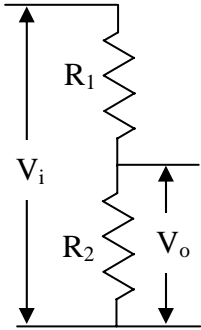


## Brief Introduction to Electronic Circuits PHYS 312

These notes give a short introduction to analog circuits. If you like to learn more about electronics (a good idea if you are thinking of becoming an experimental physicist), you can take a class offered in the summer (PHY-557). An excellent general reference is “The Art of Electronics” by Horowitz and Hill (Cambridge press).

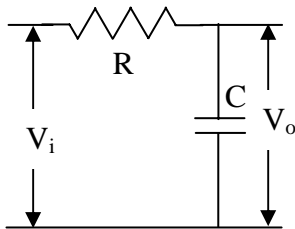
### 1. Resistive divider



$$V_o = R_2 / (R_1 + R_2) V_i$$

To show this consider a current  $I = V_i / (R_1 + R_2)$  flowing through both resistors and use Ohm’s law. Note that the current is assumed to be the same in both resistors and the current flowing to the output is assumed to be negligible. Therefore, one has to avoid “loading” the divider with any resistance comparable to  $R_2$

### 2. Low pass filter



You can analyze circuits involving capacitors and inductors by using the concept of complex impedance  $Z$

$$Z = R \quad \text{resistor}$$

$$Z = \frac{1}{i\omega C} \quad \text{capacitor}$$

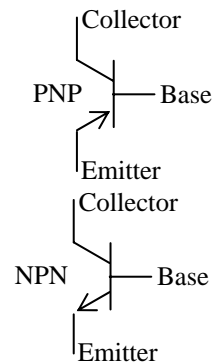
$$Z = i\omega L \quad \text{inductor}$$

Thus, a low-pass filter shown above is equivalent to the resistive divider with  $R_2$  replaced by the impedance of the capacitor.

$$V_o = \frac{V_i / i\omega C}{R + 1/i\omega C} = \frac{V_i}{i\omega RC + 1}; \quad \left| \frac{V_o}{V_i} \right| = |F(\omega)| = \frac{1}{\sqrt{1 + (RC\omega)^2}}$$

The complex transfer function  $F(\omega)$  describes the frequency response of the filter, it drops off at high frequency with characteristic cut-off frequency given by  $\omega_c = 1/RC$ . The  $\text{Arg}(F)$  gives the phase shift of the filter.

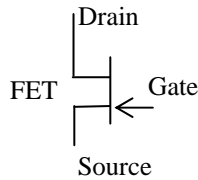
### 3. Transistors



Without going into details of the semiconductor physics you can think of a transistor as a valve. The base (gate) controls the current that flows through the collector-emitter (drain-source) circuit. Transistors come in a number of flavors. The two main types are bipolar transistors and field-effect transistors.

Bipolar transistors, the two top diagrams on the left, can be either PNP with the current flowing from the emitter to the collector or NPN with the current flowing in the opposite direction. The arrow on the emitter indicates the

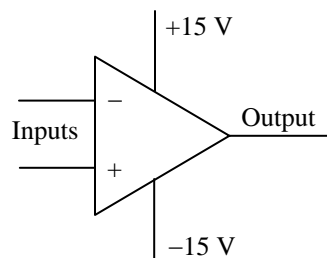
direction of current flow. The current through the collector-emitter circuit is amplified relative to base-emitter current by the gain coefficient  $\beta \sim 100$ . Another practical thing to remember is that the voltage between the base and the emitter is always about 0.7 V when any current flows through the transistor. This is a property of silicon that is used in nearly all transistors.



Field effect transistors (FET) also come in several types, only one is shown on the left. The main difference from the bipolar transistors is that they are controlled by a voltage on the gate instead of a current. The gate current of FET transistors is extremely small.

In modern electronic circuits transistors are rarely used except when the output power is relatively large. For example, a typical stereo contains mostly integrated circuits except for the output transistors driving the speakers.

#### 4. Operational Amplifiers



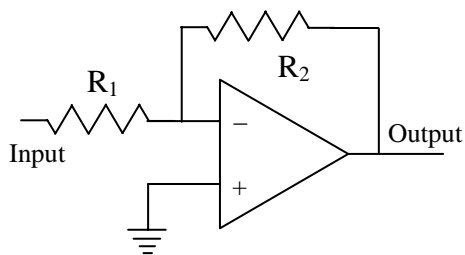
Operational amplifiers (op-amps) are the simplest and most commonly used analog integrated circuit. The circuit basically amplifies the voltage difference between the two inputs by a very large factor,  $10^6 - 10^7$ . Op-amps typically require  $\pm 15$  V power supplies, but can run almost as well with any supply voltage between  $\pm 5$  V and  $\pm 20$  V. In circuit diagrams the power supply lines are usually not shown explicitly, but you still need to prove power! The output of the op-amp is limited to be in the range between

positive and negative supply voltage.

Operational amplifiers are almost never used without a feedback, an additional circuit that sets the gain of the amplifier to a smaller and well-defined value. The behavior of op-amp circuits with feedback can be understood by following two simple rules:

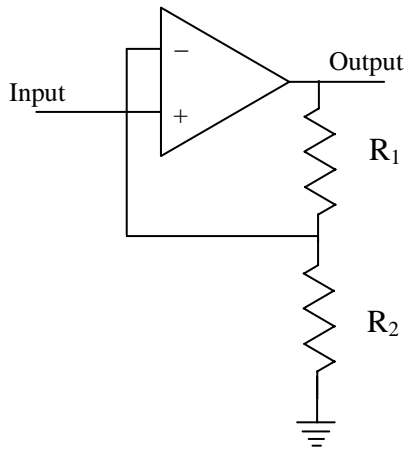
1. The output of the amplifier changes in a way to make the voltage difference between the two amplifier inputs equal to zero.
2. The current flowing into the amplifier inputs is equal to zero.

