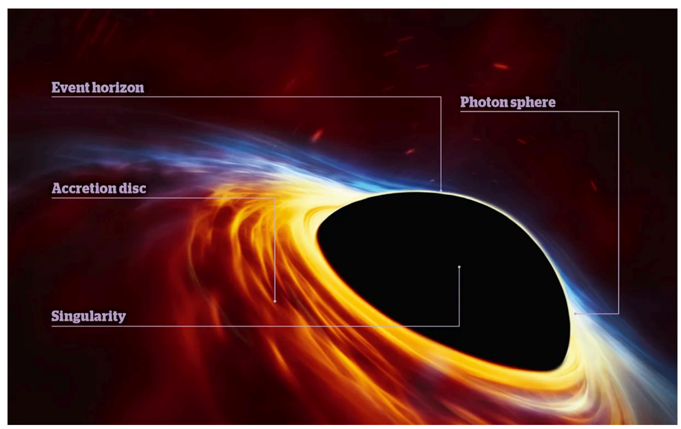
Hawking Radiation

Over trillions of years, all the universe's stars will burn out, galaxies will drift apart, and everything will cool down, resulting in a dark, empty void. But classical physics said that black holes would outlast everything else because scientists considered them indestructible. There was no proof that black holes could fizzle out. They were the universe's ultimate mystery. But in 1974, British scientist Stephen Hawking discovered black holes are not permanent cosmic monsters, but rather black holes do in fact fall victim to time, and they will slowly die.

To understand how a black hole can die, it is necessary to understand the physics and mechanics behind them. Black holes are created when the matter of massive stars is condensed into a miniscule amount of space. Imagine taking the Earth and crushing it down until it becomes the size of a golf ball. The object would have the same mass, but it would be incredibly dense. This extreme density gives black holes their signature gravitational pull. There is also essential terminology related to black holes.

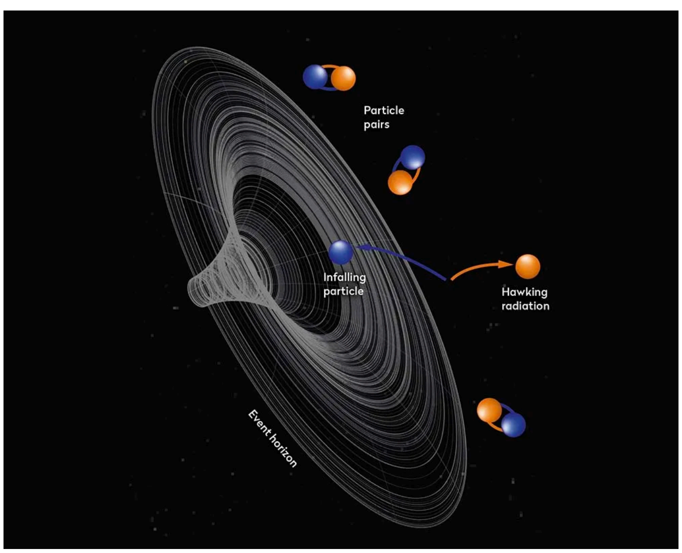


Firstly, the singularity is the center of the black hole. At this point, density and gravity are infinite, and the laws of physics fail because of the extreme conditions. Next, the event horizon is the spherical boundary that is around the singularity where anything that falls into it, even light, cannot escape the tremendous gravitational pull. Outside of the event horizon, objects can still break free from the gravitational force, but across the horizon is “the point of no return.” This is an important concept to remember, especially for understanding Hawking radiation. Before the event horizon lie accretion disks, collections of matter that orbit around the black hole. Matter in the accretion disks tends to heat up and glow because of how rapidly it orbits around the black hole. Finally, the glimmer around the black hole is called the "photon sphere," and it is caused when light from the accretion disks is bent around the black hole using extreme gravity, garnishing the dark, bleak center with a shining halo of light.

Now that the context for Hawking radiation has been set, it is time to finally discuss Hawking's findings. To do so, it is necessary to zoom into the subatomic world. People commonly associate the vacuum of space with complete nothingness. Conversely, quantum mechanics argues that there is no such thing as nothingness. Nothingness cannot exist because "empty space" is constantly bubbling with a lot of activity, known as quantum fluctuations. At the subatomic level, energy from the universe is borrowed to create pairs of tiny particles, called virtual particles. Virtual particles will always come in a matter-antimatter pair. The antimatter particle is simply the complete opposite of the particle made of matter.

Under normal circumstances, the pairs come into existence for infinitesimal amounts of time before they collide into each other. Because antimatter is the exact opposite of matter, when they collide, they destroy each other. The "energy debt" is repaid as the energy from the collision returns to the universe. Billions of these particles appear and disappear everywhere all the time, but no one notices it because the entire interaction occurs in miniscule fractions of a second. And since the energy is returned to the universe, there are no effects on human life. However, this cycle begins to break down when it happens near the event horizon of a black hole.

