CHAPTER TWO: TUNING YOUR PIANO

1. Introduction

This chapter is for those who had never tuned a piano and who would like to see if they are up to the task. *Piano Servicing, Tuning, and Rebuilding*, by Arthur Reblitz, will be a helpful reference. The hardest part of learning to tune is getting started. For those fortunate enough to have someone teach them, that is obviously the best route. Unfortunately, piano tuning teachers aren't readily available. Try the suggestions in this chapter and see how far you can get. After you are familiar with what gives you trouble, you might negotiate with your tuner for 30 minute lessons for some agreed-upon fee, or ask him to explain what he is doing as he tunes. Be careful not to impose too much on your tuner; tuning and teaching can take more than four times longer than simply tuning it up. Each tuner has her/is own methods of solving problems; these solutions can't really be taught because what you do depends on how the piano "behaves". Also, be forewarned that piano tuners are not trained teachers and some may harbor unfounded fears that they might lose a customer. These fears are unfounded because the actual number of people who succeed in displacing professional tuners is negligibly small. What you will most likely end up doing is getting a better understanding of what it takes to tune a piano, develop a sensitivity to the tuning, and end up hiring tuners more often.

For pianists, familiarity with the art of tuning provides an education that is directly relevant to their ability to produce music and to maintain their instruments. It will also enable them to communicate intelligently with their tuners. For example, the majority of piano teachers to whom I posed the question did not even know the difference between Equal temperament and historical temperaments (P. 227). The main reason why most people try to learn tuning is out of curiosity -- for the majority, piano tuning is a baffling mystery. Once people are educated to the advantages of tuned (maintained) pianos, they are more likely to call their tuners regularly. Piano tuners can hear certain sounds coming from the piano that most people, even pianists, don't notice. Those who practice tuning will become sensitized to the sounds of out-of-tune pianos. It will probably take about one year to start feeling comfortable with tuning, assuming that you have the time to practice for several hours at least once every one or two months.

Let me digress here to discuss the importance of understanding the plight of tuners and proper communications with them, from the point of view of getting your money's worth from the tuner so that your piano can be properly maintained. These considerations directly impact your ability to acquire piano technique as well as your decisions on what or how to perform, given a particular piano to play. For example, one of the most common difficulties I have noted with students is their inability to play pianissimo. From my understanding of piano tuning, there is a very simple answer to this -- most of these students' pianos are under-maintained. The hammers are too worn/compacted and the action so out of regulation that playing pianissimo is impossible. These students will never even be able to practice pianissimo! This applies also to musical expression and tone control. These under-maintained pianos are probably one of the causes of the view that piano practice is ear torture, but it should not be. ***An out-of-tune piano is one of the major causes of flubs and bad habits.***

Another factor is that you generally have no choice of a piano when asked to perform. You might encounter anything from a wonderful concert grand, to spinets, to (horrors!) a cheap baby grand that was totally neglected since it was purchased 40 years ago. Your understanding of what you can/cannot do with each of these pianos should be the first input into deciding what and how to play.

Once you start practicing tuning, you will quickly understand why your spouse vacuuming the floor, kids running around, the TV or HiFi blaring away, or pots clanging in the kitchen is not conducive to accurate, quality tuning. Why a quick, $70 tuning is no bargain compared to a $150 tuning in which the tuner reshapes and needles the hammers. Yet when you query owners what the tuner did to their pianos, they generally have *no idea*. A complaint I frequently hear from owners is that, after a tuning, the piano sounds dead or terrible. This often happens when the owner does not have a fixed reference from which to judge the piano sound -- the judgment is based on whether the owner likes the sound or not. Such perceptions are too often incorrectly influenced by the owner's past history. The owner can actually become accustomed to the sound of a detuned piano with compacted hammers so that when the tuner restores the sound, the owner doesn't like it because it is now too different from the sound or feel to which he had become accustomed. The tuner could certainly be at fault; however, the owner will need to know a minimum of tuning technicalities in order to make a correct judgment. The benefits of understanding tuning and properly maintaining the piano are under-appreciated by the general public. The most important objective of this chapter is to increase that awareness.

Piano tuning does not require good ears, such as absolute pitch, because all tuning is accomplished by comparison with a reference using beats, starting with the reference frequency of a tuning fork. In fact an absolute pitch ability may interfere with the tuning for some people. Therefore, the "only" hearing skill you will need is the ability to hear and differentiate between the various beats when two strings are struck. This ability develops with practice and is not related to knowledge of music theory or to musicality. Larger grands are easier to tune than uprights; however, most baby grands are harder to tune than good uprights. Therefore, although you should logically begin your practice with a lower quality piano (in case you damage it), it will be more difficult to tune.

2. Chromatic Scale and Temperament

Most of us have some familiarity with the *chromatic scale* and know that it must be *tempered*, but what are their precise definitions? ***Why is the chromatic scale so special and why is temperament needed?*** We first explore the mathematical basis for the chromatic scale and tempering because the mathematical approach is the most concise, clear, and precise treatment. We then discuss the historical/musical considerations for a better understanding of the relative merits of the different temperaments. A basic mathematical foundation for these concepts is essential for a good understanding of how pianos are tuned. For information on tuning, see White, Howell, Fischer, Jorgensen, or Reblitz in the Reference section at the end of this book.

a. Mathematics of the Chromatic Scale and Intervals. Three octaves of the chromatic scale are shown in Table 2.2a using the A, B, C, . . . notation. Black keys on the piano are shown as sharps, e.g. the # on the right of C represents C#, etc., and are shown only for the highest octave. ***Each successive frequency change in the chromatic scale is called a semitone and an octave has 12 semitones.*** The major intervals and the integers representing the frequency ratios for those intervals are shown above and below the chromatic scale, respectively. Except for multiples of these basic intervals, integers larger than about 10 produce intervals not readily recognizable to the ear. In reference to Table 2.2a, the most fundamental interval is the octave, in which the frequency of the higher note is twice that of the lower one. The interval between C and G is called a 5th, and the frequencies of C and G are in the ratio of 2 to 3. The major third has four semitones and the minor third has three. The number associated with each interval, e.g. four in the 4th, is the number of white keys, inclusive of the two end keys, for the C-major scale and has no further mathematical significance.

TABLE 2.2a: Frequency Ratios of Intervals in the Chromatic Scale

|--Octave--	|--5th--	|--4th--	|-Maj.3rd-	|-Min.3rd-	**|**	**|**
CDEFGAB	**C D E F**	**G A B**	**C # D #**	**E F #**	**G # A # B**	**C**
1	**2**	**3**	**4**	**5**	**6**	**8**

We can see from the above that a 4th and a 5th "add up" to an octave and a major 3rd and a minor 3rd "add up" to a 5th. Note that this is an addition in logarithmic space, as explained below. The missing integer 7 is also explained below. These are the “ideal” intervals with perfect harmony.

The "equal tempered" (ET) chromatic scale consists of "equal" half-tone or semitone rises for each successive note. They are equal in the sense that the ratio of the frequencies of any two adjacent notes is always the same. This property ensures that every note is the same as any other note (except for pitch). This uniformity of the notes allows the composer or performer to use any key without hitting bad dissonances, as further explained below. There are 12 equal semitones in an octave of an ET scale and each octave is an exact factor of two in frequency. Therefore, the frequency change for each semitone is given by

$\text{semitone}^{12} = 2$, or

$\text{semitone} = 2^{1/12} = 1.05946$. . . . . Eq. (2.1)

Eq. (2.1) defines the ET chromatic scale and allows the calculation of the frequency ratios of "intervals" in this scale. How do the "intervals" in ET compare with the frequency ratios of the ideal intervals? ***The comparisons are shown in Table 2.2b and demonstrate that the intervals from the ET scale are extremely close to the ideal intervals.***

The errors for the 3rds are the worst, over five times the errors in the other intervals, but are still only about 1%. Nonetheless, these errors are readily audible, and some piano aficionados have generously dubbed them "the rolling thirds" while in reality, they are unacceptable dissonances. It is a defect that we must learn to live with, if we are to adopt the ET scale. The errors in the 4ths and 5ths produce beats of about 1 Hz near middle C, which is barely audible in most pieces of music; however, this beat frequency doubles for every higher octave.

The integer 7, if it were included in Table 2.2a, would have represented an interval with the ratio 7/6 and would correspond to a semitone squared. The error between 7/6 and a semitone squared is over 4% and is too large to make a musically acceptable interval and was therefore excluded from Table 2.2a.

TABLE 2.2b: Ideal versus Equal Tempered Intervals

Interval	Freq. Ratio	Eq. Tempered Scale	Difference
Min.3rd:	6/5 = 1.2000	$\text{semitone}^3 = 1.1892$	+0.0108
Maj.3rd:	5/4 = 1.2500	$\text{semitone}^4 = 1.2599$	-0.0099
Fourth:	4/3 = 1.3333	$\text{semitone}^5 = 1.3348$	-0.0015
Fifth:	3/2 = 1.5000	$\text{semitone}^7 = 1.4983$	+0.0017
Octave:	2/1 = 2.0000	$\text{semitone}^{12} = 2.0000$	0.0000

It is a mathematical accident that the 12-note ET chromatic scale produces so many ratios close to the ideal intervals. ***Only the number 7, out of the smallest 8 integers (Table 2.2a), results in a totally unacceptable interval. The chromatic scale is based on a lucky mathematical accident in nature! It is constructed by using the smallest number of notes that gives the maximum number of intervals.*** No wonder early civilizations believed that there was something mystical about this scale. Increasing the number of keys in an octave does not result in much improvement of the intervals until the numbers become quite large, making that approach impractical for most musical instruments. Mathematically speaking, the unacceptable number 7 is a victim of the incompleteness (P. 225) of the chromatic scale and is therefore, not a mystery.

