Linear Circuit Experiment (MAE171a)

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class information and lab handouts will be available on
http://maecourses.ucsd.edu/labcourse/

Main Objectives of Laboratory Experiment:

modeling, building and debugging of op-amp based linear circuits for standard signal conditioning

Ingredients:

- modeling of standard op-amp circuits
- signal conditioning with application to audio (condensor microphone as input, speaker as output)
- implementation & verification of op-amp circuits
- sensitivity and error analysis

Background Theory:

- Operational Amplifiers (op-amps)
- Linear circuit theory (resistor, capacitors)
- Ordinary Differential Equations (dynamic analysis)
- Amplification, differential & summing amplifier and filtering

Outline of this lecture

- Linear circuits & purpose of lab experiment
- Background theory
  - op-amp
  - linear amplification
  - single power source
  - differential amplifier
  - summing circuit
  - filtering
- Laboratory work
  - week 1: microphone and amplification
  - week 2: mixing via difference and adding
  - week 3: filtering and power boost
- Summary

Linear Circuits & Signal Conditioning

Signal conditioning crucial for proper signal processing. Applications may include:

- Analog to Digital Conversion
  - Resolution determined by number of bits of AD converter
  - Amplify signal to maximum range for full resolution
- Noise reduction
  - Amplify signal to allow processing
  - Filter signal to reduce undesired aspects
- Feedback control
  - Feedback uses reference $r(t)$ and measurement $y(t)$
  - Compute difference $e(t) = r(t) - y(t)$
  - Amplify, Integrate and or Differentiate $e(t)$ (PID control)
- Signal generation
  - Create sinewave of proper frequency as carrier
  - Create blockwave of proper frequency for counter
  - etc. etc.

Purpose of Lab Experiment

In this laboratory experiment we focus on a (relatively simple) signal conditioning algorithms: *amplification*, *adding/difference* and basic (at most 2nd order) *filtering*.

Objective: to model, build and debug op-amp based linear circuits that allow signal conditioning algorithms.

We apply this to an audio application, where the signal of a condenser microphone needs to amplified, mixed and filtered.

Challenge: single source power supply of 5 Volt. Avoid clipping/distortion of amplified, mixed and filtered signal.

Aim of the experiment:

- insight in op-amp based linear circuits
- build and debug (frustrating)
- compare theory (ideal op-amp) with practice (build and test)
- verify circuit behavior (simulation/PSPICE)

Background Theory - op-amp

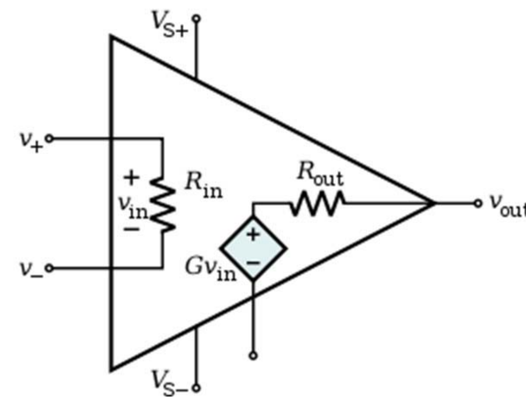
op-amp = operational amplifier

more precise definition:
DC-coupled high-gain electronic voltage amplifier with differential inputs and a single output.

- DC-coupled: constant (direct current) voltage at inputs results in a constant voltage at output
- differential inputs: two inputs V_- and V_+ and the difference $V_\delta = V_+ - V_-$ is only relevant
- high-gain: $V_{out} = G(V_+ - V_-)$ where $G >> 1$.

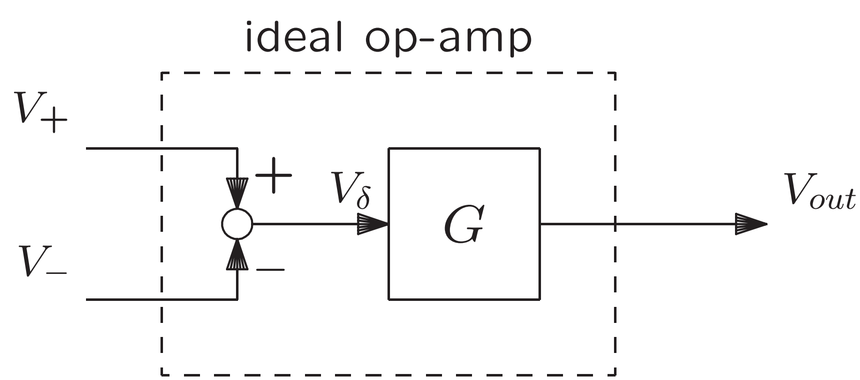
Background Theory - op-amp

Ideal op-amp (equivalent circuit right):

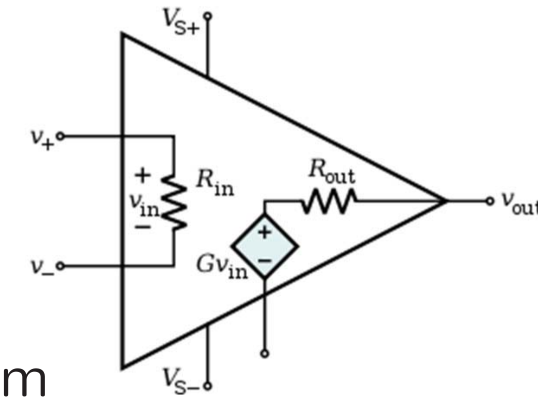


- input impedance: $R_{in} = \infty \Rightarrow i_{in} = 0$
- output impedance: $R_{out} = 0$
- gain: $V_\delta = (V_+ - V_-)$, $V_{out} = GV_\delta$, $G = \infty$
- rail-to-rail: $V_{S-} \leq V_{out} \leq V_{S+}$

Ideal op-amp (block diagram below)



Background Theory - op-amp



Infinite input impedance ($R_{in} = \infty$) useful to minimize load on sensor/input.

Zero output impedance ($R_{out} = 0$) useful to minimize load dependency and obtain maximum output power.

Rail-to-rail operation to maximize range of output V_{out} between negative source supply V_{S-} and positive source supply V_{S+}.

But why (always) infinite gain G? Obviously:

$$V_{out} = \begin{cases} V_{S+} & \text{if} \quad V_+ > V_- \\ 0 & \text{if} \quad V_+ = V_- \\ V_{S-} & \text{if} \quad V_+ < V_- \end{cases}$$

not very useful with any (small) noise on V_+ or V_-.

Background Theory - op-amp

Usefulness of op-amp with high gain G only by **feedback**!

