A Technical Analysis and Exploration of Guitar Pickups and Electronics

Hunter Manel
Bard College, hm3654@bard.edu

Follow this and additional works at: https://digitalcommons.bard.edu/senproj_s2018

Part of the Other Music Commons, and the Other Physics Commons

This work is licensed under a Creative Commons Attribution-Noncommercial-No Derivative Works 4.0 License.

Recommended Citation
https://digitalcommons.bard.edu/senproj_s2018/148

This Open Access work is protected by copyright and/or related rights. It has been provided to you by Bard College's Stevenson Library with permission from the rights-holder(s). You are free to use this work in any way that is permitted by the copyright and related rights. For other uses you need to obtain permission from the rights-holder(s) directly, unless additional rights are indicated by a Creative Commons license in the record and/or on the work itself. For more information, please contact digitalcommons@bard.edu.
A Technical Analysis and Exploration of Guitar Pickups and Electronics

A Senior Project submitted to
The Division of Science, Mathematics, and Computing
of Bard College

by
Hunter Factor

Annandale-On-Hudson, New York
May, 2018
Abstract

The development of the electric guitar during the 20th century was revolutionary for musicians and sound engineers alike. The advances in amplifying sound by way of pickups and amplifiers contributed to massive cultural movement in music, including Jazz and Rock ’n Roll. While the pickup is acknowledged as an integral component of the electric guitar, few players understand the electronics and mechanics underlying their instrument. This project aims to accomplish two goals with a focus on pickups: first, describe the physics behind the electric guitar’s amplification process, and secondly, use this understanding to build a pickup for use in an electric guitar.
Dedication

This thesis is dedicated to all the musicians who enrich my life.
Acknowledgements

I would like to thank my advisors, Matthew Deady and Paul Cadden-Zimansky, who have been extremely patient throughout this process. I have been given an incredible education and owe much of my scientific knowledge and excitement to the both of them.

I would like to thank Curtis, Hank, and Simon for tolerating and encouraging sickening, math infused, musical concepts over the last three years.

A big thank you to Aya, Grey, Isobel, Praiz, and Siena for the incredible amount of support and motivation in the few weeks leading up to the completion of this senior project.

Thank you to my grandmother, Ellen, for her sewing machine and unwavering consideration.

Thank you to my brother, Cole, for owning too many guitars.

Thank you to my mother, Jennifer, for years of musical exposure, open-mindedness, and love.

This would not have been possible without all of you.
1 Introduction

Guitar amplification is a wonder of the musical world that is taken for granted. Instrumentalists and listeners alike assume the electric guitar’s ability to produce sound with an amplifier is a kind of electronic magic. Many guitarists do not take the time to understand that their pickups are responsible for their instruments voice! That being said, understanding the science behind pickups is an incredible asset and largely beneficial when managing what sound comes out of your guitar.

1.1 The Guitar

Before attempting to trace the guitars ancestry back to its origins, it may be helpful to define what makes an instrument a guitar. While it may be safe to assume most people understand what a guitar is, this is for all those who might question the specificities. An acoustic or classical guitar acts as a particularly sound model to have in mind while dis-
cussing the iconic aspects of the instrument. The primary indications that the instrument you have in your hands is indeed a guitar are the following. Six strings (steel wound nickel for acoustic and nylon for classical) attached at the headstock by metal tuning machine heads and on the end of the body by an apparatus of varying design, called the bridge. The neck, connecting both the headstock and the body, has a flat top with metal “frets” and a rounded back, supporting the arch of one’s hand. The frets are a component that separate the guitar from many stringed instruments, enabling a player to produce discrete notes unlike an oud or something more familiar, a violin, which offers a continuous spectrum of notes upon a fretless neck. The body is often pear or eight shaped, with a hole centered below the strings in between the neck and bridge, which gives way to the hollow cavity inside. This is by no means the only description of the guitar. There are many luthiers and companies mass producing guitars with differing styles and constructions, but this generally covers all the integral components. Guitars belong to the class of instruments known as “composite chordophones,” which produce sound by plucking strings stretched between and secured at two points. “Composite” calls attention to the instrument’s dependence on a resonator which, in the case of the acoustic and classical guitar, is the bridge in conjunction with the body. The electric guitar complicates this definition only slightly
in that it has lost its dependence on a resonator, but adopted the pickup in its place. The electric guitar is often without a sound hole and cavity. It might not be worth changing its characteristic title, but rather understand the pickup as the analog to the bridge and soundboard resonator on the acoustic variant.

1.2 History of Guitar

Guitar pickups and electronics have not been around forever, for humans’ understanding of acoustics and woodworking obviously predates their knowledge of magnetism and electronics. Guitars, on the other hand, have been around for several thousand years, although their specific predecessors cannot be exactly pinpointed.

Figure 1: The lute has a very short neck with few frets to support playing in one position. Notice the severely angled neck and intricately designed sound hole.

It is often thought that the guitar is a derivative of the Ancient Greek “Kithara” or the Renaissance Era “Lute,” but the former more closely resembles a harp and the latter developed from the Arabian fretless Oud; it is worth noting that both the Oud and Lute benefitted from the development of the guitar, and not the other way around! The development of string instruments can be traced back to civilizations from about 3000-4000 years ago, namely the pre-Islamic Persian empire with their “tanburs,” an instrument resembling a barebones, fretless Sitar. Many instruments with bulbous, pear shaped bodies
and disproportionately long necks, such as the Barbat, Oud, and -Tar (lacking a prefix which usually indicates the number of strings, similar to how the Baroque Era four- and five-course are defined and named by their number of paired strings) are created during this time period or are responsible for the develop of familiar instruments like the Lute and Sitar. The society most often held accountable for the development of the guitar is that of Spain. When the aforementioned Persian chartar (four string -Tar) arrived in Spain via traveling bards and instrumentalists, it underwent structural changes, acquiring fixed frets, a smaller, more proportional neck, and doubled strings tuned to identical pitches, in order to remain appropriate in its new musical environment. As this new instrument took form, it donned the name Chitarra (or quitarra), which not only resembles the guitar in name, but physically as well.

Figure 2: A modern replica of the Spanish quitarra is designed with intricate embellishments on the body, neck and headstock. Unlike the guitar, the quitarra is equipped with 5 sets of strings similarly tuned strings, an elongated headstock, and a fretboard that does not extend onto the body.

I have drawn a direct path from the oldest of stringed instruments to the most direct
ancestor of the guitar, but this is by no means the only evolution of instruments responsible for the creation of the modern guitar. The ambiguity surrounding the genesis of the guitar alludes to the pervasive means by which instruments are spread and created. There are few direct correlations between instruments that we can trace over large intervals in time, but that will not prevent us from delving into that which we are concerned with (guitar pickups).

