The Engineering Aspects of Music

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INTRODUCTION

A PREVIOUS ARTICLE in the Spring 2003 BENT discussed the origins and structure of music. The author argued that it was engineering that made music possible for the masses, even before sound reproduction. This article considers various instruments used to make music. Again, engineering is required to make them playable and practical. Sound reproduction and the influence of computers will be mentioned briefly. Some predictions for the future will be made (the most dangerous part).

TYPES OF INSTRUMENTS

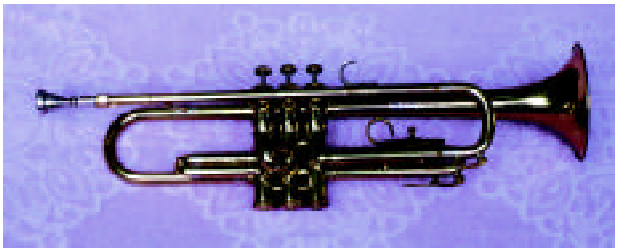
Numerous unique instruments have been invented, most of them abandoned, thankfully. Here are a few of the most common. Certainly the original, the most portable, the most popular, possibly the most versatile, and, to some composers (e.g., Wagner), the primary instrument is the human voice. Also the original computer-controlled instrument, it is beyond the scope of this paper. We will be discussing mechanical instruments, with electronic instruments as an addendum.

There are several ways of categorizing instruments. Can the sound be maintained indefinitely, or does it fade? How big is it? Can it be played while marching? What mechanism produces the sound? The latter is the most common classification, and I will use it, with an exception.

■ WINDS

The sound from a wind instrument is created by an unstable (i.e., oscillating) column of air. One of a baby's first self-actualizations is blowing air through its closed lips, creating an unpleasant buzzing sound. This is the principle behind the horns, which (one hopes) creates a more pleasing tone. The horn appears to amplify the sound, but it really only tunes the vibrations to its natural resonances, inherently eliminating unwanted frequencies, and it couples the energy efficiently to the air via an exponentially-expanding (belled) outlet. The old ear-trumpet, predecessor to the electronic hearing aid, used this latter principle in reverse.

The trumpet is probably the most impressive of the one-note instruments. In ancient times a trumpet blast called the men to prayer or to war (sometimes both). Pre-electronic armies used the bugle (a simple trumpet without valves) to signal commands (e.g., "charge!"). "Taps" is still played at military burials. Originally the trumpet was played in a very high range, so many different notes were available as harmonics of much lower fundamentals. The modern trumpet has three valves (Fig. 1) which reroute the air through extra tubing to lengthen the air column. This provides seven notes (the eighth is redundant), covering all notes but the lowest half-octave, which is not used.



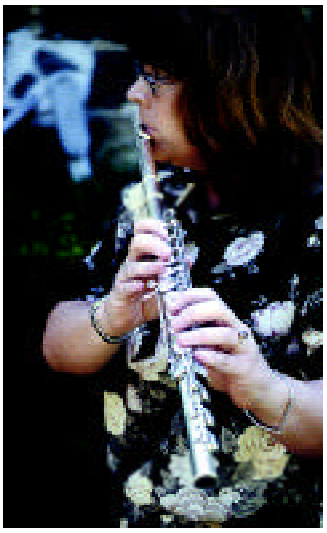
1. TRUMPET *Note valves*

2. TROMBONE *Note slide*

The slide trombone varies the path length by sliding a pair of tightly fitting tubes within another pair (Fig. 2). Thus it can play any arbitrary frequency; the player must learn the approximate positions for the notes of the scale by reflex and make fine adjustments by ear.

There are other varieties of "horns," principally of increased size to play lower frequencies. The granddaddy, the sousaphone, was invented by and named for John Phillips Sousa, the "March King." Like huge flowers, often bigger than the players, these are usually visible at the rear of a marching band.

The flute (and its smaller cousin, the piccolo, and its military cousin, the fife) is a serious refinement of the pennywhistle. Nonlinear airflow excites the resonance of



3. FLUTE *Note keys*

a column (tube) of air, a fortuitous instability. Uncovering holes shortens the effective length of the tube, creating a higher pitch. Since nature made the mistake of providing more notes than fingers, a system of levers and pads covers/uncovers the holes (Fig. 3).