Consider open-loop behavior:

$$V_{out} = GV_\delta, \text{ where } V_\delta = V_+ - V_-$$

and create a feedback of V_{out} by choosing

$$V_- = KV_{out}$$

to make

$$V_\delta = V_+ - KV_{out}$$

Then

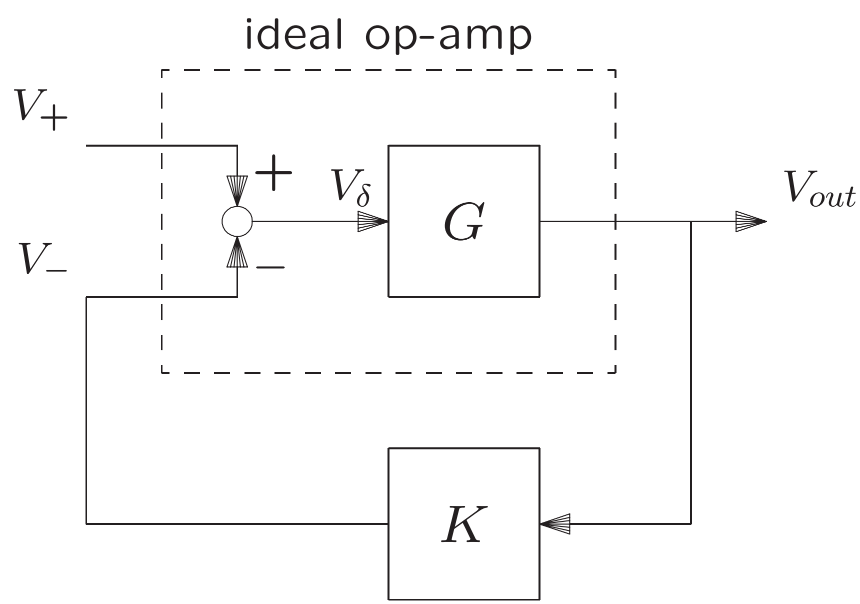
$$V_{out} = GV_\delta = GV_+ - GKV_{out}$$

allowing us to write

$$V_{out} = \frac{G}{1+GK}V_+$$

Background Theory - op-amp

So, with the feedback $V_- = KV_{out}$ we obtain $V_{out} = \frac{G}{1+GK}V_+$



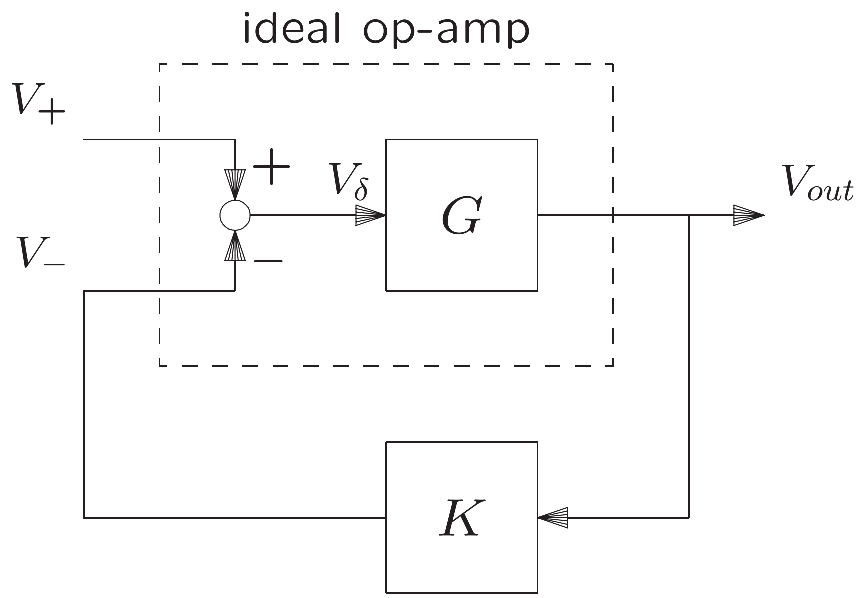
In case $G \to \infty$ we see:

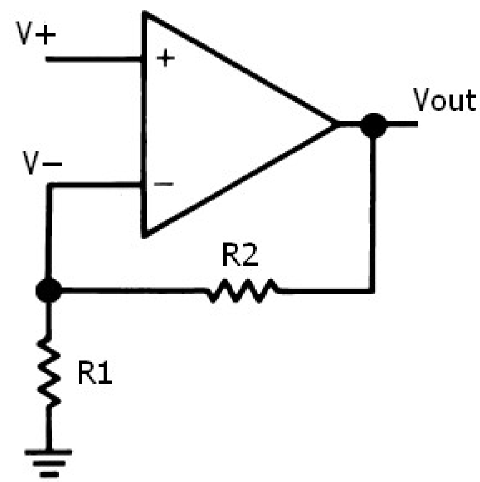
$$V_{out} = \frac{1}{K}V_+$$

- Don't care what gain G is, as long as it is LARGE
- Make sure K is well-defined and accurate
- If $0 < K < 1$ then V_+ is nicely amplified to V_{out} by $1/K$

Background Theory - op-amp

Amplification $1/K$ by feedback K of ideal high gain op-amp:





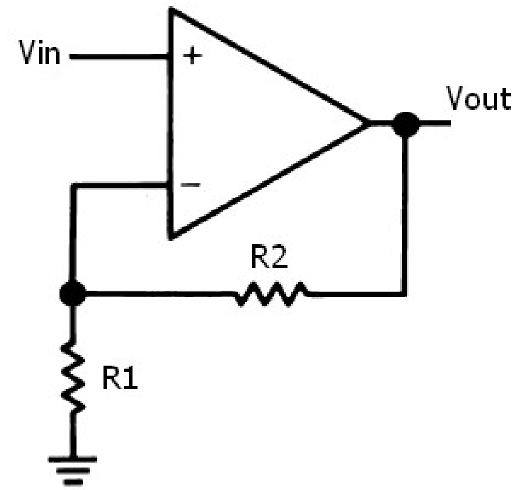
Series of R_1 and R_2 leads to voltage divisor on V_- given by:

$$V_- = \frac{R_1}{R_1 + R_2} V_{out} = K V_{out}, \;\; 0 < K \leq 1$$

and with ideal high gain op-amp we get

$$\lim_{G\to\infty} V_{out} = \lim_{G\to\infty} \frac{G}{1+GK} V_+ = \frac{1}{K} V_+ = \frac{R_1 + R_2}{R_1} V_+ = \left(1 + \frac{R_2}{R_1}\right) V_+$$

Background Theory - non-inverting amplifier (voltage follower)



Our first application circuitry:

$$V_{out} = \left(1 + \frac{R_2}{R_1}\right) V_{in}$$

So-called voltage follower in case

$R_1 = \infty$ (not present) and $R_2 = 0$

where $V_{out} = V_{in}$ but improved output impedance!

Quick (alternative) analysis based on $V_+ = V_-$ and $i_+ = i_- = 0$:

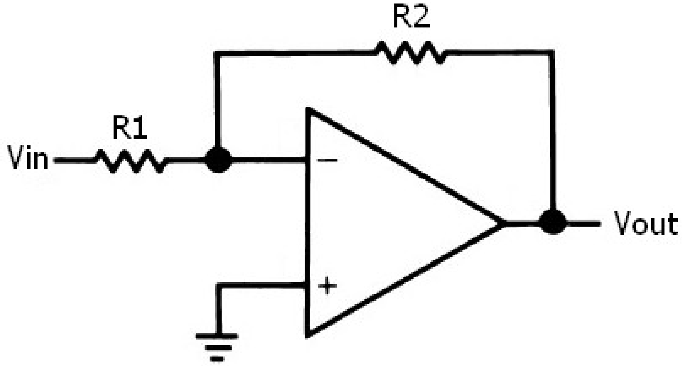
- Since $i_- = 0$ and series R_1, R_2 we have $V_- = \dfrac{R_1}{R_1 + R_2} V_{out}$
- Hence

$$V_{in} = V_+ = \frac{R_1}{R_1 + R_2} V_{out} \Rightarrow V_{out} = \frac{R_1 + R_2}{R_1} V_{in} = \left(1 + \frac{R_2}{R_1}\right) V_{in}$$

Background Theory - inverting amplifier

Similar circuit but now negative sign:

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



Quick (alternative) analysis based on $V_+ = V_-$ and $i_+ = i_- = 0$:

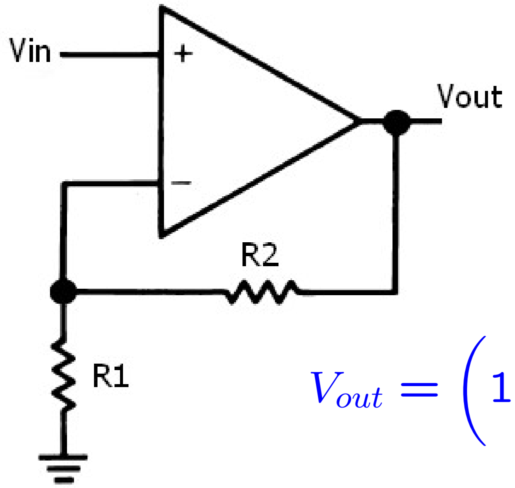
- With $V_- = V_+ = 0$ and $i_- = 0$, Kirchhoff's Current Law indicates

$$\frac{V_{in}}{R_1} + \frac{V_{out}}{R_2} = 0$$

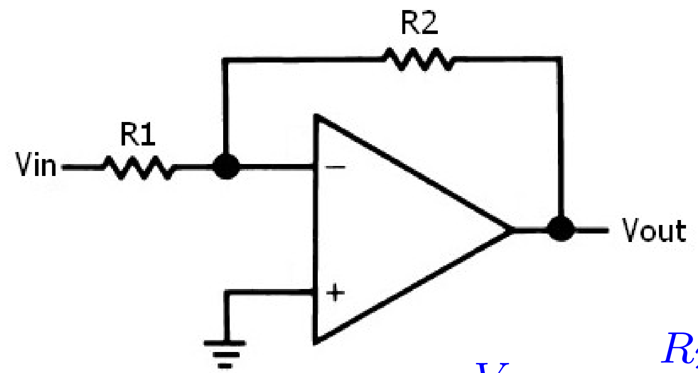
- Hence

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

Background Theory - effect or rail (source) voltages



$$V_{out} = \left(1 + \frac{R_2}{R_1}\right) V_{in}$$



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

Formulae are for ideal op-amp with boundaries imposed by negative source supply V_{S-} and positive source supply V_{S+}

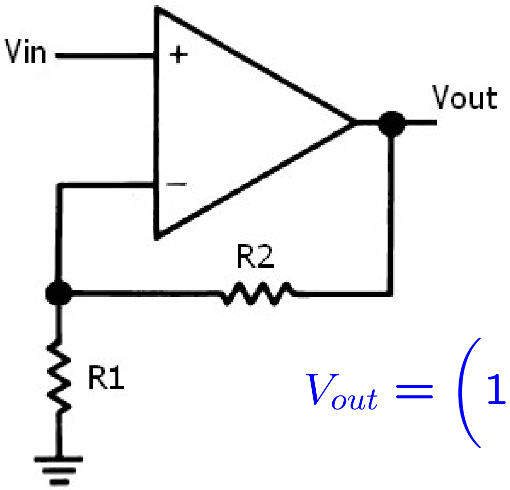
$$V_{S-} \leq V_{out} \leq V_{S+} \quad \text{(rail-to-rail op-amp)}$$

Single voltage power supply with $V_{S+} = V_{cc}$ and $V_{S-} = 0$ (ground):

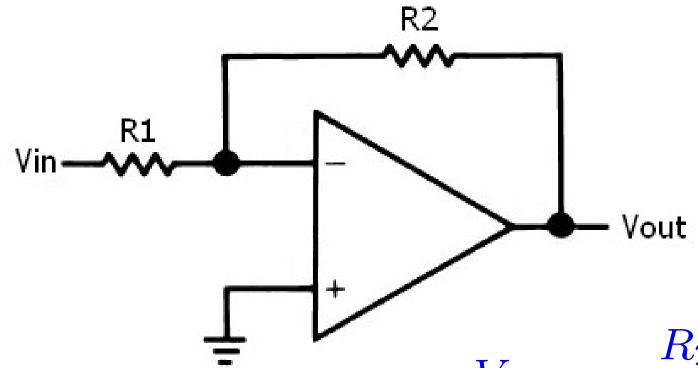
- Limits use of inverting amplifier ($V_{out} < 0$ not possible)
- Limits use of large gain R_2/R_1 ($V_{out} > V_{cc}$ not possible)

Design challenge: $0 < V_{out} < V_{cc}$ to avoid ‘clipping’ of V_{out}.

Background Theory - effect or rail (source) voltages



$$V_{out} = \left(1 + \frac{R_2}{R_1}\right) V_{in}$$



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

Single voltage power supply with $V_{S+} = V_{cc}$ and $V_{S-} = 0$ (ground) complicates amplification of

$$V_{in}(t) = a \sin(2\pi f t)$$

as $-a < V_{in}(t) < a$ (both positive and negative w.r.t. ground).

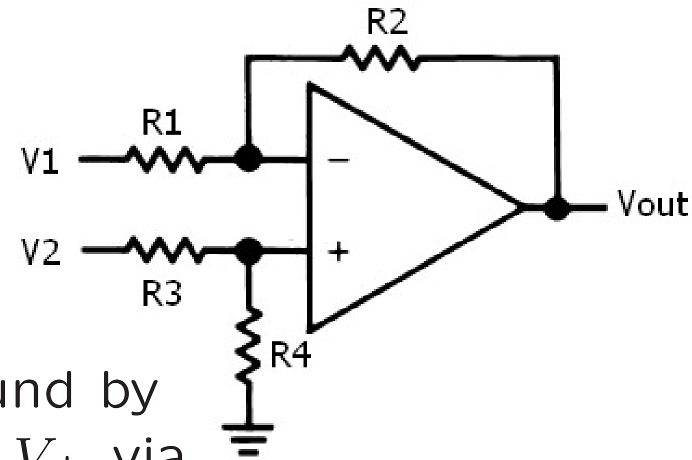
Example: audio application (as in our experiment).

To ensure $0 < V_{out} < V_{cc}$ provide offset compensation

$$V_{in}(t) = a \sin(2\pi f t) + a$$

to ensure $V_{in}(t) > 0$ and use non-inverting amplifier.

Background Theory - differential amplifier



Instead of amplifying one signal, amplify the difference:

$$V_{out} = \frac{R_1 + R_2}{R_3 + R_4} \cdot \frac{R_4}{R_1} V_2 - \frac{R_2}{R_1} V_1$$

Difference or differential amplifier is found by inverting amplifier and adding signal to V_+ via series connection of R_3 and R_4. Analysis:

- With $i_+ = 0$ the series or R_3 and R_4 leads to $V_+ = \frac{R_4}{R_3+R_4} V_2$
- With $V_- = V_+$ and Kirchhoff's Current Law we have

$$\frac{V_1 - \frac{R_4}{R_3+R_4} V_2}{R_1} + \frac{V_{out} - \frac{R_4}{R_3+R_4} V_2}{R_2} = 0$$