1.3 Guitar Pickups

As the guitar made its way to the forefront of contemporary music in the 20th century, it broke free from its role as an accompaniment and quiet solo instrument. Its progression as a lead instrument necessitated an increase in volume, which instruments like the Lute and 4-course also struggled with. The emergence of jazz especially provoked engineers to consider the guitar’s volume as it paled in comparison to that of a brass instrument, which there were potentially multiple of in any given jazz combo or band. Initially, pickup builders wanted to create a device which successfully amplified the guitar while preserving its innate, clean voice. As the technology was refined and more thoroughly understood, this model of pickup making was replaced by innovative exploration in altering and enhancing specific qualities of the guitar’s sound.
The technical and structural developments I am specifically interested in were not actualized until the most recent 70 or so years of the guitar’s lifetime. The first account of pickup creation is documented in 1927 by the American W. D. Smith [9]. Following the development of the telharmonium, phonograph, gramophone, and radio, technology created to communicate and project sound, Smith set the groundwork for amplification systems such as microphones. Les Paul is cited to have created the first electric guitar, but the Fender Telecaster is considered the first widely produced electric guitar in 1951.

1.4 Motivations

I was a musician before a physicist and as my understanding of sound, waves, and magnetism deepened through the physics curriculum, I realized how little I knew about the instrument I had been playing for half my life. This is by and large what inspired the senior thesis which is in your hands. The project serves as an intersection of my two largest interests and gives me a chance to not only apply the physics that I have been taught, but to finally become in tune with the most mysterious and integral mechanism of my instrument, the pickup.
Before understanding the technology that aids the production, manipulation, and amplification of sound, it is beneficial to understand and display how sound manifests itself in physics and consequently, nature/music/life.

2.1 Sound & Pitch

Our perception of sound is hinged on our ability as humans to receive and understand fluctuations in air pressure due to a vibrating medium. Sound propagates through the air as waves, interacting with our ear drum. Vibrating systems which produce sinusoidal waves can produce pure tones of a single frequency or complex tones composed of linear combinations of individual sinusoids. The latter is what makes up the bulk of naturally occurring sounds and music. The frequency of oscillation is what allows us to designate pitch, although it is worth acknowledging that there are subjective and psycho-acoustical
effects on pitch perception. The typical range for human hearing is 20 - 20,000 Hz, with the higher bound gradually decaying to around 10,000 - 12,000 Hz over the course of one’s life.

When measuring loudness over the wide spectrum of frequencies, we tend to use a logarithmic scale. The scale most often used to measure loudness is the decibel (dB) scale. While it shows up as a linear scale on dB vs. frequency graph, it is implicitly logarithmic. The intensity level of a sound is calculated with reference to the lowest audible intensity, approximately $10^{-12}$ W/m$^2$, using the equation

$$IL = 10 \log \frac{I}{I_{ref}}$$

where IL is expressed in units of decibel in reference to $I_{ref}$, or dB $ref$ $I_{ref}$. Frequencies are more explicit in their use of the logarithmic scale. This allows us to condense the near 20,000 units of audible frequencies onto a reasonably sized graph. A logarithmic scale creates intervals of equal ratio rather than equal intervals. By expressing equal spaces on the graph with equal proportions of frequencies we stretch the amount of space representing lower frequencies and squeeze the space representing higher ones, complementing our insensitivity to changes in lower frequencies. For example, space occupied by the frequencies 100 Hz to 1,000 Hz is the same as that taken up by 1000 Hz to 10,000 Hz.

When a string is plucked, the lowest recognizable frequency is called the fundamental and all higher naturally occurring frequencies are overtones. When an overtone is an integer multiple of the fundamental frequency, they are called harmonics, or harmonic overtones. The fundamental is called the first harmonic and the first overtone, being the first integer multiple of the fundamental, is called the second harmonic. Sometimes, in order to avoid confusion, the umbrella term, partial, is used when referring to frequencies; the fundamental
Figure 3: The above graph depicts the threshold of human hearing, both in terms of frequency (Hz) and sound intensity (W/m²). The frequency is scaled logarithmically, notice the equal space between 100 to 1,000 and 1,000 to 10,000. The intensity, on the right vertical axis, is logarithmic, but with equal intervals of ratio 10². The intensity level, in dB on the left axis is linearly scaled.

is the first partial, the second harmonic or first overtone is called the second partial, and so on and so forth.

Harmonics manifest themselves interestingly on the guitar. Natural harmonics can be singled out and played by gently pressing one’s hand on the string above a node before plucking. Artificial harmonics can be played in the same manner, but only apply to strings that are currently fretted. Fretting the instrument displaces the location of the harmonic on the neck. The most commonly used harmonics are located on the fifth, seventh, and twelfth frets; the first two can be used to tune the instrument, while the twelfth fret harmonic is the octave and can be used to determine whether a guitar is properly intonated. While the hand fretting the notes can be used to exhibit harmonics, the picking hand is used to nullify the effects of certain harmonics. By exciting the string at the position of a node, the corresponding harmonic is omitted from the resulting waveform, allowing the guitarist to
control the timbre or tone of their playing. The guitar techniques *dulce* and *sul ponticello*, meaning sweet and on the bridge respectively, stem from these effects. Harmonics are not limited to these uses and have scattered musical applications.

### 2.2 Timbre

Timbre is human’s perception of the quality of sound. Take, for instance, your experience watching a symphony orchestra in a concert hall. When listening to the orchestra, you are able to discern between the instruments even when they are playing at once! While there is variation within the sounds an instrument can create, each instrument has an associated timbre which enables humans to recognize it. The difference in timbre is due to the varying prevalence and amplitudes of partials in the wave produced by the instrument. Therefore, we are able to differentiate between instruments, even if they are playing the same note at the same frequency.

Human insensitivity at certain frequencies influences the perception of timbre. Initially, we require at least 60 milliseconds of sound in order to identify it as timbre. Any tone persisting for less than 4 milliseconds comes across as an atonal click. Human ears, being approximately 1000 times more insensitive to changes in frequencies of 100 Hz than 1000 Hz, require a greater change in amplitude at lower frequencies in order to perceive a difference in timbre.

In analyzing and producing sound, and subsequently waves, there are four important characteristics that influence the perceived timbre: the attack, decay, sustain, and release, often abbreviated as the ADSR envelope. The figure below displays an arbitrary note with these four facets plotted on an amplitude (dB) vs. time (t) graph.
The **attack** characterizes the time it takes a sound to reach its highest amplitude from its initiation. The **decay** pertains to the time it takes for the note to settle to a constant amplitude. The amplitude at which the note is held for the longest duration of time is the **sustain**. The **release** occurs after whatever mechanism playing the note is deactivated, whether a key on a synthesizer or a fretted string on a guitar, and continues until the amplitude is zero. The attack vastly influences how we perceive the note played, regardless of its frequency and associated pitch. For example, consider the different sounds produced by a guitar played finger-style and a guitar played with a pick. Not only is the latter louder, but it is often characterized with adjectives such as **sharp** while a finger-style player may be characterized as **round**. These terms are to be discussed in greater detail in the subsection “Terminology.”

