The main purpose of an analog filter circuit is to either pass or reject signals based on their frequency. There are many types of frequency-selective filter circuits; their action can usually be determined from their names. For example, a band-rejection filter will pass all frequencies except those in a specific band. Consider what happens if a parallel resonant circuit is connected in series with a signal source. It lets all frequencies pass freely, with the exception of those in a small band of frequencies around the circuit’s resonant frequency. (At its resonant frequency, the parallel circuit theoretically acts as an infinite impedance. That impedance is greatly reduced at off-resonant frequencies.)

On the other hand, should the parallel L-C circuit be placed across (in parallel with) the signal source, only the narrow band previously rejected would be allowed to pass from the source to the amplifier. Thus, we have just described a bandpass filter.

In addition to bandpass and band-rejection filters, circuits can be designed to only pass frequencies that are either above or below a certain cutoff frequency. If the circuit passes only frequencies that are below the cutoff, the circuit is called a lowpass filter, while a circuit that passes those frequencies above the cutoff is a highpass filter.

All of the different filters fall into one of two categories: active or passive. Passive filters are composed of passive components such as resistors, capacitors, and inductors. Inductors, however, are undesirable at some frequencies because of their size and/or practical performance. (At low frequencies, a real inductor’s properties vary considerably from those of an ideal inductor.) Active filters consist of passive elements along with an active element such as a transistor or an integrated-circuit op-amp. Active filters are usually designed without using inductors. Therefore they have the advantage of being less expensive on the average (because inductors can be expensive and hard to find); they are generally easier to tune; they can provide gain (and thus they do not necessarily have any insertion loss); they have a high input impedance, and have a low output impedance.

A filter can be in a circuit with active devices and still not be an active filter. For example, if a resonant circuit is connected in series with two active devices (such as transistors) it is called a passive filter. But, if the same resonant circuit is part of a feedback loop, it is then called an active filter. We saw an example of such an active filter when we discussed a tape-player preamplifier during our discussion of feedback (see the July 1983 issue of Radio-Electronics).

Basic filters
A rudimentary passive filter consists of an R-C network or an R-L network. Those networks can be found in many different types of electronic equipment performing different roles. For example,
in power supplies, such circuits are used
to filter undesirable ripple. In audio
amplifiers, different R-C networks are
used in tone-control, scratch-filter, and
rumble-filter circuits.
Let’s take a look at some actual filter
circuits and determine the effect they will
have on signals that are fed to them. Two
filter circuits—that perform the same
function using different components—
are shown in Fig. 1. When a low-
frequency signal is fed to either one of
to those circuits, the output is identical with
the input. However, as the frequency is
increased, the output is reduced—thus
they are lowpass filters. The output rolls
off at the rate shown by the curve in Fig.
2. The important frequency to note is \( f_0 \).

That’s the frequency where the output has
dropped 3 dB from its maximum value
(0.707 of the maximum). That corner
frequency (also called the half-power
point) can be determined from the values
of the components in the circuit. For the
R-C circuit in Fig. 1-a:

\[
f_0 = \frac{1}{2\pi RC}.
\]  

(1)

For the R-L circuit in Fig. 1B:

\[
f_0 = \frac{R}{2\pi L}.
\]  

(2)

Figure 3 shows two circuits, either of
which can be used to attenuate the low
frequencies (thereby creating a highpass
filter). Note that the curve shown in Fig. 4,
when compared to Fig. 2, is symmetric
about the y-axis. In Fig. 2, the output drops
in the linear portion of the curve by
6-dB every time the frequency is doubled.
In Fig. 4, the output drops by 6-dB every
time the frequency is halved. The important
point is that in the linear portion of
each curve, the slope is the same—6-dB-
per-octave.

Any of these filter circuits can be
placed between two amplifier stages. If
that’s done, the corner frequency, \( f_0 \),
is still as predicted by equation 1—
assuming that the impedance of the cir-
cuit feeding the filter is zero and the input
impedance of the circuit at the output of
the filter is infinite. Otherwise, resistors
in series with the input to the filter and in
parallel with the output from the filter,
must be considered when determining \( f_0 \).

For example, assume that the circuit in
Fig. 3-a is connected between two transis-
tors, as shown in Fig. 5-a. Figure 5-b is
the equivalent circuit involving the filter
and transistors. (The function of coupling
capacitor \( C_1 \) is to DC-isolate the transis-
tor from the filter. That capacitor is usually
of such magnitude that it can be treated
as a short for all signal voltages. ) It can be
simplified by determining the equivalent
resistance, \( R_{eq} \), of all resistances at the
output. The final circuit is shown in Fig.
5-c. Equation 1 applies there also.