The first rule assumes that the gain of the amplifier is essentially infinite and the second rule is a consequence of the amplifier internal design.



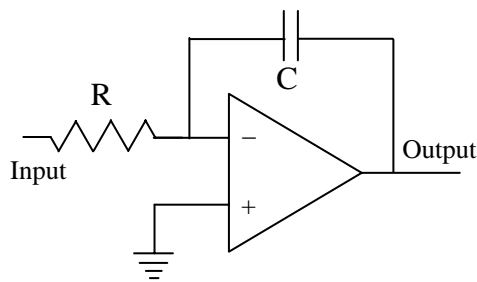
The circuit on the left is an inverting amplifier. Its analysis proceeds as follows. Suppose a voltage  $V_i$  is applied to the input. Since the “+” input of the op-amp is at ground, the “-” input must also be at zero voltage following the first op-amp rule. Therefore the current flowing through resistor  $R_1$  is  $I = V_i/R_1$ . The current going into the amplifier input is zero, therefore the same current  $I$  must flow through the resistor  $R_2$ , where it creates a voltage drop  $I R_2$ . Since one end of  $R_2$  is at ground, the output voltage (relative to ground) is  $V_o = -R_2/R_1 V_i$ . One drawback of this

circuit is that it has a low input impedance, i.e. draws a potentially significant current  $I = V_i/R_1$  from the input terminal.



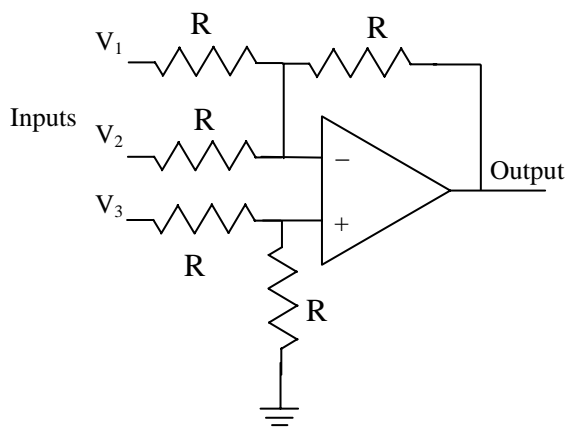
The next circuit is a non-inverting amplifier. The voltage on the “-“ terminal must be equal to the input voltage, therefore the output voltage  $V_o = (1+R_1/R_2) V_i$ . This circuit has a gain  $\geq 1$ . Its input impedance is equal to the input impedance of the op-amp, typically in the  $G\Omega$  range, and it draws virtually no current from the input.

You might have noticed that it’s the “-“ terminal that is always connected to the output through some type of circuit. This is necessary to obtain a “negative feedback”, such that if a finite voltage difference develops between the inputs, the amplifier output will drive it back to zero.



Another example of an op-amp circuit is an integrator shown on the left. You can show that the output voltage of the circuit is given by  $V_o = R/C \int V_i(t) dt$ .

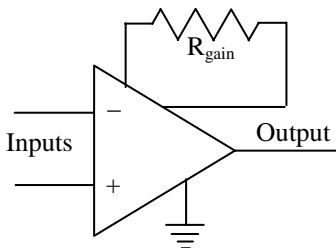
Of course, this relationship is satisfied only if the output remains within the output voltage range of the amplifier, typically 1-2 V smaller than the power supply voltage. Also note that the output current of op-amps is typically limited to 10-30 mA.



The final example is a sum/difference amplifier. For all equal resistors after a little algebra you can show that the output voltage is  $V_o = -(V_1+V_2-V_3)$ . Such circuit can be used to take a sum/difference of any number of voltage inputs.

Because of practical limitations of the op-amps, such as a limited output current and a large, but finite, input resistance, the resistor values in the above circuits should be chosen in the range 1 k $\Omega$  to 10 M $\Omega$ .

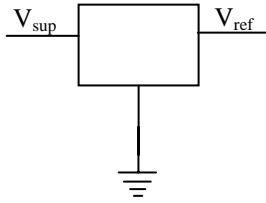
## 5. Instrumentation amplifier



The difference amplifier above has a drawback that it draws a significant current from the inputs. It turns out that a difference amplifier with high input impedance requires at least 3 op-amps. Such circuits are commonly packaged into a single chip called an instrumentation amplifier. The output is given by  $V_o = G(V_+ - V_-)$ , where the gain  $G$  is set using an external resistor. Instrumentation amplifiers are useful for measuring small voltages because they cancel common-mode noise.

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## 6. Voltage Reference



Whenever a constant voltage is needed in a circuit, a voltage reference chip is usually used. They are available with output voltages of 2.5, 5 or 10 V, which remains constant for a very wide range of supply voltages.

Many other more specialized chips are easily available, such as analog multipliers/dividers, comparators, variable-gain amplifiers, oscillators, dc-dc voltage converters, etc. The websites of major manufacturers are a good resource: [www.analog.com](http://www.analog.com), [www.ti.com](http://www.ti.com), [www.linear.com](http://www.linear.com).