Lecture 13, 15st October 2012

Analogue Electronics 10: Positive Feedback

In the two previous lectures on op-amps it was emphasised that these devices must be used with *negative feedback*. This was to *avoid saturation* and to give *well a behaved gain at all frequencies*. There are, however, some situations where negative feedback isn't employed – although not all of these are deliberate. **Positive feedback** occurs in three broad sets of circumstances:

Comparators and triggers – for making decisions

Oscillators – to build your function generator

Disasters – when you don't want positive feedback at all

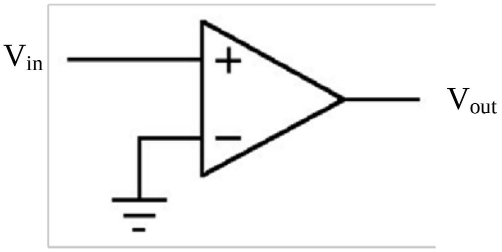
Two of these are useful and the other needs to be avoided. We will go through them in turn.

Positive feedback: comparators

The first situation where positive feedback is employed is when you want a circuit that is decisive. The examples we will use are **comparators** and more evolved circuits called **triggers**.

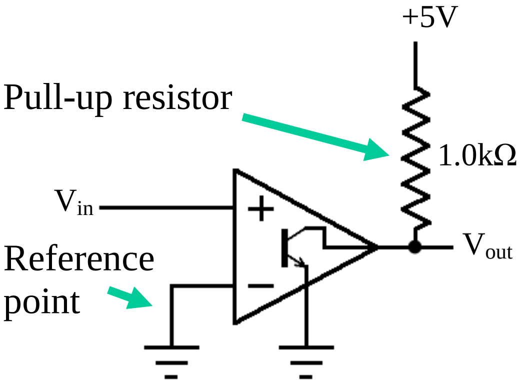
What are comparators? (H&H, 4.23, p229)

These are op-amps used for determining when *one signal is bigger than another*. For example they are used in digital voltmeters. In such a voltmeter an internal voltage is ramped up and the comparator determines *when this is equal to the voltage on the probes*. A sketch of this circuit was shown earlier in a flip-flop lecture when circuits for counting were shown.



An op-amp circuit that **saturates** simply provides the maximum output voltage which is limited by the supply voltage. Normally you try to avoid having the output of an op-amp saturating (negative feedback is used to achieve that). However with a comparator saturation is what you want. You are aiming for a "yes" or "no" answer with nothing in between.

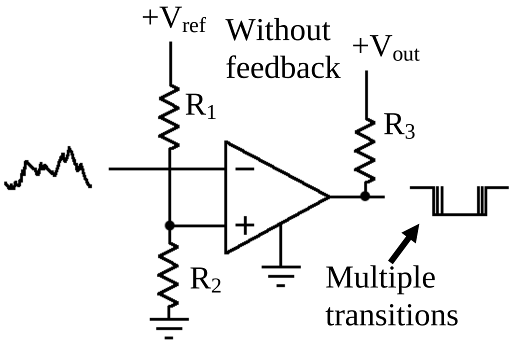
Illustrated below is a comparator circuit for determining whether the input signal is *larger or smaller than 0V*. This circuit is not yet using positive feedback. And it has problems that will be described below in more detail. But first let's have a look at the **comparator output circuit.**



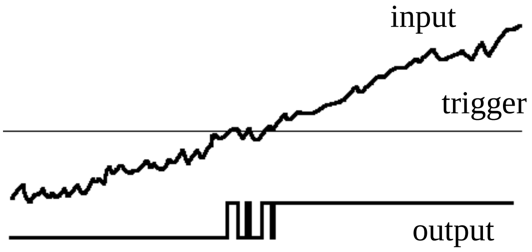
Since we are letting the output of the comparator saturate we want to *control* the **saturation voltage** for the circuit to become useful. In the circuit above a **pull-up resistor** is attached to the required saturation voltage, +5V in the example. If V_{in} is more negative than the **reference point**, ground in the example above, the op-amp gives *ground as output* (like a transistor which is operated outside the required forward bias $V_B - V_E \approx 0.6V$ to give an output at its collector). Instead the voltage drop between the saturation voltage and the output will be across the pull-up resistor. When the input passes the 0V line the output of the comparator will *suddenly rise up to the saturation voltage*. An analogue signal has become digital! In the example the output complies with the *TTL definition* of logic "1" and logic "0".

Trigger

Here an inverting op-amp is shown which is used as a comparator. The *voltage divider* (R_1, R_2) across the non-inverting input determines what the inverting input is being compared to. Note that there is *no feedback* (neither negative nor positive), so the golden rules do not apply.

