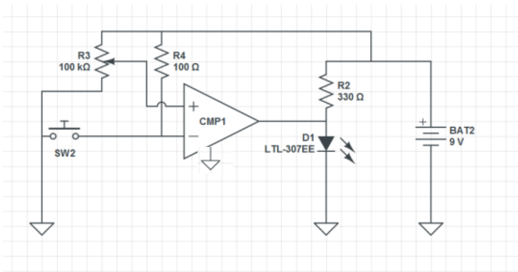
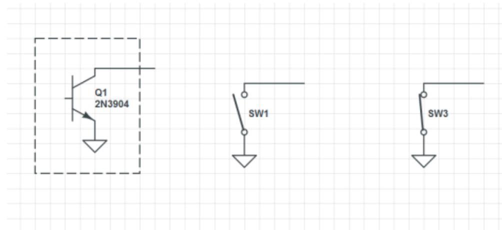
## LM311 comparator – open collector output





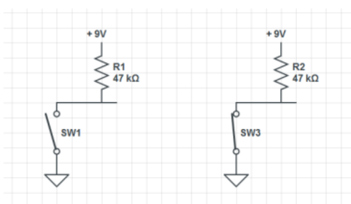

## LM311 comparator – open collector output




ON OFF



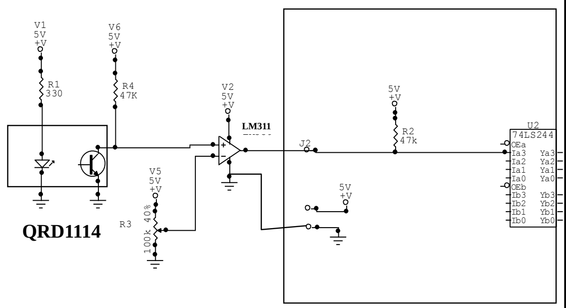
## LM311 comparator – open collector output




ON OFF

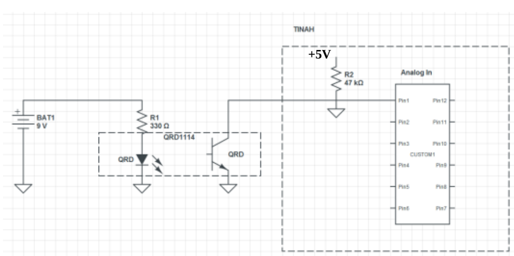


## Example: QRD1114 reflectance sensor



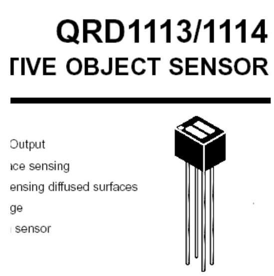



## QRD1114 simple analog connection





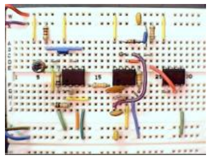

## QRD1114 reflectance sensor

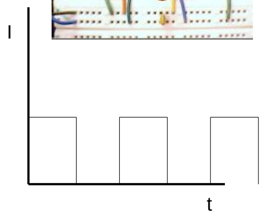



**Watch for direct cross-talk: diode and transistor can come out of the housing.**

# Lecture 2 – Analog circuits

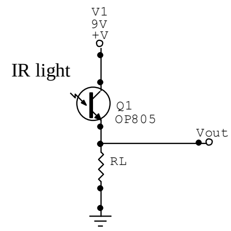
Seeing the light…..

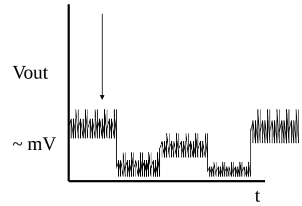






# IR detection

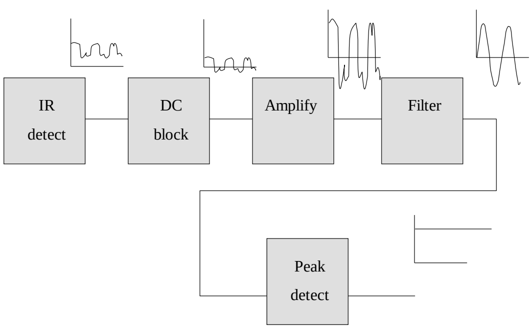
Noise sources:
- Electrical (60Hz, 120Hz, 180Hz….)
- Other electrical
- IR from lights
- IR from cameras (autofocus)
- Visible light



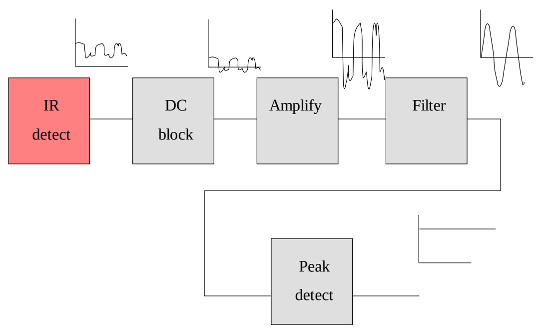




What we want: 0 – 5 V DC signal representing the IR amplitude.

# Analog circuits – filtering and detection




# Analog circuits – filtering and detection

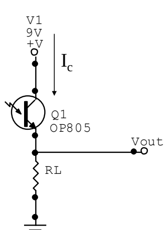



# Analog circuits – discrete devices: BJT

Application: light detection

Phototransistor:
Acts like BJT except charge carriers generated by incident light add to the base current.

