ECE 304: Types of Amplifiers

Idealized amplifier types

The table below summarizes the properties of the four types of amplifier. These properties are discussed in detail below.

<table>
<thead>
<tr>
<th>Amplifier Type</th>
<th>Gain</th>
<th>Ideal Input R</th>
<th>Ideal Output R</th>
<th>Driver</th>
<th>Driver+Amplifier Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>V/V</td>
<td>∞</td>
<td>0</td>
<td>Thevenin</td>
<td>Thevenin</td>
</tr>
<tr>
<td>Current</td>
<td>A/A</td>
<td>0</td>
<td>∞</td>
<td>Norton</td>
<td>Norton</td>
</tr>
<tr>
<td>Transconductance</td>
<td>A/V</td>
<td>∞</td>
<td>∞</td>
<td>Thevenin</td>
<td>Norton</td>
</tr>
<tr>
<td>Transresistance</td>
<td>V/A</td>
<td>0</td>
<td>0</td>
<td>Norton</td>
<td>Thevenin</td>
</tr>
</tbody>
</table>

**FIGURE 1**
Table of ideal amplifier input and output properties

Controlled sources in PSPICE

If we linearized a real-world amplifier, we could identify four different categories. With further simplification (e.g., no capacitors, no feedback, etc.) these types can be represented using the four types of dependent source shown in Figure 2→Figure 5.

**FIGURE 2:**
Simplified voltage amplifier: voltage out, voltage in; of course, the gain (in V/V) need not be 1V/V, and could be frequency dependent too. Ideally a VCVS.

**FIGURE 3:**
Simplified transconductance amplifier: Current out, voltage in; of course, the gain (in A/V) need not be 1A/V, and could be frequency dependent too. Ideally a VCCS.

**FIGURE 4:**
Simplified transresistance amplifier: Voltage out, current in; of course, the gain (in V/A) need not be 1V/A, and could be frequency dependent too. Ideally a CCVS.
FIGURE 5:
Simplified current amplifier: Current in, current out; of course, the gain (in A/A) need not be 1A/A, and could be frequency dependent too. Ideally a CCCS.

In Figure 2 → Figure 5 the input source is represented as either a Thevenin or a Norton equivalent circuit. This Thevenin or Norton equivalent could represent some electrical pre-stages that drive the simplified amplifier, or, they could represent a sensor of some kind. For example, the driver might be a thermocouple intended to convert temperature to voltage or current for electrical monitoring of temperature, or a photodiode intended to convert light to an electrical current or voltage for receiving an optical message. Whatever the sensor is, some equivalent electrical circuit has to represent it before we can make an electrical analysis of the system, and if we simplify this electrical equivalent by linearization and probably other simplifications, we end up with a Thevenin or Norton equivalent circuit for the sensor.

Likewise, in Figure 2 → Figure 5 the output load is represented as a simple load resistor. Very often we will have add load capacitance as well. This load could represent the input impedance of some electrical after-stages driven by the simplified amplifier, or, the load could represent the much simplified and linearized input impedance of some actuator, like an electrical motor for converting electrical signals to mechanical motion, or a light-emitting diode for converting an electrical message to an optical message. Whatever the actuator is, some equivalent electrical circuit has to represent it before we can make an electrical analysis of the system, and if we simplify this electrical equivalent by linearization and probably other simplifications, we end up with a simple impedance for the load.

Choosing the type of amplifier
Which of the four types of amplifier should we select for a given job? If impedance match is the most important specification, then we find the Norton or Thevenin equivalent of the driver or driving stage and select an amplifier with the best input impedance divider. For the output, we look at the actuator or the driven stage input impedance and make the output divider the best too. Of course, the selection may be more complicated if we have other specifications to meet as well, like bandwidth, voltage range, or cost.

Examples of the four types of amplifier
It is an interesting exercise to look at various amplifier stages from the viewpoint of making an ideal amplifier of the various kinds. An extended discussion is an entire course in itself. A brief presentation follows.

