Electronic Home Music Reproducing Equipment

Daniel R von Recklinghausen

John G. (Jay) McKnight, Chair
AES Historical Committee
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DANIEL R. VON RECKLINGHAUSEN

Arlington, MA

The search for amplification and control of recorded and transmitted music over the last 100 years has progressed from mechanical amplifiers to tube amplifiers to solid-state equipment. The AM radio, the record player, the FM receiver, and the tape recorder have supplemented the acoustical phonograph and the telephone. An incomplete summary of important developments in the past is presented along with challenges for the future.

Home music reproduction began when Bell invented the telephone in 1876 and Edison invented the phonograph in 1877. Instruments were manufactured soon thereafter and leased or sold to the public. Yet the listener had very little control over the reproduction and the volume of sound, the tone quality being predetermined by the manufacturer of the phonograph and record or by the telephone company and its equipment.

A great deal of effort went into various means to increase the volume or to be able to hear sounds from a greater distance. There was need for an amplifier, and various inventors devised methods that seemed to solve the problem.

Edison [1] coupled a telephone transmitter to the armature of a telegraph relay in 1877. Hughes [2], writing "on the physical action of the microphone," described the accidental discovery of the "howling telephone" when he placed both the transmitter and the receiver on a wooden sounding board, thereby having found something which provided a "relay" for the human voice in telephony. Numerous other inventors improved upon this electromechanical amplifier, notably H.W. Shreeve [3] of the Western Electric Company. The Shreeve repeater was reliable enough to qualify for commercial telephone service in toll telephone circuits (New York–Chicago 1904) and even saw service in the first transcontinental telephone service [4] inaugurated on January 25, 1915. The compact size and relatively modest power needs of the electromechanical repeater caused it to be used for 20 years more as a hearing-aid amplifier [5, pp. 64–69].

C.A. Parsons of London, England, inventor of the Auxetophone, marketed in 1907 a phonograph where the playback stylus vibration caused a valve to modulate a stream of compressed air which was fed to a reproducing horn [6]. Capable of great volume, but always having a background hiss, the modulated air stream loudspeaker is still with us today as the only means of amplification capable of producing extremely high sound pressure levels.

All these methods had the common problem described in these days as "inertia." We now recognize that the moving mass in all those devices was relatively high, and an increase in high-frequency response required an increase in driving power, which was just not available. Equalization of frequency response was possible only by empirical means.

Even radio broadcasting existed in the preelectronic days. In 1902 Pickard succeeded in transmitting intelligible speech by radio, using an 8–10-kHz spark transmitter as source and a carbon microphone in the antenna lead as a modulator [5, p. 39]. Successful broadcasting of speech and music was conducted by Fessenden [7] at Brant Rock, Massachusetts, on December 24, 1906, using a 1-kW 50-kHz alternator built by the General Electric Company under the direction of E. F. W. Alexanderson. Modulation was accomplished by a watercooled carbon microphone in the antenna ground lead. Clear reception was obtained at many locations, including ships at sea. In the following years an increasing number of transmitters were built, some of them arc transmitters. One essential tool in these stations was a mallet, used to free the carbon granules in the microphone when they had become stuck by overheating [9].

It is probable that not only electrolytic detectors were used for reception, but also the first solid-state detectors [8], the first crystal detector having been invented by Pickard in 1906. It consisted of a silicon crystal and a catwhisker. Dunwoody's detector of about the same time consisted of a carborundum crystal clamped between two brass holders. Most likely a Marconi magnetic detector would be used, connected in series with a set of magnetic headphones. These receiving sets eventually became known as crystal sets and became very popular.

The remainder of the receiving system [9] would consist of a long-wire antenna, a ground, a cylindrical antenna loading coil connected between the antenna and the main tuning coil which was connected to ground. A third coil, connected between the headphone–detector combination, was arranged so that its coupling to the main tuning coil could be varied by sliding one cylindrical coil into the other. As an alternate, pancake-shaped coils were used, variable coupling being accomplished by moving one coil with respect to the other. Tuning of each coil was accomplished by selecting one of several taps with a tap switch. All coils were large, 4–8 inches in diameter. A popular form for home construction of coils was the Quaker Oatmeal box.

The increasing number of "wireless" transmitters for various communication purposes roused popular interest in radio, and thousands of amateurs, or "hams," listened to these transmissions with their crystal sets. Operating such a set was an art, first tuning it to the station, then probing with the catwhisker, a sharp metal wire, for a sensitive spot on the unstable crystal, then retuning, reprobing, etc.

In 1883 Edison discovered current flow in vacuum while seeking the cause of blackening in lamps. This led to the invention of the vacuum diode, the "valve," by Fleming in 1904 [10]. This valve was not very popular because of the need for an additional rheostat to control heating of the filament, which burned out quickly. Furthermore it was not as sensitive as the crystal detector.

In 1906 DeForest [11] added the control grid to the Fleming diode, thereby making it a triode vacuum tube which he called Audion, and the modern age of electronics was born. The "inertialess" amplifier had been discovered.

The DeForest triode saw immediate application in radio reception as a detector superior to all other types, requiring a filament battery and a rheostat and a plate battery which could be tapped to various voltages. The early Audions were highly nonuniform and had a very poor vacuum. Probable life as a detector was 20 to 30 hours, and the filament could be expected to burn out in less than 50 hours. As late as 1915, DeForest [12] could not predict whether the anode current would go up or down when a signal was impressed—each tube was different. However, starting in 1912, both the General Electric Company and the Western Electric Company had learned to make uniform well evacuated tubes [13].

The triode tube was not only capable of detecting radio signals, but it was able to amplify audio signals as well. In 1912 the Federal Telegraph Company [14] demonstrated to the U.S. Navy the first commercial cascade audio frequency amplifier (Fig. 1). Containing three DeForest Audions, tests made at that time indicated that the amplifier increased the received signal in intensity by 120 times.

Other research with tubes continued throughout the pre-World War I period [15]. Almost simultaneously four inventors (DeForest, Armstrong, and Langmuir in the United States and Meissner in Germany) independently discovered (in the 1911–1912 period) the increased receiver sensitivity produced when a portion of the output signal was fed back to the input of a triode so as to effectively increase the input. The regenerative circuit (Fig. 2) made it possible to receive transatlantic signals in the heart of a city using relatively small antennas, heretofore impossible. The commercial importance was immediately realized, and extensive patent litigation ensued, which was not resolved until the United States Supreme Court settled in DeForest's favor in 1934.

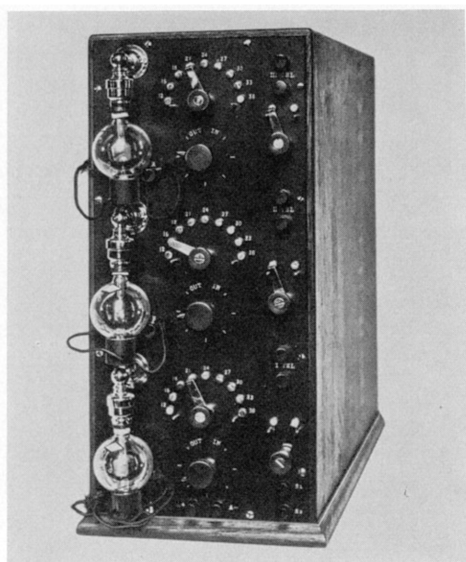


Fig. 1. Three-stage DeForest Audion amplifier. *(Courtesy ITT)*

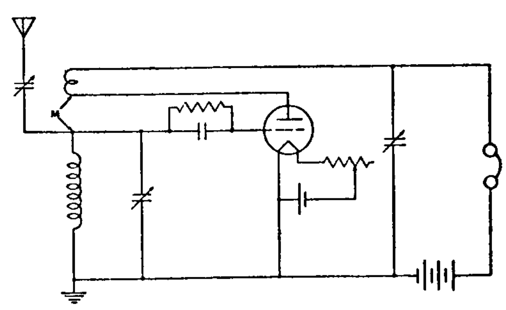


Fig. 2. Armstrong regenerative circuit. [From *Proc. IRE,* Swinyard, W., vol. 50, p. 794 (May 1962)].

