Theory

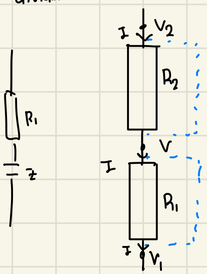
Circuit theory:

ohm's law $V = IR$

Kirchoff's law: 1: $\sum I_{in,i} = \sum I_{out,i} \Rightarrow \sum I_i = 0$

2: $\sum V_i = 0$ for a closed loop.

Potential divider:



$$\frac{V_2 - V}{R_2} = I$$

$$||$$

$$\frac{V - V_1}{R_1} = I$$

$$\frac{V - V_1}{R_1} = \frac{V_2 - V}{R_2}$$

$$R_2(V - V_1) = R_1(V_2 - V)$$

$$R_2 V - R_2 V_1 = R_1 V_2 - R_1 V$$

$$R_1 V + R_2 V = R_1 V_2 + R_2 V_1$$

$$V(R_1 + R_2) = R_1 V_2 + R_2 V_1$$

$$V = \frac{R_1 V_2 + R_2 V_1 + V_1 R_1 - V_1 R_1}{(R_1 + R_2)}$$

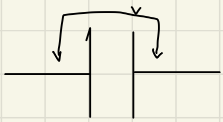
$$V = \frac{R_1 V_2 - V_1 R_1 + V_1 (R_1 + R_2)}{R_1 + R_2}$$

$$\boxed{V = V_1 + (V_2 - V_1)\frac{R_1}{R_1 + R_2}}$$

if $V_1 = 0$: $V = \frac{V_2 R_1}{R_1 + R_2}$

Complex numbers

$e^{i\theta} = \cos\theta + i\sin\theta$



$Q = CV$

$I = C\frac{dV}{dt}$

$\cos(A+B) = Re\left(e^{i(A+B)}\right)$ — Cos wave is Re of $e^{i\theta}$

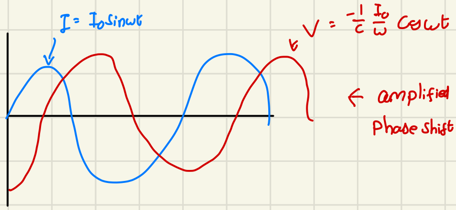
$= Re\left(e^{iA} e^{iB}\right)$ — Sin wave is Im of $e^{i\theta}$

$= Re\left[(\cos A + i\sin A)(\cos B + i\sin B)\right]$

$= \cos A\cos B - \sin A \sin B$

Suppose $I = I_0 \sin\omega t$; $V = \frac{1}{C}\int I \, dt$

$V = -\frac{1}{C}\frac{I_0}{\omega}\cos\omega t$



← amplified $(\times \frac{1}{\omega C})$

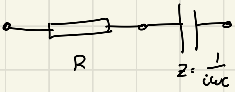
Phase shift $(-\frac{\pi}{2})$

+x direction

So $\tilde{V} = \tilde{I} Z$

Complex: mod $\Rightarrow \frac{1}{\omega C}$, arg. $= -\frac{\pi}{2}$

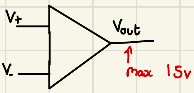
$\Rightarrow Z = \frac{1}{\omega C} e^{-i\frac{\pi}{2}} = \frac{1}{i\omega C} = Z$



Same eq. applies.

Theory

Amplifiers:



large

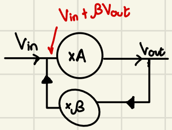
$V_{out} = G(V_+ - V_-)$

if $V_+ \gg V_-$; $V_{out} = +15V$

$\leftarrow$; $V_{out} = -15V$

feedback:

$V_{in} + \beta V_{out}$



$V_{out} = A(V_{in} + \beta V_{out})$

$V_{out} = A V_{in} + \beta A V_{out}$

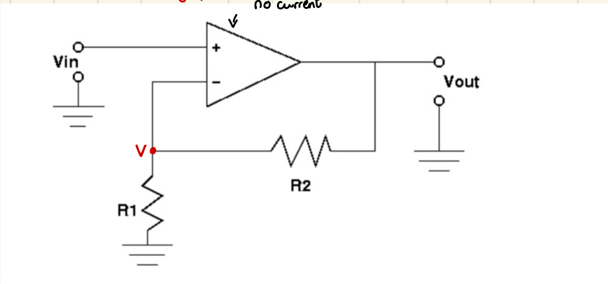
$V_{out} = \frac{A V_{in}}{1 - \beta A}$

$\frac{V_{out}}{V_{in}} = \frac{A}{1-\beta A}$ $A \to \infty$; $= -\frac{1}{\beta}$ independent of A if A is large

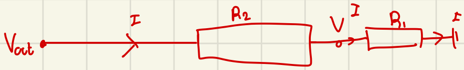
Negative feedback $(B < 0)$

$\to$ Stabalisation

GR1 => inputs draw no current



$V_{out} = G(V_{in} - V)$



$V = V_{out} \frac{R_1}{(R_1 + R_2)}$

$V_{out} = G\left(V_{in} - V_{out} \frac{R_1}{R_1 + R_2}\right)$

$V_{out} = A(V_{in} + \beta V_{out})$

$V = V_{out} \frac{R_1}{R_1 + R_2} = V_{in}$

$\beta = -\frac{R_1}{R_1 + R_2}$ => negative feedback
- stable
- doesn't depend on G

GR2 => in negative feedback circuits.
input voltages are adjusted to be equal.