VOLTAGE AMPLIFIER - VCVS

FIGURE 6:
The ideal VCVS
The ideal VCVS has several ideal properties:
1. $R_{IN} = \infty$, independent of frequency
2. $R_{OUT} = 0$, independent of frequency
3. Frequency dependence or speed of response: $A_\nu$, independent of frequency, instant response
4. Linearity: same $A_\nu$, regardless of input- or output-voltage amplitudes
5. Large voltage gain

In practice, we can only approximate these goals. For example, let's evaluate the common emitter amplifier on this basis:

PARAMETERS:
- $RC = 1k$
- $RS = 1k$
- $RL = 1k$
- $CL = 10nF$
- $V_{amp} = 7V$

**FIGURE 7:**
The common emitter (CE) amplifier with bypass capacitor $C_{BY}$

1. $R_{IN}$ not $\infty$, $R_{IN} = r_\pi$ at low frequencies.
2. $R_{OUT}$ not 0, $R_{OUT} = RC/r_O$ at low frequencies
3. Frequency dependence or speed of response: $A_\nu$, not independent of frequency, response time limited by the Miller effect
4. Linearity: $A_\nu$, limited by cutoff at upper end and by saturation at the lower end. Linearity is imperfect even for smaller output swings.
5. Gain: $A_\nu = -g_m(RC/r_O)$, which may be too small

Can the CE amplifier be improved as a voltage amplifier? A partial list of possibilities follows.

1. $R_{IN}$: can increase to $r_\pi(VF) + (\beta+1)r_\pi(CE)$ by putting a voltage follower in front or by using a lower bias current to increase $r_\pi = \beta V_{th}/I_C$
2. $R_{OUT}$ can decrease to $[(RC/r_O) +r_\pi(VF)]/\beta$ by putting a voltage follower after
3. Frequency response, also improved by leading $VF$ because lower input resistance lowers the Miller-effect time constant. Also, could use a cascode.
4. Linearity: can't help the cutoff, maybe can improve linearity for in-between voltages using an active load
5. Gain: using active load, the voltage gain can be increased to $A_\nu = -g_m r_O$, which still may be too small. Increased gain also makes amplifier more in small-signal regime, which improves linearity, Cascading stages can increase the gain.

Of course, these improvements come with some trade-offs.
Transconductance Amplifier - VCCS

**Figure 8:**
The VCCS has several ideal properties:
1. $R_{\text{IN}} = \infty$, independent of frequency
2. $R_{\text{OUT}} = \infty$, independent of frequency
3. Frequency dependence or speed of response: $G_u$, independent of frequency, instant response
4. Linearity: same $G_u$ regardless of input- or output-voltage amplitudes
5. Large transconductance gain

In practice, we can only approximate these goals. For example, let's evaluate the common emitter amplifier on this basis:

**Figure 9:**
The common emitter (CE) amplifier with bypass capacitor $C_BY$
1. $R_{\text{IN}}$ not $\infty$, $R_{\text{IN}} = r_e$ at low frequencies
2. $R_{\text{OUT}}$ not $\infty$, $R_{\text{OUT}} = R_C/r_O$ at low frequencies
3. Frequency dependence or speed of response: $G_u$, not independent of frequency, response time limited by the Miller effect
4. Linearity: $G_u$, limited by supply voltage or by cutoff at upper end and by saturation at the lower end. Linearity is imperfect even for smaller output swings
5. Transconductance gain is $I_{\text{OUT}}/V_S = g_m(R_C/r_O)/R_L$ at low frequencies, which may not be large enough

Can the CE amplifier be improved as a transconductance amplifier?
1. $R_{\text{IN}}$ can increase to $r_e(VF) + (\beta+1)r_e(\text{CE})$ by putting a voltage follower in front, or increase by using a lower bias current to increase $r_e = \beta V_{\text{th}}/I_C$
2. $R_{\text{OUT}}$ can increase to $r_O$ by using an active load
3. Frequency response, also improved by leading VF because lower input resistance lowers the Miller-effect time constant. Also, could use a cascode.
4. Linearity: can't help cutoff, maybe can improve linearity for in-between voltages using an active load to put amplifier in small-signal regime.

