# The Engineering Aspects of MUSIC

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MUSICAL PERFORMANCE IS A combination of art, science, and engineering. Artists don't like to admit it; scientists probably never think about it; and *engineers* are usually thought of in connection with sound reproduction. The artist imagines a new song which, although significantly different from the millions already composed, is conceived within a surprisingly strict framework. The desired sounds must be available from one or more of a limited number of instruments available. These inescapably use scientific principles, although it is true that many were originally designed by trial-and-error before the scientific principles were deduced.

In most cultures there are only 12 tones available as choices; although there are many other frequencies available, they will be considered repeats of one of the 12. This is where engineering enters. The 12 frequencies (and their multiples) will be the same no matter where in the world the music is to be played. Standardization is a form of engineering. Musical notation is universal, but if there are additional written instructions, they will probably be in Italian and will be known to a professional musician of any nationality. The instruments must hold their *pitch* (frequency) reasonably well as the environment (temperature, humidity, etc.) changes or they will not be able to play together. This is a good example of the difference between engineering and pure science.

Finally, the music will be performed by artists (computers will grudgingly be dealt with later), so it must be playable by the normal human mind and body. It is impractical to seat more than two persons at a keyboard, and even that is unusual. Indeed, it is rare these days to hear a performance by more than a dozen musicians. At a small establishment, one often hears a solo performer self-accompanied on a keyboard or guitar, perhaps with the feet adding bass or percussion or with some sort of electronic accompaniment.

## ORIGINS

How old is music? There is some thought that man's first attempts to communicate were closer to music than to speech, i.e., closer to moans than grunts. Even today hunters in the woods sometimes communicate by whistling, and I recently noted that the infamous "wolf whistle" has the same meaning today as in my youth half a century ago. Most documented civilizations had some sort of music.

Art has enjoyed playing the guitar for many years.

Today it is hard to imagine a world without music. Scientific studies indicate workers perform better with background music (or worse, depending on the type); cows give more milk listening to classical music than hard rock. Radio broadcasting centers on music to the extent that "talk radio" is the exception. Movies would be far less impressive without background music. We have special music for ceremonies, particularly religious rites. (If you didn't already know, the processional would alert you that a wedding was starting.) There is music in restaurants, department stores, phone answering machines, even elevators (hence the term *elevator music*, not complimentary).

## WHAT CONSTITUTES MUSIC?

This is a controversial subject, as between parents and their teenagers. The dictionary definition isn't helpful. It is easier to describe it than to define it. You know it when you hear it. My working definition is this: if you can't tell whether the musicians are playing correctly or making mistakes, it isn't good music.

## THE 12–TONE SCALE

The choice of 12 tones is not arbitrary. Recently archaeologists discovered a flute-like instrument at least 20,000 years old. The notes corresponded to white keys on the piano (see

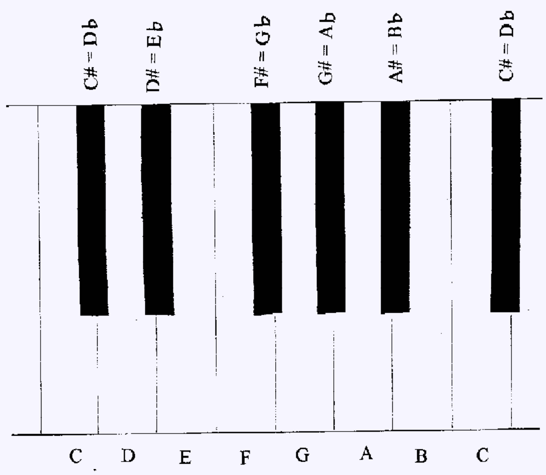


FIG. 1. NOTES ON THE KEYBOARD

### WHY START WITH "C"

C is used as reference for the center of the scale. Students learn the C scale first. C is probably the most common *key* (meaning the music is basically written with the notes of the C scale). If one plays seven consecutive white keys starting with C, one gets a C MAJOR scale. However, if one does the same starting with A, one gets the A MINOR scale, because the half-steps occur at different locations. Originally, major was thought to be effeminate, and hence less important. Today the sentiment has reversed: major is considered bold and hence primary. Standard pitch is still given in terms of A. Unfortunately, there is more than one standard; A = 440 Hz is the most common and is the international standard.

