

Black Holes and Strings: Searching for Nature's Secret Code

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Black holes exist. A watertight experimental proof has not yet been given, but astrophysicists have now convincing evidence that these remarkable objects exist all over our universe. Most black holes are formed when a burnt out star collapses under its own weight and, after a brief apocalyptic battle, becomes trapped in the most hermetic prison that exists: the event horizon, from which not even a beam of light can escape.

Although their existence has only recently been recognized, black holes have already taken a significant place in our collective consciousness. This was especially evident two years ago, during the wave of publicity surrounding the launch of the 'Large Hadron Collider, the latest expensive particle accelerator near Gen 'eve. Briefly there were wispered rumors that this device might be able to produce tiny, microscopic black holes. This rumor, while clearly unfounded, almost led to worldwide panic among the general public.

This frightening reputation is largely deserved. A black hole is the embodiment of the destructive darkness, the emptiness from which information will never return, and the horizon where our knowledge ends. Even theoretical physicists, that try to unravel the mysteries of black holes from the safe perspective of mathematical equations have nightmares about them. For a long time, the simple fact of their existence seemed sufficient to seriously destabilize the three fundamental pillars of modern physics - relativity, quantum mechanics, and thermodynamics. Stephen Hawking, who gained his fame by robbing black holes of some of their most valuable secrets, even suggested that the natural laws may have to forego their last remaining predictive power.

What was the problem? As the name suggests, a black hole has very few physical characteristics. From the outside it looks like a perfectly smooth sphere, whose size and shape is uniquely determined by just three numbers: mass, rotational speed, and electric charge. That is all. But you can throw anything into a black hole, and so there are almost infinitely many ways to make a black hole. 'So,' asked the American physicist John Wheeler - who gave black holes their appropriate name - in the early 70s to his student, Jacob Bekenstein: 'Imagine I throw all my favorite books behind the horizon of a black hole, what happens to the information in these books? Is it destroyed forever, or is it somehow preserved and retrievable? Are two black holes with the same mass, rotation speed and charge exactly identical, or can you, if you look at them very carefully under the microscope, tell them apart and perhaps even read off their history?' After some thought, Bekenstein returned with a brilliant answer: 'The information disappears into a black hole can not be destroyed' he said 'but must be registered, as via a microscopic code, on the surface of the horizon. However, to be able to decipher this secret code, one must first reconcile the laws of gravity and quantum mechanics'

That was a startling conclusion. The surprise was even doubled a year later, when Hawking famously showed that a black hole is not cold, but has a finite temperature. For an average black

hole in the sky, this temperature is very small. However, because every warm body emits radiation and particles, the consequences are profound. It means that the impossible has become possible: particles *can* escape from behind the horizon of a black hole! After this true Houdini act, it was clear that we are on the verge of a breakthrough in our understanding of the fundamental laws of nature.

Three fundamental pillars of physics

Let us introduce the above-mentioned three pillars of physics in a bit more detail.

Einstein's special theory of relativity describes how space and time are interdependent. While relativity theory may seem a bit exotic, its main slogans are well-known: 'Nothing can travel faster than light.' 'Time is not absolute but relative: a space-traveling twin stays younger than the brother who stays at home.' And of course: 'Energy equals mass.' Relativity theory is tested with great precision. The recent announcement that the spooky particles known as neutrinos might travel faster than light was later withdrawn, and only solidified experimental evidence in support of Einstein's theory. Another measurement by the 'Fermi Telescope', the space instrument that detects high-energy rays from the remotest corners of the universe, confirmed that special relativity is valid from the farthest up to the shortest possible distances.

Special relativity does not account for gravity. For that to fit in, Einstein had to extend his special theory to a more comprehensive framework, known as general relativity. In this beautiful mathematical structure, space and time form a flexible fabric, similar to an undulating carpet, along which particles move according to exactly predictable paths, determined by the universal geometric and economic principle: 'Follow the quickest route to your destination.' The curvature of space and time may sound strange, but it is a fact that, for instance, had to be taken into account for the design of the Global Positioning System. General relativity dominates at long distances. Almost all movements around us, from falling apples to rotating galaxies, the orbit of Mercury to the expanding universe itself, are described by this theory. It also predicts two remarkable phenomena: the Big Bang, the violent beginning of time, and the existence of black holes.