$\Leftarrow$

if G is big: $\frac{V_{out}}{V_{in}} = -\frac{1}{\beta} = \frac{R_1 + R_2}{R_1}$

Day 1:

Inverting Amplifier:

Theory:

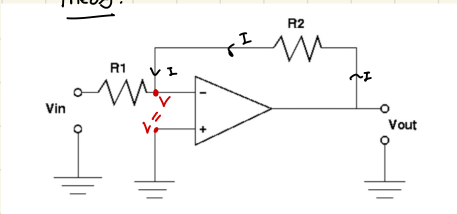
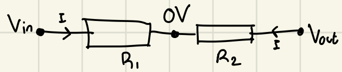


Figure 3. Inverting amplifier.

$V_+ = 0V$ (grounded)

as $V_+ \approx V_-$; $V_- = 0V$ (virtually grounded)



$\sum I_i = 0$

$\frac{V_{in}}{R_1} = -\frac{V_{out}}{R_2}$

$V_{out} = -\frac{R_2}{R_1} V_{in}$

$\frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}$

Results:

At (100 ± 0.1) Hz

R1 /kOhm	Error	R2	Error	Input PP / mV	Error / mV	Output PP/V	Error / V	Phase Shift / Degrees	Error Degrees
1	0.01	10	0.1	478	4	-4.78	0.04	179	1
1	0.01	100	5	105	2	-10.4	0.1	180	1

(Vin → Input PP / mV; Vout → Output PP/V)

$R_1 = 1k\Omega$ and $R_2 = 10k\Omega$

$\frac{V_{out}}{V_{in}} = -10$

$\sigma_{ratio} = \frac{V_{out}}{V_{in}} \sqrt{\left(\frac{4}{478}\right)^2 + \left(\frac{0.04}{4.78}\right)^2}$

$= 0.118$

$\frac{V_{out}}{V_{in}} = (10.0 \pm 0.1)$

$-\frac{R_2}{R_1} = -10$

$\sigma = 10 \times \sqrt{(0.01)^2 + (0.01)^2}$

$= 0.14$

Theory Suggests $\frac{V_{out}}{V_{in}} = -10 \pm 0.14$

=> Consistent

whereas in practice $\frac{V_{out}}{V_{in}} = -10.0 \pm 0.1$

$R_1 = 1 k\Omega$ and $R_2 = 100k\Omega$

$\frac{V_{out}}{V_{in}} = 99.05$

$\sigma = \frac{V_{out}}{V_{in}} \sqrt{\left(\frac{2}{105}\right)^2 + \left(\frac{0.1}{10.4}\right)^2}$

$= 2.11$

$\frac{V_{out}}{V_{in}} = (99.05 \pm 2.11)$

$-\frac{R_2}{R_1} = -100$

$\sigma = 100 \times \sqrt{(0.05)^2 + (0.01)^2}$

$= 5.1$

Theory Suggests => $\frac{V_{out}}{V_{in}} = -100 \pm 5.1$

=> Consistent

In practice => $\frac{V_{out}}{V_{in}} = (99.05 \pm 2.11)$

V_- was verified to be $\approx 0V$.

At high frequency: (100 kHz): (using 1kΩ and 10kΩ)

$V_{in} = (480 \pm 10)$ mV $\qquad \frac{V_{out}}{V_{in}} = -5.27 \pm 0.11$ (using method as before)

$V_{out} = (-2.53 \pm 0.01)$ V

Expected is (10.0 ± 0.1) $\quad \therefore$ it can be seen that this relation breaks down at high frequency => Gain is not infinite at high frequency

So approximation that $\frac{V_{out}}{V_{in}} = -\frac{1}{\beta}$ does not hold.

instead. $\frac{V_{out}}{V_{in}} = -\frac{G}{1-\beta G}$

it can be seen from the data at low frequency that the phase shift is $\approx 180°$ which is expected.

Summer

$\frac{1}{R_T} = \frac{2}{R}$; $R_T = \frac{R}{2}$

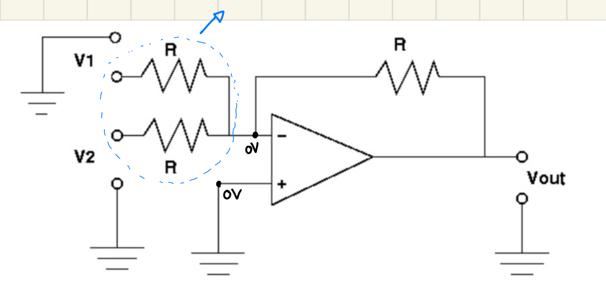
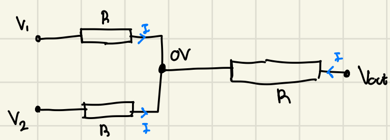


Figure 4. Summer.