5. Transconductance gain can be improved the same way as the voltage gain.

6. Another approach to increasing gain is by stacking VF stages to get an increase in current by $\beta$ per stage. Such a circuit is shown in Figure 10.

FIGURE 10:
A cascade of voltage followers to improve transconductance gain

Of course, these improvements come with some trade-offs.

TRANSRESISTANCE AMPLIFIER  – CCVS

FIGURE 11:
The ideal transresistance amplifier – a CCVS

The ideal CCVS has several ideal properties:
1. $R_{IN} = 0$, independent of frequency
2. $R_{OUT} = 0$, independent of frequency
3. Frequency dependence or speed of response: $Z_i$ independent of frequency, instant response
4. Linearity: same $Z_i$, regardless of input- or output-voltage amplitudes
5. Large transresistance gain
Again, we can only approximate these goals. For example, let's evaluate the common emitter amplifier on this basis
1. $R_{\text{IN}}$ not 0, $R_{\text{IN}} = r_\pi$ at low frequencies
2. $R_{\text{OUT}}$ not 0, $R_{\text{OUT}} = R_C/r_O$ at low frequencies
3. Frequency dependence or speed of response: $Z_i$ not independent of frequency, response time limited by the Miller effect
4. Linearity: $Z_i$, limited by supply voltage at upper end and by saturation at the lower end. Linearity is imperfect even for smaller output swings
5. Transresistance gain is $V_{\text{OUT}}/I_S = g_m(R_C/r_O)/R_L$ at low frequencies, which may not be large enough

Can the CE amplifier be improved?
1. Can decrease $R_{\text{IN}}$ by increasing the base current; $r_\pi = \beta V_{\text{th}}/I_C$
2. $R_{\text{OUT}}$ can decrease to $[(R_C/r_O) + r_\pi(V_F)]/(eta+1)$ by putting a voltage follower after
3. Frequency response, also improved by following VF because gain of CE stage is somewhat reduced. A better solution would be a cascode.
4. Linearity: can't help the supply voltage effects, maybe can improve linearity for in-between voltages using an active load
5. Transconductance gain can be improved the same way as the voltage gain.

THE IDEAL CURRENT AMPLIFIER – CCCS

The ideal CCCS has several ideal properties:
1. $R_{\text{IN}} = 0$, independent of frequency
2. $R_{\text{OUT}} = \infty$, independent of frequency
3. Frequency dependence or speed of response: $A_i$, independent of frequency, instant response
4. Linearity: same $A_i$, regardless of input- or output-voltage amplitudes
5. Large current gain

Again, we can only approximate these goals. For example, let's evaluate the common emitter amplifier on this basis
1. $R_{\text{IN}}$ not 0, $R_{\text{IN}} = r_s$ at low frequencies
2. $R_{\text{OUT}}$ not $\infty$, $R_{\text{OUT}} = R_C/r_O$ at low frequencies
3. Frequency dependence or speed of response: $A_v$, not independent of frequency, response time limited by the Miller effect
4. Linearity: $A_v$, limited by cutoff at upper end and by saturation at the lower end. Linearity is imperfect even for smaller output swings
5. Current gain is $I_{\text{OUT}}/I_S = g_m r_s (R_C/r_O)/R_L$ at low frequencies, which may not be large enough

Can the CE amplifier be improved as a current amplifier?
1. Can decrease $R_{\text{IN}}$ by increasing the base current; $r_s = \beta V_{\text{th}}/I_C$
2. $R_{\text{OUT}}$ can increase to $r_O$ by using an active load
3. Frequency response could be improved with a cascode.
4. Linearity: can't help the supply voltage effects, maybe can improve linearity for in-between voltages using an active load
5. Current gain can be improved the same way as for transconductance gain.

Summary
The basic amplifier types can be approximated by a CE amplifier and made better by adding stages. However, we will see that even bigger improvements can be made using feedback.