# 1

We first discussed dc imperfections of op-amps. These are linear non-idealities. The important ones are the bias current $I_B$, the offset current $I_{off}$ and the offset voltage $V_{off}$. We also discussed how the effects of bias current can be cancelled in the inverting amplifier configuration by connecting the +-input of the op-amp to ground through a suitably chosen resistance (see Figure 14.31 of the text). For this material see Section 14.7 of the text.

# 2

We already observed in earlier lectures that real op-amps have finite (but large) input impedance, nonzero (but small) output impedance and finite (but large) differential gain. In ac circuits using op-amps it is often important to model in the dependence of the differential gain of the op-amp on frequency. This can often be done to a reasonable approximation by a first-order model. See equation (14.23) of the text. The discussion of this frequency-dependent non-ideality is in Section 14.5 of the text. We did not cover the part of this section relating to closed-loop bandwidth and the invariance of the gain-bandwidth product under negative feedback. Those of you with an interest in control theory and applications should read the rest of this section, since this invariance of the gain-bandwidth product is an important part of the heuristic thinking of practicing control engineers.

# 3

We discussed the major nonlinear limitations of op-amps. This discussion is in Section 14.6 of the text. Please read this entire section.

# 4

Finally,we discussed a circuit that uses positive feedback to exploit the limited output voltage swing of op-amps. See Figure 1.

In discussing this circuit, we will assume that the output voltage swing limits equal the supply voltages, i.e. $\pm 15$ volts. The op-amp is assumed to be ideal in all other respects. In this circuit, observe that if $v_o$ is neither at its upper limit of 15 nor at its lower limit of $-15$ then (because the op-amp is assumed to be otherwise ideal) the summing point constraint would imply that $v_1 = 0$ (because $v_1$ would equal $v_2$, which is tied to ground). But now the slightest positive perturbation of $v_1$ (e.g. due to noise) is self-reinforcing because the enormous differential gain of the op-amp would cause this perturbation to manifest as a huge positive swing at the output which further increases the perturbation of $v_1$ in the same direction. A similar situation would arise with the slightest negative perturbation of $v_1$ from 0. In practice, therefore, the output of the op-amp would be immediately pushed to either 15 or $-15$ volts. We may therefore assume that $v_o$ is $\pm 15$.

We ask for what values of $v_{in}$ it is possible for $v_0$ to equal 15. With $v_o = 15$ we have

$$v_1 = v_{in} + (15 - v_{in})\frac{R_1}{R_1 + R_2}$$

and this had better be nonnegative if $v_0$ equals 15. This gives the condition

$$v_{in} + (15 - v_{in})\frac{R_1}{R_1 + R_2} \geq 0,$$

which can be simplified to

$$v_{in} \geq -15\frac{R_1}{R_2}$$

for the range of input voltages for which it is possible to have $v_o = 15$.

Similarly, we may ask for what values of $v_{in}$ it is possible for $v_0$ to equal $-15$. With $v_o = -15$ we have

$$v_1 = v_{in} + (-15 - v_{in})\frac{R_1}{R_1 + R_2}$$

and this had better be nonpositive if $v_0$ equals $-15$. This gives the condition

$$v_{in} + (-15 - v_{in})\frac{R_1}{R_1 + R_2} \leq 0,$$

which can be simplified to

$$v_{in} \leq 15\frac{R_1}{R_2}$$

for the range of input voltages for which it is possible to have $v_o = -15$.

The set of possible $(v_{in}, v_o)$ pairs is plotted in Figure 2. Note the very interesting feature that there is a range of values for $v_{in}$, namely $-15\frac{R_1}{R_2} \leq v_{in} \leq 15\frac{R_1}{R_2}$ where *both* values of $v_o$ are possible. This kind of circuit is said to exhibit *hysteresis* (from Greek husteresis: 'shortcoming', as opposed to hysteria, which is from Greek husterikos: 'of the womb'). The arrows on the figure are meant to indicate to you how the circuit will operate in practice. For a sufficiently negative input voltage there is only one possible output, namely $-15$. As the input voltage increases past the lower threshold of $-15\frac{R_1}{R_2}$ and enters the regime where there are two possible solutions, the output will continue to stay at $-15$, because there is no reason for it to change. However, when the input voltage crosses the upper threshold of $15\frac{R_1}{R_2}$ the output voltage will immediately jump to 15 and will stay there if the input voltage continues to increase. However, what is fascinating is that if the input voltage now decreases and crosses the upper threshold again, the output voltage will stay at the upper value of 15! If the input voltage now continues to decrease it will need to decrease all the way to the lower threshold before the output voltage jumps back to $-15$.

The circuit is exhibiting *memory* of how it got to where it is. It is a version of a *Schmitt trigger*. A better version, incorporating bias current cancellation and Zener diodes to control the upper and lower limits of the overall output voltage (denoted $v_{out}$ to distinguish it from the output of the op-amp, which was $v_o$ in the preceding discussion) is in Figure 3. There circuits are useful, for instance, as *comparators*. We may want to output 1 if an input voltage is positive and $-1$ if it is negative, while not caring very much what we decide if the input voltage is very close to 0. If we implement this by using a single threshold at 0 we face the problem that an input voltage undergoing small swings near zero causes the output voltage to keep flipping back and forth between 1 and $-1$. However, using a Schmitt trigger, we have a zone around an input voltage of zero where we may not care what the corresponding output voltage is where the voltage that is output by the comparator does not switch back and forth. Thus the problem of output oscillations is significantly mitigated.