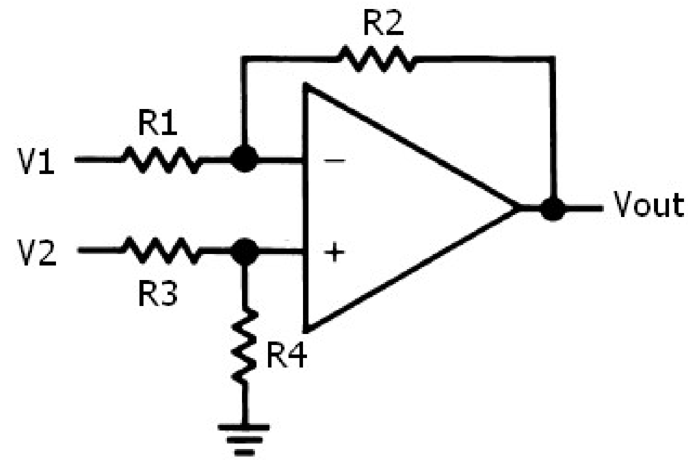
Hence

$$V_{out} = \frac{R_2}{R_1} \cdot \frac{R_4}{R_3 + R_4} V_2 + \frac{R_4}{R_3 + R_4} V_2 - \frac{R_2}{R_1} V_1$$

or

$$V_{out} = \frac{R_1 + R_2}{R_3 + R_4} \cdot \frac{R_4}{R_1} V_2 - \frac{R_2}{R_1} V_1$$

Background Theory - differential amplifier



Choice $R_1 = R_3$ and $R_2 = R_4$ reduces

$$V_{out} = \frac{R_1 + R_2}{R_3 + R_4} \cdot \frac{R_4}{R_1} V_2 - \frac{R_2}{R_1} V_1$$

to

$$V_{out} = \frac{R_2}{R_1}(V_2 - V_1)$$

create a difference/differential amplifier.

Further choice of $R_1 = R_3$, $R_2 = R_4$ *and* $R_2 = R_1$ yields

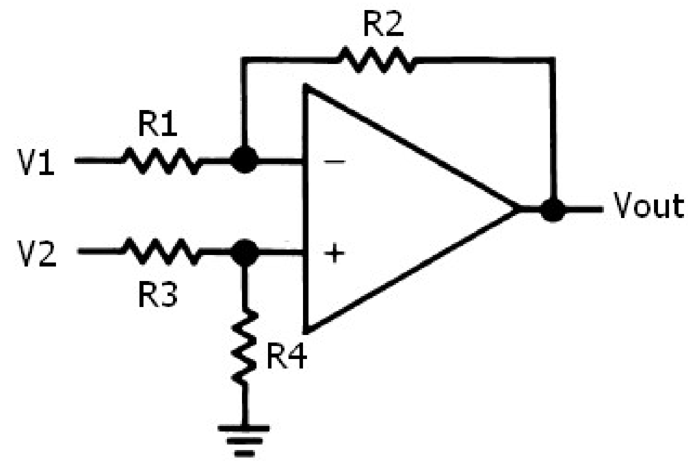
$$V_{out} = V_2 - V_1$$

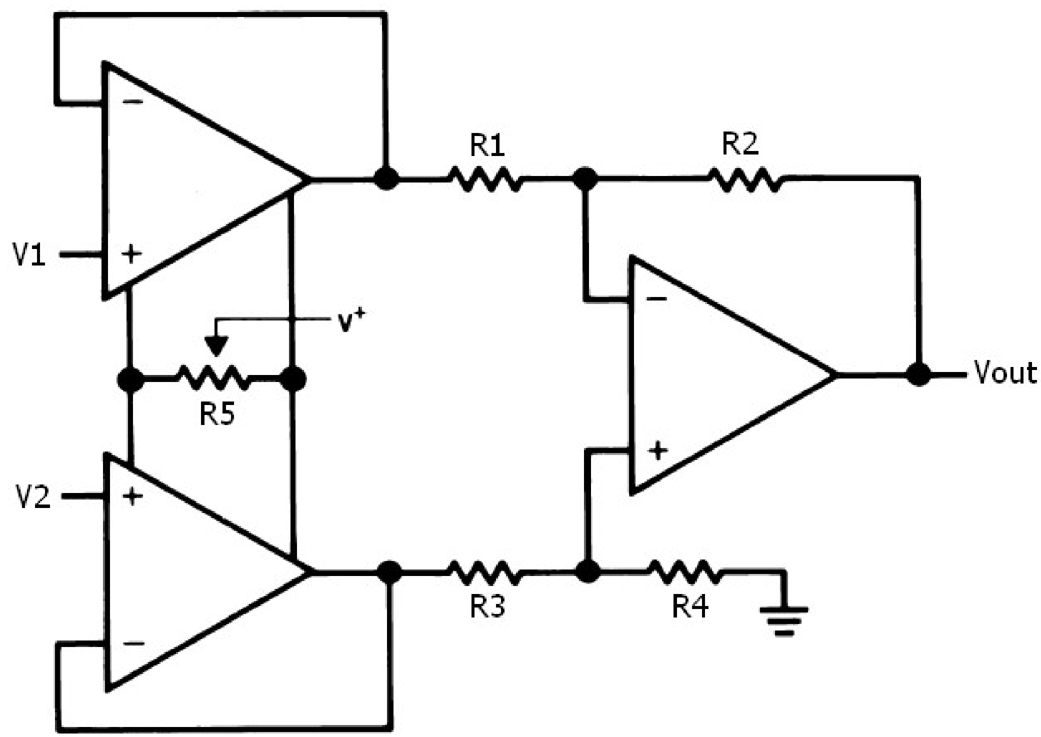
and computes the difference between input voltages V_1 and V_2.

NOTE: $V_2 > V_1$ for a single voltage power supply with $V_{S+} = V_{cc}$ and $V_{S-} = 0$ (ground) to avoid clipping of V_{out} against ground.

Background Theory - more advanced differential amplifiers

Difference amplifier does not have high input impedance (loading of sensors). Better design with voltage followers:





With

$$\frac{R_2}{R_1} = \frac{R_4}{R_3}$$

we have

$$V_{out} = \frac{R_2}{R_1}(V_2 - V_1)$$

R_5 is used to adjust offset (balance)

Background Theory - more advanced differential amplifiers

Even better differential amplifier that has a variable gain is a so-called instrumentation amplifier:

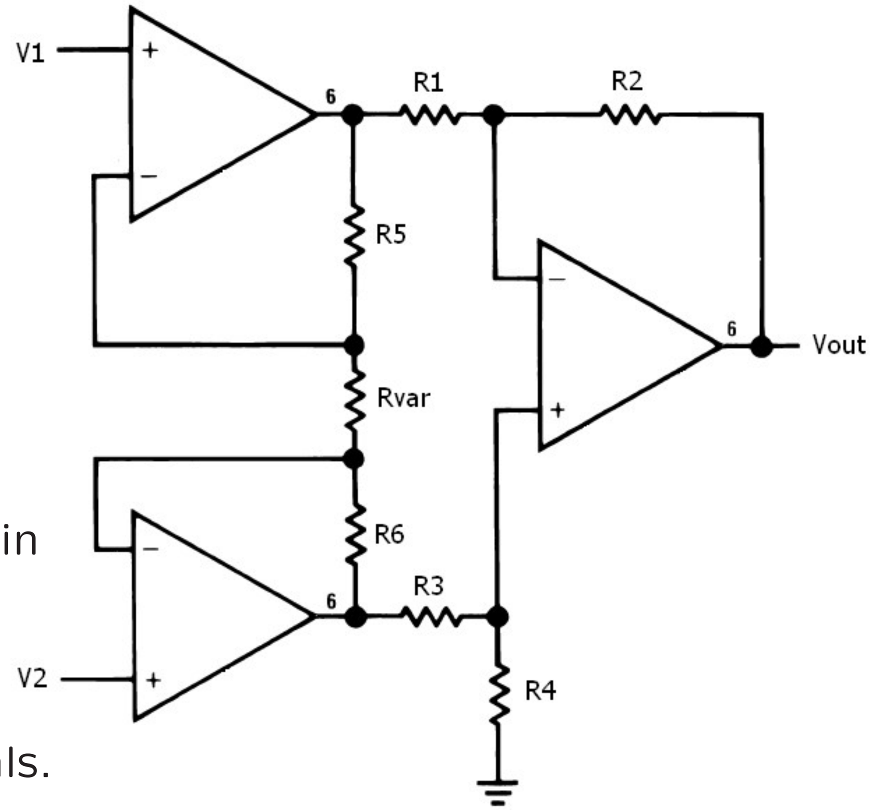
Setting all resistors

$$R_i = R,\ i = 1, 2, \ldots 5$$

except R_{var}, makes

$$V_{out} = \left(1 + \frac{2R}{R_{var}}\right)(V_2 - V_1)$$

High input impedance and variable gain via an (external) resistor R_{var} makes this ideal for the amplification of (non-grounded) instrumentation signals.