Another contributing factor to the tonal quality of an instrument is its ability to produce anharmonic partials. In an ideal system, the supports tethering a string on either end of a guitar are completely rigid, thus producing solely harmonics that are integer multiples of the fundamental frequency at which the string is oscillating. In actuality, the supports on an acoustic guitar are not completely rigid, as the bridge is constructed in such a way that it accurately communicates the waveform to the soundboard of the guitar, that way it can be amplified and produced via the sound hole. It turns out that the anharmonic effects of the non-rigid bridge are nominal for an acoustic guitar, and are less important for an electric guitar, where the supports comprising the bridge and tuning machine heads are considered perfectly rigid, and so, anharmonicity will not be discussed.

Vibrato and Tremolo, or frequency modulation (FM) and amplitude modulation (AM)
respectively, are other contributing factors to timbre, but have more relevance when discussing wind instruments and the voice.

2.3 Fourier Series & Transform

Figure 4: For a simple arbitrary wave, such as the square wave (in red), it can be shown that the sum of the fundamental sine component and odd partials converge to the equation for the original wave.

A method of quantifying and representing timbre is through the Fourier Series and Transforms. Any single valued, periodic function can be deconstructed into a linear combination of sinusoidal terms with frequencies that are integer multiples of the original function’s frequency. Therefore we can represent a composition of waves using

\[ f(t) = \sum_{n=0}^{\infty} A_n \cos \frac{n\pi t}{T} + \sum_{n=0}^{\infty} B_n \sin \frac{n\pi t}{T} \]

with period \( T = \frac{2\pi}{\omega} \) and the coefficients given by

\[ A_n = \frac{2}{T} \int_{0}^{T} f(t) \cos n\omega t \, dt \]
\[ B_n = \frac{2}{T} \int_{0}^{T} f(t) \sin n\omega t \, dt. \]
This is particularly interesting and useful in the context of the guitar. The resulting wave from a plucked guitar string can be broken down into sinusoids with commensurate frequencies, comprising the fundamental and higher partials.

![Figure 5: For a pure tone, the Fourier transform will return a graph with one peak at the frequency of oscillation.](image)

Meanwhile, the note produced through the pickup of an electric guitar is more complex; not only are the normal overtones present, but uncharacteristic, anharmonic partials are brought about as the pickup distorts the note played when converting it from an acoustic wave to an electronic signal. We may remove inconsequential higher terms beyond the scope of human pitch perception, making any analysis that much easier. A guitar also produces a note which is decaying in time, but has a repeating period associated with its waveform. The quantity that becomes more important in this case is frequency, so we define the time equation, \( f(t) \), in terms of a frequency dependent function, \( g(\omega) \), and take the inverse. If we take the distribution of frequencies and time to be continuous, we may represent these functions as

\[
    f(t) = \int_{-\infty}^{\infty} g(\omega) e^{j\omega t} \, d\omega
\]

\[
    g(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} f(t) e^{-j\omega t} \, dt.
\]
These are called the Fourier integral transforms, the latter giving the spectral density. We make this switch from the time domain associated with the Fourier series to the frequency domain associated with the Fourier transforms in order to determine the relative prevalence of each frequency within a complex waveform emitted by a guitar. This is a very powerful tool in quantifying the timbre of an instrument.

Figure 6: The Fourier transform of a complex tone, that is a linear combination of sinusoids oscillating at different frequencies, returns a graph with multiple peaks, each with its own amplitude.

2.4 Resonant Frequency & Peak

In constructing pickups for an electric guitar it is important to determine the resonant peak and frequency in order to develop a pickup that bolsters frequencies in accordance with the players desires. The resonant frequency is the frequency for which the power, current, or amplitude of a system is maximized. In the case of an RLC circuit, the resonant frequency occurs in instances of minimum impedance when the inductive and capacitive reactances are equal. Pickups are considered Variable Reluctance Sensors based on their composition (coils+magnetized metal core+permanent magnet). The resonant frequency of the pickup is thus determined based on the unwanted capacitance manifesting between coils and electronic cable connections, and inductances, which we can represent as
\[ f_o = \frac{1}{2\pi \sqrt{LC}} \]

where \( L \) is the inductance in Henries, \( C \) the capacitance in Farads, and \( f_o \) the resonant frequency of the pickup. We may suppress the resonant peak by adding capacitors or resistors in the wiring of the pickup.

### 2.5 Terminology

What do musicians mean when they describe sound with terms such as warm or bright or muddy? How are those misunderstood? How can we create a more rigid and consistent description of sound? Furthermore, there are some confusing aspects of this language; I can describe the sound that your guitar produces as warm, but I might also call your pickup warm/hot which has a completely different meaning.

**Bright**

A tone is considered bright if its composition contains an abundance of higher partials. Brightness is often confused with high pitch, which is an incorrect pairing; the pitch of a tone is not indicative of the tone with which it is played. An electric guitar is at its brightest when played close to the bridge with the tone knobs at their highest settings; in this case the least high frequencies are filtered out.

**Warm**

Warmth is thrown around rather loosely, but more often than not, it directly contrasts brightness. Where brightness is describing a wealth of higher partials, resulting in an almost glistening or piercing tone, warmth describes a tone composed of low and mid range harmonics. Warmth also answers a question of clarity as we tend to use it to describe the
sound of a vinyl played on a record player. Through this logic, it makes sense that newer albums sound worse on record players as they demand a higher level of clarity because of how they are recorded. A guitarist might play farther from the bridge or roll down their tone knob in order to achieve a warmer tone.

**Sharp & Soft**

Sharpness is used in reference to attack although it is often coupled with brightness. Opposite to sharp attack, is soft attack which is achieved in a number of ways. Some jazz guitarists use the rounded edge of their pick instead of the intended, sharp point (you might be able to guess how guitarists achieve a sharp tone from this description). Similarly, classical guitarists might use the flesh of their fingers instead of their nails, which are developed in such a way that a range of dynamics and attacks are obtainable.