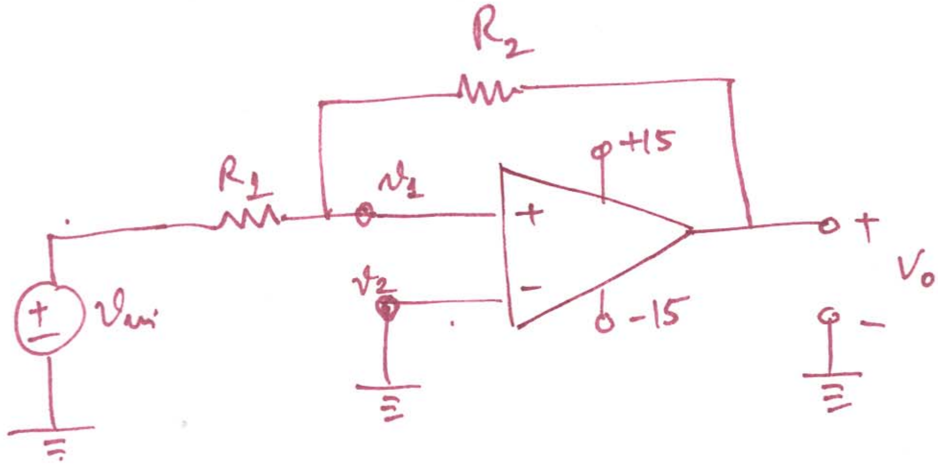


Figure 1

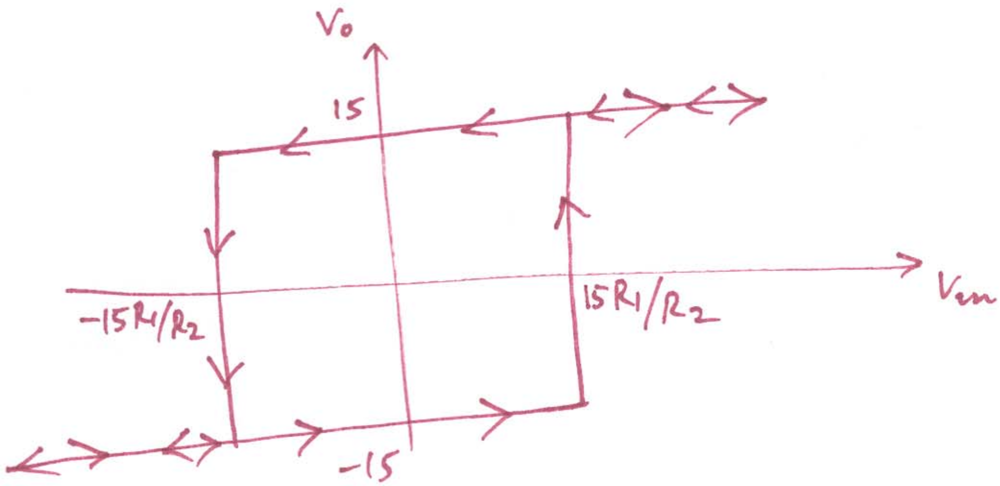


Figure 2

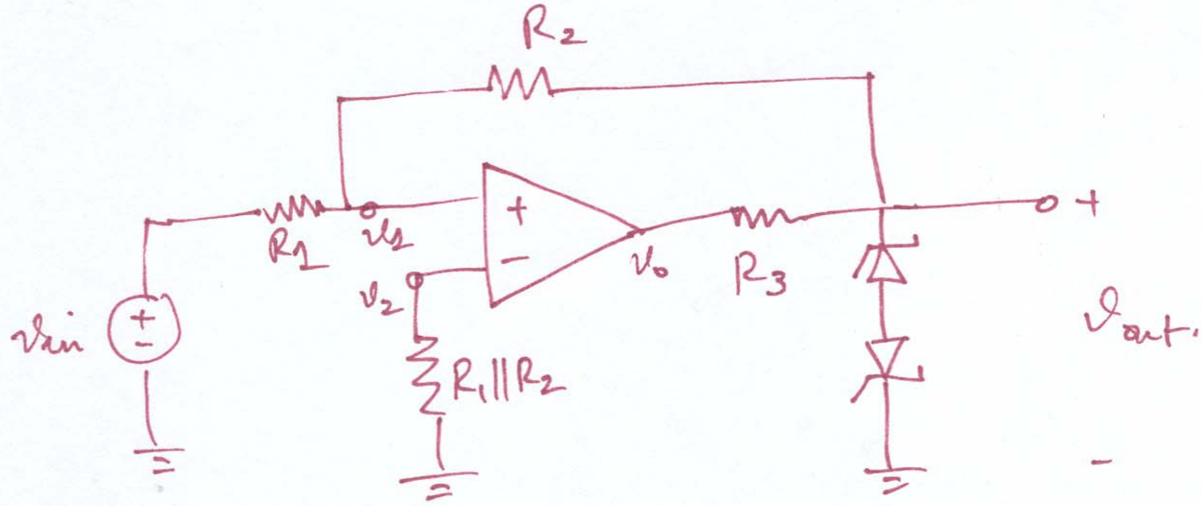


Figure 3.