$\frac{V_1}{R} + \frac{V_2}{R} = -\frac{V_{out}}{R}$

$V_1 + V_2 = -V_{out}$

R1 Kohm	Error Kohm	Input 1 mV	Error mV	input 2 mV	Error mV	ouput mV	Error mV	Phase / degrees	Error / degrees
10	0.1	454	4	510	10	960	10	179	1
1	0.01	434	4	490	10	920	10	181	1

For 10kΩ:

$V_1 + V_2 = 964$ mV

$\sigma = \sqrt{4^2 + 10^2}$

$V_1 + V_2 = (964 \pm 11)$ mV

$V_{out} = (960 \pm 10)$ mV

Theory: $V_{out} = (964 \pm 11)$ mV

Experimentally: $V_{out} = (960 \pm 10)$ mV

for 1kΩ:

$V_1 + V_2 = 924$

$\sigma = \sqrt{4^2 + 10^2}$

$V_1 + V_2 = (924 \pm 11)$ mV

$V_{out} = 920 \pm 10$ mV

Theory: $V_{out} = (924 \pm 11)$ mV

Experimentally: $V_{out} = (920 \pm 10)$ mV

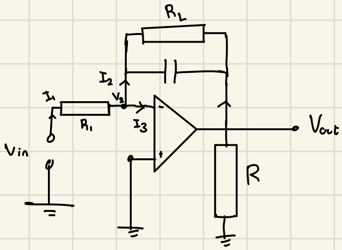
=> Consistent for both R

Also varied the phase difference between $V_1 + V_2$:

R1 Kohm	Error Kohm	Input 1 mV	Error mV	input 2 mV	Error mV	ouput mV	Error mV	Phase / degrees	Error / degrees
10	0.1	454	4	510	10	930	10	165	1
10	0.1	454	4	510	10	490	10	126	1
10	0.1	454	4	510	10	960	10	179	1

Summing law is only valid when waves have a phase difference of $n\pi$.

Integrator:



$$R_L = 1 M\Omega$$

$$I = C \frac{dV}{dt}$$

$$V_{in} = V_0 \sin \omega t$$

$$f = (100 \pm 0.1) Hz$$

$I_3 \approx 0 \therefore \quad I_1 = I_2$

$V_2 \approx 0$ (Virtual ground) $\rightarrow$ $\frac{V_{in}}{R_1} = -C \frac{dV_{out}}{dt}$ Current through $R_L \approx 0$

$$V_{out} = -\frac{1}{R_1 C} \int V_{in} \, dt$$

$$= -\frac{V_0}{R_1 C} \int \sin \omega t \, dt$$

$$V_{out} = \frac{V_0}{\omega R_1 C} \cos \omega t \qquad \boxed{V_{out} = \frac{V_{in}}{\omega R_1 C}}$$

R1 kOhm	Error kOhm	C micro F	Error	Input mV	Erro / mV	Output V	Error V	Phase Degrees	Error Degrees
1	0.01	0.1	5%	490	10	7.6	0.1	-90	1
1	0.01	0.1	5%	800	10	12.9	0.1	-90	1

$V_{in} = 490 mV$:

Theory

$$\frac{V_{in}}{\omega R_1 C} = \frac{0.49}{200\pi \times 10^3 \times 10^{-7}} = 7.80 V$$

$$\sigma = \frac{V_{in}}{\omega R C} \sqrt{\left(\frac{10}{490}\right)^2 + \left(\frac{0.1}{100}\right)^2 + (0.01)^2 + (0.05)^2}$$

$$= 0.43 V$$

$$V_{out} = (7.80 \pm 0.43) V$$

Experimentally:

$V_{out} = 7.6 \pm 0.1$

Don't overlap but close

$V_{in} = 800 mV$:

$$\frac{V_{in}}{\omega R C} = 12.73 V$$

$\sigma = 0.67$

Theory: $V_{out} = 12.73 \pm 0.67 V$ Consistent //

Experimentally: $V_{out} = 12.9 \pm 0.1 V$

Phase Shifter:

$$V = V_1 + (V_2 - V_1)\frac{R_1}{R_1+R_2}$$

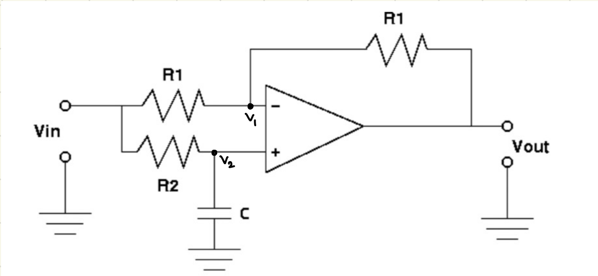
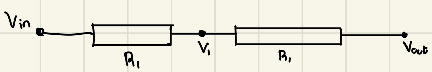
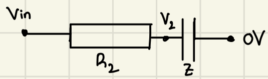