In other words, $I_c$ ;Incident light

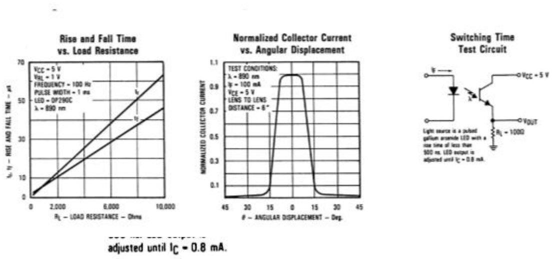



# IR detection

Build a circuit that:

- Uses an OP805 and a resistor to detect variations in light with a voltmeter.
- Determine whether increasing or decreasing the load resistance makes it more sensitive

❖ Note: OP805 will see some room light – use your hand to block it, and use the voltmeter to detect the change in signal.



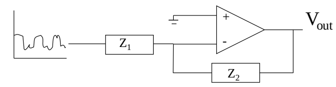

Selecting $R_L$ ….

Vout = $I_c * R_L$

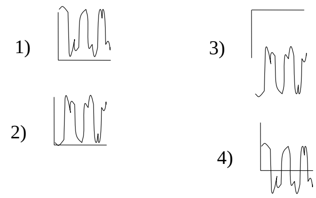
## Analog circuits – filtering and detection

$Z_2/Z_1 = 3$

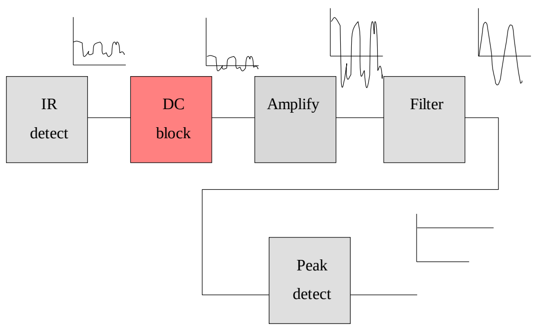
What is the result of the following:



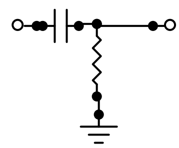

$V_{out}$ =




## Analog circuits – filtering and detection




## Analog circuits – DC block



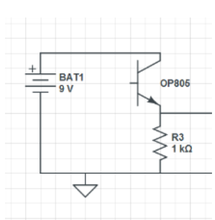
Capacitors:

- Block DC
- Pass high frequencies

## DC block

Add a DC block to your photodetector circuit:

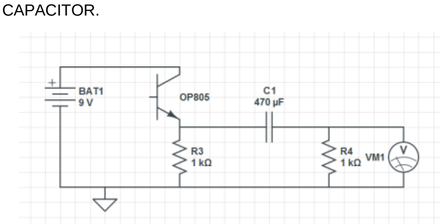
- Move your hand or light over the phototransistor and make sure the output responds only to changes in light.




## DC block

Add a DC block to your photodetector circuit:

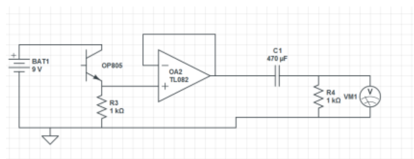
- This will be needed for lecture to see voltage changes without a scope, but is NOT THE RIGHT USE OF AN ELECTROLYTIC CAPACITOR.



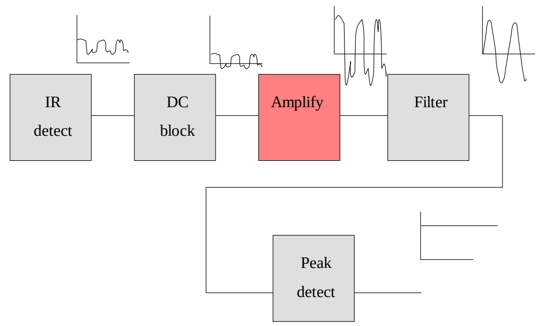
## DC block

This is a much better circuit:

- Why?

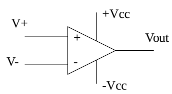



## Analog circuits – filtering and detection




## Analog circuits: Op-amps

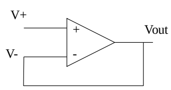
Ideal op-amp:




Vout = K ($V_+$ - $V_-$)

K ~ $10^6$ (at DC!)

With feedback to limit gain:




$V_- = V_{out}$

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

$V_{out}(1+K) = KV_+$

$V_{out}=V_+(K/(1+K))$

$V_{out}= V_+$

When negative feedback is applied to an op-amp, $V_+ = V_-$

**….if the amplifier is within its operating range.**

**The next few slides will discuss limitations**

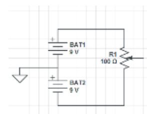
## Inverting Op-amp

Build a circuit that:

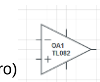
- Wire a TL082 as an inverting amplifier with 3.3 gain
- Use the potentiometer as input and the voltmeter to measure the output

❖ Use both 9V batteries

❖ Experiment with gain – start with a signal between 1 and -1V, to get an output of -9 to 9V



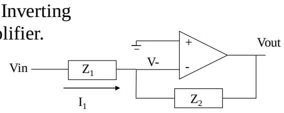

-9 to 9V adjustable Signal (set near zero)




Test output with voltmeter

## Analog circuits: Op-amps

Eg: Inverting amplifier.