The triode tube could also amplify high-frequency radio signals; however, its grid-plate capacitance was relatively high, and stable amplification was difficult to obtain until Hazeltine [16] invented the neutrodyne circuit in 1918. Here a current obtained from the plate circuit was fed back into the grid circuit in the proper magnitude and phase to balance out, or neutralize, the grid-plate capacitance inside the tube, thereby preventing oscillation and achieving stability.

Regenerative radio receivers reached the peak of their popularity in 1922 and continued as a low-cost receiver for many years thereafter. As late as 1940 a consortium of manufacturers in Germany produced an ac–dc low-cost radio[1] containing two tubes, one triode–pentode as regenerative detector—power amplifier, and one power rectifier.

The triode tube could also oscillate at radio frequencies and van der Bijl [17] of the Western Electric Company discovered that the improved triodes of 1913 had a square-law characteristic curve. He utilized the variable slope to produce a modulated wave by applying a small high-frequency signal and a relatively large modulating signal voltage to the grid of the tube. The ATT Company transmitter, constructed according to this principle at the Naval Station in Arlington, Virginia, in 1915, employed 500 tubes in parallel as class-A amplifiers and was heard as far away as Paris and Honolulu.

Soon thereafter various amateurs not satisfied with receiving signals decided also to transmit signals. The laws of the United States in 1920 specified these wavelengths [18]:

High power stations	over 1600 meters
Navy	600 to 1600 meters
Ship stations	300, 450, 600 meters
Amateurs	below 200 meters

One of these amateurs, Dr. Frank Conrad [19] of East Pittsburgh, Pennsylvania, built his amateur wireless station in 1916, obtaining call letters 8XK for it. In 1920 he converted his station to radio telephony and put on a two-hour program Wednesday and Saturday night. His programs proved to be so popular that the supply of crystal sets in the local department store was soon sold out.

On October 27, 1920, Conrad's station became the first in the world to be licensed as a commercial station. It began broadcasting with a power of 100 watts, using call letters KDKA on November 2.

In 1920 only one broadcast authorization was granted. The next year 30 authorizations were given, assigned to the wavelengths of 360 m or 833 kHz and 485 m or 619 kHz. In 1922, 639 stations were authorized, in 1923, 239, and in 1924, 286. The additional wavelength authorized was 400 m or 750 kHz. In 1924 the entire band between 550 and 1351 kHz was allocated to the broadcasters in the United States by the United States Department of Commerce. The functions of allocation and enforcement were taken over by the Federal Radio Commission in 1927, whose functions were transferred to the Federal Communications Commission in 1934. On August 28, 1922 at 5:15 p.m. WEAF, New York, broadcasted the first commercially sponsored program [20] (Queensborough Corporation, a real estate organization). The first chain broadcast on January 4, 1923, featured a telephone tieup between WEAF, New York, and WNAC, Boston.

A few years later, radio broadcasting networks were organized: November 1, 1926, the National Broadcasting Company with WEAF and WJZ as key stations, and September 18, 1927, the Columbia Broadcasting System went on the air with a basic network of 16 stations.

In Europe radio broadcasting progressed under much stricter government control; the stations were generally operated by the post office departments of the various countries. For example, the first German broadcast station [21] went on the air in 1923. In 1928 the "final" number of AM broadcast stations in Europe was reached by international agreement with spacings every 9 kHz. From that time until the end of World War II the number of stations remained constant, and only the transmitter power increased.

The result of these diverging philosophies was that American sets ended up with dials marked only in wavelength or frequency while European sets featured larger dials with the transmitter's location marked prominently.

The direction of the radio receiver industry focused from its beginnings on increased performance and operating convenience. Until 1927 all receivers used filament-type triodes [13], the filament A and plate B supply voltages generally supplied by batteries. The early triodes used the tungsten filament as the cathode without additional coating. To achieve electron emission, the filament had to be operated at white heat. Western Electric coated the filaments with barium oxide and other oxides, enabling tube operation with the filament heated only to red heat. Of these tubes, the Western Electric VT-1 tube was perhaps best known. During the beginning years of broadcasting, the tube types 200, 201, and 202 high-vacuum triodes with tungsten filaments were available.

In 1923 the broadcast receiver business was flourishing, crystal sets and regenerative sets providing most sales [8]. The most famous sets were the Westinghouse Radiola, the Clapp-Eastham, and the Grebe. Each of these receivers had one detector and two stages of audio amplification. These sets received ship signals on 600 m (500 kHz), the broadcast frequencies of 485 m (619 kHz) and 360 m (833 kHz), and the "hams" on the short-wave band 200–250 m (1200–1500 kHz). The frequency range of all "medium-wave" broadcast receivers has changed only slightly since that time.

The neutrodyne [16] circuit was developed into a receiver in 1922 (Fig. 3). This was a three-tube reflex receiver [8] in which the tubes acted both as a neutralized radio-frequency amplifier and as an audio amplifier. The same circuit, but as a five-tube set with a separate audio amplifier, was placed on the market in 1923 by Freed-Eisemann. In both sets, volume was adjusted by varying the filament voltage.

[1] "Der Kleinempfänger" (DKE).

In 1924 neutrodyne receivers were selling by the hundreds of thousands and continued to sell until the screen grid tube in 1928 (Fig. 4) with its low grid-plate capacitance made unidirectional amplification possible without need for neutralization.

Neutralization of triode radio-frequency amplifiers permitted stable stage gains of about 15 dB and also permitted the ganging of tuning of the various stages. Early receivers used variable-inductance tuning or variometers [9], the receivers of 1923 and later using variable-capacitor tuning with its better reproducibility. Popular tubes of that era were the GE type 99 and 101A triodes and the Westinghouse type WD-11 [13].

True single-knob operation of a radio was made possible by the invention of the automatic volume control circuit by Wheeler in 1926 [22]. Here a diode rectified the radio-frequency signal, fed the audio-frequency signal to the audio amplifiers, and a proportional negative-bias voltage to the radio-frequency amplifiers, thereby reducing gain. The first such set, the Philco [23] model 95, appeared with the new indirectly heated tubes. It contained two type 24 tetrode tuned radio-frequency amplifiers, one type 24 untuned radio-frequency amplifier, one type 27 triode audio amplifier, and two type 45 triodes as push–pull power amplifiers with a type 80 rectifier. 50 dB of automatic volume control was achieved. By 1932 practically every receiver on the market used automatic volume control.

A common idea is often conceived by a number of people working independently because the time is ripe for that idea. In 1912 Fessenden [15] discovered the principle of heterodyning whereby two radio-frequency signals could be combined to produce an audio-frequency beat note. Fessenden used an arc source as his local oscillator to receive unmodulated radio-frequency signals. Prior to this, all detectors had acted as valves controlling a direct current in response to the received signal.

Many inventors worked on the applications of heterodyning, with Armstrong [15] finally obtaining the superheterodyne patent in 1920 (Fig. 5). Here the radio-frequency signal and a local oscillator signal were combined in a converter (or mixer or "first" detector) to produce the heterodyned beat frequency or intermediate frequency, then amplified with fixed tuned intermediate-frequency amplifiers until finally demodulated by the detector (or "second" detector). High and constant receiver selectivity could thus be obtained with the intermediate frequency lower than the signal frequency.

The first publicly sold superheterodyne receivers were made by the General Electric Company [8] in 1924 using the Radiola brand name. The circuit used six UV 199 triodes as reflexed untuned radio-frequency stage and intermediate-frequency stage, a self-oscillating converter stage, a second neutralized intermediate-frequency stage, a detector, and two audio stages, and the set had a built-in loop antenna. The console model included a horn loudspeaker. The second harmonic of the oscillator frequency was used to prevent interaction or pulling between the signal and oscillator circuits.

The intermediate frequency was set at 42 kHz to enable the then available triodes (amplification factor about 6.6) to be used. Later superheterodynes used an intermediate frequency of 175 kHz and operated with the fundamental oscillator frequency. By 1930 superheterodynes began to take over and were in universal use in 1932. In Europe [21] the superheterodyne receiver started in about 1930, and in 1939 it was reported that 73% of the receivers were "superhets," the remainder tuned-radio-frequency sets. In 1938 the standards committee of the Radio Manufacturers Association (RMA) agreed on an intermediate frequency of 455 kHz, while in Europe 468 kHz became popular. Other frequencies such as 262 kHz and even 1600 kHz in Europe enjoyed some temporary popularity.

