The Craft of Piano Tuning

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Contents

Introduction

The craft of piano tuning is a collaboration between the ear and the hand: The ear monitors the changing pitch of a piano string as the hand adjusts its tension.

A tuner's ear can detect minute changes in the pitch of a piano string because it has become sensitive to certain aural sensations produced by two strings vibrating together, sensations that change a great deal when the pitch of one of the strings is altered slightly. A tuner's hand can accurately and stably control the tension of a piano string because it has become sensitive to the tactile sensations produced by the string and by the system through which its tension is adjusted.

Tuners develop these sensitivities of the ear and hand through practice: The ear imagines how a change in pitch might improve the sound of a piano, the hand attempts to make that change, and then the ear judges the results. By repeating this process over and over a tuner gradually becomes more expert, as the ear becomes more sensitive to the part of the sound of the string that is affected by pitch change and the hand becomes more capable of controlling that sound.

If we have an innate talent for piano tuning, we can become skilled tuners purely through this kind of repetitive practice, with very little conscious awareness of what our ear and hand are doing. But in learning to tune, most people find it useful to develop some analytical skills. Analysis can not only help us to develop sensitivity in our ears and hands more quickly and to solve problems more efficiently; it can also help us to examine the practices of other tuners, to understand why certain techniques are effective, to make our tunings more consistent and accurate, and to develop new techniques.

The aim of the two long essays that form the heart of this book—*Four Lectures on Basic Aural Piano Tuning* and *Fundamentals of*

Piano Tuning Technique—is to help tuners develop their analytical skills by describing key aspects of the physical systems that produce the sensations they experience in tuning. Essentially, the two essays are manuals of applied science: acoustics for the ear and mechanics (plus a bit of neuroscience and biomechanics) for the hand. These are the branches of science that have historically been most useful in describing the aural and tactile environment within which the practices of piano tuning have evolved.

But we should keep in mind that these two branches of science do not completely describe the environment within which we practice our craft. The risk of learning theories as complete and effective as the ones presented here is that they can easily distract our attention from whatever aspects of the tuning experience they don't describe. We are much more likely to accommodate those other aspects as we work if we use our knowledge of theory, not as the foundation of our practice, but as a tool to enhance it.

For example, piano tuners a hundred years ago had nothing like our current systematic understanding of inharmonicity, but the tunings they produced undoubtedly allowed for it even if those tunings didn't make sense in the light of the theories prevalent at the time. There are surely other aspects of piano tuning as it is practiced today that we don't understand but that tuners a hundred years from now (if there are any left) will be able to analyze and make a consistent part of their work. Recent advances in the psychology of perception, in chaos and turbulence theory, and in materials science all seem poised to make notable contributions to our understanding of our craft.

Science is concerned primarily with theory, so scientists learn to be comfortable with—indeed, to seek out—situations in which things don't work even though theory says they should. Those are precisely the situations that often lead to advances in science. But comfort with practices that don't work is disastrous to craftspeople. Instead, we learn to be comfortable with—indeed, to seek out—situations in which things work well even though they make no sense. Those are the situations in which we advance our craft and, moreover, in which we are of use to science, because they often indicate potentially fruitful avenues for exploration.

Since the theory of piano tuning does not completely describe its practice, it can't completely determine its practice. In other words, it is not possible for us say that, because of the dictates of theory, any particular practice in piano tuning is definitively correct or incorrect. In this book, therefore, I have refrained for the most part from advocating particular practices, preferring instead to point out the ones that I have observed to be common among skilled tuners. These practices are important for us to know about, not because they embody a theory, but because they have proven themselves to be effective.

Piano tuning resembles piano playing in many ways. Both are a collaborative effort of the ear and the hand in which the ear imagines a sound that the hand then attempts to produce. Both can be learned without analysis, yet both have accrued a sizable body of analytical theory. The theory in both cases is most useful when it is understood to be *descriptive* rather than *prescriptive*—in other words, to explain why skilled practitioners do what they do rather than to dictate what they ought to do. Expert piano tuners and expert piano players, even those who have made liberal use of analysis in developing their skills, are usually not consciously guided by theory in the course of their work. And ultimately, piano tuning, like piano playing, is judged not by how well it embodies a theory but by how well it fulfills its purpose.

But the purposes of piano playing and piano tuning are quite different: Piano playing is an art, whose purpose is to be musically expressive; while piano tuning is a craft, whose purpose is to make a piano more useful to a pianist.

A lack of analytical skills may not greatly impair the career of pianist, whose success is due more often to a distinctive sound than to an ability to describe the means by which it is produced. But piano tuners, who usually need to be able to make a variety of pianos useful to a variety of pianists in a variety of contexts, can benefit greatly from having well-developed analytical skills. Good analytical skills give a tuner access to a range of techniques and tactics, whereas a lack of analytical skills tends to limit a tuner to one style of tuning.

The pianist's ear is fundamentally different from the tuner's ear.

The pianist's ear must be sensitive to the artistic possibilities of piano sound and so learns to perceive it as an integrated whole. Pianists often do not distinguish the aspect of piano sound that can be altered by tuning from its other aspects.

The tuner's ear must be able not only to experience the sound of a piano as a pianist would, but also to determine if and how its tuning could be changed to make it more useful. Familiarity with tuning theory is extremely useful to us when we need to make this sort of determination, since it enables us to learn more easily from what other tuners have found to be effective and to advise pianists regarding the style of tuning that might be appropriate for them.

Analysis is especially helpful when a pianist is unhappy with the sound of a piano, whether before or after it has been tuned. It can even help us to decide whether that unhappiness has any physical basis at all. Piano sound is very complex, and it is not at all unusual for pianists (as well as piano tuners) to hear in it, to some degree, what they expect to hear. A pianist's reaction to the sound of a piano is intentionally subjective and can be affected by, among other things, the pianist's emotional state and expectations. A tuning done for a pianist with a very subjective bent by a tuner who has the pianist's full confidence is much more likely to satisfy that pianist than the identical tuning done by a tuner in whom the pianist has little faith. In the latter case, analysis may show that the tuner needs to make use of psychology to improve the sound of the piano for its player.

Even when a pianist's impression that an instrument is "out of tune" has a physical basis, it may have nothing to do with the tuning of the piano, and remediation of the problem may require skills other than tuning. To be fully prepared to make a piano more useful to a pianist, a piano technician needs to be able to voice, regulate, and repair, as well as to be familiar with keyboard harmony, piano literature, performance practices, recording technology, keyboard instrument history, and many other topics. These subjects have been thoroughly explored in a number of excellent and widely available books. I have assumed that most readers will have already been exposed to some of that material and will therefore have at least a basic working knowledge of the piano and its nomenclature.

Neither have I included in this book any information about the use of electronic tuning devices (ETDs). There are many excellent ETDs on the market today, and their effectiveness as aids in rapid and consistent tuning, pitch adjusting, minimizing ear fatigue, matching two pianos, research, and for many other uses makes them a valuable part of any contemporary tuner's toolkit. But they do not define good tuning. Any ETD can suggest a variety of acceptable tunings for a piano, and can help us to execute those tunings with great accuracy; but only a skilled aural tuner can offer an opinion as to the relative suitability of a particular tuning for the situation at hand.

In addition to the two main essays that form the heart of this book, I have included a series of supplemental readings containing useful or interesting information about the craft that I have not seen, or have seen only rarely, in print elsewhere.

Four Lectures on Basic Aural Piano Tuning

Prepared for the 2006 convention of the AIARP, Cavalese, Italy

These lectures are dedicated to my teacher, Bill Garlick,
and to my colleague and friend, Marco DeLellis,
without whom they would not have been written.

Presentations of piano tuning theory typically begin with a description of general tuning theory that is then applied more specifically to the tuning of pianos. In these lectures, I have taken a different approach, presenting the concepts of piano tuning theory to the reader just as they present themselves to a tuner in the course of tuning a piano, beginning with setting pitch and ending in the high treble and low bass.

In the traditional approach, the subject of inharmonicity—an acoustical phenomenon that is particularly pronounced in pianos and has a significant impact on piano tuning—is typically addressed as one of the last factors that modify general tuning theory in the case of the piano. The approach I have taken has required me instead to integrate the concept of inharmonicity into the material from the outset.

By relegating inharmonicity to the end of its presentation, the traditional approach seems to assume that piano tuners begin their careers working mostly on large concert instruments, in which inharmonicity presents relatively few difficulties, and then progress to tuning smaller and smaller instruments as their skill increases. It is for the benefit of those whose career paths may take the opposite trajectory that I have chosen in these lectures to deal with inharmonicity right from the start.

These lectures are, however, quite similar to most other works on piano tuning theory in at least one way: They spend an inordinate amount of time discussing the theory of temperament tuning. In a piano tuning that takes an hour, five minutes or less may be devoted to the temperament; here, the discussion of temperament tuning occupies all but the last few pages.

I think this is as it should be. A good understanding of the complexities of the temperament in an environment of high and shifting inharmonicity allows a tuner to set the temperament rapidly and securely, freeing time for the more crucial, but less theoretically complex, tuning of octaves and unisons.

Tuners have traditionally developed their skills in temperament tuning for the most part subconsciously, through years of experience tuning a variety of pianos. Although the analysis of the dynamics of the temperament in Lectures Three and Four may seem needlessly detailed, it is simply an explicit description of the complex and sophisticated, but usually intuitive, thought processes of experienced aural piano tuners.