**Hot**

Hot, not to be confused with warm, refers the resulting tone of an overwound pickup as well as the effects of this overwinding on the amp the guitar is played through. Overwinding a pickup results in a louder tone, typically increasing the warmth of the sound. More winds equates to more voltage through the pickup and into the amp. A longer cable also leads to more resistance, which might be where this adjective gets its name from, seeing that resistance results in an expulsion of heat.
3 Electronics & Wiring

Guitarists are fortunate to play the electric guitar for it lends them an incredible amount of control over their tone. Aside from being able to influence the sound of their instrument through their playing, they might decide to vary parameters, such as volume or tone, via potentiometers conveniently located below their strumming hand. It is worth acknowledging the effects of wiring a guitar’s pickups in series as opposed to parallel which is the standard. In parallel, the pickups are isolated, each with its own line to the output. On the other hand, wiring pickups in series introduces added volume, for the string is inducing a voltage in both coils, at the cost of added resistance (there is a long path for the current to travel through). These effects will not be deeply analyzed.
3.1 Potentiometers

Potentiometers, colloquially known as “Pots,” allow guitarists to manipulate their instrument’s sound in a definitive and precise manner. Technically they are also referred to as adjustable voltage dividers, which is confusing considering they can affect both current and voltage. Their two main functions are volume and tone control and they manifest themselves on the guitar in the form of rotary dials, although they can appear as linear sliders or trimpots. Most guitars have rotary pots that make, at most, one full revolution, but there exist multi-revolution pots which lend more control and specificity to the user. Pots used to control audio signals often have a logarithmic taper to accommodate for humans’ logarithmic sense of hearing, which means there is not a one-to-one correspondence between the amount the pot is turned and the change in resistance/volume. The first half rotation provides a more gradual increase in resistance compared to the second half, which contributes a quick increase in resistance. Logarithmic pots are not even truly logarithmic, but instead made of two resistance elements to approximate a logarithmic curve. The transition between the two resistances happens about halfway through a full rotation of the pot. Pots are indexed by a number and letter corresponding to the resistance (in ohms) and taper. There two systems in place that indicate taper; the newer system uses ‘A’ and ‘B’ to denote logarithmic and linear taper respectively, while the older system uses ‘A’ for linear, ‘C’ for logarithmic, and ‘F’ for antilog (which is rarely used).

3.2 Capacitors & Filters

Capacitors’ most familiar use is energy storage. However, when used in conjunction with a potentiometer on a guitar, the capacitor acquires a filtering effect. While a volume pot solely constructed of a potentiometer, controls the amplitude of an incoming signal, a tone
pot consisting of both a pot and capacitor in series controls the frequencies which pass through the capacitor to ground. A capacitor connected to a tone pot is aptly called the “tone cap.” The value associated with a tone cap is the capacitance and is measured in microfarads ($\mu F$). In deciding what value tone cap is appropriate for a given guitar, the relationship between capacitance and frequency should be understood. These quantities are inversely proportional to the Capacitive Reactance, $X_c$, defined as

$$X_c = \frac{1}{2\pi fC} = \frac{1}{\omega C}.$$

Notice that capacitive reactance has units of ohms (Ω), hinting that it is in some shape or form, a resistance. Unlike a typical resistor, the reactance works in opposition to a changing voltage, which makes sense since our voltage is oscillating periodically due to an alternating current. Now, consider the relative magnitudes of two capacitive reactances due to $C_i = 0.022\mu f$ and $C_{ii} = 0.047\mu f$, the two most frequently used capacitor values for single coil pickups, and a constant frequency. The lower capacitance begets a higher reactance, thus the $0.022\mu f$ tone cap retains more high harmonics, while the higher value tone cap sends more to the ground.
4 Magnetism

It is necessary to reintroduce and develop some physics from electromagnetism before delving into its applications in the context of the electric guitar’s pickups. I will tackle each component of the pickup by introducing the facet of magnetism that it pertains to before explaining how it works as a whole. The pickup is surprisingly simple for such a profound piece of equipment: the main ingredients being a permanent magnet, six magnetized (or magnetizable) cylindrical pole pieces within a plastic casing known as a bobbin, thousands of turns of copper wire, and a ferromagnetic guitar string. This last component is obviously not directly the pickup itself, but is a necessary constituent in the involved magnetic system. Expounding a derivation of the general magnetic field produced by a pickup offers interesting insight as to how the complex waves produced by this machinery manifest themselves.
4.1 Faraday’s Law

The pickup is an extended example of Faraday’s Law, which is broken into several cases involving loops of wire submerged in magnetic fields. The interesting phenomena occur when movement, namely a velocity, is introduced. Let’s take a loop of wire, partially submerged in a magnetic field, and begin to move it from the field. As we do so, a current begins to circulate the wire. Similarly, if we move the magnetic field from the loop, the same current flows through the wire assuming we move it at the same velocity. Finally, if we were to completely encapsulate this loop of wire in a uniform field and increase the strength of the magnetic field, we would also get a current through the wire.

![Diagram](image)

The pickup works most like the last example. A pickup emits a constant magnetic field in which the coils of wire (in the pickup) and strings are submerged. As the strings are plucked, the vibrations cause fluctuations in the magnetic flux through the magnets, inducing an electromotive force through the coils. The strength of the field is determined by the permanent magnet used. The magnitude of the flux through the magnets is determined by the string’s proximity to the pickup and how hard it is picked. We experience this magnitude as the volume of the sound and amplitude of the waveform.
4.2 Auxiliary Fields and Ampere’s Law in Magnetized Materials

An object producing a magnetic field, $B$, into vacuum does so with relative ease. The magnetic field has no problem moving through vacuum and so the scenario is used as a standard in which the Permeability of Free Space, $\mu_0$, is defined. However, there are many objects and materials that magnetic fields can interact with and consequently, the relative permeabilities of those objects must be taken into account. Unfortunately, the variable $H$ is also called the magnetic field and the two cannot be used interchangeably. To avoid confusion I will use the following definitions: the total magnetic field is $B$, which is easily related to the magnetic field, $H$, (sometimes referred to as the strength) by

$$B = \mu_0 H,$$

when in vacuum. In discussing the movement of a magnetic field through a material, we will use $M$ to describe the field produced due to the bound current, $J_b$, induced in the material when magnetized. The field $H$ is due to the free current, $J_f$, which arises from external sources. Free current is involved with the movement of charge, for example the charge from a wire connected to a battery, while the bound current is due to magnetization. Through Ampere’s Law we may relate the fields and their respective currents:

$$\nabla \times H = J_f$$

and

$$\nabla \times M = J_b.$$
Through defining the total current as \( J = J_b + J_f \), we can further relate the magnetic contributions from each field such that

\[
\frac{1}{\mu_o} B = H + M.
\]

### 4.3 Permeability & Magnetic Susceptibility

We can relate the magnetization, \( M \), to \( H \) and consequently to the magnetic field, \( B \), by the magnetic susceptibility, \( \chi_m \):

\[
M = \chi_m H = \frac{\chi_m}{\mu_o} B.
\]

It is convention to use \( H \) in place of \( B \). Magnetic susceptibility, \( \chi_m \), is a dimensionless term used to quantify whether a material feels repulsion or attraction to a magnetic field. It is used to determine whether a material is para- or diamagnetic as well; if the susceptibility is greater than zero the material is paramagnetic, while diamagnetic materials have a susceptibility less than zero. For linear media, equations that obey the equation (5), it can be shown that

\[
B = \mu_o (1 + \chi_m) H.
\]

Notice that if there is no material in question, \( \chi_m = 0 \), returning us to equation (3). We might further define the permeability as \( \mu \equiv \mu_o (1 + \chi_m) \).

