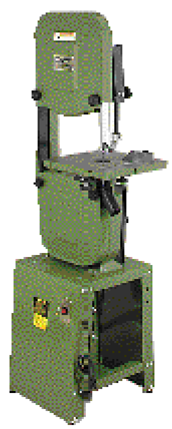
Rincon Ridge Guitars

So you want to build a Guitar

Some of these machines can cripple and mane a person in the blink of an eye. If you use any of the equipment, you are responsible for any medical needs you may encounter.

Now if that doesn't scare you off, here is some of the equipment that is needed to build a guitar:



Introduction

A Guitar has just a just a few parts

- Tuners
- Nut
- Neck
- Fret board
- Pickups
- Bridge (saddle)
- Tail piece
- End pin
- Jack
- Potentiometers
- Switches
- Electronics
- Buttons
- Pick guard

Electric Guitar is the easiest to build, and that is not an easy task. Depending on your woodworking skills, it may be best to start with a kit and not try to do one from scratch. Routing and shaping the body alone can take months to get the shape and smoothness you want.

Kits

The kit usually comes with all the parts necessary to put together your guitar. You will still have to finish and do the final assembly, not to mention all the little tweaking to get your new guitar ready to play. Here are a couple of pictures that represent the kits available:

As you can see, most of the hard work is done for you. Kits range from $80 to well over $500.00 depending on what brand and where you get it from.

Guitar making is an ART, not just a hobby. Ask Rick after his third bass guitar. Even though you may have higher goals, you may want to start with a basic kit and cheapest cost. There is no training other than experience, so if you get a low end unit to "practice" on you won't be out too much for the initial mistakes you make. Oh yes you will. Everyone makes mistakes and the more expensive the wood, and components the more expensive the mistake can be. There is nothing wrong with starting out building a kit, then once you get a feel for the building, assembly and adjustments, then move on to a more complex build. Everyone has to start somewhere.

Scratch built

This is the most complex build. Here is a picture where you get started:

Yup, just about. Cut down the tree and start to fashion the body. Yes, this tree can be a new guitar. Get the saw Martha; I got work to do…

Semi-Scratch

This is the method that Rick and Doug are doing. They purchase the neck and build the body from scratch. Research is underway to build necks, but that may still be some time in the future.
Here is the starting pieces for a semi-scratch guitar:


That is it. The neck can run anywhere from $35.00 to $400.00+. Again if this is your first build, start out with the cheapest you can find for all your parts and then build up to your goal.

Uncle Willie on Guitar Building

First, eBay is absolutely a wonderful source of parts. In fact, about anything you can imagine when it comes to guitars can be found right here on good old eBay. It can take some patience and a fast Internet connection is nice, but it's pretty much all here. Before eBay, this hobby was pretty limited, with a handful of merchants and you had to take what they had. Not so these days.

1) You can build an excellent electric guitar from parts you gather up. Like a hunter from the Stone Age, you will begin the hunt by first deciding what style you want. No sense in looking at auction after auction unless it's the style you like, right? Unless, of course, you enjoy that kind of random browsing. At my age, I find it tedious, but hey, I may not have many years left! Write it down, keep a list of what you know you need and be organized. Ask the sellers questions. Most all are helpful folk that know the guitar biz. I mean, to sell these goods, you really, really need to know your product. Novice builders have a lot of questions and when you ask a question of a seller, expect an answer, but give them a little time to respond. Never ask a technical question at an odd hour 5 minutes before auction end. Believe it or not, many of us sellers work regular business hours and do sometimes take a Sunday off.

2) But you ask, "Uncle Willie, what are the secrets?" Well, there are no secrets. The first advice I give you is, TAKE YOUR TIME. Once you are satisfied that you have gathered the list of parts you made up and they are all compatible with each other...don't just sit down and expect to slap a guitar together and have it come out perfect. Not going to happen, unless you are really lucky. Pay attention to little things that can become big problems. Like what? The scale of the neck and body must match. You should not try and install a 24.75 scale neck on a 25.5 scale body. Make sure the neck pocket in the beautiful body you bought will accept that neck without protest. Sure, you can always modify stuff on the fly, but when you do your first or second build, spend the time it takes to get compatible parts. Unless you are a great woodworker.

3) You can also get EXACTLY what you want. When it's done, it's like a car or a motorcycle; you have made it your own. It's a one of a kind in many cases. If you've done it right, your friends will bow down to you.

4) How excellent? You can build a guitar for under $350 that can rival a $3000 guitar. How's that possible? Well, it's all in the details and the patience you are willing to take to get it done. Take installation of a neck. Sometimes, you may need to shim a neck to get a good back angle that just gives you that little extra bit of low action; a piece of sandpaper close to the end of the neck gives you some extra back angle. Not a lot extra, but with instruments, less is sometimes more. You may need to install that neck two or three times to get it right. You may not need to shim it at all. Who knows? The point again is Patience.

5) But, Uncle Willie, that neck I got for a great price is a nice neck, but the screw holes in the great body I snagged just don't line up. So what? Get some dowels near the size of the neck screw holes, a drill and a bit that's about the same size as the holes and some good wood glue. Carefully drill down into the holes, don't drill to far, squirt some wood glue down in there, cut the dowels about the right length, insert into holes, let dry a day or two, cut off the excess dowel wood, sand smooth and use that great body as a template for the new holes. Voila. Pat yourself on the back.

6) It's absolutely a wonderful hobby. In fact, I've had customers over the years that turned it into a good business. You are not going to be able to quit the day job immediately, but I guarantee that it's not as hard as becoming a Rock Star. No matter how far you take it, it is always satisfying, frustrating, relaxing, and cool to tell your friends and family about, cheaper than building your own motorcycle, a great learning experience and all of this at the same time.

I'm going to end this little article with this. I love guitars. They will never let you down, they do what you tell them to do, they come in an endless variety of choices, they will be your friend forever, with care, they will last forever, you can pass them along to your kids or grandkids, they curve like a woman's shape, they are as good as your own talent and dedication, they can go wherever you go, other people love to hear a good player, they will make friends for you and with luck and real dedication, they can make you famous. What else is there that can do all that..?

Uncle Willie on Guitar Wood

On Guitar Wood...no pun intended, but I'm going against the grain here. A hardwood solid body electric guitar is not substantially different from one wood to the next. Yes, don't drop your teeth. Swamp ash, Maple, Koa, Mahogany, etc, is not going to have any substantial difference in tonality. But, Uncle Willie, you have totally flipped out now! Well, as I said, it's my opinion. It may not be yours. My point is this. The days of the lone guitarist playing straight thru a single cable are long gone. In most cases, now a days, you are running a modeling amp, you've got effect units in the signal path, you are running thru a computer, get the picture? You can make anything sound like anything you want in other words. How does wood come into play? Well, for one thing, different woods cost different money. So, it must stand to reason that the more expensive wood is the better sounding wood; the better resonating wood. Give me a break. As well, that fancy flame top does nothing to improve things. Let's go back in time and examine the Guitar Gods of the past; what do they tell us? Technique, style and dedication to the instrument make the difference. More expensive and exotic wood is not going to make you a better guitarist. It will give you some bragging rights, sure. (My apology to you players that do in fact, use just a guitar and an amp with just basic controls)

On guitar finish…ditto. A Hardwood solid body electric guitar does not substantially change from good to better based on a poly or a nitro finish. Sorry, it just is what it is. Several years ago, we put this to the test. Took an unfinished mahogany body and the same body with a nitro finish; set both up with the exact same neck, same hardware, exact same electronics, plugged into an a/b switch and straight into a single amp. Switched between the two, left all settings exactly the same. Guess what? Nobody in the room heard any difference.