$V_- = 0$

$I_1 = V_{in}/Z_1$

$V_{out} = 0 – Z_2I_1$

$V_{out}= - (Z_2/Z_1) V_{in}$

Eg 1: $Z_2 = 100k\Omega$

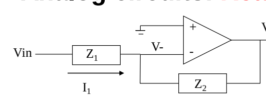
$Z_1 = 10k\Omega$ $V_{out}= - 10 V_{in}$ ← 10x gain is a “reasonable” value

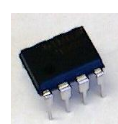
Eg 2: $Z_2 = 100k\Omega$

$Z_1 = 1 \Omega$ $V_{out}= - 100,000 V_{in}$ !!

Not likely….

## Analog circuits: Real Op-amps



Eg 2: $Z_2 = 100k\Omega$

$Z_1 = 1 \Omega$ $V_{out}= - 100,000 V_{in}$ !!

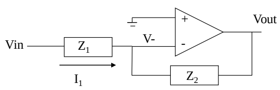
Several problems:

- $I_1$ = 1A for $V_{in}$ = 1 V !! (excessive load for upstream circuitry)
- Gain Bandwidth product ~ 3 MHz. This would limit the bandwidth of the amplifier from DC up to 30 Hz (i.e. not a very responsive system!).

## Analog circuits: Real Op-amps

Things to consider:

- Input impedance
- Gain Bandwidth product
- Bias Currents
- Voltage limitations
- Output current limitations

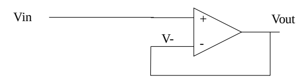



Since $V_-$ is a virtual ground, input impedance seen by $V_{in}$ is $Z_1$

## Analog circuits: Real Op-amps

Things to consider:

- Input impedance
- Gain Bandwidth product
- Bias Currents
- Voltage limitations
- Output current limitations




Since Op-amp inputs source or sink very little current (depends on type) , input impedance in this case is very high. This is a commonly used buffer to separate your low impedance circuit from a sensitive source that you need to measure without drawing current.

**electrical characteristics, $V_{CC\pm}$ = ±15 V (unless otherwise noted)**

| | PARAMETER | TEST CONDITIONS | $T_A$† | TL081C TL082C TL084C MIN | TYP | MAX | TL081AC TL082AC TL084AC MIN | TYP | MAX | TL081BC TL082BC TL084BC MIN | TYP | MAX | TL081I TL082I TL084I MIN | TYP | MAX | UNIT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_{IO}$ | Input offset voltage | $V_O$ = 0, $R_S$ = 50 Ω | 25°C | | 3 | 15 | | 3 | 6 | | 2 | 3 | | 3 | 6 | mV |
| | | | Full range | | | 20 | | | 7.5 | | | 5 | | | 9 | |
| $\alpha_{VIO}$ | Temperature coefficient of input offset voltage | $V_O$ = 0, $R_S$ = 50 Ω | Full range | | 18 | | | 18 | | | 18 | | | 18 | | μV/°C |
| $I_{IO}$ | Input offset current‡ | $V_O$ = 0 | 25°C | | 5 | 200 | | 5 | 100 | | 5 | 100 | | 5 | 100 | pA |
| | | | Full range | | | 2 | | | 2 | | | 2 | | | 10 | nA |
| $I_{IB}$ | Input bias current‡ | $V_O$ = 0 | 25°C | | 30 | 400 | | 30 | 200 | | 30 | 200 | | 30 | 200 | pA |
| | | | Full range | | | 10 | | | 7 | | | 7 | | | 20 | nA |
| $V_{ICR}$ | Common-mode input voltage range | | 25°C | ±11 | −12 to 15 | | ±11 | −12 to 15 | | ±11 | −12 to 15 | | ±11 | −12 to 15 | | V |
| $V_{OM}$ | Maximum peak output voltage swing | $R_L$ = 10 kΩ | 25°C | ±12 | ±13.5 | | ±12 | ±13.5 | | ±12 | ±13.5 | | ±12 | ±13.5 | | V |
| | | $R_L$ ≥ 10 kΩ | Full range | ±12 | | | ±12 | | | ±12 | | | ±12 | | | |
| | | $R_L$ ≥ 2 kΩ | | ±10 | ±12 | | ±10 | ±12 | | ±10 | ±12 | | ±10 | ±12 | | |
| $A_{VD}$ | Large-signal differential voltage amplification | $V_O$ = ±10 V, $R_L$ ≥ 2 kΩ | 25°C | 25 | 200 | | 50 | 200 | | 50 | 200 | | 50 | 200 | | V/mV |
| | | $V_O$ = ±10 V, $R_L$ ≥ 2 kΩ | Full range | 15 | | | 25 | | | 25 | | | 25 | | | |
| $B_1$ | Unity-gain bandwidth | | 25°C | | 3 | | | 3 | | | 3 | | | 3 | | MHz |
| $r_i$ | Input resistance | | 25°C | | $10^{12}$ | | | $10^{12}$ | | | $10^{12}$ | | | $10^{12}$ | | Ω |
| CMRR | Common-mode rejection ratio | $V_{IC}$ = $V_{ICR}$min, $V_O$ = 0, $R_S$ = 50 Ω | 25°C | 70 | 86 | | 75 | 86 | | 75 | 86 | | 75 | 86 | | dB |

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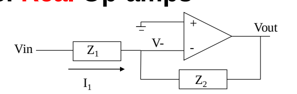
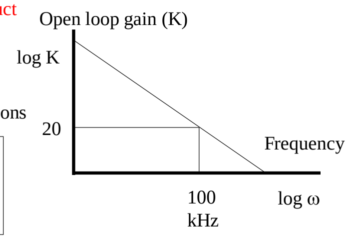
## Analog circuits: Real Op-amps

Things to consider:

- Input impedance
- Gain Bandwidth product
- Bias Currents
- Voltage limitations
- Output current limitations




Slew-rate is a similar limit: it is a limit on the rate of change of output voltage

Gain-Bandwidth limit (Hz) = Gain * Max. Frequency = CONSTANT


**electrical characteristics, $V_{CC\pm}$ = ±15 V (unless otherwise noted)**

| | PARAMETER | TEST CONDITIONS | $T_A$† | TL081C TL082C TL084C MIN | TYP | MAX | TL081AC TL082AC TL084AC MIN | TYP | MAX | TL081BC TL082BC TL084BC MIN | TYP | MAX | TL081I TL082I TL084I MIN | TYP | MAX | UNIT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_{IO}$ | Input offset voltage | $V_O$ = 0, $R_S$ = 50 Ω | 25°C | | 3 | 15 | | 3 | 6 | | 2 | 3 | | 3 | 6 | mV |
| | | | Full range | | | 20 | | | 7.5 | | | 5 | | | 9 | |
| $\alpha_{VIO}$ | Temperature coefficient of input offset voltage | $V_O$ = 0, $R_S$ = 50 Ω | Full range | | 18 | | | 18 | | | 18 | | | 18 | | μV/°C |
| $I_{IO}$ | Input offset current‡ | $V_O$ = 0 | 25°C | | 5 | 200 | | 5 | 100 | | 5 | 100 | | 5 | 100 | pA |
| | | | Full range | | | 2 | | | 2 | | | 2 | | | 10 | nA |
| $I_{IB}$ | Input bias current‡ | $V_O$ = 0 | 25°C | | 30 | 400 | | 30 | 200 | | 30 | 200 | | 30 | 200 | pA |
| | | | Full range | | | 10 | | | 7 | | | 7 | | | 20 | nA |
| $V_{ICR}$ | Common-mode input voltage range | | 25°C | ±11 | −12 to 15 | | ±11 | −12 to 15 | | ±11 | −12 to 15 | | ±11 | −12 to 15 | | V |
| $V_{OM}$ | Maximum peak output voltage swing | $R_L$ = 10 kΩ | 25°C | ±12 | ±13.5 | | ±12 | ±13.5 | | ±12 | ±13.5 | | ±12 | ±13.5 | | V |
| | | $R_L$ ≥ 10 kΩ | Full range | ±12 | | | ±12 | | | ±12 | | | ±12 | | | |
| | | $R_L$ ≥ 2 kΩ | | ±10 | ±12 | | ±10 | ±12 | | ±10 | ±12 | | ±10 | ±12 | | |
| $A_{VD}$ | Large-signal differential voltage amplification | $V_O$ = ±10 V, $R_L$ ≥ 2 kΩ | 25°C | 25 | 200 | | 50 | 200 | | 50 | 200 | | 50 | 200 | | V/mV |
| | | $V_O$ = ±10 V, $R_L$ ≥ 2 kΩ | Full range | 15 | | | 25 | | | 25 | | | 25 | | | |
| $B_1$ | Unity-gain bandwidth | | 25°C | | 3 | | | 3 | | | 3 | | | 3 | | MHz |
| $r_i$ | Input resistance | | 25°C | | $10^{12}$ | | | $10^{12}$ | | | $10^{12}$ | | | $10^{12}$ | | Ω |
| CMRR | Common-mode rejection ratio | $V_{IC}$ = $V_{ICR}$min, $V_O$ = 0, $R_S$ = 50 Ω | 25°C | 70 | 86 | | 75 | 86 | | 75 | 86 | | 75 | 86 | | dB |

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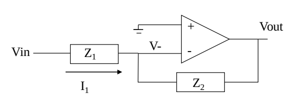
TL082: Gain*Bandwidth = 3 MHz

➔ This means that at a gain of 100, Bandwidth is 30 kHz.

## Analog circuits: Real Op-amps

Things to consider:

- Input impedance
- Gain Bandwidth product
- Bias Currents
- Voltage limitations
- Output current limitations




Op-amp terminals can act as small current sources. These Bias Currents can become large error or offset voltages if the resistors in the circuit are large.

Eg: 20 nA bias current * 10 MΩ = 200 mV!

electrical characteristics, $V_{CC\pm} = \pm15$ V (unless otherwise noted)