The clarinet (originally clarionette, Fig. 4) is the basic "reed" instrument. A thin reed is also unstable with air flowing over it and will vibrate. Again, pads operated by levers cover holes. A saxophone is a larger version, with a U-shape at the bottom to achieve extra length, and is made from brass, whereas the clarinet is wood. An oboe (and its larger cousin the bassoon) uses a double reed. They thus have additional possible modes of vibration and are more difficult to avoid interference from extraneous frequencies.

4. CLARINET *Note reed*

■ STRINGS

The violin (Fig. 5) is the premier symphonic "string" instrument. A string is shortened by holding it down with a finger. This dampens the sound quickly, so the string is normally "bowed" by a rosined bow that pulls the string to the limit of friction and then releases it in rapid repetition, vibrating it continuously. (It may indeed occasionally be "plucked" for effect, producing a short, sharp note.) The "bridge" supporting the four strings is an arch so the strings are accessible individually, although two may be played simultaneously by careful placement of the bow. The bridge rests on a hollow wooden body which acts as a "sounding board," better coupling the vibrational energy to the air. It must be carefully designed not to add any resonances of its own—a fine art. Most people recognize the name *Stradivarius*, a 17th century violin maker considered unequalled. An unplayed instrument degrades in quality. Oils from the skin help preserve the wood; vibrations are said to help, perhaps by causing aging stress to produce many tiny cracks rather than a few large ones. Any frequency may be produced, so the player must have a good "ear." Wiggling the finger will give a slight variation of the frequency, "modulation" or "vibrato" or "breadth."

Thus, a number of violins will produce an equal number of ever-so-slightly different frequencies. This produces a broad, mellow spectrum. In contrast, a solo violin tends to be relatively harsh, often described as "squeaky." Another ramification is that a violin player will consciously or unconsciously adjust the pitch to be optimum for the chord, i.e., not play a tempered scale. A violin player and a piano player will each think the other's instrument is out of tune, and in a sense both will be right.

5. FIDDLE *The country cousin of the violin*

The violin is an old instrument; the strings were originally catgut. Modern synthetics are much better. The violin's larger and lower cousins are the viola, the (violin) cello, and the (double) bass or bass viol.

The guitar is familiar to everyone, especially those who spend time with teenagers. It is probably the most common instrument for self-amusement and surely the most common for self-accompaniment. Its origins are lost in antiquity. It differs from the previous instruments in several important respects. It normally has six strings. The fingerboard has ridges called "frets" which quantize the available lengths to correspond to the notes of the scale. These also give a solid footing so the string will ring for a longer time when plucked. The six strings lie basically in a single plane so they can easily be struck simultaneously with a single pick for a complete chord, if desired.

An unamplified acoustic guitar produces only enough sound to generally be useful as a solo instrument (exception: Mexican street bands composed entirely of acoustic guitars of varying sizes), but the electrified version has become a staple of most types of bands. There are a number of variations of the guitar, and the different

6. DOBRO GUITAR

playing styles alone would fill a small book. The 12-string, generally attributed to the American Negro of pre-Civil-War times, really has six *pairs* of strings, the extras being an octave higher where practical. Having to place a small (higher-pitched) string close to a large (lower-pitched) string causes some interesting problems. (It is impossible to increase the weight of the lower strings enough by increased thickness because they become too stiff, so they are made by winding one string around another.) Adjustments in fret height, bridge height, and string length to the individual strings are difficult or impossible. Also, adjacent strings tend to hit each other when struck hard. In addition to making twice the noise, these non-ideal properties give the instrument a strong character, and it is not subtle. It is one of my favorites.

The Dobro (trademarked, Fig. 6) is held flat with a steel bar ("slide") used to define the string length. (The frets are present but are mainly for reference and are seldom used.) The bridge rests on a thin cone of aluminum, not unlike a loudspeaker. The strings are tuned to a chord. Thus, it is easy to play in mediocre fashion, but difficult to play well. Any pitch is possible, and continuously varying pitches, called "slides," are quite effective.

