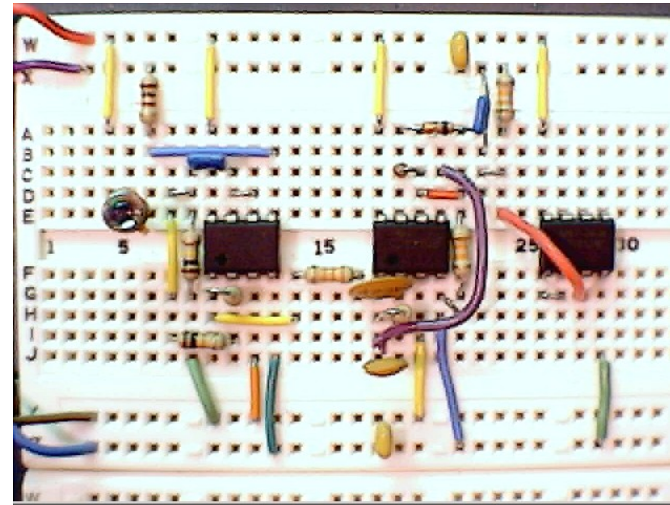
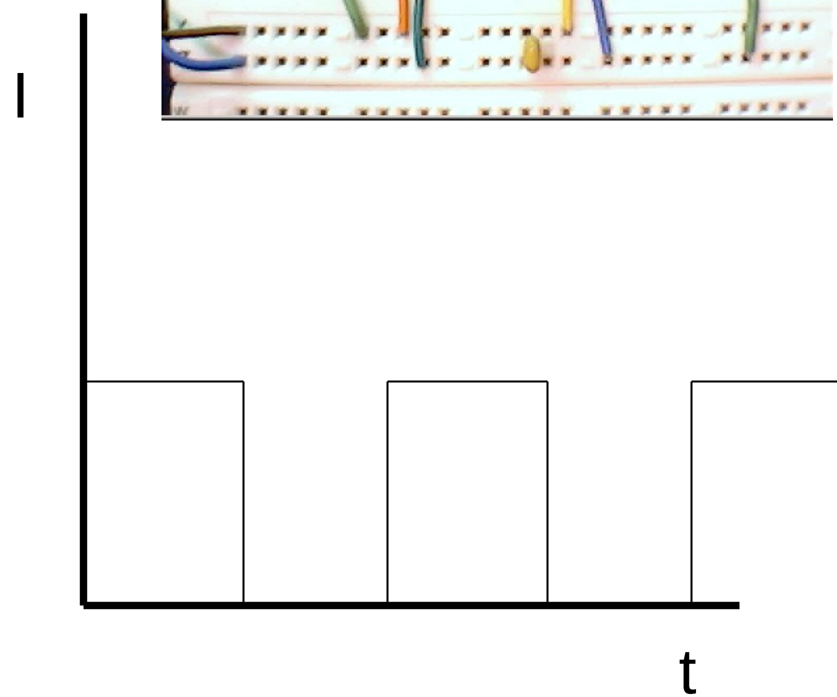
Lecture 2 – Analog circuits

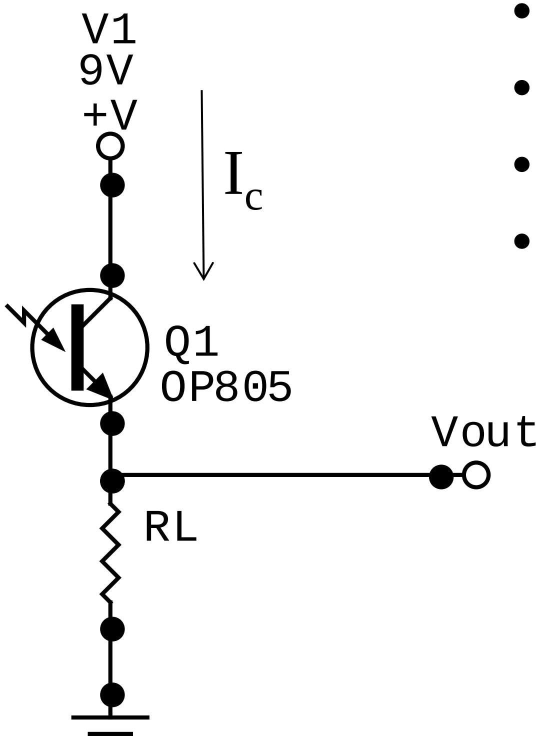
..or How to detect the Alarm beacon





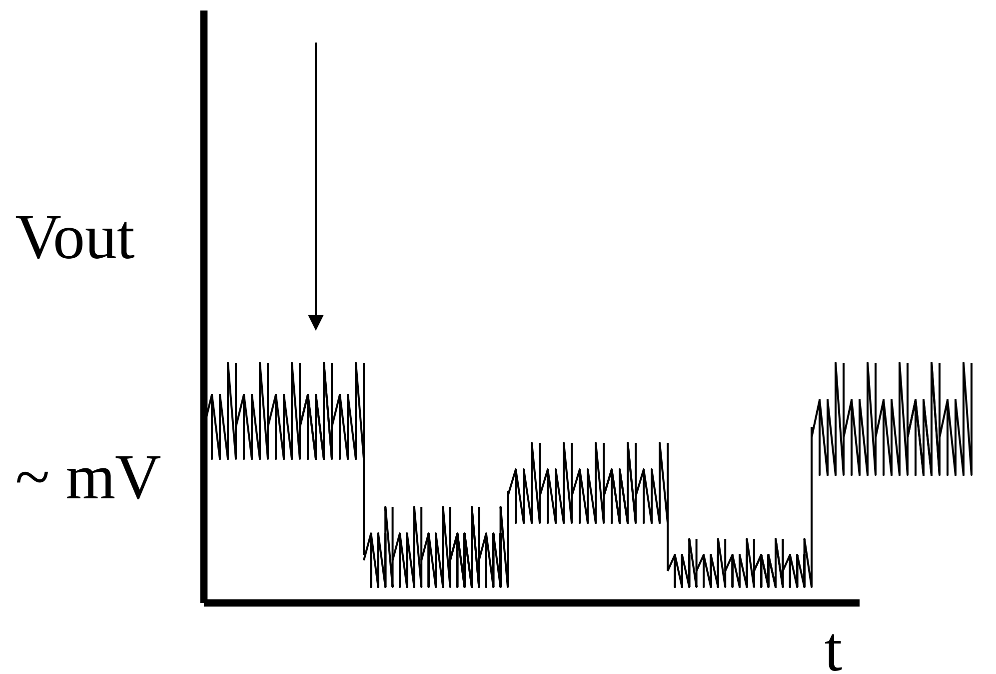
IR detection

IR light generates collector current



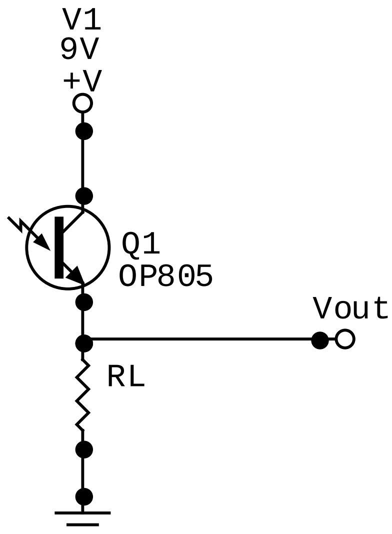
Noise sources:

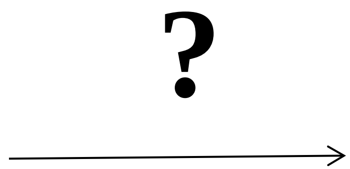
- Electrical (60Hz, 120Hz, 180Hz….)
- Other electrical
- IR from lights
- IR from cameras (autofocus)
- Visible light

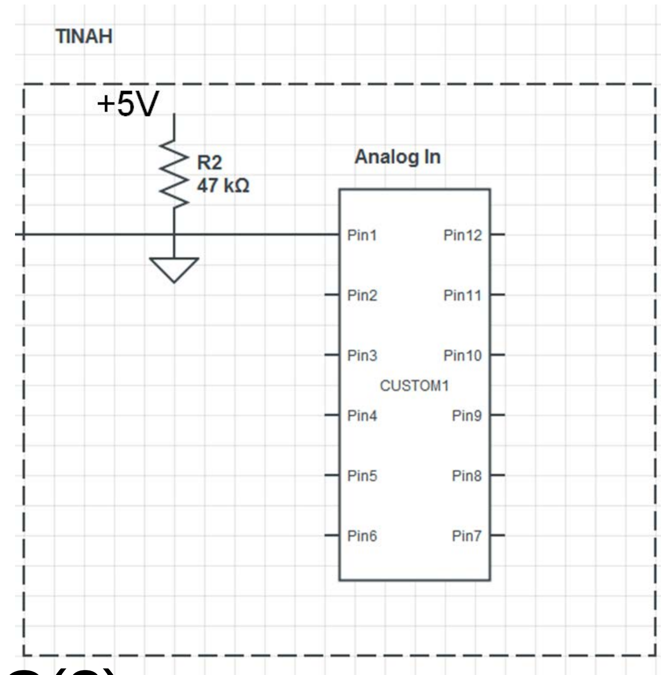


What we want: 0 – 5 V DC signal representing the IR amplitude.

Analog signal processing





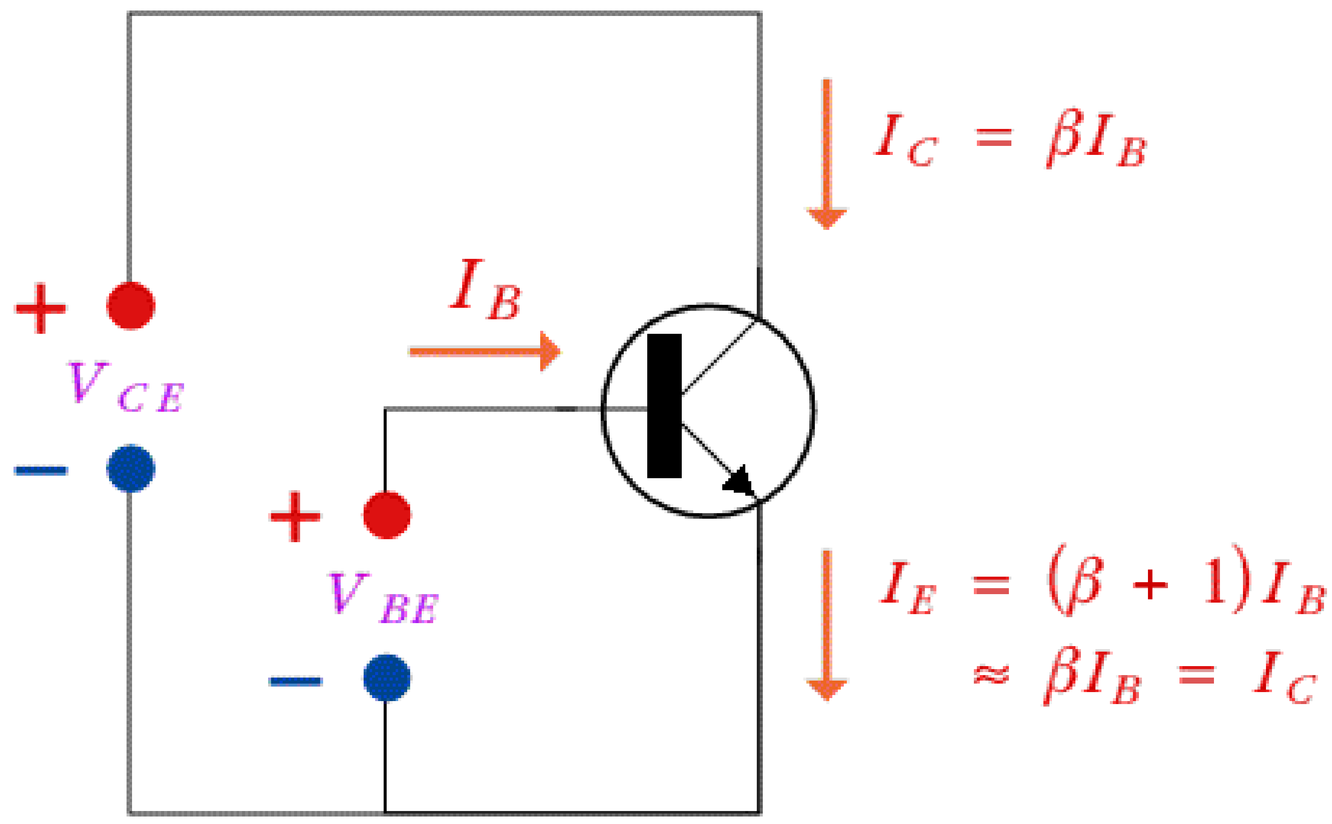


<u>Problems:</u>

- IR signal is AC, TINAH analog needs DC(?)
- IR signal is low (few mV), TINAH range is 0-5V
- Can TINAH sample analog inputs fast enough to distinguish 1kHz from 10kHz?
- Other IR sources could interfere with beacon signal

Discrete devices: BJT

Bipolar Junction Transistors



'Conventional' view of the NPN Bipolar Transistor

Diagrams courtesy of: University of St. Andrews, St Andrews, Fife KY16 9SS, Scotland