| PARAMETER | | TEST CONDITIONS | $T_A$† | TL081C TL082C TL084C MIN | TYP | MAX | TL081AC TL082AC TL084AC MIN | TYP | MAX | TL081BC TL082BC TL084BC MIN | TYP | MAX | TL081I TL082I TL084I MIN | TYP | MAX | UNIT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_{IO}$ | Input offset voltage | $V_O = 0$, $R_S = 50\ \Omega$ | 25°C | | 3 | 15 | | 3 | 6 | | 2 | 3 | | 3 | 6 | mV |
| | | | Full range | | | 20 | | | 7.5 | | | 5 | | | 9 | |
| $\alpha_{VIO}$ | Temperature coefficient of input offset voltage | $V_O = 0$, $R_S = 50\ \Omega$ | Full range | | 18 | | | 18 | | | 18 | | | 18 | | µV/°C |
| $I_{IO}$ | Input offset current‡ | $V_O = 0$ | 25°C | | 5 | 200 | | 5 | 100 | | 5 | 100 | | 5 | 100 | pA |
| | | | Full range | | | 2 | | | 2 | | | 2 | | | 10 | nA |
| $I_{IB}$ | Input bias current‡ | $V_O = 0$ | 25°C | | 30 | 400 | | 30 | 200 | | 30 | 200 | | 30 | 200 | pA |
| | | | Full range | | | 10 | | | 7 | | | 7 | | | 20 | nA |
| $V_{ICR}$ | Common-mode input voltage range | | 25°C | ±11 | −12 to 15 | | ±11 | −12 to 15 | | ±11 | −12 to 15 | | ±11 | −12 to 15 | | V |
| $V_{OM}$ | Maximum peak output voltage swing | $R_L = 10\ k\Omega$ | 25°C | ±12 | ±13.5 | | ±12 | ±13.5 | | ±12 | ±13.5 | | ±12 | ±13.5 | | V |
| | | $R_L \geq 10\ k\Omega$ | Full range | ±12 | | | ±12 | | | ±12 | | | ±12 | | | |
| | | $R_L \geq 2\ k\Omega$ | | ±10 | ±12 | | ±10 | ±12 | | ±10 | ±12 | | ±10 | ±12 | | |
| $A_{VD}$ | Large-signal differential voltage amplification | $V_O = \pm10$ V, $R_L \geq 2\ k\Omega$ | 25°C | 25 | 200 | | 50 | 200 | | 50 | 200 | | 50 | 200 | | V/mV |
| | | $V_O = \pm10$ V, $R_L \geq 2\ k\Omega$ | Full range | 15 | | | 25 | | | 25 | | | 25 | | | |
| $B_1$ | Unity-gain bandwidth | | 25°C | | 3 | | | 3 | | | 3 | | | 3 | | MHz |
| $r_i$ | Input resistance | | 25°C | | $10^{12}$ | | | $10^{12}$ | | | $10^{12}$ | | | $10^{12}$ | | Ω |
| CMRR | Common-mode rejection ratio | $V_{IC} = V_{ICR}min$, $V_O = 0$, $R_S = 50\ \Omega$ | 25°C | 70 | 86 | | 75 | 86 | | 75 | 86 | | 75 | 86 | | dB |

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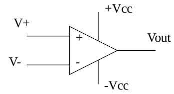
## Analog circuits: Real Op-amps




Things to consider:

- Input impedance
- Gain Bandwidth product
- Bias Currents
- Voltage limitations
- Output current limitations

Op-amp input voltages ($V_+$, $V_-$) must be at least a few volts away from the power rails (+Vcc, -Vcc). Applying input voltages equal or near the power rails will cause the Op-amp to behave unexpectedly.

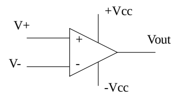
Rail-to-rail Op-amps are an expensive solution to this limitation.


electrical characteristics, $V_{CC\pm} = \pm15$ V (unless otherwise noted)

| PARAMETER | | TEST CONDITIONS | $T_A$† | TL081C TL082C TL084C MIN | TYP | MAX | TL081AC TL082AC TL084AC MIN | TYP | MAX | TL081BC TL082BC TL084BC MIN | TYP | MAX | TL081I TL082I TL084I MIN | TYP | MAX | UNIT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_{IO}$ | Input offset voltage | $V_O = 0$, $R_S = 50\ \Omega$ | 25°C | | 3 | 15 | | 3 | 6 | | 2 | 3 | | 3 | 6 | mV |
| | | | Full range | | | 20 | | | 7.5 | | | 5 | | | 9 | |
| $\alpha_{VIO}$ | Temperature coefficient of input offset voltage | $V_O = 0$, $R_S = 50\ \Omega$ | Full range | | 18 | | | 18 | | | 18 | | | 18 | | µV/°C |
| $I_{IO}$ | Input offset current‡ | $V_O = 0$ | 25°C | | 5 | 200 | | 5 | 100 | | 5 | 100 | | 5 | 100 | pA |
| | | | Full range | | | 2 | | | 2 | | | 2 | | | 10 | nA |
| $I_{IB}$ | Input bias current‡ | $V_O = 0$ | 25°C | | 30 | 400 | | 30 | 200 | | 30 | 200 | | 30 | 200 | pA |
| | | | Full range | | | 10 | | | 7 | | | 7 | | | 20 | nA |
| $V_{ICR}$ | Common-mode input voltage range | | 25°C | ±11 | −12 to 15 | | ±11 | −12 to 15 | | ±11 | −12 to 15 | | ±11 | −12 to 15 | | V |
| $V_{OM}$ | Maximum peak output voltage swing | $R_L = 10\ k\Omega$ | 25°C | ±12 | ±13.5 | | ±12 | ±13.5 | | ±12 | ±13.5 | | ±12 | ±13.5 | | V |
| | | $R_L \geq 10\ k\Omega$ | Full range | ±12 | | | ±12 | | | ±12 | | | ±12 | | | |
| | | $R_L \geq 2\ k\Omega$ | | ±10 | ±12 | | ±10 | ±12 | | ±10 | ±12 | | ±10 | ±12 | | |
| $A_{VD}$ | Large-signal differential voltage amplification | $V_O = \pm10$ V, $R_L \geq 2\ k\Omega$ | 25°C | 25 | 200 | | 50 | 200 | | 50 | 200 | | 50 | 200 | | V/mV |
| | | $V_O = \pm10$ V, $R_L \geq 2\ k\Omega$ | Full range | 15 | | | 25 | | | 25 | | | 25 | | | |
| $B_1$ | Unity-gain bandwidth | | 25°C | | 3 | | | 3 | | | 3 | | | 3 | | MHz |
| $r_i$ | Input resistance | | 25°C | | $10^{12}$ | | | $10^{12}$ | | | $10^{12}$ | | | $10^{12}$ | | Ω |
| CMRR | Common-mode rejection ratio | $V_{IC} = V_{ICR}min$, $V_O = 0$, $R_S = 50\ \Omega$ | 25°C | 70 | 86 | | 75 | 86 | | 75 | 86 | | 75 | 86 | | dB |

SLOS081E – FEBRUARY 1977 – REVISED FEBRUARY 1999


## Analog circuits: Real Op-amps




Things to consider:

- Input impedance
- Gain Bandwidth product
- Bias Currents
- Voltage limitations
- Output current / voltage limitations

Op-amp output terminals can only provide a few mA of current. Motors, lamps and similar high current devices cannot typically be driven by a normal OP-amp. High power Op-amps exist that can provide much higher current levels. Output voltage range is also limited within a few volts of the power rails.

