Electronic Circuits

We have already looked at one simple circuit, the voltage divider. In order to understand the operation of audio equipment, we need to look a little deeper into electronic circuits. The arrangement of simple circuit elements determines the behavior of the complex audio circuits used for equalization, dynamics, and mixing. With a basic understanding of these circuits, we may begin to understand what goes on inside those expensive “black boxes” that make up the recording studio.

The simplest kind of circuit that is of use is the voltage divider, which we have already encountered. This circuit is essentially two elements in series. With two-terminal circuit elements like resistors, capacitors and simple inductors, there are two ways to connect them together: end-to end (series) and both ends together (parallel).

Series resistance adds so that the overall resistance is the sum of the two individual resistances:

\[ R_{\text{total}} = R_1 + R_2 \quad \text{resistors in series} \]

In the parallel case, the total impedance is more complicated to calculate:

\[ R_{\text{total}} = \frac{R_1 R_2}{R_1 + R_2} \quad \text{or} \quad \frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} \quad \text{resistors in parallel} \]

With series-connected elements, the total impedance is always larger than either element alone. In parallel, the circuit total impedance is always lower than either element alone.

Parallel capacitance adds directly:

\[ C_{\text{total}} = C_1 + C_2 \quad \text{capacitors in parallel} \]
(each capacitor adds area to the effective total capacitor surface) but adds like the resistor parallel case when connected in series:

\[
\frac{1}{C_{\text{total}}} = \frac{1}{C_1} + \frac{1}{C_2}, \quad \text{capacitors in series}
\]

Inductance adds in the same way as resistance:

\[
L_{\text{total}} = L_1 + L_2, \quad \text{inductors in series}
\]

\[
\frac{1}{L_{\text{total}}} = \frac{1}{L_1} + \frac{1}{L_2}, \quad \text{inductors in parallel}
\]

The general case for more than two resistors or inductors in parallel or multiple capacitors in series is:

\[
\frac{1}{x_{\text{total}}} = \frac{1}{x_1} + \frac{1}{x_2} + ... + \frac{1}{x_n}
\]

**Impedance matching**

In order to transfer a signal from one circuit or device to another, their relative impedances may be optimized either to transfer voltage or power, the product of voltage and current. For most audio circuits, voltage carries the signal. When driving loudspeakers, however, both current and voltage must be considered since both contribute to the power needed to drive the mechanical device. The absolute impedance levels will affect the amount of noise added to the signal; both from sources inherent in the circuits as well as from externally coupled or induced sources. The relative impedances will determine how much of the output signal voltage is captured by the input of the next device in the signal chain. To maximize voltage transfer, the input impedance should be much higher than the output impedance, while to transfer power the impedances should be equal. This makes connecting devices together something of a “balancing” act.

Even very complicated circuits can be modeled as a simple circuit consisting of a voltage source and series resistance, known as a Thevenin equivalent circuit. In essence, this is what a device input would “see” when connected to the output. \( R_s \) represents the output impedance (series resistance, in this case), with the signal represented by the voltage source. The voltage seen by the input \( R_L \) (device input impedance appearing as the load resistance on the output circuit) depends on the ratio \( R_L/(R_s+R_L) \). The tables below demonstrate the effect of varying the input impedance connected to a fixed output (source) impedance as it relates to both voltage and power transfer.

**Voltage transfer:**

\[
V_{\text{out}} = V_{\text{in}} \left( \frac{R_L}{R_L + R_s} \right) \quad \text{[assuming } V_{\text{in}} = 1 \text{ V]}
\]

<table>
<thead>
<tr>
<th>( R_s ) (ohms)</th>
<th>( R_L ) (ohms)</th>
<th>( V_{\text{out}} ) (volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1</td>
<td>0.0099</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
<td>0.091</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>0.5</td>
</tr>
<tr>
<td>100</td>
<td>1,000</td>
<td>0.91</td>
</tr>
<tr>
<td>100</td>
<td>10,000</td>
<td>0.99</td>
</tr>
</tbody>
</table>
Power transfer: \[ P_{out} = \frac{V_{out}^2}{R_L} = \left( \frac{V_{in} \left( \frac{R_L}{R_L + R_S} \right)}{R_L} \right)^2 \]

Below are some real device impedances, as they are specified and as they are actually measured:

<table>
<thead>
<tr>
<th>Device type</th>
<th>Specified $Z_{in}$ (ohms)</th>
<th>Real $Z_{in}$ (ohms)</th>
<th>Specified $Z_{out}$ (ohms)</th>
<th>Real $Z_{out}$ (ohms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>microphone</td>
<td>-----</td>
<td>-----</td>
<td>150</td>
<td>110</td>
</tr>
<tr>
<td>mic preamp</td>
<td>600</td>
<td>3000</td>
<td>600</td>
<td>110</td>
</tr>
<tr>
<td>Low Z line amp</td>
<td>600</td>
<td>2800</td>
<td>600</td>
<td>110</td>
</tr>
<tr>
<td>Hi Z line amp</td>
<td>5000</td>
<td>5000</td>
<td>100</td>
<td>47</td>
</tr>
<tr>
<td>power amp</td>
<td>600</td>
<td>2800</td>
<td>8</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Below are some real device impedances, as they are specified and as they are actually measured:

<table>
<thead>
<tr>
<th>R (ohms)</th>
<th>R (ohms)</th>
<th>$P_{out}$ (mW)</th>
<th>$P_{total}$ (mW)</th>
<th>$P_{out} / P_{total}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1</td>
<td>0.1</td>
<td>9.9</td>
<td>1</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
<td>0.81</td>
<td>9.1</td>
<td>8.9</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>2.5</td>
<td>5.0</td>
<td>50</td>
</tr>
<tr>
<td>100</td>
<td>1000</td>
<td>0.83</td>
<td>0.9</td>
<td>92</td>
</tr>
</tbody>
</table>

Low impedance transmission systems have the following advantages:

1. Reduced inherent thermal noise due to lower resistances. Thermal noise is generated by random motion in circuit elements caused by heat in the devices. Thermal noise voltage (rms) can be calculated from the equation:
   \[ v_n = \sqrt{4kTRB} \]
   where $k =$ Boltzmann’s constant (1.38 x $10^{-23}$ joule/°K), $T =$ temperature (°K), $R =$ resistance (Ω), and $B$ is bandwidth ($f_{max} - f_{min}$) in Hz. At room temperature, a 20 kHz bandwidth 1 kΩ circuit has a minimum of about 0.3 μV of noise while a 1 MΩ circuit generates about 9 μV of noise. While this may seem like a very small amount of noise, when multiplied by 60 dB (1000x) of gain in a microphone preamp, it becomes considerable.

2. Reduced susceptibility to electromagnetic coupling of external signals.

Balanced differential low impedance transmission systems have an additional advantage:

1. Reduced coupling of radiated noise due to rejection of common mode signals from electromagnetically coupled sources. (This will be explained later.)
Electronic Circuit Symbols and Schematics

Electronic circuits used in audio devices are documented in drawings known as schematic diagrams or simply as schematics. These pictures are descriptions of the interconnection of the basic electronic circuit elements that comprise the audio device. Each element is depicted by a symbol, often including a number indicating the actual value of the component. While the schematic is mainly intended to provide information to a service person should the device require repair, the schematic offers a quick way of studying the device: it shows the signal path and what the device is doing to the signal, if we know what to look for. We will discuss the basic symbols and what they describe. With a bit of knowledge about the function of the basic circuit elements, even complicated schematics can be understood in a block-function way.

The schematic is intended to convey very detailed information to a service person without requiring prior knowledge of the specific device. While a user can often interpret the schematic diagram, a simpler picture of the device operation is frequently provided: the block diagram. The block diagram shows the device as a series of interconnected functional blocks that depict the device in a less detailed manner. The block diagram is most useful to the user because it simplifies the information in a way that conveys the electronic processes as functions like gain, mixing, filtering, etc. With a little knowledge, however, it is possible to read a schematic and mentally convert it to a block diagram in order to fully understand the functions of a device. (Or you could read the operator’s manual...)

resistor

capacitor

inductor

ground

earth

AC voltage source

DC voltage source

diode

NPN bipolar transistor

n-channel J-FET

vacuum tube

op-amp
The way to convert a schematic into a more useful block diagram is to become familiar with the common circuit topologies encountered in audio devices. Fortunately, there are relatively few circuit types that are employed in analog audio devices: amplifiers, filters, mixers, and the occasional dynamic range processing block (which is really a special kind of amplifier.) Once we get used to recognizing these circuits, we can rapidly understand the signal path as it flows through the device. Since most modern audio devices are constructed from op-amp circuits, we can easily recognize the function of each block by knowing the way op-amp circuits function.