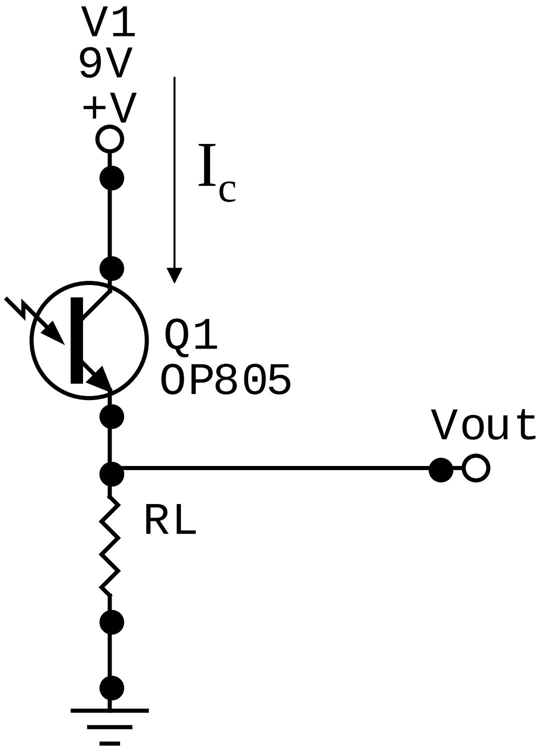
Analog circuits – discrete devices: BJT

Application: light detection

Phototransistor:

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

In other words, $I_c \propto$ Incident light

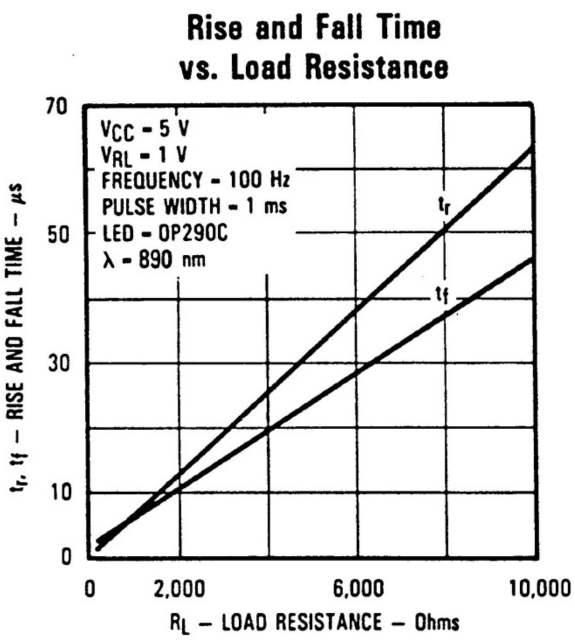


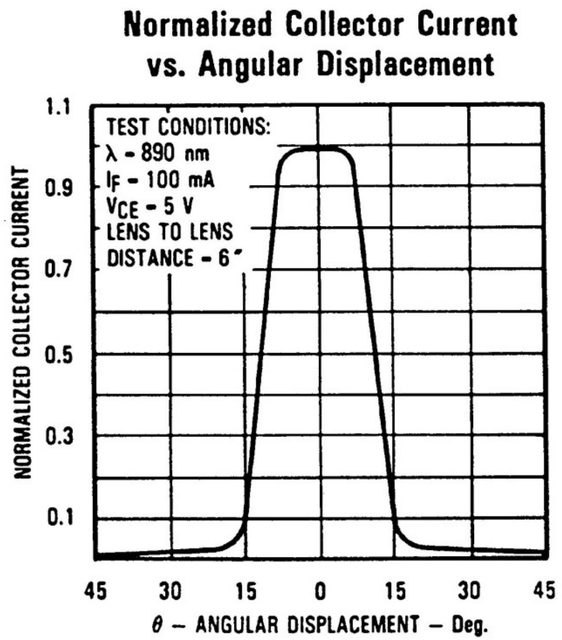
IR detection

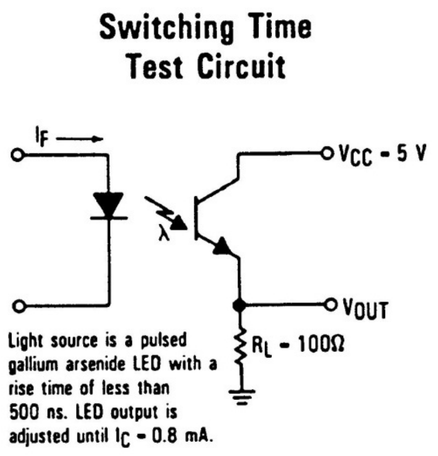
Build a circuit that:

- 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.







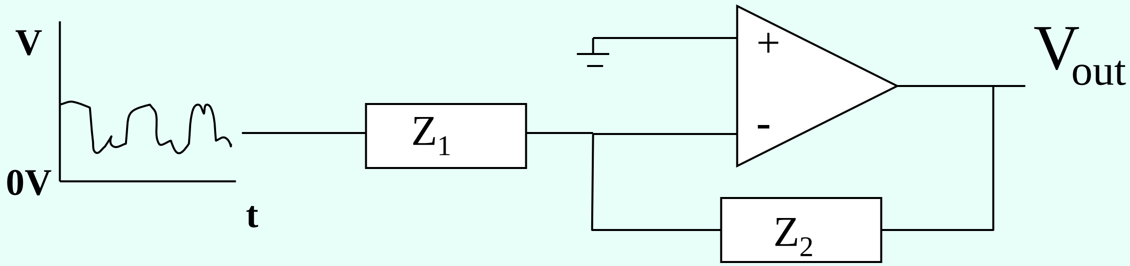
Selecting R_L ….

$Vout = I_c * R_L$

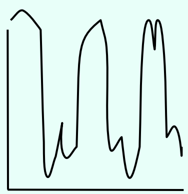
Analog circuits – filtering and detection

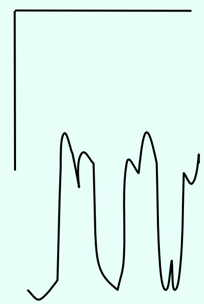
$Z_2/Z_1 = 3$

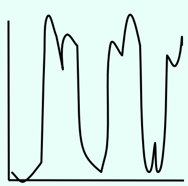
What is the result of the following:

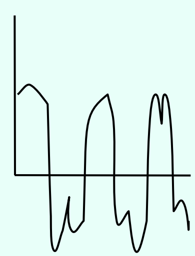


$V_{out} =$

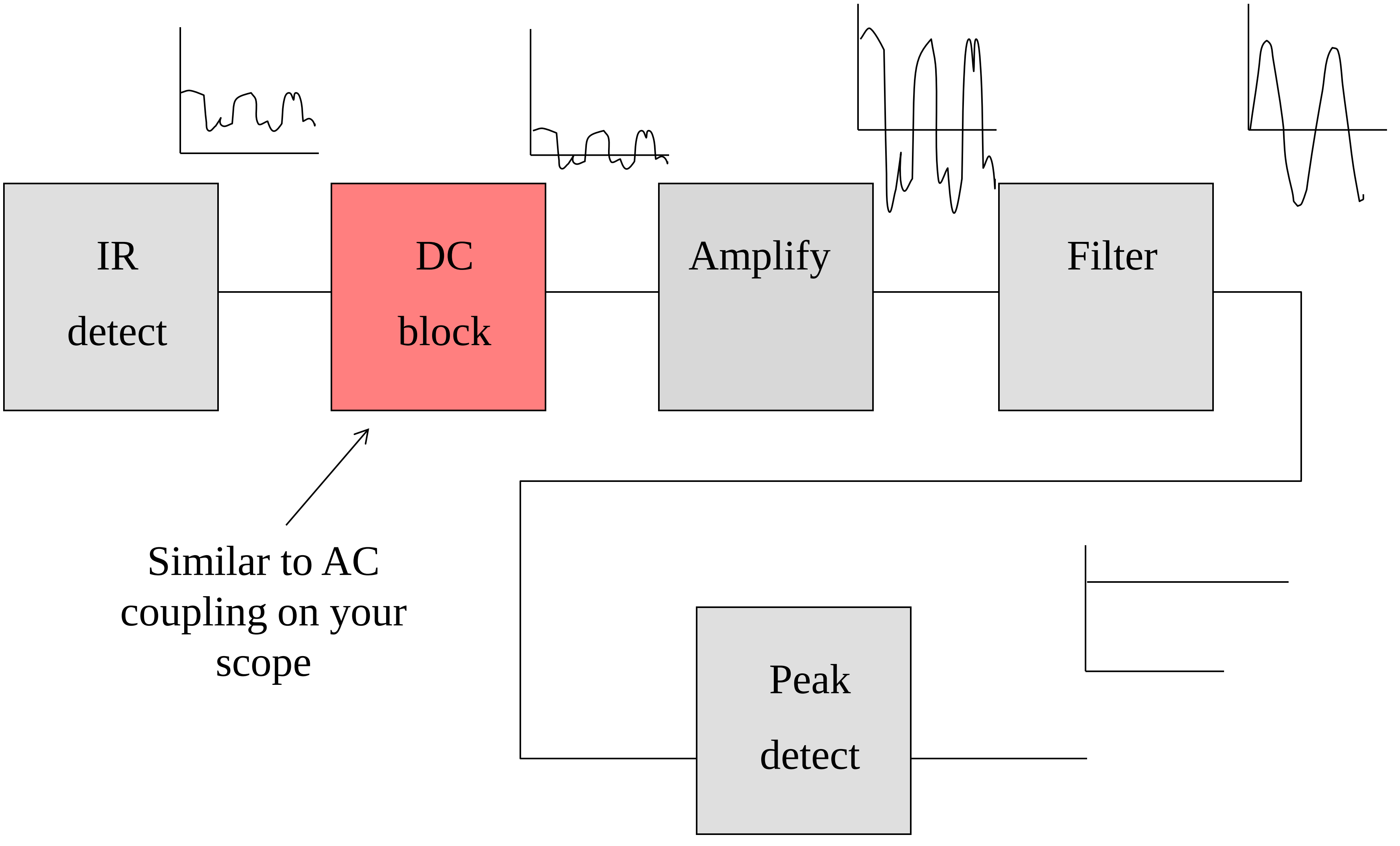
1) 

3) 

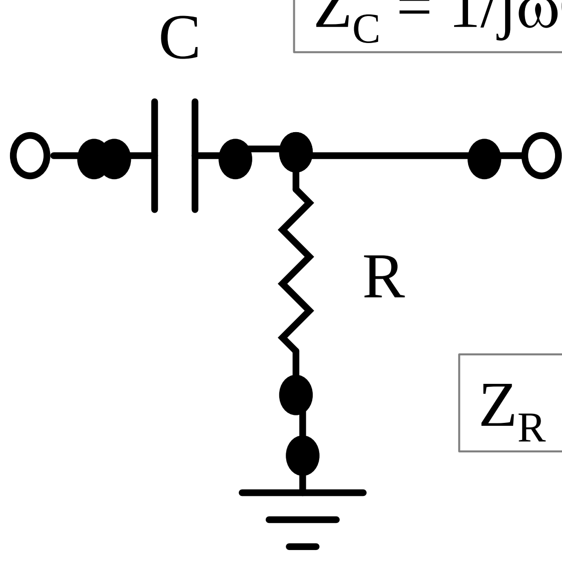
2) 

4) 

Analog circuits – filtering and detection



Analog circuits – DC block



$Z_C = 1/j\omega C$

$Z_R = R$

Capacitors:

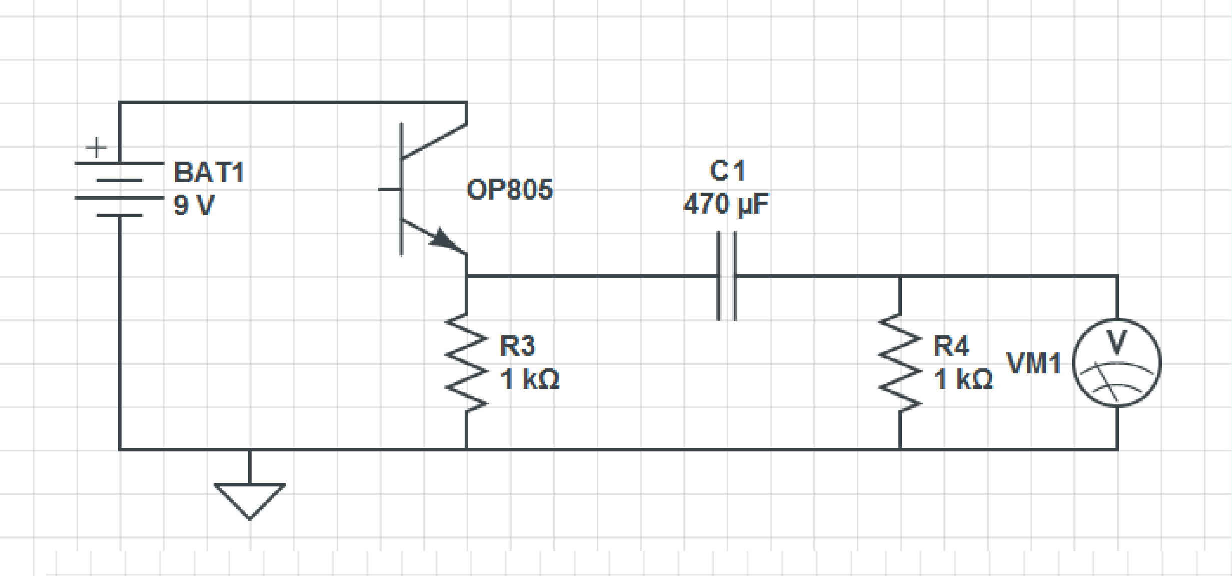
- Block DC
- Pass high frequencies > $1/(2\pi RC)$

