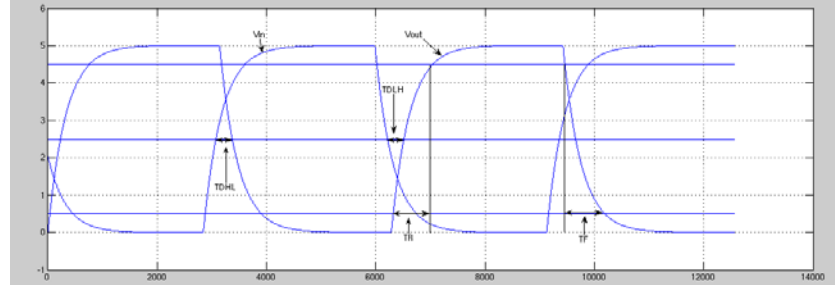


The Wein-Bridge oscillator is a very good low-frequency sinusoidal oscillator. However there are many applications where higher frequencies are needed and often, for example for digital clocks, a pure sinusoidal waveform is not needed. In this lab we will test two widely used oscillators which are partly digital and partly analog (or mixed-mode) circuits.

### 1. The Ring Oscillator:

The ring oscillator is simply a ring of  $N$  digital inverters each output connected to another input. To oscillate  $N$  must be an odd number  $N \geq 3$ . It is often used as a test circuit on VLSI chips where  $N$  might be several 100s. The period of the oscillation depends on the delay times of the inverter  $T_{DHL}$  and  $T_{DLH}$  as  $P = N (T_{DHL} + T_{DLH})$ .

One can estimate  $T_{DHL} + T_{DLH}$  by measuring  $P$ , but one cannot separate  $T_{DHL}$  and  $T_{DLH}$  in this way. In practice it is very difficult to measure  $T_{DHL}$  and  $T_{DLH}$  directly because the capacitances in the circuit are so small that the measuring devices seriously distort the measurement. We will use an antique CMOS chip, the CD4069, which contains 6 inverters. Although the CD4046 gates are more than 100 times bigger than those in a modern CMOS chip, they are still tricky to measure directly.

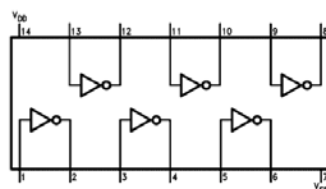


(a) Connect all 6 inverters together in line and feedback the output of inverter 5 to the input of inverter 1. This will provide a 5-element ring oscillator and the 6<sup>th</sup> inverter will be a buffer, so we don't have to connect a scope to the ring directly. The delays are primarily RC effects  $T_{DHL} = 0.67R_N C_{LOAD}$  and  $T_{DLH} = 0.67R_P C_{LOAD}$ . The load capacitance has two parts, the input of the load (or loads) gate, and the output of the gate under test.

We can use this setup to estimate a lot of useful parameter, such  $R_0 = 0.5 (R_N + R_P)$ ,  $C_{LOAD} = (C_{IN} + C_{OUT})$  and  $C_{SCOPE}$ . For convenience we can also define  $T_0 = 0.5 (T_{DHL} + T_{DLH})$  and  $T_{IN} = 0.67R_0 C_{IN}$ . Then the period of the 5-element ring is  $10T_0 + 2T_{IN}$  and that of a 3-element ring is  $10T_0 + 2T_{IN}$ . Measure the period of both rings and compute  $T_0$  and  $T_{IN}$ . Connect a second scope probe (in 10X position) to the output of gate 1 and find  $T_{SCOPE}$ . Finally add a 10pf capacitor from the output of gate 1 to ground. This will add a delay of  $2 \cdot 0.67 \cdot R_0 \cdot 10\text{pf}$ . Measure this delay and use it to find  $R_0$ ,  $C_{SCOPE}$ ,  $C_{IN}$ , and  $C_{OUT}$ . You should find that all of these capacitances are of similar order. This means that you can't measure  $T_{DHL}$  or  $T_{DLH}$  directly by putting a scope on the input and output of a gate, because the scope will nearly double the gate delay!

Make a hard copy of the scope display for the 3-element and 5-element rings for your report. You will notice that the waveform of the 5-element ring is "squarer" because the period increases with  $N$  but the rise and fall times do not.

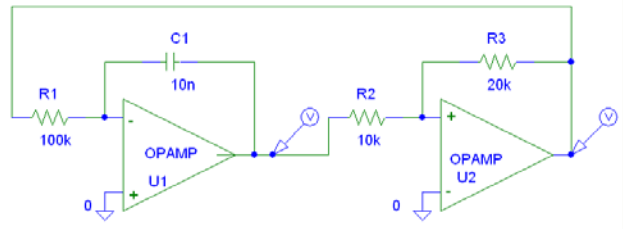
(b) One use of the ring oscillator in integrated circuits is to provide a quick and accurate measurement of the time delay  $T_0$ . For example  $T_0$  changes with supply voltage. The CD4069 can be operated with  $V_{DD}$  between +3 and +15 v. Change the supply voltage on your  $N = 5$  ring to map out  $T_0$  as a function of  $V_{DD}$ . Plot your results on linear-linear axes.



Pinout for the CD4069 Hex Inverter

## 2. A Relaxation Oscillator:

Another very popular oscillator (which is used in the Wavetek function generators in the lab) is a relaxation oscillator based on an integrator and a Schmitt trigger as shown to the right. The ST is the positive feedback circuit based on opamp U2. It is bistable with output voltage limited by either the positive or the negative supply voltage. The output of the ST is a square wave, whereas the output of the integrator is a triangle wave.



- Setup the ST alone using an LF411 opamp with  $\pm 15$  v supplies. Measure its  $V_{in}$  vs  $V_{out}$  characteristic using a triangle wave of full amplitude to sweep the input. Sweep the input slowly,  $V_{in}$  should be less than 1 KHz, so time delays do not distort the display. Display the input and output time series on the scope, showing the switching points clearly, and make a hard copy. Put the scope in X-Y mode and make plot with  $V_{in}$  on the horizontal axis and  $V_{out}$  on the vertical axis. Compare the measured switching level with the theoretical value.
- Calculate the frequency as a function of  $R1$ ,  $R2$ ,  $R3$  and  $C1$ .
- Set  $R3 = 20K$  and  $R2 = 10K$ , and find appropriate values of  $R1$  and  $C1$  to get a frequency of 1 KHz. The values in the circuit diagram are of the correct order but they are not correct for 1 KHz.
- Setup the circuit with the calculated values and measure the frequency. It should be very close to 1 KHz, but perhaps a bit lower. Make a hard copy of the scope trace on both outputs, showing the frequency clearly. According to the theory the frequency should be independent of supply voltage. Reduce the supply voltages to  $\pm 5$  v and remeasure the frequency. How much does it change (if any)?
- Adjust the  $R1$ ,  $C1$  combination to change the frequency to 30 KHz. Make a hard copy of the scope trace as before. You will see that the triangle peak gets rounded and the square wave has a noticeable rise and fall time. This is due to slew rate limiting in the Schmitt trigger opamp. You can reduce the slew rate problem a lot by reducing the amplitude. Try reducing the supply voltages to  $\pm 5$  v and make a hard copy of the trace. You will see much less peak rounding and sharper rise and fall times because the opamp doesn't have to slew as far during the transitions.

Don't forget to photograph your circuit, and include it with your report.