LECTURE ONE

Intervals and Beats

The use of beats in piano tuning—The range of usable beat rates—Setting pitch with beats—The frequency relationships of octaves and semitones—The partial series—The pitches of the first six partials—Virtual strings—Cents and beats—Tuning unisons using partials—Tuning octaves using partials—The intervals of basic aural piano tuning—The influence of partials above the 6th—The distinctiveness of 5th-partial intervals in equal temperament

THE USE OF BEATS IN PIANO TUNING

The piano is a musical instrument, and so most people assume that piano tuning is a musical skill. Two musical skills that are familiar to most people and that have to do with determining the pitches of notes are *perfect pitch*, an innate ability to identify the pitches of isolated notes, and *relative pitch*, a learned ability to identify the pitch relationships among notes. Therefore, most people assume that piano tuners use these two skills in the practice of their craft.

When we begin to tune a piano, however, we use these musical skills only if the piano in front of us is unusually far out of tune; for example, if its overall pitch level is a semitone flat. In that case, if we have perfect pitch we can bring it approximately into tune by matching its notes one by one to our inner sense of pitch; or, if we lack perfect pitch, we can instead tune one of its notes to a standard pitch and then use our sense of relative pitch to tune the rest by playing simple arpeggios and scales.

Once the notes of the piano are reasonably close to being in tune, however, we cease to listen to them in a musical way. Instead, we begin to play only *intervals*—two notes struck simultaneously—

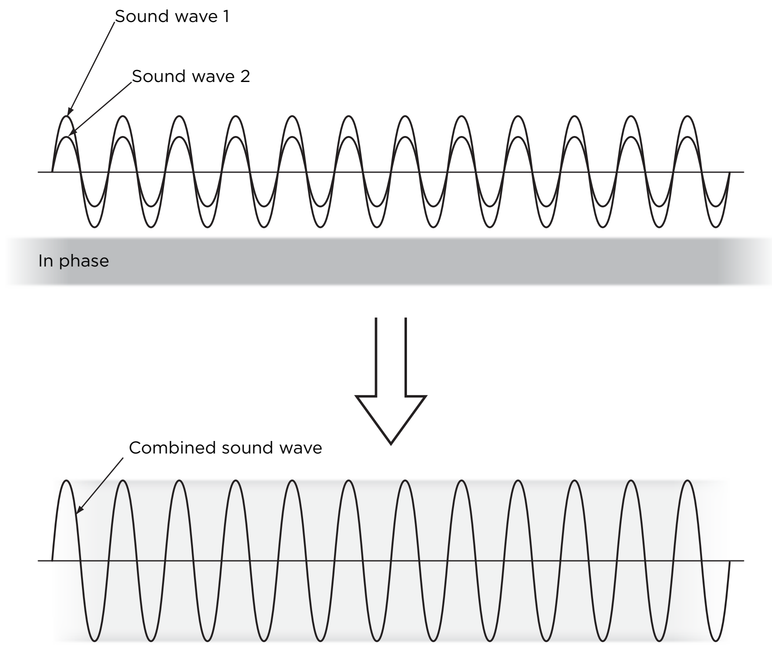

FIGURE 1.1. *When two sound waves of the same frequency combine in phase, they produce a stronger wave.*

and to tune notes by listening for an acoustical phenomenon known as *beats*.

Imagine two sound waves, both having the same frequency. If we listen to them at the same time and their crests and troughs happen to match each other exactly—if they are *in phase*—then they strengthen each other, as shown in Figure 1.1.

If, on the other hand, the crests of one match the troughs of the other—if they are *out of phase*—then the two waves weaken each other, as shown in Figure 1.2.

Now imagine that the two waves have slightly different frequencies. In that case, they go regularly in and out of phase, as shown in Figure 1.3, alternately strengthening and weakening each other. This periodic strengthening and weakening of the combined wave, which we hear as a regular increase and decrease in its volume, is called *beating*.

The rate at which two waves beat is equal to the difference in their frequencies. For example, if one wave has a frequency of 440

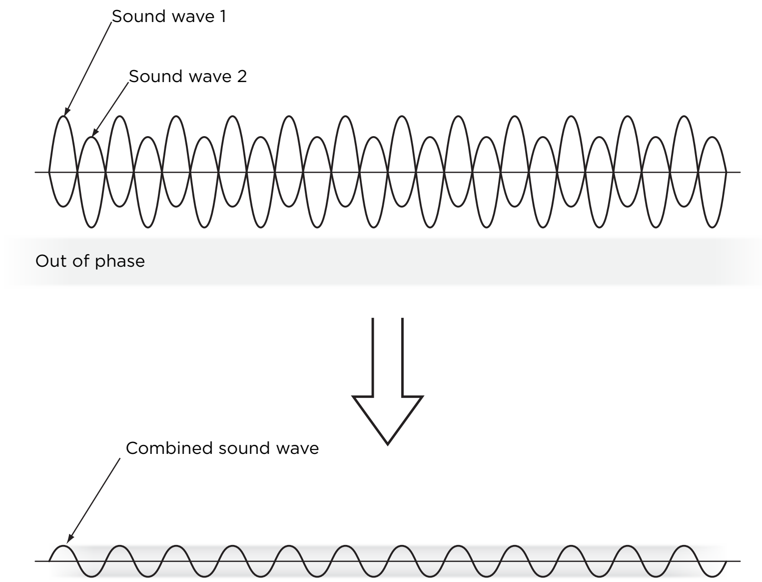

FIGURE 1.2. *When two sound waves of the same frequency combine out of phase, they produce a weaker wave.*

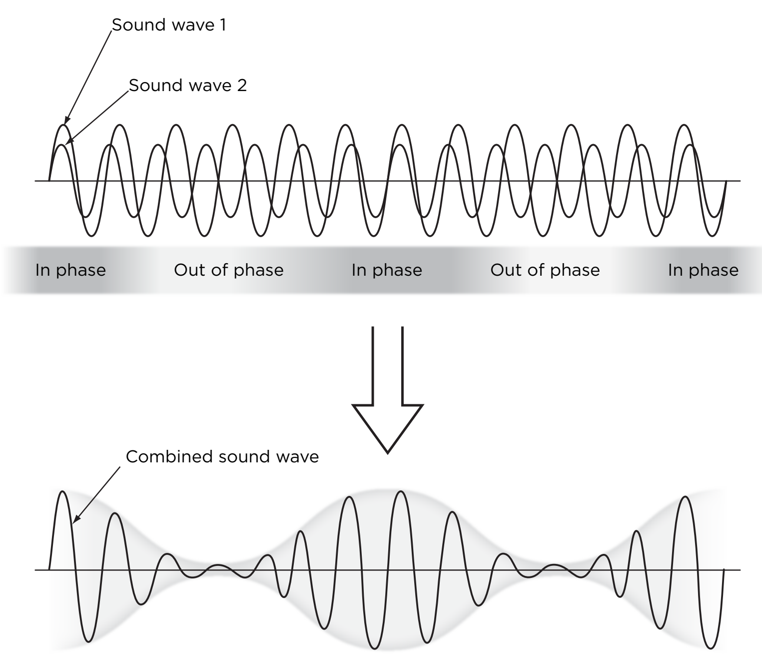

FIGURE 1.3. *When two sound waves of slightly different frequencies combine, they regularly strengthen and weaken each other.*

cycles per second, or Hertz (Hz), and the other has a frequency of 439Hz, then they beat at the rate of 440 minus 439, or 1, beat per second (bps).

Notice that the more closely matched two frequencies are, the slower their beat rate. A wave whose frequency is 440Hz beats with a wave whose frequency is 438Hz at a rate of 2bps, but at a rate of only 0.5bps with a wave whose frequency is 439.5Hz.

Notice also that a beat rate gives no direct information about pitch, since any two notes whose frequencies differ by the same amount beat at the same rate. Counting beats, in other words, is only useful for determining the pitch of a note if the pitch of the note with which it is beating is already known.

Beats offer us a way of adjusting the relative pitches of two notes with tremendous accuracy, much more than is possible through the use of either perfect or relative pitch. In fact, listening to beats allows piano tuners to achieve aurally a refinement and consistency in tuning that closely matches, and at the highest levels surpasses, tunings achieved by the most sophisticated electronic devices.

Keep in mind, though, that the ability to hear and manipulate beat rates is a technical, not a musical, skill. Most pianists do not consciously isolate beat rates, but instead hear them as one component of the overall tone quality of a piano. To please pianists, therefore, a piano tuner, whose ear has learned to isolate the beat rates of intervals, must also be able to perceive piano sound as a musician does—as an integrated whole.

THE RANGE OF USABLE BEAT RATES

The amount of time an interval on a piano sustains after being struck limits the amount of time we have to detect, identify, and alter its beat rate. In the bass, where sustain is relatively long, we might be able to listen to an interval for as long as five seconds, and to identify a beat rate of two or three times in those five seconds. In the high treble, where sustain times are relatively shorter, many tuners restrike intervals several times a second.

Most tuners find that they can most accurately count beats at rates somewhere between 2bps and 10bps. We can listen to and compare beat rates more rapid than around 15bps, but at those speeds we tend to hear differences in beat rate more as differences in texture.