The world of the smallest distances is ruled by a different theory: quantum mechanics. This theory was, after notable preparatory work by Planck, Einstein and Bohr, developed in the twenties by a fresh young generation of physicists, who fearlessly and shamelessly turned all established values on their head. And that was necessary, because the quantum world is perverse, and full of unusual uncertainties. Everything fluctuates, and nothing is what it seems. Waves are particles, and particles are waves, which may be at two different places at the same time. And even worse: a central principle on which all of science seemed to be based, that identical initial conditions lead to the same final result, was simply untrue. Despite Einstein's indignant protest ('God does not play dice'), there is now convincing experimental evidence that chance and randomness indeed dominate at the smallest scale.

Although it took some effort, the quantum theory can be beautifully reconciled with special relativity. The first step was taken by Dirac, who predicted that the electron must have a twin brother, a particle with exactly the same characteristics but with the opposite charge. (This anti-

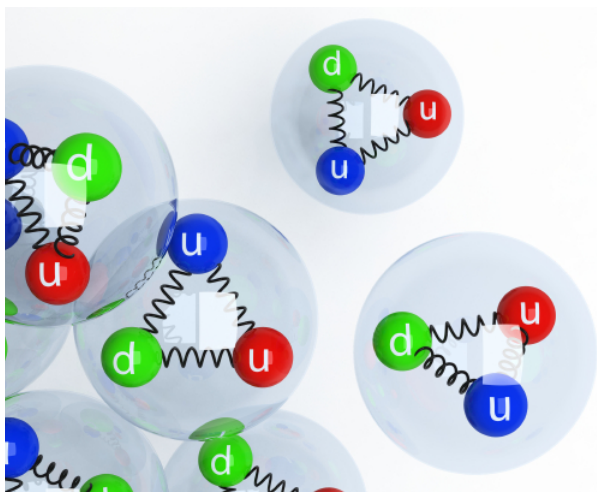


Figure 1. The internal structure of nucleons, such as protons and neutrons, is described by quantum chromodynamics. According to this theory, a proton consists of three quarks, each with a different color. The quarks are bound together by the strong nuclear force. It is transmitted by gluons.

particle, the positron, is now the ‘P’ in PET scanning, the imaging technique that has saved many lives.) Dirac’s work was equally brilliant followed up by Feynman, Schwinger and others, who developed quantum electrodynamics, or QED, the theory that describes the interaction between electrons and photons. A little later, helped by important contributions from my mentors Gerard ’t Hooft and Martinus Veltman, this theory – enlivened with some additional colors – was successfully extended to a precise mathematical description of the two nuclear forces: the weak and strong interactions.

The weak nuclear force causes the splitting of atomic nuclei, and is, despite its name, responsible for enormous destructive force of nuclear weapons. The strong nuclear force, on the other hand, is responsible for holding the nucleons tightly together. It is described by the theory known as quantum chromodynamics, or QCD, according to which nuclear particles such as neutrons and protons are made up from even smaller building blocks: quarks and gluons. These smaller particles themselves can not be observed directly, because the strong force keeps them always trapped inside an atomic nucleus. But we can still imagine what they look like. They are a colorful bunch. A quark carries one of three colors: red, green or blue. The gluons, the sticky particles that glue everything inside the nucleus together, carry two colors. They are able to change the color of a quark. In this way they are responsible for the strong nuclear force, that binds the quarks in white-colored combinations. Later on, we will meet this colorful theory again in a surprising place.

The oldest of the three pillars is thermodynamics, It was developed in the nineteenth century by thinkers such as Clausius, Maxwell and Boltzmann. This is the theory of large numbers and, as the name suggests, of heat phenomena. It describes how energy spreads out evenly over the myriad atoms in a gas, liquid or solid, and thus feels as heat. Thermodynamics is also the theory of ignorance, and paradoxically, for this reason it is more fundamental than any other theory. indeed, although we always are learning more, there is much more that we do *not* know. For example, we do not know exactly where all the molecules in a gas are and which way they move. We can only give a statistical description in terms of probabilities. This ignorance steadily increases in time: this is the famous second law of thermodynamics.