Note that the frequency ratios of the 4th and 5th do not add up to that of the octave (1.5000 + 1.3333 = 2.8333 vs. 2.0000). Instead, they add up in logarithmic space because (3/2)x(4/3) = 2. In logarithmic space, multiplication becomes addition. Why might this be significant? The answer is because the geometry of the cochlea of the ear seems to have a logarithmic component. Detecting acoustic frequencies on a logarithmic scale accomplishes two things: you can hear a wider frequency range for a given size of cochlea, and analyzing ratios of frequencies becomes simple because instead of multiplying or dividing two frequencies, you only need to add or subtract their logarithms. For example, if C3 is detected by the cochlea at one position and C4 at another position 2mm away, then C5 will be detected at a distance of 4 mm, exactly as in the slide rule calculator. To show you how useful this is, given F5, the brain knows that F4 will be found 2mm back! Therefore, intervals (remember, intervals are frequency divisions) and harmonies are particularly simple to analyze in a logarithmically constructed cochlea. When we play intervals, we are performing mathematical operations in logarithmic space on a mechanical computer called the piano, as was done in the 1950's using the slide rule. ***Thus the logarithmic nature of the chromatic scale has many more consequences than just providing a wider frequency range than a linear scale.*** The logarithmic scale assures that the two notes of every interval are separated by the same distance no matter where you are on the piano. By adopting a logarithmic chromatic scale, the piano keyboard is mathematically matched to the human ear in a mechanical way! This is probably one reason for why harmonies are pleasant to the ear - harmonies are most easily deciphered and remembered by the human hearing mechanism.

Suppose that we did not know Eq. 2.1; can we generate the ET chromatic scale from the interval relationships? If the answer is yes, a piano tuner can tune a piano without having to make any calculations. These interval relationships, it turns out, completely determine the frequencies of all the notes of the 12 note chromatic scale. ***A temperament is a set of interval relationships that defines a specific chromatic scale; tempering generally involves detuning from perfect intervals.*** From a musical point of view, there is no single "chromatic scale" that is best above all else although ET has the unique property that it allows free transpositions. Needless to say, ***ET is not the only musically useful temperament, and we will discuss other temperaments below.*** Temperament is not an option but a necessity; we *must* choose a temperament in order to accommodate the mathematical difficulties discussed below and in following sections b & c. ***Most musical instruments based on the chromatic scale must be tempered.*** For example, the holes in wind instruments and the frets of the guitar must be spaced for a specific tempered scale. The violin is a devilishly clever instrument because it avoids all temperament problems by spacing the open strings in fifths. If you tune the A(440) string correctly and tune all the others in 5ths, these others will be close, but not tempered. You can still avoid temperament problems by fingering all notes except one (the correctly tuned A-440). In addition, the vibrato is larger than the temperament corrections, making temperament differences inaudible.

The requirement of tempering arises because a chromatic scale tuned to one scale (e.g., C-major with perfect intervals) does not produce acceptable intervals in other scales. If you wrote a composition in C-major having many perfect intervals and then transposed it, terrible dissonances can result. There is an even more fundamental problem. Perfect intervals in one scale also produce dissonances in other scales needed in the same piece of music. Tempering schemes were therefore devised to minimize these dissonances by minimizing the de-tuning from perfect intervals in the most important intervals and shifting most of the dissonances into the less used intervals. The dissonance associated with the worst interval came to be known as **"the wolf"**.

The main problem is, of course, interval purity; the above discussion makes it clear that no matter what you do, there is going to be a dissonance somewhere. ***It might come as a shock to some that the piano is a fundamentally imperfect instrument!*** The piano gives us every note, but locks us into one temperament; on the other hand, we must finger every note on the violin, but it is free of temperament restrictions.

The name "chromatic scale" applies to any 12-note scale with any temperament. ***For the piano, the chromatic scale does not allow the use of frequencies between the notes (as you can with the violin), so that there is an infinite number of missing notes. In this sense, the chromatic scale is (mathematically) <u>incomplete</u>.*** Nonetheless, the 12-note scale is sufficiently complete for a majority of musical applications. The situation is analogous to digital photography. When the resolution is sufficient, you cannot see the difference between a digital photo and an analog one with much higher information density. Similarly, ***the 12-note scale has sufficient pitch resolution for a sufficiently large number of musical applications.*** This 12-note scale is a good compromise between having more notes per octave for greater completeness and having enough frequency range to span the range of the human ear, for a given instrument or musical notation system with a limited number of notes.

There is healthy debate about which temperament is best musically. ET was known from the earliest history of tuning. There are definite advantages to standardizing to one temperament, but that is probably not possible or even desirable in view of the diversity of opinions on music and the fact that much music now exist, that were written with specific temperaments in mind. Therefore we shall now explore the various temperaments.

b. Temperament, Music, and the Circle of Fifths. The above mathematical approach is not the way in which the chromatic scale was historically developed. Musicians first started with intervals and tried to find a music scale with the minimum number of notes that would produce those intervals. The requirement of a minimum number of notes is obviously desirable since it determines the number of keys, strings, holes, etc. needed to construct a musical instrument. Intervals are necessary because if you want to play more than one note at a time, those notes will create dissonances that are unpleasant to the ear unless they form harmonious intervals. The reason why dissonances are so unpleasant to the ear may have something to do with the difficulty of processing dissonant information through the brain. It is certainly easier, in terms of memory and comprehension, to deal with harmonious intervals than dissonances. Some dissonances are nearly impossible for most brains to figure out if two dissonant notes are played simultaneously. Therefore, if the brain is overloaded with the task of trying to figure out complex dissonances, it becomes impossible to relax and enjoy the music, or follow the musical idea. Clearly, any scale must produce good intervals if we are to compose advanced, complex music requiring more than one note at a time.

We saw in Tables 2.2a and b that the optimum number of notes in a scale turned out to be 12. Unfortunately, there isn't any 12-note scale that can produce exact intervals everywhere. Music would sound better if a scale with perfect intervals everywhere could be found. Many such attempts have been made, mainly by increasing the number of notes per octave, especially using guitars and organs, but none of these scales have gained acceptance. It is relatively easy to increase the number of notes per octave with a guitar-like instrument because all you need to do is to add strings and frets. The latest schemes being devised today involve computer generated scales in which the computer adjusts the frequencies with every transposition; this scheme is called adaptive tuning (Sethares).

The most basic concept needed to understand temperaments is the concept of the circle of fifths. To describe a circle of fifths, take any octave. Start with the lowest note and go up in 5ths. After two 5ths, you will go outside of this octave. When this happens, go down one octave so that you can keep going up in 5ths and still stay within the original octave. Do this for twelve 5ths, and you will end up at the highest note of the octave! That is, if you start at C4, you will end up with C5 and this is why it is called a circle. Not only that, but every note you hit when playing the 5ths is a different note. This means that the circle of fifths hits every note once and only once, a key property useful for tuning the scale and for studying it mathematically.

c. Pythagorean, Equal, Meantone, and "Well" Temperaments. ***Historical developments are central to discussions of temperament because mathematics was no help; practical tuning algorithms could only be invented by the tuners of the time. Pythagoras is credited with inventing the Pythagorean Temperament at around 550 BC, in which the chromatic scale is generated by tuning in perfect 5ths, using the circle of fifths.*** Unfortunately, the twelve perfect 5ths in the circle of fifths do not make an exact factor of two. Therefore, the final note you get is not exactly the octave note but is too high in frequency by what is called the **"Pythagorean comma", about 23 cents (a cent is one hundredths of a semitone)**. Since a 4th plus a 5th make up an octave, the Pythagorean temperament results in a scale with perfect 4ths and 5ths, but the octave is dissonant. It turns out that tuning in perfect 5ths leaves the 3rds in bad shape, another disadvantage of the Pythagorean temperament. Now if we were to tune by contracting each 5th by 23/12 cents, we would end up with exactly one octave and that is one way of tuning an **Equal Temperament (ET)** scale. In fact, we shall use this method in the section on tuning (6c). The ET scale was already known within a hundred years or so after invention of the Pythagorean temperament. Thus ET is not a "modern temperament" (a frequent misconception).

Following the introduction of the Pythagorean temperament, all newer temperaments were efforts at improving on it. The first method was to halve the Pythagorean comma by distributing it among two final 5ths. ***One major development was Meantone Temperament, in which the 3rds were made just (exact) instead of the 5ths.*** Musically, 3rds play more prominent roles than 5ths, so that meantone made sense, because during its heyday music made greater use of 3rds. Unfortunately, meantone has a wolf worse than Pythagorean.