Imagine a matter-antimatter pair coming about right on the razor-thin boundary of the event horizon of a black hole. Before the particles can collide with each other, extreme gravity acts on them and intervenes. One particle is pulled across the event horizon, falling straight into the black hole, while the other particle rushes away from the black hole out into the universe. Due to their separation, it is not possible for the particles to collide with each other, meaning they still have an "energy debt" to the universe. The laws of the universe clearly state that energy must be conserved, but if there is no collision to return the energy, is it possible to give the energy back? Does the behavior of virtual particles near the event horizon break the laws of physics?



Thankfully, no. The universe finds a workaround to conserve energy. The virtual particles are split, sending the particle in opposite directions. The particle that escaped the grip of the black hole becomes a permanent particle with positive energy. This means to balance the energy, the particle that falls into the black hole must have negative energy. Think of it using this analogy. The two particles take a loan of $100 from the universal bank. Then, the gravity splits the particles apart. The permanent particle with positive energy shoots off with $50. The universe still requires $50, and the negative energy particle can't repay it, so it has a -$50 debt. Since the negative energy particle is inside the black hole, the black hole must cover the payment from its own account.

When the particle with negative energy crosses the event horizon, it enters a region of space where the laws of physics don't operate the same as for the rest of the universe. In most regions of the universe, a particle cannot have negative energy; it is simply impossible. However, in a black hole, real particles can have negative energy due to its infinitely deep gravity well. To understand how gravity wells work, imagine a massive canyon. If someone stops at the top of the canyon, they have a high amount of "stored" energy called gravitational potential energy. If that person parachutes down the canyon, more and more of that "stored" energy that they had at the top of the canyon gets converted into kinetic energy, or energy caused by motion. Once they reach the surface of the Earth, they have no gravitational potential energy. In this scenario, the surface of the Earth is the "zero energy level," where there is no gravitational potential.

Zooming out to the cosmic scale, the "zero energy level" is flat, empty space. Think of it as sea level on Earth. If matter goes below the "zero energy level" or "universal sea level," then it begins to gather negative gravitational potential energy. Since a black hole has a massive "gravitational canyon" with infinite depth, particles rush down, and eventually even real particles have negative energy. This allows the negative particle from the particle pair discussed before to have a place in black holes.

This is the entire process of how Hawking radiation occurs. To an external observer, the positive energy particles shooting away from the black hole will be seen as a type of radiation, and because the negative energy particles fall into the black hole, the black hole is forced to slowly give up some of its mass to continuously pay off "energy debts." Over massive periods of time, black holes will greatly shrink, or even disappear, a process called "black hole evaporation."

But this leaves a huge problem in modern physics. The fact that black holes can evaporate, even if it takes a massive span of time, introduces a massive controversy. It is called the Black Hole Information Paradox. There are two sides of this paradox: quantum mechanics and general relativity. However, before explaining the paradox, it's important to understand what information means. In the physics sense, information is how particles are arranged in a system. Think of it as a type of recipe. Quantum mechanics states that information is always preserved; it cannot be destroyed. For example, if an object were burned, with technology powerful enough, it must be possible to retrace every single atom that came out of the reaction. Theoretically, from there, it would be possible to perfectly reconstruct the object in its original form.

The quantum mechanics side says information cannot be destroyed, but Hawking radiation proposes that through the evaporation process of a black hole, all the information trapped inside will also disappear. So, many scientists argue that the information somehow escapes because those are the laws of the universe. On the contrary, general relativity contradicts that conclusion because it states that nothing can escape the event horizon of a black hole, and the information does disappear and is forgotten from the universe. If information does somehow manage to escape the gravity of the black hole, then general relativity is wrong. But if the information is forced to stay in the black hole until evaporation, then quantum mechanics is wrong. Both possibilities of the paradox break physics.

So, does that mean Hawking radiation does not exist? The answer is definitely no. Physicists all over the world are getting closer and closer to proving that Hawking's 1974 theory is a reality. The black hole information paradox just highlights a lack of understanding in how the universe works and just exposes the fact that quantum mechanics and general relativity are both areas of science that don't know how to smoothly incorporate each other. In conclusion, Hawking radiation shows that black holes aren't permanent and something as small as quantum field fluctuations can cause this "cosmic monster" to slowly evaporate.

Works Cited

Baez, John. “Hawking Radiation.” *Math.Ucr.Edu*, 1994, https://math.ucr.edu/home/baez/physics/Relativity/BlackHoles/hawking.html. Accessed 17 July 2026.