Al this sounds like a fairly useless starting point for a predictive theory of physics. Fortunately,

however, it is in many situations possible to accurately quantify our ignorance. And as a famous epistemologist, the former US defense secretary Donald Rumsfeld, once highlighted, it is much better deal with 'known unknowns' than with 'unknown unknowns'. The degree of ignorance goes by the name 'entropy'. One can regard the entropy of a system as the total amount information stored inside of it. The smallest unit of information is the famous bit: 0 or 1, yes or no, heads or tails. A somewhat larger unit is the zettabyte, or in other words 10^{21} bytes - this is a good current estimate of the total digital information stored on all computers in the world. That sounds like a whole lot of information, but it amounts to the entropy contained in a single grain of salt.

What makes the thermodynamics so fundamental? When Clausius and others performed their groundbreaking work, it was not yet known what molecules and atoms look like. The periodic table, the list of all existing chemical elements, did not yet exist. However, the main laws of thermodynamics are still completely accurate and useful. Their validity is so general that they transcend and do not depend on the detailed nature and properties of matter. So even in an (imaginary?) another universe, with a different periodic table, they would still remain valid.

Quantum Gravity

Two of the three pillars have a rather strained relationship: general relativity and quantum mechanics can't stand each other very well. Yet they must eventually be combined into one single framework: the theory of quantum gravity.

What is that, 'quantum gravity'? The first hint of the need for such a theory was found in 1899 by Max Planck, even before he formulated his famous quantum hypothesis. He considered first the following two questions. 'How does a rainbow appear?' And: 'Why are some stars colored blue and others red?' The answer to these questions were already well known. The rainbow arises because the color of a light beam depends on its wavelength: blue has a shorter wavelength than red. White light that passes through a raindrop gets diffracted and splits up into light with different colors – literally all the colors of the rainbow. It was also already understood that the color of light depends on the temperature of the light source: blue stars are hotter than red stars. Planck brilliantly combined these two pieces of data, and derived that the energy of a photon – the particle of light – depends on its wavelength: the shorter the wavelength, the higher the energy. To write this relationship, he introduced a new constant of nature: the Planck constant \hbar .

Planck immediately recognized that this new constant was as fundamental as three other famous constants, the Newton's constant G_N , which determines the strength of the force of gravity, the speed of light c , and the Boltzmann constant k_B , that specifies the relationship between temperature and energy. The four constants allowed Planck to introduce a system of natural units, the so-called Planck units of time, length, weight and temperature. This system of units, he said, must be used if you want to communicate with an alien civilization somewhere in another galaxy, and want to explain how old, big, heavy and hot you are. Indeed, nobody in the Andromeda galaxy knows what centimeters, seconds, kilograms and degrees are.

We can explain Planck's units with the help of a thought experiment – one of Einstein's favorite pastimes. Let us try to make the wavelength of a light particle as small as possible. Via Planck's

relation, we know that the light particle will carry more and more energy. Can we make this energy arbitrarily large energy or does that create a problem? Well, remember that ‘energy is mass.’ And what happens if you stuff more and more mass in a smaller and smaller volume? At some point, the light particle will collapse under its own weight and form a black hole! OK, it is a tiny black hole – as light as a grain of salt and with a radius equal to the Planck length, about 10^{-32} cm – but it is still a black hole. Or maybe not? Because we have also learned that everything is so random and uncertain at such an incredibly small scales. Indeed, in the quantum world, the tiniest black holes are exceedingly short-lived: according to Hawking’s famous formula it will have a temperature of about 10^{32} degrees Celsius, and, consequently, it evaporates into a cloud of elementary after less than 10^{-43} second.

Welcome to the confusing world of quantum gravity.

The quantum black hole

Astronomical black holes are not tiny and unstable, but very heavy, large and practically indestructible. Observations show that in the densely populated center of most galaxies, including ours, are monstrous black holes, which many hundreds of millions of times heavier than the sun. Why would such a huge and heavy black hole care the least about the disturbing uncertainties of the tiny quantum world?