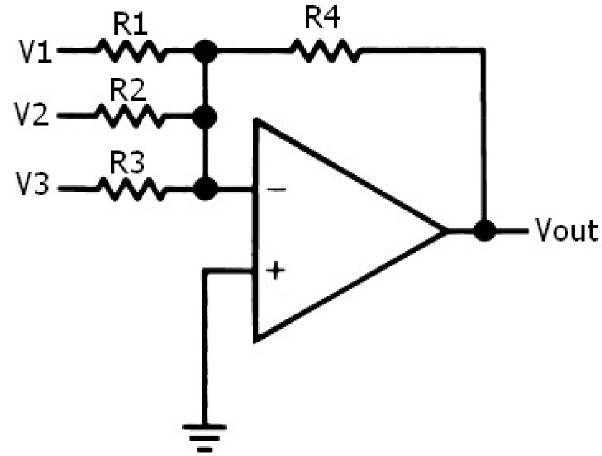


Instrumentation amplifiers are made & sold as a single chip.

Background Theory - inverting summing amplifier

Inverting amplifier can also be extended to add signals:

$$V_{out} = -R_4 \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \right)$$



Analysis follows from Kirchhoff's Current Law for the − input of the op-amp:

- With $V_- = V_+$ we have $V_- = 0$
- With $i_- = 0$ we have

$$\frac{V_{out}}{R_4} + \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = 0$$

Hence

$$V_{out} = -R_4 \cdot \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \right)$$

creating a weighted sum of signals.

Background Theory - inverting summing amplifier

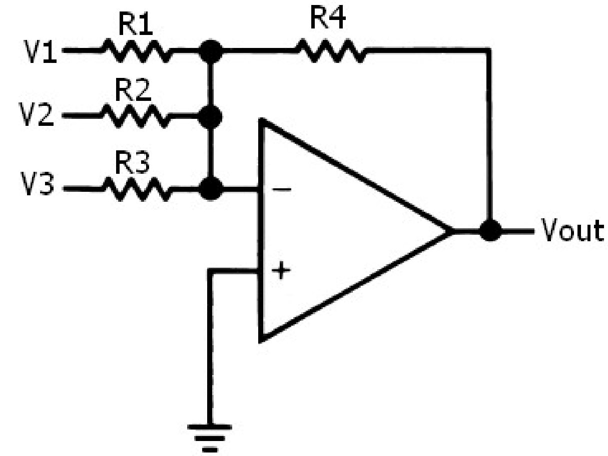
The choice $R_1 = R_2 = R_3$ reduces

$$V_{out} = -R_4 \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \right)$$

to

$$V_{out} = -\frac{R_4}{R_1}(V_1 + V_2 + V_3)$$

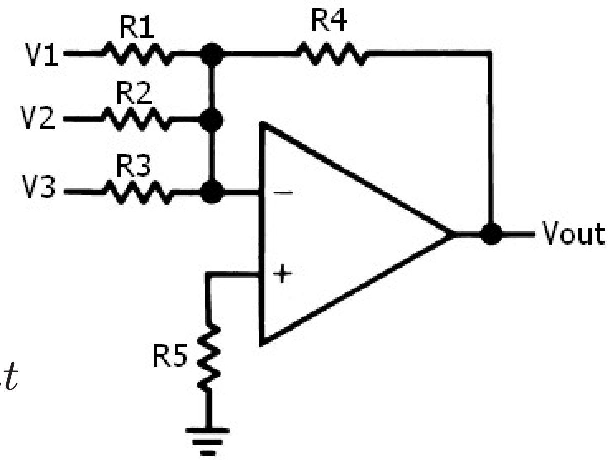
simply amplifying the sum of the signals.



Oftentimes extra resistor R_5 is added:

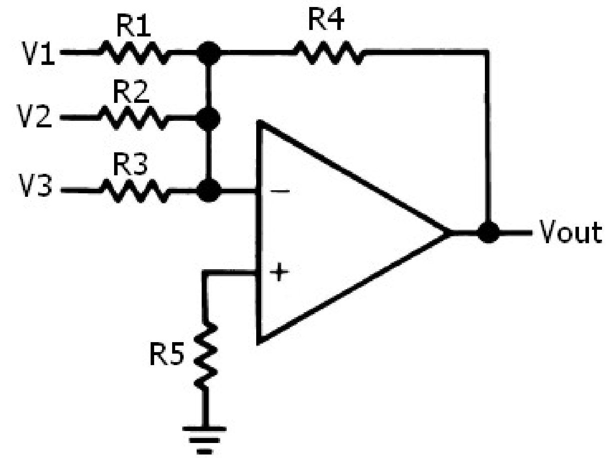
$$\frac{1}{R_5} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}$$

to account for possible small (bias) input currents $i_- \neq 0$, $i_+ \neq 0$. This ensures V_{out} remains sum, without bias/offset.



Background Theory - inverting summing amplifier

Inverting summing amplifier:



$$V_{out} = -R_4 \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \right)$$

and for $R_1 = R_2 = R_3$:

$$V_{out} = -\frac{R_4}{R_1}(V_1 + V_2 + V_3)$$

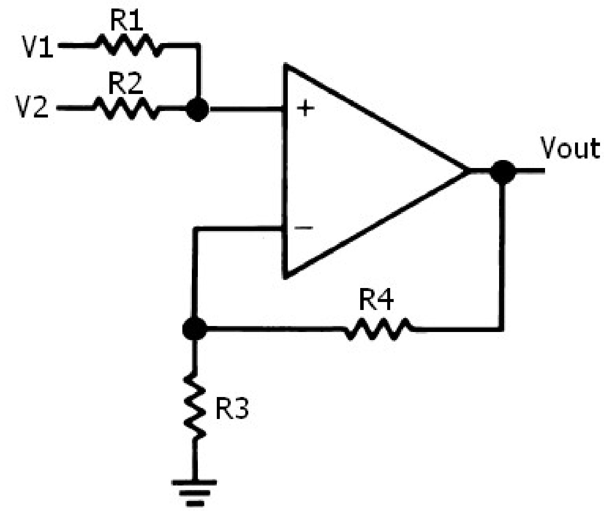
has a limitation for single source voltage supplies:

Single voltage power supply with $V_{S+} = V_{cc}$ and $V_{S-} = 0$:

- Limits use of inverting summer ($V_{out} < 0$ not possible)
- Limits use of large gain R_4/R_1 ($V_{out} > V_{cc}$ not possible)

'clipping' of V_{out} will occur if sum of input signals is positive.