The divergence of \( B \) is zero for it is a magnetic field due to a current. That being said, \( \nabla \cdot H \), where \( H \) is due to a free current, is not necessarily zero. Often the bar magnet
example is used to explain this phenomenon which is convenient considering the bar magnet is an integral component of the electric guitar's pickup.

### 4.4 Ferromagnetism

It would be incorrect to consider the magnetic susceptibility $\chi_m$ and permeability $\mu$ of a ferromagnetic material in the exact manner that we would when concerned with a para- or diamagnet. Within ferromagnets, these quantities are determined by the proportionality between a differential change in $H$ and the resulting change in $M$ and $B$. Therefore, $\chi_m$ and $\mu$ are varying functions dependent on $H$ and not innate qualities of a given material.

The dipoles in a ferromagnet are influenced by their neighboring dipoles, they like to align themselves parallel to adjacent dipoles. In fact, this happens within neighborhoods, or more technically, domains, which are collections of dipoles pointing in the same direction. For most magnetizable objects, the aggregate of domains results in zero field outside the object. Meanwhile, in the case of permanent magnets, the domains are aligned such that they compound and produce a field. By exposing an object to a strong external magnetic field, each individual dipole experiences and resists the consequent torque as they would prefer to remain aligned to their neighboring dipoles. That being said, the dipoles along the boundaries of adjacent domains are not parallel. It is here that the torque imposes its influence, affecting those dipoles whose direction is more parallel to the external field. Over time, favorable domains grow, overtaking those that were not parallel enough to the imposed field.

Eventually these domains engulf the entirety of the object at which point it is deemed saturated. Materials that are easily forced out of this newly magnetized state are considered “soft” magnetic materials, whereas permanent magnets retain their magnetization and are
Figure 7: A series of randomly directed domains exposed to an upwards pointing, uniform magnetic field eventually results in all dipoles pointing along the field.

thus “hard” magnetic materials. The AlNiCo permanent magnets used in guitars are good examples of “hard” magnetic materials, holding their magnetization over decades; even though the strength of the magnet deteriorates over time, the difference in tone is sought after and found in vintage guitars with older magnets. The strings of the guitar are ferromagnetic as well, but at no point reach a saturation point where they can maintain the induced magnetic polarization.

This phenomenon is often expressed via Hysteresis Loops. (Reference Figure) shows the relationship between the magnetization and $H$-field. What is particularly interesting and explicit in this representation is the effect of a magnetized material’s history on its ability to be further saturated. If a magnet was previously magnetized/saturated it requires exposure to a field of specific magnitude in order to re-magnetize or become saturated again. It can be shown that for an object previously magnetized, $|M|$ is valued at $H = 0$, unlike a newly magnetized object which has a magnetization of zero when exposed to zero field.

Hysteresis loops comprise a few key components, namely the coercive force, remnant magnetization, and saturation point. Starting at the origin, we can trace the effect of an increased $H$-field up to the saturation point, which acts as an upper bound for the curve whose slope goes to zero as $M \rightarrow M_s$. Once a material has achieved saturation and is removed from the field, it is left with magnetization, $M_r$, known as the remnant magneti-
zation. The coercive force or coercivity is defined as the strength of field needed in order to return a magnetized material to its original, unmagnetized state. We can qualify materials as hard or soft ferromagnets based on these parameters and the area of the hysteresis curve. A wider curve brings $M_r$ closer to $M_s$, and thus requires a stronger, negative $H$ field in order to undo the magnetization.

4.5 The Magnetic Field due to a Pickup

The motion of the string greatly impacts the resulting voltage through the pickup. I will provide a derivation of the equation relating voltage to the displacement and velocity of a string. The final equation also highlights the other dependencies of the voltage, further informing the specific consequences of varying physical parameters, e.g., the use of thicker guitar strings or lowering the action. The following derivation and figure are largely informed by McDonald’s paper, “Electric Guitar Pickups.”
Figure 9: The pickup lies in the $xz$–plane, with length and depth, $w$. The shaded circle indicates the string’s location after a displacement by $x(t)$ and $y(t)$ from the unshaded rest position. The string has radius $a$ and is separated from the pickup by a distance, $h$. The whole system is exposed to a uniform magnetic field with magnitude $B_o$.

In the case of our pickup’s permanent magnet, we assume the presence of a uniform magnetization such that the magnet only has an external surface current.

$$\nabla \times H = 0$$

Under these specific circumstances, a scalar potential may be defined such that

$$H = -\nabla \phi.$$  

Utilizing the relationship between $B$ and $H$, we can work backwards to deduce the value of the scalar potential. A switch to cylindrical coordinates will also be made, with the origin centered in the middle of the string and the $z$ axis running along the length of the string, parallel to the pickup.

$$H_o = \frac{B_o}{\mu_o} = \frac{B_o}{\mu_o} \hat{y} = \frac{\partial}{\partial y} \frac{y B_o}{\mu_o} \hat{y} = -\nabla \left( -\frac{y B_o}{\mu_o} \right) = -\nabla \left( \frac{-B_o r \sin \theta}{\mu_o} \right)$$
\[
\phi(r < a) = -\frac{B_0 r \sin \theta}{\mu_0} + \frac{A r}{a} \sin \theta \\
\phi(r > a) = -\frac{B_0 r \sin \theta}{\mu_0} + \frac{A a}{r} \sin \theta
\]

Maxwell’s equation \(\nabla \cdot B = 0\) necessitates continuity of the radial component of the field through the surface of the string. Using the limits of \(r\) approaching \(a\) from infinity and zero, \(A\) can be determined in terms of magnetic constants \(B_0, \mu_0,\) and \(\mu_{\text{rel}}\). Starting with \(r\) from the inside of the string, we arrive at

\[
B_r(r = a^-) = \mu_0 \mu_{\text{rel}} H_r(r = a^-) = -\left. \frac{\partial}{\partial r} \left( -\frac{B_0 r \sin \theta}{\mu_0} + \frac{A r}{a} \sin \theta \right) \right|_{r=a} = \left( \frac{B_0 \sin \theta}{\mu_0} - \frac{A}{a} \sin \theta \right) \mu_0 \mu_{\text{rel}} = \mu_{\text{rel}} \left( B_0 \sin \theta - \frac{A \mu_0}{a} \sin \theta \right)
\]

For the flipside of this equation, we evaluate \(r\) from infinity to \(a\) and do not include a \(\mu_{\text{rel}}\) term for we are not inside the string and unconcerned with a magnetic permeability:

\[
B_r(r = a^+) = \mu_0 H_r(r = a^+) = -\left. \frac{\partial}{\partial r} \left( -B_0 r \sin \theta + \mu_0 \frac{A}{r} \sin \theta \right) \right|_{r=a} = \left( B_0 \sin \theta - \mu_0 A \frac{a}{a^2} \sin \theta \right) = \left( B_0 \sin \theta + \frac{\mu_0 A}{a} \sin \theta \right).
\]