Point is, if it gives you pleasure, go with it, certainly. But don't expect a major miracle; you want the best your instrument can provide, it's in your fingers. Not in a magic voodoo combination of woods and finishes.

Uncle Willie on Pickups

Let me establish first and foremost, that these are my opinions. Based on 35 years of building, selling, modifying, customizing, etc., you are reading one old man's opinion.

There is a seemingly endless variety of pickups out there for electric guitars. You can spend some major money on these things. So what are you paying for exactly? And, what makes them work? How did they get those crazy names?

1) The name. With anything these days, the name makes a big difference. After all, somebody has to pay for the marketing campaign and the fancy packaging. Guess who pays?

2) The output. Traditionally, the higher the output, the higher the price. Why is that? I don't know. There are a couple of ways it's done. Some high-output pickups get to be high output by using stronger than normal magnets. I never liked this concept. Why? The stronger the magnet, the less sustain you'll have. You see, a strong magnet will actually attract the strings, thus causing the string vibration, which is what the pickup picks up, to be damped or slowed down by the magnet. If you don't want much sustain, then that's OK. If you like sustain, and who doesn't, then it's not a good thing. Another method, which may be a bit more common, is adding more turns of the copper wire used in pickup manufacturing which will, essentially, increase the voltage generated by string vibration. Downside? Yes...of course...the more wire, the more likely chance of hum, since this also affects the resistance and impedance. This is not an electrical class, so if you want to learn about resistance and impedance, GOOGLE.

3) Humbucker or Single Coil? One issue that has always been with us as it relates to a single coil pickup is hum. Depending on the actual AC (wall outlet) frequency, as well as the actual signal from your strings, you are going to get some hum. You are going to get more the hotter the output is. The simple explanation for this is the pickup is acting as a transformer. Thus, Grasshopper, the lower the outputs of a single coil, the cleaner it's going to be. That's without adding fancy and equally expensive measures to counteract the hum. But, Uncle Willie, this flies in the face of what we thought was conventional thinking. Yes, it does, so sorry. If you want the cleanest, least cost way to get that single coil Bright and Crisp tone, use low output pickups. Period. Don't get hung up on the hype, folks. Go back in time to the Guitar Gods of the past once again and take a lesson. One final note, on a 3 single coil guitar, in many cases, the middle unit is reverse wound, so when you switch to the neck and middle pickup, or the bridge and middle pickup, you are mimicking a Humbucker. This brings me to the Humbucker. Way back in the stone age of the 1950's, yes, I was around back then, two guys tried to figure out a way to overcome the hum, Seth Lover and Ray Butts. These dudes evolved the guitar massively, yet you probably did not even know their names, right? A regular old Humbucker uses two coils, instead of one (as in single coil). Both coils generate a signal from the string. The coils work in series. The difference is, the coils are reversed. In technical terms, this means reversed polarity and reverse wound. Don't worry about the technical aspect. This concept is also exactly why a Humbucker is Warm and Fat sounding. Warm and Fat, as opposed to Bright and Crisp. The simple concept is hum and interference is greatly reduced due to a concept called rejection. In a nutshell, these two coils greatly cancel out the hum.

An interesting side note on Humbuckers. Although the traditional unit is a side by side coil design, we do now have "stacked Humbuckers", where the coils are mounted on top of each other, thus preserving the look and size of the traditional single coil.

It all boils down to this. Lower output = cleaner pickup sound. Single Coil = Bright and Crisp. Humbucker = Warm and Fat.

No matter how many flavors and how much it cost, it still comes down to the same simple concepts that have been with us since the invention of an electric guitar. I'm going to save my thoughts on Rail Humbuckers, Coil splits, Coil taps, and some other esoteric designs for a future article.

So, until next time, keep practicing, because that where the REAL difference in guitars takes place. It's all in your fingers.

Internet Links

All Parts (www.allparts.com) – Name says it all.
Stewart-MacDonald (www.stewmac.com) – Everything at a reasonable price and quality
Allied Lutherie (www.alliedlutherie.com/index.html) – High quality products.
Warmoth Direct (www.warmoth.com) – Everything you need (a little pricy)
WD Music (www.wdmusic.com) – Wide range of prices and quality (some kits)
International Luthiers Supply (www.internationalluthiers.com) – Kits, Parts, Services
Luthiers Mercantile International (www.lmii.com) – Wood and tools
Project Guitar (www.projectguitar.com/ref/supply.htm) – Links to parts and supplies
Mighty Mite (www.mightymite.com) – High quality parts (no kits)
Martin & Co. (www.martinguitar.com/index.html) – Great acoustic kits ($350.00+)
Moses Graphite (www.mosesgraphite.com/products.html) – Necks (high price)
EBay (www.ebay.com) – Lots of stuff

Basic Guitar Set-up 101
by
Charles Tauber, Copyright þ1996

"Things should be made as simple as possible, but no simpler." Albert Einstein

Introduction

Many of the techniques and much of the theory which I have outlined below is based upon what I have learned from those generous enough to share with me what they knew. The techniques I have described are only one way of doing things; there is no one right method, though some methods are quicker and easier than others. What is more important than rigidly adhering to a set of techniques is to understand the theory behind the techniques. Understanding the theory provides you with a basis for separating the facts in guitar set-up from the abundant mythology. Once you understand what you are trying to accomplish (the theory) you can adopt, or adapt, specific techniques for accomplishing each task.

While the following discussion strictly applies to steel string acoustic guitars, the basic theory is the same for classical and electric guitars, as well as a wide variety of other fretted string instruments.

The Four Adjustments

There are four, and only four, basic, universal adjustments that affect the playability of every guitar. These are as follows:

- Adjusting the amount of relief (or "bow") in the neck
- Adjusting the string height at the saddle
- Adjusting the string height at the nut
- Adjusting the intonation.

These four adjustments are what I refer to as "basic guitar set-up".

In contrast with "repair" work, which is work that may need to be performed on a specific instrument in order to maximize the playability of that particular instrument, set-up work is a series of adjustments that need to be performed at least once on every guitar. Very few manufactures take adequate time to properly perform these adjustments. Even when manufacturers do, the set-up is very general and aimed at the "average" player, rather than the specific preferences of an individual player.

Neck Relief

When reduced to its simplest, the mechanics of the guitar is little more than the mechanical amplification of vibrating strings which are stretched across a (semi) rigid structure. To understand guitar set-up, it is helpful to know a little about how the strings vibrate and the structure which maintains their tension. The tension on the strings is maintained by fixing and supporting each end of the strings, one end at the head and the other at the bridge. While at rest, due to the tension imposed upon each string, each string forms a nearly perfect straight line between its end-supports - the nut at the head and the saddle at the bridge. For a guitar, the vibration of a string is initiated by first displacing the string from its rest position - the straight - line position it assumes while it is at rest and under tension - and then releasing it. The elasticity of the string, and the tension imposed upon the string, causes the string to overshoot its natural rest position until it reaches nearly the same displacement in the opposite direction. Due to a "loss" of energy with each overshoot, the amplitude of the string diminishes ("decays") until it eventually returns to its rest position.

