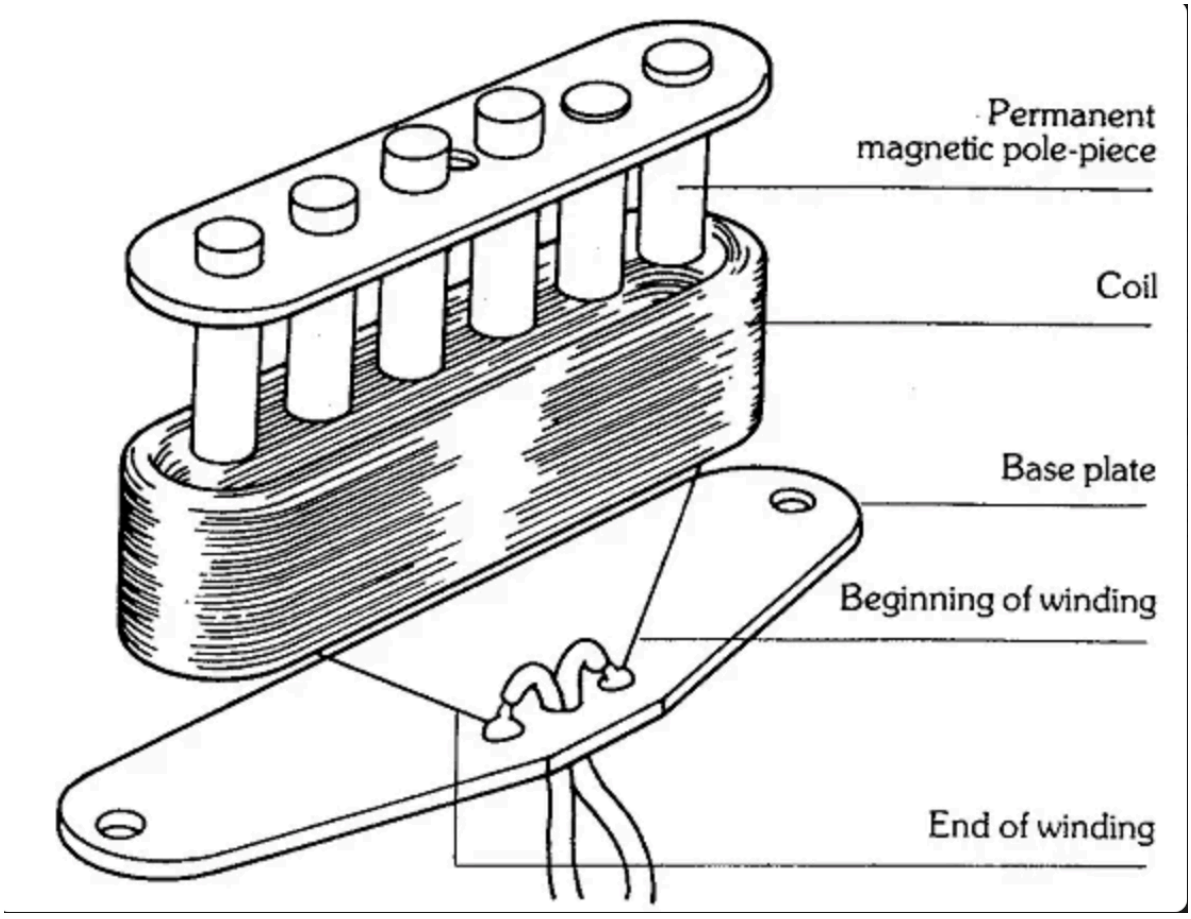
02 - 2024 The Science of the Electric Guitar

The unique sound of the electric guitar owes much of its magic to a simple and overlooked, yet crucial component: the pickup. Functioning at the ears of the instrument, pickups are small devices that convert the vibrations of metal strings into electrical signals that are amplified and transformed into music.

Acting as transducers, pickups use principles of electromagnetism to capture subtle nuances in string vibrations, a process involving the inducing electrical currents in coils of wire, generating a signal that faithfully represents the sound of the vibrating strings.