Figure 5. Phase shifter.

$$Z = \frac{1}{j\omega C} = \frac{-j}{\omega C}$$





$$V_1 = V_{out} + (V_{in} - V_{out})\frac{R_1}{2R_1}$$

$$V_1 = \frac{1}{2}(V_{in} + V_{out})$$

Equal for negative feedback

$$V_2 = -V_{in}\frac{\frac{1}{\omega C}j}{R_2 - \frac{1}{\omega C}j}$$

$$(V_{in} + V_{out}) = 2V_{in}\left[\frac{\frac{1}{j\omega C}}{R_2 + \frac{1}{j\omega C}}\right]$$

$$V_{out} = 2V_{in}\left[\frac{\frac{1}{j\omega C}}{R_2 + \frac{1}{j\omega C}} - \frac{1}{2}\right]$$

$$= 2V_{in}\left[\frac{1}{R_2\omega Cj+1} \times \frac{1 - R_2\omega Cj}{1 - R_2\omega Cj} - \frac{1}{2}\right]$$

$$= 2V_{in}\underbrace{\left[\frac{1 - R_2\omega Cj}{1 + (R_2\omega C)^2} - \frac{1}{2}\right]}_{x}$$

looking for $V_{out} = x V_{in}$, x complex

$$x = \frac{2 - 2R_2\omega Cj - 1 - (R_2\omega C)^2}{1 + (R_2\omega C)^2}$$

$$x = \frac{1 - (R_2\omega C)^2 - 2R_2\omega Cj}{1 + (R_2\omega C)^2}$$

$$\arg x = \arctan\left(\frac{2R_2\omega C}{1 - (R_2\omega C)^2}\right) = 60$$

$$\frac{R_2\omega C}{1 - (R_2\omega C)^2} = \frac{\sqrt{3}}{2}$$

$$-\frac{\sqrt{3}}{2} + \frac{\sqrt{3}}{2}R_2^2\omega^2C^2 + R_2\omega C = 0$$

quadratic eqn in R_2

if $\omega = 2000\pi$, $C = 10n\,F$

$$R_2 = 9188.8\,\Omega$$

∴ Phase difference of 60° is achieved roughly by $R = 10\,k\Omega$ and $C = 10nF$ at $f = 1000\,Hz$

Gain Limitation:

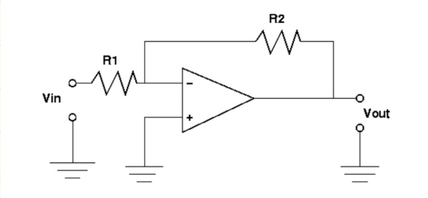


Figure 3. Inverting amplifier.

$R_1 = 1k\Omega$ $\qquad$ $R_2 = 10k\Omega \,/ 100k\Omega$

Check 1:

Fall/μs	Error on Fall/μs	Pk-Pk/mV	Error on Pk-Pk/mV	Frequency/kHz	R1/kOhms	Error on R1/kOhms	R2/kOhms	Error on R2/kOhms
3.9	0.1	190	5	100	1	0.01	100	5
Fall/ns	**Error on Fall/ns**	**Pk-Pk/mV**	**Error on Pk-Pk/mV**	**Frequency/MHz**	**R1/kOhms**	**Error on R1/kOhms**	**R2/kOhms**	**Error on R2/kOhms**
300	10	140	5	1.2	1	0.01	10	0.1

for the $10k\Omega$:

Pk - Pk = (140 ± 5) mV

Fall time = (300 ± 10) ns

Slew rate = $\dfrac{140 \times 10^{-3}}{300 \times 10^{-9}} = (4.6 \pm 0.22) \times 10^{5}\ Vs^{-1}$

$\sigma = 4.6 \times 10^{5} \times \sqrt{\left(\frac{10}{300}\right)^2 + \left(\frac{5}{140}\right)^2}$

$= 2.2 \times 10^{4}$

For $100k\Omega$:

Pk - Pk = 190 ± 5 mV

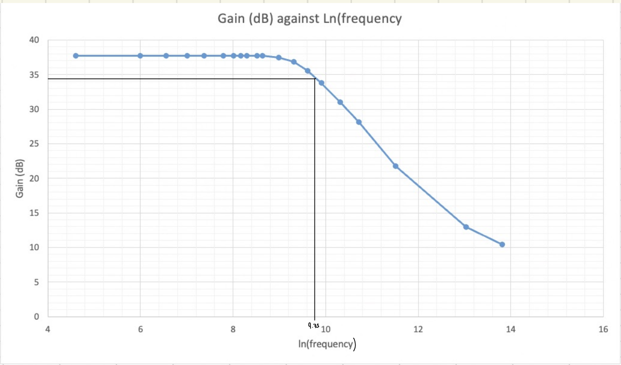
fall time = $3.9\ \mu s \pm 0.1\ \mu s$

Slew rate = $\dfrac{190}{3.9 \times 10^{-3}} = (4.87 \pm 0.18) \times 10^{4}\ Vs^{-1}$

