NuSTAR) to detect high-energy X-rays. It will carry out a census of black holes of all sizes across the universe and investigate how jets form. JAXA's Astro-H satellite, due for launch in 2014, will carry advanced instruments that measure accretion flows precisely. ESA is studying the feasibility of the Large Observatory for X-ray Timing (LOFT) to measure flickering changes in X-ray emissions more closely. In 2021, the three space agencies hope to launch the most powerful X-ray telescope yet, ATHENA, which will be able to observe the details of black holes at the earliest cosmic times when galaxies were forming.

**RADIO-WAVE STUDIES**

The mysterious jets emitted from the accretion discs of large and small black holes reveal themselves at radio wavelengths. They will be studied using the Low Frequency ARray (LOFAR), consisting of more than 5000 antennas being built in stations across Europe. The first working station in the UK is based at the Chilbolton Observatory in Hampshire.

**FUTURE RADIO-TELESCOPES**

The South African MeerKat array and the Australian Square Kilometre Array Pathfinder (ASKAP) are being constructed as pathfinder projects for the largest telescope ever, the Square Kilometre Array (SKA), consisting of thousands of antennas spread across South Africa and Australia. MeerKat will be able to detect explosive radio sources associated with black holes. SKA promises to take black-hole research to a new level. It will look for rare binaries containing a black hole and a pulsar (a neutron star that emits regular radio pulses) in both our galaxy and those nearby. Measuring how the black hole's strong gravity affects the pulsar "ticks" will provide a test of general relativity. SKA will also operate as a low-frequency gravitational wave detector (p13), able to detect events in the early universe such as mergers of galactic black holes.
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**Optical and infrared observations**

Measurements with the Hubble Space Telescope of the velocity of gases and stars swirling around the centre of galaxies and globular clusters have provided definite evidence for the presence of massive black holes. The use of adaptive optics (an optical system that compensates for the distorting effects of atmospheric turbulence) on the Very Large Telescope of the European Southern Observatory enabled a team, including Marc Sarzi and others at the Universities of Hertfordshire and Oxford, to monitor the densely packed stars moving around the centres of a number of galaxies and to determine the masses of the central black holes.

**The gamma-ray universe**

The extreme environment of a black hole also emits gamma-rays, which are detected by the ESA observatory Integral launched in 2001 and NASA's Fermi Gamma-ray Telescope. In addition, these observatories monitor the sky for gamma-ray bursts — transient emissions thought to signal cataclysmic events such as the collapse of a massive star into a black hole, or the collision of black holes or neutron stars. NASA's Swift mission, in which the UK participated, is largely dedicated to monitoring the sky for gamma-ray bursts. Recently, a team including UK astronomers, discovered a flash of gamma-rays and X-rays from a very distant AGN more than 13 billion light years away, when the universe was just 500 million years old. The optical “afterglow” detected by the Gemini North telescope in Hawaii and United Kingdom Infrared Telescope (UKIRT) enabled the redshift to be measured accurately.

**Cosmic-ray messengers**

Ultrahigh-energy particles reach the Earth and are detected by the international Pierre Auger Observatory in Argentina. Recent data collected seem to indicate that their origins are supermassive black holes that generate magnetic fields powerful enough to accelerate protons to very high energies.

**Digital sky surveys**

Following the US Sloan Digital Sky Survey (SDSS), which found many of the most distant quasars, it was the UK-led UKIRT Infrared Deep Sky Survey (UKIDSS) that found the most distant supermassive black hole in 2011 (p11). Surveys with the UK-initiated VISTA, and the Australian SkyMapper telescopes (currently being constructed), will look for very distant AGNs, while another instrument, the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), in which the UK is involved, will investigate variable AGN phenomena.

**High-energy neutrinos**

A particle detector installed at the South Pole is searching for high-energy neutrinos associated with cataclysmic phenomena involving black holes. It will be followed by a European project to create a multi-kilometre neutrino telescope, KM3Net, at the bottom of the Mediterranean Sea.