■ BANJO

Originally the banjo (Fig. 7) was a poor imitation of a guitar—two strings missing and the remaining four tuned to a chord. But with the addition of a fifth string (again, attributed to the American Negro), the banjo acquired a unique character. The extra string is shorter (higher-pitched) than the rest, not fingerable, and on the wrong (low-note) side! This one note, never changing, is struck repeatedly, a constant thread running through the music independent of what the other strings are playing. (This is also true of certain other instruments such as the dulcimer and bagpipes.) The bridge for the strings rests on a drumhead, so the tones are short, percussive, and *loud*. Even a beginner can make a delightful amount of noise on a five-string banjo.

There are a number of playing styles, but the most popular was developed by Earl Scruggs, who still performs. He also invented special tuning pegs with stops so two strings can be tuned to a different key while playing.

■ MANDOLIN

A mandolin (Fig. 8) is a cross between a fiddle and a guitar. It has four pairs (or even triplets) of strings with violin tuning, but has frets and strings in a plane so it is played more like a guitar.

8. MANDOLIN *Note strings in triplets*

■ HARP

Also in a class of its own, rather than altering string length, the harp (Fig. 9) has a large number of strings, but not enough for all notes. The others are obtained by altering string length by means of foot pedals connected to extra tuning pegs. The strings are plucked directly by the fingers, near the middle (as opposed to most string instruments) for a rather pure tone. It incorporates a small sounding board, but resting it on a wood floor enhances the sound. It has a beautiful, soothing sound and requires much practice to play. Moving it is a two-person job, which limits its popularity.

There are smaller versions of the harp. One modern version, really quite different, is the autoharp (trademarked, Fig. 10). Originally designed as a child's instrument, its playing has been advanced to an art form by some, notably Mother Maybelle Carter of the famous

7. BANJO *Note fifth string*

9. HARP

Carter family, and it is receiving increased attention, chiefly in the folk and bluegrass domains. There is a string for each note over about three octaves. All are struck simultaneously, but the unwanted notes are damped out by pads on a bar depressed by a finger of the other hand. Thus, it plays by chords, although by carefully limiting the upper range of the strings struck, a melody may be more or less played. (If you depress two keys, for instance C and G chords, you get the one note common to both chords, that is—G. I haven't learned to do that and haven't yet heard anyone else do it.) Since all strings are struck, it has a harsh, thumping attack, almost adding its own percussion. This can be enhanced by selecting the chord slightly *after* the strings are struck.

The instrument was designed to lie flat on a table to act as a sounding board, but this was unacceptable to wandering troubadours who have attached shoulder straps, or even learned to cradle the instrument while playing it. This gives it a poor response to the low notes, but when used with an electronic pickup, the response can be corrected. It is naturally a popular instrument for self-accompaniment.

10. AUTOHARP *If you can operate a telephone keypad, you can play one*

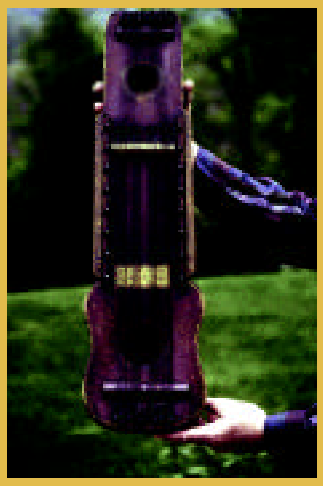
■ KEYBOARDS

A piano may be classified either as a string instrument, because it has such, or a percussion instrument, because the strings are struck by hammers (actuated indirectly by keys), but neither really suits. A separate category is needed—keyboards. As indicated earlier, each key is assigned one corresponding note, although as many as three strings are used. The piano has 88 keys, over seven octaves, ranging from almost the low end of human hearing to an octave from the top (which sounds pure mainly because you can't hear the overtones).

The full name for the instrument is the pianoforte, literally the softloud. The volume is proportional to how hard the keys are struck, not true of previous instruments such as the organ and the harpsichord.