SETTING PITCH WITH BEATS

We begin to tune a piano by setting one note in its midrange to a standard pitch. The note most commonly used for this is A above middle C. To a contemporary American piano tuner, this note has various names, the most common being A4. The lowest C in the piano is called C1; the notes above that are C♯1, D1, D♯1, and so on up to the next C, which is called C2. The three lowest notes in the piano are called A0, A♯0, and B0. The highest note in the piano is called C8.

By international agreement, note A4 should be tuned to vibrate at a frequency of 440Hz. We tune A4 to that frequency by matching it to an independent pitch source, such as a tuning fork, which has been manufactured to vibrate at 440Hz.

Since in virtually all pianos there are three strings on note A4, we first mute two of the strings so that only one is allowed to sound; otherwise, the sound of the two extra strings would interfere with the sound of the string we want to tune. Then we play the unison formed by our pitch source and the one remaining open string of A4.

If the two pitches are close but not identical, they will beat, as we have seen, at a rate equal to the difference in their frequencies. If, for example, our string has a frequency of 439Hz, it will beat with our 440Hz pitch source at the rate of 1bps.

Notice, however, that if our string has a frequency of 441Hz, it will also beat with our pitch source at the rate of 1bps. It may be difficult for us to tell whether the string is sharp or flat to the pitch source if the two are very closely matched. If we are unsure, we can easily find out by sharpening or flattening the string, listening for the beats to increase or decrease in speed. When we hear no beats at all, we infer that the open string is tuned to 440Hz.

Next we unmute the other two strings one at a time and using our tuned string as a point of reference eliminate beats between the first string and the other two. When we are done, we infer that all three strings of the unison are tuned to 440Hz.

This process of setting pitch by listening to beats is not particular to piano tuners. Most instruments, whether they are stringed or wind instruments, are tuned in this way, and not by the use of perfect or relative pitch. A standard pitch is played by a pitch source or by a member of the ensemble, and then all the musicians play that same note, listening for and eliminating beats.

THE FREQUENCY RELATIONSHIPS OF OCTAVES AND SEMITONES

The next note that a piano tuner would typically tune is A3, the note an octave below A4.

An octave is composed of two notes whose frequencies differ by a factor of two. To put it another way, raising or lowering the pitch of a note by an octave is equivalent to multiplying or dividing its frequency by two. The frequency of A3, then, is half that of A4; and since the frequency of A4 is, by international agreement, 440Hz, the frequency of A3 should be 220Hz.

To tune A3 using A4 as a reference, we mute all but one string of A3 and play the octave A3-A4, listening for beats. The difference between the frequency of A4 and that of A3 is 440 minus 220, or 220, Hertz; therefore, there should be a beat of 220bps between the two pitches. However, we have seen that this beat is far too rapid to be useful in piano tuning. It is so rapid, in fact, that if we perceive it at all it is not as a beat but as an actual pitch. This phantom pitch at 220Hz is called a *difference tone*, since its frequency is equal to the difference between the two component frequencies of the interval.

If the two component notes of the octave A3-A4 are too far apart for us to be able to hear beats between them, how then can we tune A3 by listening to beats? Let's put that question to one side for the moment and see if we can tune a smaller interval on the piano by listening to the beats between its two component notes.

The semitones G♯4-A4 and A4-A♯4 are the smallest intervals in the piano that have A4 as one of their notes; perhaps they beat slowly enough for us to tune them by counting beats. We can calculate the beat rate of the semitone G♯4-A4 by calculating the frequency of G♯4, and then subtracting that number from 440Hz.

The way in which an octave is divided into smaller intervals is called its *temperament*, and the region of the piano in which a tuner makes this division is called *the temperament*. Many hundreds of systems of temperament tuning have been devised over the years, but by far the most common system used today is *equal temperament*, the division of the octave into twelve semitones of equal size.

Lowering a pitch an octave is, as we have seen, equivalent to dividing its frequency by two. To lower A4 by one-twelfth that amount—by one equally tempered semitone—we have to divide its frequency by a different, smaller factor. This factor, divided by itself twelve times, should produce a quotient of exactly one half—in other words, the factor that drops the pitch of a note by exactly one octave. This smaller factor is the *twelfth root of two*. The number one, divided by the twelfth root of two twelve times, becomes exactly one half. This is a mathematical way of saying that lowering a note by twelve equally tempered semitones is the same as lowering it an octave.

The twelfth root of two is an irrational number—when written as a decimal it is always approximate no matter how many decimal places we use. Approximated to five decimal places it is 1.05946, which is more than accurate enough for our purposes. If we divide 1 by this number twelve times, we get 0.50002, very close to one half.

To derive the frequency of G♯4 from A4, then, we divide 440Hz by the twelfth root of two. Dividing 440Hz by 1.05946, we get about 415Hz. Subtracting that frequency from A4, we find that the semitone G♯4-A4 beats at about 25bps. That, as we have seen, is too fast for a tuner to hear accurately, so we can't tune G♯4 to A4 directly by listening to the beat of the interval. Furthermore, any interval that includes A4 and is larger than a semitone will clearly beat even more quickly. How, then, using beats, can we tune any intervals at all from A4? To understand how, we first have to understand the *partial series*.

THE PARTIAL SERIES

Any time a string that is fixed at either end and held under tension is set into motion, it vibrates back and forth over its whole length at a frequency that we hear as the pitch of the string. In addition, the string spontaneously divides into shorter lengths, each vibrating at a different frequency. The string divides in half, in effect making two strings half as long as the original, each one of which vibrates twice as fast as the whole string. The string also divides into thirds, making three even shorter strings that vibrate three times as fast as the whole string; into fourths, making four strings that vibrate four times as fast; and so on.

The effect of this spontaneous division of the string into smaller segments is that when the string is played not just one but a whole series of higher frequencies is produced, each higher frequency being an integral multiple of the frequency of the whole string. Each of these many frequencies produced by the string contributes to its overall sound, and so collectively they are called *partial pitches*, or *partials* for short.

While in theory this series of partial pitches is infinite, the partial series of a real piano string does not go on indefinitely. The higher partials of piano strings have progressively less volume and sustain than the lower ones, and eventually become so short and weak as to effectively cease to exist. In any case, the limit of frequencies that most people can hear is around 20,000Hz, so of course any partials above that frequency can't be heard and therefore make no contribution to the sound of a string. As a consequence, the treble strings in a piano have many fewer audible partials than those in the bass. It is quite easy to hear partials up to the 32nd in the low bass of a piano, quite difficult to hear partials above the 2nd in the high treble.

THE PITCHES OF THE FIRST SIX PARTIALS

We have seen that when two notes are an octave apart, the frequency of the upper note is twice that of the lower note. The 2nd partial, which is twice the frequency of the 1st, is therefore an octave above the 1st partial. On our note A4, then, the 2nd partial is A5. Its frequency should be 2 times 440, or 880, Hertz.

Similarly, the 4th partial, which is twice the frequency of the 2nd, is an octave above the 2nd partial—two octaves above the 1st. On our note A4, the 4th partial is A6. Its frequency should be 4 times 440, or 1760, Hertz.

The 3rd partial is a twelfth—an octave plus a fifth—above the 1st partial. On our note A4, the 3rd partial is E6, and its frequency should be 3 times 440, or 1320, Hertz.

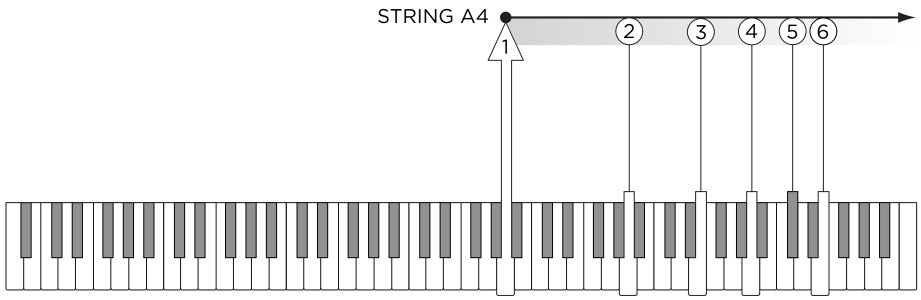

FIGURE 1.4. *The first six partials of A4.*

The 6th partial is a nineteenth—a double octave plus a fifth—above the 1st partial, an octave higher than the 3rd partial. On our note A4, the 6th partial is E7. Its frequency should be 6 times 440, or 2640, Hertz.

Notice that the pitch of a partial always goes up an octave when its number doubles. The 2nd partial is always an octave higher than the 1st, the 4th an octave higher than the 2nd, the 6th an octave higher than the 3rd, the 10th an octave higher than the 5th, and so on.

The 5th partial is a major seventeenth—two octaves plus a major third—above the 1st. On our note A4, the 5th partial is C♯7. Its frequency should be 5 times 440, or 2200, Hertz.

These first six partials of A4 are shown schematically in Figure 1.4. They are the only ones that are isolated and analyzed in basic aural piano tuning. In ascending order, beginning with the 2nd partial, they will always be an octave, a twelfth, two octaves, a major seventeenth, and a nineteenth above the 1st partial.

VIRTUAL STRINGS

As we have seen, the 2nd partial of a vibrating string is produced by its spontaneous division in half. Let's now expand that idea in a way that will help us later to conceptualize some of the more complicated aspects of tuning theory.