Fig. 1). The *distance* between notes (really frequency ratio) is called the *interval*. Unfortunately, our ancestors didn't start with zero (some ancient cultures had no zero, e.g., Roman numerals), so there is no *first* interval; that would be the note itself. The next key is a *second*. As far as I know, students are still taught to count from one to 10 instead of zero to nine, and their lives are ruined mathematically anyway.

Neither is it a coincidence that the notes are not evenly spaced physically on the keyboard; indeed, there are more white keys than black. Many simple songs can be played on the white keys only (note that the seven notes will not be evenly spaced); many Appalachian folk tunes can be played with the black keys only (five notes = pentatonic, from the Greek). At this point, please accept that it works. Try hitting keys at random making no distinction between white and black, and then at random using only the white keys; the latter will sound noticeably better. Using only the black keys will sound better yet.

The most basic interval is the eighth (12 half-tones, a half-tone being the smallest interval possible on the keyboard regardless of key color), called an *octave* (Latin for eight). It is so basic that the keyboard pattern just repeats past an octave. Men and women singing an octave apart are considered *in unison*, and many people cannot tell that there are two notes being played if they are an octave apart.

A taut string when plucked will vibrate at a *fundamental* frequency. The middle will move back and forth, but the ends are constrained and cannot move. In wave transmission theory this is a *standing wave*. If the string is also constrained in the middle and one end (i.e., half the string) plucked, the frequency will double. This is an octave. Thus all like notes (e.g., all Cs) are equally spaced linearly on the keyboard, but logarithmically in frequency.

If the string is constrained at the one-third point and the long (2/3) section plucked, the note is a fifth interval higher, the fourth white key up (C to G). We need a name for the black key below G. *Flatting* a note lowers it a half-tone, so the note is termed *G-flat*. Conversely, *sharp* raises a note a half-tone. Thus F-sharp is the same note as G-flat. Although theoretically only one or the other is necessary, it can be quite clumsy to write music with only one. In a given piece of music one will make more sense than the other. A *natural* undoes the effect of an existing sharp or flat. The fifth will be a fourth below the octave; the two do not add to an eighth because of the problem of not starting with zero. Some other intervals are: major third 5:4 frequency ratio, minor third 6:5, and major sixth 5:3. These ratios were first discovered by Pythagoras, of *right-triangle* fame. The rational ratios mean that some harmonics of some notes line up with other harmonics of other notes, part of the explanation behind harmony. (If you observe the waveforms on an oscilloscope, you will find that the overtones are not EXACT multiples; this is because the string is not truly linear. You will also note that the frequency changes slightly with amplitude.)

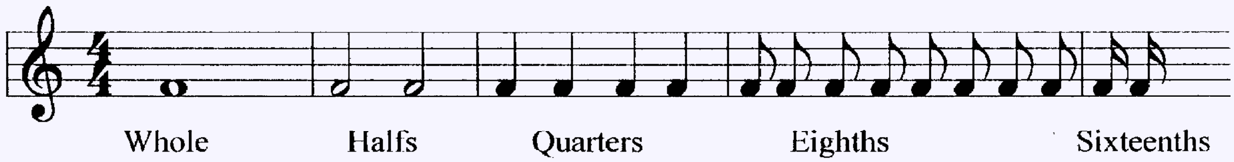


Fig. 2 Note Duration

## THE (EQUAL) TEMPERED SCALE

The 12 tones of the scale thus derived are close to being equally spaced on a logarithmic scale, but not quite. There are many advantages to *fudging* the frequencies so the spacing is exactly even. This is called the *tempered* scale and was championed by J.S. Bach, who wrote an entire ensemble of pieces to advertise it named "The Well-Tempered Clavier." (I like to think of J.S. Bach as an engineer. He is reported to have said, "Music is a combination of math and magic.") If a piano is tuned by octaves rather than fifths, at the ends of the keyboard (which sound pretty much like *clunk* and *clink* anyway) the difference is only about half a half-tone, a minor difference given the advantages to be gained. With the tempered scale, a song may be moved up or down in *key* to accommodate a singer and still sound the same. A *C* instrument and a *B-flat* instrument will be in tune on all notes if one is shifted by two half-tones. For example, on the tempered scale a minor sixth is a frequency ratio of 1.68, while computing it from an octave and a (true) major third would give 1.6.