Background Theory - non-inverting summing amplifier



Based on a non-inverting amplifier signals can also be summed:

$$V_{out} = \left(1 + \frac{R_4}{R_3}\right) \frac{R_1 R_2}{R_1 + R_2} \left(\frac{V_1}{R_1} + \frac{V_2}{R_2}\right)$$

Analysis:

- due to $i_- = 0$ we have $V_- = \frac{R_3}{R_3+R_4} V_{out}$
- Due to $V_+ - V_-$ and $i_+ = 0$ with Kirchhoff's Current Law:

Hence

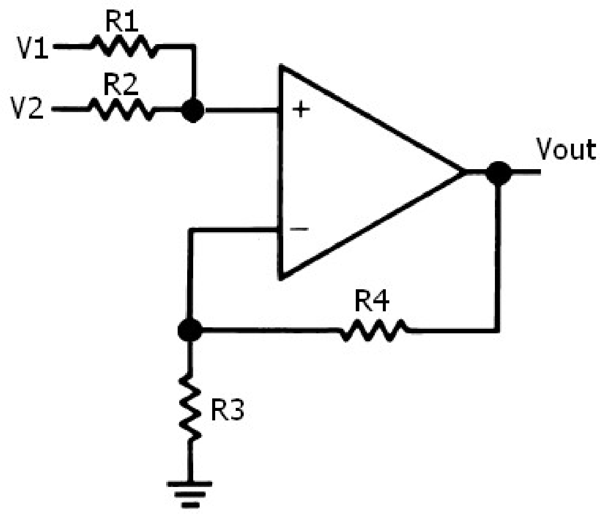
$$\frac{V_1 - \frac{R_3}{R_3+R_4} V_{out}}{R_1} + \frac{V_2 - \frac{R_3}{R_3+R_4} V_{out}}{R_2} = 0$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} = \left(\frac{1}{R_1} + \frac{1}{R_2}\right) \frac{R_3}{R_3 + R_4} V_{out}$$

and

$$V_{out} = \left(1 + \frac{R_4}{R_3}\right) \frac{R_1 R_2}{R_1 + R_2} \left(\frac{V_1}{R_1} + \frac{V_2}{R_2}\right)$$

Background Theory - non-inverting summing amplifier



The choice $R_1 = R_2$ reduces

$$V_{out} = \left(1 + \frac{R_4}{R_3}\right) \frac{R_1 R_2}{R_1 + R_2} \left(\frac{V_1}{R_1} + \frac{V_2}{R_2}\right)$$

to

$$V_{out} = \left(1 + \frac{R_4}{R_3}\right) \frac{V_1 + V_2}{2}$$

indicating amplifciation of the sum V_1 and V_2 if $R_4 \geq R_3$.

Further choice of also $R_1 = R_2 = R_3 = R_4$ leads to

$$V_{out} = V_1 + V_2$$

indicating a simple summation of V_1 and V_2.

Unlike inverting summing amplifier, no extra resistor can be added to compensate for bias input current.
Not desirable: source impedance part of gain calculation. . .

Background Theory - filtering

So far, all circuits were build using op-amps and resistors.

When building filters, mostly capacitors are used as negative, positive or grounding elements.

Interesting phenomena: resistor value of capacitor depends on frequency of signal.

Analysis for capacitor: capacitance C is ratio between charge Q and applied voltage V:

$$C = \frac{Q}{V}$$

Since charge $Q(t)$ at any time is found by flow of electrons:

$$Q(t) = \int_{\tau=0}^{t} i(\tau) d\tau$$

we have

$$V(t) = \frac{Q(t)}{C} = \frac{1}{C} \int_{\tau=0}^{t} i(\tau) d\tau$$

Background Theory - filtering

Application of Laplace transform to

$$V(t) = \frac{Q(t)}{C} = \frac{1}{C}\int_{\tau=0}^{t} i(\tau)d\tau$$

yields

$$V(s) = \frac{1}{Cs} i(s)$$

Hence we can define the impedance/resistence of a capacitor as

$$R(s) = \frac{V(s)}{i(s)} = \frac{1}{Cs}$$

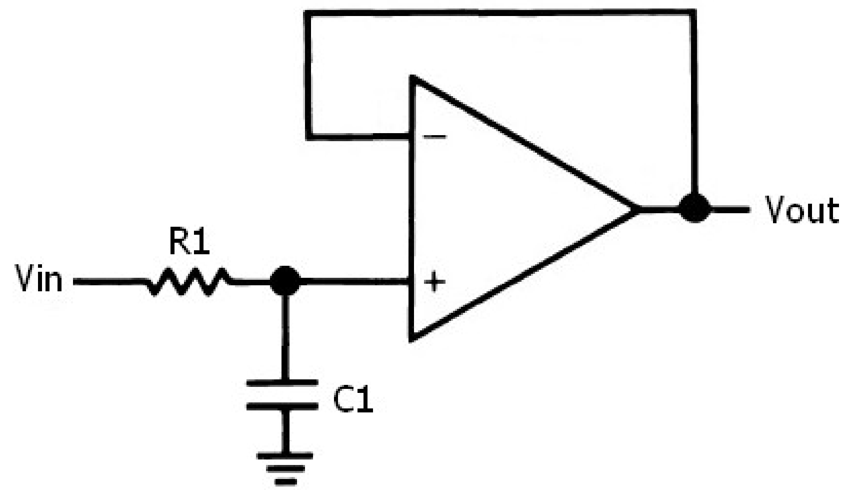
With Fourier analysis we use $s = j\omega$ and we find the frequency dependent 'equivalent resistor value of a capacitor':

$$R(j\omega) = \frac{1}{jC\omega}$$

This value will allow analysis of op-amp circuits based on resistors (as we have done so far)

Background Theory - filtering

Consider simple 1st oder RC-filter with voltage follower op-amp.



Due to $i_+ = 0$ we have

$$V_+(j\omega) = \frac{\frac{1}{C_1 j\omega}}{R_1 + \frac{1}{C_1 j\omega}} V_{in}(j\omega)$$

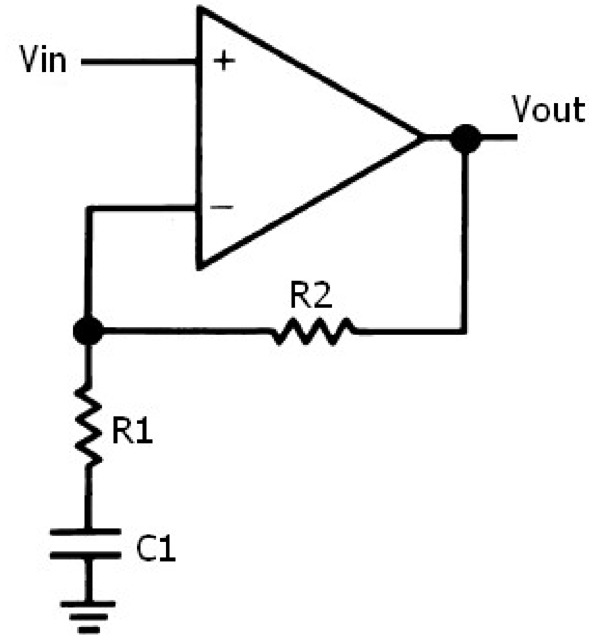
With $V_{out} = V_- = V_+$ we have

$$V_{out}(j\omega) = \frac{1}{R_1 C_1 j\omega + 1} V_{in}(j\omega)$$

This is a 1st order low-pass filter with a cut-off frequency

$$\omega_c = \frac{1}{R_1 C_1} \text{ rad/s or } f_c = \frac{1}{2\pi R_1 C_1} \text{ Hz}$$

Background Theory - filtering



Consider circuit of non-inverting amplifier where R_1 is now series of R_1 and C_1. Equivalent series resistance is given by

$$R_1 + \frac{1}{jC_1\omega}$$

Application of gain formula for non-inverting amplifier yields:

$$V_{out}(j\omega) = \left(1 + \frac{R_2}{R_1 + \frac{1}{jC_1\omega}}\right) V_{in}(j\omega)$$

We can directly see:

- For low frequencies $\omega \rightarrow 0$ we obtain a Voltage follower with $V_{out} = V_{in}$
- For high frequencies $\omega \rightarrow \infty$ we obtain our usual non-inverting amplifier $V_{out}(j\omega) = \left(1 + \frac{R_2}{R_1}\right) V_{in}(j\omega)$

Background Theory - filtering

Transition between low and high frequency can be studies better by writing $V_{out}(s) = G(s)V_{in}(s)$ where $G(s)$ is a transfer function.