**Searching for gravitational waves**

The only way to “see” a black hole directly is via the phenomenon of gravitational waves. General relativity predicts that accelerating objects should cause ripples in spacetime. For example, two black holes colliding should shake the spacetime region around them generating gravitational waves. A team led by Jim Hough at the University of Glasgow, has played a major role in developing the ultra-sensitive detectors now being deployed with ground-based instruments (Advanced LIGO in the US, and GEO 600 and VIRGO in Europe). A future ESA space mission, the European Laser Interferometer Space Antenna (e-LISA), if realised, could measure the basic properties of black holes such as mass and spin.

UK groups are also at the forefront of modelling theoretically what the instruments can expect to see. Leor Barack at Southampton is developing detailed models of the orbital dynamics of inspiralling binary black holes and Mark Hannam at Cardiff University carries out numerical simulations of the eventual black-hole collision.
The properties of black holes have caused physicists to re-formulate their basic theories of matter.

While astronomers have been hunting for black holes in the universe, mathematical physicists have been probing the equations that describe their properties right down at the microscopic level where the laws of quantum mechanics rule. When described in terms of curved spacetime by general relativity, the standard black hole is a simple sphere. However, theorists have proposed other related objects. In 1988, the American physicist, Kip Thorne, suggested that spacetime could be shaped to form a "wormhole" between different regions of space, a concept much used in science fiction to enable interstellar space-travel. Others have considered objects that have no event horizon – a naked singularity, or alternative objects to black holes such as gravastars, which could form when a star collapses. Mathematicians, including Mihalis Dafermos in Cambridge, have made huge progress in developing mathematical techniques to understand the properties of black holes.

Black holes lose it!

One fundamentally important problem raised in the 1970s by Stephen Hawking and the Israeli physicist, Jacob Bekenstein, has since generated some extraordinary breakthroughs. They realised that because black holes were "black" and thus perfect absorbers of energy, they must have an entropy.* Bekenstein showed that it would be proportional to the surface area of the black hole's event horizon. The bigger the black hole became as matter fell in, the more entropy it gained. According to the second law of thermodynamics,* objects with entropy must also have a finite temperature, so Hawking concluded that black holes must also radiate energy in some form.

Combining quantum theory with the no-hair theorem (p5), Hawking calculated that the temperature of the black hole was given by the randomised emission of particles with energies typical of a black body* – *Hawking radiation.* His explanation was that just outside the event horizon, quantum fluctuations, as predicted by the uncertainty principle* of quantum mechanics, would lead to the formation of pairs of particles and antiparticles. One particle could fall back into the black hole, while the other escaped as radiation. The black hole would gradually heat up as it lost mass until it evaporated – although an astrophysical-size black hole would take longer than the age of the universe to disappear.

The Information Paradox

This scenario raised an ugly problem: the matter that went into the black hole consisted of particles with definite quantum states, in other words, encoded information. However, the black-body radiation emitted is, by definition, featureless, so information about the quantum states appears to be irrevocably lost in the black-hole singularity. Quantum theory says that this is impossible – information can always be retrieved from a dynamic system just by tracing back the
The mathematics of higher dimensions has provided a rewarding route to understanding the quantum nature of black holes. This issue became known as the information paradox, and alarmingly suggested that the physics was breaking down. Arguments about whether information was really lost continued between Hawking and his contemporaries until the end of the 1990s.

To explain the worrying contradiction, Hawking even suggested that the information might be siphoned into another universe. Others have proposed that alternative exotic quantum objects can form, instead of black holes, such as the gravastar – a bubble of spacetime “superfluid” in which information is retained.

Taking a version incorporating higher-dimensional objects called D-branes, Andrew Strominger and Cumrun Vafa at Harvard University, in the mid-1990s, imagined a particular type of black hole in five dimensions (four of space and one of time) with a surface squirming with strings. They set about counting all the possible quantum micro-states, and came up with about the same entropy-to-area ratio as Bekenstein’s original, more classical calculation. Their result was subsequently extended to 4D black holes. It is sometimes called the holographic principle because the quantum information is treated as though it were encoded on a 2D surface. Thomas Mohaupt at the University of Liverpool and collaborators were able to construct black-hole solutions taking account of the tiny corrections to general relativity, as predicted by string theory.