In the mid 1920s a popular triode, such as the 01A, had a retail price of $9.00 [13], equivalent to about $50–$100

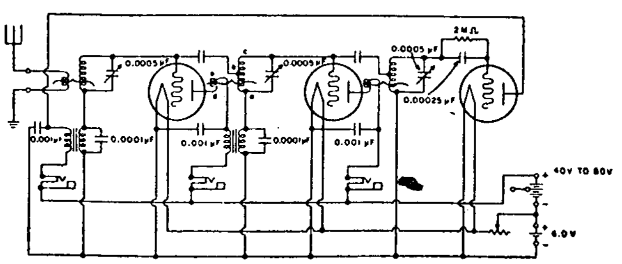
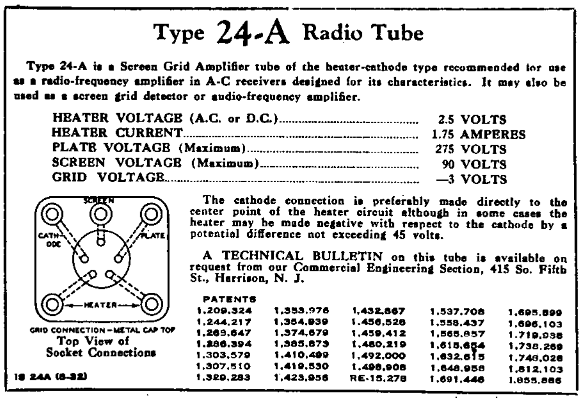


Fig. 3. Hazeltine Neutrodyne circuit (reflex receiver). [From *Proc. IRE*, Swinyard, W., vol. 50, p. 795, (May 1962)]



Type 24-A Radio Tube

Type 24-A is a Screen Grid Amplifier tube of the heater-cathode type recommended for use as a radio-frequency amplifier in A-C receivers designed for its characteristics. It may also be used as a screen grid detector or audio-frequency amplifier.

HEATER VOLTAGE (A.C. or D.C.) .... 2.5 VOLTS
HEATER CURRENT .... 1.75 AMPERES
PLATE VOLTAGE (Maximum) .... 275 VOLTS
SCREEN VOLTAGE (Maximum) .... 90 VOLTS
GRID VOLTAGE .... —3 VOLTS

The cathode connection is preferably made directly to the center point of the heater circuit although in some cases the heater may be made negative with respect to the cathode by a potential difference not exceeding 45 volts.

A TECHNICAL BULLETIN on this tube is available on request from our Commercial Engineering Section, 415 So. Fifth St., Harrison, N. J.

PATENTS

1,209,324	1,353,976	1,432,867	1,537,708	1,695,899
1,244,217	1,354,939	1,456,528	1,558,437	1,696,103
1,269,647	1,374,679	1,459,412	1,565,857	1,719,938
1,286,394	1,385,873	1,480,219	1,615,654	1,738,269
1,303,579	1,410,499	1,492,000	1,632,615	1,746,026
1,307,510	1,419,530	1,498,908	1,648,958	1,812,103
1,329,283	1,423,956	RE-15,278	1,691,446	1,855,886

Fig. 4. Data sheet once packed with every tube. *(Courtesy RCA)*

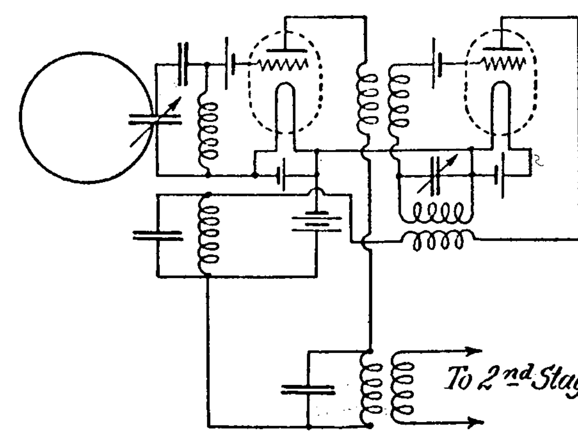


Fig. 5. Basic superheterodyne second-harmonic circuit [From *Proc. IRE*, Swinyard, W., vol. 50, p. 796 (May 1962)]

at today's prices. All sorts of ingenious tricks were devised to minimize tube count, while maximizing performance.

The most popular trick of minimizing tube count in radio receivers of the 1920s was "reflexing." It is not known who discovered that a tube could amplify signals not only in one frequency range but in several frequency ranges simultaneously. Consequently many receivers, particularly neutrodyne receivers, were designed in which the same tube acted both as a radio-frequency amplifier and as an audio amplifier. The earliest superheterodynes also made use of reflexing as shown above.

Unfortunately all reflex receivers [24] had the common failing of interaction (later known as intermodulation) between the two signals because of tube nonlinearity. This resulted in such side effects as the inability to tune the volume to zero, even though no more desired audio-frequency signal passed through the stage.

Reflex circuits disappeared as soon as tubes became less expensive than the additional circuit complexity entailed, approximately in the early 1930s in the United States and in the mid-1930s in Europe.

During the years around 1920 another circuit appeared which today has an important influence on all reproduction of music. Previously when attempting to boost power, output tubes in parallel would be used. Later it was discovered that a larger power increase could also be obtained with two tubes operating in push–pull, that is, when one tube had an increasing signal, the other had a decreasing signal, causing one of the plate circuits to "push" current into the load while the other tube proceeded to "pull." Since driving signals of opposite phase were required to result in an output signal of opposite phase, both input or driving transformers and output transformers were required.

Beginning in the 1930s driving transformers were eliminated with the advent of indirectly heated tubes, to reoccur when high-power tube amplifiers were designed and again when transistors were used in audio circuits around 1960. Not until complementary NPN and PNP transistors became available did both output and input transformers become obsolete in home audio equipment.

Push–pull circuits not only had lower distortion than "single-ended" circuits (even harmonics generated in the output stage tend to cancel), but also output transformers did not suffer from saturation problems by the direct idling current, thereby extending low-frequency response. Furthermore, the circuit had low sensitivity to power-supply hum. It is now the universal output circuit.

The first attempted "loudspeaking" radio resulted in horns attached to telephone receivers [8]. This soon proved to be unsatisfactory. The moving-armature loudspeaker was the next popular reproducer. Balanced-armature receivers, because of their simplicity of construction, survived in the United States until the 1930s and in Europe until about 1940 in a German two-tube receiver, the DKE model.

In 1925 Rice and Kellogg [25] of the General Electric Company described the moving-coil loudspeaker with first use in the Radiola model 104 in 1926, which also included a 1-watt amplifier. At a price of $250 this model also provided power for the Radiola 28 superheterodyne receiver, which became the first batteryless radio receiver.

Prior to the early 1920s power amplifiers were probably quite small because Rice and Kellogg first had to build their own amplifier in order to test the concept of their loudspeaker. In 1923 Green and Maxfield [26] described public address systems, and in 1924 Martin and Fletcher [27] described high-quality transmission and reproduction of speech and music.

The state-of-the-art commercial power amplifiers of 1926 were the Western Electric [28] amplifiers employing directly heated 205-D triode tubes, operating single-ended and in push–pull and delivering 2.5 and 10 watts, respectively. These amplifiers were used successfully into the 1930s in movie theaters for sound reproduction of talking pictures, generally in conjunction with highly efficient horn loudspeakers of "theater-size" dimensions.

The desire to be able to play music louder than was possible before led to a type of competition which took its name from the automobile trade, the "horsepower race." A powerful receiver of 1925, using the new "low-mu" triodes and a B battery eliminator generally had less than ½ watt output [13]. While the 1926 Radiola model 104 was capable of 1 watt output, a typical 1929 "high-performance" set used the new oxide filament low-mu power triode type 45 capable of 1 to 3 watts (single-ended or push–pull) to the loudspeakers. Contributing to this increased output was the advent of indirectly heated tubes, such as the type 27 triode and the type 24 screen grid tube, which permitted a receiver to be operated directly of the one power line without hum introduced in the cathode circuit, the oxide-coated tubular metal cathode enclosing the heater and shielding the tube elements from its hum field.

The search for higher power prior to 1930 took two basically different routes which later combined. In Europe engineers at Philips [29] discovered that the high-current low-voltage knee of the zero-grid bias curve of a tetrode or pentode permitted a larger audio power output to be obtained from such a tube than that available from a triode optimized for the same heater. This led to the development of pentode power tubes (with an oxide coated filament) which appeared first around 1930.

