compromises form the bases of various meantone temperaments.

The scale of just intonation (or just scale) is based on the major triad, a group of three notes that sound particularly harmonious (for example, C : E : G). The notes of the major triad are spaced in two intervals: a major third (C : E) and a minor third (E : G). When these intervals are made as consonant as possible, the notes in the major triad are found to have frequencies in the ratios 4:5:6. The scale of just intonation assigns this ratio to the three major triads (tonic, subdominant, and dominant).

The ultimate compromise is equal temperament, which makes all semitones the same. The scale of equal temperament consists of five equal whole tones and two semitones; the whole tones are twice the size of the semitones. Twelve equal semitones (each having a ratio $2^{1/12} = 1.05946$) make up an octave. Rather than deal with ratios, it is customary to compare tones by using cents. One cent is 1/100 of a semitone in equal temperament. Thus an octave is 1200 cents, a tempered fifth is 700 cents, and so forth. *See* SCALE (MUSIC). Thomas D. Rossing

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Musical instruments

Musical instruments evolved from simple found objects: hollow logs, perhaps with animal skins stretched over the ends, bamboo tubes or large seashells, and stretched bowstrings. They are now classified as percussion instruments, wind instruments, and string instruments, but other divisions are possible.

Conventional Instruments

A useful distinction is between impulsively excited instruments such as bells, drums, and plucked strings, in which the sound gradually decays after an initial input of energy, and sustained-tone instruments such as flutes, trumpets, and violins, in which energy is supplied continuously. Because extended objects can vibrate in many characteristic ways, termed normal modes, the sounds they produce are combinations of many different frequencies. The lowest of these frequencies is called the fundamental, and the others are called upper partials. In an impulsively excited instrument, the mode frequencies are determined by the shape of the vibrating object, and there is no necessary relation between them. In a sustained-tone instrument, the frequencies of the upper partials are all exact integer multiples of the fundamental frequency, and they are called harmonics. *See* HARMONIC (PERIODIC PHENOMENA); MODE OF VIBRATION; MUSICAL ACOUSTICS; VIBRATION.

Sustained-tone instruments generate sound by means of a mechanism, such as a moving bow or a pressure-controlled valve, which essentially inserts a negative acoustic resistance into the system. Because of feedback coupling and the fact that the generator mechanism is inherently nonlinear, an exactly repetitive waveform is produced in which all overtones have frequencies that are exact integer multiples of that of the fundamental. Such overtones are called harmonics, the fundamental being the first harmonic. This harmonic structure is, however, not exactly maintained during transients, particularly the attack transient, when the inharmonic normal modes of the resonator may be momentarily excited.

A system diagram for a sustained-tone musical instrument is shown in **Fig. 1**. For an instrument such as the violin all parts of the system are present, while for wind instruments there is no separate sound radiator. For impulsive instruments, such as the guitar or the drum, there is no nonlinear generator and the energy source operates only momentarily. In all