This allows us to write

$$V_{out}(s) = \left(1 + \frac{R_2}{R_1 + \frac{1}{C_1 s}}\right) V_{in}(s)$$

as

$$V_{out}(s) = \left(1 + \frac{R_2 C_1 s}{R_1 C_1 s + 1}\right) V_{in}(s) = \frac{(R_1 + R_2)C_1 s + 1}{R_1 C_1 s + 1} V_{in}(s)$$

making

$$G(s) = \frac{(R_1 + R_2)C_1 s + 1}{R_1 C_1 s + 1}$$

Background Theory - filtering

The transfer function

$$G(s) = \frac{(R_1 + R_2)C_1 s + 1}{R_1 C_1 s + 1}$$

has the following properties:

- single pole at $p_1 = -\frac{1}{R_1 C_1}$ and found by solving $R_1 C_1 s + 1 = 0$.
- single zero at $z_1 = -\frac{1}{(R_1+R_2)C_1}$ and found by solving $(R_1 + R_2)C_1 s + 1 = 0$.
- DC-gain of 1 and found by substitution $s = 0$ in $G(s)$. Related to the final value theorem for a step input signal $v_{in}(t)$:

  $$\lim_{t\to\infty} V_{out}(t) = \lim_{s\to 0} s \cdot V_{out}(s) = \lim_{s\to 0} s \cdot G(s) \cdot \frac{1}{s} = \lim_{s\to 0} G(s)$$

  where $\frac{1}{s}$ is the Laplace transform of the step input $v_{in}(t)$.
- High frequency gain of $\frac{R_1+R_2}{R_1} = 1 + \frac{R_2}{R_1}$ and found by computing $s \to \infty$.

Background Theory - filtering

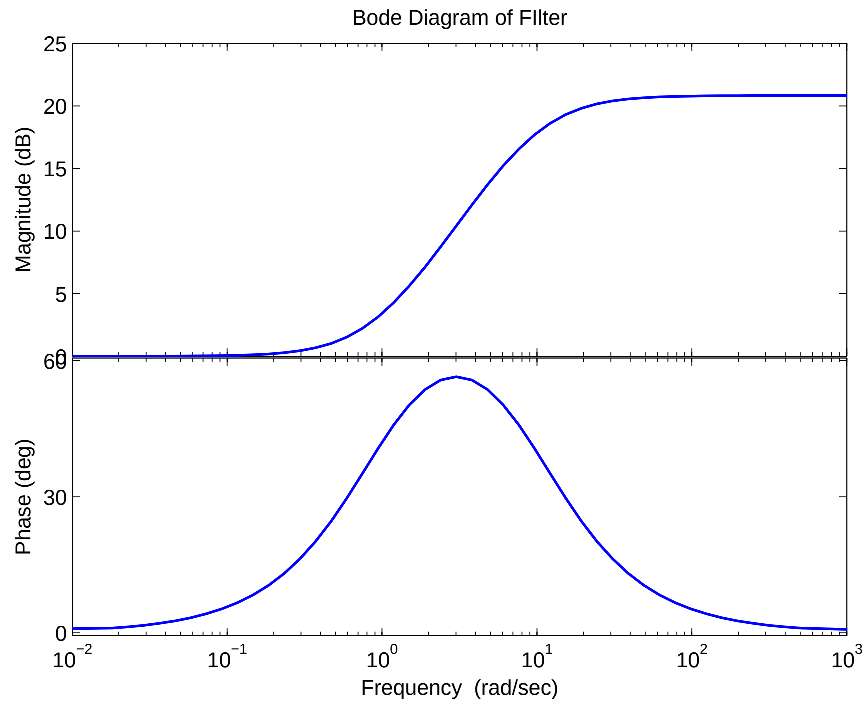
The transfer function

$$G(s) = \frac{(R_1 + R_2)C_1 s + 1}{R_1 C_1 s + 1}$$

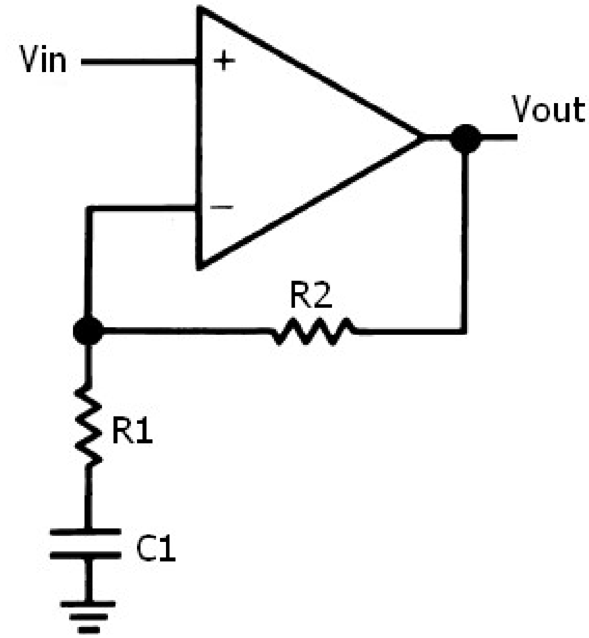
is a first order system where zero $z_1 = -\frac{1}{(R_1+R_2)C_1} < p_1 = -\frac{1}{R_1 C_1}$.
This indicates $G(s)$ is a lead filter.

Easy to study in Matlab:

```
>> R2=100e3;R1=10e3;C1=10e-6;
>> G=tf([(R1+R2)*C1 1],[R1*C1 1]);
>> bode(G)
```



Background Theory - filtering



Amplification lead filter circuit with

$$V_{out}(j\omega) = \left(1 + \frac{R_2}{R_1 + \frac{1}{jC_1\omega}}\right) V_{in}(j\omega)$$

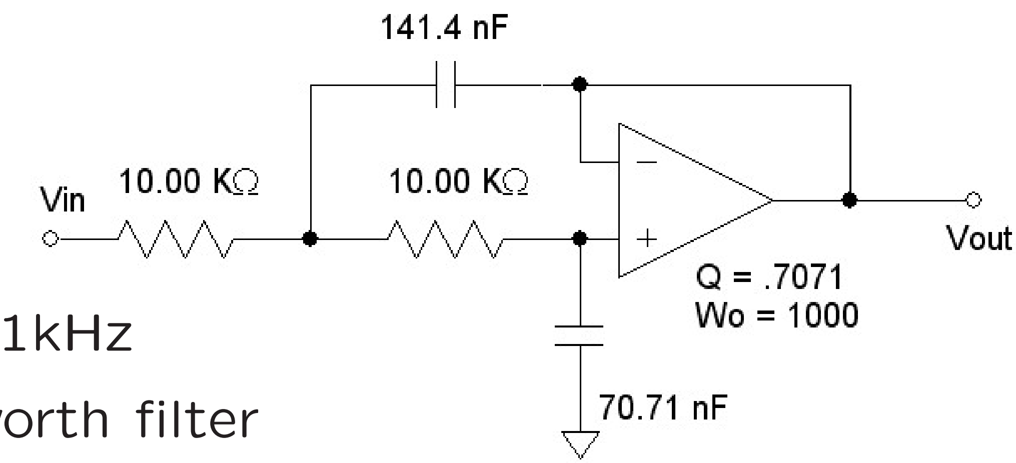
will be used to strongly amplify a small high frequent signal but maintain (follow) the DC-offset.

