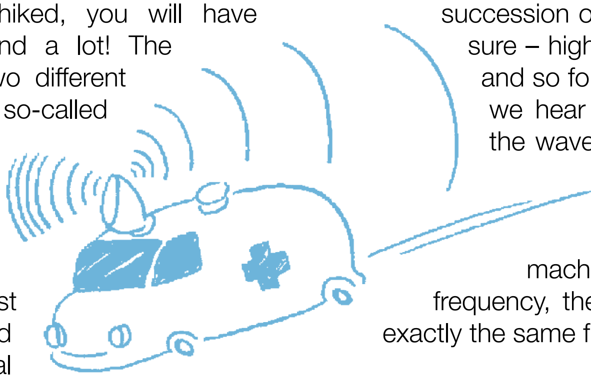
"I wasn't speeding. I was demonstrating to my colleagues how police radar employs the principles of the Doppler effect."

The Doppler Shift

The Stretching of Waves

What is the sound of a car engine? Well, actually, that depends very much on where you are! If you sit inside the car, and have time to listen to the engine, you'll hear a constant humming of the machine. Quite a muffled sound, actually, because nowadays car manufacturers try to make sure that you hear as little of the engine sound as possible.

But if you sit by the side of a road, then a passing car sounds quite different. If it is approaching, the sound will be quite high-pitched, but at the moment the car passes you by and recedes in the distance, the sound will switch from high to low pitch. Wreeeeeeeerooouuummmm! If you have ever hitchhiked, you will have heard that kind of sound a lot! The reason why you hear two different pitches of sound is the so-called Doppler effect. It happens with all kinds of waves!



But with sound waves it can be explained most easily, because sound waves are just rhythmical compressions of air. If there is total silence, then the air pressure (↗[1]) is the same everywhere. But as soon as, at one place, the pressure is a bit different from other places, this pressure difference will wobble through the air, spreading out in a wave-like manner. It is this pressure wave which we perceive as sound, as soon as it reaches our ear. And the shorter the wavelength, the higher the frequency, and the higher the pitch of the perceived sound.

Vibrating Machines and Their Sound

Why does a car engine make a noise, after all? Well, such a machine has a lot of movable parts, and when an engine is running, many of these parts are vibrating. If such a piece of, say, vibrating metal, has contact to the air, it will make the air vibrate, too. Well, it will compress the air around it a little bit every few fractions of a second.

What is reaching our ear when we hear a sound is a succession of high pressure – low pressure – high pressure – low pressure – and so forth. As we have mentioned, we hear a higher pitch the shorter the wavelength, in other words, the faster the air changes between high and low pressure. Normally, if a machine vibrates with a certain frequency, then we'll hear a sound with exactly the same frequency.

Now, what happens when the machine is moving?

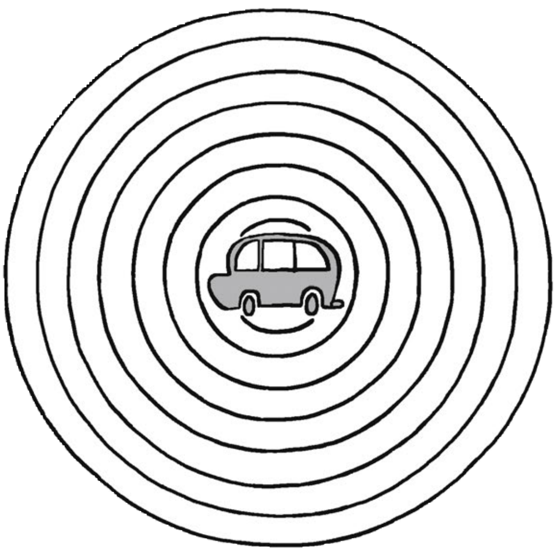
Moving Sound Waves Get Stretched – and Thus Pitched

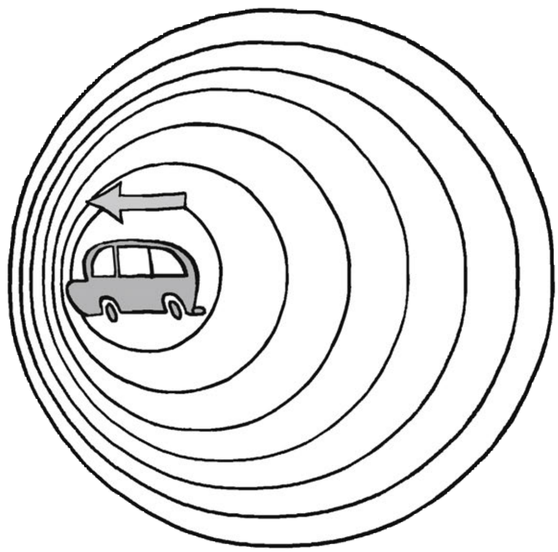
What happens is that the sound wave does not leave it in every direction with the same frequency. Rather, in the direction in which the engine moves,

↗[1]: *"Vacuum and Air Pressure" on page 23*

B. Bahr, B. Lemmer, R. Piccolo, *Quirky Quarks*, DOI 10.1007/978-3-662-49509-4_4

the waves are compressed. In the opposite direction, they are stretched. So if a noisy machine approaches us, it pushes the sound waves in front of it together. What then reaches our ear is a wave with a smaller wavelength – and that means a higher frequency, which in turn means a higher pitch. On the other hand, if the machine moves away from us, then the air waves that hit our ear are stretched slightly – so the wavelength is larger, and thus the frequency lower. We then hear a lower pitch.