The alternative is called the *scientific* (or *just*) scale and is what an expert musician with any pitch available (e.g., violin) will instinctively play. Another way of putting it is that a violinist will play a given note slightly differently depending on what other notes are being played. The tempered scale should thus have been termed the *engineering* scale, but engineering hadn't been defined yet.

## RHYTHM, MELODY, AND HARMONY

Music can be conveniently divided into rhythm, melody, and harmony, although they are not independent: a given melody will sound quite different if the time dependence (rhythm) is altered. It is said that we owe rhythm to Africa, melody to the Orient, and harmony to the West. This is surely an oversimplification, but there is considerable justification. We place heavy emphasis on harmony, which notes sound good together. Usually the first thing a novice guitar player learns is *chords*. Oddly, harmony was not only the last of the three to be developed, but is relatively recent, measured in centuries.

## RHYTHM

Every old movie set in Africa had the sound of *jungle drums*. One might think that a *primitive* people would be capable of only primitive rhythms, but the opposite is true. I have heard a 13-piece rhythm band (rhythm being defined as percussion not having identifiable tones like a xylophone) play patterns so intricate that *music* seemed unnecessary.

Rhythm is basically the timing element of music. Again, it is written in a way that is highly structured, yet allows for a near-infinite number of combinations with notation available for additional slight variations. The system is basically binary, which, as any computer designer can tell you, is much better than decimal. It follows simple rules: Each time ink is added to the note (see Fig. 2), the duration is halved; adding a tail to the whole note makes it a half, filling in the circle makes it a quarter, adding one flag an eighth, two a sixteenth, etc. Actually, anything shorter than a sixteenth is hard to discern and is usually denoted by a general-purpose *grace* note of short but unspecified duration. Just the values listed give 32 possibilities, not counting lengthening by *tying* additional notes together.

What about non-binary? The most common variation is a *triplet*, three notes in the space of two, or three beats to a measure (waltz). This may also be done with five, seven, etc., but it takes an experienced musician to hear these, much less play them. Modification is possible by written instruction. There is some shorthand, the most common being a dot which adds half again to the length of whatever it follows.

Logically, a whole note would be one beat (count), but this is impractical because anything longer would require tying on additional notes. Instead, a whole note has four beats, which fills a standard *measure* (Fig. 2). Measures, denoted by vertical bars, break the music into intervals, usually, but not necessarily, regular. This is partly for convenience (it is easier to read), but it also implies a rhythmic emphasis (the first beat of a measure is usually accented). An *accidental*, an inserted sharp, flat, or natural, applies to all following notes on the same line within the measure, but is cancelled by a new measure so the musician need not have a long memory. Also, numbering the measures enables a conductor to instantly let the orchestra know which


Fig. 3 Musical Scale and Staff

particular section is (dis)pleasing. The music could be played without them, and, indeed for some styles (e.g., plainsong), they are not appropriate and are omitted.

The time signature (numbers at the beginning; Fig. 2) gives the meter: the top number tells the number of beats in a measure (four, here), and the bottom number, really the denominator of a fraction, tells what type of note gets one beat (a quarter note here). Likewise, the time signature is not absolutely necessary and is sometimes omitted, particularly for irregular pieces (plainsong, again). Modern music usually gives the metronome, the number of beats to a minute. Given this and the choice of basic note means that a quarter-note in one piece might last the same time as a half-note in another, and an eighth-note in a third! This is less confusing than it sounds, because the style of music usually makes the sense obvious anyway.