Active Electronic Elements

Active elements require outside power supply to function, unlike passive components. They use an input signal to modulate a supplied voltage (or current) to amplify the input signal. The main gain element in audio circuits is the transistor, which is able to amplify signals by using a small current to control a larger current derived from a voltage provided by a power supply. Amplifiers can be made of separate transistors (discrete) or may be fabricated multi-transistor devices called integrated circuits (ICs). The standard audio IC is the operational amplifier, or op-amp. Using negative feedback (some of the output signal inverted and routed back to combine with the input) and tailoring the feedback component network, most audio circuits, including amplifiers, mixers, and filters, may be implemented using op-amps alone. While audio op-amps and other audio integrated circuits have been improved greatly in recent years, there are still very high performance circuits, notably microphone preamps, which benefit from discrete construction. The individual transistors and other components can be hand-selected to deliver the best possible performance.

There is much interest recently in the vacuum tube as a gain element, although the tube largely fell out of widespread use when the transistor was developed. Basically, a filament in a vacuum is heated electrically and placed near a cathode, which allows electrons to be released by the cathode. Another element, the plate, is made positive relative to the cathode so it attracts electrons. By placing a grid in between, close to the cathode, a signal imposed on the grid controls the flow of electrons from the cathode to the plate, thereby producing amplification. Since tubes must operate at high voltages (up to several hundred volts), they are unsuitable for battery power and, hence, portable use. They produce a lot of heat, since the filament must be heated to incandescence in order to create current flow in the device. Nevertheless, tubes are making a comeback, in part due to the harmonic content of their distortion, which is perceived as more “musical” (or less harsh) than that generated by transistor circuits.

There is a type of transistor, called field-effect (or FET), which operates more like a vacuum tube than a regular transistor. They produce similar distortion spectra to vacuum tubes and are popular in power amplifiers and preamps. Some op-amps used in audio circuits use FET input stages.

While we won’t go deeply into circuit design, a basic understanding of active devices will allow the engineer to understand basic signal flow in schematic diagrams, often simplifying the job of understanding complicated devices like mixers. It should also make troubleshooting problems in equipment less mysterious.
Bipolar Transistors: signal current into the base terminal (B) controls the current in the collector terminal (C), which is amplified by the current gain ($\beta$ or $h_{fe}$) of the transistor. The output voltage depends on the resistors used in the circuit (Ohm’s Law again!). If a resistor is placed in the collector lead (C), the circuit is an inverting voltage amplifier. If it is placed in the emitter lead (E), the circuit gives current gain but no voltage gain: it functions like an impedance converter, or buffer. The transistor can also be connected as a current gain device as it often appears in power supply circuits where the base current is regulated to control a larger collector current.

Field Effect Transistors: FETs are physically different in construction and operation from the bipolar transistor. Whereas bipolar transistors are often thought of as current devices, FETs are voltage devices: while the base current into the bipolar transistor determines the collector current, the gate (G) voltage to the FET determines the source (S) to drain (D) current. As we’ll see, this more resembles the operation of a vacuum tube than a bipolar transistor. FETs have much higher input impedances than do bipolar transistors, so they are quite simple to use in audio applications. Since the FET acts much like a voltage-controlled resistance, it can be used as an analog switch as well as an amplifier.

Vacuum tubes: Before there were transistors, there were vacuum tubes. Thermionic devices like vacuum tubes operate at high temperatures in a vacuum. The filament (F) is heated electrically until it glows red-hot. This heats a cathode (C) until it sheds electrons that are attracted to the plate (P) by a high positive voltage bias. A control grid (G) is placed between the cathode and plate and the signal voltage applied to the grid controls the current flow in the plate electrode. This describes a simple triode; more complicated tubes with additional electrodes are also common. Due to the vacuum separating the electrodes, tubes have very high input impedances so they are easy to employ in audio circuits. The requirement for high voltages, however, make their circuitry depend on high voltage capacitors and can be hazardous to the casual experimenter. Although the relationship between temperature, impedance, and inherent noise would tend to make vacuum tubes noisy, they can be low noise devices if properly designed and constructed. Vacuum tube audio circuitry has enjoyed a renaissance, partly induced by the explosion of digital recording techniques which no longer introduces the tape compression and head bump effects of analog magnetic recorders which tend to make an audio signal sound “warmer” by altering the harmonic content of the reproduced signals. Tube circuits are capable of clean, undistorted amplifi-
cation when operated well below their limits.