The general shape assumed by the vibrating string is that of a shallow curve that begins at one end of the string, is a maximum at the string's mid-span, and ends at the other end of the string. Thus, there is no displacement of the string at the nut or saddle, and there is a maximum displacement near the 12th fret, the string's theoretical mid-point. The amplitude of a vibrating string depends upon several factors including string tension, string material and the initial displacement of the string (i.e. how heavily the string is plucked or struck). The same set of strings when tuned below concert pitch will have greater amplitude than when at pitch. Similarly, a lower tension string (such as "silk and steel", or light gage), when tuned to pitch, will have a greater vibrating amplitude than a higher tension string (such as phosphor bronze, or medium gage) tuned to the same pitch. Any string type will have greater amplitude if struck harder (i.e. given a greater initial displacement). Thus, the amplitude of the vibrating strings will vary depending upon the type and gage of strings used and the player's "style" of playing.

To accommodate the amplitude of the vibrating string, there are two options: either raise the height of the strings (the "action") sufficiently that the bottom of the vibrating strings do not touch the tops of the frets, or make the top of successive frets assume the shape of the vibrating string. The string height can be minimized by doing the latter, which reduces the distance that the strings must be depressed for fretting. This, in turn, makes the guitar easier to play.

Practically, the way in which the tops of successive frets are made to conform to the amplitude of the vibrating strings is to introduce a slight curvature to the neck. This curvature, which is a slight upwards concavity, is usually referred to as neck "relief". The amount of neck relief required depends upon several factors, including string height, and, of course, string amplitude. If the string height is sufficiently great, no neck relief is required; the vibrating strings will clear the tops of the frets regardless. This, however, increases the distance that the strings must be depressed, which makes the guitar harder to play. (Depressing a string against a fret stretches the string, increasing the tension imposed on that string. The more the string is stretched, the greater the tension; the greater the tension the greater the force required to depress the string further.)

Since the amplitude of the vibrating string depends upon the type and tension of strings used and the "attack" used to displace the strings, the amount of neck relief must also depend upon these same factors as well as the individual preferences of the player. While there is no one universally correct setting for neck relief which accommodates all the variations of these factors, as a general guideline, approximately 1/64" or 1/32" of relief is typical. This is generally measured at a fret that is at the mid-span of the neck (typically the 7th fret) and is the distance from the top of the fret to the bottom of a string when the string is fretted at the first fret and at a fret where the neck joins the guitar body, typically the 14th fret. By simultaneously depressing a fully-tensioned string against the first and 14th fret, the string forms a straight edge spanning the first and 14th frets. Alternatively, a metal straight-edge can be laid along the fingerboard (on top of the frets) and the distance measured from the top of the 7th fret to the bottom of the straight edge.

For a guitar equipped with an adjustable truss rod, adjusting the amount of neck bow is quite simple. While there are a number of designs of adjustable truss rods, each shares the same basic principles of operation. Specifically, when a threaded nut is tightened on a threaded metal rod, the resulting tension in the rod alters the curvature of the neck in which the rod is embedded. Adjustment of the rod involves tightening or loosening the nut on the rod. Tightening the nut increases the tension in the rod, and consequently increases the amount which the rod counteracts the pull of the strings, thereby reducing the bow in the neck.

The truss rod nut may be located at either end of the rod, at either the guitar's head or from inside the soundhole. At the guitar's head, the nut is often concealed under a small plastic or wooden plate, fastened with small screws. From the soundhole, the truss rod nut may be directly accessible through a hole in the cross brace, or may be located at the heel block, often accessible only by completely loosening the strings. To tighten or loosed the nut, you will require either an Allan key or specialized socket wrench. (Standard Allan keys are available at most hardware stores and specialized socket wrenches for this purpose are available for several dollars from luthier supply houses. Some manufacturers will include an appropriate wrench or key, particularly if they use a non-standard arrangement (i.e. Larrivee).)

Since the amount of string tension imposed upon the neck changes the curvature (bow) of the neck, whenever possible, the adjustment should be done while the guitar strings are at full tension. Where this is not possible (i.e. some Fender electric guitars) it is an iterative process in which an adjustment is made with no string tension and then the measurement is taken after the strings are returned to full tension. This is repeated until the adjustment is correct. The required number of turns of the nut depends upon the amount of bow in the neck, the truss rod design and its installation. Regardless, the adjustment required rarely exceeds one or two full turns of the nut, and is often less than one. Usually, the truss rod nut is tightened by turning clockwise and loosened by turning counter-clockwise.

In addition to this adjustment, it is often helpful to sight down the neck - from nut to soundhole - to observe the "trueness" of the fingerboard and identify any frets which may not be fully seated. A true fingerboard is one which has no bumps or hollows along its length (i.e. is "flat"). For guitars with a joint between the neck and the body, it is a common fault to have a hump in the fingerboard just beyond the joint, typically beyond the 14th fret. The truer the fingerboard, the lower the string height can be set prior to the strings buzzing against the frets.

For guitars with either no adjustable truss rod, or that have sufficiently untrue fingerboards, the remedy is the same; remove the frets and dress (true) the fingerboard, followed by refretting. This procedure is "involved" and takes a skilled repairperson several hours to complete; adjusting the truss rod is a trivial adjustment that can be performed by the layperson in minutes. Hence, truing of the fingerboard will not be discussed in this article.

It is very important to understand how changing the amount of bow in the neck affects the height of the strings relative to the tops of the frets. Ideally, from the point of view of ease of playing, the guitarist desires the fingerboard surface to be straight ("true") along its length and parallel (or nearly parallel) to the bottom of the guitar's strings. This would result in the strings maintaining a constant distance above the fingerboard along the fingerboard's entire length. This, in turn, would require a uniform effort to depress the strings and would provide the greatest ease of playing.

If a curvature (bow) is introduced into the fingerboard (and neck), the strings will no longer be a uniform distance from the tops of the frets; some places along the string will be closer to the frets, while others will be farther away. If the curvature is concave upwards ("bowed"), the strings will be at their maximum height above the tops of the frets at the mid-span of the curve. Conversely, if the curvature is concave downwards ("back-bowed"), the strings will be at their minimum height above the tops of the frets at the mid-span of the curve. The characteristic symptoms of an overly bowed neck are a high action at the nut that becomes higher around the 7th fret. The characteristic symptoms of a back-bowed neck is fret buzz in the middle frets, around the 7th fret, and buzzing of the open strings against the first fret. Often, action exhibiting either of these characteristics is a result of an incorrect neck bow, and is "fixed" by adjusting the bow in the neck.

It is important to note that the curvature of the neck affects the string height at both the nut and at the middle frets. It is, therefore, essential that the correct amount of neck bow be set prior to any adjustment of the string height at the nut or saddle. While the amount of bow affects the string height, it should never be used to specifically attempt to adjust the string height at either the nut or saddle. Adjusting the amount of neck bow is a separate adjustment that must be made prior to and independent of adjusting the string height at the nut and saddle. This cannot be over emphasized. First set the correct amount of bow in the neck, then, once it has been set, leave it at that setting and then adjust the string height at the nut or saddle, if necessary.

Adjusting the String Height at the Saddle

The saddle height can be adjusted either before or after adjusting the string height at the nut. My preference is to adjust the string height at the saddle prior to adjusting the nut.

Begin by measuring the distance from the top of the twelfth fret to the bottom of the sixth string while all of the guitar's strings are at full tension. I prefer to make this measurement by laying a 6 inch ruler, on edge, adjacent to and parallel to the string. The ruler is supported at one end at the twelfth fret and along its length by the adjacent frets, eleven, ten, nine, etc. The ruler I use is calibrated along its end - as well as along its length – and conveniently measures the distance from the top of the twelfth fret to the bottom of a string. Any similar method which measures the distance from the top of the twelfth fret to the bottom of the string can be used. Repeat for each remaining string.