In 2002, another idea was proposed by Samir Mathur of Ohio State University, who suggested that black holes were balls of strings, with a fuzzy surface instead of an event horizon, and no singularity. These fuzzballs would have the same classical properties of black holes but would also retain the quantum information as strings.

Such black holes, though not real physical objects, do not lose quantum information, so seem to solve the information paradox.

THE QUANTUM INFORMATION APPROACH
Sam Braunstein at the University of York recently formulated an approach using his expertise in the relatively new field of quantum information theory. This describes the behaviour of pairs of particles that are “quantum entangled” such that the information held by one particle is automatically encoded in the second. Braunstein uses an alternative explanation of Hawking radiation – that one of two entangled particles just inside the event horizon can tunnel out (also predicted by the uncertainty principle). Starting from a simple quantum-mechanical model of an event horizon with some black-hole properties but not specifically including the curved spacetime of gravity, his picture allows information to escape encoded in quantum particles.

STRING THEORY TO THE RESCUE
A major breakthrough in understanding black-hole behaviour came from efforts to unify general relativity and quantum mechanics into an all-encompassing “quantum field theory” that regarded fundamental particles as tiny strings. These exist in a universe with up to 11 dimensions depending on the version of string theory, with six or seven of the dimensions rolled up on a very small scale.

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* Entropy is the measure of the number of ways that objects or energy states can be arranged; it is thus a measure of disorder. It is linked to temperature, which is a manifestation of the random motions of particles.
* The second law of thermodynamics says that all systems tend to increase to maximum entropy.
* A black body absorbs all incident radiation and emits a characteristic spectrum of radiation that depends on its temperature.
* The uncertainty principle imparts a degree of probability to all quantum processes, allowing particles to be created transiently from energy in the vacuum (quantum fluctuations) and to escape through energy barriers (tunnelling).
Black-hole mathematics has opened up new approaches to understanding the laws of Nature

Strominger and Vafa’s holographic approach (p15) to reconciling the classical geometry of black holes with the higher-dimensional quantum world of branes and strings has provided a new set of mathematical tools for physics. Shortly after their work was announced, Juan Maldacena at the Princeton Institute for Advanced Study reported a remarkable insight: he showed that their type of 5D string theory including gravity was precisely mathematically equivalent to a 4D quantum field theory describing strongly interacting systems. Examples are atomic nuclei, which are ultimately comprised of fundamental particles called quarks and gluons bound through the strong force.* Such systems are notoriously difficult to study theoretically, whereas the mathematics of higher-dimensional black holes is easier to manipulate. A 5D black hole thus offered the archetypal mathematical structure for investigating this fundamental force.

APPLICATIONS

UK research groups are playing a significant role in applying these black-hole ideas to fundamental physics. Andrei Starinets at Oxford has exploited the correspondence between black-hole and quantum theories to explain what physicists should expect to see when high-energy beams of atomic nuclei are smashed together in the Large Hadron Collider (LHC) experiment at CERN in Geneva. The aim of these experiments is to create and study conditions in the universe just after the Big Bang. The dynamic behaviour of the resulting plasma of quarks and gluons can be modelled in terms of the excitations of these exotic, stringy black holes. Toby Wiseman at Imperial College London has even been working in the opposite direction, using the version of quantum theory used to describe a quark-gluon plasma to model the thermodynamics of black holes.