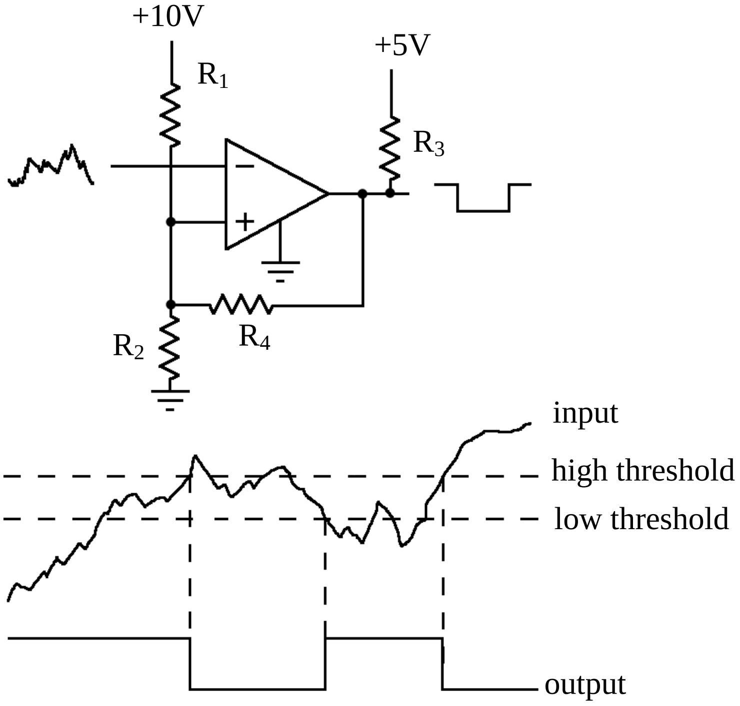


The purpose of a **trigger** is to reliably give notice *when* a defined input state is reached (it has not to raise the flag at the instant when the input condition is met, but after a *defined time interval*, so that the time of the input meeting the condition can be determined). The device above can be *slow to switch* (which is not a show stopper, but also not desirable). The problem is that a *noisy input signal* will lead to the *trigger firing many times* in quick succession. Therefore this circuit is indecisive and not that useful. The switching behaviour in response to noisy data is illustrated below.



Schmitt Trigger: (H&H, 4.24, p231)

Now we are going to modify the basic trigger above by adding *positive feedback*, via R_4 in the next circuit below. This is known as the **Schmidt Trigger**. The positive feedback has two effects. First it *speeds up the response* by quickly driving the circuit into saturation, which has its output level controlled by V_{out} and R_3. Secondly it makes the system *more robust when presented with noisy input*. The output voltage modifies the voltage at the non-inverting input, i.e. *the voltage threshold that the input is being compared to*. If the output is high the threshold moves to a lower voltage and vice versa, i.e. there is a **gap** *between the two voltage levels* required for the trigger to change state when the signal passes the **two thresholds** from *lower-to-higher* or from *higher-to-lower* values. This means that once a decision has been made the signal needs to move back also the gap voltage before the trigger switches back. The gap size is controlled by the size of R_4 and typically is chosen to be *larger than the expected* *noise of the signal*. In effect the circuit has been made more decisive via the use of positive feedback.



Positive feedback: oscillators

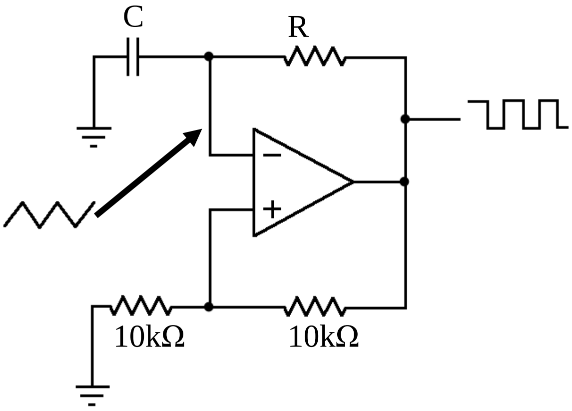
Motivation: Oscillators are *ubiquitous* in digital electronic instruments. Those devices that don't contain an oscillator are either trivial or are driven by another device that does contain an oscillator. Even most analog circuits have a digital backend for readout these days (the few exceptions as the entirely analogous stand-alone electrometers from the back of the museum shelf in the standard laboratory only confirm the rule).