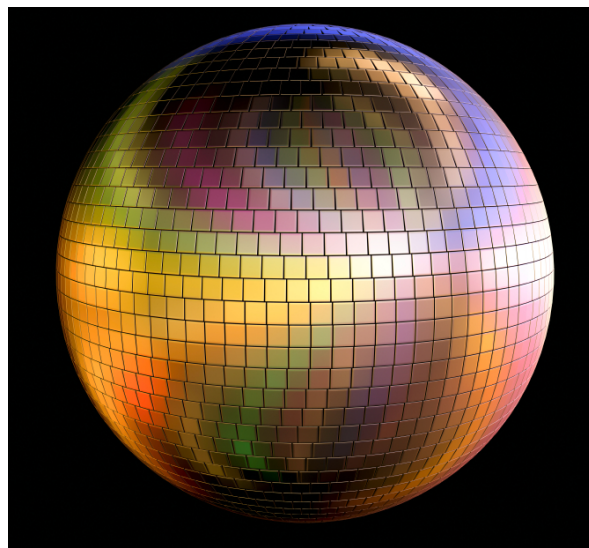
Consider it a form of justice. A black hole is, as it were, trying to tear time apart: a perfectly functioning watch that is located very close to a black hole horizon, will appear to be standing still when viewed by an outside observer. A nanosecond on the horizon takes an eternity for an outside observer, a full millennium in our national history passes, when measured by the watch on the horizon in less than an instant. This absurd time distortion is reminiscent of Zeno’s paradox. And just as Achilles must surrender to the turtle, the black hole must abide by the rules of the world of the fastest and smallest: the theory of quantum gravity.

But how can we find out what the surface of a perfectly smooth black sphere, a great dark nothing, looks like at the smallest scale? Here comes the third pillar, thermodynamics – the theory of ignorance, to the rescue. It turns out that black holes indeed behave according rules that look exactly like the laws of thermodynamics. Just as entropy can only increase with time, a large black hole can only become bigger and bigger by gobbling up more and more matter. From this seemingly superficial analogy, Bekenstein and Hawking were able to deduce a precise conclusion: the entropy of a black hole – the total amount of information that the black hole has gulped – must be equal to the surface area of the event horizon, measured in Planck units.

To visualize this area law, imagine that the black hole horizon is divided into tiny squares, each with an area of the Planck length squared, and that each square carries one bit of information. For a black hole of several solar masses, this corresponds to more than 10^{75} bytes. That is a fast amount of hidden knowledge.

This result of Bekenstein and Hawking is now widely recognized as an important guideline – thanks in large part to later work by ’t Hooft and Leonard Susskind. With foresight they elevated

Figure 2. The amount of information that has disappeared inside a black hole is proportional to the surface of the horizon, measured in Planck units. We can imagine that the horizon consists of many tiny little square cells, each having an area the size of a Planck length squared. Each of these microscopic cells contains one bit of information.



the area law into the credo of a scientific revolution, and gave it a catchy name: ‘the holographic principle’. This principle requires that everything within the horizon of a black hole and, more generally, within an arbitrary region of space (e.g. this lecture hall) can be faithfully represented on the surrounding surface, as via a hologram. We do not yet know what this ‘holographic plate’ is made from, except that it is built up from a mysterious secret alphabet, with tiny letters the size of a Planck length. How can we figure out what this secret alphabet looks like, so that we can start and try to decipher it?

String theory

It is about time for string theory to enter the scene. String theory is based on the (at first sight bold) hypothesis that all elementary particles such as electrons, quarks, photons and gluons, look like tiny strings, vibrating filaments the size of the Planck length. From this assumption follows a fascinating world, which closely resembles the universe in which we find ourselves, and in which gravity and quantum mechanics can happily coexist.

String theory was discovered more than forty years ago, partly by accident, from an attempt to understand the strong nuclear force. The approach was temporarily suspended because a better theory was found: quantum chromodynamics, the theory of quarks and gluons, which we discussed earlier. Luckily, Gerard 't Hooft derived that quantum chromodynamics, when correctly viewed, looks exactly like a string theory. He showed that gluons, as befits true glue particles, tend to stick together by stringing up long cords, which bind the quarks together. This string of gluons creates the strong nuclear force, which hold the quarks captive inside atomic nucleus. As it turns out, a string of gluons behaves in exactly the same fashion as the ‘string’ in string theory. The existence of strings can thus be deduced, as a logical consequence of the experimentally confirmed theory of strong interactions.