Although the ideal string height depends upon the preferences of the player and the type and construction of the guitar, a typical "good" playing string height ("action") for a steel string acoustic guitar is about 3/32" at the sixth (bass E) string and about 5/64" at the first (treble E) string, as measured from the top of the twelfth fret to the bottom of the strings. The intermediate strings increase in string height gradually from the first to sixth strings. The increase in string height from one string to the next accommodates the increase in vibrating amplitude that accompanies the increase in string diameter. Due to the type of music played, the materials from which the strings are manufactured, the string tensions used and the type of guitar construction, classical guitars have a higher action, while many electric guitars have a lower action.

There are only three possibilities for the measured string height: the strings are at the desired height, the strings are higher than desired or the strings are lower than desired. In the first case, no adjustment is required. Each of the other two possibilities are discussed below.

STRINGS TOO HIGH

Using elementary geometry, it can be shown that a change in the string height at the twelfth fret requires about twice the amount of change at the saddle. For example, if a string height measured at the twelfth fret is 4/32", and the desired measurement is 3/32", the change in height at the saddle necessary to lower the string by 1/32" at the twelfth fret is about 2/32".

Using the measurements taken, calculate the amount that each string needs to be lowered at the saddle. Measure the amount of saddle height that is projecting above the top surface of the bridge. The saddle must project at least 1/16" from the top of the bridge. This ensures that the strings exert a sufficient downward force on the saddle to prevent the strings from vibrating side-to-side on the top surface of the saddle. The side-to-side vibration often causes a string to rattle or be muted. If the 1/16" projection can not be maintained, a neck reset or shaving of the bridge may be necessary, both of which are jobs for either the professional repairperson or the skilled amateur.

As an optional next step, you may wish to mark, using a pencil, the location along the saddle at which the strings cross the saddle. Completely loosen all of the strings and remove the saddle from the bridge, noting or marking at which end of the saddle is the first string. Although the saddle should only fit snugly, but not tightly, its removal can often be facilitated with a pair of pliers. (Saddles should never be glued to the bridge.)

Most steel string acoustic guitars, as well as most electric and some classical guitars, have the top surface of the fingerboard domed or arched across its width. (Many players find a domed fingerboard easier and more comfortable to play.) To achieve the correct height of each string, the contour of the top (bearing) surface of the saddle will generally follow the same curvature as the surface of the fingerboard. However, to accommodate the slight increase in string height towards the bass strings, the saddle contour deviates somewhat from the contour of the fingerboard.

From the top surface of the saddle, measure, and mark with a pencil, the calculated reduction in saddle height required for each string. A smooth curve can be drawn through the pencil marks on the face of the saddle. Clamp the saddle in a vise and remove the excess saddle height with a file, filing to the drawn line. When this step is correctly completed, the top (string bearing) surface of the saddle will be flat across its width and curved along its length.

A string supported by a relatively large, flat bearing surface will tend to vibrate from side to side over the width of the supporting surface. This causes the string to vibrate against the supporting surface, resulting in either a buzzing sound or a muted string. To prevent this, the width of the top surface of the saddle must be reduced by chamfering the top edges of the saddle and rounding the remaining surface. Premature string breakage at the point of contact of the saddle is the result of rounding the saddle to too sharp a point (too small a radius). Creating too extreme a point also results in premature wear of the saddle; a string will quickly wear a notch into the top of the saddle. Except in very certain circumstances, a guitar saddle should not be notched to accommodate the strings. A notched saddle is often the cause of poor intonation, buzzing and muted strings.

In addition to the importance of correctly shaping the top of the saddle, it is also very important to accurately locate where each string is supported, or "breaks", across the width of the saddle. Accurately locating where each string breaks over the saddle and shaping of the top surface of the saddle are discussed below in the section entitled "Setting Intonation". Upon completing the shaping of the saddle, the saddle is returned to the bridge and the guitar retuned.

STRINGS TOO LOW

If the strings are too low, either a new, taller saddle can be made or the height of the existing saddle can be raised using shims. In making a new saddle one begins with an oversize saddle-blank, and the process of completing the saddle is very similar to reducing the height of an overly tall saddle, as described above.

Materials for shims can be plastic, wood, metal or paper, although I generally use wood veneers of maple or rosewood. Shims are cut to the width of the saddle, and are stacked underneath the saddle in the slot in the bridge. Placing shims beneath a saddle reduces the amount of the saddle that sits within the slot in the bridge. Effectively, the depth of the slot is reduced by the thickness of the shims, which places a practical limit on the amount that a saddle can be shimmed. Ideally, a minimum of half of the total height of the saddle should be within the slot, with the remainder projecting above the top of the bridge. Provided that the saddle is the correct width for the slot, this ensures that the saddle is adequately supported and prevents the saddle from leaning under the pressure applied by the strings.

Some guitars are fitted with a saddle design which readily allows the saddle height to be adjusted. Generally, these arrangements consist of a saddle suspended between two threaded posts, the height of which can be adjusted using a screw driver. While this arrangement makes it relatively easy to adjust the saddle height, it has a number of significant disadvantages, which explains why it is not more commonly used.

Adjusting the String Height at the Nut

Once the neck relief and the string height at the saddle have been correctly set, the string height at the nut can be adjusted, if necessary. At the nut, each string sits in a slot cut into the top surface of the nut. The purpose of the slots is to maintain the spacing of the guitar's strings and, in guitars without a "zero fret", to maintain the height of the strings at the nut. The first thing to determine is whether or not the string height at the nut requires adjustment. There are a number of ways of doing this, some qualitative and some quantitative; I prefer to use qualitative methods. Quantitative methods, which I will not discuss in detail here, involve using feeler gages similar to the way in which they are used in setting the string slot depth, as described below.

Qualitative methods, by definition, involve determining by feel, rather than measurement, whether or not the strings are too high or if they are too low. To begin with, check that the string height at the nut is not too high. The criteria used to determine if the string height at the nut is too high is that the effort required to fret any or all strings at the first fret should not be greater than the effort required to do so at any other fret. One test of this is to play a barre chord at the first fret and at, say, the seventh fret. If it requires more effort to apply the barre at the first fret, then the nut is too high. (Recall that since you have already adjusted the bow in the neck and the string height at the saddle, the string height beyond about the third fret should already be as low as you prefer it.) Another test is to compare the amount of effort required to depress a single string against the first fret with the amount of effort necessary to depress the same string at the second fret while the string is still depressed at the first fret. This can be done by fretting a string at the first fret with the first finger of the left hand then, without lifting the first finger, depress the same string at the second fret with the second finger of the left hand. Compare the effort required in each case. If more effort is required to fret the first fret, the string height at the nut is too high.

Next, provided that the string height at the nut was not found to be too high, it is necessary to ensure that the string height at the nut is not too low. The usual symptom of a nut being too low is that an unfretted string will vibrate against the first fret when the string is plucked. This results in a buzzing sound.

Qualitatively, the ideal string height at the nut is one in which if you pluck each open string slightly harder than you would during normal playing, the open string will just begin to vibrate against the first fret. To check that the strings are not too low, individually pluck each string quite firmly; the string should just begin to buzz when plucked slightly harder than it would be during normal playing. If it won't buzz at all, the strings are probably higher than they need to be; if it buzzes at less than normal plucking force, the string height at the nut is too low.