When a key is released, a damper rests on its strings. However, a foot pedal holds all dampers off, which has two marvelous effects: The primary one is that the player can play a key, then move on to another, and another, to build up a chord that could not be spanned by the hand. More subtle and often overlooked, but an important contributor to the instruments character, is that the unused strings are free to vibrate sympathetically and reinforce overtones, thus creating a full harmonic structure. (The East Indian sitar has a set of non-played strings that ring sympathetically.)

Easily the most impressive single instrument and one of the oldest is the pipe organ. (Two exceptions: the theatre organ, which is a pipe organ plus percussion, bells, and whistles; and the electronic synthesizer, which can theoretically produce the sound of any instrument and play through as many amplifiers as you can afford.) Originally the "wind" (pressurized air) was supplied by bellows operated by serfs. A rope attached to a warning bell (or directly to the poor slave) could be pulled by the keyboardist if he felt the pressure was insufficient. Depressing a key opened valves which fed air to that particular note in the various "ranks" or sets of pipes. Those ranks not wanted were "stopped" by pushing in a knob, hence the expression "pulling out all the stops," meaning maximum output. The particular rank might be a fundamental, or a different octave, or even a fifth or a fourth. Thus a single key can produce a collection of sounds, and a "full organ" can hold its own against an orchestra. Volume is controlled mostly by selecting stops, but a few of the ranks are enclosed in a box with variable louvers controlled by "Great" and "Swell" (denoting multiple keyboards) "crescendo" pedals.



EXTINCT INSTRUMENTS

An example of an extinct instrument is the UKELIN (trademarked, above). On one end strings are bowed individually for the melody; on the other strings are struck in groups (chords) for accompaniment. Another somewhat similar instrument is the MARXOPHONE (also trademarked, below). There are several sets of strings in chords for one hand, while the other plays the melody on individual strings struck by hammers actuated directly by the fingers.

Naturally these were found predominantly in cathedrals and concert halls, becoming permanent fixtures. In fact, each organ is designed to fit its building, both physically and musically. Home versions were developed which generally used reeds instead of pipes. Reed organs were later electronically amplified. Eventually the sounds were generated entirely electronically: 12 oscillators generated the top 12 tones, and the lower octaves were obtained by frequency dividers. Today it is all done by programming a computer. We have come full circle—in some of the better electronic organs, each referenced file is a digitized version of a recording of an actual organ pipe!

Other keyboard instruments are: the harpsichord, in which the strings are plucked by leather fingers or "quills"; the celeste, in which chimes are struck; and the carillon, in which steeple bells are rung.

The piano accordion (and relatives) is a reed instrument where the wind (air) is supplied by a bellows compressed and expanded by the player's hands (wrists, really), while one hand plays a short organ keyboard and the other pushes buttons that select complete chords. A talented player is practically a one-man band.

■ PERCUSSION

Percussionists have at their command more instruments than the rest of the orchestra combined. To a percussionist, any (non-living) object will produce an interesting sound when struck properly. Most familiar, and certainly among the oldest instruments, are the drums, of which there are many types. Originally used to communicate or to add drama to a rite (the latter still used by the military) or to keep foot soldiers in step, in the modern orchestra/band they generally emphasize, establish, or sometimes counterpoint the beat.

Drums are made by stretching a sheet of synthetic plastic (originally an animal hide) tightly over the end of a large cylinder (originally probably a hollow log or a clay vessel). The large area gives efficient coupling to the air (much noise) and the cylinder enhances the tonal quality somewhat. A second drumhead on the other end of the cylinder may be used to vibrate sympathetically. If springs are stretched across it we get the rattling sound of a snare drum. With the tympani, or kettledrum, a foot pedal actuates a system of levers and rods to vary the tension on the drumhead to change the "pitch." It is resonant enough that it is tuned for each piece of music. The largest drum in the U.S. is a bass drum of a college marching band that is so large it must be carried by a pickup truck.

Cymbals, struck individually or crashed together, give the familiar shimmering sound. Rivets loosely fastened in holes can increase the effect. A near but larger relative, the gong, is used to announce important events such as the arrival of royalty—at least in movies.