But string theory is more ambitious: it aims to give a unified description of all the forces of nature, including gravity. This is possible because a string can occur in two guises: closed or open.

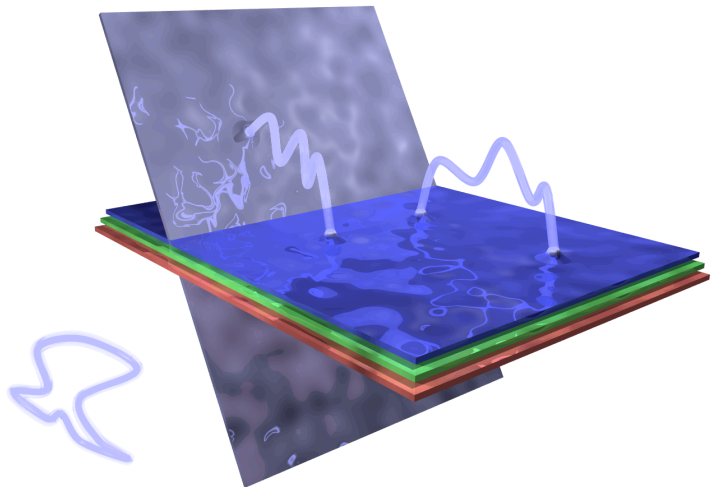
Closed strings have no ends. They have a distinct role: they carry the force of gravity. Any object with mass or energy can emit or absorb closed strings, and this is how objects can feel each other's gravitational field. A very heavy object emits a lot of closed strings, and thereby causes a curvature of space and time, just as in Einstein's general relativity theory. Open strings have two ends. They are responsible for all other forces: the electro-magnetism and two nuclear forces.

In 1995, the American physicist Joseph Polchinski made a remarkable discovery. He showed that it is possible to limit the freedom of movement of open strings: there exist so-called 'D-membranes', to which open strings are attached. The strings are free to slide back and forth along the D-membrane, but their ends can not leave the membranes surface. These D-membranes seem at first sight an artificial toy, but they provide the key to the mystery of black holes.

Let us consider a large number of D-membranes, bunched together like a stack of cards. To distinguish them from each other, imagine we give each membrane a different color. The open strings must follow suit: they must each choose two colors, which indicate the pair of membranes to which their ends are attached. Thus the membrane surface looks like a multi-colored spaghetti soup of open strings. It turns out that these colored open strings behave exactly as gluons, the glue particles that create the strong interactions. In particular, they stitch together in the same way, by sticking their ends to each other, thereby forming long strings. However, these open strings can only move along the membrane surface (unlike normal gluons, which can freely travel in three dimensions). In other words, the open-string theory on a large stack of D-membranes looks like a two-dimensional version of quantum chromodynamics.

There is also another view, a dual perspective on this colorful spectacle. An open string can bind with both ends to another open string, and thereby form a closed string. Such closed string has no end, and therefore it is not glued to the membrane surface: it can leave the membrane and travel freely into the surrounding space. Via this mechanism, D-membranes can thus emit closed strings. But as we have learned, closed strings cause gravity, and D-membranes must thus be massive objects. In fact, this mass can be substantial. Suppose we make a very thick and heavy stack of D-membranes. Suppose that we give them a spherical shape, say, like the horizon of a black hole. Indeed, if one makes the stack of D-membranes thick and heavy enough, then the total

Figure 3. A stack of three colored D-membranes, along which the ends of open strings can move. (An open string with two ends attached to a colored membrane behaves like a gluon; a string with one end attached to a colored membrane and the other end to a the grey membrane behaves like a quark.) Closed strings are not attached to membranes and are free to move about.



mass density of this sphere are so enormous that only one thing can happen: it forms a black hole!

How can this be? Viewed one way (the ‘open string perspective’) we observe a stack of D-membranes, which looks like a two-dimensional multicolored soup of gluon, and viewed the other way (the ‘closed string perspective’) it looks like a black hole! These two physical systems are so different, how can the two objects possibly be the same? It was the Argentinian physicist Juan Maldacena, who first dared make the following bold statement: ‘The three-dimensional environment of a black hole can be exactly described by means of the multicolored theory of quarks and gluons, living on the two-dimensional surface horizon.’ This is the celebrated AdS/CFT duality, the string theory realization of the holographic principle of ’t Hooft and Susskind.