DC block

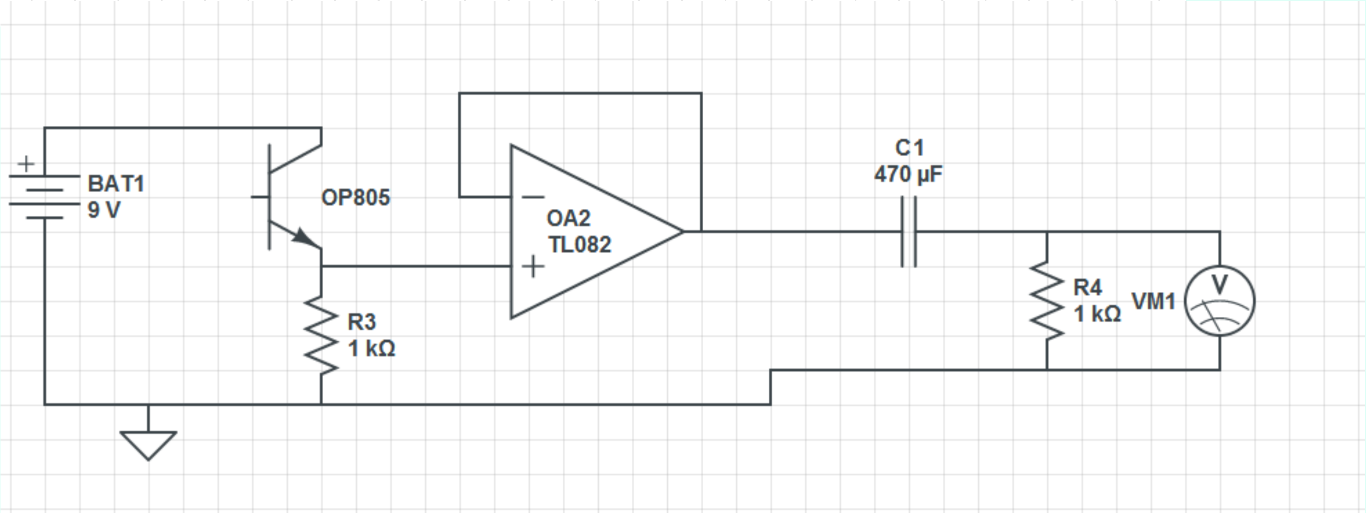
Imaging adding a DC block to your photodetector circuit:

- Which circuit would you build? Why?

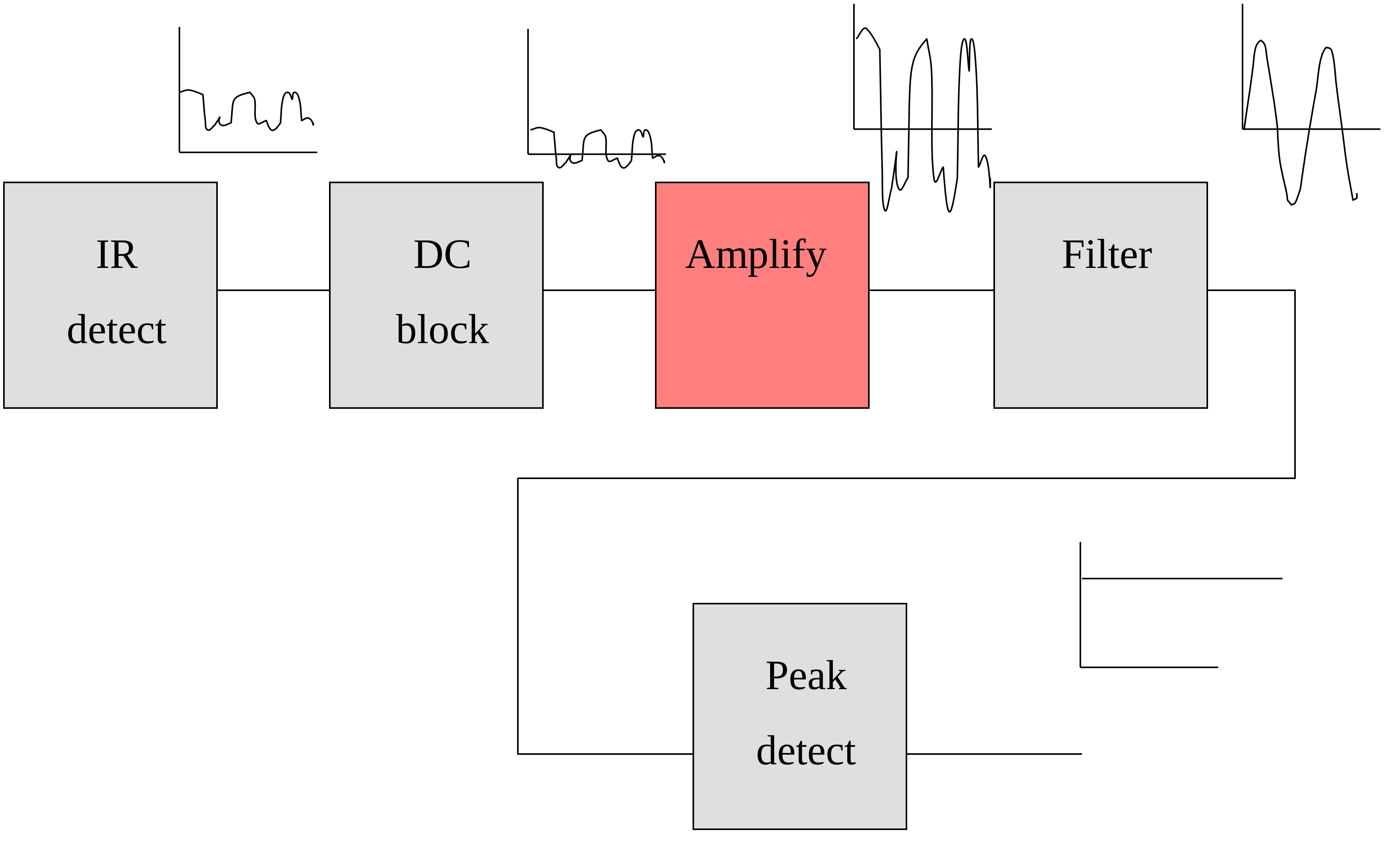
1)



2)

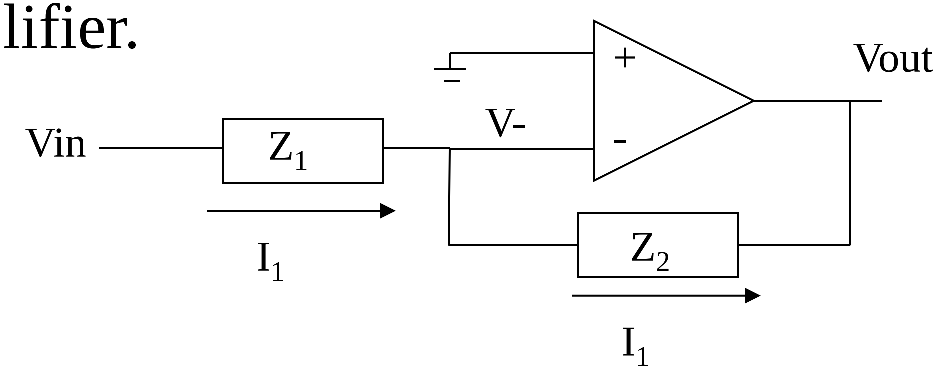


Analog circuits – filtering and detection



Analog circuits: Op-amps

Eg: Inverting amplifier.



$V_- = 0$

$I_1 = V_{in}/Z_1$

$V_{out} = 0 - Z_2 I_1$

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

Eg 1: $Z_2 = 100k\Omega$

$Z_1 = 10k\Omega$ $\quad V_{out} = -10\, V_{in}$

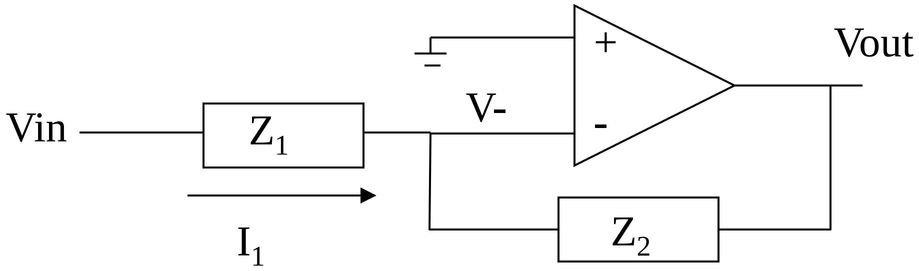
10x gain is a "reasonable" value

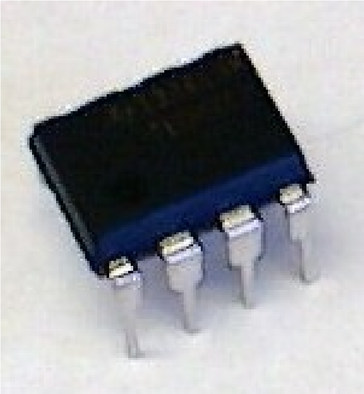
Eg 2: $Z_2 = 100k\Omega$

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

Not likely…. Why?

Analog circuits: Real Op-amps





Eg 2: $Z_2 = 100\text{k}\Omega$

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

Several problems:

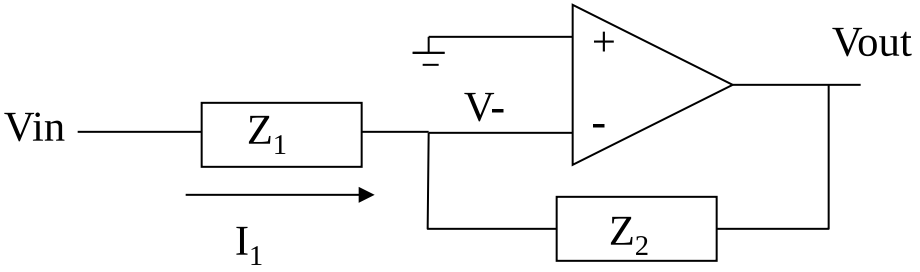
• I_1 = 1A for V_{in} = 1 V !! (excessive load for upstream circuitry)

• 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

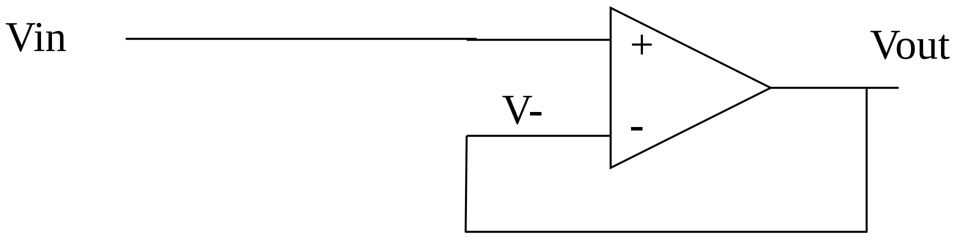


Since V_- is a virtual ground, input impedance seen by V_{in} is Z_1

Analog circuits: Real Op-amps

Things to consider:

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

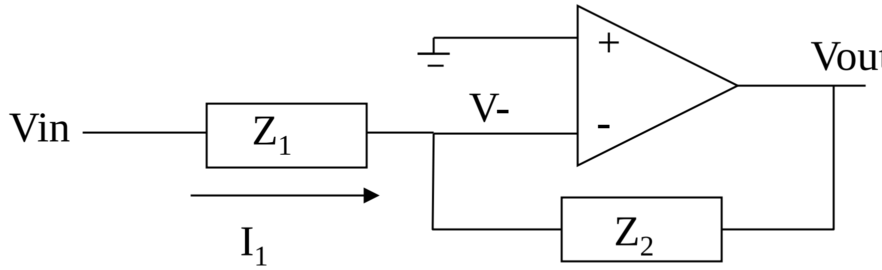


Since Op-amp inputs source or sink very little current (depends on type) , input impedance in this case is very high. This is a commonly used buffer to separate your low impedance circuit from a sensitive source that you need to measure without drawing current.