To further understand how a pickup works, we must first understand the anatomy of the devices.

A typical pickup consists of six cylindrical polar magnets with the south pole facing the guitar strings, a coil of copper wire wrapped around the magnets, and a base plate. When the metal strings of the guitar vibrate, it disturbs the magnetic field of the cylindrical; magnets inducing a small electrical current in the copper wire.

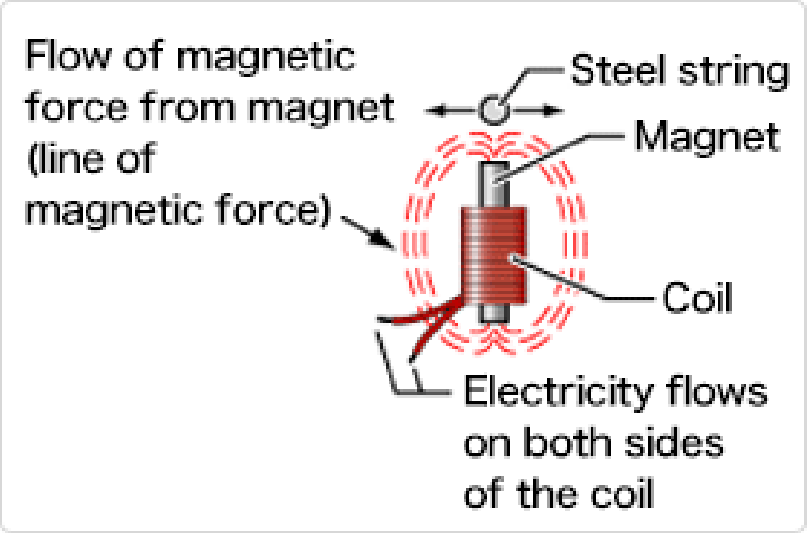


There are two basic types of pickups with a similar anatomy used in the common electric guitar, single coil and humbucker pickups. Both types fulfill the same purpose, but are constructed slightly differently.

A single coil pickup consists of a single coil of copper wire wrapped around the magnets, whereas the humbucker consists of two coils wired in a series, with the second coil's magnets, or pole pieces inverted. We'll get into the differences of functionality and tonal quality later.

So now that we know the structure of pickups, how do they transfer the vibrations of guitar strings into those electrical signals that are read by the amplifier?

Firstly, let's look at the role of the pole pieces. Like all magnets, the pole pieces are composed of molecules that are arranged so that the electrons spin in the same direction. This movement creates a magnetic force that flows from the north seeking pole to a south seeking pole, creating the magnetic field around the pole pieces. Because of the magnetism of the pickup, the strings of the guitar also become magnetized. When these strings vibrate, they cause a disturbance in the field of the pole pieces.



This disturbance is what causes an electrical current to form the coil around the pole pieces. But why does a disturbance in the magnetic field cause an electrical current? The answer lies in Faraday's law of electromagnetic induction.

Formulated by nineteenth century English scientist Michael Faraday, the law states that any change in the magnetic environment of a coil of wire will cause a voltage, or

electromotive force, to be induced in the wire. This electromotive force can be produced by various means from moving a magnet toward and away from a coil, rotating the coil relative to the magnet, etc. The induced electromagnetic force is equal to the negative of the rate of change of the magnetic flux times the number of turns in the coil.

This phenomenon of electromagnetic induction is the fundamental principle behind the operation of electric generators, transformers, and other commonly used electrical devices. In simple terms, Faraday's law explains how a changing magnetic field can create an electric current in a conductor.

Now that we know how pickups work, what's the difference between the sound quality and functioning of a single and double coil pickup?

A single coil pickup works exactly as explained above, but a double coil, or humbucker, goes through an extra process because of the extra copper coil. The two coils of a humbucker are usually wired in a series with the second coil's pole pieces inverted (the north side of the magnet faces the strings). The effect of the inverted poles is the canceling out of interference and hum in the final sound. This combination of the opposite magnetic polarity and wiring causes the pickup to sense a different pole of the same magnet. The coils are internally connected in a series, (start to start, or finish to finish,) making them wired in opposite directions. With each coil creating an opposite effect, all unwanted noise is effectively canceled out.