Examples: oscillators or digital waveform generators are used in digital multimeters, oscilloscopes, RF receivers, computers and every type of computer peripheral, virtually every digital instrument. Digital devices are *synchronous logic circuits*. Each gate is being switched in response to oscillations of the same clock. You are well used to hearing about the clock speed of computers.

Oscillators are used as a regularly spaced series of pulses as a reference for stability or accuracy (a time base) or to produce accurate waveforms (e.g. as the ramp generator in an oscilloscope).

We will look at the **relaxation oscillator** (simpler to understand) and the **Wien bridge oscillator** (more ideal). Both make use of both positive and negative feedback.

Relaxation oscillator (H&H, 5.13, p284)
How about having both the inverting and the non-inverting input be the result of feedback? Let's play this idea through and look at the following circuit, the **relaxation oscillator**.



It works by charging a capacitor C through a resistor R and then discharging it through R again once the voltage reaches a threshold. As you can see there isn't actually an input, just an output. The circuit, by itself, is *unstable and just starts oscillating*. The charging and discharging of the capacity is seen on the inverting input of the comparator (and indicated by a little cartoon). The output state of the comparator defines the direction of the current through the resistor, i.e. whether the capacity is being charged or discharged.

Say that initially the op-amp is at *positive saturation*. The capacitor *starts charging* towards +V with *time constant RC*. Because of the voltage divider on the positive feedback branch, the input to the inverting input is being compared to half the maximum output voltage. When the capacitor reaches half maximum charge the op-amp switches to *negative saturation* and the capacitor *begins to discharge* until it is oppositely charged half the maximum level, where the output state changes again. This cycle *repeats indefinitely*. Positive feedback is being used in a manner related to its use in the Schmitt Trigger. It alters the criterion for making a decision (here the question is "to charge or not to charge") based on the current output.

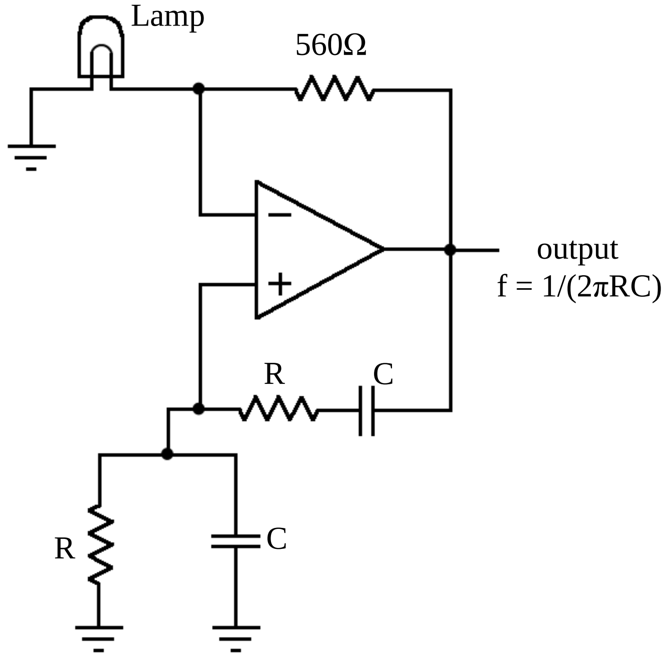
The oscillator has a **period** of 2.2 RC. By *selecting the right resistor and capacitor* in the negative feedback branch you can *choose your oscillation period*. It is sensible to choose an op-amp that is going to behave well at positive and negative saturation.

This way the generation of square waves is fairly simple. In real applications more circuitry is applied to better stabilise and control the oscillator. Laser cut crystals are used in order to control the values of the capacity and resistance to define the oscillation rate to better than 4 to 6 digits, i.e. clocking chips with a rating of e.g. 10.000MHz are basic standard and do only cost of the order of a few pound in retail.

The generation of triangle waves can be facilitated by a more or less fine sequence of digital steps. The shape further can be smoothed out by sufficiently large capacities charging up in the regime where their behaviour is linear to good approximation.

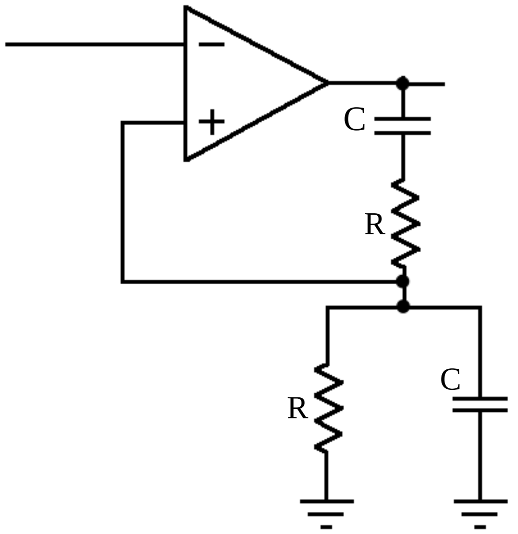
Wien Bridge Oscillator (H&H, 5.17, p296)
On your function generator you will find a third choice: the generation of sine waves. This is facilitated by a **Wien Bridge oscillator** circuit. Its basic layout is shown below.