Setting these equal to one another, we arrive at \(A\).

\[
\mu_{\text{rel}} \left( B_0 \sin \theta - \frac{A \mu_0}{a} \sin \theta \right) = B_0 \sin \theta + \frac{A \mu_0}{a} \sin \theta
\]

\[
A = \frac{a B_0 \mu_{\text{rel}} - 1}{\mu_0 \mu_{\text{rel}} + 1}
\]

28
With the newly defined \( A \) we might begin to develop the scalar potential outside of the string

\[
\phi(r > a) = \frac{B_o r \sin \theta}{\mu_o} + \frac{a B_o \mu_{rel} - 1}{\mu_o \mu_{rel} + 1} a \frac{r}{r} \sin \theta = -\frac{B_o}{\mu_o} \left( r + \frac{a^2 \mu_{rel} - 1}{r \mu_{rel} + 1} \right) \sin \theta
\]

Now that we have the complete scalar potential \( \phi \), we can ascertain some information about the magnetic field \( H \) and finally, \( B_o \). The gradient in cylindrical takes the following form:

\[
-\nabla \phi \equiv -\left( \frac{\partial \phi}{\partial r} \hat{\mathbf{r}} + \frac{1}{r} \frac{\partial \phi}{\partial \theta} \hat{\mathbf{\theta}} + \frac{\partial \phi}{\partial z} \hat{\mathbf{z}} \right)
\]

where the \( z \) component vanishes since we are working in the \( r\theta \)-plane. Recalling the relation given by equation (2), it follows that

\[
B_o = -\mu_o \left[ -\frac{B_o \sin \theta}{\mu_o} \left( 1 - \frac{a^2 \mu_{rel} - 1}{r^2 \mu_{rel} + 1} \right) \hat{\mathbf{r}} - \frac{B_o \cos \theta}{\mu_o r} \left( r + \frac{a^2 \mu_{rel} - 1}{r \mu_{rel} + 1} \right) \hat{\mathbf{\theta}} \right]
\]

\[
= B_o \left[ \sin \theta \left( 1 - \frac{a^2 \mu_{rel} - 1}{r^2 \mu_{rel} + 1} \right) \hat{\mathbf{r}} + \cos \theta \left( 1 + \frac{a^2 \mu_{rel} - 1}{r^2 \mu_{rel} + 1} \right) \hat{\mathbf{\theta}} \right]
\]

Take note of the quantity \( \frac{\mu_{rel} - 1}{\mu_{rel} + 1} \), which is approximately 1, if we take \( \mu_{rel} \gg 1 \). In the case of guitar strings, which are made of nickel and steel, the relative permeability is on the order of \( 10^2 \) to \( 10^4 \), which legitimates this approximation.

Now that the magnetic field has been established, we can turn our attention to the flux through the coil in the pickup, which lies in the \( xz \)-plane (alternatively, the plane exists for some constant \( y \)). Switching back to cartesian coordinates, we define the magnetic field’s \( y \)-component as
$$B_y = B_r \sin \theta + B_\theta \cos \theta = B_o \left[ 1 + a^2 \mu_{rel} - \frac{1}{\mu_{rel} + 1} \frac{y^2 - x^2}{(x^2 + y^2)^2} \right]$$

where

$$x = r \sin \theta$$
$$y = r \cos \theta$$

From here we solve for the magnetic flux $\Phi_B$ in accordance with $\int \mathbf{B} \cdot d\mathbf{a}$. Since the field only has motion perpendicular to the area of the pickup and is without a $z$ dependence, the flux may be rewritten as $w \int B_y(x, y_d) \, dl$. Integrating over the length of the pickup from $(x - w/2)$ to $(x + w/2)$ at the string displacement height $y_d$,

$$\Phi_B = w \int_{x - w/2}^{x + w/2} B_y(x, y_d) \, dl = B_o \left[ w + a^2 \mu_{rel} - \frac{1}{\mu_{rel} + 1} \left( \frac{x + w/2}{(x + w/2)^2 + y_d^2} - \frac{x - w/2}{(x - w/2)^2 + y_d^2} \right) \right].$$

We can further expand this flux equation by setting $y_d = (y + h)$, effectively returning the origin to the stationary center of the string

$$\Phi = B_o w \left[ w + a^2 \mu_{rel} - \frac{1}{\mu_{rel} + 1} \left( \frac{x + w/2}{(x + w/2)^2 + (y + h)^2} - \frac{x - w/2}{(x - w/2)^2 + (y + h)^2} \right) \right]$$

$$= B_o w^2 \left[ 1 + a^2 \mu_{rel} - \frac{1}{\mu_{rel} + 1} \left( \frac{(y + h)^2 - x^2 + w^2/4}{(x^2 - w^2/4)^2 + 2(x^2 + w^2/4)(y + h)^2 + (y + h)^4} \right) \right].$$

Taking a negative time derivative of the magnetic flux brings about the voltage through the pickup coil, which we simplify further under the assumption that the string fluctuations, $x(t)$ and $y(t)$, are much smaller than the string height, $h$, and dimensions of cross section
of the pickup, $w$. Thus, the voltage is

$$V = -\dot{\Phi} \approx B_0 a^2 w^2 \frac{\mu_{rel} - 1}{\mu_{rel} + 1} \left[ 2x\ddot{x} \frac{3h^2 - w^2/4}{(h^2 + w^2/4)^3} + \frac{2h\dot{y}}{(h^2 + w^2/4)^2} \right]$$

Recall that the permeability, $\mu_{rel}$, is on the order of $10^4$ so we can further approximate the voltage as

$$V = -\dot{\Phi} \approx B_0 a^2 l^2 \left[ 2x\ddot{x} \frac{3h^2 - l^2/4}{(h^2 + l^2/4)^3} + \frac{2h\dot{y}}{(h^2 + l^2/4)^2} \right],$$

where I have changed the variable for the dimensions of the pickup coil from $w$ to $l$ as not to get confused with the angular frequency, $\omega$.

As shown in the above equations, the voltage is explicitly proportional to the strength of the magnetic field from the pickup, $B_0$, the cross sectional area of the pickup coil, $l^2$, and the square of the string radius, $a^2$. But these are dependencies that we could easily intuit!

Of course the magnitude of the resulting change in flux is dependent on the strength of the field.