In the United States Barton [30] described the class-B amplifier in 1931. A class-A amplifier is one in which the output tube (or other device) conducts throughout the signal input cycle. In a class-B amplifier one tube conducts for one half-cycle while the other conducts for the other half.

Barton's class-B circuit permitted the power of amplifiers to be increased beyond what was considered possible by the mere addition of a power output tube. A further power increase caused by increased peak plate currents was made possible by increasing the grid voltage drive to positive instantaneous voltages, while maintaining the output tube bias voltage, the C-battery, at a fixed voltage rather than that determined by cathode resistor voltage drop. Up to that time the use of a positive grid signal was equivalent to entering a forbidden region. With tube types then available output powers approaching more than 10 watts were soon achieved, the driver amplifiers providing the peak grid current.

In 1935 both paths converged as the indirectly heated beam-power tetrode [31] became available. Performing like a pentode, but with greater available low-voltage current, this tube, the 6L6, was originally manufactured with a metal envelope. Later on it became available with various glass envelopes and capable of 6.5 watt power output (single-ended) to 24 watts (class-AB push–pull, no grid current with cathode bias) to 60 watts (class-AB push–pull with grid current). This tube became the standard high-power audio-amplifier tube used in designs rated between 20 and 50 watts appearing as late as the 1960s.

When electrically recorded phonograph records were described by Maxfield and Harrison [32] in 1926, along with their improved acoustic reproducer, the electric phonograph pickup had already been invented. The Western Electric 4A pickup [28] was used for the reproduction of the talking picture sound recorded on 16-inch 33⅓-r/min records according to the Vitaphone method first demonstrated publicly in early 1927.

The improved acoustic phonograph, the Orthophonic Victrola [5] of 1926, only one year later had an all-electric phonograph rival, the Brunswick Panatrope, produced by the Brunswick-Balke-Collender Company aided by engineers from RCA, General Electric, and Westinghouse. Soon other all-electric phonographs and radio–phonograph combinations appeared, with the effect that the acoustic phonograph was virtually displaced in the United States in 1930 by the all-electric radio–phonograph combinations. Acoustic phonographs continued to be produced for ten more years in Europe and as portable instruments worldwide.

The electric phonograph pickup of the years starting with about 1927 was the magnetic pickup, which had a balanced armature using a horseshoe magnet. The output was a good fraction of 1 volt, and the upper frequency limited by a resonance was between 2½ and 4 kHz. Using replaceable "needles," the tracking force was several ounces.

The connection of such pickups to the radio circuits of the 1920s and 1930s was governed principally by the desire to obtain enough amplification, since the output from a pickup was less than that of a high-level detector. Little effort was made to properly equalize a pickup response, since each recording company had its own, often secret, recording curve, each manufacturer striving for its own distinctive sound. The radio-phonograph engineers had to make the best of such a situation, which was complicated by the fact that economic considerations did not permit an additional phono preamplifier tube for the receiver and switches were often unreliable. One of the common solutions was to use one of the intermediate frequency amplifier tubes as a preamplifier [33] for the pickup, choosing the values of the high-frequency bypass components so as to provide for some equalization. This also simplified the switching to a simple disabling of amplification ahead of that stage.

The engineer's life was made a little easier when Sawyer [34] in 1931 described the bimorph Rochelle salt transducer, which became known as the crystal pickup. These pickups, first produced by the Brush Development Company, were comparatively light in weight, requiring only 1 or 2 ounces of tracking force, had an available "permanent" stylus, and produced an output of up to 2 volts when loaded by a grid leak resistor while having constant-amplitude characteristics. This meant less gain and less equalization required than before, and the popular low-cost connection was between the grid of the output tube and ground. Perhaps a million radios had such a "phono" jack connection, and an untold number of electric phonograph attachments contained such a pickup and a simple motor-driven turntable.

Radios and radio–phonographs of the 1930s had magnetic loudspeakers only in the lowest models and electrodynamic loudspeakers in almost all others. The Radio industry [8], having converted from battery-operated receivers to B battery eliminators (Philadelphia Storage Battery Company, 1924), to A battery eliminators (same company soon thereafter), to the radio with integral A and B eliminators (Zenith, 1926), to ac filament tubes (1926), also converted to power-line operation of the loudspeaker. The magnetic field of the typical electrodynamic loudspeaker was a wound coil, a choke, which could be used to filter the rectified high voltage (or B+ voltage) required by the circuit.

It worked, but the loudspeaker emitted a humming sound caused by imperfect filtering. Pridham [35] of Magnavox invented the hum-bucking coil in 1929 which consisted of a few turns of wire wound beside the field coil and connected in series with the voice coil in such a fashion to minimize hum.

Since filter capacitors were expensive, often unreliable, and as electrolytic capacitors with a liquid electrolyte often sensitive to orientation, marginal power supply filtering was the rule rather than the exception of the 1930s. Other ingenious hum-reducing tricks were used. They included partial filtering of hum in the grid circuit, adjusted in such amplitude and phase to cancel hum in the plate circuit (Rechnitzer [36] of Telefunken, 1928), or the use of tapped filter chokes (McLennan [37], International General Electric, 1931), or the adjustment of the operating voltages of one tube in a push–pull circuit to minimize hum. Hum in earlier low current stages was often adequately suppressed by additional filtering.

The beginning uses of light-weight magnetic pickups (General Electric [38], 1948) focused on another source of hum—leakage current from the heater to the cathode and hum coupling from the filament into the cathode and grid circuits. The solution was to use the cathode type tubes with a filtered direct-current filament supply. Scott [39] (model 210 A, 1947) used two 12.6-volt 150-mA preamplifier tubes with filaments connected in series as the cathode resistor of the 6L6 push–pull power amplifier. Not until transistors and integrated circuits permitted small assemblies, have equivalent input hum levels reached any significantly lower value.

Volume controls, or high-impedance potentiometers made from pressed graphite or carbon, became available in about 1925 and were used as volume controls in all power-line operated radios manufactured, with the exception of regenerative sets. Long-distance telephone circuits, as shown in a 1919 patent issued to T. B. Wier [40] of Western Electric, used a volume control along with a filter which removed high-frequency noise.

Tone controls are another matter: no clear record of achievement exists here. To this date, tone controls are a boon or a bane, panacea or pandemonium. The compiler of the *Radiotron Designers Handbook* [24, pp. 635–678] writes, "Tone control is a controversial subject with very strong conflicting views held by many competent authorities." To this day these words are true; however, many forms of tone control fall under the general heading of equalization or correction of frequency response of program material intentionally preequalized according to some standard. For example, the equalizer circuits used to compensate for the RIAA characteristic of records, or the NAB characteristic of certain tape recordings are not tone controls in the conventional sense, although they at one time fell into the "controversial" category.

However, the user-adjustable controls affecting tone quality are contested. For the purist no tone controls are desirable, "flat response" is the ideal.

Historically, tone controls started as low-pass filters, usually switched as a passive filter (that is, not containing amplifiers) designed to remove high-frequency noise; similarly bass boost filters are really a simple R-C low-pass filter having finite, limited attenuation at high frequencies. Such switch type controls were described by Scroggie [41] in 1932. The result was that radio consoles [24] of the 1930s all the way into the 1960s had a series of switches which controlled tone quality. Such a "quality switch" usually varied in complexity in proportion to the quality level of the set. A series of interlocked push-button switches that might also vary the selectivity of the set were often labeled poetically "orchestra," "jazz," "alto," "tenor," "distant," and many other titles. There was often justified suspicion that none of the switch positions in certain sets resulted in flat response. Starting in the late 1930s certain of these switch positions changed the frequency response by changing resistor–capacitor networks in the feedback loop of the power output stage.

One early pioneer in tone control circuitry is Aceves [42] who in 1930 and 1931 applied for patents granted in 1934 using inductors and capacitors as tone control in conjunction with an amplifier.

Continuous tone controls appeared first in the late 1930s, mostly as a high-frequency RC filter. This control is still with us as a "tone" control in simple radios or tape or record players and is generally "flat" in its extreme position. A variation of it is a tone control which attenuates bass in one extreme position ("speech"), treble in the other extreme, and has relatively flat response in the middle ("music").