You are going to use sine waves of well controlled amplitude and phase to characterize amplifiers and filters that you build in checkpoint A2. More broadly, a perfect sine wave is necessary for testing hi-fi amplifiers for example.



This device is produces a *sine wave with very low distortion*. As you will see, a *single frequency* is selected and saturating the op-amp is *carefully avoided*. As you can see from the illustration above, both the positive and negative feedback circuits are a bit more complicated than for the relaxation oscillator case. To understand this oscillators behaviour we will look at the positive and the negative feedback half of this oscillator circuit separately.

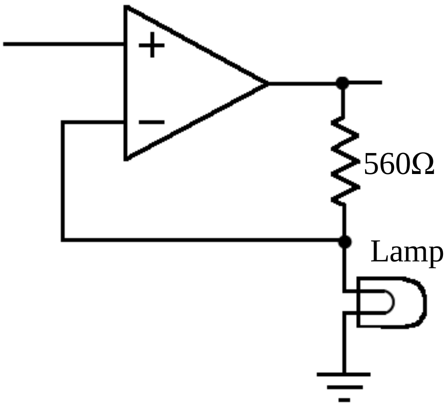
Positive feedback part of Wien Bridge:



The feedback to the non-inverting input is drawn from a potential divider which has both a low-pass and high-pass character with the time constant RC. It can be analysed by evaluating the complex impedance of the top part and the bottom part. Then these impedances are substituted into the equation for a voltage divider.

Doing so you will find that it feeds back preferentially at *one frequency* (f=1/(2πRC)). At the preferred frequency 1/3 of the output signal is fed back. All *other frequencies are attenuated*. For the preferred frequency there is also *no phase shift*, it is pure positive feedback.

Negative feedback part of Wien Bridge:



For an *undistorted sine wave* to be created the *gain has to be kept low* in order to avoid saturation. This can be achieved by having a *gain which decreases* when the current flowing becomes too high, i.e. we need a resistor with a *resistance that increases* in response to the current flowing through it.

For illustration here a light bulb is used as such a current responsive feedback element. When the output is rising the current heats the lamp element. This increases the resistance and therefore reduces the gain. Equilibrium will be reached where the heating by the current limits the further increase of the resistance. The gain limit becomes self-regulated.

In the function generator on your laboratory table no lamps are used as current response feedback element. Instead special resistors with an inverted response to temperature changes may be used, i.e. when flowing current heats them up their resistivity increases, like for a thread in a light bulb.

The resulting circuit, with both positive and negative feedback branches produces a *perfect sine wave*. The frequency of the *sine wave can be tuned by choosing the values* for the resistance and the capacitance in the positive feedback branch.

Positive feedback: disasters

You now have seen that comparators use positive feedback alone. In oscillators both positive and negative feedback are employed. In the next example we are going to look at the case where *negative feedback accidentally becomes positive feedback*. This is where **disaster** strikes and where you *lose control* over your circuit.

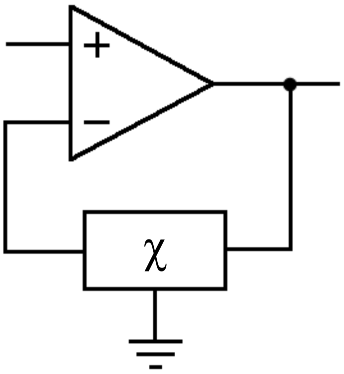
Unfortunately *pathological oscillations* easily can crop up in circuits. To make a circuit oscillate this way you need two things:

1. *Gain* – if you don't amplify the pathological signal it will quickly die away.
2. *Positive feedback* – if the output is always used to enhance the input then any random noise can set the circuit oscillating.