$\sigma = 48717 \sqrt{\left(\frac{5}{190}\right)^2 + \left(\frac{0.1}{3.9}\right)^2}$

$= 1781\ Vs^{-1}$

Check 2+3:



← graph for the $100k\Omega$ resistor

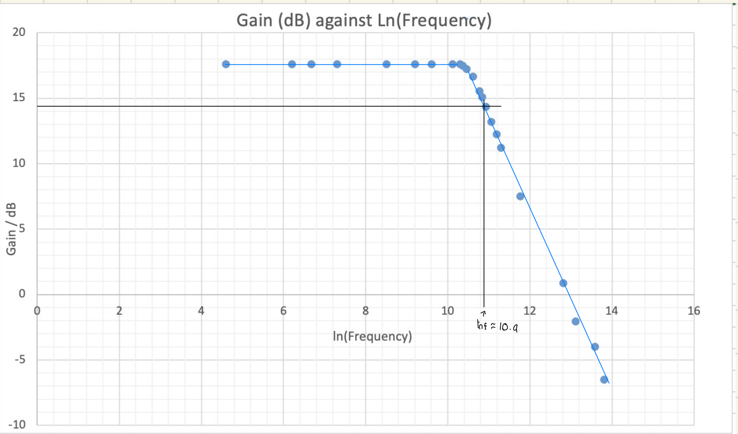
- 3dB point, gain is $\frac{1}{\sqrt{2}}$ of original

$\frac{1}{\sqrt{2}}(77) = 54.6$

↳ in dB → 34.74

$\ln(f) \approx 9.75$

$f = e^{9.75} = 17150$ Hz ⇒ - 3dB point for $100k\Omega$, $1k\Omega$ inverting amplifier circuit and for the 10 kΩ resistor:



max gain = 7.56

$\frac{1}{\sqrt{2}}(7.56) = 5.35$

in dB = 14.56 dB

$\ln f \approx 10.9$

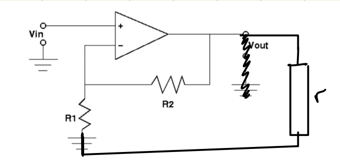
$f \approx 54\,175$ Hz

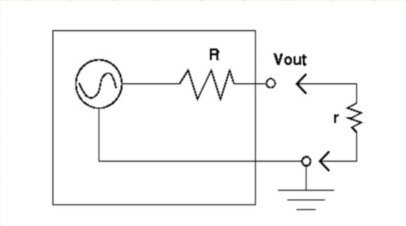
It can be seen that bandwidth increases as gain decreases.

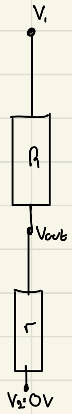
Check 4: at 1 MHz → $\varphi = -45° \pm 2$

at 370 Hz → $\varphi = 180° \pm 1$

output impedance:







$V_{out} = V_1\left(\frac{r}{R+r}\right)$

as $V_2 = 0$

Check 1:

High frequency used so gain was not infinite. Used 1 MHz

Connected a small resistance resistor in parallel with the output terminal.

Peak-Peak output voltage with no resistor ⇒ $V_1 = 0.31 \pm 0.01$ V

with resistor ⇒ $V_2 = 0.23 \pm 0.01$ V

Voltage drop: $\frac{V_2}{V_1} = \frac{r}{(R+r)}$

Using $r = 100\Omega \pm 1\Omega$

$R = \frac{rV_1}{V_2} - r$

$\sigma = \frac{rV_1}{V_2}\sqrt{\left(\frac{0.01}{0.31}\right)^2 + \left(\frac{0.01}{0.23}\right)^2 + (0.01)^2}$

$= \frac{100 \times 0.31}{0.23} - 100 = 34.78\,\Omega$

$= 7.42$

$\sigma_R = \sqrt{(7.42)^2 + 1^2} = 7.49\,\Omega$

So $R = (34.78 \pm 7.49)\,\Omega$ ← internal resistance.