The next milestone is represented by Bach's Well Tempered Clavier in which music was written with ***"key color"*** in mind, which was a property of **Well Temperaments (WT)**. These were non-ET temperaments that struck a compromise between meantone and Pythagorean. This concept worked because Pythagorean tuning ended up sharp, while meantone is flat (ET and WT give perfect octaves). In addition, WT presented the possibility of not only good 3rds, but also good 5ths. ***The simplest WT (to tune) was devised by Kirnberger, a student of Bach. But it has a terrible wolf. "Better" WTs (all temperaments are compromises and they all have advantages and disadvantages) were devised by Werckmeister and by Young (which is almost the same as Valotti). If we broadly classify tunings as Meantone, WT, or Pythagorean, then ET is a WT because ET is neither sharp nor flat.***

The violin takes advantage of its unique design to circumvent these temperament problems. The open strings make intervals of a 5th with each other, so that the violin naturally tunes Pythagorean (anyone can tune it!). Since the 3rds can always be fingered **just** (meaning exact), it has all the advantages of the Pythagorean, meantone, and WT, with no wolf in sight! In addition, it has a complete set of frequencies (infinite) within its frequency range. Little wonder that the violin is held in such high esteem by musicians.

Since about 1850, ET had been almost universally accepted because of its musical freedom and the trend towards increasing dissonance by composers. All the other temperaments are generically classified as "historical temperaments", which is clearly a misnomer. Most WTs are relatively easy to tune, and most harpsichord owners had to tune their own instruments, which is why they used WT. ***This historical use of WT gave rise to the concept of key color in which each key, depending on the temperament, endowed specific colors to the music, mainly through the small de-tunings that create "tension" and other effects. After listening to music played on pianos tuned to WT, ET tends to sound muddy and bland.*** Thus key color does matter. On the other hand, there is always some kind of a wolf in the WTs which can be very annoying.

For playing most of the music composed around the times of Bach, Mozart, and Beethoven, WT works best. As an example, Beethoven chose intervals for the dissonant ninths in the first movement of his Moonlight Sonata that are less dissonant in WT. These great composers were acutely aware of temperament. You will see a dramatic demonstration of WT if you listen to the last movement of Beethoven's Waldstein played in ET and WT. This movement is heavily pedaled, making harmony a major issue.

From Bach’s time to about Chopin’s time, tuners and composers seldom documented their tunings and we have precious little information on those tunings. At one time, in the early 1900s, it was believed that Bach used ET because, how else would he be able to write music in all the keys unless you could freely transpose from one to the other? Some writers even made the preposterous statement that Bach invented ET! Such arguments, and the fact that there was no “standard WT” to choose from, led to the acceptance of ET as the universal tuning used by tuners, to this day. Standardization to ET also assured tuners of a good career because ET was too difficult for anyone but well trained tuners to accurately tune.

As pianists became better informed and investigated the WTs, they re-discovered key color. In 1975, Herbert Anton Kellner concluded that Bach had written his music with key color in mind, and that Bach used a WT, not ET. But which WT? Kellner guessed at a WT which most tuners justifiably rejected as too speculative. Subsequent search concentrated on well known WTs such as Kirnberger, Werckmeister, and Young. They all produced key color but still left open the question of what Bach used. ***In 2004, Bradley Lehman proposed that the strange spirals at the top of the cover page of Bach’s “Well Tempered Clavier” manuscript represented a tuning diagram (see Larips.com), and used the diagram to produce a WT that is fairly close to Valloti.*** Bach’s tunings were mainly for harpsichord and organ, since pianos as we know them today didn’t exist at that time. One requirement of harpsichord tuning is that it be simple enough so that it can be done in about 10 minutes on a familiar instrument, and Lehman’s Bach tuning met that criterion. Thus we now have a pretty good idea of what temperament Bach used.

If we decide to adopt WT instead of ET, which WT should we standardize to? Firstly, the differences between the “good” WTs are not as large as the differences between ET and most WTs, so practically any WT you pick would be an improvement. We do not need to pick a specific WT - we can specify the best WT for each piece we play; this option is practical only for electronic and self-tuning pianos that can switch temperaments easily. In order to intelligently pick the “best” WT, we must know what we are seeking in a WT. We seek: (1) pure harmonies and (2) key color. Unfortunately, we can not have both because they tend to be mutually exclusive. Pure harmony is an improvement over ET, but is not as sophisticated as key color. We will encounter this type of phenomenon in “stretch” (see 5.j below) whereby the music sounds better if the intervals are tuned slightly sharp. Unlike stretch, however, key color is created by dissonances associated with the Pythagorean comma. ***With this caveat, therefore, we should pick a WT with the best key color and least dissonance, which is Young. If you want to hear what a clear harmony sounds like, try Kirnberger, which has the largest number of just intervals.***

We now see that picking a WT is not only a matter of solving the Pythagorean comma, but also of gaining key color to enhance music – in a way, we are creating something good from something bad. The price we pay is that composers must learn key color, but they have naturally done so in the past. It is certainly a joy to listen to music played in WT, but it is even more fascinating to *play* music in WT. Chopin is somewhat of an enigma in this regard because he loved the black keys and used keys far from “home” (home means near C major, with few accidentals, as normally tuned). He probably considered the black keys easier to play (once you learn FFP, section III.4.b, Ch. One), so that the fears many students feel when they see all those sharps and flats in Chopin’s music is not justified. Chopin used one tuner who later committed suicide, and there is no record of how he tuned. Who knows? Could it be that he tuned Chopin’s piano to favor the black keys? Because of the “far out” keys he tended to use, Chopin’s music benefits only slightly from

WT, as normally tuned and frequently hits WT wolves. ***Conclusions: We should get away from ET because of the joy of playing on WT; if we must pick one WT, it should be Young; otherwise, it is best to have a choice of WTs (as in electronic pianos); if you want to hear pure harmonies, try Kirnberger. The WTs will teach us key color which not only enhances the music, but also sharpens our sense of musicality.***

3. Tuning Tools

You will need one tuning lever (also called tuning hammer), several rubber wedges, a felt muting strip, and one or two tuning forks and ear plugs or ear muffs. Professional tuners nowadays also use electronic tuning aids, but we will not consider them here because they are not cost effective for the amateur. We shall learn aural tuning -- tuning by ear. All professional tuners must be good aural tuners even if they use electronic tuning aids. Grands use the larger rubber muting wedges and uprights require the smaller ones with wire handles. Four wedges of each type will suffice. You can buy these by mail order or you can ask your tuner to buy them for you. The most popular muting strips are felt, about 4 ft long, 5/8 inch wide. They are used to mute the two side strings of the 3-string notes in the octave used to "set the bearings" (section 6). They also come as ganged rubber wedges but these don't work as well. The strips also come in rubber, but rubber does not mute as well and is not as stable as felt (they can move or pop out while tuning). The disadvantage of the felt strip is that it will leave a layer of felt fiber on the soundboard after you are finished, which will need to be vacuumed out.

A high quality tuning lever consists of an extendable handle, a head that attaches to the tip of the handle, and an interchangeable socket that screws into the head. It is a good idea to have a piano tuning pin which you can insert into the socket using a vise grip so that you can screw the socket into the head firmly. Otherwise, if you grab on the socket with the vise grip, you can scratch it up. If the socket is not firmly in the head, it will come off during tuning. Most pianos require a #2 socket, unless your piano has been re-strung using larger tuning pins. The standard head is a 5 degree head. This "5 degree" is the angle between the socket axis and the handle. Both the heads and sockets come in various lengths, but "standard" or "medium" length will do.

Get two tuning forks, A440 and C523.3 of good quality. Develop a good habit of holding them at the narrow neck of the handle so that your fingers do not interfere with their vibrations. Tap the tip of the fork firmly against a muscular part of your knee and test the sustain. It should be audible for 10 to 20 seconds when placed close to your ear. The best way to hear the fork is to place the tip of the handle against the triangular cartilage (ear lobe) that sticks out towards the middle of the ear hole. You can adjust the loudness of the fork by pressing the ear lobe in or out using the end of the fork. Do not use whistles; they are too inaccurate. Ear muffs are necessary protection devices, since ear damage is a tuner's occupational hazard. It is necessary to hit the keys hard (pound the keys -- to use a tuners' jargon) in order to tune properly as explained below, and the sound intensity from such pounding can damage the ear, resulting in hearing loss and tinnitus.

4. Preparation

Prepare for tuning by removing the music stand so that the tuning pins are accessible (grand piano). For the following section, you need no further preparation. For "setting the bearings", you need to mute all the side strings of the triplet strings within the "bearings octave" using the muting strip so that when you play any note within this octave, only the center string will vibrate. You will probably have to mute close to two octaves depending on the tuning algorithm. Try out the entire algorithm first to determine the highest and lowest notes you need to mute. Then mute all the notes in between. Use the rounded end of the wire handle of the upright mute to press the felt into the spaces between the outer strings of adjacent notes.

5. Getting Started

Without a teacher, you cannot dive right into tuning. You will quickly lose your bearing and have no idea how to get back. Therefore, ***you must first learn/practice certain tuning procedures so that you don't end up with an unplayable piano that you cannot restore.*** This section is an attempt to get you to the level at which you might try a real tuning, without running into those types of difficulties.