LOWERING THE STRING HEIGHT AT THE NUT

If you found that the string height at the nut was too high, the following method can be used to reduce that height. The string height at the nut is usually measured adjacent to the nut as the vertical distance from the surface of the fingerboard to the bottom of the string. Quantitatively, the ideal string height at the nut for each string is the minimum height above the fingerboard that just allows that vibrating string to clear the first fret. Typically, this is several thousandths of an inch greater than the height of the first fret. Any higher than this and the string is unnecessarily difficult to depress; any lower and the string vibrates ("buzzes") against the first fret. Thus, the ideal string height at the nut depends upon the height of the first fret and the amplitude of the vibrating string (at the first fret). Since the height of the fret wire varies from one manufacturer to the next, and the amplitude of the vibrating string depends upon the player's attack and the type and tension of strings used, there is no universally correct dimension for string height at the nut. Instead, it is necessary to set the string height at the nut based upon theory, the particular preferences of the player and the particulars of the individual instrument.

The method described below for adjusting string height at the nut is very similar to that given by Dan Erlewine in his book "Guitar Player Repair Guide". The tools necessary for this adjustment are a short straight edge (ruler), a standard set of feeler gauges and either a set of calibrated nut files or an X-Acto saw and a tear-drop needle file. Feeler gauges are thin, accurately calibrated metal strips that are used for gauging the size of a gap. The feeler gauges need not be a special set; they can be obtained from any auto-supply or hardware store or purchased from a luthier supply house. Nut files are special files that are manufactured to cut a round-bottomed slot of a particular width. Although a complete set of nut files includes widths ranging from .010" to .058", a "starter" set consisting of .016", .025" and .035" widths is quite adequate. While nut files are easy to work with and remove much of the guess work from nut slot filing, they are expensive, and not essential. An excellent alternative is to purchase an X-Acto saw blade which attaches to a standard X-Acto knife handle and one or more needle files. The saw and handle is available at hobby shops, is inexpensive and is very useful in cutting nut and saddle materials. Small tear-drop shaped needle files are available at hardware stores and hobby shops in at least two different sizes and can be used very effectively for cutting the slots in guitar nuts.

Begin by measuring the height of the first fret. One way of measuring this is to place a straight edge on the top of the first two frets, so that it straddles the first and second frets, and then slide feeler gauges - individually, or stacked - between the fingerboard and the straight edge, until the gages just fill the space between the fingerboard and the straight edge. (The straight edge runs parallel to the strings, while the feeler gages are inserted from the edge of the fingerboard parallel to the frets, midway between frets one and two.) A typical fret height is about .040". To the fret height you measure, add about .008", which is about the amount by which the string will vertically clear the first fret. This total is the approximate height above the fingerboard that each string should be. As a subtle adjustment, I often vary the nut height by about two or three thousandths of an inch from first to sixth strings, with the first string being lower than the sixth. Stack the appropriate combination of feeler gauges to obtain a combined thickness of the correct value.

Reduce the tension on the first string sufficiently that you can lift the string out of its slot and slide it towards the second string, letting the first string rest on the top of the nut. With all but the first string at full tension, place the end of the stacked gauges on top of the fingerboard so that the edges of the gages are touching the nut. The gages are inserted under the first string from the treble side of the fingerboard so that the length of the gauges runs parallel to the frets and all but the first half of an inch or so overhangs the edge of the fingerboard.

Using either a nut file or the X-Acto saw, deepen the slot until you just begin to contact the top surface of the stack of feeler gauges with the file or saw. The slot should be filed (or cut) so that the string breaks over the nut at the leading edge of the slot - at the face of the nut nearest the bridge. This is accomplished by filing or sawing the slot at a downward angle from the fingerboard towards the head. Failure to have the string break at the leading edge of the nut can result in poor intonation and string buzz. The width of the slot should be several thousandths of an inch larger than the diameter of the string. If the slot is too narrow, the string will bind in the slot, often causing premature string breakage. One symptom of a binding nut slot, in addition to frequent string breakage, is that the change in tension in the vibrating portion of the string does not occur smoothly when adjusting the tuning pegs; the string's pitch changes suddenly, lagging behind the adjustment in the tuning peg. Once you have filed to the appropriate depth, remove the stack of gages, reposition the first string and return the string to full tension.

Repeat the process for the second string, sliding the stack of gages beneath the first string and extending under the third string. When completed, repeat the process for the third string, using either a nut file or a needle file to deepen the slot; the saw kerf is not sufficiently wide to accommodate the diameter of strings larger than the second. To adjust the height of the fourth string, insert the gages from the bass side of the fingerboard and repeat the same process. Repeat for the fifth and sixth strings.

RAISING THE STRING HEIGHT AT THE NUT

If you found that the string height at the nut was too low, or you cut the string slots too deep, the string height at the nut can be increased. One common way of increasing the string height at the nut is to place a shim beneath the nut. To do this, remove the nut, cut a shim to the same width as the nut, glue the shim to the bottom of the nut and re-glue the nut to the neck. Guitar necks are commonly made from mahogany or maple, and shims can easily be made from a matching veneer, and if necessary, the visible edge of the veneer can be stained with an appropriate color of felt tip pen. Once the nut has been shimmed sufficiently, the string height can then be lowered, if necessary, using the same procedure as described above.

Intonation

Generally, intonation refers to the ability of an instrument to play in tune. Specifically, intonation refers to how closely the notes produced by an instrument (or voice) conform to desired pitches. Hidden within this one simple statement are two quite complex questions: "what are the desired pitches?" and, once those pitches are determined, "how can an instrument be adjusted so that it accurately produces the desired pitches?" Since both of these issues are quite complex, and involve such diverse areas of study as instrument making, acoustics, music theory, and human perception, my intention in this section is to address these questions by giving an overview of the most basic theory relevant to setting-up the intonation of a guitar.

In the process of answering these questions, we must first understand what pitch is, and determine which pitches are desired. To do so, we must understand some of the basics of musical acoustics and the vibration of strings. Once this has been introduced, we can then examine the practical aspects of adjusting the guitar so that it will produce these pitches.

BASICS OF MUSICAL ACOUSTICS

Sound is produced as a result of the movement of an object. When an object which has been at rest is disturbed, the object vibrates. The vibration of that object is transmitted through a medium, usually air, by similarly disturbing the medium, until the disturbance reaches our ear drums. The disturbance of our ear drums is what our brain interprets, and what we call sound. In interpreting sound, we can differentiate between "noise" and other sounds, such as speech, the wind rustling through the trees or the sound of a guitar string. In contrast with noise, sounds which we perceive to be musical in nature are produced by an object undergoing a repetitive oscillating motion that is sustained over some period of time. The vibration of a guitar string is an example of this type of sustained motion, which is often referred to as "periodic vibration".

Physicists have rigorously characterized periodic vibration in terms of several parameters, of which the most important to this discussion is the number of times the object oscillates during a given time period. This quantity is referred to as the frequency of vibration, and can be measured in repetitions ("cycles") per second, which is often called a Hertz (Hz), in honor of the physicist Heinrich Hertz. From the musician's perspective, the "pitch" of a musical sound and the frequency of vibration of that sound are synonymous: the higher the frequency of vibration, the higher the pitch of the sound.

Although an object can be forced to vibrate at virtually any frequency, the practical range of frequencies that most people can hear is limited to the range from about 15 Hz to 15,000 Hz. Given that musical notes of any frequency within this range can be produced and heard, which frequencies should be used to make music? If you were to play a single line melody comprised of individual notes played successively one after the other, you would be free to choose whatever frequencies you like. However, as soon as a second line, or harmony, is played with the melody, you would find that by virtue of the relationship of the sounds, many frequencies sound very harsh and very undesirable.