Simon Ross, Ruth Gregory and others at Durham are also investigating various aspects of the correspondence. They are, for example, applying the idea to the technologically important high-temperature superconductors (which conduct electricity without resistance). These and other similar materials seem to involve strong quantum electronic interactions that are mathematically difficult to untangle; the black-hole description may offer a simpler approach.
Black holes | an essential component of our universe

Gary Gibbons and others at Cambridge, Durham and elsewhere have also been studying the properties of **higher-dimensional black holes**. Gregory and colleagues at Durham investigated 2D “black strings”, showing them to be unstable. Harvey Reall and Roberto Emparan at Cambridge discovered that Einstein’s equation in five dimensions admits solutions describing rotating doughnut-shaped black holes – “black rings”. This discovery demonstrated that the no-hair theorem (p5) is not valid in higher dimensions. Black rings present a challenge for string theorists attempting to understand the microscopic description of black holes. Reall has also found that some higher-dimensional black holes are unstable if they rotate sufficiently rapidly, in contrast with Kerr black holes (p4), which are believed to be stable. An even more exotic object, a spherical black hole surrounded by a ring – a **black Saturn** – is possible. Some of these objects are difficult to analyse mathematically, so Wiseman uses computer techniques to model the behaviour of his higher-dimensional black holes.

Higher-dimensional black holes with branes are not mere mathematical fancy. Cosmologists such as Gregory have suggested that our whole universe could be a 4D hyper-surface, or brane, existing within the bulk of a higher-dimensional space, with the extra dimensions rolled up on the scale of a millimetre or less. This would explain one important mystery: why gravity is so much weaker than the other forces of Nature. Formulating gravity in higher dimensions predicts that it can leak away from our brane and into the bulk, while the other forces remain stuck on the brane surface.

**MINI BLACK-HOLE CREATION**

If these extra dimensions exist, then particle-physics experiments at the LHC could be energetic enough to generate **higher-dimensional mini-black holes**. They would evaporate immediately leaving behind tell-tale trails of particles. Researchers such as Elizabeth Winstanley at the University of Sheffield have been investigating the mechanism of evaporation. Particle physicists such as James Frost at Cambridge are using the results to look for black holes at the LHC. So far, they have not been detected, but could still be generated in a higher-energy regime.

**PRIMORDIAL BLACK HOLES**

Theorists, including Bernard Carr at Queen Mary, University of London, have also considered that black holes of varying masses could have been created from quantum fluctuations in the intense energy density of the primordial universe. The smaller ones would have decayed rapidly in a burst of gamma-rays, which might be detected by instruments such as the Fermi gamma-ray telescope and the Auger cosmic-ray detector (p13). Although not a mainstream idea, if primordial black holes were ever discovered, they would provide a unique probe of gravity – and if big enough, could be candidates for the large amounts of invisible **dark matter** that cosmologists think must exist in the universe to explain the gravitational dynamics and evolution of galaxies and galaxy clusters.

Higher-dimensional mini-black holes could be created in the LHC at CERN; they would, however, evaporate immediately.

Black holes as described by a general relativity theory with just one extra dimension
A waterfall is the equivalent of a one-dimensional black hole, with the force of the water flow equivalent to gravity. If fish (instead of light waves) cannot swim upstream faster than the velocity of the flow, they will be swept over the edge of the waterfall, which represents the event horizon.

In 2009, scientists at the Israel Institute of Technology (Technion) created an acoustic black hole in a BEC that was sculpted with magnetic fields such that the flow of atoms was accelerated to supersonic speeds. When the atoms traversed the subsonic/supersonic boundary – the event horizon – a sound wave moving towards them in the opposite direction would never be able to get past them. One advantage of choosing a BEC is that its temperature is only just above absolute zero, making it easier to see the equivalent of Hawking radiation – in this case in the form of pairs of quantum vibrations called phonons. Nevertheless, the phenomenon was still too low to detect.

**NEW HORIZONS**

Black-hole solutions provide a powerful conduit in searching for a unified theory of Nature. However, apart from inferences from astrophysical observations, it is difficult to test whether the ideas are right. A “killer test” would be demonstrating the existence of Hawking radiation. Unfortunately, the tepid Hawking radiation expected from astrophysical black holes would not be detectable because it would be masked by the pervasive, higher temperature background radiation left over from the Big Bang.

There is another approach: it turns out that Einstein’s equations, when quantum effects are added in, can also describe both sound and light waves moving in a medium. Research groups around the world have been investigating analogues of black-hole behaviour in a variety of media: gases, clouds of ions, very low-temperature quantum fluids such as superfluid helium and Bose–Einstein condensates (BEC, a gas of cold atoms all in the same quantum state), and also transparent solids, and even water.