The first things to learn are what not to do, in order to avoid destroying the piano, which is not difficult. If you tighten a string too much, it will break. The initial instructions are designed to minimize string breakage from amateurish moves, so read them carefully. Plan ahead so that you know what to do in case you break a string. A broken string per se, even when left for long periods of time, is no disaster to a piano. However, it is probably wise to conduct your first practices just before you intend to call your tuner. Once you know how to tune, string breakage is a rare problem except for very old or abused pianos. The tuning pins are turned by such small amounts during tuning that the strings almost never break. One common mistake beginners make is to place the lever on the wrong tuning pin. Since turning the pin does not cause any audible change, they keep turning it until the string breaks. One way to avoid this is to always start by tuning flat, as recommended below, and to ***never turn the pin without listening to the sound***.

The most important consideration for a starting tuner is to preserve the condition of the pinblock. The pressure of the pinblock on the pin is enormous. Now you will never have to do this, but if you were to hypothetically turn the pin 180 degrees very rapidly, the heat generated at the interface between pin and pinblock would be sufficient to cook the wood and alter its molecular structure. Clearly, all rotations of the pin must be conducted in slow, small, increments. If you need to remove a pin by turning it, rotate only a quarter turn (counter clock-wise), wait a moment for the heat to dissipate away from the interface, then repeat the procedure, etc.; without such precautions, the wood surrounding the pin will turn to charcoal.

I will describe everything assuming a grand piano, but the corresponding motion for the upright should be obvious. ***There are two basic motions in tuning. The first is to turn the pin so as to either pull or release the string. The second is to rock the pin back towards you (to pull on the string) or rock it forwards, towards the string, to release it.*** The rocking motion, if done to extreme, will enlarge the hole and damage the pinblock. Note that the hole is somewhat elliptical at the top surface of the pinblock because the string is pulling the pin in the direction of the major axis of the ellipse. Thus a small amount of backwards rocking does not enlarge the ellipse because the pin is always pulled into the front end of the ellipse by the string. Also, the pin is not straight but bent elastically towards the string by the pull of the string. Therefore, the rocking motion can be quite effective in moving the string. Even a small amount of forward rocking, within the elasticity of the wood, is harmless. It is clear from these considerations that ***you must use the rotation whenever possible, and use the rocking motion only when absolutely necessary***. Only very small rocking motions should be used. For the extreme high notes (top two octaves), the motion needed to tune the string is so small that you may not be able to control it adequately by rotating the pin. Rocking provides much finer control, and can be used for that final miniscule motion to bring it into perfect tune.

Now, what is the easiest way to start practicing? First, let's choose the easiest notes to tune. These lie in the C3-C4 octave. Lower notes are harder to tune because of their high harmonic content, and the higher notes are difficult because the amount of pin rotation needed to tune becomes extremely small. Note that middle C is C4; the B just below it is B3 and the D immediately above middle C is D4. That is, the octave number 1, 2, 3, . . . changes at C, not at A. Let's choose G3 as our practice note and start numbering the strings. Each note in this region has 3 strings. Starting from the left, let's number the strings 123 (for G3), 456 (for G3#), 789 (for A3), etc. Place a wedge between strings 3 and 4 in order to mute string 3 so that when you play G3, only 1 and 2 can vibrate. Place the wedge about midway between the bridge and agraffe.

There are two basic types of tuning: unison and harmonic. In unison, the two strings are tuned identically. In harmonic tuning, one string is tuned to a harmonic of the other, such as thirds, fourths, fifths, and octaves. The three strings of each note are tuned in unison, which is easier than harmonic tuning, so let's try that first.

a. Engaging and Manipulating the Tuning Lever. If your tuning lever has adjustable length, pull it out about 3 inches and lock it in place. Hold the handle of the tuning lever in your RH and the socket in your LH and engage the socket over the pin. Orient the handle so that it is approximately perpendicular to the strings and pointing to your right. Lightly jiggle the handle around the pin with your RH and engage the socket with your LH so that the socket is securely engaged, as far down as it will go. From day one, ***develop a habit of jiggling the socket so that it is securely engaged.*** At this point, the handle is probably not perfectly perpendicular to the strings; choose the socket position so that the handle is as close to perpendicular as the socket position will allow. Now find a way to brace your RH so that you can apply firm pressure on the lever. For example, you can grab the tip of the handle with the thumb and one or two fingers, and brace the arm on the wooden piano frame or brace your pinky against the tuning pins directly under the handle. If the handle is closer to the plate (the metal frame) over the strings, you might brace your hand against the plate. You should not grab the handle like you hold a tennis racket and push-pull to turn the pin -- this will not give enough control. You may be able to do that after years of practice, but in the beginning, grabbing the handle and pushing without bracing against something is too difficult to control accurately. So ***develop a habit of***

finding good places to brace your hand against, depending on where the handle is. Practice these positions making sure that you can exert controlled, constant, powerful pressure on the handle, but do not turn any pins yet.

The lever handle must point to the right so that when you turn it towards you (the string goes sharp), you counteract the force of the string and free the pin from the front side of the hole (towards the string). This allows the pin to turn more freely because of the reduction in friction. When you tune flat, both you and the string are trying to turn the pin in the same direction. Then the pin would turn too easily, except for the fact that both your push and the string's pull jam the pin against the front of the hole, increasing the pressure (friction) and preventing the pin from rotating too easily. If you had placed the handle to the left, you run into trouble for both the sharp and flat motions. For the sharp motion, both you and the string jam the pin against the front of the hole, making it doubly difficult to turn the pin, and damaging the hole. For the flat motion, the lever tends to lift the pin off from the front edge of the hole and reduces the friction. In addition, both the lever and string are turning the pin in the same direction. Now the pin now turns too easily. The lever handle must point to the left for uprights. Looking down on the tuning pin, the lever should point to 3 o'clock for grands and to 9 o'clock for uprights. In both cases, the lever is on the side of the last winding of the string.

Professional tuners do not use these lever positions. Most use 1-2 o'clock for grands and 10-11 o'clock for uprights and Reblitz recommends 6 o'clock for grands and 12 o'clock for uprights. In order to understand why, let's first consider positioning the lever at 12 o'clock on a grand (it is similar at 6 o'clock). Now the friction of the pin with the pinblock is the same for both the sharp and flat motions. However, in the sharp motion, you are going against the string tension and in the flat motion, the string is helping you. Therefore, the difference in force needed between sharp and flat motions is much larger than the difference when the lever is at 3 o'clock, which is a disadvantage. However, unlike the 3 o'clock position, the pin does not rock back and forth during tuning so that when you release the pressure on the tuning lever, the pin does not spring back -- it is more stable -- and you can get higher accuracy.

The 1-2 o'clock position is a good compromise that makes use of both of the advantages of the 3 o'clock and 12 o'clock positions. Beginners do not have the accuracy to take full advantage of the 1-2 o'clock position, so my suggestion is to start with the 3 o'clock position, which should be easier at first, and transition to the 1-2 o'clock position as your accuracy increases. When you become good, the higher accuracy of the 1-2 o'clock position can speed up your tuning so that you can tune each string in a few seconds. At the 3 o'clock position, you will need to guess how much the pin will spring back and over-tune by that amount, which takes more time. Clearly, exactly where you place the lever will become more important as you improve.

b. Setting the Pin. ***It is important to "set the pin" correctly in order for the tuning to hold.*** If you look down on the pin, the string comes around the right side of the pin (grands -- it is on the left for uprights) and twirls around it. Therefore if you rotate the pin cw (clockwise), you will tune sharp and vice versa. The string tension is always trying to rotate the pin ccw (counter clock-wise, or flat). Normally, a piano de-tunes flat as you play it. However, because the grip of the pinblock on the pin is so strong, the pin is never straight but is always twisted.

If you rotate it cw and stop, the top of the pin will be twisted cw with respect to the bottom. In this position, the top of the pin wants to rotate ccw (the pin wants to untwist) but can't because it is held by the pinblock. Remember that the string is also trying to rotate it ccw. The two forces together can be sufficient to quickly de-tune the piano flat when you play something loud.

If the pin is turned ccw, the opposite happens -- the pin will want to untwist cw, which opposes the string force. This reduces the net torque on the pin, making the tuning more stable. In fact, you can twist the pin so far ccw that the untwisting force is much larger than the string force and the piano can then de-tune itself sharp as you play. Clearly, you must properly "set the pin" in order produce a stable tuning. This requirement will be taken into account in the following tuning instructions.

c. Tuning Unisons. Now engage the tuning lever on the pin for string 1. We will tune string 1 to string 2. ***The motion you will practice is: (1) flat, (2) sharp, (3) flat, (4) sharp and (5) flat (tune).*** Except for (1), each motion must be smaller than the previous one. As you improve, you will add or eliminate steps as you see fit. We are assuming that the two strings are almost in tune. As you tune, you must follow two rules: ***(A) never turn the pin unless you are simultaneously listening to the sound, and (B) never release the pressure on the tuning lever handle until that motion is complete.***

For example, let's start with motion (1) flat: keep playing the note every second or two with the LH so that there is a continuous sound, while pushing the end of the lever handle away from you with the thumb and 2nd finger. Play the note in such a way as to maintain a continuous sound. Don't lift the key for any length of time, as this will stop the sound. Keep the key down and play with a quick up-and-down motion so that there is no break in the sound. The pinky and the rest of your RH should be braced against the piano. The required motion of the lever is a few millimeters. First, you will feel an increasing resistance, and then the pin will start to rotate. Before the pin begins to rotate, you should hear a change in the sound. As you turn the pin, listen for string 1 going flat, creating a beat with the center string; the beat frequency increasing as you turn. Stop at a beat frequency of 2 to 3 per second. The tip of the tuning lever should move less than one cm. Remember, never rotate the pin when there is no sound because you will immediately lose track of where you are with respect to how the beats are changing. Always maintain constant pressure on the lever until that motion is completed for the same reason.