The analysis of this circuit—as well as
more complex filter circuits that have
more than one corner frequency—can be
accomplished in two simple steps. First,
short the input, \( e_{in} \), and note the total
resistance across the capacitor. In this
case it is \( 2.7K + R_{eq} \). Using equation 1, we
determine that:

\[
f_{out} = \frac{1}{2\pi RC}.
\]  

(3)

The frequency at which the rolloff starts is
\( f_{out} \), as shown in Fig. 4.

The next step is to place a short across
the output and leave \( e_{in} \) open. There is
no parallel R-C combination in the circuit
when that is done; the only frequency
indicated in the response calculations of
the filter is \( f_0 \), and its curve in Fig. 4.

Now let’s look at a more complex filter
circuit—one in which there will be more
than one corner frequency. We will use
the procedure noted above to analyze the
circuit in Fig. 6 and find those corner
frequencies. One \( f_{0} \) corner frequency is
the beginning of the rolloff characteristic curve and a second \( f_{0} \) corner frequency is
on a curve with rising characteristics.
The two resulting curves are then added to
provide a curve illustrating the overall
response of the circuit as shown in Fig. 7.
First, we short \( e_{in} \), and note the total
resistance across \( C-R3 \) in parallel with
the sum of \( R1 \) and \( R2 \). Substituting this
information into equation 1, we find that one
of the corner frequencies, where the high-
frequency roll off starts, is:

\[
f_{out} = \frac{1}{2\pi ((R1 + R2)/R3)C}.
\]  

We continue by leaving \( e_{in} \) open and
shorting \( e_{out} \). Then, \( R2 \) is across both
\( R3 \) and \( C \). By inserting those values into
equation 1 we find for the second corner
frequency:

\[
R1 \quad 2.7K
c
\]  

FIG. 4—THE OUTPUT OF THE HIGHPASS filters shown in Fig. 3 decreases as the frequency decreases.

FIG. 5—TO WORK WITH a filter between two transistor circuits, you must first find the simplified
equivalent circuit.
The curves add as shown in Fig. 7. The total curve indicates the overall response of the filter. The two equations differ only by the resistance factors. Because $R_2||R_3$ is smaller than $(R_1 + R_2)||R_3$, $f_{o2}$ is higher in frequency than $f_{o1}$. A similar procedure may be used to determine the frequency response of other complex arrangements.

![Curves with $f_{o1}$ corner frequency](image)

**FIG. 8—TO INCREASE THE ROLLOFF RATE, you can use more than one filter in a circuit.**

The combination of $R_2$ and $C_2$ is a second filter network, with a corner frequency at $f_{o2}$. Those corner frequencies are determined through use of equation 1 for each R-C combination. Curves with those corner frequencies are shown in Fig. 9. Each curve illustrates a rolloff at the rate of 6 dB-per-octave. Adding the two curves results in a characteristic with an eventual rolloff of 12 dB-per-octave.

If more resistors and capacitors are added to a circuit of the type shown in Fig. 8, a procedure similar to that used with the circuit in Fig. 6 may also be used. But this time, the circuit must be split into two portions with each containing the individual filter sections, and each section is analyzed as if the other section does not exist. The effects on the frequency response of each of the two sections are then added to determine the circuit’s overall response.

Other two-section filters (two R-C networks) can be combined to generate a bandpass filter circuit. That is illustrated in Fig. 10. There is low frequency rolloff due to the $C_1-R_1$ section of the filter and high frequency rolloff due to the $R_2-C_2$ filter. The corner frequencies, $f_{o1}$ and $f_{o2}$, are determined for the $R_1-C_1$ combination and the $R_2-C_2$ combination, respectively. When $f_{o1}$ is substantially less than $f_{o2}$, the response curve for the circuit is as shown in Fig. 11-a. Should $f_{o1}$ be higher in frequency than $f_{o2}$, the curve in Fig. 11-b applies.