**ACOUSTIC BLACK HOLES**

In the 1970s, William Unruh at the University of British Columbia realised that it might be possible to simulate a gravitational black hole with sound waves in a fluid flowing at supersonic speeds. To see how this works, imagine a shoal of fish swimming upstream in a river flowing over a waterfall. When the flow was greater than the maximum speed of the fish, they would inevitably be swept into the one-dimensional black hole of the waterfall, whose event horizon was the point at which the speeds of the water flow and fish matched.

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Another promising approach, suggested by Ulf Leonhardt at the University of St Andrews, is to manipulate light waves in a static medium. Light waves are slowed down in glass, as measured by the change in refractive index for a given wavelength, and if the light is intense enough it actually alters the refractive index as it travels through. The team sent intense pulses of laser light down a carefully micro-structured glass fibre, effectively creating a change in refractive index moving at the speed of light. A second laser pulse with a wavelength such that it moved slightly faster, followed the first pulse but could not get past the moving optical distortion – the event horizon – left in the wake of the first pulse, and so could not catch up with it. This is, in fact, equivalent to a “white hole” an object where nothing can enter. If the second laser travelled in the opposite direction, then it would have created a black hole on the other side of the event horizon.

Calculations showed that such a system could create Hawking radiation, and recently, Italian scientists including Daniele Faccio at Heriot-Watt University believed they had detected it in an experiment using solid silica glass. They put a light detector perpendicular to the laser beams and detected extra photons consistent with the spontaneous emission characteristics associated with Hawking radiation. Leonhardt and Faccio now plan to refine their experiments and investigate further. Leonhardt plans to use optical wave-guides on semiconductor chips rather than fibres, which will be more flexible in terms of creating the optimum design.

Surprisingly, a beautifully simple experiment just using water waves has also detected the analogue of Hawking radiation. Unruh and colleagues created a white hole in a trough of flowing water by placing an aircraft-wing-shaped obstacle in its path such that a region of high-velocity flow prevented surface waves generated downstream from travelling upstream. The blocking point behaves like a white hole, from which pairs of shallow waves were generated.

Scientists in the UK are planning experiments to create optical black holes by manipulating the velocity of laser pulses in silica glass and with waveguides on chips that have properties analogous to Hawking radiation – thus showing how the underlying physics applies in a broader context.

Physicists are looking at different optical materials to exploit black-hole analogues in a useful way. American and Chinese physicists have made a circular black-hole device using metamaterials, which are composed of layered structures with electromagnetic properties tuned to bend the path of electromagnetic radiation in a desired way. Concentric strips of metamaterial trap and guide incident microwaves to a central core of absorbing material, where they are converted into heat. If adapted to work at visible wavelengths, such a device could be used to collect light extremely efficiently, and might have use in solar cells, for example.

Analogue black holes open up a new field of “horizon physics”, which may lead to new technologies such as the generation of entangled pairs of photons as needed for quantum computing; it might also be possible to create a black-hole laser. Some scientists have even speculated that black holes could act as unbelievably powerful quantum computers, if coded instructions could be input into the black hole and then read-out via Hawking radiation. Seth Lloyd of the Massachusetts Institute of Technology has calculated that a 1-kg black hole could carry out $10^{51}$ operations a second.
The IOP thanks all the researchers who helped with the preparation of this booklet. Most physics and astronomy and mathematics departments in the UK carry out research on some aspect of black holes; however, only a limited proportion of this work could be mentioned here.

Further information sources

1. NASA's Imagine the Universe!
http://imagine.gsfc.nasa.gov/docs/science/know_l2/black_holes.html

2. Cambridge Relativity Black Holes
www.damtp.cam.ac.uk/research/gr/public/bh_hawk.html

3. Astrophysical black holes
http://astronomyonline.org/Stars/BlackHole.asp

http://en.wikipedia.org/wiki/Black_hole

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