What is the rationale behind the above 5 motions? Assuming that the two strings are in reasonable tune, you first tune string 1 flat in step (1) to make sure that in step (2) you will pass the tuning point. This also protects against the possibility that you had placed the lever on the wrong tuning pin; as long as you are turning flat, you will never break a string.

After (1) you are flat for sure, so in step (2) you can listen to the tuning point as you pass through it. Go past it until you hear a beat frequency of about 2 to 3 per second on the sharp side, and stop. Now you know where the tuning point is, and what it sounds like. The reason for going so far past the tuning point is that you want to set the pin, as explained above.

Now go back flat again, step (3), but this time, stop just past the tuning point, as soon as you can hear any incipient beats. The reason why you don't want to go too far past the tuning point is that you don't want to undo the "setting of the pin" in step (2). Again, note exactly what the tuning point sounds like. It should sound perfectly clean and pure. This step assures that you did not set the pin too far.

Now conduct the final tuning by going sharp (step 4), by as little as you can beyond perfect tune, and then bringing it into tune by turning flat (step 5). Note that your final motion must always be flat in order to set the pin. Once you become good, you might be able to do the whole thing in two motions (sharp, flat), or three (flat, sharp, flat).

Ideally, from step (1) to final tune, you should maintain the sound with no stoppage, and you should always be exerting pressure on the handle; never letting go of the lever. Initially, you will probably have to do this motion by motion. When you become proficient, the whole operation will take only a few seconds. But at first, it will take *a lot* longer. Until you develop your "tuning muscles" you will tire quickly and may have to stop from time to time to recover. Not only the hand/arm muscles, but the mental and ear concentration required to focus on the beats can be quite a strain and can quickly cause fatigue. You will need to develop "tuning stamina" gradually. Most people do better by listening through one ear than through both, so turn your head to see which ear is better.

The most common mistake beginners make at this stage is to try to listen for beats by pausing the tuning motion. Beats are difficult to hear when nothing is changing. If the pin is not being turned, it is difficult to decide which of the many things you are hearing is the beat that you need to concentrate on. ***What tuners do is to keep moving the lever and then listening to <u>the changes in the beats</u>.*** When the beats are changing, it is easier to identify the particular beat that you are using for tuning that string. Therefore, slowing down the tuning motion doesn't make it easier. Thus the beginner is between a rock and a hard place. Turning the pin too quickly will result in all hell breaking loose and losing track of where you are. On the other hand, turning too slowly will make it difficult to identify the beats. Therefore work on determining the range of motion you need to get the beats and the right speed with which you can steadily turn the pin to make the beats come and go. In case you get hopelessly lost, mute strings 2 and 3 by placing a wedge between them, play the note and see if you can find another note on the piano that comes close. If that note is lower than G3, then you need to tune it sharp to bring it back, and vice versa.

Now that you have tuned string 1 to string 2, reposition the wedge so that you mute 1, leaving 2 and 3 free to vibrate. Tune 3 to 2. When you are satisfied, remove the wedge and see if the G is now free of beats. You have tuned one note! If the G was in reasonable tune before you started, you haven't accomplished much, so find a note nearby that is out of tune and see if you can "clean it up". Notice that in this scheme, you are always tuning one single string to another single string. In principle, if you are really good, strings 1 and 2 are in perfect tune after you finish tuning 1, so you don't need the wedge any more. You should be able to tune 3 to 1 and 2 vibrating together. In practice this doesn't work until you become really proficient. This is because of a phenomenon called sympathetic vibration.

d. Sympathetic Vibrations. The accuracy required to bring two strings into perfect tune is so high that it is a nearly impossible job. It turns out that, in practice, this is made easier because ***when the frequencies approach within a certain interval called the "sympathetic vibration range", the two strings change their frequencies towards each other so that they vibrate with the same frequency.*** This happens because the two strings are not independent, but are coupled to each other at the bridge. When coupled, the string vibrating at the higher frequency will drive the slower string to vibrate at a slightly higher frequency, and vice versa. The net effect is to drive both frequencies towards the average frequency of the two. Thus when you tune 1 and 2 unison, you have no idea whether they are in perfect tune or merely within the sympathetic vibration range (unless you are an experienced tuner). In the beginning, you will most likely not be in perfect tune.

Now if you were to try to tune a third string to the two strings in sympathetic vibration, the third string will bring the string closest to it in frequency into sympathetic vibration. But the other string may be too far off in frequency. It will break off the sympathetic vibration, and will sound dissonant. The result is that no matter where you are, you will always hear beats -- the tuning point disappears! It might appear that if the third string were tuned to the average frequency of the two strings in sympathetic vibration, all three should go into sympathetic vibration. This does not appear to be the case unless all three frequencies are in perfect tune. If the first two strings are sufficiently off, a complex transfer of energy takes place among the three strings. Even when the first two are close, there will be higher harmonics that will prevent all beats from disappearing when a third string is introduced. In addition, there are frequent cases in which you cannot totally eliminate all beats because the two strings are not identical. Therefore, a beginner will become totally lost, if he were to try to tune a third string to a pair of strings. ***Until you become proficient at detecting the sympathetic vibration range, always tune one string to one; never one to two.*** In addition, just because you tuned 1 to 2 and 3 to 2, it does not mean that the three strings will sound "clean" together. Always check; if it is not completely "clean", you will need to find the offending string and try again.

Note the use of the term "clean". With enough practice, you will soon get away from listening to beats, but instead, you will be looking for a pure sound that results somewhere within the sympathetic vibration range. This point will depend on what types of harmonics each string produces. In principle, when tuning unisons, you are trying to match the fundamentals. In practice, a slight error in the fundamentals is inaudible compared to the same error in a high harmonic. Unfortunately, these high harmonics are generally not exact harmonics but vary from string to string. Thus, when the fundamentals are matched, these high harmonics create high frequency beats that make the note "muddy" or "tinny". When the fundamentals are de-tuned ever so slightly so that the harmonics do not beat, the note "cleans up". ***Reality is even more complicated because some strings, especially for the lower quality pianos, will have extraneous resonances of their own, making it impossible to completely eliminate certain beats.*** These beats become very troublesome if you need to use this note to tune another one.

e. Making that Final Infinitesimal Motion. We now advance to the next level of difficulty. Find a note near G5 that is slightly out of tune, and repeat the above procedure for G3. The tuning motions are now much smaller for these higher notes, making them more difficult. In fact you may not be able to achieve sufficient accuracy by rotating the pin. We need to learn a new skill. ***This skill requires you to pound on the notes, so put on your ear muffs or ear plugs.***

Typically, you would get through motion (4) successfully, but for motion (5) the pin would either not move or jump past the tuning point. ***In order to make the string advance in smaller increments, press on the lever at a pressure slightly below the point at which the pin will jump. Now strike hard on the note while maintaining the same pressure on the lever.*** The added string tension from the hard hammer blow will advance the string by a small amount. Repeat this until it is in perfect tune. It is important to never release the pressure on the lever and to keep the pressure constant during these repeated small advances, or you will quickly lose track of where you are. When it is in perfect tune, and you release the lever, the pin might spring back, leaving the string slightly flat. You will have to learn from experience, how much it will spring back and compensate for it during the tuning process.

The need to pound on the string to advance it is one reason you often hear tuners pounding on the piano. It is a good idea to get into the habit of pounding on most of the notes because this stabilizes the tuning. The resulting sound can be so loud as to damage the ear, and one of the occupational hazards of tuners is ear damage from pounding. Use of ear plugs is the solution. When pounding, you will still easily hear the beats even with ear plugs. The most common initial symptom of ear damage is tinnitus (ringing in the ear). You can minimize the pounding force by increasing the pressure on the lever. Also, less pounding is required if the lever is parallel to the string instead of perpendicular to it, and even less if you point it to the left. This is another reason why many tuners use their levers more parallel to the strings than perpendicular. Note that there are two ways to point it parallel: towards the strings (12 o'clock) and away from the strings (6 o'clock). As you gain experience, experiment with different lever positions as this will give you many options for solving various problems. For example, with the most popular 5-degree head on your lever, you may not be able to point the lever handle to the right for the highest octave because it may hit the wooden piano frame.

f. Equalizing String Tension. ***Pounding is also helpful for distributing the string tension more evenly among all the non-speaking sections of the string, such as the duplex scale section, but especially in the section between the capo bar and the agraffe.*** There is controversy as to whether equalizing the tension will improve the sound. There is little question that the even tension will make the tuning more stable. However, whether it makes a *material* difference in stability may be debatable, especially if the pins were correctly set during tuning. In many pianos, the duplex sections are almost completely muted out using felts because they might cause undesirable oscillations. In fact, the over-strung section is muted out in almost every piano. Beginners need not worry about the tension in these "non-speaking" sections of the strings. Thus heavy pounding, though a useful skill to learn, is not necessary for a beginner.