The interesting phenomena can be found when looking at the $x$ and $y$ terms. Assuming the horizontal movement of the string can be accurately represented by a simple solenoid such as, $x = \sin \omega t$, the resulting $2x\ddot{x} = \omega \sin 2\omega t$ term indicates that the movement of the string parallel to the pickup is largely responsible for even harmonics and not the fundamental, which can be attributed to the perpendicular movement. The voltage can be described in this binary way when we consider the movement as simply sinusoidal, but notice that the form of the voltage is rather complex even for a pure tone. Given the complex waveform describing the actual movement of the string, the voltage would take the form of something
much more complicated.
5 Pickups

Finally, we arrive at a description of the pickup and its various manifestations in electric guitars. While the pickup underwent the bulk of its many structural developments over the course of the 20th century, it has continued to progress in a subtle, more powerful manner. Technological advancements in machinery, especially those in regards to precision, have allowed for great innovations in the quality of sound produced by the pickup. This is highlighted especially well by Fishman’s Fluence series pickups, whose coils are 3-D printed. There are a few major categories of pickups that are worth mentioning due to their impact on construction, sound, and the guitar they are placed within.

5.1 Styles

The most direct and obvious distinction one can make when identifying pickups is whether they are single coils or humbuckers. The descriptor single coil is rather telling, referring
to the one coil of wire around the bobbin. Humbuckers are composed of a set of adjacent pickups, whose magnetic rods have opposite polarity with coils wound in opposite directions. The pickups are organized in this way to remove the 60 Hz mains hum that is emitted by electric equipment due to AC current. Generally, when playing a guitar with single coil pickups, this hum can be heard. In the case of a humbucker, the field produced by the mains wiring induces a current in the each of the coils with opposite orientation, causing them to cancel. Luckily, the opposite polarity of the magnetic poles allows the guitar string to induce currents that work additively, therefore filtering only unwanted noise from external fields.

Figure 10: Single coil pickups are the more familiar of the two, with their slightly slimmer profile and implementation in iconic guitars such as the Fender Stratocaster and Telecaster.

Another characterization of pickups is whether they are passive or active. Passive pickups adhere to the typical pickup composition of a bobbin, magnetic poles, and numerous turns of copper wire. These pickups are exceptional in that they provide a wide range of tones and have an innately high output. That being said, they are more susceptible to external fields and noise, and in overwinding to obtain more output, passive pickups lose a lot of their high end. In order to bypass this tone-output trade off, active pickups were
created. Active pickups require many fewer winds, therefore they are inherently quieter. To circumvent an issue with low output, a small preamp is included to boost the gain. Since the coil is physically smaller, any influence or noise that would be induced by an external field is greatly mitigated. While active pickups seem like the cure-all for noise and volume related pickup problems brought about by passive pickups, active pickups are not as versatile tonally, each model fine tuned for a specific use or genre of music. Therefore, pickup companies tend to develop many variations of each style of pickup in order to cater to the large audience of guitar players.

We may also differentiate between pickups by the type of magnet they use. The most popular magnets used in guitar pickups are AlNiCo, composed of aluminum, nickel, and cobalt. Ceramic pickups were introduced in the late 1970’s as war made cobalt difficult and expensive to obtain, momentarily hindering the rate of production of AlNiCo based pickups. Now, both magnets are used in pickups, offering a wider array of sounds and characteristics.

Figure 11: The stacked humbucker cancels the mains hum through reverse wound, stacked single coil pickups.
The wire that makes up the coil in a pickup is typically copper. This is due to its low resistivity which can be determined through

\[ R = \frac{\rho L}{A} \]

where \( R \) is the DC resistance, \( L \) is the length, and \( A \) the cross sectional area. The resistivity is measured in Ohm-Meters (\( \Omega \cdot m \)), and the resistivity of copper is \( 1.68 \cdot 10^{-8} \Omega m \). It is worth noting that this is not the lowest known resistivity, which belongs to silver with a resistivity of \( 1.59 \cdot 10^{-8} \Omega m \). The marginal decrease in resistivity is accompanied by a large increase in price, so copper remains the more economic/practical choice (Seymour Duncan’s Zephyr line of pickups roughly run $300 for a single pickup and $700 for a set, whereas copper-wound pickups cost somewhere between $70 and $150.). The diameter of wire is indexed by the AWG (American Wire Gauge) system, which labels wires 1-60 with decreasing diameter. The most popular wire gauges for pickups are 42 - 44 AWG (0.0025 in. - 0.0020 in. diameter). Most resources only list gauges up to 40, but the diameter can be determined for a given gauge using the equation

\[ d_n = 0.005\text{in} \cdot 92^{(36-n)/39} \]

where \( n \) is the wire gauge in question.

5.2 Analysis

In order to make quantitative judgements about timbres of electric guitars, I took samples from [insert host of guitar names here]. In taking these samples, I tried to standardize the
process to the best of my ability. Since I am only concerned with the timbral qualities inherent to the pickup, I removed as much of the pick attack as possible. Each of the samples were created by resting the pick on the string before playing (akin to the classical guitar technique ‘rest stroke’) instead of typically picking each string, which introduces a lot of attack and a spike in amplitude at the beginning of the samples that would need to be filtered out. The length of sample does not really matter because the overtone series and composition can be determined from fairly short samples, however, I tried to keep each note played to about 8 - 10 seconds long, or until the note is inaudible. Samples were taken at the typical rate of 44100 Hz, and exported at 16384. All notes played were A2 (110 Hz), except for those played on the Strandberg Boden-Metal 7 and Schecter Damian where Ab2 (105 Hz) was played instead (these guitars were tuned a half step down and have locking tuners which prohibit them from moving too far out of tune). The guitars were played DI (direct input) to remove any influence an amplifier inevitably has on tone.
5.2.1 '96 Gibson Les Paul

Seymour Duncan Invader (Neck)

Seymour Duncan’s Invader pickups are ceramic humbuckers with oversized metal oxide poles and are geared toward hard rock and metal guitarists. While it would have been nice to compare the bridge and neck Invaders for their tonal differences, the wiring on the bridge pickup was poorly soldered, rendering it useless. Of the two, the neck pickup has a slightly lower output and more prevalent low and mid range harmonics. Seymour Duncan’s goal with this line of pickups was to retain as much clarity in a note while not sacrificing the depth and bass heavy tone necessary to play metal. The figure shows that the bass response is certainly there, with the first, second, and third partials exhibiting high amplitudes, but they sneak a few higher partials in for added definition and brightness.
5.2.2 Schecter Damien Platinum-6

EMG pickups are polarizing pickups in the guitar world; their attack and bite are unrivaled in the hard rock community, but fall short in many other genres of music for they lack diversity. They are very high output pickups with an emphasis on sustain and definition for the modern metal player. The Schecter Damien Platinum-6 cleverly integrates both an AlNiCo humbucker in the neck and a ceramic humbucker in the bridge. Of all the guitars sampled, the Schecter had the longest sustained notes of 10 seconds.