In the years following World War II, a number of tone control circuits appeared which were able to attenuate the response progressively less as the control was advanced, had a flat response position, and then a progressively larger boost with further advance of control setting. Separate controls for bass and treble were provided, and these are still with us in essentially unchanged function.

Originally most of these bass and treble controls were passive, the repeatability of frequency response dependent upon the accuracy of attenuation of the potentiometer. Others sought to have separate boost, flat, and attenuate networks and attempted to use the tone control as a fader control between those networks [39]. Finally, P. J. Baxandall [43] developed the negative-feedback tone control in 1952, a circuit which combined a continuous bass control with a continuous treble control having input, output, and amplifier input terminals, and a common high-gain amplifier connected between the amplifier input and output terminals of both controls. This circuit gained rapid acceptance because of its simplicity and is in almost universal use today, providing unity gain in the "flat response" position, rather than an insertion loss required to be larger than the maximum desired boost.

Radio and radio–phonograph designers of the late 1920s discovered that their sets sounded "thin" at low volume. Jacobs [44] in 1930 applied for a patent for a volume control in which the bass frequencies are attenuated less than high frequencies at low control settings. His loudness control, or compensated volume control, is still with us today.

Any broadcast or recording medium always suffers from the combination of finite bandwidth and finite signal-to-noise ratio. Improved broadcasting or recording media show improved numbers, but the same types of limits still exist. A large number of schemes have been invented over the years to make the ear believe that the received or reproduced signal is improved over the unprocessed version. One of the most successful is preemphasis, where certain frequencies are boosted in transmission and then attenuated along with noise upon reproduction.

Ever since the advent of broadcasting and recording, the engineers have attempted to make maximum use of the medium. Adjusting modulation level or "riding gain" is a standard method. The compressor for records dates back to 1927 when Mitchell [45] (Columbia Records) varied sensitivity of the electrodynamic record cutter with a rectified audio signal.

The expander, at the other end of the music reproduction chain, dates back to 1931 when Cook [46] (United Research Corporation) invented the volume expander, consisting of variable-gain tubes receiving a rectified and filtered gain control signal in proportion to the input signal. Thus loud music passages could be reproduced even louder.

The problems of compression and expansion are still with us today. First, if the two are not matched, unnatural reproduction can exist. In particular, reference levels have to be maintained carefully. Second, since compressors and expanders obtain their control signal from a rectified and filtered program signal, there is a delay between cause and effect. For example, a compressor may show temporary overshoot of output, and an expander may show periods of high gain with high noise reproduction after a program peak has passed. Swishing noises and thumping noises may be heard.

Etzrodt [47] (Siemens and Halske) proposed in 1932 that the control signal of a compressor for use by a matching expander be transmitted along with the compressed program material.

Other complete closed-loop schemes involve the splitting of the audio-frequency bands into multiple frequency ranges, compression and expansion after transmittal and then recombination, as invented by Hammond [48] in 1931. Barney [49] (Bell Telephone Laboratories) proposed a two-frequency-band scheme in 1942. The most successful of these schemes is still with us today, the frequency selective compressor–expander scheme by Dolby [50] (1965). Here multiple-frequency-range compression and expansion using the diode voltage–current law as basis over a limited volume range in multiple-frequency ranges have proven successful in many recordings and broadcasts.

All the automatic noise-reducing schemes referred to above are closed systems, that is, the program material is processed prior and after recording or transmission. Other schemes tried to obtain the most "listenable" signal from whatever the program might be.

In 1930 W. Van B. Roberts [51] (RCA) applied the automatic volume control bias voltage to a one-tube audio amplifier stage. The tube's grid-plate capacitance reduced frequency response for weak signals (or no AVC) and permitted a wider range for stronger signals.

After many other futile tries by others, H. H. Scott [52] introduced his dynamic noise suppressor in 1946. Scott realized that the effective bandwidth of the human ear varies with reproduced signal level, and that a lesser bandwidth is acceptable for low-volume signals. Reduction of bandwidth at low and high frequencies was sensed by the absence of program material in the high bass and low treble regions, respectively, and effected by reactance tubes. Scott's Dynaural noise suppressor was successful until the beginning of stereophonic records in 1957 and was used to process many 78-r/min in master recordings into long-playing records. Burwen's [53] noise-reducing system, adjusted to wide-dynamic-range program material as available today, has been able to remove the swishing problems of earlier systems by nonlinear processing.

Circuit theory advanced over the years. Although Ohm's law dates back to 1827 and Kirchoff's laws to 1845, complex quantities in electrical engineering were only vulgarized by Steinmetz in 1894.

Prior to 1932 it was thought by all scientiests that no more than 6 dB feedback could be applied to any device [54]. They reasoned that negative feedback behaved similar to positive feedback, where any more than 6 dB caused oscillation. In 1932 Nyquist proved his stability criterion, which was experimentally confirmed by Peterson in 1934. The advantages of negative feedback were systemically discussed by Black [55] in 1934, and the relations of amplitude and phase were clarified by Bode in 1940. Not until about 1945 were most of the fundamental feedback concepts made known [56].

It is, therefore, not surprising that most electronic equipment prior to 1945 contained little or no feedback. This may be the cause of published arguments in the trade press until the late 1950s about the sound of triode amplifiers and pentode amplifiers. The difference in internal impedance and distortion between designs using moderate amounts of feedback can account for the argued differences. However, these arguments have now been settled, or rather overshadowed, by arguments over tube sound and transistor sound. Today arguments about distortion, its nature, definition, audibility, and measurement persist. From some of the arguments advanced, this subject will not be resolved soon.

Feedback amplifiers for music reproduction became available soon after World War II [39]. Prior to this, adjustments to amplifiers were made only after an exhaustive graphical analysis of published tube characteristics [57]. Distortion-measuring equipment during that time consisted of wave analyzers (or selective voltmeters) which had to be tuned to each harmonic. State-of-the-art oscillators produced less than 1-percent distortion.

The situation changes rapidly thereafter. In 1949 McIntosh and Gow [58] described a new 50-watt amplifier which had a then unheard-of guarantee of less than 1% distortion at full power over the entire audio range between 20 and 20 000 Hz, and less than ¼% distortion at midfrequencies. This performance was accomplished using a bifilar wound driver transformer and a bifilar wound output transformer in a common feedback loop. This model cost nearly $300 with amplifier and power supply on separate chassis and set a new standard for high-fidelity music reproduction.

The tape recorder, the Magnetophon, which was brought to the United States from Germany as one of the spoils of war, was used in the transcribed Bing Crosby broadcasts of 1946. The popular tape recorder, the Brush "Soundmirror," used black iron oxide paperbacked type 100 tape by the Minnesota Mining and Manufacturing Company, soon to be followed by "acetate" plastic tape with a red iron oxide, type 110. In 1947 General Electric released the variable-reluctance pickup [59] with an available accessory preamplifier, containing one 6SC7 high-mu dual triode. In 1948 Columbia Records [60] introduced long-playing records, followed in 1949 by RCA's 45-r/min record [61].

In 1949 it was also possible to make stereophonic tape recordings by using two half-channel recording heads "staggered" by mounting space normally required by the full-track recording and playback heads [65].

The consumer electronics industry tried valiantly to keep pace with all these new developments. In 1935 the ac–dc radio had been the latest development, and in 1939, 1.4-volt miniature tubes permitted portable battery-operated sets which led to the 1946 Belmont pocket radio [8].

In the late 1940s the music lover could choose from several makes of equipment, the electronics built on a chassis with tubes and capacitors and transformers sticking up and the controls out front behind a spaced flat panel. When desired, it could be installed into a piece of furniture by doing cabinet work. Loudspeakers came as bare "chassis" or in a cabinet styled for "professional" use. Interconnections were left to the user's dexterity. Separate power supplies for the field windings of electrodynamic loudspeakers were no longer required, the high-flux Alnico permanent magnet systems took the place of electromagnets.

In the late 1940s loudspeakers for home music reproduction were relatively efficient, and the average separate amplifier had an output of 10 watts. Toward the end of the 1950s the benefit of wider and smoother frequency response of the "low-efficiency" bookshelf loudspeaker was compensated by an increase in amplifier power to an average of perhaps 20 watts. In the 1950s stereo records and stereophonic broadcasting necessitated two channels, each averaging perhaps 20 watt output, or a total of 40 watts. Today, to reproduce higher peak sound levels seems to indicate an average of 4×20 watts or 2×40 watts, or 80 watts. Already, amplifiers of several hundred watts per channel exist.