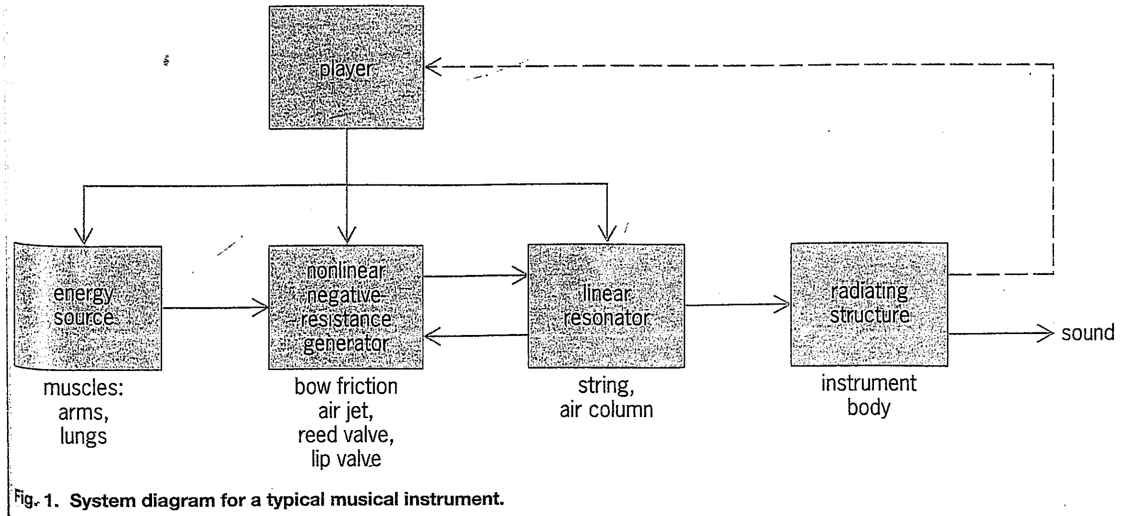

Fig. 1. System diagram for a typical musical instrument.

cases the sound output power is only about 1% of the input power, which is dissipated in frictional, viscous, and thermal losses.

Percussion instruments. Instruments such as drums, bells, gongs, and xylophones are called percussion instruments because the sound is initiated by a blow from some sort of hammer.

Drums. A vibrating membrane has many closely spaced modes, and the sound of a drum does not give any strong impression of musical pitch. If the membrane is stretched over an air volume, however, the resonances of this volume may emphasize certain frequencies, as in timpani or tom-toms, to produce a pitched sound. The player can vary the pitch by varying membrane tension, and can also modify the sound by striking the drumhead near the center or near the edge to preferentially excite different vibrational modes. *See* PITCH; RESONANCE (ACOUSTICS AND MECHANICS).

Tuned percussion instruments. If a heavy metal object is struck with a metal hammer, it stores a great deal of mechanical energy and can vibrate and radiate sound for many seconds. By careful shaping of the metal, usually bronze, by casting and subsequent machining, the vibrational frequencies can be brought into almost integer ratios, so that object becomes a bell with a pleasant sound and well-defined musical pitch. In a typical church bell, five or more modes are carefully tuned, one of which is in a minor-third frequency ratio 6:5 to the prime or fundamental, to give a characteristic sound. Because cast bells are large and heavy, orchestras use sets of metal tubes to produce an approximation to a bell sound.

A rather flat metal shell struck with a soft hammer is generally called a gong. Only the first one or two modes are excited, and the sound has a soft and well-pitched note. If the shell is made from a rather thin sheet and is slightly conical in form, it is usually called a cymbal. Because the metal is thin, a blow with even a soft hammer can excite it into a quite large vibration, and this causes interactions between vibration modes, giving a characteristic shimmering sound.

Xylophones and marimbas consist of a graded set of slats of wood mounted on a frame and struck with a wooden mallet. The playing range is typically three to four octaves, though larger instruments have been built. Each slat is undercut with a circular arch to tune the first overtone, and in the marimba there is a tube resonator underneath each bar. Similar instruments are also made with metal bars.

Wind instruments. All wind instruments rely upon the vibration of a column of air enclosed by rigid walls. Sound waves propagate along this column and are reflected at its ends, the relative sign of the reflected pressure wave depending upon whether the end is open or closed. For a cylindrical air column open at both ends, the possible vibrations are those with an integral number of half wavelengths of sound along the tube, giving a frequency sequence 2, 4, 6, ... times $c/4L$, where c is the velocity of sound in air (343 m/s or 1125 ft/s) and L is the length of the tube. The same result applies to an almost complete conical tube, irrespective of whether the narrow end is open or closed. For a cylindrical tube closed at one end, possible vibrations must have an odd number of quarter wavelengths along the tube, giving a sequence 1, 3, 5, ... for a tube of the same length. These mode frequencies are, however, not quite exact, because of frequency-dependent end corrections. For brass instruments, the air column is nearly cylindrical for one-half to two-thirds of its length, beginning at the mouthpiece end, but flares to a bell at the open end. This flare raises the frequencies of all the modes, compared with a cylindrical tube of the same length, giving a sequence such as 1.4, 4, 6, 8, ... The first mode is not used in playing. *See* CAVITY RESONATOR.

