Why time goes more slowly at a lower place and what a black hole is

Suppose you throw a ball upward. You will see that the speed of the ball decreases as the ball ascends. The kinetic energy of the ball will decrease as well, since the kinetic energy of an object is proportional to the square of the speed of the object.

Suppose you throw a ball downward. You will see that the speed of the ball increases as it descends. The kinetic energy of the ball will also increase.

Now, suppose that you "throw" (i.e. shoot) a light particle, known as a photon, upward. As you may already know, the speed of light is always a constant, so the speed of the photon will not increase as the photon ascends as was the case with a ball. However, it still remains true that the energy of the photon will decrease due to gravity.

Similarly, if you throw a photon downward, the energy of photon will increase even though the speed won't change.

The difference between a photon with lower energy and one with higher energy is that the photon with higher energy will have a higher frequency.[1] Remember that light is a wave and waves oscillate at particular frequencies. If something oscillates 10,000 times per second, for example, its frequency is 10000 Hz. It is not hard to imagine that a photon oscillating rapidly would have higher energy than one oscillating slowly.

Given this, if you emit a photon, say one with a frequency of 10000 Hz, upward from a low place, a detector located at a higher place will record the frequency of the photon to be lower than the original frequency-let us say 9999 Hz.[2] Consider the following question: How long does it take for the photon at the lower place to oscillate 9999 times? Since the photon oscillates once every 1/10000 sec, it will take 0.9999 seconds. It will take 1.0000 sec, however, for the photon at the higher place to oscillate the same number of times.

So, if you send a light signal upward for 0.9999 sec, the detector at the higher place will receive it over the course of 1.0000 sec. In other words, while 0.9999 sec elapses at the lower place, 1.0000 sec will elapse as the light signal travels past the higher place. The same conclusion can be drawn about shooting light downward from the higher place to

[1] Max Planck, one of the greatest physicists of the early 20th century, revolutionized physics by proposing that light is made out of small units, which are now called "photons," and that the energy of each photon is proportional to the frequency of that photon. His proposal successfully explained the spectrum of what is called "blackbody radiation," which had baffled physicists in the 19th century. Albert Einstein later won a Nobel Prize for using this proposal to successfully explain what is called the "photoelectric effect." (I will write more on Planck's proposal and Einstein's work in another article.)

[2] The values used here are chosen for their heuristic, not realistic, nature.

the lower place. The light with a frequency of 9999 Hz shot downward will become light with a frequency of 10000 Hz, and 1.0000 sec will elapse at the high place while 0.9999 sec elapse at the low place. In summary, time goes more slowly at the lower place due to gravitational pull.[3] (Remember that the ball thrown upward goes more slowly as it ascends because of gravitation.) I want to emphasize that time "actually" goes slower; it doesn't simply "appear" to do so.[4] If you are not still convinced, think along this line. What will happen if time didn't go slower at the lower place? Let's shoot light with 9999 Hz downward from the higher place during 100 sec. Then, 999900 oscillations will be sent. If we now assume that time at the low place went at the exactly same rate as the high place, a detector at the low place would receive this signal during 100 sec. However, as the frequency of the light at the low place is now 10000 Hz, it should receive 1000000 oscilations. Now, there is a contradiction. Where did the detector at the low place get the extra $100(= 1000000 - 999900)$ oscillations? Surely, it cannot detect oscillations that were never sent. That time actually goes slower at a lower place is inevitable, as long as gravity affects the energy of photon.

A black hole exhibits an extreme case of this phenomenon. It is very well-known to the public that a black hole is a very massive object of a certain size with gravitation so strong that anything inside of it, even light, the fastest thing in the entire universe, cannot escape. What is not well-known is how time is related to a black hole. This is the subject to which we now turn.

The boundary of a black hole is called its "horizon." Just outside of the horizon, due to the gravitational pull of the black hole, time will pass much more slowly compared to the time experienced by an observer located farther from the black hole. (Remember that a photon will lose its energy as it ascends away from the black hole.) At the horizon, time will "stop" in comparison with the time experienced by an outside observer. Now, let's think about how this is related to the fact that nothing can escape outside of a black hole.[5] Suppose that Michael is just outside of the horizon, and he throws a ball toward Jane, who is situated far from the black hole. According to Michael's measurements, it will take perhaps 100 seconds for the ball to reach Jane. However, Jane will measure that it takes much longer, say 10000 seconds, for the ball to reach her, as time goes much faster for Jane than for Michael.

Conversely, if Jane throws a ball toward Michael and measures that it takes 10000 seconds for the ball to reach him, Michael will observe that it takes 100 seconds for him to receive the ball.

Let us consider a more extreme case. If Michael were at the horizon and threw any object,

[3] Both this fact and the change of frequency of the photon due to gravitation were experimentally verified in the 20th century.

[4] Lorentz, who found out the most important formula in special relativity, later noted that he nevertheless failed to discover special relativity because he didnt consider the possibility that both times were real; he discriminated between them by calling one "true time" and the other "local time." Einstein, who realized that both times are real, is regarded as the discoverer of special relativity.

[5] Of course, Hawking showed that a black hole can emit particles, but we are going to put aside this issue for our current purposes.

be it a ball or a photon, Jane will measure that it takes infinite time to reach her. Taking infinite time means "never." Nothing thrown out of the black hole ever reaches her.

Analogously, if Michael were at the horizon and Jane threw any object, be it ball or a photon, to him, the object will seem to take infinite time to reach its destination. Taking infinite time means "never." Nothing thrown toward a black hole by Jane ever reaches the black hole. Considering that a black hole sucks everything, this is strange, isn't it? The resolution is simple. This conclusion was only considering Jane's point of view. From the point of view of Michael or the object thrown it takes *finite* time to reach the black hole. So, don't be relieved! Watch out for black holes! You can be sucked in!

This article consisted of a qualitative discussion rather than a quantitative one. We will revisit the topic from a quantitative perspective in our article, "By how much does time go more slowly at a lower place?"

Summary

- Time goes more slowly at a lower place.
- The boundary of a black hole is called its "horizon."
- At the horizon, time will "stop" in comparison with the time experienced by an outside observer.
- Therefore, nothing thrown out of the black hole ever reaches her.
- To an outside observer, nothing thrown toward a black hole ever reaches the black hole.
- Nevertheless, from the point of view of the object thrown it takes *finite* time to reach the black hole.