Statistically, a power output increase of about 3 dB per decade cannot continue at this pace. The consequences of home-type amplifiers by the turn of the century having output power ratings in the kilowatt per channel range provide quite a stimulus to a fertile imagination.

Amplifier quality has also improved over the years. If total harmonic distortion over the total audio frequency range is used as one measure, halving of distortion every decade seems to have occurred with the average now around ½ percent.

The improvements in phonograph pickups, resulting in wider frequency response and lower tracking force, have also resulted in lower output voltages. If reference recording levels of 3.5 cm/s per channel at 1000 Hz or 5 cm/s lateral modulation are used as a "medium loud" signal, the pickup output levels have decreased at an irregular rate of 3 to 6 dB per decade. As a result, the gain of amplifiers measured between the phono input and the loudspeaker output has increased by more than 6 dB per decade. It is to the credit of the amplifier designers that the signal-to-noise ratio has not been degraded but has actually improved.

Fortunately there were several major developments which made all this possible. Electronic engineers in the tube era were often frustrated by the singularity of the tube—electron flow is always from the cathode to the other elements—they wanted a device with current flow in the opposite direction to be able to devise a better push-pull circuit or a better direct coupled circuit.

Although few realized it at the time, the solution was described in 1948 by Bardeen and Brattain [63] of Bell Telephone Laboratories. The germanium point contact transistor of 1950 was a fragile device, prone to oscillate, yet it amplified and did not require heater power. Just three years after the original announcement, Shockley's work on the theoretical aspects of p-n junctions resulted in the development of the (germanium) junction transistor in 1951 by Shockley [64] and his coworkers at Bell Telephone Laboratories.

Soon other manufacturers produced transistors for commercial use. In November of 1952 the *Proceedings of Institute of Radio Engineers* was a special issue on transistors. The then current transistor manufacturers advertised their products. Federated Semiconductor Company (sales agents for Germanium Products Corporation), Transistor Products, RCA, and Raytheon advertised products, the latter company achieving fame with the CK 721 and CK 722 germanium junction transistors introduced a few months later. These types were used by many an engineer who wanted to learn about these new devices.

The same issue also had a theoretical paper by Shockley describing "a unipolar field-effect transistor," a device that was yet to be made.

The first consumer application of transistors was in hearing-aid amplifiers, which up to the early 1950s contained usually three subminiature vacuum tubes as amplifiers.

In 1954 Regency marketed the first transistorized radio. The 1957 Radio Shack catalog [65] lists DeWald, Hallicrafters, Regency, and "Famous Make" transistor radios at about three times the price of ac-dc tube radios.

The same catalog also shows the first transistorized high-fidelity product, a three-transistor preamplifier for microphone or magnetic pickup produced by the Fisher Radio Corporation.

The first transistor high-fidelity amplifiers were produced in 1961 by Transistronics [66], the model TEC S 15. A matching tuner, model TEC 15 MPx, was also offered. In the following years a number of companies offered transistorized music reproduction equipment.

The use of more rugged transistors helped the engineers to design more reliable equipment. The author was at that time successful in analyzing the demands on performance of output transistors and devising circuits which would provide protection against excessive dissipation [67]. Since that time, protection of amplifiers by electronic means other than fuses has become standard for all high-power transistor circuits.

In 1959 Kilby [68] of Texas Instruments described a solid-state circuit in which all elements (transistors, diodes, resistors, and capacitors) were made by standard semiconductor processes. This first integrated circuit became the forerunner of all the integrated circuits used by the millions in computers, calculators, and many other applications. Soon thereafter Noyce [69] of Fairchild Semiconductor developed the planar semiconductor process which permitted isolated function of these parts. Originally devised as a means to decrease space requirements, to increase reliability by eliminating human error, and decrease manufacturing costs (all achieved), the integrated circuit manufacturers also achieved devices which were closely matched to each other. Because of this matching and more particularly from understanding the nature of semiconductor behavior, linear integrated circuits became possible. Widlar [70] of Fairchild Semiconductor in 1965 succeeded in devising the μA709 operational amplifier, an integrated circuit which has spawned all operational amplifiers used today, from instrumentation to music reproduction. Of the latter, the first commercial use of operational amplifiers as equalized preamplifiers by Scott in 1969 resulted in reduced noise and improved circuit stability.

During the 1930s the Loewe Company [71] in Germany offered a series of radios which contained an early form of integrated circuit, two or three vacuum tube sections along with resistors, and capacitors inside a common evacuated glass envelope.

The successful transistorized designs had both signal source and load under complete control of the designer. The first transistorized record playing system, the KLH model 11, introduced in 1962, used 12 germanium transistors (Fig. 6). Packaged in a three-piece suitcase (at a retail price of under $200) and soon emulated by others, this model became the successful forerunner of today's compact music systems.

After having worked with many improvements over standard amplitude modulation systems in radio transmission systems, Armstrong in 1936 demonstrated his FM broadcasting system before the Federal Communications Commission [20]. The demonstrated superior fidelity and signal-to-noise ratio coupled with the wider bandwidth requirement resulted in the construction of experimental 50-kW FM broadcast stations in 1938, Armstrong's in Alpine, New Jersey and Shepard's on Mt. Wachusett, Massachusetts. Two years later the Federal Communications Commission (FCC) set standards and authorized FM broadcasting on 40 channels in the 41–45-MHz band. A number of stations started broadcasting, and FM receivers became available. However, World War II interferred with all this, and in 1945 the FCC moved FM broadcasting to 88–108 MHz, the "new" FM band, allowing for 100 channels. Unfortunately most of the program material was identical to that supplied, either by records or the network line, to the AM station owned by the same broadcast license holder.

Although Armstrong had specified frequency modulation, not too many engineers realized that frequency modulation might be caused by incidental phase modulation due to multipath. In 1948 Arguimbau and Granlund [72] demonstrated the need for fast limiting and a wide-band detector to suppress distortion and to capture interferring signals. The model 310A Scott [73] tuner was the first FM tuner making use of these requirements.

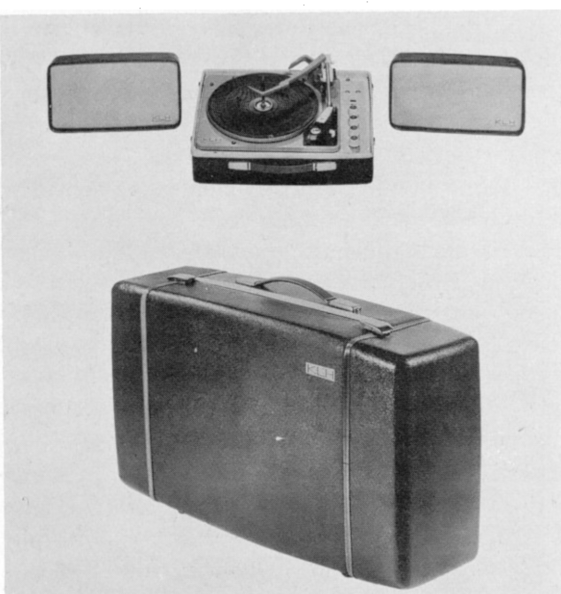


Fig. 6. Compact phonograph. *(Courtesy KLH)*

In 1953 Armstrong [20] demonstrated before the FCC a system of FM broadcasting which permitted two independent programs to be broadcast by the same FM station without mutual interference. The second program, modulated on a subcarrier (which in turn modulates the FM station carrier) resulted not in stereo directly, but in background music broadcasting by the subsidiary communication authorization (SCA), granted by the FCC in 1955. Previous to this date, background music had been provided, since 1935, using leased telephone lines.

Normally of limited fidelity to provide "canned music" to factories and stores, the idea of two signals on one station itself stimulated interest in stereophonic broadcasting.

Stereophonic music transmission [74] dates back to 1881 when music from the Paris opera was transmitted by two telephones to a remote location.

In the 1930s Bell Telephone Laboratories [75] demonstrated stereophonic music transmission and reproduction and Blumlein [76] showed a method of recording stereophonic information on a phonograph record. In 1957 the method of orthogonal stereophonic recording, the left channel on the inner groove wall of a record and the right channel on the outer wall, was adopted. Some radio stations began to broadcast stereo signals, usually the left channel on FM and the right channel on AM. Stereophonic recordings became popular very quickly.