The sound of a single coil is bright, clear and sharp, and tends to sound gritty when overdriven or distorted. Humbuckers emphasize midrange sounds, are warmer and have enhanced sustain. Here's two demonstrations of the difference in sound:

Jimi Hendrix is known to use Fender Stratocasters, a guitar with single coil pickups. The heavy interference of the pickups contributes to the trademark distorted sound of psychedelic rock:

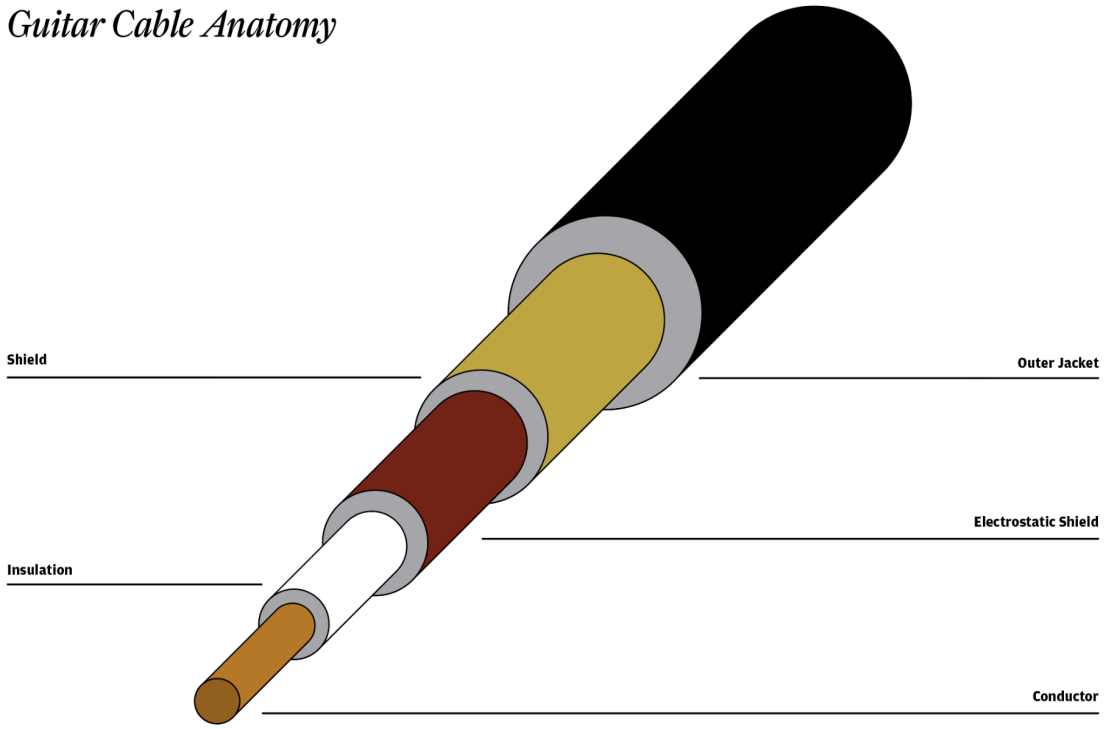
(The Jimi Hendrix Experience live at the Atlanta Pop Festival)
https://www.youtube.com/watch?v=cJunCsrhJjg

Jimmy Page usually uses a Gibson Les Paul, which has a double coiled humbucker pickup. The sound is much clearer with almost no distortion. The clarity of guitars with humbuckers are why they're the preferred instrument for jazz and hard rock.

(Led Zeppelin live at Madison Square Garden)
https://www.youtube.com/watch?v=-X6wBDnyh1E

Now that we understand how an electrical current is formed within the pickups, how is that current transferred from the guitar to the amplifier?