This cannot be measured with $r = 10k\Omega$ as this is much larger than R:

$\frac{V_2}{V_1} = \frac{r}{R+r}$ => denominator would be $\approx r$

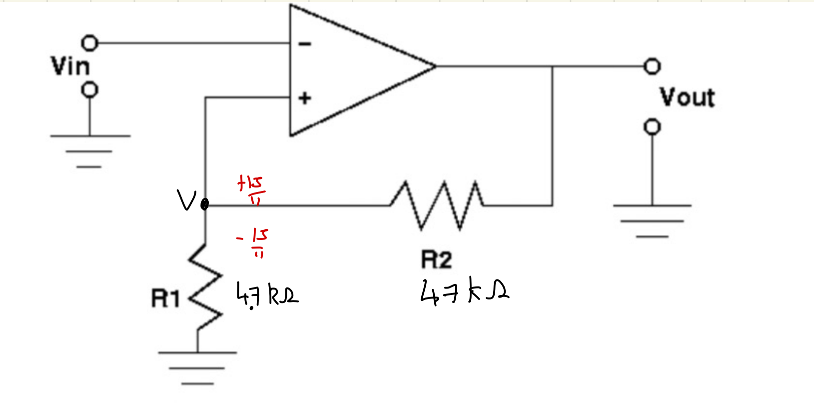
So R cannot be determined.

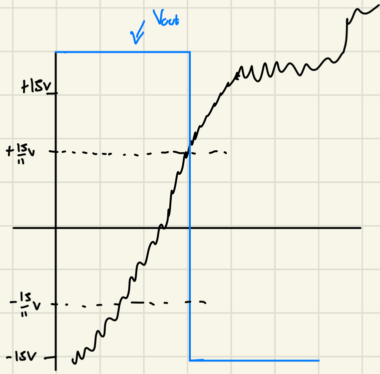
$\therefore \frac{V_2}{V_1} \approx 1$, no difference in voltage measurements.

Day 2:

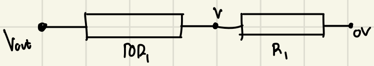
$V_+ \neq V_-$ => positive feedback.

Schmitt trigger





When V_{out} flips to $-15V$ the trigger point also flips to $-\frac{15}{11}V$ so noise won't flip V_{out}.



$V = V_{out}\left(\frac{R_1}{R_1 + 10R_1}\right) = \frac{V_{out}}{11}$

Point at which output flips from $+15V$ to $-15V$

Should be $V_+ = \frac{R_1}{R_1+R_2} V_{out}$

$= \frac{4.7}{4.7+47} 15 = \frac{15}{11}V = 1.36V$

$R_1 = 4.7\,k\Omega \pm 0.047\,k\Omega$

$R_2 = 47\,k\Omega \pm 2.35\,k\Omega$

Measured to be: $V_+ = 1.29 \pm 0.02V$, $V_- = -1.33 \pm 0.02V$

This difference is due to the output voltage is not equal to 15V, experimentally it is $13.81 \pm 0.02\,V$

In theory:

- $V_+ = \frac{13.81}{11} = 1.26 \pm 0.06\,V$

$$\sigma_{V_+} = 1.25 \sqrt{\left(\frac{0.02}{13.81}\right)^2 + \left(\frac{0.0042}{0.09}\right)^2}$$
$$= 0.06$$

- $V_- = \frac{-13.75}{11} = -1.25 \pm 0.06\,V$

$R_1 + R_2 = 51.7 \pm 2.35\ k\Omega$

$$\sigma = \sqrt{(0.047)^2 + (2.35)^2} = 2.35$$

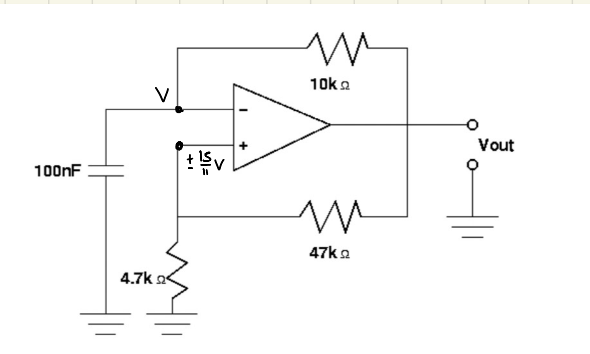
$$\frac{R_1}{R_1 + R_2} = \frac{1}{11} = 0.09 \pm 0.0042$$

$$\sigma = \frac{1}{11}\sqrt{(0.01)^2 + \left(\frac{2.35}{51.7}\right)^2} = 0.0042$$

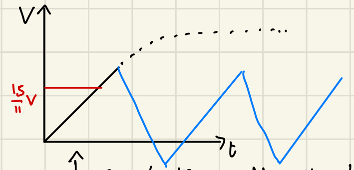
- So $V_+ = 1.29 \pm 0.02\,V$ (measured) is consistent with theory $\rightarrow V_+ = 1.26 \pm 0.06\,V$

- $V_- = -1.33 \pm 0.02\,V$ (measured) is consistent with theory $\rightarrow V_- = -1.25 \pm 0.06\,V$

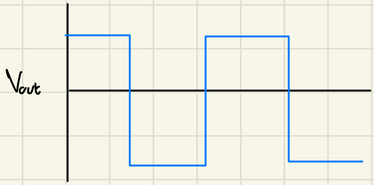
Astable multivibrator:



$I = C\frac{dV}{dt}$



↑ once at $\frac{15}{11}$V, V_{out} flips to −15V
So capacitor discharges



- output is square wave. And set input frequency = output

$$I = C\frac{\Delta V}{\Delta t} \Rightarrow \text{finite region}$$

$$\Delta t = \frac{C}{I}\Delta V$$

$$f = \frac{I}{C}\frac{1}{\Delta V}$$

$\Delta V = 5.03V \pm 0.02V$ ← measured

$I = \frac{V}{R} = \frac{13.56 - 2.5}{10 \times 10^3} = 1.106 mA \pm 0.011 mA$ => Current through $10 k\Omega$ resistor

$V_{out} = (13.56 \pm 0.02)\ V$

$V = (2.5 \pm 0.02)\ V$

$\sigma_V = \sqrt{\left(\frac{0.02}{13.56}\right)^2 + \left(\frac{0.02}{2.5}\right)^2} = 8.13 \times 10^{-3}$

$\sigma_I = I\sqrt{\left(\frac{8.13 \times 10^{-3}}{11.06}\right)^2 + (0.01)^2} = \pm 0.011\ mA$

$f = \frac{1.106 \times 10^{-3}}{100 \times 10^{-9}} \frac{1}{5.03} = 2198.8\ Hz$

$\sigma_f = f\sqrt{\left(\frac{0.011}{1.106}\right)^2 + (0.05)^2 + \left(\frac{0.02}{5.03}\right)^2}$

$\sigma_f = 112.4\ Hz$

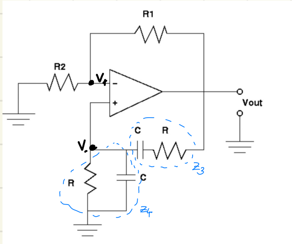
$f = 2.198 \pm 0.112\ kHz$ ← theory

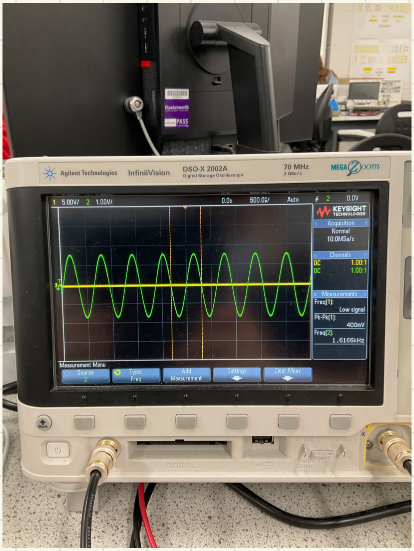
Consistent with measured value

Measured $f = 2.142 \pm 0.001\ kHz$

Wein Bridge oscillator

$f_{out} = 1.61 \pm 0.01\,kHz$ → error as 0.01 oscillation on reading.





We used the oscilloscope to measure the maximum peak to peak V_+ to be $1.6 \pm 0.1\,V$ and V_- to be $1.6 \pm 0.1\,V$. Therefore they are the same.
↓
negative feedback

by connecting one end to ground and one to the measured point.

$$\frac{R_1}{R_2} = \frac{Z_3}{Z_4} = \frac{1}{Z_4} Z_3$$

$$Z = \frac{1}{i\omega c}$$

$$Z_3 = \frac{1}{j\omega c} + R$$

$$\frac{1}{Z_4} = j\omega c + \frac{1}{R}$$

$$\frac{Z_3}{Z_4} = \left(j\omega c + \frac{1}{R}\right)\left(\frac{1}{j\omega c} + R\right)$$
$$= 1 + j\omega Rc + \frac{1}{j\omega Rc} + 1$$
$$= 2 + \frac{1}{j\omega Rc} + j\omega Rc$$

$$\frac{R_1}{R_2} = 2 + \underbrace{\left(\omega Rc - \frac{1}{\omega Rc}\right)}_{=0} j$$

no complex term in $\frac{R_1}{R_2}$

$$R\omega c = \frac{1}{\omega Rc}$$
$$R^2\omega^2c^2 = 1$$
$$\omega = \frac{1}{Rc}$$
$$f = \frac{1}{2\pi Rc}$$

now: $R = 10^4 \pm 1\%\ \Omega$
$= 10^4 \pm 10^2\ \Omega$

$C = 10^{-8} \pm 20\%\ F$

So $f = \frac{1}{2\pi Rc} = 1592\ Hz$

$$\sigma_f = f\sqrt{(0.01)^2 + (0.2)^2}$$
$$= 319\ Hz$$

So $f = 1590 \pm 320\,Hz$
$f = 1.59 \pm 0.32\,kHz$ ← theoretical

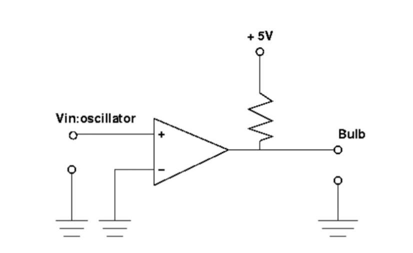
consistent

Measured $f = 1.61 \pm 0.01\,kHz$

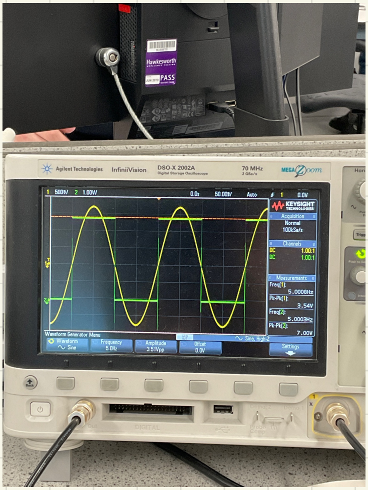
Flash ADC:

Day 3

Now using Lm311 chip instead of 741 chip

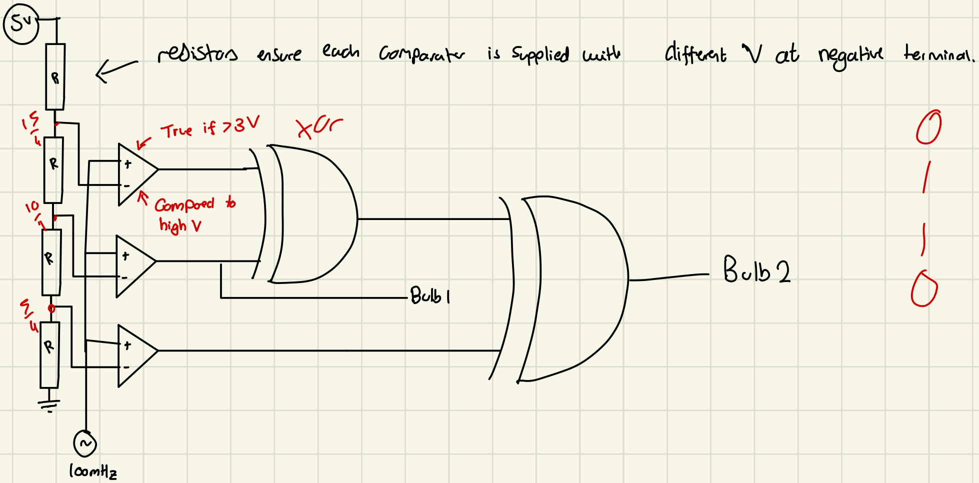


Using a frequency of 5 Hz allowed us to see the LED flashing confirming comparator works.
Then changing this output to display on the oscilloscope gave a digital output further confirming the comparator works.



- Then using the filament bulb the bulb did not light up. This is due to a low current.
- With the bulb, the square wave output had a smaller amplitude.

2-bit ADC:



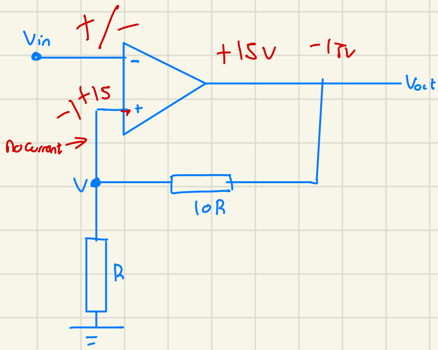
With this circuit, neither bulb will light for $V_{in} < 1V$

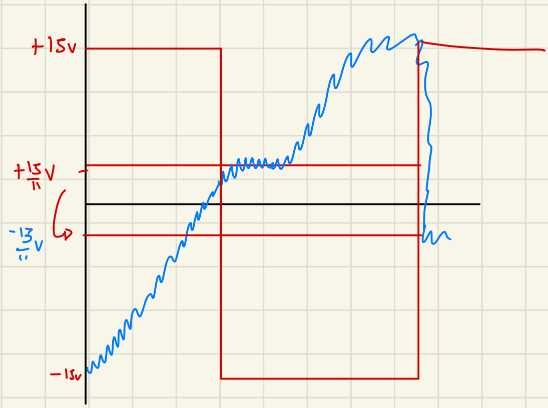
bulb 2 will light for $1V < V_{in} < 2V$

bulb 3 will light for $2V < V_{in} < 3V$

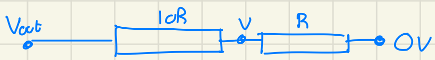
both will light for $V_{in} > 3V$

Schmitt trigger





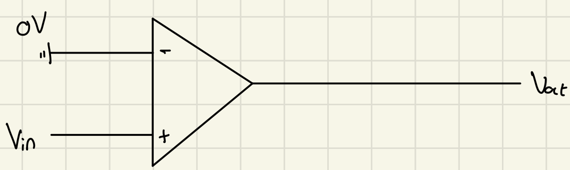
PD



$$V = V_{out}\frac{R}{11R} = \frac{V_{out}}{11}$$

$$V = \frac{1}{11}V_{out}$$

Normal comparitor:



when $V_{in} < 0$, $V_{out} = -15v$

$V_{in} > 0$ $V_{out} = +15v$