Realizing the need for a common volume control, Scott in 1958 released a short-lived piece of equipment called the Stereodapter, controlling two "monophonic" amplifiers.

Shortly thereafter (in 1958) stereophonic music reproduction equipment became available, the record player initially being restricted to a pickup made by ELAC of Germany. Soon other makes began to appear.

After hearings and field tests conducted by the National Stereophonic Radio Committee, the FCC chose in 1961 a system which allowed stereophonic broadcasting [77]. Again the author was successful in designing equipment [78] which could receive these stereophonic broadcasts while excluding the simultaneous broadcast of background music.

Today stereophonic broadcasting is a normal source of program material for home listening. Similarly, tape recordings (since 1947, available prerecorded in stereo since about 1956) and most particularly tape cartridges [79] (since 1965) (recorded for reproduction of music in automobiles) and tape cassettes [80] (since 1966) along with stereophonic records are the sources of music for the home listener.

The radio, once the major source of home entertainment, still exists in ever-increasing numbers, selling at an average of 45 million radios per year over the last 10 years in the United States alone [81]. Table radios and clock radios for the home and portable radios and auto radios for the home-away-from-home comprise the bulk of the production. Because of the price competition, very few manufacturers have followed the lead of KLH (Fig. 7) who in 1960 introduced a table model radio (model 8) which was capable of flat acoustic frequency response of all but the bottom octave of FM broadcast limits.

Radio–phonograph consoles, once the prestige music reproducers in the home, have been declining in the recent few years, giving way to high-fidelity components, which have been rising in popularity ever since their introduction in the years following World War II.

Home music reproduction has had the benefit of the almost regular introduction of a new service or a new convenience. In the last 30 years came the magnetic tape recorder, the long-playing record, the ''component'' amplifier, the high-quality tuner, background music via FM, prerecorded tapes, stereophonic records, stereophonic broadcasting, the automobile tape cartridge, and the tape cassette.

The introduction in 1970 of four-channel sound is still in the undecided stage because several incompatible systems exist. There are systems which mix four channels into two channels for recording and broadcasting, the original material in part recoverable by a mixing and automatic fading technique. There are systems which are two-channel and where stereophonic material is enhanced by additional delays and reverberation. Then there are systems which transmit and record four channels using subsidiary modulation techniques. Finally, there are systems of using multiple tape tracks. Some additional systems have been proposed for FM broadcasting.[2]

At this time the solution is not clear, and sales of four-channel equipment and recordings have been a disappointment to many. The quadraphonic broadcasting proposals have been analyzed and tested and are now in the hands of the FCC for further testing and possible decision. Not until there is an easily available source of low-cost program material to the average nontechnical consumer will four-channel sound become popular.

Before this happens, there is another service which might entice the public: when stereophonic broadcasting was proposed prior to 1960, there were several methods of FM broadcasting, other for TV broadcasting, and others for AM broadcasting. Interest in AM stereophonic broadcasting has reawakened, with committee meetings[3] currently (March 1977) going on and field tests scheduled for midyear. Perhaps a new service will result from this effort.

In the 100 years since the introduction of the phonograph, the attempt has been to bring the stage or the concert hall into the home. Success has been remarkable, but not complete. Fidelity has been improved and multiple channels were used for greater realism. The listening room always had its own contributing acoustics, not the least of which is the transmission of sound in both directions through walls and doors and windows. The resulting restriction of the dynamic range, and the inability to use a very large number of channels have resulted in less than perfect sound. The use of headphones has largely removed the sound transmission problem, but has introduced new problems, the restriction of movement of the wearer of headphones, his discomfort, and the lack of feedback on the acoustic image while the listener moves his head. The first two problems seem to be problems which may be resolved. The latter is a problem for the future: how to have two recorded channels of program material for the two ears and how to present them to the mobile listener, presenting him a stationary music image, predetermined by the record. The listener will then be the determining part of the feedback loop. Furthermore, how will multiple listeners be accommodated, perhaps without headphones? Also, how can multiple program desires be handled without interference to each other? Here loudspeakers with nearby electronically controlled sound absorption may provide the answer.

All of these ideas, when in the process of development, will result in new challenges which then may be overcome.

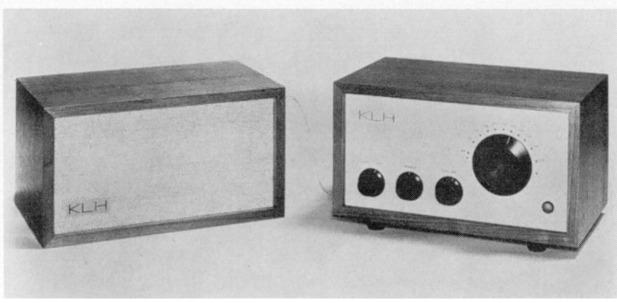


Fig. 7. Compact radio. *(Courtesy KLH)*

[2] The report to the Federal Communications Commission by the National Quadraphonic Radio Committee is available for a fee from the Electronic Industries Association (EIA), Washington, DC 20006.

[3] National AM Stereo Radio Committee, E. M. Tingley (EIA), Secretary.

REFERENCES

[1] ''Edison's Pressure Relay,'' *The Telegraphic J.*, vol. 5, pp. 149-150 (July 1, 1877).

[2] D. E. Hughes, ''On the Action of Sonorous Vibrations in Varying the Force of an Electric Current,'' *Proc. Roy. Soc. (London)*, vol. 27, pp. 362-369 (1878).

[3] H. E. Shreeve (W.E.Co.), U.S. Patents 791,655-6 (1905).

[4] T. Shaw, ''The Conquest of Distance by Wire Telephony,'' *Bell Sys. Tech. J.*, vol. 23, pp. 337-421 (Oct. 1944).

[5] F. V. Hunt, *Electroacoustics*, Harvard University Press, Cambridge, MA, 1954.

[6] O. Read and W. W. Welch, *From Tin Foil to Stereo*, 2nd ed. Howard W. Sams & Co., (Indianapolis, IN, 1976), pp. 149, 158.

[7] R. A. Fessenden, ''Recent Progress in Wireless Telephony,'' *Sci. American*, vol. 96, pp. 68-69 (Jan. 19, 1907).

[8] W. O. Swinyard, ''The Development of the Art of Radio Receiving from the Early 1920's to the Present,'' *Proc. IRE*, pp. 793-798 (May 1962).

[9] J. T. Brothers, ''Historical Development of Component Parts Field,'' *Proc. IRE*, vol. 50, pp. 912-919 (May 1962).

[10] J. A. Fleming, U.S. Patent 803,684 (1905).

[11] L. DeForest, U.S. Patent 879,532 (1908).

[12] L. DeForest, "Discussion of E. H. Armstrong's Papers," *Proc. IRE (Corr.)*, vol. 3, p. 239 (Sept. 1915).

[13] E. W. Herold, "The Impact of Receiving Tubes on Broadcast and TV Receivers," *Proc. IRE*, vol. 50, pp. 805-809 (May 1962).

[14] F. J. Mann, "Federal Telephone and Radio Corporation, A Historical Review 1909-1946," *Elec. Commun.*, vol. 23, pp. 377-405 (Dec. 1946).

[15] C. Buff, "Radio Receivers—Past and Present," *Proc. IRE*, vol. 50, pp. 884-891 (May 1962).

[16] L. A. Hazeltine, "Tuned Radio Frequency Amplification with Neutralization of Capacity Coupling," *Proc. Radio Club of Am.*, vol. 2 (March 1923).

[17] R. A. Heising, "Modulation Methods," *Proc. IRE*, vol. 50, pp. 896-901 (May 1962).

[18] J. O. Weldon, "Transmitters," *Proc. IRE*, vol. 50, pp. 901-906 (May 1962).

[19] R. F. Guy, "AM and FM Broadcasting," *Proc. IRE*, vol. 50, pp. 811-817 (May 1962).

[20] "A Play-by-Play Retrospective," *Broadcasting*, vol. 79, pp. 74-154 (Nov. 2, 1970).

[21] "Die Entwicklungsrichtung des Rundfunks," *Radio Amateur*, vol. 19, pp. 149-150 (May 1942).