The 2nd partial of the whole string can be thought of as the virtual 1st partial of the virtual 1/2-strings formed by the division of the whole string. Similarly, the 4th partial of the whole string can be thought of as the virtual 2nd partial of the same virtual 1/2-strings,

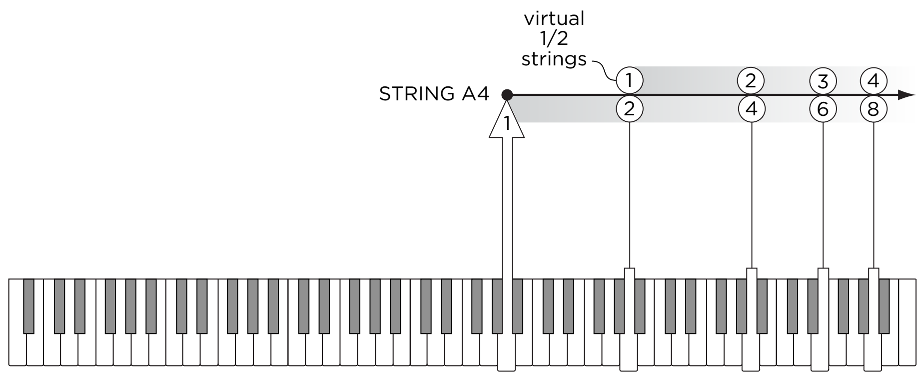

FIGURE 1.5. *The virtual 1/2-strings of A4.*

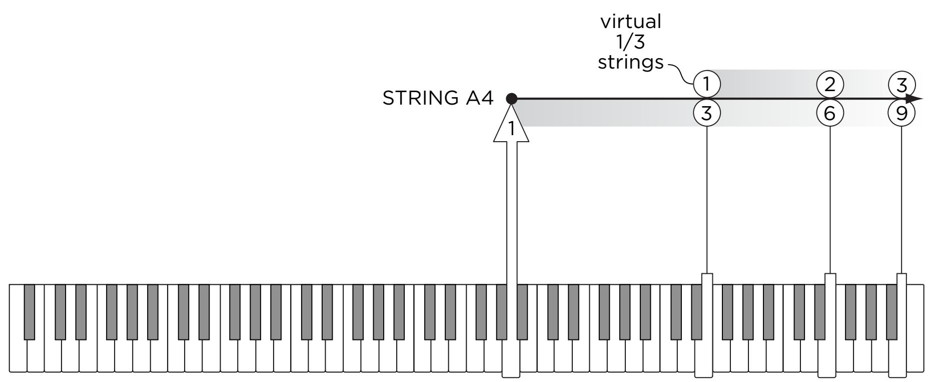

FIGURE 1.6. *The virtual 1/3-strings of A4.*

since it is an octave above their virtual 1st partial; and the 6th partial of the whole string can be thought of as the virtual 3rd partial of the virtual 1/2-strings, since it is a perfect twelfth above their virtual 1st partial. This alternate way of conceptualizing the partial series of A4 is shown in Figure 1.5.

To put it another way, we can think of the whole string not only as spontaneously dividing in half; *we can also think of the virtual 1/2-strings formed by this division as having a complete virtual partial series of their own, exactly equivalent in their pitch relationships to the partial series of the whole string, only an octave higher.* This virtual partial series is composed of all the partials of the whole string whose numbers are multiples of 2.

Now let's picture the whole string as being divided into three identical smaller strings, as shown in Figure 1.6. The virtual 1st partial of these virtual 1/3-strings is the 3rd partial of the whole string. The virtual 2nd partial of the virtual 1/3-strings is the 6th partial of the whole string, an octave above the 3rd partial of the whole string. The virtual 3rd partial of the virtual 1/3-strings is the 9th partial of the whole string, a perfect twelfth above the 3rd partial of the whole string.

These virtual 1/3-strings, in other words, can also be thought of as having their own complete virtual partial series, exactly equivalent in their pitch relationships to the partial series of the whole string, only a perfect twelfth higher. This virtual partial series is composed of all the partials of the whole string whose numbers are multiples of 3.

Similarly, we can picture the whole string as being divided into virtual 1/4-strings, with a virtual partial series composed of all the partials of the whole string whose numbers are multiples of 4; into virtual 1/5-strings, with a virtual partial series composed of all the partials of the whole string whose numbers are multiples of 5; and into virtual 1/6-strings, with a virtual partial series composed of all the partials of the whole string that are multiples of 6. To make a general statement, *each partial of the whole string can also be thought of as the 1st partial of a virtual string having a complete partial series composed of all the partials of the whole string whose numbers are multiples of the number of the partial.*

CENTS AND BEATS

Let's return now to our unison at A4. The pitch source we used to tune its first string sounded only the pitch A440, and so it beat only with the 1st partial of the string. But when we unmuted a second string and listened to the unison between the two strings, we would have heard beats not only between their 1st partials, but also between all their other pairs of audible partials.

Let's say that the second string was flat relative to the first by one-hundredth the distance between A4 and G♯4. This distance, one hundredth of a semitone, is called a *cent*.

What would be the beat rate of this out-of-tune unison? To know that, we would have to know the frequencies of the two strings and find the difference between them. We already know the frequency of the first string: We set it to 440Hz. Now, in the same way that we were able to derive the frequency of G♯4 from A4 by dividing the frequency of A4 by the twelfth root of two, we can find out what the frequency of the out-of-tune 1st partial of the second string would be by dividing the frequency of A4 by one hundredth that amount, or one cent. That would be the twelve-hundredth root of two, which is around 1.00058.

Dividing 440Hz by 1.00058, we get 439.74Hz. This should be the frequency of the 1st partial of the second string. The 1st partial of the second string, then, should beat with the 1st partial of the first string at the rate equal to their difference, about 0.25bps.

As we have seen, for a piano tuner this is a rather slow beat, difficult to hear accurately. However, the 2nd partials of the two strings should beat twice as fast. Here's why: Although the 2nd partials are also one cent apart, their frequencies are double the frequencies of the 1st partials, and therefore so is their beat rate. The 2nd partial of the first string should be twice the frequency of its 1st partial—twice 440, or 880, Hertz—and the 2nd partial of the second string should be twice the frequency of its 1st partial—twice 439.74, or 879.49Hz. These two 2nd partials, therefore, should beat at double the rate of the 1st partials, about 0.5bps, which is much easier to hear.

There is a crucial distinction to be made here between cents and beats. Cents represent a fraction of a semitone: One cent is always one-hundredth of a semitone, whether we are in the middle of the piano, the bass, or the treble. The number of beats per second represented by one cent of difference, however, changes depending on the frequencies of the notes involved. The higher notes are in the piano, the higher their frequencies, and therefore the more beats a cent of difference represents.

Beat rates double when an interval goes up an octave, and halve when an interval drops an octave. As we have just seen, at 440Hz, one cent is about a quarter of a beat; while at 880Hz, a cent is about half a beat. At 1760Hz, an octave higher, a cent and a beat are roughly equivalent.

To put it another way, one beat per second at 440Hz, a region of the piano where semitones are about 25Hz apart, is equivalent to about four cents. But that same beat per second at 880Hz, an octave higher, a region where semitones are about 50Hz apart, is only equivalent to about two cents; and an octave higher still, where semitones are about 100Hz apart, a beat and a cent are roughly equivalent.

TUNING UNISONS USING PARTIALS

Returning to our unison, if we calculate its beat rate at this higher level, an octave above the 2nd partial level—in other words, at the level of the 4th partial—we find that the unison should indeed beat at the rate of about 1bps: The 4th partial of the first string should have a frequency of 4 times 440, or 1760, Hertz; and one cent down from that (1760 divided by 1.00058) is 1758.99Hz, making the beat between the two partials just about 1bps.

At the level of the 8th partials, an octave higher still, the partials should beat twice a second. All these pairs of partials are one cent apart, but the higher their frequencies, the greater the difference between them in terms of Hertz, and therefore of beats.

The presence of all these faster-beating higher partials enables us to tune our unison with much greater refinement than if we could only hear the relatively slow beat at the level of the 1st partials. Eliminating the twice-a-second beat of the 8th partials is much easier than eliminating the once-in-four-seconds beat of the 1st partials. And, of course, the unison has many additional pairs of higher partials that beat even more rapidly.

Notice that when we tune this way, listening to beats, our ears are more often than not focused on pitches higher than those of the notes we are tuning. If we always tuned using perfect or relative pitch, our ears would remain focused on the pitches of the 1st partials of notes. Instead, since we listen to beats, our ears are usually focused on pitches much higher than that.

Listening to beats allows us to tune unisons in the piano with great refinement, much greater than is the case with almost any other instrument with the exception of the organ and its relatives. But in the organ, unisons are tuned for a different purpose. They are usually tuned between ranks of pipes with different timbres for the purpose of creating novel tone colors. In the piano, unisons are tuned among three strings that are as identical as possible for the purpose of creating greater volume and richness.

The three strings of a piano unison inevitably have minute differences in tone color. These differences come from a variety of sources, including the density of the hammer felt striking each string, the precise moment the hammer contacts each string, and the position of each string on the bridge. In addition, the vibrations of the three strings influence each other through the bridge. The large number of higher partials, the long sustain time, and the lack of vibrato in piano strings mean that these slight variations in tone will all be audible in the sound of the unison.

The sound of a single piano string is pure and lifeless compared with the sound of a three-stringed unison, which, being much more complex, helps to give the illusion of life to piano tone. It is often said that the most important interval in piano tuning is the unison. This is not just because unisons that have gone out of tune will be noticed by pianists long before other intervals that have drifted much more. It is also because the tuning of its unisons determines to such a great degree the tone quality of a piano.