In woodwind instruments the length of the air column, and thus the note to be played, can be changed by opening finger holes along the instrument body. Since there are 12 notes in an octave, and a human has only 10 fingers, this necessitates either compromise fingerings or else a complex system of keys as in modern instruments. In brass instruments all notes must emerge through the flared horn to maintain uniform sound quality, and pitch is changed as discussed below.

Air jet–driven instruments. In instruments of the flute family, a narrow jet of air is blown from the player's mouth, or from a narrow slit in the case of recorders and organ pipes, to cross an aperture near one end of a more or less cylindrical pipe and strike against a sharp edge. As the air jet blows into and out of the pipe mouth, it excites the pipe modes. The deflection of the jet is in turn governed by the airflow into and out of the pipe caused by the sound waves. For the system to work, there must be a match between the frequency of the mode that is excited and the travel time of waves on the jet from the player's lip to the sharp edge. The player can therefore select the mode to be played by varying lip position and blowing pressure. Once the oscillation is established, nonlinear effects generate all harmonics of the fundamental, and these are amplified because of their close match to the resonances of the tube. For a modern flute, the playing range is just over three octaves. Loudness is controlled primarily by varying the area of the lip aperture. *See* JET FLOW.

Reed-driven instruments. Many woodwind instruments use a reed valve to inject an oscillating flow of air into the instrument tube. In clarinets, which have a cylindrical tube, and in saxophones, which have a broad conical bore, the reed is a single piece of thinned cane clamped against an aperture in a carefully shaped mouthpiece. In the oboe and bassoon, which have a narrow conical bore, the reed consists of two similar pieces of thinned cane bound together. The vibration of the reed is controlled by the sound pressure in the instrument, and it effectively closes one end of the tube. Its small vibration allows puffs of air to enter from the player's mouth to maintain the sound oscillation, which is locked to one of the modes of vibration of the air column. Nonlinear effects generate all harmonics of the frequency being played, and these are amplified by the well-aligned resonances of the air column—all harmonics for a conical bore and only odd harmonics for a cylindrical one. For all these instruments, the playing range is about three octaves. Loudness is increased by reducing lip pressure on the reed, allowing it to vibrate to larger amplitude, together with a modest increase in blowing pressure.

Lip-driven instruments. In brass instruments the player's lips provide a vibrating valve under the control of the resonances of the air column. Because of the geometry of the lip-valve motion, it is necessary for the player to adjust lip tension so that the natural frequency of vibration of the lips themselves matches that of the air column for the note to be played. Because of the necessity for this match, it is possible for the player to select any of the natural modes of the air column at will, thus allowing the playing of bugle calls without the use of any valves or slides. In "natural" horns and trumpets with no valves, a whole octave of notes can be played using the 8th to 16th modes of the horn. Again, nonlinear effects generate exact harmonics of the pitch being played, and the player controls loudness primarily by controlling blowing pressure, which can be very high. Notes between the natural modes of the horn are played either by using a slide to add extra cylindrical length, as in the trombone, or by using a set of finger-operated valves to insert extra tube lengths, as in the French horn or trumpet. A set of three valves that lower the pitch by one, two, or three semitones, respectively, is adequate.

Pipe organs. A pipe organ contains as many as 10,000 pipes. Most of these are flutelike flue pipes, but there are also pipes with single metal reeds. Since each pipe need produce only one note, a great range of shapes and tone colors is possible. In addition, depressing the key of one note can sound many pipes at suboctaves, octaves, and higher multiples of the note frequency, as controlled by drawstops. An organ has as many as five keyboards and one pedalboard, and the action either may be completely mechanical or may involve pneumatic, electric, or electropneumatic actuators. Loudness and tone quality are both varied by means of stop selection, but some pipe ranks are enclosed in chambers with louvred fronts controlled by a swell pedal, allowing additional control of loudness.