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

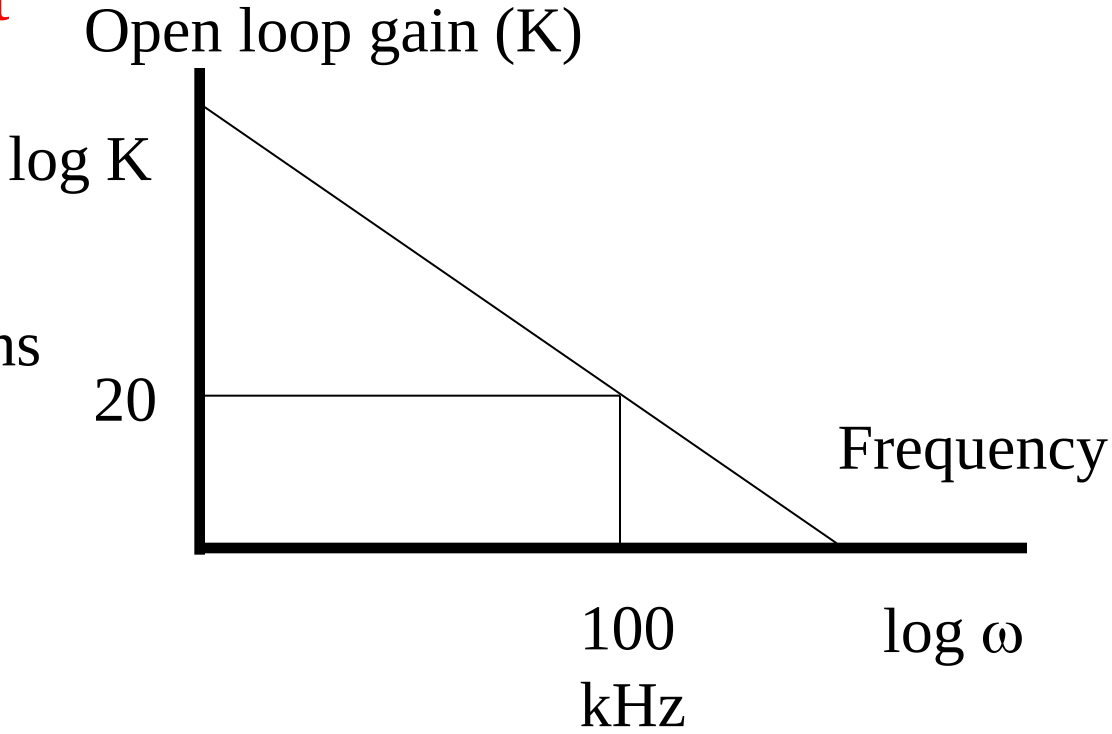
PARAMETER		TEST CONDITIONS	T_A†	TL081C TL082C TL084C			TL081AC TL082AC TL084AC			TL081BC TL082BC TL084BC			TL081I TL082I TL084I			UNIT
				MIN	TYP	MAX	MIN	TYP	MAX	MIN	TYP	MAX	MIN	TYP	MAX	
V_{IO}	Input offset voltage	V_O = 0, R_S = 50 Ω	25°C		3	15		3	6		2	3		3	6	mV
			Full range			20			7.5			5			9	
α_{VIO}	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	Full range	±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

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)

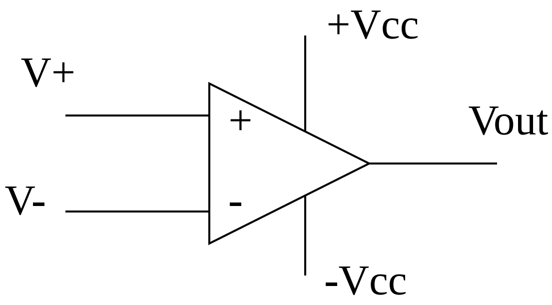
PARAMETER		TEST CONDITIONS	T_A†	TL081C TL082C TL084C			TL081AC TL082AC TL084AC			TL081BC TL082BC TL084BC			TL081I TL082I TL084I			UNIT
				MIN	TYP	MAX	MIN	TYP	MAX	MIN	TYP	MAX	MIN	TYP	MAX	
V_{IO}	Input offset voltage	V_O = 0, R_S = 50 Ω	25°C		3	15		3	6		2	3		3	6	mV
			Full range			20			7.5			5			9	
α_{VIO}	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	Full range	±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

SLOS081E – FEBRUARY 1977 – REVISED FEBRUARY 1999

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

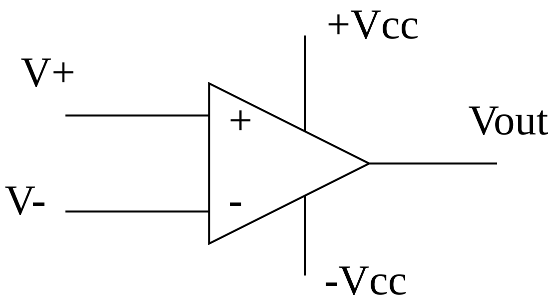
Op-amp input voltages (V_+, V_-) must be at least a few volts away from the power rails (+Vcc, -Vcc). Applying input voltages equal or near the power rails will cause the Op-amp to behave unexpectedly.

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			TL081AC TL082AC TL084AC			TLO81BC TL082BC TL084BC			TL081I TL082I TL084I			UNIT
				MIN	TYP	MAX	MIN	TYP	MAX	MIN	TYP	MAX	MIN	TYP	MAX	
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	
α_{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

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.

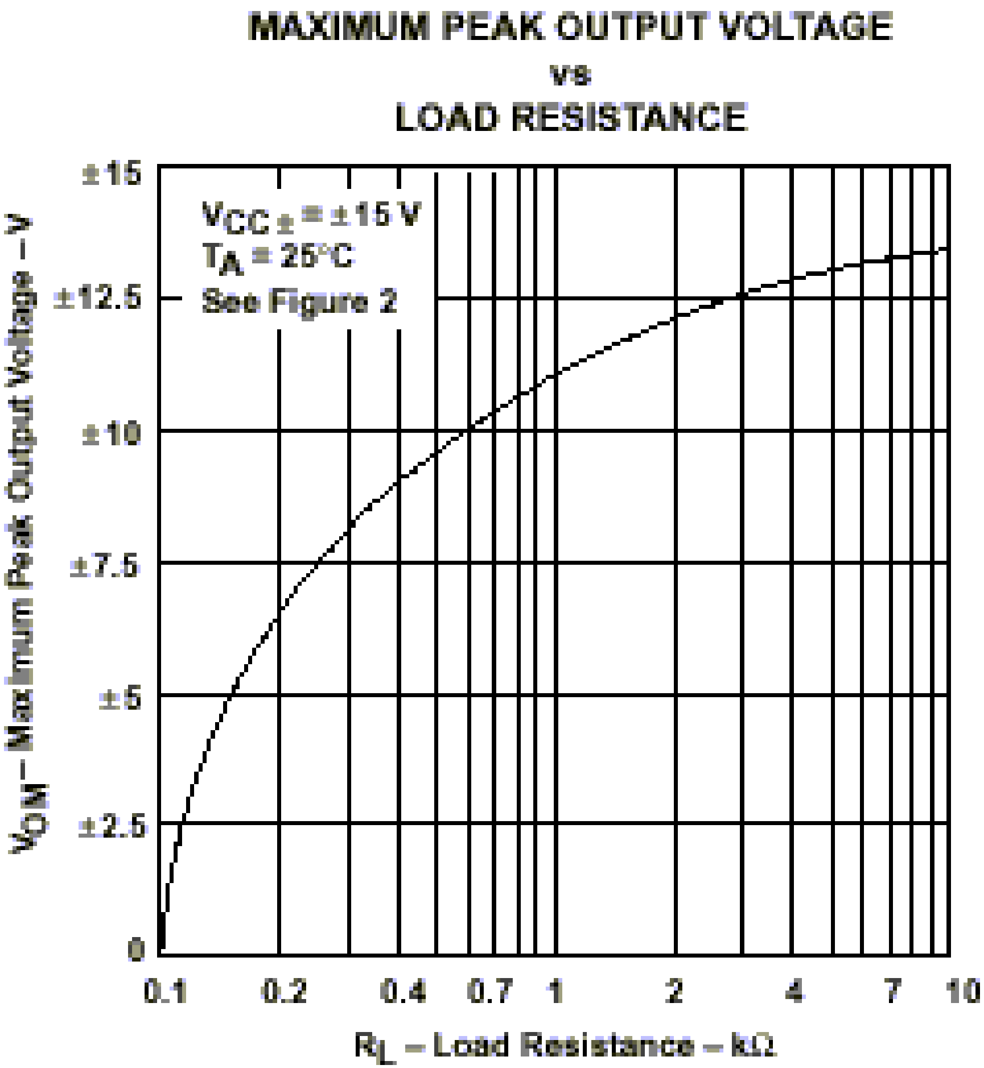
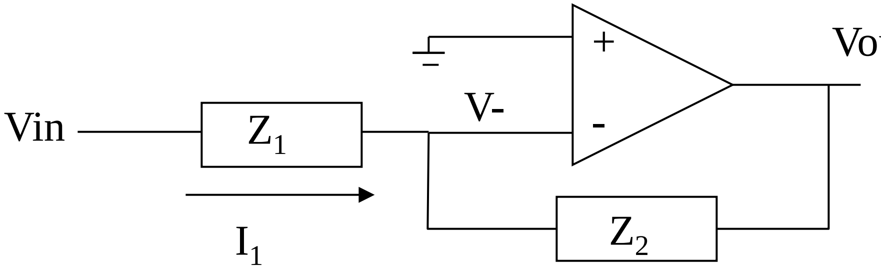

MAXIMUM PEAK OUTPUT VOLTAGE
vs
LOAD RESISTANCE
$V_{CC\pm} = \pm 15$ V
$T_A = 25°C$
See Figure 2
±15
±12.5
±10
±7.5
±5
±2.5
0
V_{OM} – Maximum Peak Output Voltage – V
0.1
0.2
0.4
0.7
1
2
4
7
10
R_L – Load Resistance – kΩ

Figure 9

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!

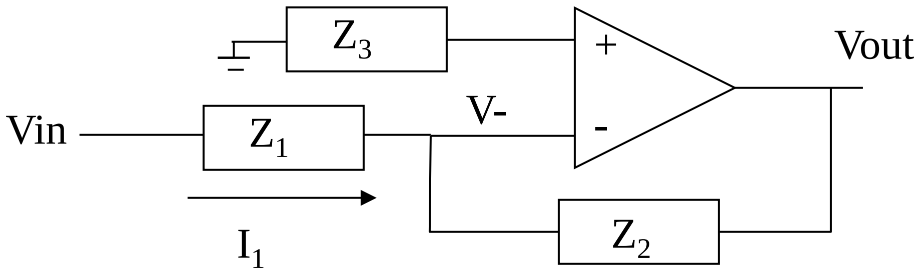
electrical characteristics, $V_{CC\pm}$ = ±15 V (unless otherwise noted)

PARAMETER		TEST CONDITIONS	T_A†	TL081C TL082C TL084C			TL081AC TL082AC TL084AC			TL081BC TL082BC TL084BC			TL081I TL082I TL084I			UNIT
				MIN	TYP	MAX	MIN	TYP	MAX	MIN	TYP	MAX	MIN	TYP	MAX	
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	
α_{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	Full range	±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

Analog circuits: Real Op-amps

Things to consider:

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



The circuit above corrects for bias current induced error and is now only subject to offset current. Z3 = Z1||Z2

Analog circuits: Real Op-amps

Summary:

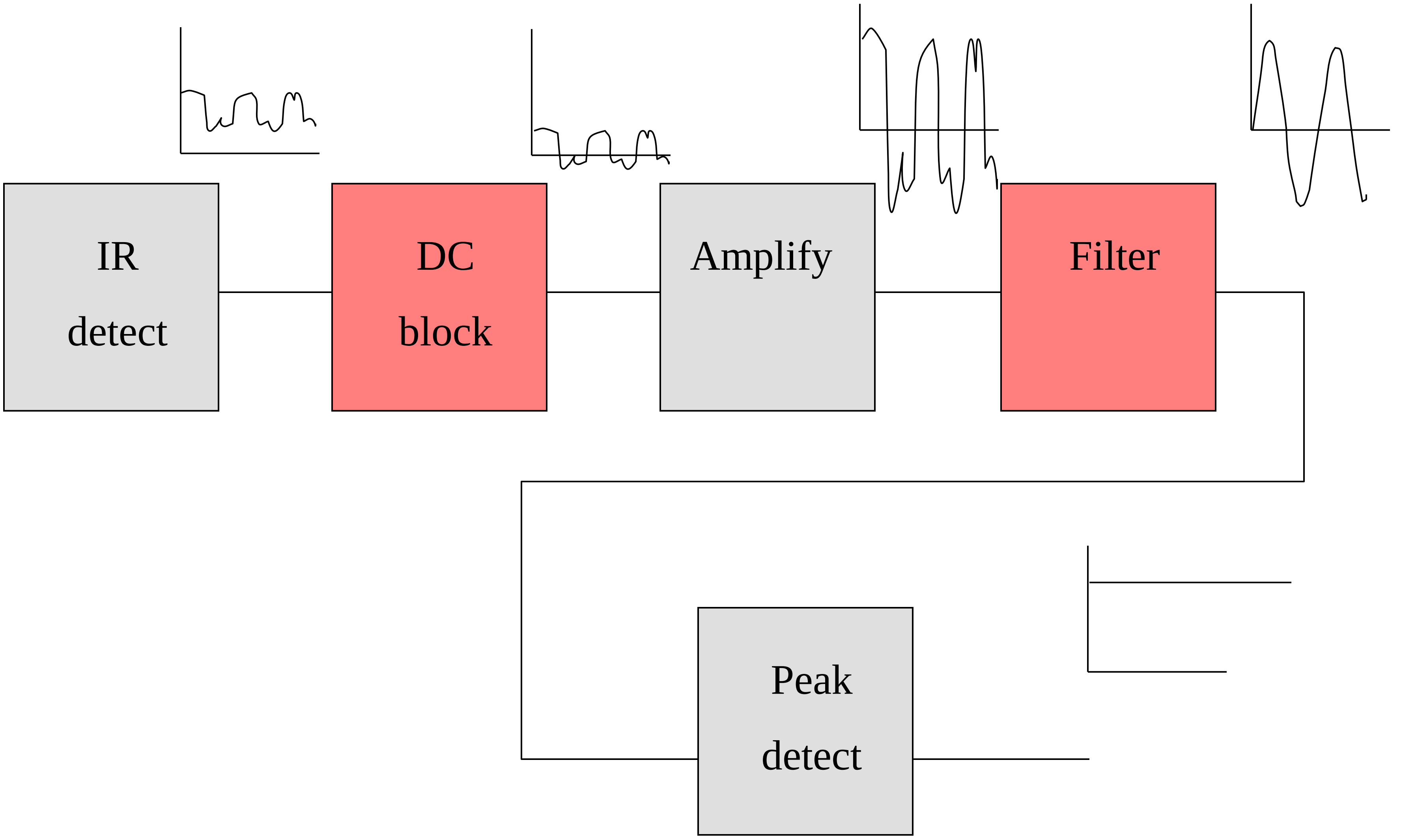
- Keep resistors in 1K to 500K range unless you really know what you’re doing.