TUNING OCTAVES USING PARTIALS

Let's return now to the octave we wanted to tune between A3 and A4. We have seen that the beat between the 1st partials of these two notes is too rapid to hear. However, we have also seen that the whole string A3 can be thought of as being divided into virtual 1/2-strings whose pitch is an octave higher than A3, or A4. Although we cannot tune the 1st partial of A3 directly to the 1st partial of A4, *we can tune a unison between the virtual 1/2-strings of A3 and the whole string of A4*, as shown in Figure 1.7. We can hear beats between all the partials of the virtual 1/2-strings and the whole string, just as when we tuned a unison among the three whole strings of A4. And although we are not listening directly to the 1st partial of A3, once we have matched the virtual 1/2-strings of A3 to the whole string of A4, we can infer that the 1st partial of A3 has been correctly tuned an octave lower than A4.

Notice that the 2nd partial of A3 has the same pitch as the 1st

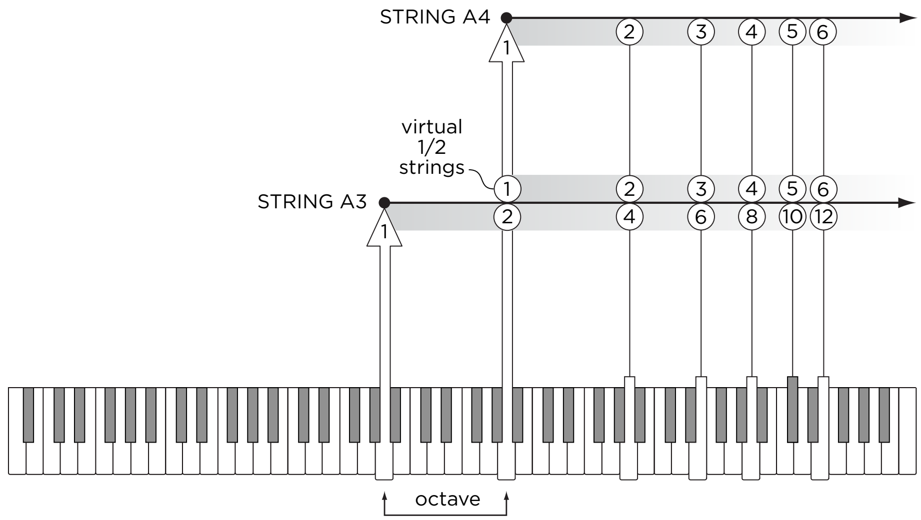

FIGURE 1.7. *The coincident partials of the octave A3–A4.*

partial of A4. If there are no beats between these two partials, we say that *the octave is pure at the 2:1 level*. Similarly, the 4th partial of A3 has the same pitch as the 2nd partial of A4. If we eliminate beats between these two partials, we say that *the octave is pure at the 4:2 level*. The 6th partial of A3 has the same pitch as the 3rd partial of A4. If we there are no beats between these two partials, we say that *the octave is pure at the 6:3 level*.

Pairs of partial like these, whose pitches are close enough to each other to have the same pitch name, are called *coincident partials*.

In the unison, all partials are coincident.

In the octave, every partial in the upper note is coincident with a partial twice its number in the lower note. All these pairs of coincident partials can be expressed as ratios, such as 4:2, 6:3, 8:4, and so on. If we remove the common factors from these ratios, they all reduce down to the ratio of 2:1. This ratio, whose numbers have no common factors, is the *fundamental ratio* of the octave.

The fundamental ratio of the octave, 2:1, indicates not only that the 2:1 level is its lowest level of coincident partials, but also that an octave is tuned as a unison between the virtual 1/2-strings of its lower note and the whole string of its upper note.

THE INTERVALS OF BASIC AURAL PIANO TUNING

All the intervals of basic aural piano tuning are tuned in the same way the octave is tuned: as unisons. Some, like the octave, are tuned as unisons between a whole string and a virtual string; others are tuned as unisons between two virtual strings.

Each interval of basic aural piano tuning has a fundamental ratio, composed, like the 2:1 fundamental ratio of the octave, of two integers with no common factors. The fundamental ratio of each interval, like the fundamental ratio of the octave, indicates not only the lowest level of coincident partials of that interval, but also what combination of whole and virtual strings form the unison whose beat we listen to when we tune the interval.

Since in basic aural piano tuning we isolate and analyze no partial higher than the 6th, we can generate a complete list of all the intervals of basic aural piano tuning by combining the integers 1 through 6 into every possible ratio that has no common factors, as shown in Table 1.1.

FUNDAMENTAL RATIO	INTERVAL
1:1	unison
2:1	octave
3:2	perfect fifth (P5)
3:1	perfect twelfth (P12)
4:3	perfect fourth (P4)
4:1	double octave
5:4	major third (M3)
5:3	major sixth (M6)
5:2	major tenth (M10)
5:1	major seventeenth (M17)
6:5	minor third (m3)
6:1	perfect nineteenth (P19)

TABLE 1.1. *The fundamental ratios of the intervals of basic aural piano tuning.*

In addition to its lowest pair of coincident partials, indicated by its fundamental ratio, each interval also has higher levels of coincident partials, all of which are multiples of the fundamental ratio. If one of these higher levels of coincident partials does not include a partial higher than the 6th, then that level is isolated and analyzed in basic aural piano tuning.

In the following list of the intervals of basic aural piano tuning, the intervals have been arranged in order of size. For each interval, the fundamental ratio of the interval is given, along with any multiples of that ratio that use no partial higher than the 6th. For each pair of coincident partials in the list, the pitch of the coincident partials is given for the case in which A3 is the lower note of the interval.

Unison
Fundamental ratio, 1:1. Six levels of coincident partials have no partial higher than the 6th. In the unison at A3, these partials are coincident at A3 (1:1), A4 (2:2), E5 (3:3), A5 (4:4), C♯6 (5:5), and E6 (6:6).

Minor third (m3)
Fundamental ratio, 6:5. Only one level of coincident partials has no partial higher than the 6th. In the m3 A3-C4, these partials are coincident at E6.

Major third (M3)
Fundamental ratio, 5:4. Only one level of coincident partials has no partial higher than the 6th. In the M3 A3-C♯4, these partials are coincident at C♯6.

Perfect fourth (P4)
Fundamental ratio, 4:3. Only one pair of coincident partials has no partial higher than the 6th. In the P4 A3-D4, these partials are coincident at A5.

Perfect fifth (P5)
Fundamental ratio, 3:2. Two pairs of coincident partials have no partial higher than the 6th. In the P5 A3-E4, the 3rd partial of the lower note is coincident with the 2nd partial of the upper note at E5 (the 3:2 P5), and the 6th partial of the lower note is coincident with the 4th partial of the upper note at E6 (the 6:4 P5).

Major sixth (M6)
Fundamental ratio, 5:3. Only one pair of coincident partials has no partial higher than the 6th. In the M6 A3-F♯4, these partials are coincident at C♯6.

Octave
Fundamental ratio, 2:1. Three pairs of coincident partials have no partial higher than the 6th. In the octave A3-A4, the 2nd partial of the lower note is coincident with the 1st partial of the upper note at A4 (the 2:1 octave), the 4th partial of the lower note is coincident with the 2nd partial of the upper note at A5 (the 4:2 octave), and the 6th partial of the lower note is coincident with the 3rd partial of the upper note at E6 (the 6:3 octave).

Major tenth (M10)
Fundamental ratio, 5:2. Only one pair of coincident partials has no partial higher than the 6th. In the M10 A3-C♯5, these partials are coincident at C♯6.

Perfect twelfth (P12)
Fundamental ratio, 3:1. Two pairs of coincident partials have no partial higher than the 6th. In the P12 A3-E5, the 3rd partial of the lower note is coincident with the 1st partial of the upper note at E5 (the 3:1 P12), and the 6th partial of the lower note is coincident with the 2nd partial of the upper note at E6 (the 6:2 P12).

Double octave
Fundamental ratio, 4:1. Only one pair of coincident partials has no partial higher than the 6th. In the double octave A3-A5, these partials are coincident at A5.

Major seventeenth (M17)
Fundamental ratio, 5:1. Only one pair of coincident partials has no partial higher than the 6th. In the M17 A3-C♯6, these partials are coincident at C♯6.

Perfect nineteenth (P19)
Fundamental ratio, 6:1. Only one pair of coincident partials has no partial higher than the 6th. In the P19 A3-E6, these partials are coincident at E6.

It is no coincidence that these intervals of basic aural piano tuning are by and large the same intervals that are thought of as consonant in traditional harmony. But they are not used in piano tuning because of this fact. Rather, they are used in piano tuning because their beat rates are convenient. In music, dissonance is as common as consonance, if not more common. If dissonant intervals, such as minor seconds and tritones, had useful beat rates in the midrange of the piano, they would undoubtedly be used in piano tuning just as commonly as consonances.

Note that the spelling of intervals in piano tuning is a simplified version of the spelling of intervals in traditional keyboard harmony. In piano tuning, every black key on the piano is called a *sharp*, never a flat. For a piano tuner, therefore, the interval between D and the black note that lies between F and G is always spelled D-F♯, whereas in the spelling practices of traditional keyboard harmony the upper note could also be called G♭.