## MELODY

The notation system for the notes of the scale is shown in Fig. 3. Alternate lines and spaces are used to denote the white keys of the keyboard. The black keys are reached by modifying notes with sharps or flats. The lower *C* shown is halfway between the upper *treble-clef* staff (corresponding generally to female voices and higher-pitched instruments) and the lower *bass-clef* staff (corresponding to male voices and lower pitches) and requires an extra line called a *ledger* line. The ledger line is effectively another line added to the staff to extend its limited range and can appear either above or below either clef. Additional ledger lines are used if notes are correspondingly farther from the staff. Partly for this reason, the two staffs are normally written much farther apart than shown. Middle C is about the center of the piano keyboard. Why not allot each of the 12 tones a line or space? The method used is more compact and parallels the keyboard: if 12 identical keys were used, either the keys would be too narrow for the average thumb or the octave span too wide for the average hand.

## HARMONY

Today the strongest conscious effort is toward harmony. The most feared mistake is a *wrong note*, meaning one that doesn't *fit* in with the others, since few in the audience will know how the score was actually marked. For reasons that are not fully understood, some combinations of notes (primarily meaning played simultaneously) sound better (generally meaning more pleasant) than others. In fact, *harmony* or *chord* implies pleasant; the opposite being termed *dissonance* or *discord*. Consensus of what sounds pleasant has varied somewhat with century and ethnic group, but some basics are evident. A good composer will intentionally include some discords, or the music sounds too sweet—childish or *syrupy*. (The simple tune "Chopsticks" begins with a discord.)

A (major) second interval (two half-tones apart; see Fig. 4) sounds discordant; a minor second is worse. A major third is pleasant, a common chord. A minor third is acceptable, but less joyful. A soprano and an alto singing a Christmas carol will often sing in *parallel thirds*. The fourth is only a half-step up from a major third, so there is only one, no major or minor. It is pretty much neutral. Parallel fourths sound oriental. Other than the octave, the fifth is the most basic interval in the scale and is termed *perfect* because the distance between it and an octave is a (perfect) fourth. It is neutral; it can sound either major or minor depending on the other notes. Left-hand accompaniment (lower notes) will often be in fifths. If a note is added in the middle of a fifth, it will split the fifth into a major third and a minor third (numbering problem again). If the major third is on the bottom, we get a *major triad*, or simply *major chord*, and vice-versa (see Figs. 5 and 6). Indeed, if you stop only the middle note, your ear will continue to hear either major or minor, depending on what it was originally (see MEMORY, later)! If the key of a song is changed from major to minor (and this is occasionally done for effect), the mood goes from happy, upbeat, and outgoing to solemn, mournful, introverted. Even most non-musicians have a vague concept of major and minor, which is good, because I can't explain it; how a mere change in frequency can induce a totally different mood is beyond me! A given mode is suited to a given text; I frequently get complaints about some of the mismatches in our hymnal.

A flatted fifth interval, also called a *tritone*, is universally considered discordant, although it does appear in one common chord. Oddly, this interval is the midpoint of the octave! A major sixth is a minor third short of an octave, and vice versa. Both sixths are pleasant. A man and a woman singing a country duet may use parallel sixths. A

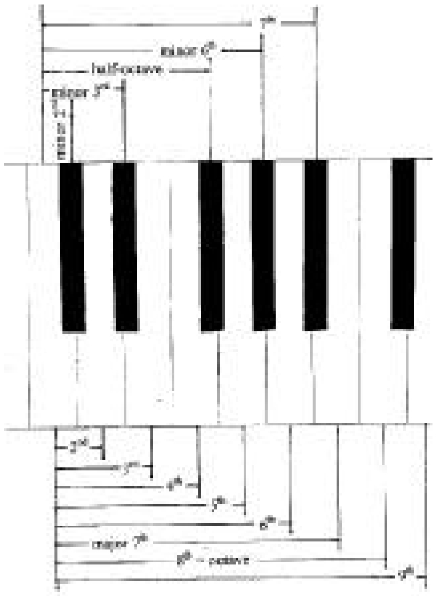


FIG. 4 INTERVALS ON THE KEYBOARD

major sixth added to a major triad gives a *sixth* chord, used a lot in jazz and door chimes (see Fig. 7).