My personal opinion is that the sound from the duplex scale strings does not add to the piano sound. In fact, this sound is inaudible and is muted out when they become audible in the bass. Thus the “art of tuning the duplex scale” is a myth although most piano tuners (including Reblitz!) have been taught to believe it by the manufacturers, because it makes for a good sales pitch. The only reason why you want to tune the duplex scale is that the bridge wants to be at a node of both the speaking and non-speaking lengths; otherwise, tuning becomes difficult, sustain may be shortened, and you lose uniformity. Using mechanical engineering terminology, we can say that tuning the duplex scale optimizes the vibrational impedance of the bridge. In other words, the myth does not detract from the tuners’ ability to do their job. Nonetheless, a proper understanding is certainly preferable. The duplex scale is needed to allow the bridge to move more freely, not for producing sound. Obviously, the duplex scale will improve the quality of the sound (from the speaking lengths) because it optimizes the impedance of the bridge, but not because it produces any sound. The facts that the duplex scale is muted out in the bass and is totally inaudible in the treble prove that the sound from the duplex scale is not needed. Even in the inaudible treble, the duplex scale is “tuned” in the sense that the aliquot bar is placed at a location such that the length of the duplex part of the string is a harmonic length of the speaking section of the string in order to optimize the impedance (“aliquot” means fractional or harmonic). If the sound from the duplex scale were audible, the duplex scale would have to be tuned as carefully as the speaking length. However, for impedance matching, the tuning need only be approximate, which is what is done in practice. Some manufacturers have stretched this duplex scale myth to ridiculous lengths by claiming a second duplex scale on the pin side. Since the hammer can only transmit tensile strain to this length of string (because of the rigid Capo bar), this part of the string cannot vibrate to produce sound. Consequently, practically no manufacturer specifies that the non-speaking lengths on the pin side be tuned.

g. Rocking It in the Treble. ***The most difficult notes to tune are the highest ones.*** Here you need incredible accuracy in moving the strings and the beats are difficult to hear. Beginners can easily lose their bearing and have a hard time finding their way back. One advantage of the need for such small motions is that now, you can use the pin-rocking motion to tune. Since the motion is so small, rocking the pin does not damage the pinblock. ***To rock the pin, place the lever parallel to the strings and pointing towards the strings (away from you). To tune sharp, pull up on the lever, and to tune flat, press down.*** First, make sure that the tuning point is close to the center of the rocking motion. If it is not, rotate the pin so that it is. Since this rotation is much larger than that needed for the final tuning, it is not difficult, but remember to correctly set the pin. It is better if the tuning point is front of center (towards the string), but bringing it too far forward would risk damaging the pinblock when you try to tune flat. Note that tuning sharp is not as damaging to the pinblock as tuning flat because the pin is already jammed up against the front of the hole.

h. Rumblings in the Bass. ***The lowest bass strings are second in difficulty (to the highest notes) to tune.*** These strings produce sound composed mostly of higher harmonics. Near the tuning point, the beats are so slow and soft that they are difficult to hear. Sometimes, you can "hear" them better by pressing your knee against the piano to feel for the vibrations than by trying to hear them with your ears, especially in the single string section. You can practice unison tuning only down to the last double string section. ***See if you can recognize the high pitched, metallic, ringing beats that are prevalent in this region.*** Try eliminating these and see if you need to de-tune slightly in order to eliminate them. If you can hear these high, ringing, beats, it means that you are well on your way. Don't worry if you can't even recognize them at first--beginners are not expected to.

i. Harmonic Tuning. Once you are satisfied with your ability to tune unisons, start practicing tuning octaves. Take any octave near middle C and mute out the upper two side strings of each note by inserting a wedge between them. Tune the upper note to the one an octave below, and vice versa. As with unisons, start near middle C, then work up to the highest treble, and then practice in the bass. Repeat the same practice with 5ths, 4ths, and major 3rds.

After you can tune perfect harmonics, try de-tuning to see if you can hear the increasing beat frequency as you deviate very slightly from perfect tune. Try to identify various beat frequencies, especially 1bps (beat per second) and 10bps, using 5ths. These skills will come in handy later.

j. What is Stretch? Harmonic tuning is always associated with a phenomenon called stretch. Harmonics in piano strings are never exact because real strings attached to real ends do not behave like ideal mathematical strings. This property of inexact harmonics is called inharmonicity. The difference between the actual and theoretical harmonic frequencies is called stretch. Experimentally, it is found that most harmonics are sharp compared to their ideal theoretical values, although there can be a few that are flat.

According to one research result (Young, 1952), stretch is caused by inharmonicity due to the stiffness of strings. Ideal mathematical strings have zero stiffness. Stiffness is what is called an extrinsic property -- it depends on the dimensions of the wire. If this explanation is correct, then stretch must also be extrinsic. Given the same type of steel, the wire is stiffer if it is fatter or shorter. One consequence of this dependence on stiffness is an increase in the frequency with harmonic mode number; i.e., the wire appears stiffer to harmonics with shorter wavelengths. Stiffer wires vibrate faster because they have an extra restoring force, in addition to the string tension. This inharmonicity from stiffness has been calculated to within several percent accuracy so that the theory appears to be sound, and this single mechanism appears to account for most of the observed stretch.

These calculations show that stretch is about 1.2 cents for the second mode of vibration at C4 and doubles about every 8 semitones at higher frequency (C4 = middle C, the first mode is the lowest, or fundamental frequency, one cent is one hundredth of a semitone, and there are 12 semitones in an octave). The stretch becomes smaller for lower notes, especially below C3, because the wire wound strings are quite flexible. Stretch increases rapidly with mode number and decreases even more rapidly with string length. In principle, stretch is smaller for larger pianos and larger for lower tension pianos if the same diameter strings are used. Stretch presents problems in scale design since abrupt changes in string type, diameter, length, etc., will produce a discontinuous change in stretch. Very high mode harmonics, if they happen to be unusually loud, present problems in tuning because of their large stretch -- tuning out their beats could throw the lower, more important, harmonics audibly out of tune.

Since larger pianos tend to have smaller stretch, but also tend to sound better, one might conclude that smaller stretch is better. However, the difference in stretch is generally small, and the tone quality of a piano is largely controlled by properties other than stretch.

In harmonic tuning you tune, for example, the fundamental or a harmonic of the upper note to a higher harmonic of the lower note. The resulting new note is not an exact multiple of the lower note, but is sharp by the amount of stretch. What is so interesting about stretch is that a scale with stretch produces "livelier" music than one without! This has caused some tuners to tune in double octaves instead of single octaves, which increases the stretch.

The amount of stretch is unique to each piano and, in fact, is unique to each note of each piano. Modern electronic tuning aids are sufficiently powerful to record the stretch for all the desired notes of individual pianos. Tuners with electronic tuning aids can also calculate an average stretch for each piano or stretch function and tune the piano accordingly. In fact, there are anecdotal accounts of pianists requesting stretch in excess of the natural stretch of the piano. In aural tuning, stretch is naturally, and accurately, taken into account. Therefore, although stretch is an important aspect of tuning, the tuner does not have to do anything special to include stretch, if all you want is the natural stretch of the piano.

k. Precision, Precision, Precision. ***The name of the game in tuning is precision.*** All tuning procedures are arranged in such a way that you tune the first note to the tuning fork, the second to the first, etc., in sequence. Therefore, any errors will quickly add up. In fact, an error at one point will often make some succeeding steps impossible. This happens because you are listening for the smallest hint of beats and if the beats were not totally eliminated in one note, you can't use it to tune another as those beats will be clearly heard. In fact, for beginners, this will happen frequently before you learn how precise you need to be. When this happens, you will hear beats that you can't eliminate. In that case, go back to your reference note and see if you hear the same beat; if you do, there is the source of your problem -- fix it.

The best way to assure precision is by checking the tuning. Errors occur because every string is different and you are never sure that the beat you hear is the one you are looking for, especially for the beginner. Another factor is that you need to count beats per second (bps), and your idea of, say 2bps, will be different on different days or at different times of the same day until you have those "beat speeds" well memorized. Because of the critical importance of precision, it pays to check each tuned note. This is especially true when "setting the bearings" which is explained below. Unfortunately, it is just as difficult to check as it is to tune correctly; that is, a person who cannot tune sufficiently accurately is usually unable to perform a meaningful check. In addition, if the tuning is sufficiently off, the checking doesn't work. Therefore, ***I have provided methods of tuning below that use a minimum of checks.*** The resulting tuning will not be very good initially, for Equal temperament. The Kirnberger temperament (see below) is easier to tune accurately. On the other hand, beginners can't produce good tunings anyway, no matter what methods they use. At least, the procedures presented below will provide a tuning which should not be a disaster and which will improve as your skills improve. ***In fact, the procedure described here is probably the fastest way to learn.*** After you have improved sufficiently, you can then investigate the checking procedures, such as those given in Reblitz, or "Tuning" by Jorgensen.