The modern practice of equal temperament tuning does not recognize traditional harmonic distinctions: All intervals are named solely on the basis of the number of semitones they comprise. For example, piano tuners always refer to the interval A♯-D as a major third, even though in traditional keyboard harmony this name would be incorrect, and the interval would properly be called a diminished fourth.

The only time we need to be aware of the distinctions traditional keyboard harmony makes among the different ways of spelling identical-looking keyboard intervals is when we are tuning historical temperaments. If the spelling practices of traditional keyboard harmony are important to the conceptual framework of a historical temperament, then of course they should be retained.

THE INFLUENCE OF PARTIALS ABOVE THE 6TH

Partials decrease in volume and sustain as they go up the partial series, and so higher pairs of coincident partials gradually contribute less and less to the overall sound of an interval. In octaves in the low bass, the 32:16 pair of coincident partials is clearly audible; in the highest octaves of the piano, only the lowest few pairs of coincident partials can be heard.

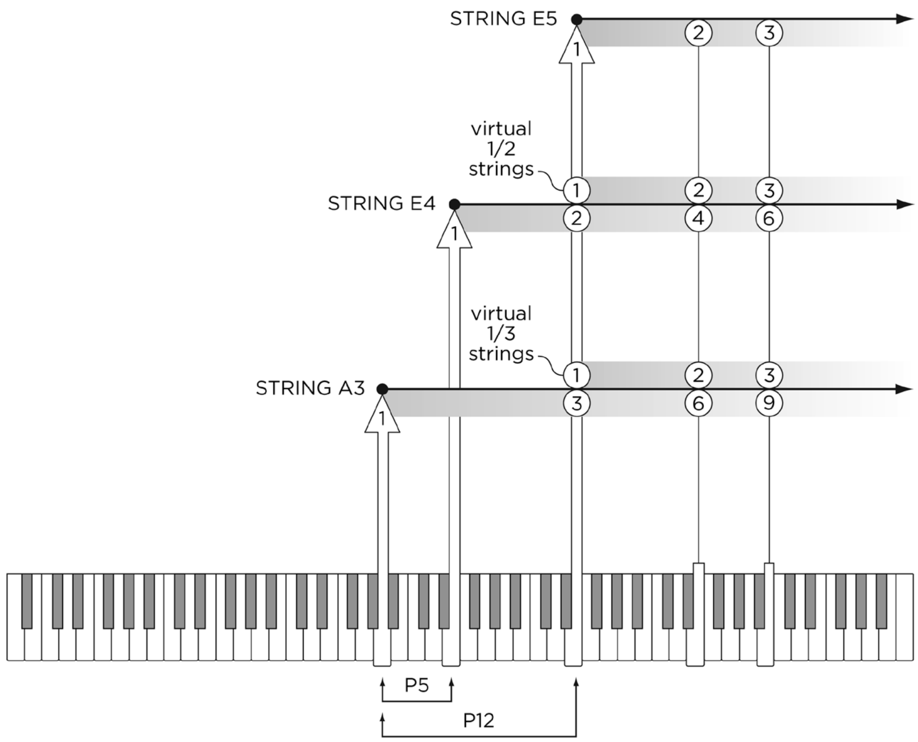

FIGURE 1.8. *The coincident partials of the P5 A3-E4 and the P12 A3-E5.*

And while it is true that a beginning tuner needs to analyze coincident partials only up to the 6th, we should keep in mind that these higher levels of coincident partials contribute to the sounds of intervals as long as they are physically present in the strings and are not so high in pitch as to be inaudible. Two factors determine the extent to which higher levels of coincident partials influence the way we tune an interval: to what extent they are audible, and how the interval is tempered.

The number of audible coincident partials in an interval is limited by the physical restrictions of music wire and the physiological limits of human hearing.

The unison, with a fundamental ratio of 1:1, has the greatest number of audible coincident partials, since every partial in one string matches a partial in the other.

The octave, with a fundamental ratio of 2:1, has the next greatest number of audible coincident partials: Every even-numbered

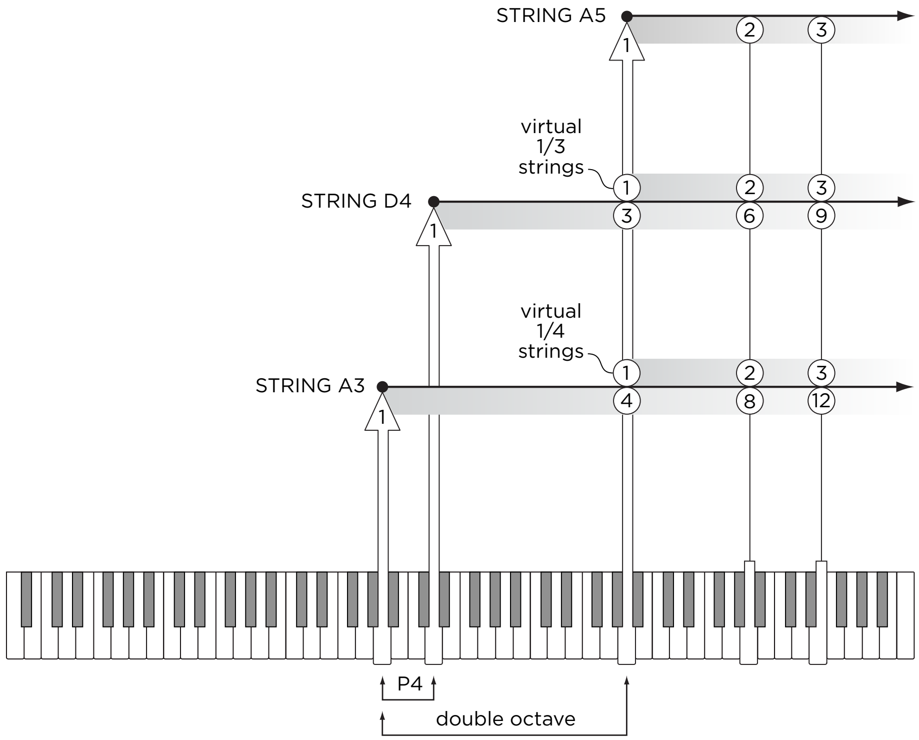

FIGURE 1.9. *The coincident partials of the P4 A3-D4 and the double octave A3-E5.*

partial of the lower string is coincident with a partial of the higher string, and all the partials of the higher string are coincident with a partial of the lower string.

The two intervals with the next greatest number of audible coincident partials are the P5, with a fundamental ratio of 3:2, and the P12, with a fundamental ratio of 3:1. The coincident partials of these two intervals are shown in Figure 1.8. Notice that tuning a P5 is equivalent to tuning a unison between virtual 1/3-strings and virtual 1/2-strings, while tuning a P12 is equivalent to tuning a unison between virtual 1/3-strings and a whole string. If we assume that a whole string has about the same number of audible partials as virtual 1/2-strings of the same pitch, we can expect both intervals to have about the same number of audible coincident partials.

The two intervals with the next greatest number of audible coincident partials are the P4, with a fundamental ratio of 4:3, and the double octave, with a fundamental ratio of 4:1, shown in Figure

1.9. The reason these two intervals are roughly equivalent in their number of audible coincident partials should now be clear: The virtual 1/4-strings of the lower note form unisons with the virtual 1/3-strings of the upper note of the P4 and the whole string that is the upper note of the double octave.

The four intervals with the next greatest number of audible coincident partials, all shown in Figure 1.10, are the M3, with a fundamental ratio of 5:4; the M6, with a fundamental ratio of 5:3; the M10, with a fundamental ratio of 5:2; and the M17, with a fundamental ratio of 5:1. The virtual 1/5-strings of the lower note form unisons with the virtual 1/4-strings of the upper note of the M3, the virtual 1/3-strings of the upper note of the M6, the virtual 1/2-strings of the upper note of the M10, and the whole string that is the upper note of the M17.

Finally, the intervals of basic aural tuning with the least number of audible coincident partials are the m3, with a fundamental ratio of 6:5, and the P19, with a fundamental ratio of 6:1.

To draw a general conclusion, the lower the first number of the fundamental ratio of an interval, the greater is its number of audible coincident partials.

Although the m3 has, along with the P19, the least number of audible coincident partials of all the intervals of basic aural piano tuning, it sounds much rougher to the ear than the P19. The reason is that the ear hears in a m3 the beating of its coincident partials not only at the 6:5 level, but also at the 7:6 level—in other words, the beating of the unison formed by the virtual 1/7-strings of the lower note and the virtual 1/6-strings of the upper note. The 7:6 m3 has a very rapid beat in equal temperament and contributes a good deal of its characteristic roughness to the sound of the m3.

THE DISTINCTIVENESS OF 5TH-PARTIAL INTERVALS IN EQUAL TEMPERAMENT

This brings us to the second factor that influences the extent to which we must take into account higher levels of coincident partials in tuning the intervals of basic aural piano tuning: the way the intervals are tempered.