MAXIMUM PEAK OUTPUT VOLTAGE
vs
LOAD RESISTANCE

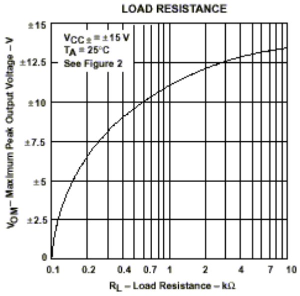


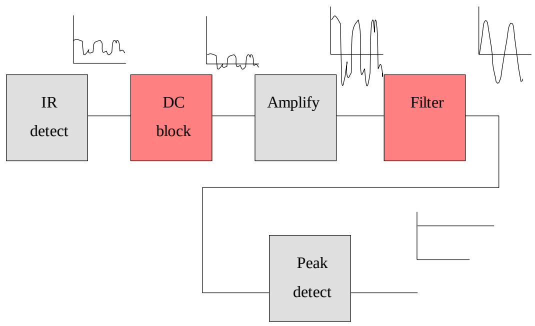

Figure 9

## Analog circuits: Real Op-amps

**Summary**:

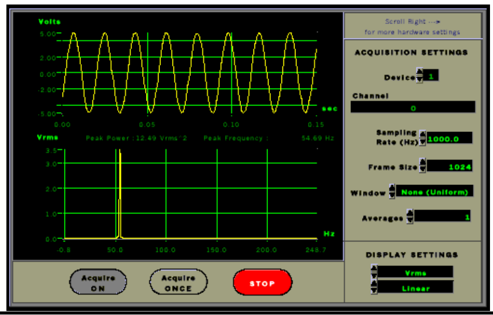
- Keep resistors in 1K to 500K range unless you really know what you're doing.
- Don't ask a single amplifier to provide huge gains (>30?)
- Don't drive motors, lamps, or other heavy loads with a normal op-amp (power op-amps exist for this)
- Keep input voltages away from the op-amp voltage rails (unless using rail-to-rail opamps)

## Analog circuits – filtering and detection

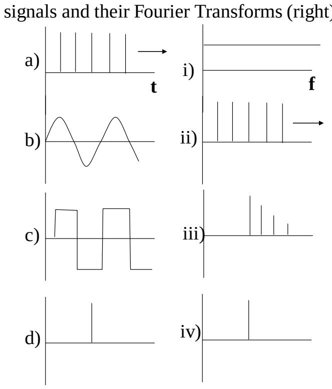



## Analog circuits: Filters

To understand filters you should first understand the difference between the TIME DOMAIN and FREQUENCY DOMAIN



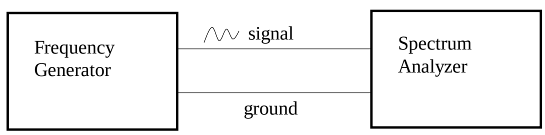

Which is the correct match between the following time-domain (left) signals and their Fourier Transforms (right) ?




1) a-i, b-iv, c-ii, d-iii
2) a-ii, b-iv, c-iii, d-i
3) a-iii, b-iv, c-i, d-ii
4) a-iv, b-ii, c-iii, d-i

## Analog circuits: Filters

Demo: Frequency generator and Spectrum analyzer




## Analog circuits: Filters

"Transfer Function" = Vout/Vin = H(ω)

So: $V_{out}(\omega) = H(\omega) * V_{in}(\omega)$

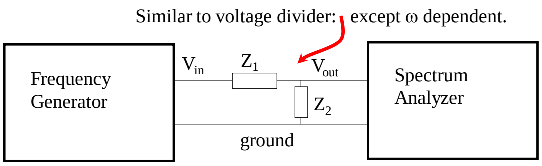
$Z_{cap} = 1/j\,\omega C$

$Z_{ind} = j\,\omega L$

$Z_{res} = R$

This is all in terms of ω since, in general, impedances are functions of ω.

Similar to voltage divider: except ω dependent.