6. Tuning Procedures and Temperament

Tuning consists of "setting the bearings" in an octave near middle C, and then "copying" this octave to all the other keys. You will need various harmonic tunings to set the bearings and only the middle string of each note in the "bearings octave" is initially tuned. The "copying" is performed by tuning in octaves. Once one string of each note is tuned in this way, the remaining string(s) of each note are tuned in unison.

In setting the bearings, we must choose which temperament to use. As explained in section 2 above, most pianos today are tuned to Equal temperament (ET), but the historical temperaments may be showing signs of gaining popularity, especially the Well temperaments (WT). Therefore, I have chosen ET and one WT, Kirnberger II (K-II), for this chapter. K-II is one of the easiest temperaments to tune; therefore, we will visit that first. Most people who are unfamiliar with the different temperaments may not notice any difference at first between ET and K-II; they will both sound terrific compared to a piano out of tune. Most pianists, on the other hand, should hear a distinct difference and be able to form an opinion or preference if certain pieces of music are played and the differences are pointed out to them. The easiest way to listen to the differences for the uninitiated is to use an electronic piano that has all these temperaments built into it, and to play the same piece, using each temperament. For an easy test piece, try Beethoven's Moonlight Sonata, 1st movement; for a more difficult piece, try the 3rd movement of his Waldstein Sonata. Also, try some of your favorite Chopin pieces. My suggestion is for a beginner to learn K-II first so that you can get started without too much difficulty, and then learn ET when you can tackle more difficult stuff. One drawback of this scheme is that you may like K-II so much over ET that you may never decide to learn ET. Once you get used to K-II, ET will sound a little lacking, or "muddy". However, you cannot really be considered a tuner unless you can tune ET. Also, there are many WTs that you may want to look into, that are superior to K-II in several respects (see 2.c).

You can start tuning ET anywhere, but most tuners use the A440 fork to start, because orchestras generally tune to A440. The objective in K-II is to have C major and as many "nearby" scales as possible to be just (have perfect chords), so the tuning is started from middle C (C4 = 261.6, but most tuners will use a C523.3 tuning fork to tune C4 partly because the higher harmonic gives twice the accuracy). Now, the A that results from K-II tuned from the correct C does not result in A440. Therefore, you will need two tuning forks: A for ET and C for K-II. Alternatively, you can just start with only a C fork and start tuning ET from C. Having two tuning forks is an advantage because whether you start from C or from A, you can check your ET when you get to the other note.

a. Tuning the Piano to the Tuning Fork. One of the most difficult steps in the tuning process is tuning the piano to the tuning fork. This difficulty arises from two causes: (1) the tuning fork has a different (usually shorter) sustain than the piano so that the fork dies off before you can make an accurate comparison and (2) the fork puts out a pure sine wave, without the loud harmonics of the piano strings. Therefore, you cannot use beats with higher harmonics to increase the accuracy of the tuning as you can with two piano strings. One advantage of electronic tuners is that they can be programmed to provide square wave reference tones that contain large numbers of high harmonics. These high harmonics (they create those sharp corners of square waves – you will need to know polynomial math or Fourier transforms to understand this) are useful for increasing the tuning accuracy. We must therefore solve these two problems in order to tune the piano accurately to the tuning fork.

Both difficulties can be solved if we can use the piano as the tuning fork and make this transfer from fork to piano using some high piano harmonic. To accomplish such a transfer, find any note within the muted notes that makes loud beats with the fork. If you can't find any, use the note a half tone down or up; for example, for tuning fork A, use Ab or A# on the piano. If these beat frequencies are a bit too high, try these same notes an octave lower. Now tune the A on the piano so it makes the same frequency beats with these reference notes (Ab, A#, or any other note you had picked). The best way to hear the tuning fork is to press it against your ear lobe, as described above, section 3, or to press it against any large, hard, flat surface.

b. Kirnberger II. Mute all side strings from F3 to F4. Tune C4 (middle C) to the fork. Then use

C4 to tune G3 (4th), E4 (3rd), F3 (5th), and F4 (4th), and
G3 to tune D4 (5th) and B3 (3rd). Then use
B3 to tune F#3 (4th),
F#3 to tune Db4 (5th),
F3 to tune Bb3 (4th),
Bb3 to tune Eb4 (4th) and
Eb4 to tune Ab3 (5th). All tunings up to here are just. Now tune A3 such that the F3-A3 and A3-D4 beat frequencies are the same.

You are done with setting the bearings!

Now tune up in just octaves to the highest notes, then tune down to the lowest notes, using the bearings octave as reference. In all these tunings, tune just one new octave string while muting the others, then tune the remaining one or two strings in unison to the newly tuned string.

This is one time you might break the "tune one string against one" rule. If your reference note is a (tuned) 3-string note, use it as it is. This will test the quality of your tuning. If you have a hard time using it to tune a new single string, then your unison tuning of the reference note may not have been sufficiently accurate and you should go back and clean it up. Of course, if after considerable effort, you cannot tune 3 against 1, you will have no choice but to mute two of the three in order to advance. When all the treble and bass notes are done, the only un-tuned strings left are the ones you muted for setting the bearings. Tune these in unison to their center strings, starting with the lowest note, by pulling the felt off one loop at a time.

c. Equal Temperament (ET). I present here the simplest ET tuning scheme. More accurate algorithms can be found in the literature (Reblitz, Jorgensen). No self-respecting professional tuner would use this scheme; however, when you get good at it, you can produce a useable ET. For the beginner, the more complete and precise schemes will not necessarily give better results. With those complex methods, a beginner can quickly get confused without any idea of what he did wrong. With the method shown here, you can quickly develop the ability to find out what you did wrong.

Mute the side strings from G3 to C#5. Tune A4 to the A440 fork. Tune A3 to A4. ***Then tune A3-E4 in a contracted 5th; by tuning E4 slightly flat until you hear a beat of about 1 Hz.*** The contracted 5th should beat a little under 1 Hz at the bottom of the muted range (A3) and about 1.5 Hz near the top. The beat frequencies of the 5ths should increase smoothly with increasing pitch. Keep tuning up in contracted 5ths until you cannot go up any more without leaving the muted range, then tune one octave down, and repeat this up-in-5ths and down-one-octave procedure until you get to A4. For example, you started with a contracted A3-E4. Then tune a contracted E4-B4. The next 5th will take you above the highest muted note, C#4, so tune one octave down, B4-B3. All octaves are, of course, just. To get the contracted 5th, start from just and tune flat in order to increase the beat frequency to the desired value and set the pin correctly at the same time. If you had done everything perfectly, the last D4-A4 should be a contracted 5th with a beat frequency of slightly over 1 Hz without any tuning. Then, you are done. You have just done a "circle of fifths". The miracle of the circle of fifths is that it tunes every note once, without skipping any within the A3-A4 octave!

If the final D4-A4 is not correct, you made some errors somewhere. In that case, reverse the procedure, starting from A4, going down in contracted 5ths and up in octaves, until you reach A3, where the final A3-E4 should be a contracted 5th with a beat frequency slightly under 1 Hz. For going down in 5ths, you create a contracted 5th by tuning the lower note sharp from just. However, this tuning action will not set the pin. In order to set the pin correctly, you must first go too sharp, and then decrease the beat frequency to the desired value. Therefore, going down in 5ths is more difficult than going up in 5ths.

An alternative method is to start with A and tune to C by going up in 5ths, and checking this C with a tuning fork. If your C is too sharp, your 5ths were not sufficiently contracted, and vice versa. Another variation is to tune up in 5ths from A3 a little over half way, and then tune down from A4 to the last note that you tuned coming up.

Once the bearings are set, continue as described in the Kirnberger section above.

7. Making Minor Repairs (Voicing and Polishing the Capstans)

Once you start tuning, you cannot help but get involved in small repairs and conducting some maintenance.

a. Hammer Voicing. ***A common problem seen with many pianos is compacted hammers. The condition of the hammer is much more important to the proper development of piano technique and for cultivating performance skills, than many people realize.*** Numerous places in this book refer to the importance of practicing musically in order to acquire technique. But you can't play musically if the hammer can't do its job, a critical point that is overlooked even by many tuners (often because they are afraid that the extra cost will drive customers away). For a grand piano, a sure sign of compacted hammers is that you find the need to close the lid at least partially in order to play soft passages. Another sure sign is that you tend to use the soft pedal to help you play softly. Compacted hammers either give you a loud sound or none at all. Each note tends to start with an annoying percussive bang that is too strong, and the sound is overly bright. It is these percussive bangs that are so damaging to the tuners'/pianist's ear. A properly voiced piano enables control over the entire dynamic range and produces a more pleasing sound.

Let's first see how a compacted hammer can produce such extreme results. How do small, light hammers produce loud sounds by striking with relatively low force on strings under such high tension? If you were to try to push down on the string or try to pluck it, you will need quite a large force just to make a small sound. The answer lies in an incredible phenomenon that occurs when tightly stretched strings are struck at right angles to the string. ***It turns out that the force produced by the hammer at the instant of impact is theoretically infinite!*** This nearly infinite force is what enables the light hammer to overcome practically any achievable tension on the string and cause it to vibrate.