- 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, or use a transistor)

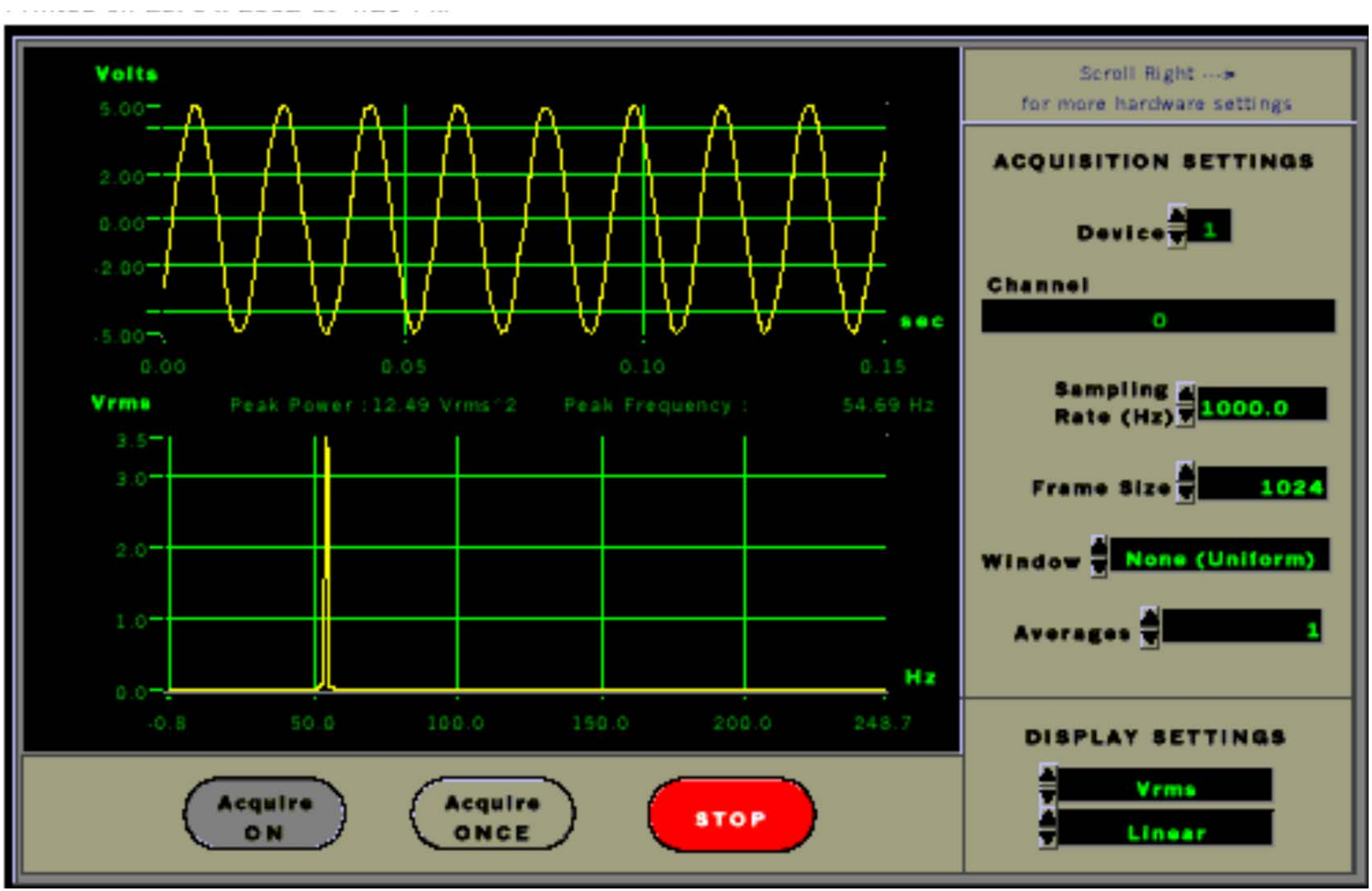
- Keep input voltages away from the op-amp voltage rails (unless using rail-to-rail opamps)

Analog circuits – filtering and detection



Analog circuits: Filters

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



Analog circuits: Filters

"Transfer Function" = Vout/Vin = H(ω)

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

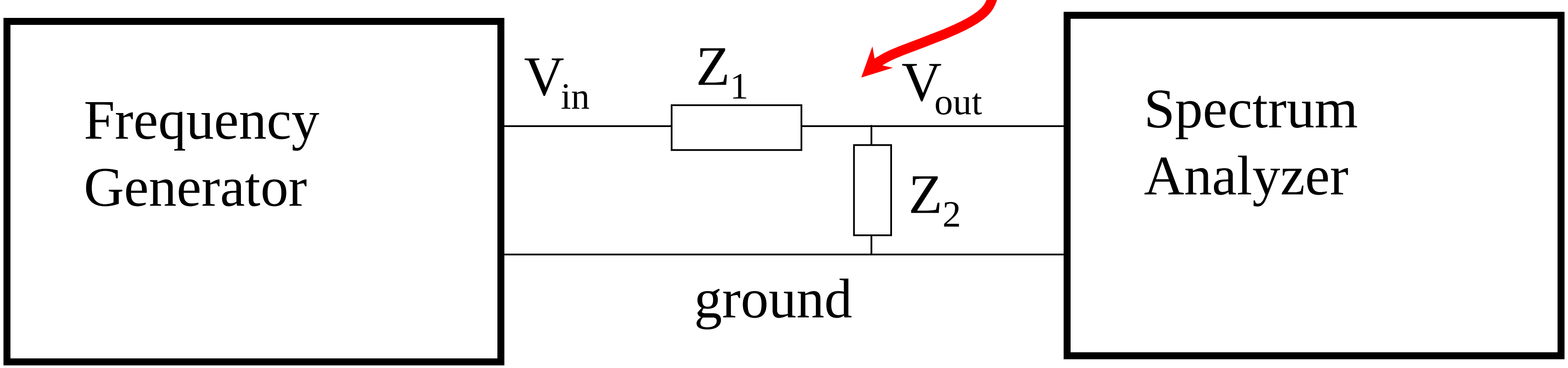
This is all in terms of ω since, in general, impedances are functions of ω.

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

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

$Z_{res} = R$

Similar to voltage divider: except ω dependent.



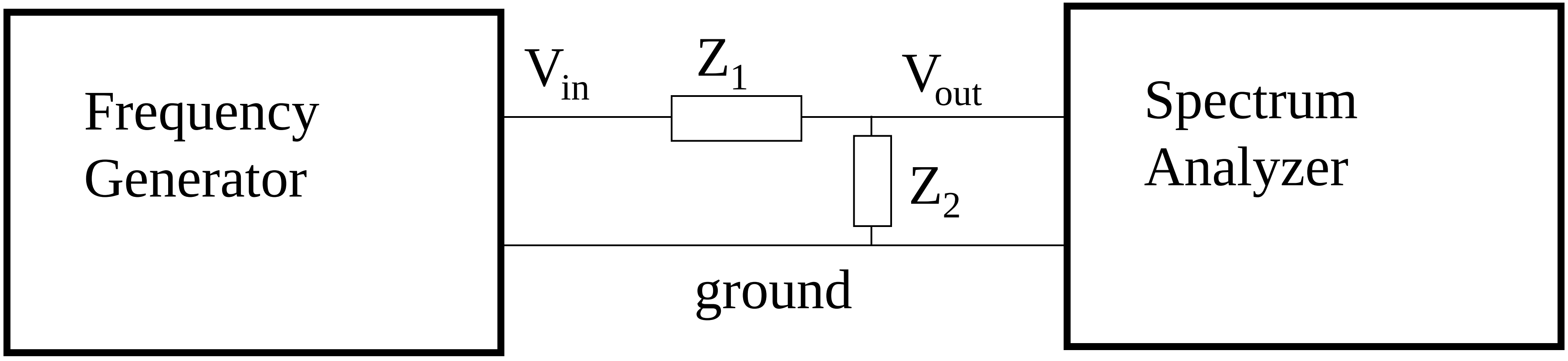
Analog circuits: Filters

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

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

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

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



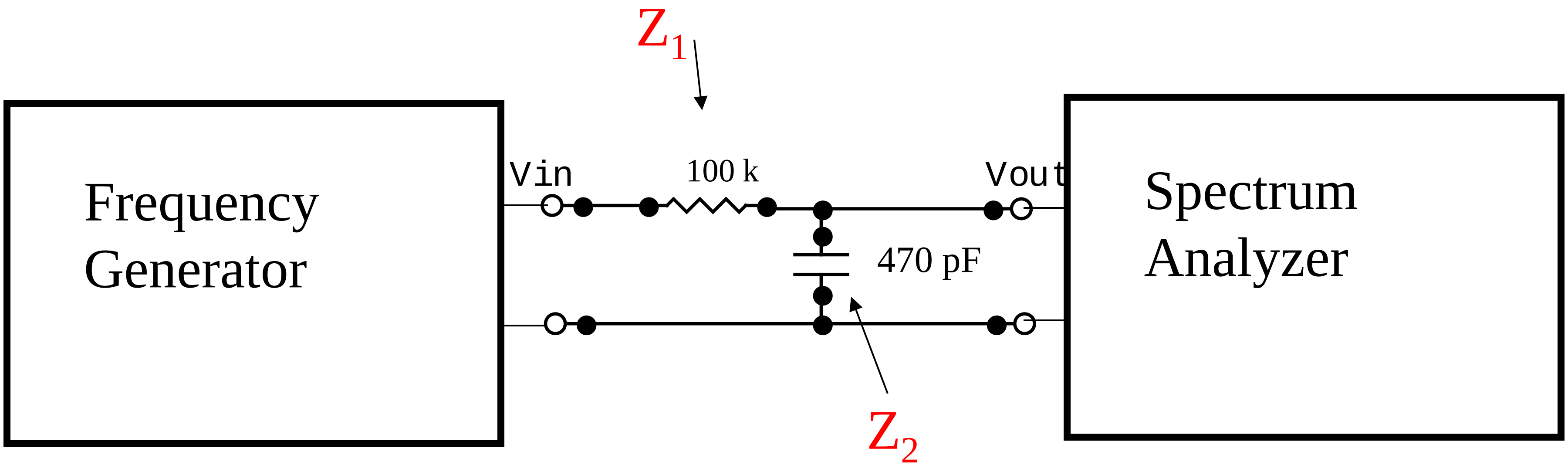
Analog circuits: Filters

Now plug in a resistor and a capacitor:

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

$Z_1 = R$

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

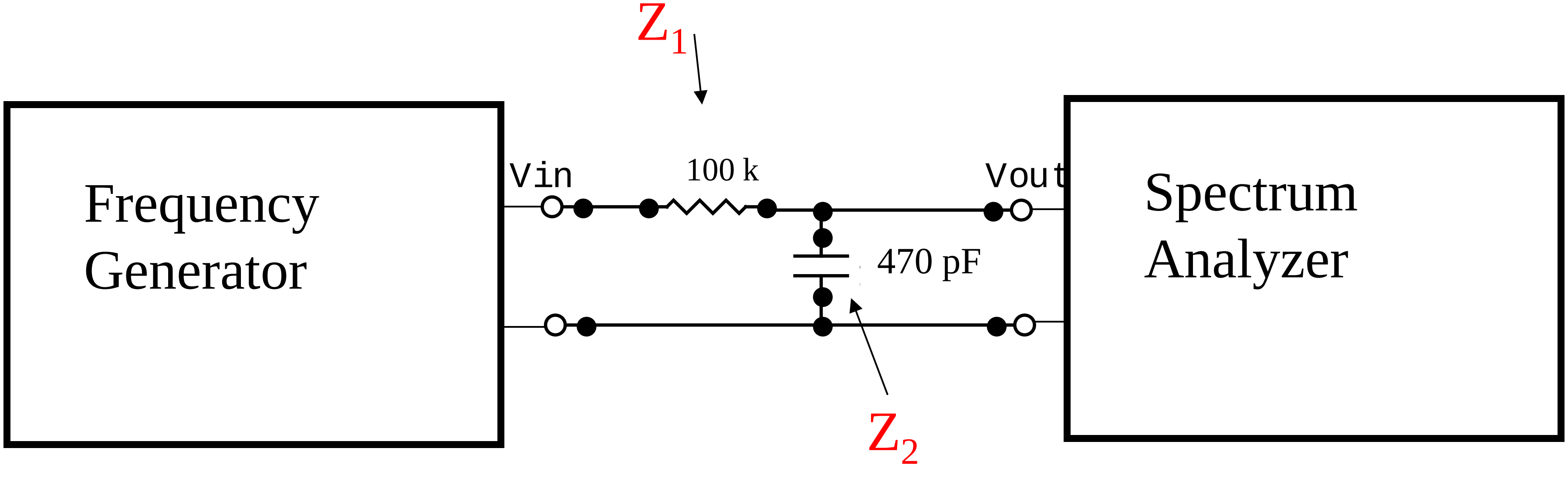


Analog circuits: Filters

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

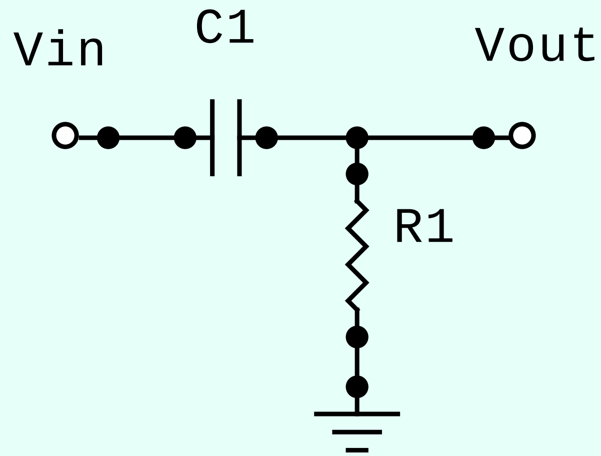
For low frequencies (small ω), H = 1
For high frequencies (large ω), H = 0
This is a LOW PASS FILTER

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

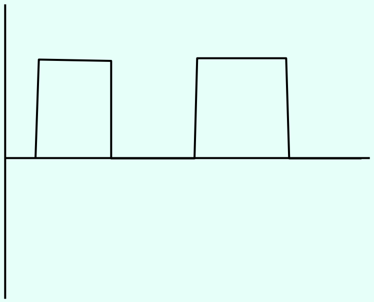


$f_0 = 1/(2\pi RC) = 3.3\text{ kHz}$

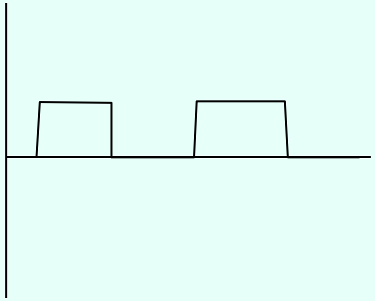
Analog circuits: Filters



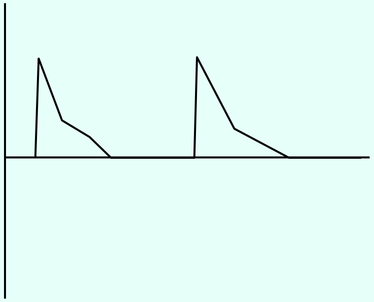
How does this circuit affect the following waveform:



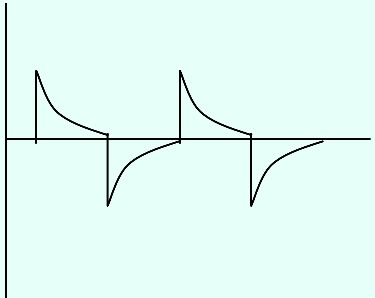
1)



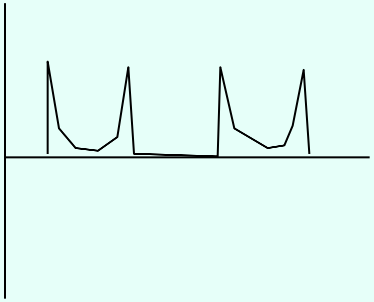
3)



2)



4)



Analog circuits: Transfer Functions

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

Vertical axis:

$20\log_{10}(H)$

(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

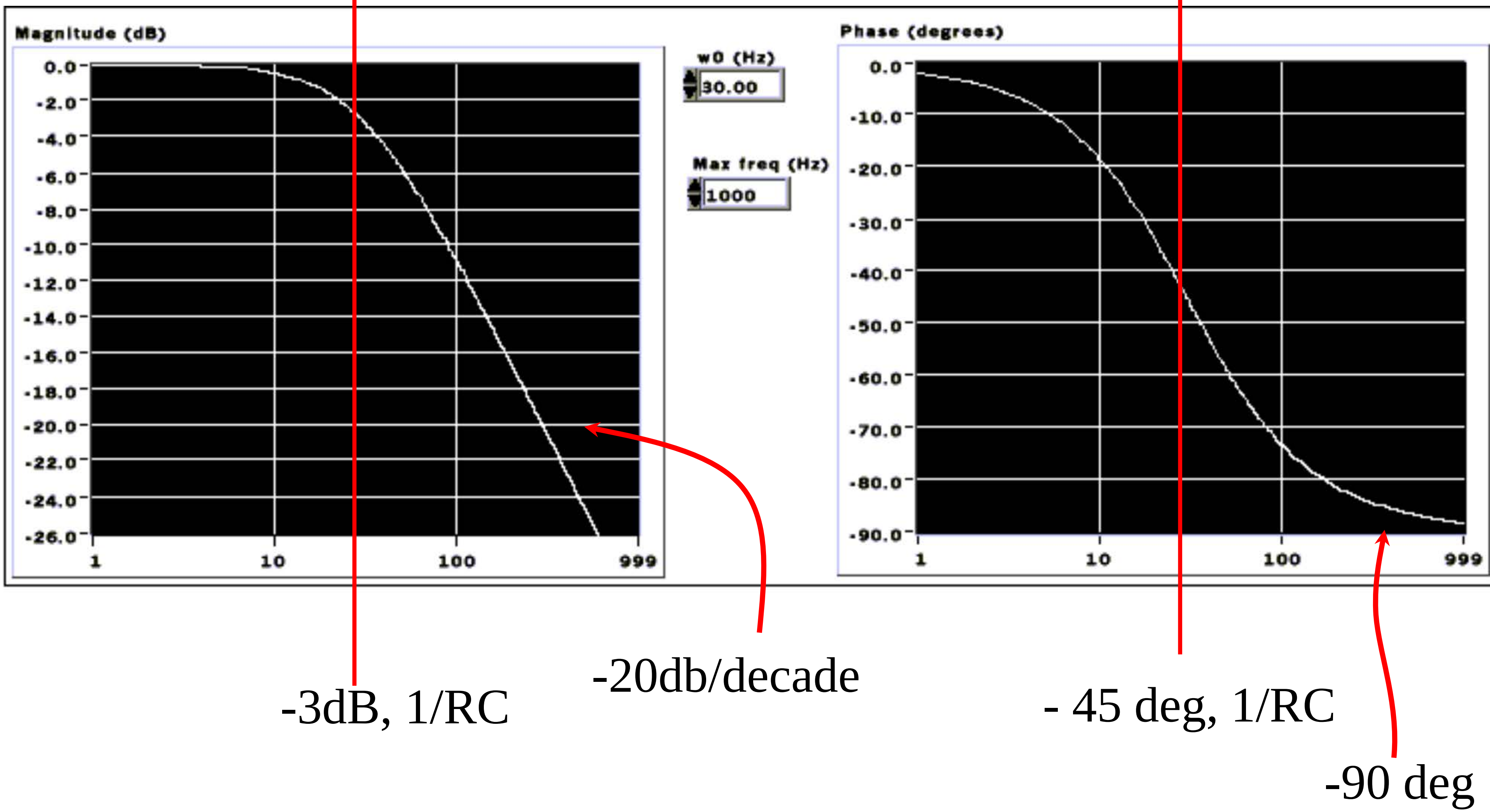
Pole: $1/(1+j\omega/\omega_0)$ -20 db/decade in amplitude after ω_0, -90 phase

Zero: $(1+j\omega/\omega_0)$ +20 db/decade in amplitude after ω_0, +90 phase

Analog circuits: Simple Pole

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

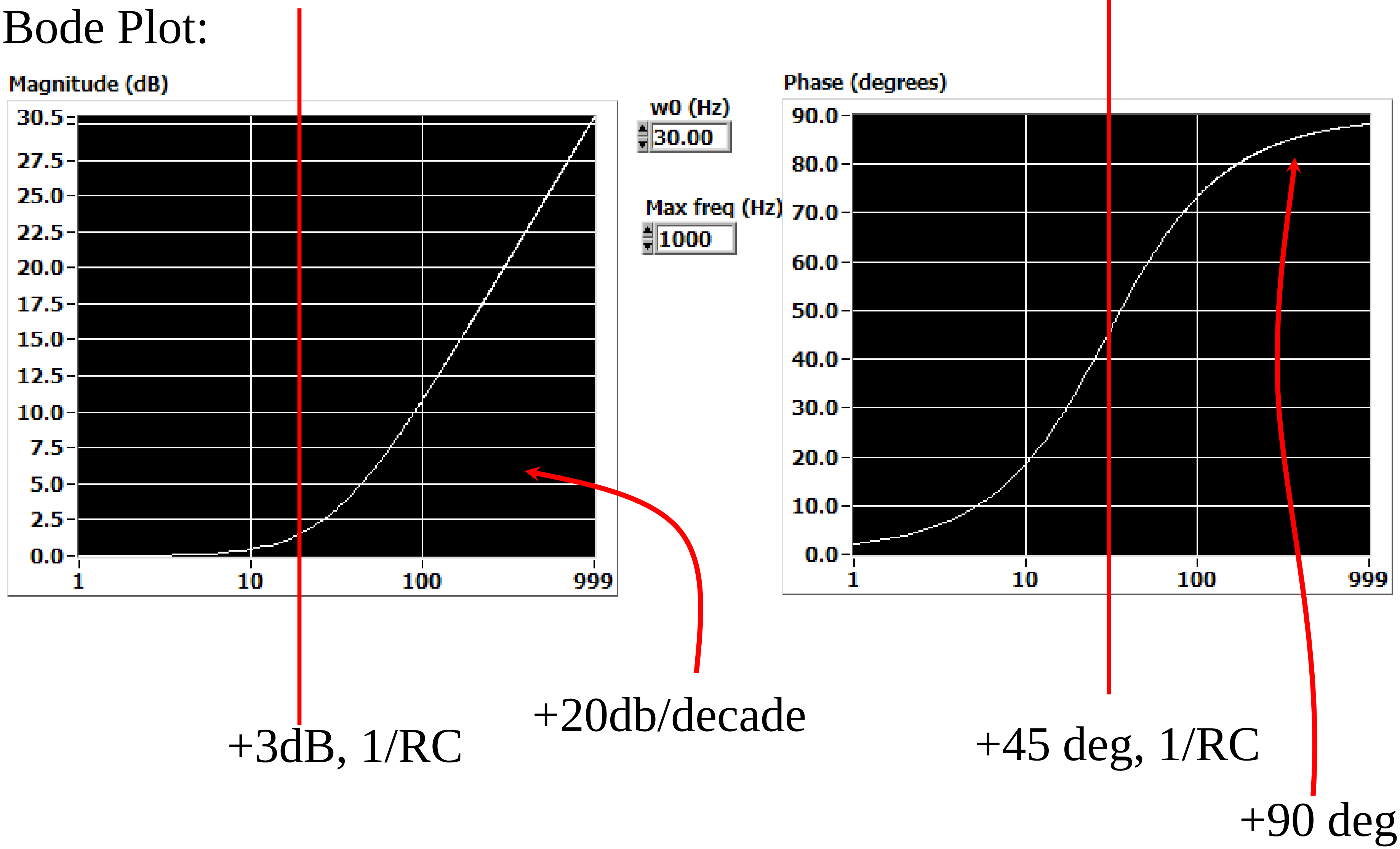
Bode Plot:



Analog circuits: Simple Zero

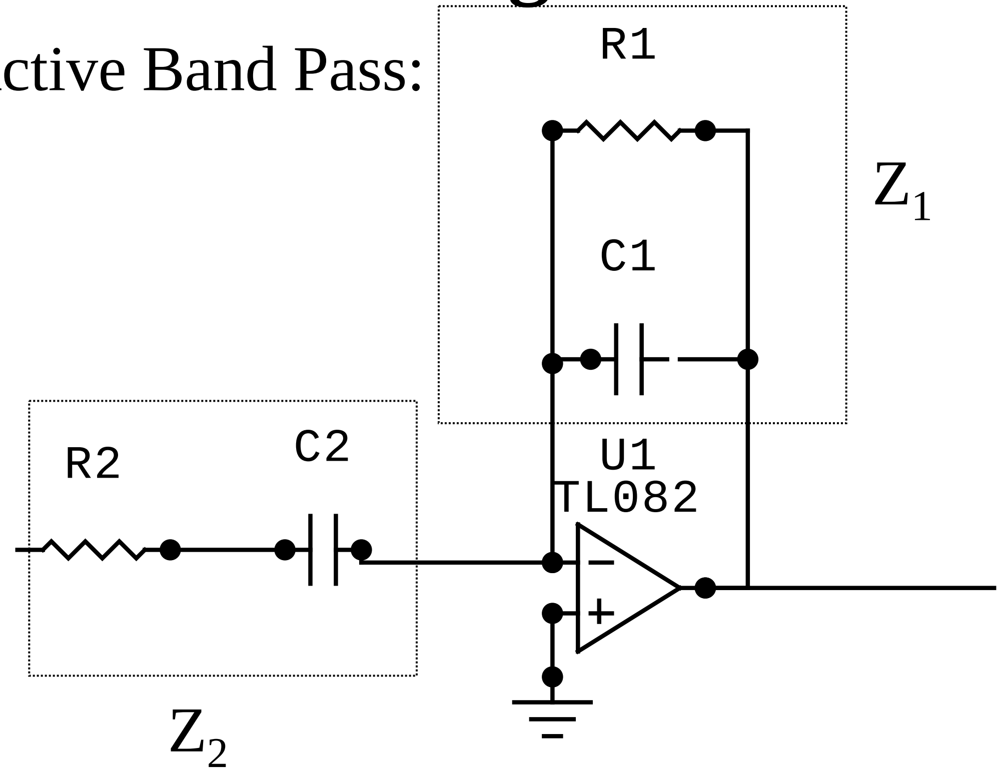
$$H(\omega) = 1 + j\omega RC$$

Bode Plot:



Analog circuits: Active Filters

Active Band Pass:



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

$H = -(Z_1/Z_2)$

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: Transfer Functions

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

Zero at ω=0

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

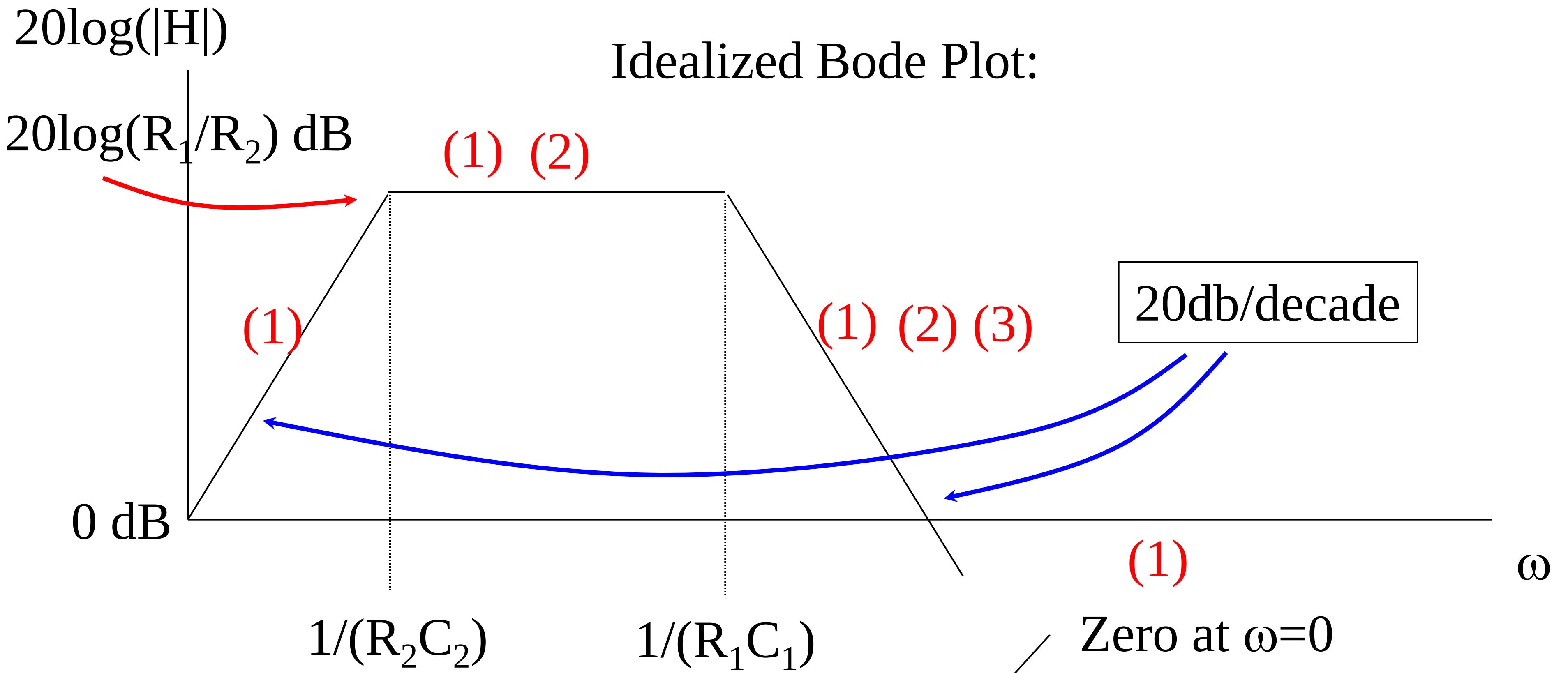
Pole at $\omega = 1/(R_2C_2)$

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

Pole: $1/(1+j\omega/\omega_0)$ -20 db/decade in amplitude after ω_0, -90 phase

Zero: $(1+j\omega/\omega_0)$ +20 db/decade in amplitude after ω_0, +90 phase

Analog circuits: Active Filters



Zero at ω=0

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

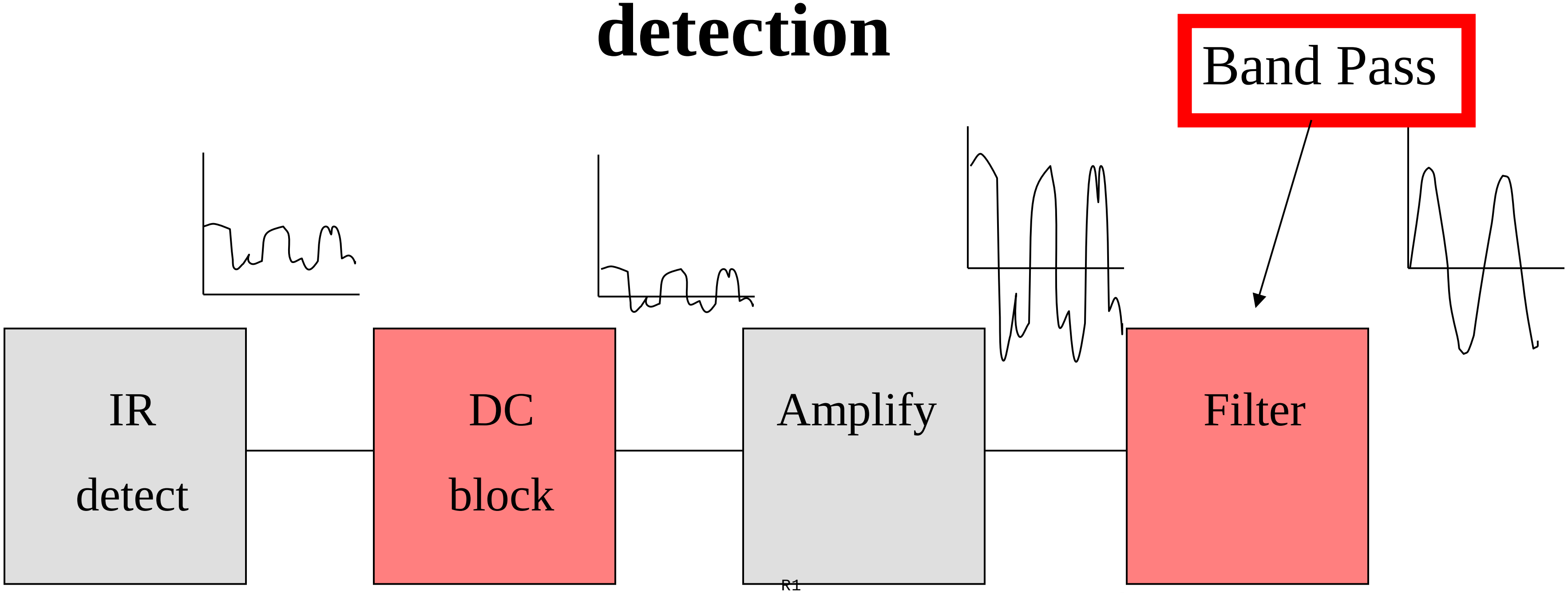
(2)

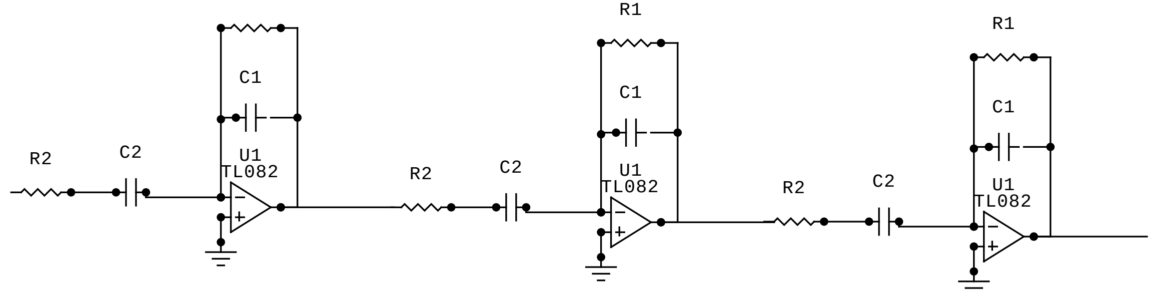
Pole at $\omega = 1/(R_2 C_2)$

(3)

Pole at $\omega = 1/(R_1 C_1)$

Analog circuits – filtering and detection





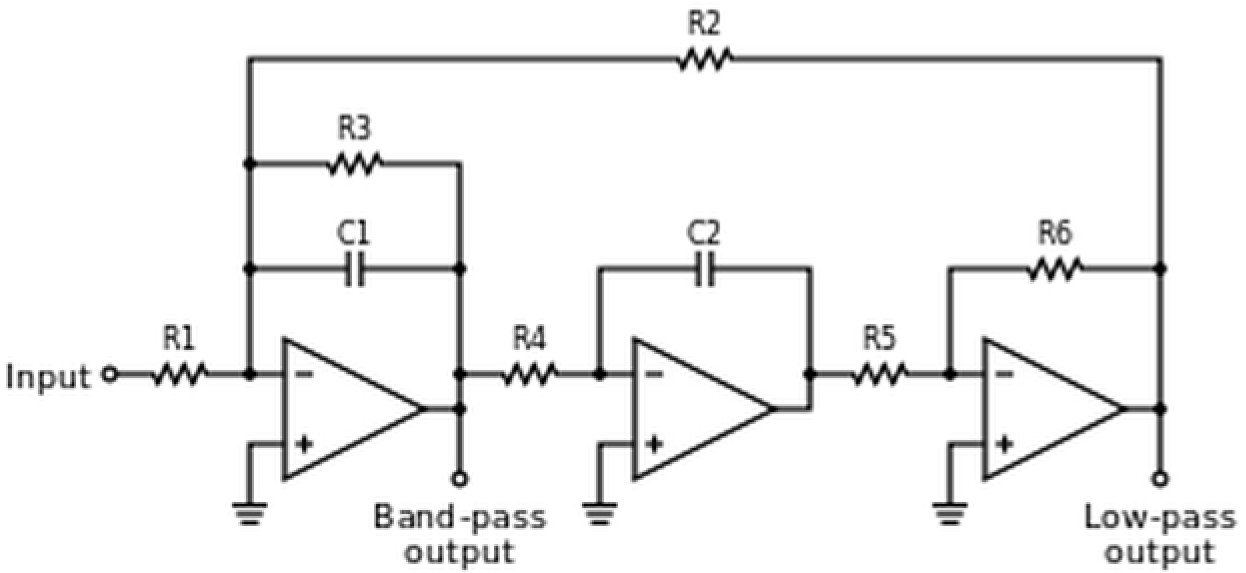
High pass

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

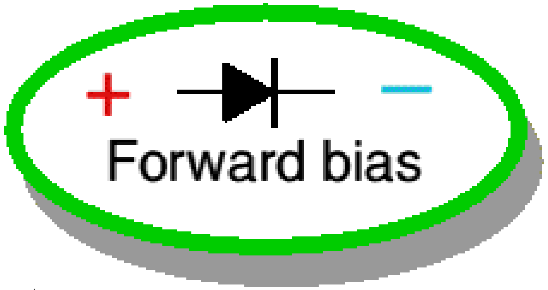


with bandpass gain $G_{bpf} = -R_4/R_2$. In both cases, the

- Natural frequency is $\omega_0 = 1/\sqrt{R_2 R_4 C_1 C_2}$.
- Quality factor is $Q = \sqrt{\dfrac{R_3^2 C_1}{R_2 R_4 C_2}}$.