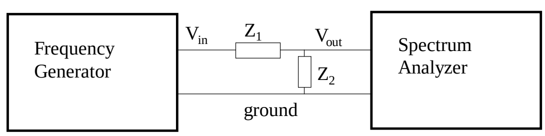

## Analog circuits: Filters

$V_{out}(\omega) = [V_{in}(\omega)/(Z_1+Z_2)] * Z_2$

$$H(\omega) = \frac{Z_2}{Z_1 + Z_2}$$

So: $H(\omega) = Z_2/(Z_1+Z_2)$

For resistors, this is just the well known voltage divider: $R_2/(R_1+R_2)$



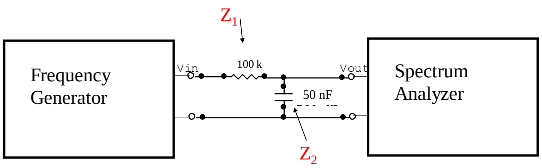
## Analog circuits: Filters

Now plug in a resistor and a capacitor:

$Z_2 = 1/j\,\omega C$ ⟶ $H(\omega) = \frac{1/j\omega C}{R + 1/j\omega C}$

$Z_1 = R$

$$= \frac{1}{1 + j\omega RC}$$

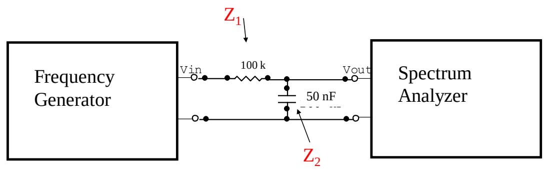



## Analog circuits: Filters

$$H(\omega) = \frac{1}{1 + j\omega RC}$$

For low frequencies (small ω), H = 1
For high frequencies (large ω), H = 0
**This is a LOW PASS FILTER**

At w = 1/RC, H begins to decrease in amplitude.



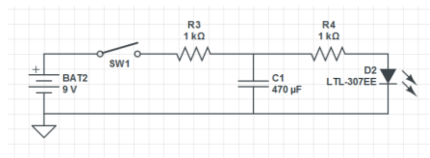

$f_0 = 1/(2\pi RC) = 30$ Hz

## Low Pass Filter

Build a circuit that:

- Uses a capacitor, a switch, an LED and resistors, to implement a low pass filter.
- When the button is pressed and held, the LED should light slowly.
- Calculate the time constant – see if it matches what you see.

## Low Pass Filter




## Analog circuits: Transfer Functions

**Bode plots**: a graphical representation of frequency response on logarithmic axes.

**Vertical axis:**

$\log_{10}(H)$

$dBV = 20\log_{10}(|V|)$

(20 is used instead of 10 so the result will represent power ~ $V^2$)

-3 dB = ½ as much power as 0 dB

$V_{out}$ is $1/\sqrt{2}$ of $V_{in}$ at -3dB

**Horizontal axis:**

$\log_{10}(f)$

Log of frequency is used to ensure linear plots from $1/f$ or $1/f^n$ functions

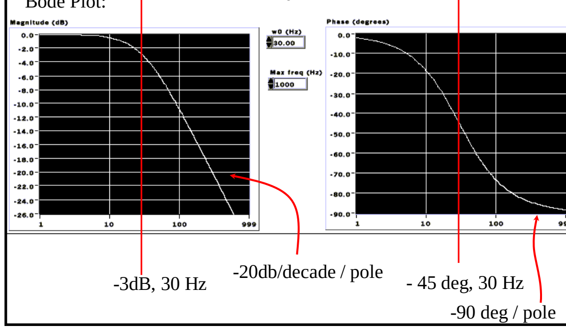
**Pole:** $1/(1+j\omega/\omega_0)$ -20 db/decade in amplitude after $\omega_0$, -90 phase

**Zero:** $(1+j\omega/\omega_0)$ +20 db/decade in amplitude after $\omega_0$, +90 phase

## Analog circuits: Filters

$$H(\omega) = \frac{1}{1 + j\omega RC}$$

Bode Plot:



## Analog circuits: Transfer Functions

**Bode plots**: a graphical representation of frequency response on logarithmic axes.

Zero at ω=0

$$H(\omega) = -\frac{j\omega R_1 C_2}{(1+j\omega R_2 C_2)(1+j\omega R_1 C_1)}$$

Pole at $\omega = 1/(R_2C_2)$ Pole at $\omega = 1/(R_1C_1)$

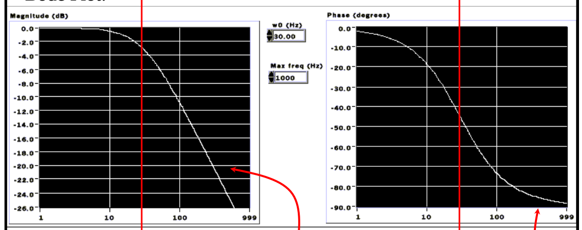
**Pole: $1/(1+j\omega/\omega_0)$** -20 db/decade in amplitude after $\omega_0$, -90 phase

**Zero: $(1+j\omega/\omega_0)$** +20 db/decade in amplitude after $\omega_0$, +90 phase

## Analog circuits: Simple Pole

$$H(\omega) = \frac{1}{1+j\omega RC}$$

Bode Plot:

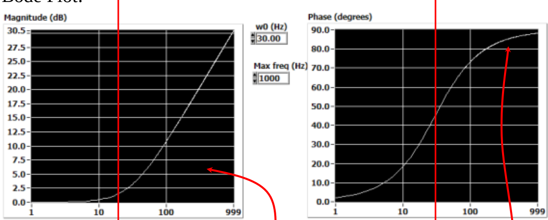



-3dB, 1/RC -20db/decade - 45 deg, 1/RC -90 deg

## Analog circuits: Simple Zero

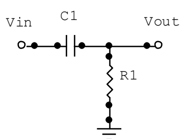
$$H(\omega) = 1 + j\omega RC$$

Bode Plot:

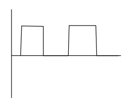


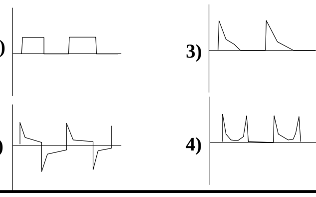

+3dB, 1/RC +20db/decade +45 deg, 1/RC +90 deg

## Analog circuits: Filters



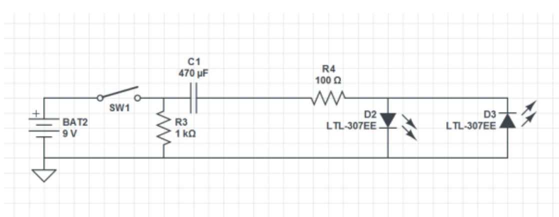

**How does this circuit affect the following waveform:**





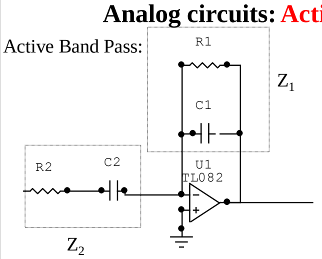

## High Pass Filter

Build and explain what this circuit does:




## Analog circuits: Active Filters

Active Band Pass:



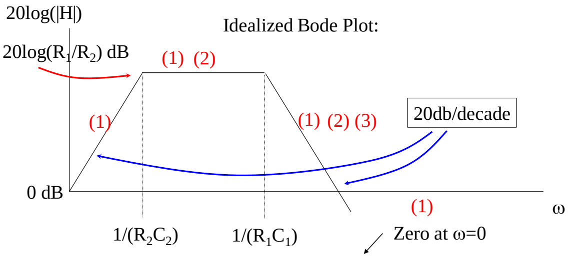

Combines a high and a low pass filter to create a pass "band".

Zero at ω=0

$$H(\omega) = -\frac{j\omega R_1 C_2}{(1+j\omega R_2 C_2)(1+j\omega R_1 C_1)}$$

Pole at $\omega = 1/(R_2C_2)$ Pole at $\omega = 1/(R_1C_1)$

## Analog circuits: Active Filters



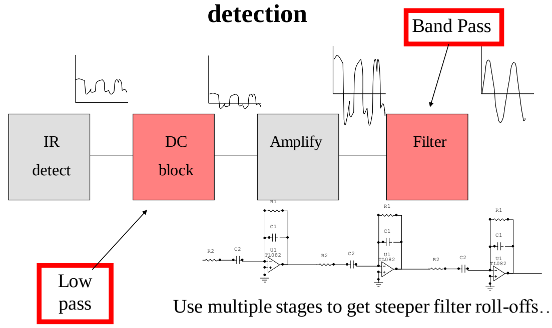

Zero at ω=0

$$H(\omega) = -\frac{j\omega R_1 C_2}{(1+j\omega R_2 C_2)(1+j\omega R_1 C_1)}$$

(2) Pole at $\omega=1/(R_2C_2)$

(3) Pole at $\omega=1/(R_1C_1)$

## Analog circuits – filtering and detection

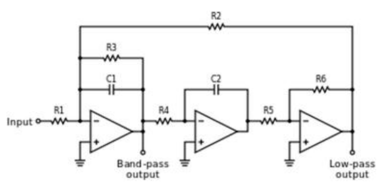



Use multiple stages to get steeper filter roll-offs…

$H_{tot}(\omega) = H_1(\omega) * H_2(\omega) * H_3(\omega)$

Remember –20dB/dec for each POLE

## More advanced filters: Biquad



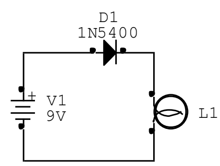

with bandpass gain $G_{bpf} = -R_4/R_2$. In both cases, the

- Natural frequency is $\omega_0 = 1/\sqrt{R_2R_4C_1C_2}$.
- Quality factor is $Q = \sqrt{\frac{R_3^2C_1}{R_2R_4C_2}}$.

The bandwidth is approximated by $B = \omega_0/Q$.

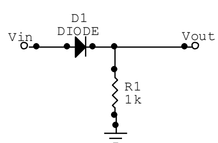


## Discrete devices: diodes






**$V_{in}$ = 9V DC, $V_{out}$ is connected to scope only.**



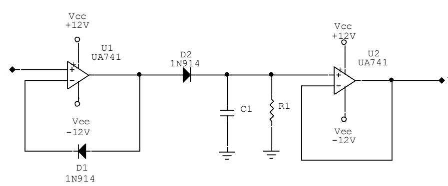

**a) $V_{out}$ = 9 V if R1 = 1K**
**b) $V_{out}$ = ~8.3 V regardless of R1**
**c) $V_{out}$ = ~8.3 V if R1 = 1K**
**d) $V_{out}$ = 9 V if R1 is removed**
**e) $V_{out}$ = ~8.3 V if R1 is removed**

**The following are true:** **(Try it with your own meter)**

1. **a**
2. **b,c,e**
3. **c,d**
4. **a,e**
5. **c**



DISCUSSION Q: What is wrong with this circuit, when implemented with a TL082 OP-AMP?



# Debugging Circuits

Learn to systematically check your circuits:

- **Power rails:**
  - Check that 15V is really 15V; if not, localize the component that is shorting the power rail. Check power at each chip.
- **Physical check**:
  - Check pinouts, missing/loose wires, etc.
- **Isolate stages** where possible
  - Check output of stage 1 – if ok plug into stage 2 and see if stage 1 output is degraded.
  - If ok check output of stage 2 etc
- **Keep wiring TIDY!**

## Lab 2 Tips

**•Capacitors – electrolytic capacitors have polarity, may explode if inserted backwards**


**•Gain – make sure that gain does not saturate the signal, this will generate unwanted noise after filtering.**