Historically, there have been a variety of schemes for determining the precise relationships which yield pleasing ("consonant") musical sounds. The earliest method is attributed to the ancient Greek scholar, Pythagoras, who is most famous for his theorem related to right angled triangles. Pythagoras is credited with being the first to define the relationship between two consonant notes or pitches. For this purpose, he devised a simple instrument called a monochord, which consisted of a single string stretched across two fixed end-supports with an intermediary moveable third support. The third support divided the single string into two separate segments so that, when plucked, one pitch could be produced from each segment. By moving the third support along the length of the string, the ratio of the lengths of the two segments could be varied. He found that when the lengths of the segments are in the ratios of 1:1, 1:2, 2:3 or 3:4, plucking the two segments produces pitches that are consonant. (The musical intervals represented by these ratios are the unison, octave, fifth and fourth, respectively.)

Based solely upon the consonant ratios 1:2, 2:3 and 3:4, a musical scale can be established in which the ratios of the string lengths are entirely comprised of whole numbers. If we start on a note called C, the note C', an octave higher, will be in the ratio 1:2. The first note between C and C', a fourth from C to F, is the ratio of 3:4. The second note, a fifth above C, gives the note G at a ratio of 2:3. A fourth below G gives the ratio of 3/2 of 3/4, or 9/8, for the note D. When this process is continued, the major scale, with its ratios, is obtained as follows:

C	D	E	F	G	A	B	C'
1:1	8:9	64:81	3:4	2:3	16:27	128:243	1:2

This scale is referred to as the Pythagorean diatonic scale. Missing from the diatonic scale are the chromatic notes – the sharps and flats. If one continues with the same process of obtaining the ratios of the string lengths until all of the chromatic notes are found, one observes the curious result that two sizes of semitones exist, and that the size of the semitone depends upon where it occurs and from what starting point it was calculated. (One size of semitone, for example, from F to F#, is 2,048:2,187, while the other size of semitone, say, from E to F, is 243:256.) This gives rise to a number of difficulties inherent in this scheme, the result of which is that how consonant a particular note sounds depends upon the reference being used. For example, one expects the note B#, which should be the same pitch as C', to be in the ratio of 1:2. However, if one starts on the note C and reaches B# in 12 steps of a fifth at a time (i.e. C, G, D, A, E, B, F#, C#, G#, D#, A#, E#, B#) the note obtained for B# is actually 262,144:531,441 rather than 1:2. The amount of this "error", which is also exactly the difference in the two sizes of semitones, is referred to as the Pythagorean Comma. Its magnitude is 524288:531441, as seen, for example, in the ratio between B#:C'.

Practically, this unavoidable consequence of the Pythagorean scheme is of great importance. For example, if you were to play a piece of music in the key of C, if any time the octave C' was played it produced the pitch of B#, it would sound quite dissonant - it would sound sharp. Similarly, if in playing a piece of music you require B# and actually get C', it too will sound quite dissonant - it will sound flat. For centuries, the means of dealing with this deficiency was to alter the tuning of an instrument to suit the particular key in which a piece of music was played, while also avoiding changing keys into one which would encounter particularly dissonant intervals that resulted from the Pythagorean Comma.

In attempts to overcome, or "temper", the deficiencies of the Pythagorean system, a number of other schemes have been devised, each with varying degrees of acceptance and success. One scheme for doing so is equal temperament. In this scheme, the problems that arose in the scheme of Pythagorean temperament, from having two different sizes of semitones, are eliminated by dividing the octave into 12 equal parts, one for each of the 12 semitones that comprise the octave. The only commonalities between Pythagorean and equal temperament are that the frequency of the octave is exactly twice that of the starting note and that notes which are in unison have the same frequency: that is, only the consonant ratios 1:2 and 1:1 are retained. All other notes differ between the two schemes.

In order to maintain the frequency of the octave at twice the frequency of the starting note, and for each of the 12 semitones to be of equal size, each semitone must be equal to 2 to the exponent 1/12 times the frequency of the previous note. (21/12 is equal to 1.05946..., not a whole number, and not the ratio of two whole numbers.) Thus, the frequency of the note C# is 21/12 times the frequency of C, the frequency of D is 21/12 times the frequency of C#, or 22/12 times the frequency of C, D# is 21/12 times the frequency of D, or 23/12 times the frequency of C, and so on. In general, the "nth" semitone above a starting note is 2n/12 times the vibrating frequency of the starting note. The advantage of this scheme is its consistency: each and every semitone is exactly the same size. The consequence of this is that, for example, an interval between two notes an octave apart will always sound the same regardless of the two notes being compared: the interval of C to C' is exactly the same as F# to F#' or C to B#. Similarly, the interval of a perfect fifth from C to G will sound exactly the same as the same interval from, say, B to F#. The disadvantage of this scheme is that the "purity" or "sweetness" of some of the Pythagorean intervals is lost as a result of the tempering. Thus, equal temperament is a compromise between the ability to play equally in tune in any key and the loss of purity of some of the intervals.

Equal temperament began to be widely used in the latter half of the 18th century. The Well Tempered Klavier, by J.S. Bach, was written as a testament to the versatility of equal temperament, with one prelude and fugue written in each and every key. Today, equal temperament is universally used in music of the Western culture, with the exception of "Early Music" instruments which strive to authentically recreate the sound of music which predated the use of equal temperament.

After centuries of debate, the note "A" has been standardized to be 440 Hz: this standard is referred to as "concert pitch". With A 440 Hz as the starting point, and equal temperament as the mathematical scheme, the vibrating frequency of every musical note can be determined by calculation.

Having determined which frequencies (pitches) we require an instrument to be capable of making, it is helpful to first understand a little of how the object undergoing vibration produces these notes before turning to the practical aspects of setting up an instrument. Thus, we next turn our attention to the vibrating string.

VIBRATING STRINGS

Consider a "simple" string of uniform diameter and cross section supported at each of its ends. The string is of vibrating length L, subject to a tension T and made of a material of density per unit length d. Then, when the string is excited, the fundamental frequency, f, at which it will vibrate, is theoretically given by

$$f = 1/(2L) \times \text{þ}(T/d). \qquad (1)$$

Of particular interest to this discussion is the fact that the vibrating frequency of a string is inversely proportional to its length: as the vibrating length of the string becomes shorter, its frequency of vibration (pitch) increases. While maintaining the same tension on a string (i.e. not retuning the string), more than one pitch can be obtained from that string by "stopping" it anywhere along its length. Stopping a string divides the string into segments, often resulting in one segment vibrating while the others effectively do not. Since each vibrating segment of the string is shorter than the unstopped string, the frequency of vibration of each segment is higher than that of the unstopped string. Thus, an infinite number of vibrating frequencies – all higher in pitch than the unstopped (or "open") string - can be obtained by stopping the string.

The strings of "string instruments" - guitars, lutes, banjos, violins, violas, etc. - are generally stopped in one of three ways. The first of these is to touch the string at a specific location along its length, which causes the point of contact with the string to remain stationary while the entire string vibrates. This stationary point, called a node, forces the entire string to vibrate in whole-number divisions of the unstopped string length. Thus, a node can occur at the exact midpoint of the string, which divides the string precisely in two, at exactly a third of the string, which divides the string precisely in three, or at locations that divide the string in 4, 5, 6, etc. The notes produced this way are often referred to as "harmonics". Since these are exact whole-number divisions of the string, the pitches of the notes produced belong to Pythagorean temperament, rather than equal temperament.