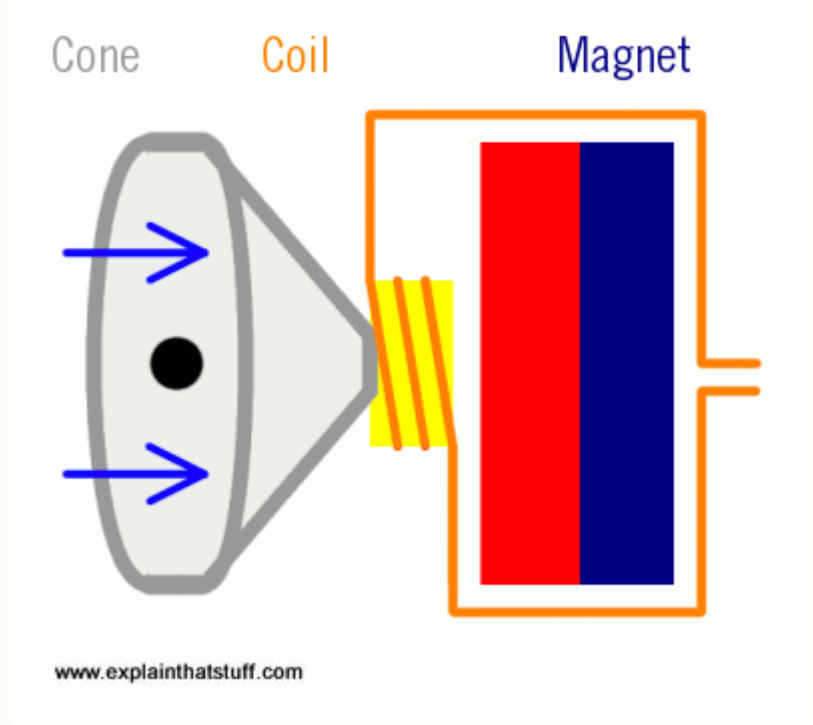
This is achieved through a connected cable. A guitar cable is typically made of a conductive copper wire surrounded by a non-conductive insulating material and an outer shield.



The conductive wire carries the electrical signal from the guitar to the amplifier. The insulating material prevents interference in the signal when traveling from guitar to amp. The electrostatic shield discharges static electricity to prevent the buildup of static charges that cause damage in circuits. All these components are encased in an outer jacket.

Once an electrical signal enters the amp, it passes through a series of transistors and circuits that strengthen the signal through a process called voltage amplification. This strong electric current passes through another coil of wire, generating a magnetic field.

The wire is placed in front of a permanent magnet in the speaker system. Similar to the pickups, the coil of wire and permanent magnet interact with each other causing the speaker cone to move back and forth, converting magnetic and electrical energy into mechanical energy. The movement of the cone creates changes in air pressure that is perceived as sound.