With the seventh, the terminology becomes confusing. If a minor third is added to a minor triad, the result is termed a minor seventh; if a major third is added to a major triad, we get a major seventh. The first sounds very minor, the second quite dissonant. If we add a MINOR third to a MAJOR triad, we get a DOMINANT seventh (Fig 8), usually referred to simply as a *seventh* chord, familiar even to beginners. It sounds reasonably pleasant, surprising because the top note is only a whole tone away from the octave, but unfinished.

An eighth is an octave, which brings us back to the same note. However, a note plus its octave sounds *fuller* (see OVERTONES later). A ninth is a major second beyond an octave, but it doesn't sound nearly as bad as a simple major second, especially on top of a major triad (see Fig 9). This is an illustration of why two Cs an octave apart are not really the same note. A full ninth chord is a seventh plus the ninth. An eleventh is a fourth past an octave, or adding another third to a ninth. A thirteenth is adding another third on top of an eleventh. It contains all seven notes of the scale, so no further additions are defined.

One might think that dividing the 12 tones into equal intervals would give a pleasing sound, but this is not so because the scale is logarithmic. The half-octave already has been cited as the universal dissonance. Dividing the octave into three major thirds gives an *augmented* chord (Fig. 10); so called because the fifth is augmented. Dividing it into four minor thirds gives a *diminished* chord (Fig. 11). Both are dissonant chords. Dividing the octave into six (major) seconds gives what one would expect; it is so bad that it doesn't have a name.

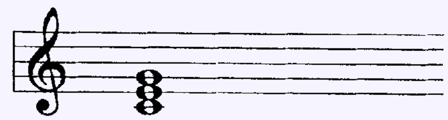

Fig. 5 C-Major Triad (C-E-G)

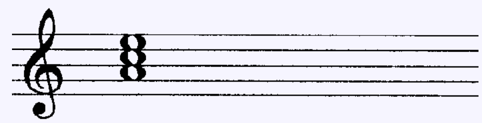

Fig. 6 A-Minor Triad (A-C-E)

Fig. 7 C-Sixth

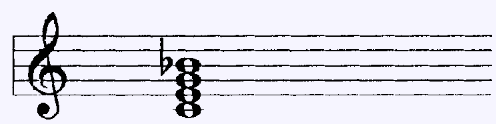

Fig. 8 C-Seventh

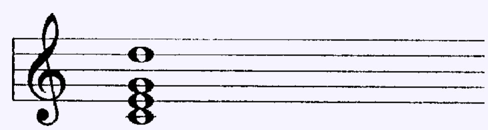

Fig. 9 C-Ninth

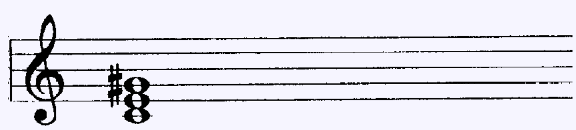

Fig. 10 C+ (Augmented) = E+ = G#+

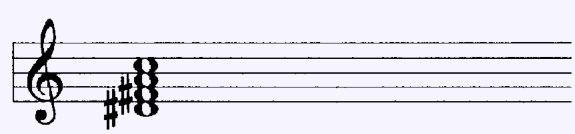

Fig. 11 C° (Diminished) = D#° = F#° = A°

### J.S. BACH AND THE UNFINISHED SEVENTH

The story goes that J.S. Bach's younger brother would sneak downstairs in the middle of the night, play a seventh chord on the piano, and hide. J.S. would run downstairs, try to find and thrash the imp (usually unsuccessfully), and go to the piano and *resolve* the chord, or else he could not get to sleep.