And if the machine passes us by? Well, then we hear the typical sound of a car engine, or a siren rushing past us: the pitch of the sound goes from higher to lower the moment it is on level with us.

The Doppler Effect for Light

The shifting in sound is probably something that has been experienced by almost everybody. But did you know that this Doppler effect also happens for all other kind of waves – in particular for light waves (➚[2])? And even better, using the Doppler effect one can actually measure the temperature of the sun, or how fast it rotates!

Well, one can if one has very precise measurements. You see, the sun in general is quite hot, and a lot of electromagnetic radiation reaches us from there, having all kinds of different frequencies. That is why the sun seems nearly white to us: its light contains all the colors of the spectrum.

If one looks very closely, however, one can see that there are some very specific frequencies which are missing! These are the so-called Fraunhofer lines, and physicists have known of their presence more than a hundred years before they understood the reason for their presence (or rather absence). Some

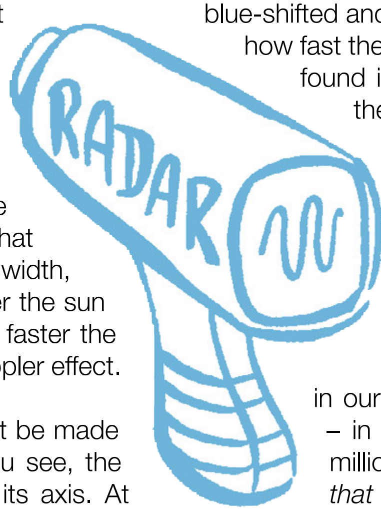
➚[2]: *"Light" on page 7*

of the frequencies are missing, because they correspond to photons which have precisely the right energy to initiate a quantum leap of energy in the hydrogen (and other) atoms in the sun. For light with these frequencies, the plasma in the sun is completely opaque, while for all other colors of light it is basically transparent.

How Hot Is the Sun?

But now imagine that the hydrogen atoms in the sun don't all just sit there – they move! And they move quite a bit, the hotter they are. While a resting hydrogen atom needs to be hit by a photon with precisely the right frequency in order to absorb it, it can have a slightly lower frequency if the atom is, just in this second, moving towards the radiation. Because of the Doppler effect, a moving atom will see a photon with a slightly higher "pitch", which means a little bit higher energy.

What does that mean? It means that in the spectrum of the sun, there are not just precisely those frequencies missing which are responsible for the quantum leaps in hydrogen atoms – but also the frequencies slightly lower and slightly higher. They are also blocked out because of the Doppler effect! One says that the Fraunhofer lines have a certain width, and this width gets bigger the hotter the sun is – the higher the temperature the faster the hydrogen atoms, the bigger the Doppler effect.



And the Fraunhofer lines cannot just be made wider, they can also be shifted! You see, the sun is not fixed, it rotates around its axis. At its equator about one revolution in 25 days. That means that if you look at the light coming from the right edge of the sun (↗[3]), the Fraunhofer lines will be shifted to lower frequencies, while in the light from the left edge has Fraunhofer lines shifted to higher frequencies. And that happens, again, because of the Doppler effect: light coming from those parts of the sun which move away from us has lower frequencies – it's like the car moving away from us. One calls this light red-shifted. Consequently, light from the other edge of the sun is called blue-shifted.

Sgr A*: A Supermassive Black Hole – Proven by the Doppler Effect

The Doppler effect was also used in order to prove for the first time that there has to be a black hole (↗[4]) in the center of our Milky Way. You see, in the central region of our galaxy there are lots of stars orbiting a common center. We know this because we can see the microwave radiation from them arriving at the Earth. And because some of the radiation is blue-shifted and some is red-shifted, we also know how fast they orbit the center. And, people have found in the seventies of the last century, they rotate so fast that there needs to be an enormous mass which they all move around – such a great mass, in fact, that no normal star would be stable under that weight.

Nowadays we know much more about the supermassive black hole in our center – also called Sagittarius A* – in particular that it is more than four million times as heavy as our sun. Now *that* makes for some Doppler effect!

↗[3]: *"Nuclear Fusion" on page 175*
↗[4]: *"Black Holes" on page 91*