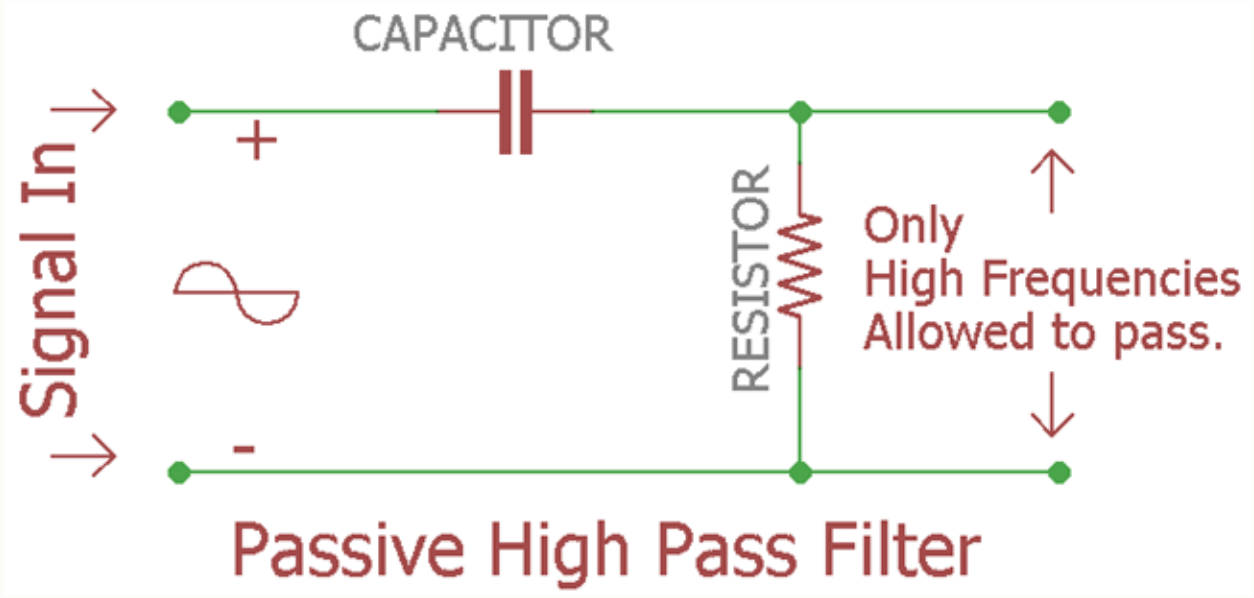


Besides pickup types, there are other factors to consider that lead to the final sound the speaker produces, amp settings. The knobs on the amplifier change the input, output, and tone quality. The tone is changed through filter circuits designed to alter the frequency of the electrical signal in the amp.

There are three basic tone adjustments that can be made on the amp, bass, midrange, and treble. Let's use the treble setting for this example. Treble is used for adjusting the level of the higher audio frequencies. The filter circuit allows the passage of certain frequencies through the circuit while attenuating, or weakening others. For the treble setting, when set higher, the filter circuit makes the higher frequencies of the input stronger, and muffles lower ones.

The basic components of a treble circuit, or high pass filter, consist of a series of resistors, capacitors, and transducers.

First, the electrical signal enters the circuit. It then encounters the capacitor, which stores the excess electrical energy in the form of an electric field. It consists of two conductive plates separated by an insulating material. When a voltage is applied to these plates, it causes the accumulation of positive charges on one plate and negative charges on the other. This separation of charge between the plates allows the capacitor to store energy. In this circuit, at low frequencies, the reactance of the capacitor is high, acting like an open circuit and blocking the input signal. However, as the frequency increases, the reactance of the capacitor decreases, allowing high-frequency signals to pass through.



After going through the capacitor, the electrical signal passes through a resistor. Resistors are made of varying materials that have a specific controlled level of resistance to the flow of the electrical current. This could come in the form of carbon powders to metal films. In a high pass filter, the resistor is often used in series with the capacitor to form a voltage divider, cutting off any lower frequencies that were missed by the capacitor.

So, when dialing the treble knob higher on an amp, you are increasing the strength and resistance of the capacitor and transistor, which results in a higher frequency, or higher pitched sound.

Using the two video examples from earlier (The Jimi Hendrix Experience at Atlanta Pop Festival, and Led Zeppelin at Madison Square Garden), let's see how different amp settings, or filter circuits, can contribute to the speaker's final sound.

When playing Purple Haze, Jimi Hendrix's amp settings look something like this:

Combined with the heavy interference of single coil pickups, the gain, or input signal, on Hendrix's amplifier is high. An increased input causes more of the electrical signal from the guitar's pickups to pass through the amp. This results in the distorted sound quality of the final result. The treble is set equally high to compensate for this distortion. Emphasizing the higher pitched sounds of the guitar increases clarity. Without increased treble, the guitar would sound too sloppy with no definitive differences between chords.

Jimmy Page's amp settings for Over The Hills and Far Away look like this:

Notice the gain is significantly lower, making the end result less distorted, but still high enough to give a slightly overdriven sound. The emphasis on the bass and midrange the humbucker pickup makes the tone sound warmer and more well rounded with a higher frequency range. The treble is also set high to enhance clarity.

The intricate process between pickups, chords and amplifiers is the heart of the sound production of electric guitars. From the conversion of string vibrations to electrical signals to the transfer, amplification, and shaping of the signals, every component contributes to the unique tone of the guitar. Understanding the technology of this instrument can not only enhance your appreciation for music, but increase understanding of magnetism, circuits, electricity, and the endless possibilities of electronics.

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