[22] H. A. Wheeler, "Automatic Volume Control for Radio Receiving Sets," *Proc. IRE*, vol. 16, pp. 30-39 (Jan. 1928).

[23] W. E. Holland and W. A. MacDonald, "The Philco '95' Screengrid Plus," *Radio Broadcast*, vol. 16, pp. 111-112 (Dec. 1929).

[24] F. Langford-Smith, *Radiotron Designer's Handbook*, 4th ed. (Wireless Press, Sidney, 1953), pp. 1140-1146.

[25] C. W. Rice and E. W. Kellogg, "Notes on the Development of a New Type of Hornless Loudspeaker," *Trans. AIEE*, vol. 44, pp. 461-475 (Apr. 1925).

[26] I. W. Green and J. P. Maxfield, "Public Address Systems," *Trans. AIEE*, vol. 43, p. 64 (1923)

[27] W. H. Martin and H. Fletcher, "High Quality Transmission and Reproduction of Speech and Music," *Trans. AIEE*, vol. 43, p. 384 (1924).

[28] J. K. Hilliard, "Movie Sound Reproduction," *Audio*, vol. 61, pp. 44-60 (Mar. 1977).

[29] G. Host and B. D. H. Tellegen, U.S. Patent 1,945,040 (1934).

[30] L. E. Barton, "High Audio Output from Relatively Small Tubes," *Proc. IRE*, vol. 19, pp. 1131-1149 (July 1931).

[31] O. H. Schade, "Beam Power Tubes," *Proc. IRE*, vol. 26, pp. 137-181 (Feb. 1938).

[32] J. P. Maxfield and H. C. Harrison, "Methods of High Quality Recording and Reproducing of Music and Speech Based on Telephone Research," *Bell Sys. Tech. J.*, vol. 5, pp. 493-523 (July 1926).

[33] H. Pitsch, "Anschluss des Tonabnehmers," *Auslese der Funktech.*, vol. 3, pp. 4-5 (Apr. 1941).

[34] C. B. Sawyer, "The Use of Rochelle Salt Crystals for Electrical Reproducers and Microphones," *Proc. IRE*, vol. 19, pp. 2020-2029 (Nov. 1931).

[35] E. S. Pridham, U.S. Patent 1,901,331 (1933).

[36] R. Rechnitzer, German Patent 603,008 (1928).

[37] M. A. McLennan, German Patent 642,384 (1931).

[38] W. S. Bachman, U.S. Patent 2,511,633 (1950).

[39] H. H. Scott, "Dynamic Noise Suppressor," *Electronics*, vol. 20, p. 96 (Dec. 1947).

[40] T. B. Wier, U.S. Patent 1,617,428 (1927).

[41] M. G. Scroggie, "Amplifier Tone Control Circuits," *Wireless Eng.*, vol. 9, p. 3 (Jan. 1932).

[42] J. G. Aceves, U.S. Patents, 1,984,357 and 1,984,450 (1934).

[43] P. J. Baxandall, "Negative Feedback Tone Control-Independent Variation of Bass and Treble Without Switches," *Wireless World*, vol. 58, p. 402 (Oct. 1952).

[44] C. T. Jacobs, U.S. Patent 1,938,256 (1933).

[45] F. A. Mitchell, U.S. Patent 1,792,859 (1931).

[46] E. D. Cook, U.S. Patent 1,928,410 (1933).

[47] K. Etzrodt, U.S. Patent 2,065,489 (1936).

[48] J. H. Hammond, Jr., U.S. Patent 2,008,825 (1935).

[49] H. L. Barney, U.S. Patent 2,358,045 (1944).

[50] R. M. Dolby, Brit. Patent 1,120,541 (1968).

[51] W. Van B. Roberts, U.S. Patent Re 21,018 (1939).

[52] H. H. Scott, U.S. Patent 2,606,972 (1952).

[53] R. S. Burwen, U.S. Patent 3,678,416 (1972).

[54] V. Belevitch, "Summary of the History of Circuit Theory," *Proc. IRE*, vol. 50, pp. 848-855 (May 1962).

[55] H. S. Black. U.S. Patent 2,102,671.

[56] H. W. Bode, *Network Analysis and Feedback Amplifier Design* (Van Nostrand, New York 1945).

[57] F. Langforth-Smith, *Radiotron Designers Handbook*, 3rd ed. (Wireless Press, Sidney, 1940). pp. 268-294.

[58] F. H. McIntosh and G. J. Gow, "Description and Analysis of a New 50 Watt Amplifier Circuit," *Audio Eng.*, vol. 33, p. 9 (Dec. 1949).

[59] A. Douglas, "The G. E. Variable Reluctance Pickup," *Electronic Eng.*, vol. 21, p. 21 (Jan. 1949).

[60] P. C. Goldmark, R. Snepvangers, and W. S. Backman, "The Columbia Long-Playing Microgroove Recording System," *Proc. IRE*, vol. 37, pp. 923-927 (Aug. 1949).

[61] B. R. Carson, A. D. Burt, and H. I. Reiskind, "A Record Changer and Record of Complementary Design," *RCA Rev.*, vol. 10, pp. 173-190 (June 1949).

[62] M. Camras, "Stereophonic Magnetic Recorder," *Proc. IRE*, vol. 37, pp. 442-447 (Apr. 1949).

[63] J. Bardeen and W. H. Brattain, "The Transistor, a Semiconductor Triode," *Phys. Rev.*, vol. 74, pp. 230-231 (July 15, 1948).

[64] W. Shockley, M. Sparks, and G. K. Teal, "P-N Junction Transistors," *Phys. Rev.*, vol. 83, pp. 151-162 (July 1, 1951).

[65] *Music in Your Home*, Catalog 57-HF (Radio Shack Corporation, Boston, 1956).

[66] "Product Review Section, Amplifiers, Tuners," *Audio*, vol. 45, pp. 36-49 (Aug. 1961).

[67] D. R. von Recklinghausen, U.S. Patent 3,668,545 (1972).

[68] J. S. Kilby, "Invention of the Integrated Circuit," *IEEE Trans. Electron Dev.*, vol. ED-23, pp. 648-654 (July 1976).

[69] R. N. Noyce, U.S. Patent 2,981,877 (1961).

[70] R. J. Widlar, "A Unique Circuit Design for a High Performance Operational Amplifier Especially Suited to Monolithic Construction," *Proc. 1965 NEC*, pp. 85-89.

[71] P. H. Brans, *Röhren Vademecum 1945-1946*. (Regelien, Berlin, 1946), pp. 128-185.

[72] L. B. Arguimbau and J. Granlund, ''Frequency Modulation Transmission Under Multipath Conditions,'' *Rep 42*, Mass. Inst. of Technol. Res. Lab. of Electronics, 1948.

[73] D. R. von Recklinghausen, J. W. Casey, and V. H. Pomper, ''New FM-Only Tuner,'' *Radio and Telev. News*, vol. 52, (Dec. 1954).

[74] W. H. Offenhauser, Jr., ''Binaural and Stereophonic Sound in Retrospect,'' *J. Audio Eng. Soc.*, vol. 6, pp. 67-68 (Apr. 1958).

[75] H. Fletcher *et al.*, ''Symposim on Auditory Perspective,'' *Bell Sys. Tech. J.*, vol. 13, p. 329 (1934).

[76] A. D. Blumlein, Brit. Patent 394,325 (1933).

[77] ''Rules and Regulations to Permit FM Broadcasting Stations to Transmit Stereophonic Programs on a Multiplex Basis,'' Docket No. 13506, Federal Communications Commission, Washington, Apr. 20, 1961.

[78] D. R. von Recklinghausen, ''An FM Mulitplex Stereo Adaptor,'' *Audio*, vol. 45, pp. 21-23 (June 1961).

[79] T. R. Naimy, ''An Eight-Track Stereo Cartridge for Automotive Use,'' *J. Audio Eng. Soc.*, vol. 15, pp. 23-25 (Jan. 1967).

[80] L. F. Ottens, The Compact Cassette for Audio Tape Recorders,'' *J. Audio Eng. Soc.*, vol. 15, pp. 26-28 (Jan. 1967).

[81] *Consumer Electronics Annual Review*, vol. 2A-376 (Electronic Industries Association, Washington, DC, 1976), pp. 5-27.