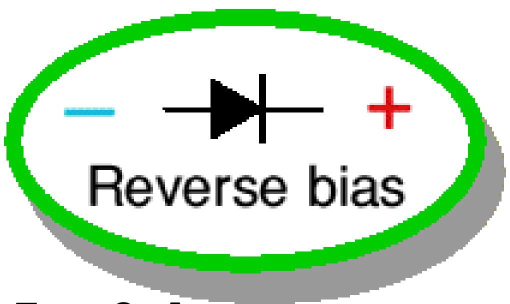
The bandwidth is approximated by $B = \omega_0/Q$,

Discrete devices: diodes



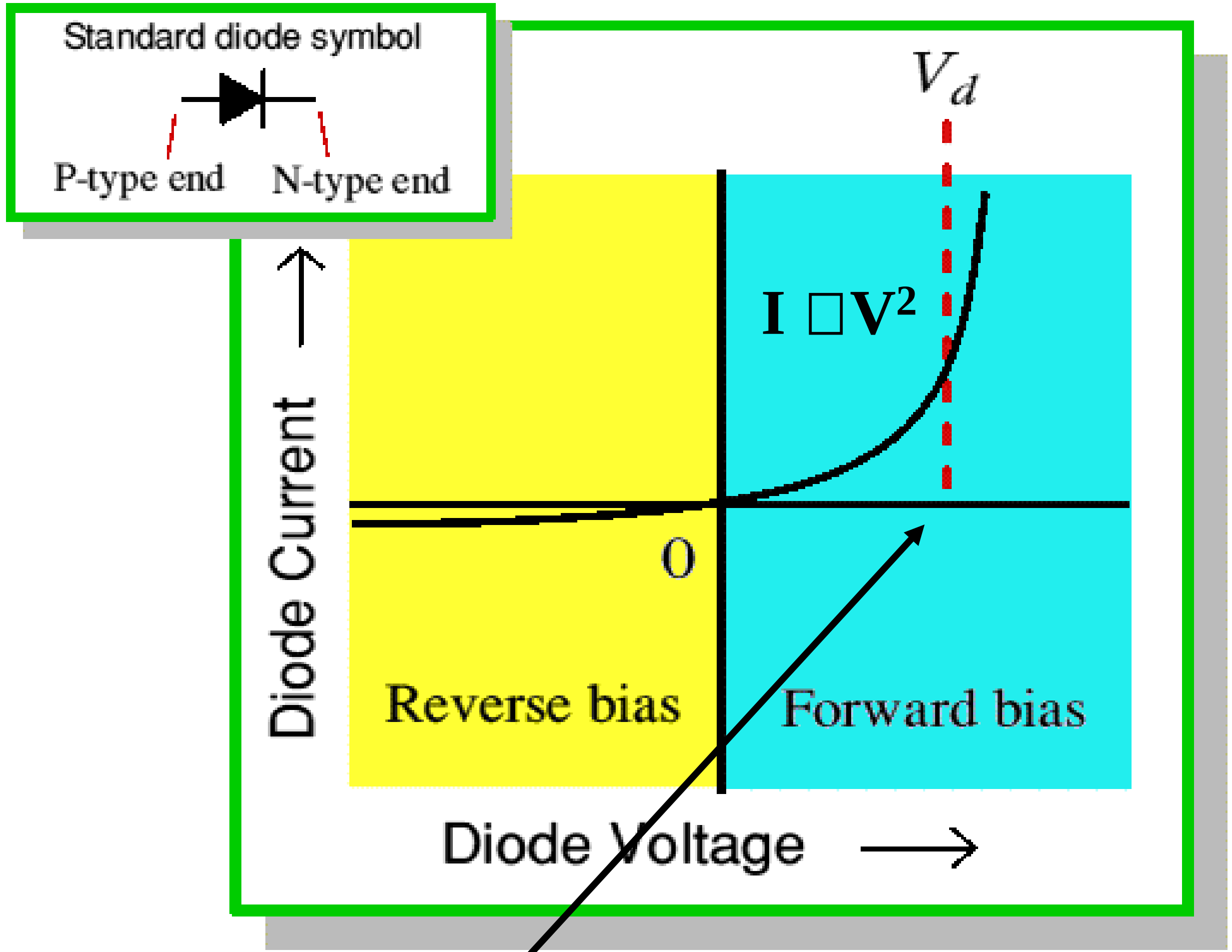
ΔV = 0.7 V

Treat as conductor



I = 0 A

Treat as open circuit



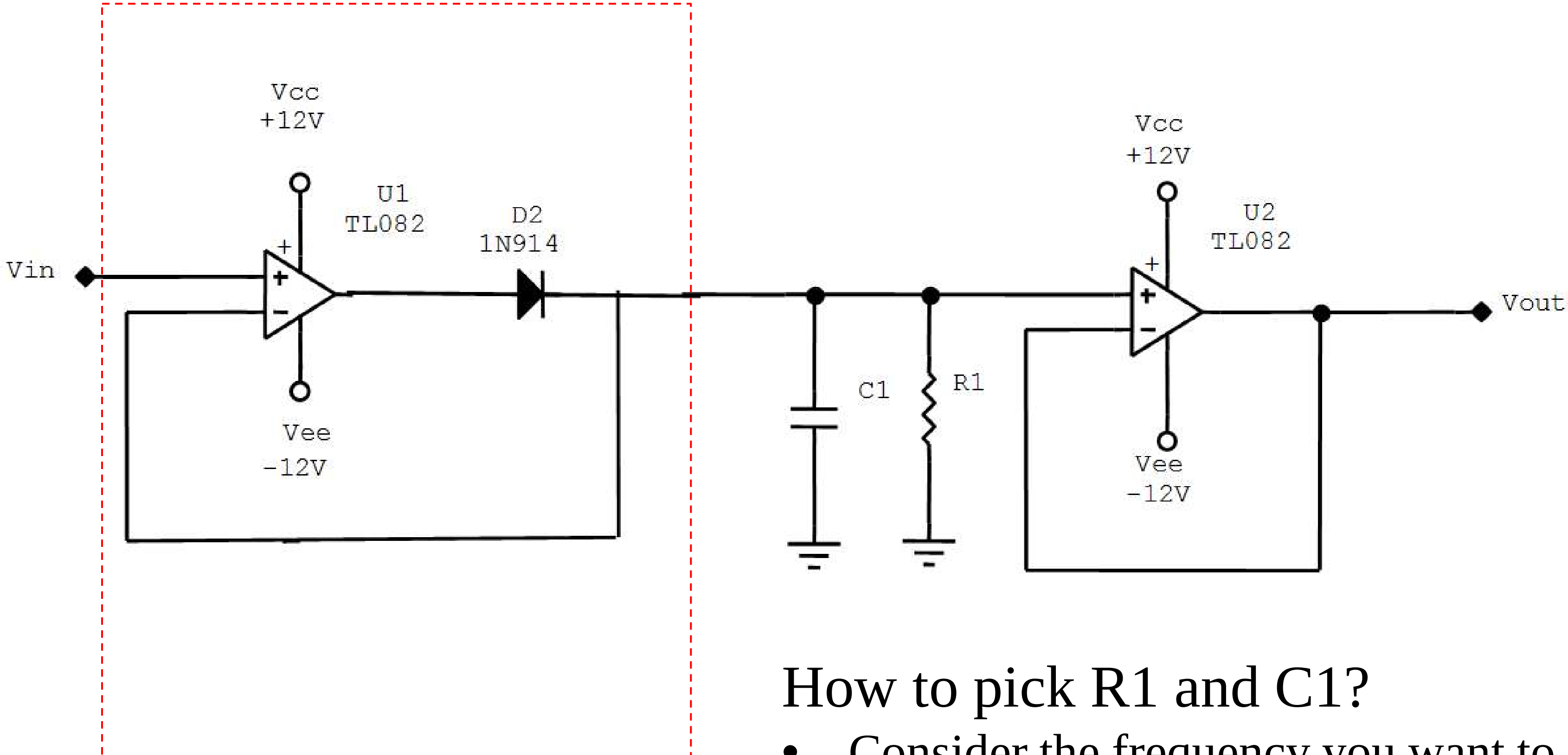
Typical ~ 0.7 V

Diagrams courtesy of: University of St. Andrews, St Andrews, Fife KY16 9SS, Scotland

SUPER-DIODE rectifier circuit

This circuit acts like a perfect diode, without the 0.7V deadband prior to turn-on.

What bad thing happens if R1 is too big?



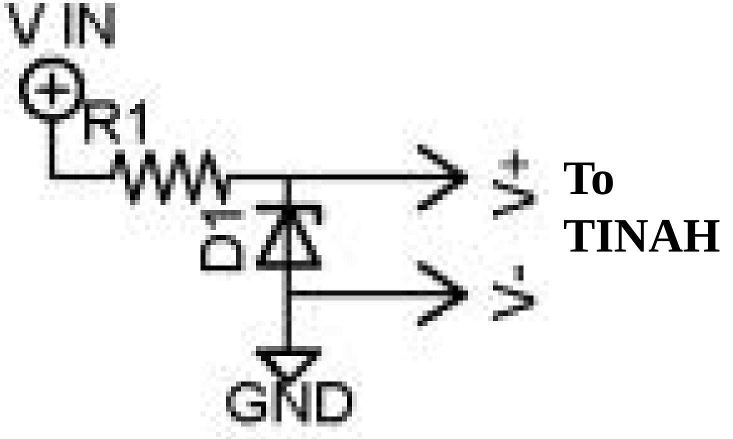
How to pick R1 and C1?

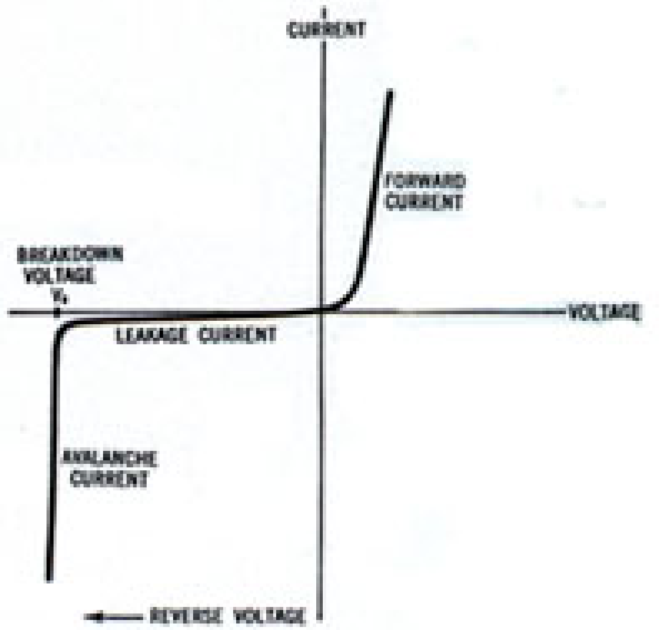
- Consider the frequency you want to filter out
- Consider the response time you want

Zener Diodes

Use 5V Zener Diodes to protect your TINAH Board

Zener diodes (5V1)





Current-voltage characteristics of a typical P-N junction.

Zener diodes conduct under reverse bias when a specific voltage is exceeded – in our case 5.1V

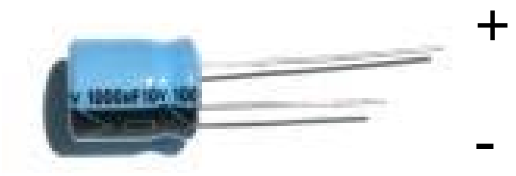
Debugging Circuits

Learn to systematically check your circuits:

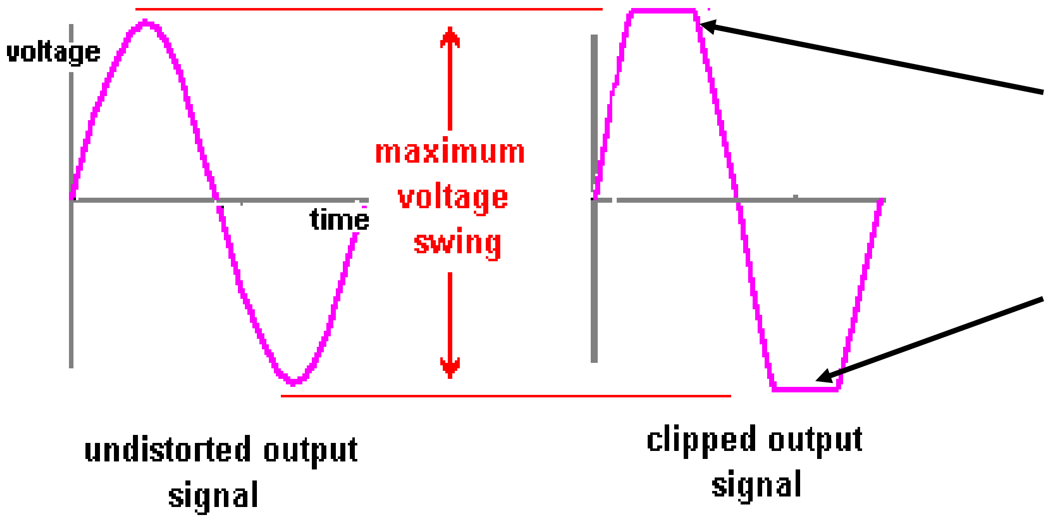
- **Power rails:**
  - Check that 15V is really 15V; if not, localize the component that is shorting the power rail. Check power at each chip.
- **Physical check**:
  - Check pinouts, missing/loose wires, etc.
- **Isolate stages** where possible
  - Check output of stage 1 – if ok plug into stage 2 and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



Sharp corners have high-frequency noise

Saturation looks like DC signal!