Here is the calculation for that force. Imagine that the hammer is at its highest point after striking the string (grand piano). The string at this point in time makes a triangle with its original horizontal position (this is just an idealized approximation, see below). The shortest leg of this triangle is the length between the agraffe and the impact point of the hammer. The second shortest leg is from the hammer to the bridge. The longest is the original horizontal configuration of the string, a straight line from bridge to agraffe. Now if we drop a vertical line from the hammer strike point down to the original string position, we get two right triangles back-to-back. These are two extremely skinny right triangles that have very small angles at the agraffe and at the bridge; we will call these small angles "theta"s.

The only thing we know at this time is the force of the hammer, but this is not the force that moves the string, because the hammer must overcome the string tension before the string will yield. That is, the string cannot move up unless it can elongate. This can be understood by considering the two right triangles described above. The string had the length of the long legs of the right triangles before the hammer struck, but after the strike, the string is the hypotenuse, which is longer. That is, if the string were absolutely inelastic and the ends of the string were rigidly fixed, no amount of hammer force will cause the string to move.

A simple analysis shows that the *extra* tension force F (in addition to the original string tension) produced by the hammer strike is given by f = Fsin(theta), where f is the force of the hammer. It does not matter which right triangle we use for this calculation (the one on the bridge side or on the agraffe side). Therefore, the extra string tension F = f/sin(theta). At the initial moment of the strike, theta = 0, and therefore

F = infinity! This happens because sin(0) = 0. Of course, F can get to infinity only if the string cannot stretch and nothing else can move. What happens in reality is that as F increases towards infinity, something gives (the string stretches, the bridge moves, etc.) so that the hammer begins to move the string and theta increases from zero, making F finite (but still many orders of magnitude larger than your finger force).

This force multiplication explains why a small child can produce quite a loud sound on the piano in spite of the hundreds of pounds of tension on the strings. It also explains why an ordinary person can break a string just playing the piano, especially if the string is old and has lost its elasticity. The lack of elasticity causes the F to increase far more than if the string were more elastic, the string cannot stretch, and theta remains close to zero. This situation is greatly exacerbated if the hammer is also compacted so that there is a large, flat, hard groove that contacts the string. In that case, the hammer surface has no give and the instantaneous "f" in the above equation becomes very large. Since all this happens near theta = 0 for a compacted hammer, the force multiplication factor is also increased. The result is a broken string.

The above calculation is a gross over-simplification and is correct only qualitatively. In reality, a hammer strike initially throws out a traveling wave towards the bridge, similarly to what happens when you grab one end of a rope and flick it. The way to calculate such waveforms is to solve certain differential equations that are well known. The computer has made the solution of such differential equations a simple matter and realistic calculations of these waveforms can now be made routinely. Therefore, although the above results are not accurate, they give a qualitative understanding of what is happening, and what the important mechanisms and controlling factors are.

For example, the above calculation shows that it is not the transverse vibration energy of the string, but the tensile force on the string, that is responsible for the piano sound. The energy imparted by the hammer is stored in the entire piano, not just the strings. This is quite analogous to the bow and arrow -- when the string is pulled, all the energy is stored in the bow, not the string. And all of this energy is transferred via the tension in the string. In this example, the mechanical advantage and force multiplication calculated above (near theta = 0) is easy to see. It is the same principle on which the harp is based.

The easiest way to understand why compacted hammers produce higher harmonics is to realize that the impact occurs in a shorter time. When things happen faster, the string generates higher frequency components in response to the faster event.

The above paragraphs make it clear that a compacted hammer will produce a large initial impact on the string whereas a properly voiced hammer will be much gentler on the string thus imparting more of its energy to the lower frequencies than the harmonics. Because the same amount of energy is dissipated in a shorter amount of time for the compacted hammer, the instantaneous sound level can be much higher than for a properly voiced hammer, especially at the higher frequencies. Such short sound spikes can damage the ear without causing any pain. Common symptoms of such damage are tinnitus (ringing in the ear) and hearing loss at high frequencies. Piano tuners, when they must tune a piano with such worn hammers, would be wise to wear ear plugs. It is clear that voicing the hammer is at least as important as tuning the piano, especially because we are talking about potential ear damage. An out-of-tune piano with good hammers does not damage the ear. Yet many piano owners will have their pianos tuned but neglect the voicing.

The two most important procedures in voicing are hammer re-shaping and needling. When the flattened strike point on the hammer exceeds about 1 cm, it is time to re-shape the hammer. Note that you have to distinguish between the string groove length and flattened area; even in hammers with good voicing, the grooves may be over 5 mm long. In the final analysis you will have to judge on the basis of the sound. Shaping is accomplished by shaving the "shoulders" of the hammer so that it regains its previous rounded shape at the strike point. It is usually performed using 1 inch wide strips of sandpaper attached to strips of wood or metal with glue or double sided tape. You might start with 80 grit garnet paper and finish it off with 150 grit garnet paper. The sanding motion must be in the plane of the hammer; never sand across the plane. There is almost never a need to sand off the strike point. Therefore, leave about 2 mm of the center of the strike point untouched.

Needling is not easy because the proper needling location and needling depth depend on the particular hammer (manufacturer) and how it was originally voiced. Especially in the treble, hammers are often voiced at the factory using hardeners such as lacquer, etc. Needling mistakes are generally irreversible. Deep needling is usually required on the shoulders just off the strike point. Very careful and shallow needling of the strike point area may be needed. The tone of the piano is extremely sensitive to shallow needling at the strike point, so that you must know exactly what you are doing. When properly needled, the hammer should allow you to control very soft sounds as well as produce loud sounds without harshness. You get the feeling of complete tonal control. You can now open your grand piano fully and play very softly without the soft pedal! You can also produce those loud, rich, authoritative tones.

b. Polishing the Capstans. Polishing the capstans can be a rewarding maintenance procedure. They may need polishing if they have not been cleaned in over 10 years, sometimes sooner. Press down on the keys slowly to see if you can feel a friction in the action. A frictionless action will feel like sliding an oily finger along a smooth glassware. When friction is present, it feels like the motion of a clean finger on squeaky clean glass. In order to be able to get to the capstans, you will need to lift the action off from the keys by unscrewing the screws that hold the action down for the grand. For uprights you generally need to unscrew the knobs that hold the action in place; make sure that the pedal rods, etc., are disengaged.

When the action is removed, the keys can be lifted out after removing the key stop rail. First make sure that all the keys are numbered so that you can replace them in the correct order. This is a good time to remove all the keys and clean any previously inaccessible areas as well as the sides of the keys. You can use a mild cleaning agent such as a cloth dampened with Windex for cleaning the sides of the keys.

See if the top, spherical contact areas of the capstans are tarnished. If they do not have a shiny polish, they are tarnished. Use any good brass/bronze/copper polish (such as Noxon) to polish and buff up the contact areas. Reassemble, and the action should now be much smoother.

References

Items in **bold** are reviewed below.

Bach Bibliography.
Bertrand, OTT., *Liszt et la Pedagogie du Piano, Collection Psychology et Pedaogie de la Musique*, (1978) E. A. P. France.
Boissier, August., *A Diary of Franz Liszt as Teacher 1831-32*, translated by Elyse Mach.
Bree, Malwine, *The Leschetizky Method*, Dover, Mineola, NY, 1977.
Bruser, Madeline, *The Art of Practicing*, Bell Tower, NY, 1997.
Cannel, Ward, and Marx, Fred, *How to play the piano despite years of lessons*, What music is, and how to make it at home, Crown & Bridge, NY, 1976.
Chan, Angela, *Comparative Study of the Methodologies of Three Distinguished Piano Teachers of the Nineteenth Century: Beethoven, Czerny and Liszt.*
Eigeldinger, Jean-Jacques, *Chopin, pianist and teacher as seen by his pupils*,Cambridge Univ. Press, 1986.
Elson, Margaret, *Passionate Practice*, Regent Press, Oakland, CA, 2002.
Fay, Amy, *Music Study in Germany*.
Fine, Larry, *The Piano Book*, Brookside Press, 4th Ed., Nov. 2000.
Fink, Seymour, *Mastering Piano Technique*, Amadeus Press, 1992.
Fischer, J. C., *Piano Tuning*, Dover, N.Y., 1975.
Five Lectures on the Acoustics of the Piano,, Royal Institute of Technology Seminar, Anders Askenfelt, Ed., Stockholm, May 27, 1988.
Fraser, Alan, *The Craft of Piano Playing*, Scarecrow Press, 2003.
Gieseking, Walter, and Leimer, Karl, *Piano Technique*, 2 books in one, Dover, NY,1972.
Gilmore, Don A., *In Pursuit of the Self-Tuning Piano*.
Howell, W. D., *Professional Piano Tuning*, New Era Printing Co., Conn. 1966.
Green, Barry, and Gallwey, Timothy, *The Inner Game of Music*, Doubleday, 1986.
Hinson, Maurice, *Guide to the Pianist's Repertoire*, 3rd Edition, Indiana Univ. Press, 2000.
Hofman, Josef, *Piano Playing, With Piano Questions Answered*, Dover, NY, 1909.
Jaynes, E. T., *The Physical Basis of Music.*
(Explanation of why Liszt could not teach, best description of Thumb Over method in literature.)
Jorgensen, Owen H, *Tuning*, Michigan St. Univ. Press, 1991.
Lhevine, Josef, *Basic Principles in Piano Playing*, Dover, NY, 1972.