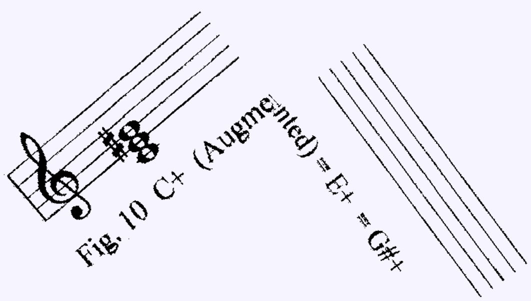

Fig. 10 C+ (Augmented) = E+ = G#+

### BREAKING THE RULES

The opening of J.S. Bach's famous "Toccata and Fugue in D-Minor," played by Captain Nemo in "Twenty Thousand Leagues Under the Sea," centers on a diminished chord. The theme song from "Sound of Music" by Richard Rodgers opens with a ninth (the HILLS…). It also ends on a major seventh. "Climb Ev'ry Mountain" from the same show contains major sevenths, minor sevenths, minor sixths, and augmenteds. Analyzing the songs scientifically, one would expect them to be discordant; so much for analysis.

## OVERTONES / HARMONICS

As mentioned earlier, a taut string when constrained at the center will vibrate at twice the *fundamental* frequency. If the constraint is quickly removed, it will continue to vibrate at twice the frequency. In fact, if it is *open* but plucked at one-quarter the length, it will vibrate at BOTH single and double frequencies simultaneously. Likewise, the string can vibrate at three- four- etc., times the fundamental. These extra frequencies in music are called *overtones*; in engineering, *harmonics*. Using the same numbering system as before, the first harmonic is the fundamental itself, the second harmonic is twice the frequency, etc., which makes sense here. Overtones give an instrument *character*, distinguishing it from others. Probably the purest tone comes from a flute or an organ pipe of the same name. A computer can generate truly pure tones, but these quickly sound toylike and childish.

The overtones can produce *extra* notes. If a high C string on a piano is held open by depressing the key slowly and holding it, and a low C key struck hard and then damped, a complete chord will *ring* on the high string. Sometimes the overtone is purposely used with no fundamental at all. A trio of buglers can play a complete chord although they are all tuned to the same fundamental.

## ATTACK, DECAY, AND RELEASE

Physical (non-electronic) instruments cannot generate a tone instantaneously. In fact, for some the initial sound is totally different from the eventual. What happens during the development of the tone(s) is called *attack*; engineers will recognize this as an initial transient before steady-state. Attack is a major distinguishing feature of instruments. Two instruments that have similar harmonic structure are nearly indistinguishable once they reach steady state, e.g., some organ stops are named after the instrument they sound like. The attack can range from insignificant to crude to the entire note. With the autoharp, all strings are struck and the unwanted ones damped out, so it has a harsh, percussive attack. An organ pipe takes time for the standing wave to develop; the initial sound is simply that of rushing air, wind noise. This is called *chiff* and is artificially inserted by some electronic instruments to better simulate the real thing. A xylophone makes a fairly pure tone, but the initial sound, not surprisingly, is that of a hammer hitting metal. A violin bowed gently can produce a smoothly increasing tone with no perceptible attack.

*Decay* is how fast the tone dies out. An organ has no decay at all, one of its principal features. But mathematicians and electronic engineers know that suddenly ending a pure tone has the same theoretical spectrum as suddenly starting one, a paradox, because in the time domain they are exact opposites!

## MEMORY

An aspect of listening that generally receives insufficient attention in the texts is the workings of the human memory. Of course, melody would be meaningless if you couldn't remember the previous note, but it goes much, much deeper. Two chords that sound good individually may sound poor in juxtaposition. When an unaccompanied soloist sings "Oh, Say Can You See?" the ear hears a complete triad-plus-octave even though only one note at a time was sung. The actual accompaniment uses varying chords, and the line sounds quite different accompanied.

## CONCLUSION

Obviously, one doesn't have to understand music to appreciate it (e.g., rock concerts, assuming some actually go for the music), but engineers usually like to understand how things work; that is one reason I am an engineer. A short article cannot substitute for a music degree, but I hope this will inspire a greater interest and understanding of music among amateurs and non-musicians.

One of the limitations on music mentioned at the beginning was the instruments themselves—that they be buildable and playable by humans. (Computers have made surprisingly little inroad here.) A subsequent article will explore the engineering aspects of instruments. Electronic applications, an entire subject in itself, will be summarized. Lastly, some thoughts on the future of music will be presented.

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Art holds nine patents. His hobbies include electronics, audio, music, cars, water-skiing, and cycling.