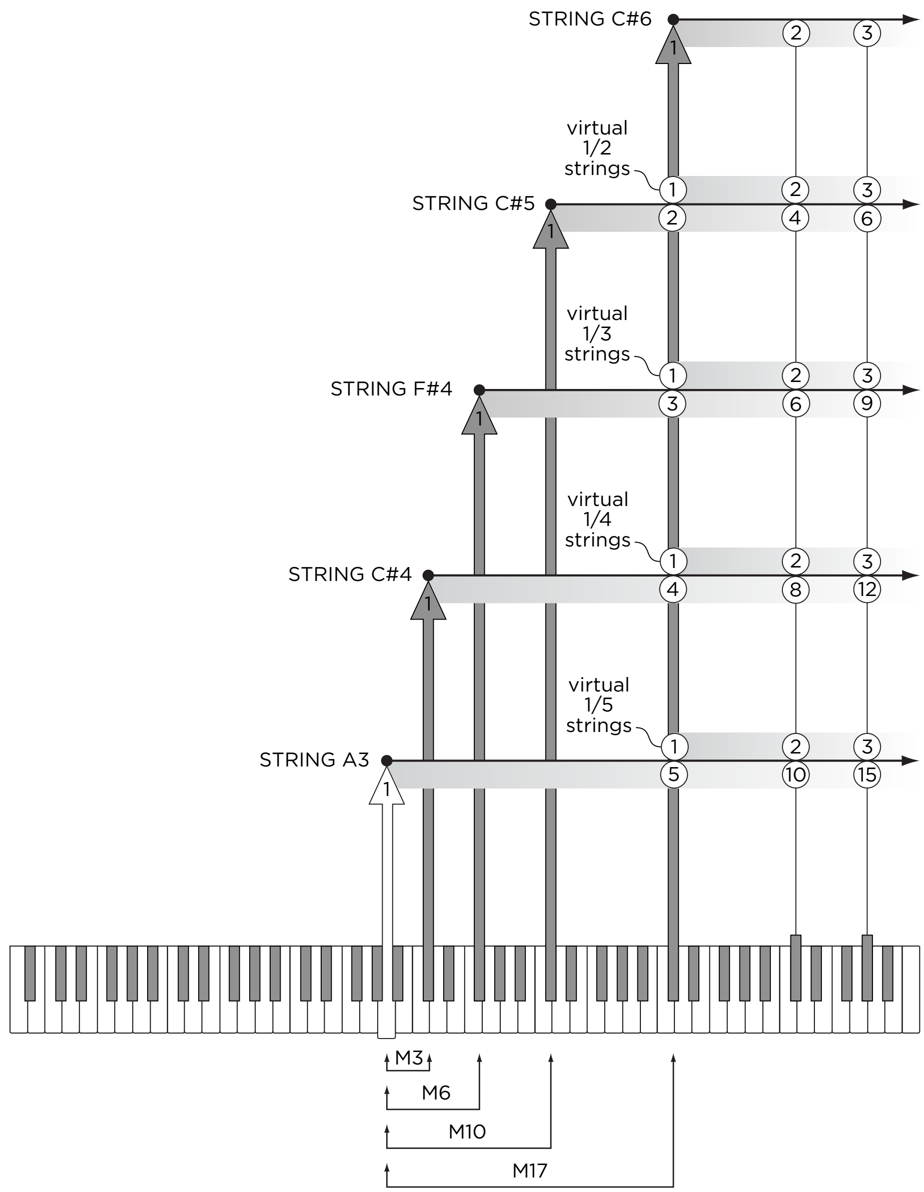

FIGURE 1.10. *The coincident partials of the M3 A3-C♯4, the M6 A3-F♯4, the M10 A3-C♯5, and the M17 A3-C♯6.*

The unison is never tempered. It is always meant to be tuned pure; in other words, all its many pairs of coincident partials are meant to match perfectly and produce no beats.

The octave and the double octave are also never tempered: All their pairs of coincident partials are meant to match perfectly and produce no beats. However, since there are only half as many audible pairs of coincident partials in the octave as in the unison, octaves are generally not as objectionable as unisons if both are equally out of tune. Double octaves, with even fewer pairs of audible coincident upper partials, are generally less objectionable still.

In equal temperament, the P4, the P5, the P12, and the P19 are all tempered to a very small degree, around two cents.

The remaining intervals, the m3, the M3, the M6, the M10, and the M17, are much more heavily tempered: sixteen cents for the m3 and M6, and fourteen cents for the rest. They are tempered so much that the beating at their lowest level of coincident partials is quite easy for the ear to distinguish from the much more rapid beating at higher levels. This quality of having one rapid and easily distinguished beat gives the latter intervals a fundamentally different character from the former.

Notice that all the latter intervals include the 5th partial, while none of the former do. This means that when we tune an interval lacking the 5th partial in equal temperament, we ordinarily listen as much to its texture, to its cloud of beating coincident partials, as we do to a particular beat rate at one specific level of coincident partials. In contrast, when we tune a 5th-partial interval in equal temperament, we typically ignore the contribution to its texture of its higher levels of audible coincident partials and hear it as an interval with a single crisp, clear beat.

We have seen that the P4, P5, and P12 have more audible pairs of coincident partials than the other tempered intervals of basic aural piano tuning. Therefore, tempering them makes them rougher than it makes the other intervals. Perhaps one of the reasons that equal temperament has become the standard temperament of modern piano tuning is that it allows the P4, P5, and P12 to be lightly tempered, at the expense of the 5th-partial intervals.

Fundamentals of Piano Tuning Technique

The current widespread use of electronic tuning devices has revealed a basic truth about piano tuning: It is a skill of the hand more than it is a skill of the ear. In learning piano tuning, a tuner's attention has traditionally been focused on training the ear to hear beats and on distributing those beats among the intervals of a piano, while the hand has been left to develop on its own. Yet now that the visual display of a machine can be readily substituted for the ear, allowing virtually anyone to produce an acceptable tuning without any aural skills at all, it is clearer than ever before how crucial good hand skills are to the practice of the craft.

In a way, tuners have always known this. It is a commonplace among tuners that one's skill is revealed by unison tuning. The three strings of a unison should be, from the standpoint of the ear, the easiest strings in a piano to tune, since they are all meant to be exactly the same pitch. In practice, though, unison tuning is capable of seemingly endless refinement. This is because a tuner's mastery of the subtle nuances of unison tuning depends almost entirely on the finely developed capability of the hand to accurately make minute and stable changes in the pitch of a piano string.

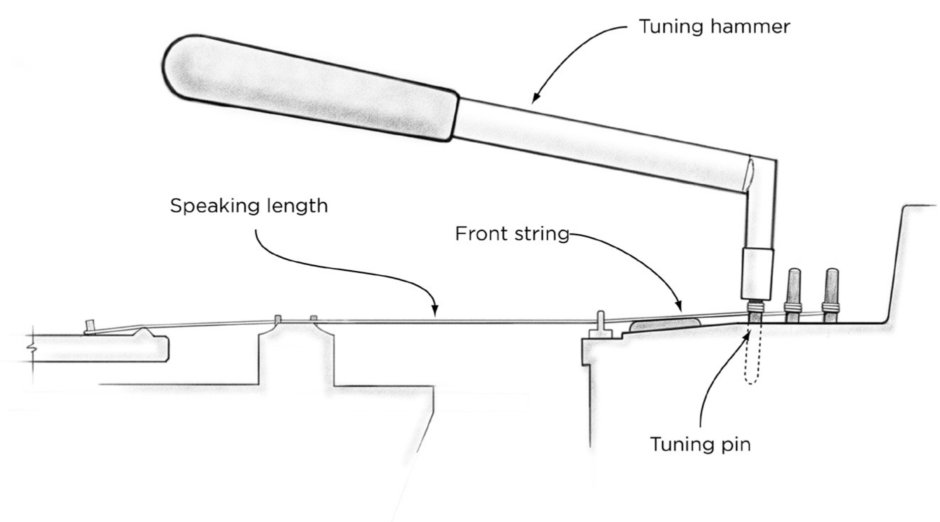

FIGURE 1. *The system through which the tension of the speaking length is adjusted and stabilized.*

The Speaking Length

When we tune a piano string, we adjust the tension of one small segment, called the *speaking length*. The speaking length lies between the two termination points of the string—a bridge pin and an upper termination such as an agraffe or capo bar. The vibrations of the speaking length are transmitted through the bridge to the soundboard, producing the sound we listen to when we tune.

But we don't adjust the tension of the speaking length directly. Instead, we adjust it by manipulating the tension of the *front string*, the portion of the string that lies on the near side of the upper termination.

We manipulate the tension of the front string by manipulating the *tuning pin* to which it is attached.

We manipulate the tuning pin with a *tuning hammer*.

And finally, we manipulate the tuning hammer with our hand.

The process of stably adjusting the tension of the speaking length by manipulating the front string, tuning pin, and tuning hammer is generally referred to as *setting the pin*. It may seem like an unnecessarily complex and roundabout way to tune a string, but we should not be too quick to condemn it. It has evolved into its current form over the span of several centuries, and it remains the universal method for tuning piano strings, numerous patents of alternative systems notwithstanding. Using this system, a skilled tuner can quickly, reliably, and accurately make a change in the pitch of A4 of two tenths of a cent, equivalent to one part in 10,000. Clearly, this system is well suited to its purpose.

The Front String

The front string has two functions: to change the tension of the speaking length, and to hold the speaking length at pitch.

The two hallmarks of expert piano tuning, accuracy and stability, depend on our ability to control the front string as it performs these two functions. Accurate tuning requires accurate manipulation of the speaking length with the front string, and stable tuning requires a finely developed sense of what tension of the front string will stably hold the speaking length at pitch.