In the circuits drawn in Figs. 8 and 10, the $R_2-C_2$ combinations probably have some effect on $f_{o2}$. (The responses of those filters are shown in Figs. 9 and 11.) To minimize their interrelated effects, components should be chosen so that the $R_2-C_2$ circuit has a minor shunting effect on $R_1$ and $C_1$ and that the $R_1-C_1$ combination has only a minor effect on loading the $R_2-C_2$ combination. It is best if the two circuits were completely isolated from each other by placing each R-C filter between different transistors in a three-transistor amplifier circuit.

### Active filters

An active filter involving bipolar transistors, is shown in Fig. 12. Here we assume that $R_F$ is much greater than $r_e$, the internal emitter resistance of Q2. Capacitor $C_1$, along with the output impedance of Q1 and the input impedance of Q2, form one high pass filter. The corner frequency, $f_{o1}$, due to those components is

$$f_{o1} = \frac{1}{2\pi C_1(R_c + \beta r_e||R_b)}$$

if we assume that the impedance of $C_2$ is much higher than $r_e$ at $f_z$. Here, $R_c$ is the impedance at the input of the filter, $\beta r_e$ is the impedance reflected from the emitter circuit of Q2 into its base circuit, and $r_b||R_b$ is the resistance at the output of the filter. Due to those resistances, the output rolls off at frequencies below $f_{o1}$.

A second corner frequency, $f_{o2}$, is caused by the presence of $C_2$ and $R_F$ in the emitter circuit. Because $C_2$ shunts a portion ($R_F$) of the total resistance in the emitter circuit, feedback due to the presence of this resistor is reduced as the frequency increases. Hence beginning at $f_{o2}$, the output increases with the applied frequency. It is equal to $1/2\pi C_2 R_F$.

Next consider the total resistance in the emitter circuit not shunted by $C_2$. It is $R_T = R_b + r_e/R_F$ where $r_e/R_F$ is the resistance reflected from the base circuit into the emitter circuit. A corner frequency due to the action of those resistances along with the $C_2-R_F$ combination is $f_{o3}$

$$f_{o3} = \frac{1}{2\pi C_2 (R_b r_e/(R_b + R_f))}$$

Voltage begins to roll off at that frequency.

It is obvious that $f_{o3}$ is at a higher frequency than is $f_{o2}$ because the resistance...
in the denominator of the equation for \( f_{o3} \) is lower than that for \( f_{o2} \). Usually, \( f_{o1} \) is lower than either \( f_{o2} \) or \( f_{o3} \) because the capacitance of \( C_1 \) and the input and output resistors in the circuit, are all large. The value of \( R_F \) is seldom negligible when considering the factors in equation for \( f_{o1} \) because \( C_2 \) can frequently be considered as an open circuit at \( f_{o1} \) Hz.

Four curves are shown in Fig. 13. Three of these represent the response of individual filter sections in the circuit, with rolloff or amplitude increases starting at the three corner frequencies. The total curve shows the overall effect on the response of the combination of the three.

**Using op-amps**

Now we'll look at an active filter that is designed around an op-amp. In the circuit shown in Fig. 14-a, the capacitor in the feedback loop attenuates the high frequencies, therefore, the circuit behaves as a lowpass filter. The frequency at which the output has been attenuated 3 dB can be approximated from equation 1 when \( R \) and \( C \) are identical in both filter sections. If they should differ, then

\[
f_o = \frac{1}{2\pi \sqrt{(R_1C_1)(R_2C_2)}}
\]

where \( R_1 \) and \( C_1 \) are the components in one of the R-C networks and \( R_2 \) and \( C_2 \) are the components in the second R-C network. An inverting circuit could just as well have been used here. Figure 14-b shows such an arrangement. Equation 3 still applies. Negative feedback is applied through \( C_1 \)—high frequencies are fed through \( C_1 \) back to the input, to increase the rolloff rate. In both lowpass-filter circuits, \( R_1 \) and \( R_2 \) are usually made equal—about 10,000 ohms.

Highpass filters can be formed using circuits identical to those drawn in Fig. 14. All that's necessary is to interchange the locations of components in the \( R_1-C_1 \) filter as well as components in the \( R_2-C_2 \) filter. As before, equation 3 applies.

In the article on high frequency circuits (see the August 1983 issue of *Radio-Electronics*), the \( Q \) of an L-C circuit was defined. That same definition also applies to bandpass and band-rejection types of R-C circuits. As you recall, the \( Q \) of a bandpass circuit is equal to \( f_r / (f_H - f_L) \) where \( f_r \) is the center or resonant frequency, \( f_H \) is the frequency above resonance where the gain has dropped 3-dB from what it is at resonance, and \( f_L \) is the frequency below resonance with the 3-dB gain reduction.