String instruments. A vibrating string clamped at its two ends has modes in very nearly exact harmonic relationship, the deviation being caused by string stiffness. In addition, the length of a vibrating string can easily be changed by pressing a finger against it. Strings are therefore a good basis for musical instruments. The problem is that, being very thin, a string radiates very little sound. Its vibrations must therefore be coupled to a much larger structure, the soundboard or body of the instrument, to achieve adequate sound level. The musical quality of the instrument depends largely on the design and resonances of the radiating structure which, generally being of wood, varies considerably from one instrument to another that is outwardly similar. In impulsive instruments the string can be excited either by plucking, as in the guitar or harp, or by hitting with a soft hammer, as in the piano. In sustained tone instruments such as the violin, the string is excited by drawing a horsehair bow across it at a constant velocity.

Plucked string instruments. Since the modes of a thin string are very nearly harmonic, the overtones of plucked strings are also nearly harmonic. The relative amplitudes of different modes can, however, be varied greatly by changing the plucking point. A plucking position near the end of the string increases the relative amplitudes of high-frequency modes and thus brightens the tone. Loudness is increased by increasing the force of the plucking action. The relative amplitudes of the overtones, and thus the tone quality, are also affected by the resonance properties of the instrument body, and great attention is paid to this by the maker. In guitars the lowest body resonance involves motion of air through the guitar rose as well as motion of the upper plate and back, while for higher modes only the plate vibrations are important.

Bowed string instruments. Strings can be excited by the motion of a bow because the static frictional force between bow and string is greater than the sliding friction. The string successively sticks to the moving bow, or else slips back under the much smaller sliding friction. The vibration frequency of the string is determined only by its length and tension, and the sound quality varies only slightly with bowing position. Loudness is increased by increasing bow speed and contact force on the string. Violins, violas, and cellos have carved arched top and back plates, the shapes of which are carefully adjusted by the maker to achieve the desired body resonance frequencies which are important for tone quality. The shape of the traditional f-holes controls the lowest resonance, which also involves motion of the enclosed air.

Pianos and harpsichords. The notes on a piano have one, two, or three steel strings, the lower strings being overwrapped with brass or copper wire. Because of string stiffness, the octaves are stretched to a little greater than a 2:1 frequency ratio. String vibration is communicated through a bridge to a flat, ribbed wooden soundboard. Felted hammers are made to hit the strings through a complex mechanical action which also raises dampers from individual strings. Two pedals control damper motion, and a third allows only a single string of each note to be struck. Loudness is increased by increasing the force of the finger stroke on the keyboard.

The harpsichord is an earlier and mechanically simpler instrument in which single unwrapped metal strings are plucked by quill (now nylon) plectra. Most harpsichords have two sets of strings, usually with one set pitched an octave above the other. There is also usually a lute stop which applies felt dampers to all the strings to give a soft effect. Large harpsichords have two keyboards and extra sets of strings, often including a set at suboctave pitch. Both tone quality and loudness are varied by varying the string sets used. No variation in plucking force is possible.

Human voice. While not really a musical instrument, the human singing voice is often involved in music. The larynx contains two vocal folds which can open and close like the human lips. When nearly closed, they can be made to vibrate by air pressure in the lungs—the frequency of vibration, and thus the musical pitch of the sound, being controlled by muscular tension. Vocal fold vibration releases successive pulses of air into the base of the vocal tract, giving a sound with high harmonic content. The spectral envelope of the sound is modified by resonances of the vocal tract, giving bands of emphasis called formants. The frequencies of the first three formants, typically around 500, 1500, and 2500 Hz, can be changed by movement of the tongue, jaw, and lips to change the resonance frequencies of the vocal tract, and thus produce characteristic vowel sounds. Consonants are produced as bursts of noise with shaped frequency envelopes. *See* SPEECH. Neville H. Fletcher