![Op-amp Circuit Diagram](image)

**Op-amps:** Op-amps are integrated circuits, meaning many transistors and resistors are combined in a functional circuit where terminals are provided to connect external components and power. Capacitors and inductors are difficult to implement in silicon and are connected externally through pins on the integrated circuit. The output voltage $V_{out}$ is equal to the difference between the voltages at the $V(\text{+})$ and $V(-)$ inputs multiplied by the device gain, which is very high. In real use, some of the output voltage is fed back into the negative input, stabilizing the device, giving precise amplification and allowing other operations to be implemented as a function of the external circuit. The input impedance is very high and the output impedance is very low. It is nearly a “perfect” amplifier. The external circuit can either be inverting or non-inverting, depending on the connections. It can also be a filter and a summing amplifier, hence the popularity of the op-amp in audio devices. Another important use for the op-amp is the differential amplifier: it amplifies the signal difference between the inputs, but not any voltage common to both inputs (so-called common mode signal). Since induced hum and noise are usually common mode signals, they are rejected by the op-amp input. Such differential lines became known as balanced lines in audio terminology, because in addition to being differential, the impedances at both ends were equal, or balanced. This is not always necessarily the case, but the name stuck. Strictly speaking, differential and balanced refer to two different things.

**Op-amp theory**

![Op-amp Theory Diagram](image)

In the inverting case, the positive input is grounded and the input voltage connects through an input resistor $R_{in}$. In an “ideal” op-amp, the input impedance is so high that no current can flow through it and therefore, (by Ohm’s Law) there can be no voltage difference between the two input terminals. This forces the voltage at the inverting input to be “virtually” at ground potential when the (+) terminal is grounded, thus the inverting input is called a *virtual* ground. Since no current can flow in or out of the inverting input, any input current must flow through the $R_{i}$ resistance but in the opposite direction, causing the output voltage to be inverted from the input voltage. The inverting op-amp input impedance is just $R_{in}$.

In the non-inverting case, the signal is fed directly to the non-inverting input and the inverting input is fed a por-
tion of the output voltage through the voltage divider \( R_1 \) and \( R_2 \). The inverting terminal now sees both the input voltage from the (+) input and a portion of the non-inverted output, so the gain of the circuit is a little greater than the equivalent inverting op-amp circuit. The non-inverting input impedance is very high.

Below are several common op-amp circuits used in audio equipment. Of particular interest are the summing amplifier, which forms the heart of a mixer, and the differential amplifier that is often used to produce a balanced input circuit.

So, what gives it “that sound”?

Much of what we perceive as the “character” of an audio system is due to subtle imperfections in the behavior of the electronic elements. The descriptions of the devices given so far are idealized and ignore the small deviations caused by effects like stray capacitances and inductances because their effects are relatively small. But when a large collection of these devices are combined in complicated circuitry, the imperfections all add together in unpredictable ways and can generate a sonic signature that gives each device its own special sound. Sometimes these effects can be desirable, but they are always due to deviations from the ideal behavior of the components.

Passive devices are usually thought of as behaving exactly like their models: capacitors have only capacitance and not any resistance or inductance. In reality, there are small (sometimes not so small) inductances and capacitances associated with resistors; so when extreme conditions exist in terms of signal frequency, these stray reactances can change the effective value of the impedance from what we see if we measure the resistance with a DC resistance meter. Carbon-composition resistors will differ from metal film resistors and wire-wound resistors in their behavior and sound in some applications. Capacitors have a large but finite resistance in parallel with the capacitance and will eventually discharge even if completely disconnected from any external circuitry. Transformers will saturate when a signal is too large and saturates the metal core with magnetic flux. All of these effects may contribute to the sound of a circuit under extreme conditions.

While passive elements contribute somewhat to the deviation from the ideal, active devices are prone to exhibit more significant limitations. Amplifiers may have problems with signals that change very rapidly and have very wide dynamic ranges. There is a limit to how fast a device like an op-amp can change its output voltage, for example. This is called slew-rate limiting. Although the small signal bandwidth of the amplifier might be more than sufficient, the output stage cannot produce big instantaneous voltage swings and consequently the amplified signal cannot exactly follow the input. When you pass through several such stages in a mixer, you will begin to hear the result.

While we might be tempted to consider the shortcomings of analog circuits to be a problem, we have become quite used to the sound of transformers and vacuum tubes as applied to music recording since we heard popular music that way for many decades. Design engineers might like to have linear and quiet circuits, while many recording engineers want the sound that tubes and inductors have conferred on music recording, which we have come to define as the “warm” sound of the “oldies”. With the advent of digital recording and processing, we now have the ability to simulate the sound of the traditional analog recording system in computer-based recording programs. Among the most popular plug-ins for computer recording programs are analog simulation and digital models of classic tube/transformer audio compressors and equalizers.

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Common Op-amp Circuits

- Inverting Amplifier
- Non-inverting amplifier
- Low-pass filter
- High-pass filter
- Summing amplifier (inverting)
- Buffer amplifier (unity gain, non-inverting)
- Differential (balanced) amplifier