We will now be looking at some more active filters and we will present a number of different equations for determining the various \( C \)'s and \( R \)'s that are needed. We will not derive the equations; the filters will be presented in "cookbook" form. You'll achieve good performance if the given relationships are observed. Rolloff will approach the ideals of 40 dB-per-octave for the circuits we'll discuss.

A typical bandpass filter circuit using resistors and capacitors is shown in Fig. 15. Before you determine what components you use, you must calculate just what \( Q \) must be. Let us say you want a peak response at 1000 Hz and that the gain should be down 3 dB at 900 Hz and 1100 Hz. \( Q \) must then be 1000/ (1100 − 900) = 5.

Continue the design by letting \( C_1 \) be equal to \( C_2 \). Calculate \( R_1 \) by setting it equal to 100,000/\( Q \). Because \( Q = 5 \), \( R_1 = 20,000 \) ohms. The relationship for determining \( R_2 \) is 5250/\( Q \), so in this ex-
ample, R2 should be set equal to 1050 ohms. The value of R3 is equal to the product of 20,000 ohms and Q. For this problem, R3 = 100,000 ohms.

For the circuit in Fig. 15

\[ f_0 = \frac{1}{2\pi} \sqrt{C_1 C_2 R_3 (R_1 + R_2)} \]  

(4)

Because C1 is identical to C2, the product of the two capacitances is \( C^2 \). To determine C, equation 4 becomes

\[ C = \frac{1}{2\pi f_0} \sqrt{R_3 (R_1 + R_2)} \]  

(5)

Substituting \( f_0 = 1000 \), \( R_3 = 1000000 \), and \( R_1 || R_2 = 998 \) into equation 5 yields the fact that C = 0.016 \( \mu \)F. If you follow the results, you can obtain a capable filtering circuit.

A band rejection or notch filter is in Fig. 16-a. Here, Q is determined as before. Capacitor C1 is usually made equal to C2 and the resonant frequency, as indicated in equation 3, is:

\[ f_0 = \frac{1}{2\pi} \sqrt{R_1 R_2 C_1 C_2} \].

Once Q has been determined, the ratio of R2 to R1 in the circuit can be set equal to 4Q². Make R1 equal to about 100,000/Q, R3 equal to about 5250/Q and R4 equal to about 50/R3. Using this information, calculate the C’s for the circuit through use of equation 3.

Another type of notch filter (often called the twin-T arrangement) built around an op-amp is shown in Fig. 16-b. In that circuit, \( f_n \) can be determined using equation 1. Because Q can be very high, the rolloff is sharp.

Constant-k and m-derived filters

Constant-k filters get their name from the fact that the product of the capacitive and inductive reactances \( X_C X_L \) is constant at all frequencies. They exhibit reasonably sharp rolloff with a smooth passband. However, sharpness of rolloff can be improved considerably by using an m-derived filter.

An m-derived filter can be recognized by the parallel-resonant or series-resonant circuit in series or across the line respectively. They produce essentially infinite attenuation of the frequency to which they are tuned (thus zero transmission of that frequency along the line).

Schematics of both constant-k and m-derived filters are shown in Figs. 17 through 19.

Component values in the circuits depend on the resistance at the input to the filter circuit as well as the resistance at its output. In this discussion, we assume them to be equal—that is the usual case. We can denote that resistance by the letter R. If input and output resistances differ, let R equal the average value of the resistance at the input and output. Rolloff will be affected by that mismatch. But resistance can be adjusted to the ideal by merely adding the proper transistor circuits at the input and output of the filter.

In the bandpass circuits, the Q of the coils do affect the sharpness of rolloff, but only to a minor degree. Rolloff at the low end of the pass band starts at \( f_1 \), while rolloff at the high end of the passband starts at \( f_2 \). (\( f_1 \) and \( f_2 \) were defined above). For these circuits the resonant frequency is equal to \( \sqrt{f_1 f_2} \).

The various filter circuits shown include equations to indicate the approximate values of the components to be used in the circuits. Using those, you should be able to design a practical circuit.

Several constant-k or m-derived filter sections may be combined to sharpen rolloff and increase attenuation at different frequencies, if required. Input and output impedance matching will not be disturbed by such combinations.

Next time we’ll look at another aspect of solid-state devices—how they can be used in switching applications.