Amplification. The sound or vibration of any conventional musical instrument can be picked up, amplified, recorded, or reproduced. Many conventional musical instruments are amplified during live performance. Thus they can be considered electronic in the limited sense that all electronic musical instruments have amplifiers, and deliver their tones to listeners over loudspeakers or earphones. For instruments having mechanical vibrators such as tuned strings, reeds, or bars, vibration pickups can be placed in contact with (or in proximity to) the vibrators (**Fig. 2**). For resonant-air-column instruments such as brass, microphones can be placed in the sound field. The amplified sound can then reinforce or even dominate the direct sound from the instrument. *See* AMPLIFIER; AUDIO AMPLIFIER; MICROPHONE; SOUND RECORDING; SOUND-REPRODUCING SYSTEMS; TRANSDUCER.

Electronic amplification circuitry allows the performer to control the tone of the instrument in unconventional ways, such as changing the tone timbre or even the frequency. However, before such control can be effective, the direct tone from the instrument must be reduced to allow the modified tone to dominate. For this purpose, amplified instruments are usually redesigned to reduce direct sound output. Examples are solid-body electric guitars, electropianos with struck strings (or reeds) but without soundboards, amplified enclosed-reed organs, and brass instruments with mutes containing microphones. Such redesign also permits the instrument to be played more softly than normal, either for greater dynamic expression or for practice without disturbing other people, such as in a classroom where music students practice or receive instruction individually or in groups.

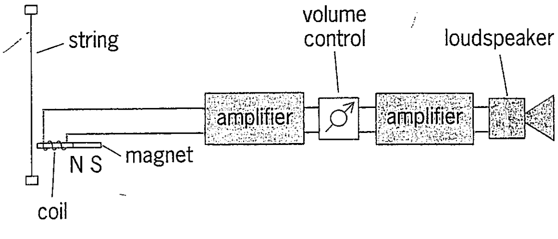

Fig. 2. Electrical scheme of an amplified electropiano. (*After H. F. Olson, Music, Physics and Engineering, Dover, 1967*)

Changing the timbre of the conventional tone usually involves alteration of the relative amount of the harmonics in the tone spectrum. One method is to pick up the vibration or sound at different points along the string, for example, either by moving the pickup or by using several pickups mounted at different positions and selecting or mixing the outputs. Another method is to use a single pickup (or set) with tone controls or resonant filter circuits that can be varied or switched manually or by foot pedals during performance. Dynamic use of such controls can provide new timbre effects not possible in the original conventional instrument.

Another kind of dynamic timbre-changing effect is the Leslie effect, used often on the output of electronic keyboard instruments, such as Hammond organs. A Leslie effect is created by rotating one or more directional speakers inside a cabinet such that a mixture of Doppler-shifted reflections is generated. Many electronic "effects" can be considered imitations of the Leslie effect to varying degrees, such as a tremolo circuit, which imparts a simple periodic amplitude modulation on the sound, and the chorus effect, which is typically a sum of electronically delayed copies of the sound, slightly mistuned.

In addition to changing the harmonic mix, new harmonics are often created by using controlled amounts of distortion. Nonlinear distortion is often used by electric guitar players, and sometimes by keyboard players as well. When nonlinear distortion is applied to a harmonic, single-pitched sound, that is, a single note as opposed to a chord, the distortion is harmonic, and generally brightens the tone. If two or more notes are present, at different pitches, then intermodulation distortion occurs, giving rise to many new frequencies, and typically a more distorted sound.

Often in electronic amplification there is a feedback path from the loudspeaker to the vibrating source, such as acoustic coupling from an amplifier loudspeaker to the strings of an electric guitar. Such feedback can cause objectionable "squealing" noises, but it can also be used to provide indefinite sustain for certain harmonics. In effect, the amplifier becomes part of the instrument. *See* FEEDBACK CIRCUIT.

Electrical, Electronic, and Software Instruments

Electrical musical instruments produce electrical tone signals for amplification (and loudspeaker listening) without using tuned mechanical vibrators or air columns. Early electrical instruments predated electronics, generating their tone signals by electromagnetic or electrostatic rotating machinery. Later,