Carlip, Steve. “Hawking Radiation.” *Physics LibreTexts*, 5 Dec. 2014, https://phys.libretexts.org/Bookshelves/Astronomy__Cosmology/Supplemental_Modules_(Astronomy_and_Cosmology)/Cosmology/Carlip/Hawking_Radiation. Accessed 17 July 2026.

Dev Lunawat. “How Can Hawking Radiation Cause Death of Black Holes?” *ScienceABC*, Science ABC, 12 Apr. 2019, https://www.scienceabc.com/nature/universe/death-of-a-black-hole-hawking-radiation. Accessed 18 July 2026.

Engelhardt, Netta. *The Black HOLE Information Paradox a Resolution on the Horizon 2023 MIT Physics Annual 42*. 2023, https://physics.mit.edu/wp-content/uploads/2023/09/PhysicsAtMIT_2023_Engelhardt_Feature.pdf. Accessed 17 July 2026.

Gottesman, Daniel. “Black Hole Evaporation and Information Loss.” *Perimeterinstitute.Ca*, 2026, https://perimeterinstitute.ca/personal/dgottesman/infoloss.html. Accessed 17 July 2026.

Lerner, Louise. “What Is a Black Hole? | University of Chicago News.” *News.Uchicago.Edu*, Oct. 2024, https://news.uchicago.edu/explainer/black-holes-explained#formation. Accessed 17 July 2026.

Musser, George. “In Quantum Mechanics, Nothingness Is the Potential to Be Anything | Quanta Magazine.” *Quanta Magazine*, 5 Jan. 2026, https://www.quantamagazine.org/in-quantum-mechanics-nothingness-is-the-potential-to-be-anything-20260105/. Accessed 17 July 2026.

NASA. “Black Holes - NASA Science.” *Science.Nasa.Gov*, NASA, 8 May 2024, https://science.nasa.gov/universe/black-holes/. Accessed 17 July 2026.

Siegel, Ethan. “We CanNot Avoid a Singularity Inside Every Black Hole.” *Big Think*, 16 May 2023, https://bigthink.com/starts-with-a-bang/singularity-inside-black-hole/. Accessed 17 July 2026.

Strassler, Matt. “Black Hole Information Paradox: An Introduction.” *Of Particular Significance*, 4 Feb. 2014, https://profmattstrassler.com/articles-and-posts/relativity-space-astronomy-and-cosmology/black-holes/black-hole-information-paradox-an-introduction/. Accessed 17 July 2026.

Stuart, Colin. “What Is Hawking Radiation?” *Www.Skyatnightmagazine.Com*, 24 Jan. 2024, https://www.skyatnightmagazine.com/space-science/hawking-radiation. Accessed 17 July 2026.

---. “Yes, Black Holes Can Die, in Theory. This Is How It Would Happen.” *Www.Skyatnightmagazine.Com*, 15 Feb. 2024, https://www.skyatnightmagazine.com/space-science/black-holes-die. Accessed 17 July 2026.

Stuart, Colin, and Ben Skuse. “What Is a Black Hole?” *Www.Skyatnightmagazine.Com*, 24 Nov. 2025, https://www.skyatnightmagazine.com/space-science/black-hole. Accessed 17 July 2026.

Team, HSCprep. “Gravitational Potential Energy and Energy Changes in Space.” *Hscprep.Com.Au*, HSCprep, 22 Nov. 2024, https://hscprep.com.au/hsc-physics/gravitational-potential-energy-and-energy-changes-in-space/. Accessed 17 July 2026.

The Editors of Encyclopedia Britannica. “Black Hole | Definition, Formation, & Facts.” *Encyclopædia Britannica*, 19 July 2018, https://www.britannica.com/science/black-hole. Accessed 17 July 2026.

The Physics of the Universe. “Singularities - Black Holes and Wormholes - the Physics of the Universe.” *Physicsoftheuniverse.Com*, 2009, https://www.physicsoftheuniverse.com/topics_blackholes_singularities.html. Accessed 17 July 2026.

Wikipedia Contributors. “Virtual Particle.” *Wikipedia*, 11 Feb. 2021, https://en.wikipedia.org/wiki/Virtual_particle. Accessed 17 July 2026.

“HubbleSite: Black Holes: Gravity’S Relentless Pull Interactive: Encyclopedia.” *Www.Stsci.Edu*, https://www.stsci.edu/~marel/black_holes/encyc_mod3_q10.html. Accessed 17 July 2026.

“The Fate of the Universe.” *Www.Parkes.Atnf.Csiro.Au*, https://www.parkes.atnf.csiro.au/people/sar049/eternal_life/universe/universe.html. Accessed 17 July 2026.