EMG 85 (Neck)

The AlNiCo EMG 85 is the loudest pickup in the room, with the pronounced emphasis on the fundamental of all the pickups I've looked at. This is certainly a bass and mid range pickup, and while the AlNiCo saves what little high range it has, the higher partial amplitudes fall off rather quickly after frequencies of 500 Hz.
The bridge pickup is characteristically the more colorful of the two and is intended to be used in lead guitar situations. This is made evident by its larger amplitudes in the mid to high range. EMG suggests pairing these two pickups for a “blistering” tone; when used in conjunction with one another, a large range of harmonics and tones is achievable.
5.2.3 Strandberg Boden Metal 7

The Strandberg Boden series is a special line of guitars for multiple reasons. First and foremost, the Fishman Fluence series pickups are 3D printed instead of wound, which severely reduces any inconsistencies that would come about in a hand wound or machine wound pickup. Like the Schecter Damien, the Boden also contains an AlNiCo pickup in the neck and a ceramic pickup in the bridge. Furthermore, the pickups have two voicings which alter the pickup’s tone and can be selected by pulling the tone knobs out (they act like buttons). Fishman developed these pickups with versatility in mind.

Fishman Fluence Modern Alnico Humbucker (Neck)

While not the pickup with the most distinct fundamental, this neck pickup provides back-
bone with emphasized second, third, and fourth partials while circumventing muddy tone with emphasized higher partials. The AlNiCo neck pickup is incredibly interesting for it has a periodicity about which harmonics are accentuated. Notice that every fourth harmonic is lower than the preceding three throughout the Fourier spectrum.

Fishman Fluence Modern Ceramic Humbucker (Bridge)
6 Constructing a Pickup

6.1 Method

The most difficult aspect of building a pickup is winding the coil. A single coil pickup typically contains 5000 - 8000 turns of wire. Pickup winding machines often cost hundreds of dollars, so my goal was to develop an alternative method. The two DIY methods of winding I entertained were with a drill or sewing machine. I decided to use the sewing machine for a couple of reasons: I was lent a Singer Touch & Sew Deluxe Model 629, which was convenient and fortunate, and sewing machines often have a foot pedal which can control the speed of rotation, which I decided would be helpful in winding the pickup.

The Singer has a bulbous counter-clockwise rotating component on its end that I retrofitted a pickup mount to. This simply entailed routing two holes in its face, one in the center for mounting the pickup and one off to the side as a support. The latter screw was more specifically implemented to oppose the pull from the spool of wire and keep the pickup
as secure as possible while spinning. A screw was fed through the inside of the cap and tightened to the pickup on the outside.

I used a mechanical counter to keep track of the number of winds. The Singer has an arm located at its front that moves vertically for every one wind. I attached the mechanical counter to the arm with three 6 in. cables and a taught spring. The counter was nailed to a set of wooden boards that I sat the sewing machine on. The sewing machine was heavy enough that it required no securing of its own and kept the whole apparatus in place while running. The spool of wire was housed in the box it arrived in, suspended by a drum stick that I pushed through the sides of the box. While this seems like a crude method of creating an axle, I deemed
it satisfactory because it allowed the spool to spin when pulled by the pickup, but was otherwise stationary. I guided the wire by hand when winding to make sure the pickup was wound evenly.

Before winding the pickup, the wire has to be fed through one of two lead holes in the pickup and wound several times. This is where the electric wiring will be soldered after the winding is complete. In the event that one winds multiple pickups to be used in one guitar, it is worth noting the direction of winding and polarity of the magnetic poles in order to successfully cancel hum and keep the outputs in phase.

It is recommended that first time winders use 42 AWG enameled copper wire, which is the thickest wire used for pickups. The wire snaps very easily and is to be wound with significant care. Any jump in acceleration of the sewing machine will result in the wire snapping, so a gradual increase in acceleration is suggested. If possible, it is best to wind the pickup in one attempt, that way there is little time for the pickup to unfurl. Any extra space between the wire will result in a larger capacitance.

In some cases, engineers 3D print or create their own bobbins, but seeing that I was not interested in the effects of bobbin construction, I purchased a bobbin with AlNiCo 2 rod magnets polarized such that north was pointing up.
6.2 Failed Procedures of Analysis and Production

The initial plan was to vary physical parameters, such as distance between the string and pickup as well as rotation of the pickup while at a fixed distance from the pickup, and measure their effect on the output and waveform from a plucked string. This was done using a wooden monochord (while the monochord actually had three strings, only one was ever plucked) and a pickup from a very cheap, Dean electric guitar. The monochord was outfitted with a makeshift bridge and support system similar to an acoustic guitar. The scale length was set to 25.5 in. which is the scale length of most electric guitars, and more specifically, the Telecaster. I decided that all samples taken would be of plucked A strings, so the monochord string was tuned to A2, or 110 Hz. Ten samples were taken at with the pickup located under the second, third, fourth, and fifth harmonics. I tried to pluck the string as consistently as possible throughout the samples and made sure I was accurately plucking at each given harmonic. The samples were taken in the music editing software Audacity; Audacity can conveniently take the FFT (fast Fourier transform) of any audio sample and export the dB vs. frequency data as a .txt file. I was to average the frequency
data from the FFT’s, but had problems exporting the data due to a low sample rate. Unlike other recording software, Audacity’s default sample rate is not 44100 Hz. While it would have been nice to determine the effects of pickup distance empirically, the derivation in Chapter 3 is more effective in communicating the voltage’s dependence.

While the information provided in Chapter 5 is insightful, a minor lapse in judgement rendered most of it useless for my purposes. The goal was to build a set of passive pickups, and the data taken from various electric guitars was meant to inform this building process; the problem that arose was that many of the guitar samples were taken through active pickups. This means the correspondence between output and number of turns of wire in the coil is different from my creation. Furthermore, the overtone series of a given note and the tonal range/versatility of each pickup is in a way unique to that pickup.
Thus, the information I can ascertain and use from each guitar is very small. That being said, data from a host of diverse guitars with active pickups in conjunction with a couple guitars containing passive pickups highlights the wide range of tones that can be expressed with an electric guitar. Moving forward, I hope to take more thorough measurements of each instrument before sampling. Given more time with each instrument, I would determine the locations of the harmonics with respect to each instrument’s scale length and pickups, in order to analyze the compounding effects of the pickup placement and resonant frequency.

The pickup winder was nearly successful, but could not produce a pickup for the following reasons. First, I overestimated the integrity of the plastic that the pickup was mounted to. As pickups were mounted and remounted, the hole that I made for the screw became stripped making it more difficult to secure the pickup to the cap. This is what influenced me to change how I was mounting the pickup to the cap (from the inside rather than the outside). Secondly, the Singer is fairly old and is not very precise in its acceleration with
the foot pedal, so even when pushing the pedal with the utmost care, the cap would make large jumps in rotational speed, causing the wire to snap. While the wire was secured rather haphazardly upon a drumstick, I do not believe that it greatly contributed to the failure of this approach. In future attempts, I hope to stabilize and secure the pickup better as well as find a newer sewing machine that rotates more cleanly.

Figure 14: Pickup mid-wind
References


[17] EMG: 81,
   http://www.emgpickups.com/81.html#info

[18] EMG: 85,
   http://www.emgpickups.com/85.html#info