The second method of stopping a string is by using the fingers to depress a string directly against the fingerboard, as is done with the violin family of instruments. The placement of the player's finger on the string stops the string and defines the vibrating length (and pitch) of that string. Thus, producing a desired pitch largely involves placing the fingers (stopping) in the correct location along the length of the string. The third way of stopping is by depressing the string against a fixed bar or chord - a "fret" - which generally spans the width of the fingerboard. (Depressing the string against a fret is usually referred to as "fretting" the string.) The use of one or more frets allows the musician to accurately, and repeatable, shorten the vibrating length of a string by depressing the string against a fret. The frets finalize where along the length of the strings they are stopped. Thus, the task of obtaining the desired pitches involves obtaining the correct vibrating string length to produce the desired pitch.

While there are a variety of methods for calculating the placement of frets, they are nearly universally based on equal temperament. Conceptually, the simplest of these determines what shortened string length is required to produce the next note one semi-tone higher in pitch. This is calculated by dividing the unstopped vibrating string length by 21/12. For example, for a 650 mm long guitar string supported at one end by a nut and at the other end by a saddle, the (theoretical) distance from the saddle to the first fret is 650/21/12 = 613.5 mm. Each successive fret location can be determined recursively using the vibrating string length of the previous fret to determine the required string length for the next fret. To continue the example, theoretically, the second fret location is 613.5/21/12= 579.1 mm when measured from the saddle. (In practice, for reasons that will become apparent from the discussion below, it is generally easier to measure the fret locations based upon the remaining non-vibrating portion of the string, from the nut location to the fret, rather than the vibrating portion of the string, from the saddle to the fret.)

Unfortunately, the vibration of a string is considerably more complex than was assumed for the "simple" string described by equation (1). Practically, the primary condition not accounted for in equation (1) is related to the geometry of the fretted string. When the string is unfretted and in its rest position, it assumes the shortest distance between its two end supports - namely, a straight line. As the string is depressed against a fret (or fingerboard), it no longer forms a straight line between its end supports. Instead, the string is stretched to form two straight segments, extending first from one end support down to the fret, and then from the fret up to the other end support. The stretching of the string increases the tension on that string. As can be seen from equation (1), this has the effect of increasing the pitch of the vibrating string. For frets which are accurately placed in accordance with equal temperament, the fretted notes will sound sharp. In order to compensate for this increase in tension, an adjustment is made to the instrument which increases the length of the vibrating portion of the string. Increasing the string length by the correct amount flattens the pitch of the slightly sharpened fretted note, thereby producing the correct pitch. This slight increase in vibrating string length is referred to as "compensation".

The amount of compensation required is directly proportional to the amount of the increase in string tension that results from fretting a particular string. The amount of this increase in tension depends upon the amount that a string is stretched as a result of fretting, the tension on that string, the mechanical properties of the string and the vibrating string length. The amount that the string is stretched depends largely upon how far it must be depressed until it contacts the fret, which depends upon how high the strings are above the tops of the frets. Thus, for the same guitar, a high action will require greater compensation than a relatively low action.

The tension on a string, the mechanical properties of the string and the vibrating string length are all inter-related, as suggested in equation (1). If one were to tune a typical high E (first) guitar string down two octaves, until it is the same pitch as the low E (sixth) string, the tension on that string would be very low - in fact, it would be reduced to 1/4 of its original value. As a consequence of the very low tension, the string would not sound very well: it would lack volume and sustain. This highlights the fact that the best sound is obtained from a string that is at a tension relatively near its breaking strength. In this example, the string tension is nowhere near its breaking strength. One of the ways to increase the tension on this string is to increase its density per unit length. This is accomplished by increasing the effective diameter of the string, either by using a larger diameter wire, or by winding a thick string around a thinner "core" string. Thus, while maintaining the same string length, the tension necessary to tune the string to pitch increases as the diameter increases. Conversely, while maintaining the string length and tension, strings of descending pitches can be obtained by progressively increasing the diameter of successive strings. This is essentially what is done on guitars and related string instruments. However, a consequence of this is that the increase in density per unit length is accompanied by an increase in the stiffness of the string, which increases its resistance to being fretted. The result is that the greater the diameter of the string, the greater is the compensation required. Furthermore, since each of the strings on a guitar is of a different diameter and slightly different tension, each string requires its own unique amount of compensation.

ADJUSTING THE INTONATION OF A GUITAR

From the previous discussion, we have seen that the guitar's frets are placed according to equal temperament and that the action of fretting a string increases the tension, and consequently pitch, of the fretted notes. To compensate for this increase in pitch, the length of each string is increased slightly by an amount dependent upon each individual string. In this section, we will examine the practical aspects of how to adjust the guitar so that the notes produced by the fretting of the strings are in accordance with the frequencies required for equal temperament.

Fret positions, as briefly described above, are determined without regard for the compensation that the strings will require. This means that the 12th fret, the octave of the open string, is located at precisely half of the theoretical - non-compensated – vibrating string length: the distance from the face of the nut closest to the bridge to the 12th fret is exactly half of the theoretical vibrating string length. The theoretical vibrating string length is often referred to as the "scale length" to distinguish it from the actual final vibrating string length, or the "compensated length". On a compensated string, since the distance from the nut to the saddle is increased by the amount of the necessary compensation, the distance from the nut to the 12th fret is shorter than the distance from the 12th fret to the saddle by the amount of the compensation. Typically, the amount of compensation required is between about 3 mm (1/8") and 5 mm (3/16"), depending upon the string.

The procedure used to adjust the intonation is to alter the precise string length of each string until the pitch of two notes produced on the same string is identical. The two notes that are compared are the note produced by fretting a string at the 12th fret and the note produced by the harmonic at the 12th fret of the same string. These notes are both octaves of the open string and are in unison with each other. As previously noted, harmonics are produced when a string is divided into a whole number of equal vibrating segments and, consequently, belong to the scheme of Pythagorean temperament. Recall, however, that the frets are placed using equal temperament and that the only places where the two schemes produce notes of the same frequency are at the unison (1:1) and the octave (1:2). Comparing the pitches of any notes other than the unison or octave is like comparing apples and oranges; they will not, and should not, be the same. (An example of this is that, with the exception of octaves of the open string, the correct position (i.e. the one that produces the clearest sound) for stopping a string to obtain a harmonic is not directly above the center of the corresponding fret, but is slightly offset.) This is particularly relevant during routine tuning of the instrument.

The two pitches - the 12th fret note and the 12th fret harmonic - can be compared with the unaided ear, although more accurate results can be obtained by using an electronic tuner. The intonation is correctly adjusted when the two pitches are identical. Practically, however, there is limit to the ability of the human ear to differentiate between differences in pitch. This varies depending upon the frequency and intensity of the note as well as one's own physical limitations and musical training. To aid in quantifying deviations in frequency, a semitone has been divided into 100 parts, each part being called a "cent". A well trained musical ear can generally distinguish between frequencies 3 or 4 cents apart. When setting the intonation, it is preferable, though not essential, to use an electronic tuner which is calibrated incents.

Prior to performing any adjustment of the intonation, the intonation of the instrument to be set-up should be accessed. This should be done using a new set of strings that are all tuned to the pitch at which you will usually play them. (All subsequent intonation adjustment should be done with the same new strings all tuned to pitch.) In addition, the string height at the nut and saddle should be correctly set-up, since the compensation required is, in part, dependant upon string height. Beginning with the sixth string, compare the 12th fret note with the 12th fret harmonic: record the discrepancy and repeat for each of the remaining strings. If, for any string, it is found that the discrepancy between the two notes is greater than 3 or 4 cents - or audibly different - the vibrating string length for that string will require lengthening or shortening. Notes which sound sharp require the string to be lengthened, while notes which should flat require the string to be shortened. If the notes are of the same pitch, no adjustment is required: the intonation of the guitar is properly set-up.