Lacking the skill to adjust the speaking length with the front string, a novice tuner often finds it difficult to tune accurately, and may, for example, move a tuning pin and its attached front string a fair amount without making any discernible change in the pitch of the speaking length, only to find that a very slight additional motion suddenly changes its pitch a great deal. This is because changes in the tension of the front string only produce changes in the tension of the speaking length once they are great enough to overcome the static friction of the upper termination point of the string. Once this static friction is overcome, the friction at the upper termination changes to kinetic, or rolling, friction, which for typical piano strings and upper terminations is much lower than static friction. This lower kinetic friction allows the tension of the front string to pass through to the speaking length more easily, resulting in a sudden large change in the pitch of the speaking length.

A novice tuner also frequently finds it difficult to tune stably, and may, for example, put the speaking length exactly at target pitch only to find that a few forceful blows on the key throw it wildly out of tune, even though the tuning pin has not been touched again.

To hold the speaking length stably at pitch, the tension of the front string must be slightly higher than the tension of the speaking length. When the speaking length is struck forcefully, a shock wave runs down the string to the upper termination and the tension of the speaking length increases slightly. The tension of the front string must be high enough that when the shock wave reaches the upper termination, the momentary release of static friction there doesn't allow the increased tension of the speaking length to pull some of the front string across the upper termination, thereby flattening the pitch of the speaking length.

On the other hand, the tension of the front string must not be too much higher than that of the speaking length, or it may pull the speaking length across the upper termination, sharpening its pitch. This can happen either spontaneously or as the result of a forceful blow.

Although in theory there is one ideal tension for any given front string that will hold a particular speaking length most securely at pitch, as a practical matter there is a range of tensions for the front string that hold the speaking length securely. The hand skill of piano tuning consists to a large extent of determining what that range is, and then of putting the speaking length at pitch with the front string in that range.

Of the two hallmarks of good tuning, accuracy and stability, stability is probably the more important. From a practical standpoint, it is preferable to leave a string stable but slightly out of tune than to leave it perfectly in tune but unstable.

The Tuning Pin

The motions of the tuning pin—The axes of a strung tuning pin

THE MOTIONS OF THE TUNING PIN

A tuning pin is a short, thick section of steel rod, squared off at one end so that it can be manipulated with a tuning hammer, pierced by a hole just below the squared-off portion so that a string can be securely attached to it, and threaded at the other end so that it can, when necessary, be turned out of its hole in a pin block. The hole, being smaller than the tuning pin, holds the pin by friction.

A tuning pin mounted in a pin block can move in only two directions:

First, it can rotate around its long axis. When a rotational force around this axis is applied to the squared-off portion of the pin, the exposed portion above the pin block *twists*, flexing around its long axis. It can twist only a small amount, though, because at a certain point the force becomes sufficiently large to overcome the static friction of the pin block on the threaded portion of the pin, and the pin begins to *turn*. The change from twisting to turning begins at the top of the pin and moves down. Once the entire pin has begun to turn, it continues as long as rotational force is applied it until it either comes free of the block again or buries itself completely.

The second way a tuning pin mounted in a pin block can move is by rotating around one of the infinite number of short axes that pass through it from side to side—in other words, by *tilting*: When the top of the pin moves in one direction, the bottom tries to move in the opposite direction.

We will assume that these short, tilting axes are located halfway down the portion of the tuning pin that is gripped by the pin block—roughly, its threaded portion. Of course, if the pin block has pin bushings, the tilting axes are higher than they are in a block without bushings.

Tilting a tuning pin moves it only a limited amount. As the pin tilts, it flexes almost exclusively in the exposed portion above the pin block; the wood of the pin block, compressed by the pin, flexes as well. The more we tilt a pin, the more elastic forces in both it and the pin block resist further tilting. This means that most of the motion we produce when we tilt a pin occurs when we first apply force.

Within the ordinary range of forces used in piano tuning, a tuning pin can be considered to be perfectly elastic: Whether we flex it by twisting or by tilting, as soon as we release it the pin immediately springs back to its original, unflexed state.

The same is true of the wood of the pin block: Upon release of the ordinary tilting forces of tuning, it immediately springs back to its unflexed state. However, we must take some care in tilting the pin, since the wood of the pin block can be forced more easily than the pin past its elastic limit, and be permanently crushed.

Because of its elasticity, the tuning pin is not ordinarily a source of instability in tuning. The portion of the tuning pin above the pin block springs into a stable position as soon as we release it.

Nor, I believe, is the portion of the tuning pin gripped by the pin block unstable. Experiments I have conducted at my workbench seem to indicate that when a pin is turned and then released, about three-fourths of the twist in its gripped portion releases. The remaining twist appears to be quite stable, releasing only when the pin is moved again.

Two properties of the tuning pin make it a useful way for us to manipulate the front string.

First, since we can turn a tuning pin to any one of an infinite number of rotational positions in the pin block, we can set the front string to any tension we like. For any given tension of the speaking length, each particular position of the tuning pin directly corresponds to one particular tension of the front string. We take full advantage of this correspondence when we tune, because in practice the way that we set the tension of the front string is by setting the rotational position of the tuning pin.

Second, since we have two ways of flexing the tuning pin without turning it in the block—twisting and tilting—we have two ways of temporarily changing the tension of the front string without repositioning the tuning pin. This increases enormously the facility with which we can set pins.

In a piano with tuning pins of average tightness, twisting and tilting usually both produce roughly the same amount of change in the tension of the front string.

THE AXES OF A STRUNG TUNING PIN

A tuning pin is continuously both twisted and tilted by the tension of its attached string.

The string leaves the pin at a tangent, so it applies a constant rotational force around the long axis of the pin. The radius of a tuning pin is roughly 1/8 of an inch, and a typical string in a piano has a tension of around 160 pounds. This means that the string applies a constant rotational force to the pin of around 20 inch-pounds. The pin will not turn under the influence of this force unless its friction against the pin block is less than that, but the exposed portion of the pin will always be twisted slightly, exactly enough to counterbalance the tension of the string.

In addition, because the string leaves the tuning pin from a spot above its tilting axis, it applies a constant tilting force to the pin in the direction of the hitch pins, slightly bending the exposed portion of the pin and compressing the wood of the pin block. In an older piano, one often sees a space developing between the tuning pins and the pin block on the side of the pins opposite the strings, evidence of the crushing force of years of continuous tilting.

A mounted and strung tuning pin can be thought of as dividing three-dimensional space along the three Cartesian axes, as shown in Figure 2. One of the axes—the vertical, or *Y*, axis—is the same as the long axis of the tuning pin. The tuning pin turns around this axis. A second axis—the *X* axis—is horizontal and perpendicular to the string. The tuning pin tilts around this axis toward and away from the hitch pin. Tilting in this direction has the greatest effect on the tension of the front string. The third axis—the *Z* axis—is also horizontal, and runs along the line of the string. The tuning pin tilts from side to side around this axis. Tilting the pin around this axis has the least effect on the tension of the front string.

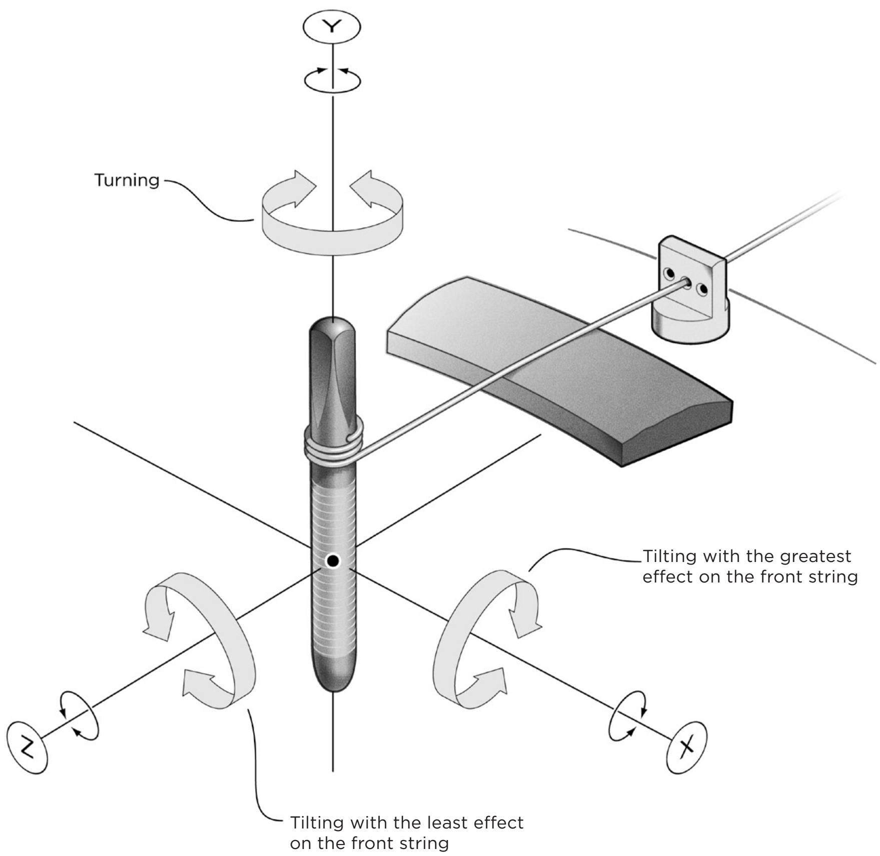

FIGURE 2. *The axes of a strung tuning pin.*