Modern bands have adapted a large number of ordinary items, some basically sound effects: the whip (actually a wooden clapper), hollow wood blocks (the tick-tock

in any song about clocks), sleigh bells (e.g., in Leroy Anderson's "Sleigh Ride"), cowbell, and washboard (simulated usually). For the "Anvil Chorus" we used the steel end plate from a torpedo and an ordinary hammer. The result was quite impressive; the row of musicians directly in front of us said their ears rang for the rest of the day.

There are a number of percussion instruments that have actual tones—xylophone, vibraphone, chimes, and glockenspiel. These are usually played by percussionists, who must be able to read notes also.

The steel drum is an invention of the Caribbean islanders. Fashioned from 55-gallon drums abandoned by the U.S. military, the ends are hammered into multiple domes of varying size to produce different notes. Upon arrival at an island, one may be greeted by an entire band of these producing surprisingly melodious sounds.

The reader can review much of the above in a more enjoyable format by listening to a recording of Benjamin Britten's "Young Person's Guide to the Orchestra."

■ ELECTRONICS

Aside from radio and recording, electronics was first used with microphones to amplify the voices of solo singers, eliminating the need for operatic voices. Next, it was used for instruments whose sound was not loud enough, such as a guitar. Then someone got the idea of mounting the microphone directly on the guitar to reduce extraneous pickup. But because the strings were usually metal, the pickup need not be acoustic at all, but could be magnetic. The magnetic pickup was also insensitive to ambient sounds directly. (The guitar body still acted as a microphone somewhat.) Since the sound could now be adjusted electronically as desired, the hollow guitar body was no longer necessary. Les Paul and Leo Fender perfected the solid-body guitar, and the (musical) world hasn't been the same since. When I graduated and found a paying job, one of my first major purchases was a Fender "Stratocaster"; the model is still made.

The pickup is an integral part of the instrument, not an addition. There is little sound without an "amp," not even enough to practice. However, the strings ring a long time, as virtually no energy is coupled to the air. The amount of sound can be raised to the threshold of pain just by turning a knob. Even so, there is seldom a feedback problem as the body of the guitar is a piece of wood (surprisingly heavy—the wide straps are not just for show). One Beatles' song we played begins with a tone of *increasing* volume; this was achieved by holding the guitar body directly against the speaker cabinet for positive feedback.

An additional dimension was added by a lever-spring arrangement on the ends of the strings, which varied the tension and hence the pitch. The "twang bar" is the audio equivalent of a roller-coaster and can make you catch your breath when used effectively. Indeed, in early rock-and-roll there was a popular genre of instrumental song in which twang was actually part of the melody and not an adjunct.

The steel guitar has no "body" as such; a number of strings are stretched across a piece of steel or other material, and an electronic pickup is essential. Played like a Dobro, each set of strings is tuned to a chord, but pedals or knee levers can alter the pitch of certain strings to change the chord. It is rather complicated to play well, and the number of guitarists who can also play "steel" is probably less than a percent.

For the many small churches dotting the countryside, pipe organs were out of the question, and the piano became the standard instrument. But a piano didn't fit many classic hymn tunes written for the organ. (Once past the keyboard, the two instruments are in many respects opposite; again, only a small percentage of keyboardists play both equally well.) With electronics readily available after WWII, a number of companies produced electronic organs of varying quality, and these were found in most churches, funeral parlors, and radio and TV studios. Some attempted to reproduce the harmonic structure of organ pipes, but some made no pretense, relying on purely electronic gimmicks.

Likewise, computers were "taught" to play music, but these sounded like toys—too pure, too perfect. After a couple of decades, computer-chip capability had advanced to the point that they could successfully mimic a real instrument. (Even a simple song contains a large amount of information; a pop song will not fit on a 3.5-inch diskette.) Non-ideal characteristics had to be built in to make the computer sound real; "perfect" music sounds uninteresting. With a pipe organ in a cathedral, the sound is continuously changing as the tones reverberate and reinforce or cancel, even for a continuous chord. A crude but rather effective method for simulating this was to mount the loudspeakers of an electronic organ on a rotating disc called a Leslie, after the inventor.

The logical extension of the electronic organ was the music synthesizer, basically a computer connected to a keyboard. (A similar instrument is available using a guitar fingerboard.) These can reproduce the sound of most common instruments, including a chorus of human voices (singing "aaahh"), plus unique sounds of their own. Often you are not hearing the instrument you think you are, but a synthesizer.