You may reasonably wonder why this is a big deal: in almost all circuits we avoid positive feedback. Unfortunately things aren't so simple…

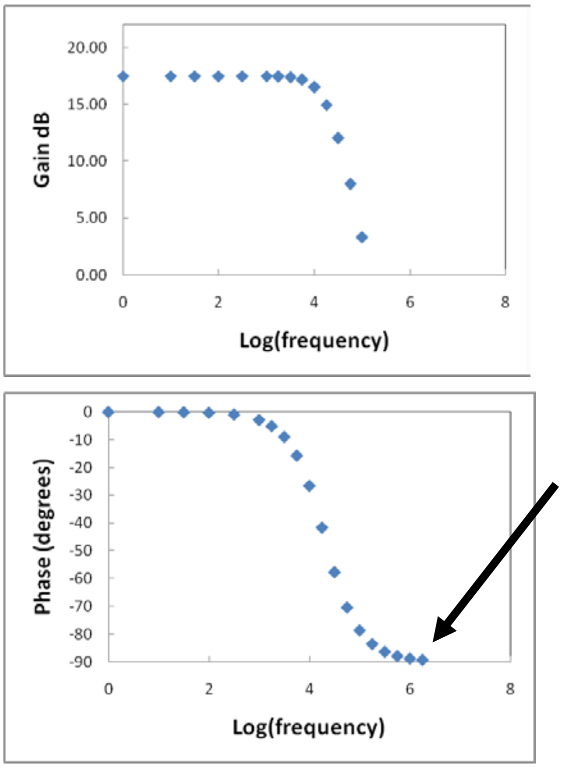
In most op-amp circuits we use negative feedback. We often deliberately introduce reactive components into the feedback network (and within op-amps additional reactive components exist anyway). These components result in phase shifts. Here comes the catch: *if the total phase shift becomes 180° negative feedback becomes positive*! If this happens your circuit is doomed, caught in self-sustained oscillation with maximum amplitude. Only switching off the power, i.e. removing the gain, will stop it from oscillating.

To get a grip on this problem, let's look at the *generalised form of feedback* for an inverting op-amp circuit:



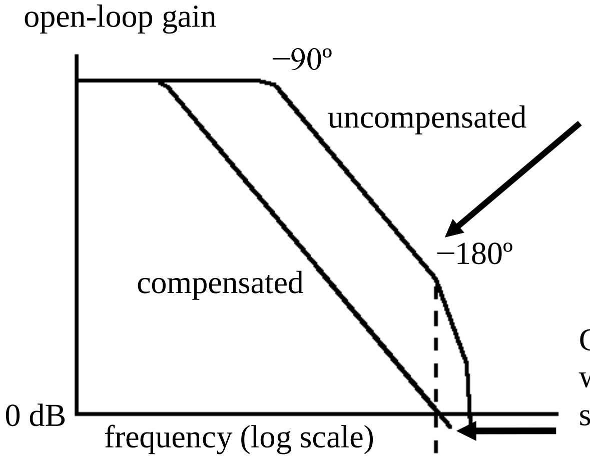
Whether this amplifier is using negative or positive feedback depends on the behaviour of χ. If, for example, the box gives two low pass filtering steps and you operate it at to high a frequency the circuit runs into a 180° phase shift – boom, your circuit starts a life of its own. Why is that so? Remember: You can associate every "shoulder" in a gain plot with a 90° phase shift. The situation for one shoulder in a low pass filter circuit is shown below. The 90° phase shift occurs at high frequencies. You need only two of these to provide a high-frequency threshold from which you get a phase shift close enough to 180°. A fast noise pulse, e.g. a transient occurring when you switch on the power, then can be sufficient to start off the oscillation.

Low-pass filter



You only need two of these to give a phase shift of -180°.

The problematic performance characteristics of the circuit can be seen in the Bode plot below. The *uncompensated circuit* features two shoulders (from the two low-passes) each providing a −90° phase shift. At the second shoulder the *gain is still larger than 1* (i.e. 0dB, chosen as the x-axis in the plot), hence the circuit will oscillate at this frequency. The way to take control of the situation is to introduce **compensation**, like it was done to compensate for the input bias current. The effect of the compensation is two-fold: *the first shoulder is moved* to a *lower frequency* and *the gain* above the new position if the first shoulder effectively is *reduced* with respect to the uncompensated circuit. If the *gain reduction is large enough* for the effective gain to become *smaller than 1 at the point of the second shoulder* there will be no oscillations. The circuit becomes stable.



Too much gain where phase shift is dangerous

Gain < 1 where phase shift is dangerous

Note that the *open-loop gain is not reduced*. Only the frequency range for which it can be reached is reduced. In real-life applications the open-loop gain will be reduced by the chosen feedback to a significantly lower value to gain stability and to increase the frequency reach of the op-amp. So, the compensation to safe-guard against oscillations *effectively only reduces the frequency range of the op-amp* with respect to the uncompensated but risky circuit.