If an adjustment is required, it is usually helpful to first ensure that the saddle is located so that it can support the strings at their correctly compensated lengths. If the saddle is not correctly located, the strings cannot be supported at their correct length and the instrument cannot be properly intonated. On most commercially manufactured guitars, a narrow, 3/32" or 1/8" wide saddle provides the end-support for the strings at the bridge. The saddle is inserted in a slot in the bridge and is usually slanted to provide greater compensation as the diameter of the strings increases. Where each string breaks over the thickness of the saddle determines the precise vibrating length of each string. The primary factor in adjusting the guitar to play in tune is obtaining the precise, correctly compensated string length. To determine if the saddle is in the correct location, first determine the guitar's scale length, add an approximation of the necessary compensation and then measure the location of the saddle relative to the nut (or zero fret, if the guitar has one). To determine the guitar's scale length - the theoretical string length used to calculate the placement of the frets - double the measured distance from the face of the nut (or zero fret) to the middle of the 12th fret. (A 36" long, straight edge that is calibrated in either or both inches or millimeters is helpful.) To this measurement, add an approximation of the compensation necessary: about 3 mm to the length of the first (treble E) string and about 5 mm to the length of the sixth (bass E) string. For example, if you measured 320 mm from the nut to the 12th fret, doubling it gives a 640 mm scale length. Ideally, the first and sixth strings should break over the center of the saddle's thickness at about 643 mm and 645 mm, respectively, when measured from the face of the nut. While Guitar scale lengths are often calculated in inches, I find millimeters are easier to work with, regardless of which units were originally used to place the frets.

A relatively frequent impediment to correctly setting the intonation is that the saddle is located too close to the nut, not allowing a sufficient increase in string length. The most common case of this, due to an insufficient slant of the saddle, or simply due to insufficient compensation being given, is not being able to sufficiently lengthen the sixth string, with the consequence that it plays sharp. Another frequently seen impediment is the saddle not being of sufficient width to accommodate the range of compensation required from one string to the next. The very common example of this is that the second ("B") string cannot be sufficiently lengthened, and consequently plays sharp. This is due to the fact that the second string on steel string acoustic guitars generally requires greater compensation than its immediate neighbors, and requires a string length for which the string should break behind (i.e. longer than) the thickness of the saddle. (For electric guitars and classical guitars, typically it is the third string, rather than the second, where this occurs.) It is quite common to find steel string acoustic guitars whose second string is insufficiently compensated. One simple remedy to this problem is to use a thicker saddle. If the saddle is either incorrectly located, or insufficiently thick, the saddle must either be moved, replaced with a thicker one or a compromise made, with the string length adjusted within the physical limitations of the saddle location.

The exact amount of compensation required is determined by trial and error. The correct amount results in the 12th fret note and 12 fret harmonic being exactly the same pitch. Practically, a simple way of adjusting the string length is to cut one inch segments from the excess length of a set of guitar strings. By bending a short length of string into a "V" shape, it can be slid under the string - between the bottom of the string and the top of the saddle – and re-positioned on the top of the saddle, as necessary, to change the vibrating string length until the pitches of the notes match. (To aid in inserting the "V" under one of the guitar strings, it is often necessary to loosen the string somewhat, insert the "V", and then return the string to pitch. Once under a string, a pair of pliers is often helpful in re-positioning the "V".) The gage of the string to use to make the "V" depends upon the gage of the guitar string it will support and the shape of the top of the saddle: feel free to experiment and choose what works best for you. It is somewhat easier if the top of the saddle is flat across its width, as is the case with a new saddle or in some circumstances when lowering the saddle height. Once the "V" has been correctly located, its center can be marked with a sharp pencil on the top of the sad le. When this has been repeated for each of the strings, the saddle is removed from the guitar and the top of the saddle is shaped.

Shaping of the top of the saddle involves two components. The first is to shape the top surface of the saddle so that the string breaks at a precise location on the width of the saddle. This determines the exact vibrating string length of each string. The second component of shaping the top of the saddle is to provide a "clean" support for the string. This involves bringing the top of the saddle to a rounded point so as to support the string over a narrow area, while not being so sharp as to be easily grooved by the string or cause pre-mature string breakage. The length of the saddle can be divided into one segment for each string, and the top of each segment can be individually beveled and rounded with a file to correctly position the point created at precisely the pencil marking determined using the "V"s. When completed, the shaped saddle can then be returned to the bridge and the instrument brought to pitch and tuned.

TUNING A GUITAR

As a prerequisite to playing in tune, a guitar's intonation must be correctly adjusted. However, even after the intonation has been correctly adjusted for each individual string, the guitar as a whole will only sound in tune if each of the strings is properly tuned relative to each of the others. There are numerous correct methods for tuning a guitar, as well as numerous incorrect methods. What differentiates the correct methods from the incorrect methods is the adherence to, or violation of, one simple principle. Rather than get caught up in the specific aspects of each of these methods, we will examine the general principle. Once the general principle is understood, you are then free to create your own method.

Virtually all tuning methods involve altering the tension of a string until a note produced on that string exactly matches a standard to which the note is being compared. The standard can be a note produced by a pitch pipe, a tuning fork, or an indicator on an electronic tuner. Of these, an electronic tuner likely provides the easiest means of initial tuning since each string is compared to an independent standard, rather than to the other strings, and most tuners provide a visual indication of when the string is in tune.

If an electronic tuner is used to tune only one string, or not used at all, then once one string is tuned to a standard, the guitar is tuned to itself using notes produced by the guitar. In any method which tunes the guitar to itself, there is one basic principle that must be honored. This principle is that - except in very specific ways - one cannot mix equal temperament and Pythagorean temperament. Recall that harmonics belong to Pythagorean temperament and all fretted notes belong to equal temperament, and that the only notes which are the same between the two are octaves and unisons. Practically, this means that a guitar cannot be correctly tuned using any method that compares any fretted note with any harmonic that is not an octave (or multiple of an octave) of an open string. For example, the harmonic produced at the fifth fret is a fourth higher than the open string. The harmonic at the seventh fret is two octaves above the open string. A common, and incorrect, method of tuning is to compare the pitch of the harmonic on the fifth fret of, say, the sixth string with the seventh fret harmonic on the fifth string. This compares an octave (of the fifth string) to a fourth (of the sixth string). The fourth belongs to Pythagorean tuning while the octave is common to both Pythagorean and equal temperaments. If the fifth string is tuned this way, the fretted notes of the fifth string will be out of tune with the fretted notes on the sixth string. Conversely, it is consistent, and correct, to compare the fifth fret note on the first string - an equal temperament note "A" - with the seventh fret harmonic of the fifth string - a note two octaves above the open A string common to both equal and Pythagorean temperament. Any method based upon not mixing equal and Pythagorean temperament is correct.

Once the instrument has been correctly tuned using only equal temperament notes, many more experienced players will often tweak the tuning slightly for certain notes. As was mentioned earlier, certain notes loose a quality of "purity" as a result of the equal temperament. As a compromise, many players will alter the tuning - not the intonation - of the instrument so that notes specific to a key in which they play regain some of the lost purity. This is a question of personal preference and, to some degree, musical training. Since electronic tuners give notes belonging to equal temperament, they are of no use to the average player in tweaking the tuning.