For many years attempts have been made to create new electronic instruments having no acoustic counterparts. An example is the Theremin, in which the frequency (pitch) is determined by the positioning of the operator's hand (by sensing capacitance). None of these has been very successful. Some modern composers have tried to "teach" computers to compose. The results may sound pleasant to the computer, but they don't to me.

THE FUTURE

Before the advent of radio, recording, TV, and now the Internet, bands were everywhere—dances, weddings, and playing in the park. With sound reproduction nearing perfection, we will probably go to the opposite extreme. Schools are already questioning whether a student really needs to learn how to add; will a music student be encouraged or discouraged by having music readily available at

a level of accomplishment they can never hope to achieve? Worse yet, the perfection is usually achieved electronically; when you hear "one" recording you are usually listening to a composite of a dozen or more "takes."

The frailty of human nature cannot compete with the computer. The promoter of a mega-concert cannot cancel because one singer has laryngitis; that part will be "lip-synced," if not the entire performance. If the sound all comes out of loudspeakers anyway, what's the difference? At many church services the organist is not seated at the organ; she was there yesterday, and the organ remembers what she played. She may be "playing" at several churches, all of which, of course, insist on having their services at the same time. Or, the church may not even have an organist. The choir may be accompanied by an organist on disc, or even a full orchestra. Most professional musicians need a second job to make a living.

At present the limiting factor in accurate sound reproduction is the loudspeaker (usually aggravated by the room it is in). Eventually, the electronic impulses will be wired directly into the brain; this is already being done in rudimentary fashion for some types of deafness.

What will future music be like? Will we continue to use (or at least simulate) traditional instruments, or will we turn to weird sounds like the background music of a science-fiction movie? (The Hewlett-Packard Company was founded to build oscillators for sound effects for Disney Studios.) If the appearance of some of our young people is any indication, I'm glad I won't be around!

With electronics becoming an ever-larger factor, engineering will become more important, for better or for worse. What you hear, not only on recordings but at live performances, is usually determined by an "audio engineer." (The next time you are at a concert, see if there aren't more instruments on stage than you can hear; e.g., the lead singer's guitar is turned off because he doesn't play all that well.) Judging from some recordings I have heard, there is a need for sound engineers with good musical taste (not to mention writers and performers interested in inspiring achievement rather than shock effect).

I enjoy listening to a CD of the world's best artists, but I also enjoy banging out my own compositions on my out-of-tune piano for my friends. My hope for the future is that there will still be room for both!

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.

Arthur D. Delagrange, *Massachusetts Beta '61*, received a B.S. and M.S. from MIT in 1962 and a Ph.D. from the University of Maryland in 1974, all in electrical engineering. He worked at the Naval Surface Warfare Center (now closed) in Silver Spring, MD, during 1959-94.

Art holds 10 patents and has authored 68 governmental reports, 22 articles in trade magazines, and one chapter in *The Art and Science of Analog Design* edited by Jim Williams (Butterworth-Heinemann). He has written articles for THE BENT on the C&O Canal (Fall 1999), the B&O Railroad (Spring 2000), automobiles (Spring 2001 and Fall 2001), and the power boat (Summer 2002).

Since retiring, Art has done consulting both as a free lance and for Advanced Research and Technology, Burtonsville, MD. He and his wife Janice live near Mt. Airy, MD. His hobbies include electronics, audio, cars, water-skiing, cycling, and music.

As a musician, Art is mostly self-taught, his formal training consisting of grade-school band, two months of piano lessons, and two introductory college courses. He has performed publicly on at least a dozen instruments, with varying results and has served as an interim church-choir director. He has written about 30 songs—from children's music to reasonable recordings. His personal favorite styles are folk, bluegrass, early rock, classical, and gospel/sacred.

DEDICATION

This article is dedicated to the musicians who have lost their lives traveling to concerts, who include, discouragingly, many of his favorites.

References

1. "The Language of Music," Klaus Liepmann, Ronald Press, 1953
2. "What to Listen for in Music," Aaron Copland, Mentor Books, 1957