What is that, a ‘duality’? Strictly speaking, it is not more than the assumption that two at first sight very different physical systems are in fact, when viewed at a deeper level, completely identical. So a duality often starts with a clever guess. However, this guess can be tested in many ways, and thus slowly but surely, it grows into a well-trusted and very useful tool. The AdS/CFT duality has withstood many tests. In particular, it confirms the predicted area law for the entropy of a black hole, and gives a detailed interpretation of the holographic principle. String theory has thereby achieved an impressive success.

The String Landscape

Does this mean that string theory has cracked the Planckian secret code? Not really. The mystery is reduced but not solved. String theory gives us, as it were, the alphabet in which the secret code is written. That’s a big step forward. But we do not know the language and the actual text yet. String theory has many unknown parameters. String theory starts its life in nine dimensions. Of these nine dimensions, we see around us only three. The other six are rolled in a small little ball, of about the size of the Planck length. The form of the coiled up dimensions is not well understood. But we know that there are many possible forms. At last count there are about $10^{1,000,000}$ - that’s a 1 with one million zeros – possible shapes. All these shapes together form the so-called landscape of string theory. Only a very small hidden island in this vast landscape will describe a universe that looks like ours.

We can compare the situation with ‘The Library of Babel’, the well-known story of the Argentinean writer Jorge Luis Borges. This library has an infinite number of hexagonal rooms with bookshelves. It is filled with all possible books, typed in an alphabet of 24 letters. In each book, the letters and spaces appear in some random order. But because all possible books are present, the library also includes any literary work of art ever written, or that ever will be written. A book in the library can be compared with a certain shape of the curled up extra dimensions. String theory provides us with a library of Babel of possible universes. The art that we have not mastered yet is to find the book in which the letter form the exciting true story, that describes our universe. But we are convinced that this book exists.

Emergent Space

We know that there are deep secrets hidden behind the horizon of a black hole. But by consistent reasoning, and with the help of string theory, theoretical physicists succeeded in lifting a small corner of the veil. The most striking lesson that we have learned is that everything that occurs near a black hole can be faithfully reproduced, as by means of a hologram, by means of a two-dimensional system, that lives on the horizon. This is a rather far-reaching conclusion: it means that, from the hologram, the third dimension of our space must somehow materialize out of nothing. The third spatial dimension is ‘emergent’.

This insight is forced on us because we know that the rules of gravity and quantum mechanics must be unified in a consistent manner. Einstein, who in the last 20 years of his life struggled with the same question, would most likely not have accepted this conclusion. He believed in the predictable geometric world of general relativity, and made many attempts to make the fickle quantum world into a mirage. But the quantum rules have so far been proven unshakable, while the three-dimensional geometrical space is starting to look more and more like an optical illusion.

Our story also gives a new perspective on the origin of the law of gravity. The hologram on the horizon has the natural tendency to evolve towards configurations with ever increasing entropy. In the emergent space, this tendency must manifest itself as an attractive force. A familiar example of such an entropic force is the elastic force of a stretched rubber band: it tries to contract because an unstretched rubber band has more entropy than a stretched one. In the case of the black hole, this entropic force will manifest itself in the nearby surrounding space as the gravitational pull of the black hole. This new perspective on gravity has been most forcefully advocated by my twin brother, Erik Verlinde. Since then, he has taken the story even further, and proposed that the origin of the mysterious dark matter and dark energy in our universe may be explained by applying this new perspective, not just to the gravity near a black hole horizon, but also to the gravity in the far away regions near the horizon of our observable universe.

This story has made many surprising twists. Where at first there seemed no structure, the absolute blackness of a black hole, there now appears to lie an important key. Instead of a bottomless pit, in which all of our knowledge disappears, the black hole is now seen as a Rosetta stone that will help us unravel the secret code in which the deepest natural laws are written. But we’re not there yet, and there will still be any new twists on the horizon. The riddle of the black hole will give theoretical physicists still many long sleepless nights.