From the previous analysis we see:

- Gain at DC ($\omega = 0$) is simply 1.
- Gain at higher frequencies approaches $1 + \frac{R_2}{R_1}$

Background Theory - filtering

Another fine filter:



- 2nd order low pass Butterworth filter
- Pass-band frequency of 1kHz
- 2nd order 1kHz Butterworth filter is a standard 2nd order system

$$V_{out}(s) = G(s)V_{in}(s)$$

where

$$G(s) = \frac{\omega_n^2}{s^2 + 2\beta\omega_n 2 + \omega_n^2}$$

with $\omega_n = 2\pi \cdot 1000$, $\beta = \sqrt{1/2} \approx 0.707$.

Background Theory - filtering

$$V_{out}(s) = G(s)V_{in}(s)$$

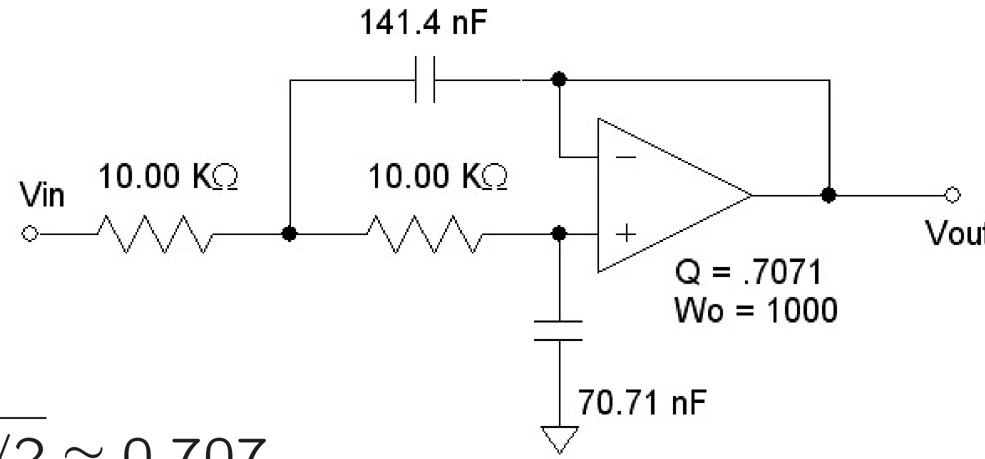
where

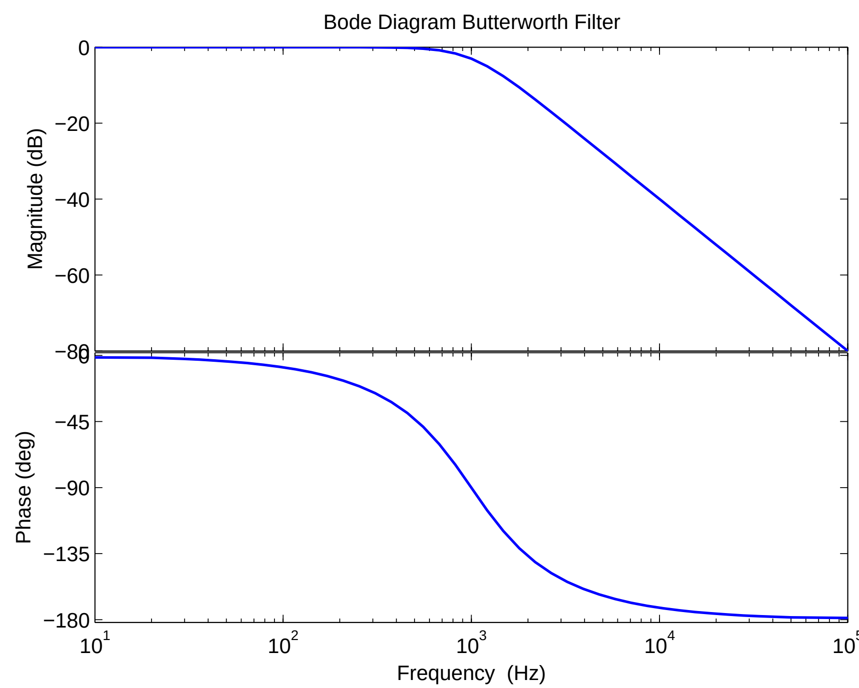
$$G(s) = \frac{\omega_n^2}{s^2 + 2\beta\omega_n 2 + \omega_n^2}$$

with $\omega_n = 2\pi \cdot 1000$, $\beta = \sqrt{1/2} \approx 0.707$
means:

- well damped filter
- -40dB/dec above 1kHz

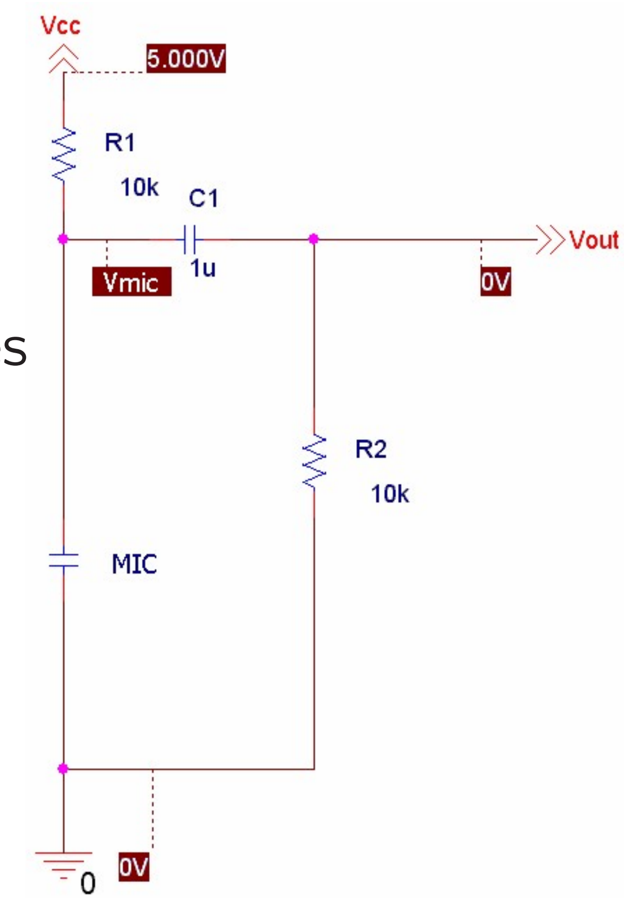
```
>> [num,den]=butter(2,2*pi*1000,'s');
>> G=tf(num,den);
>> bode(G)
```





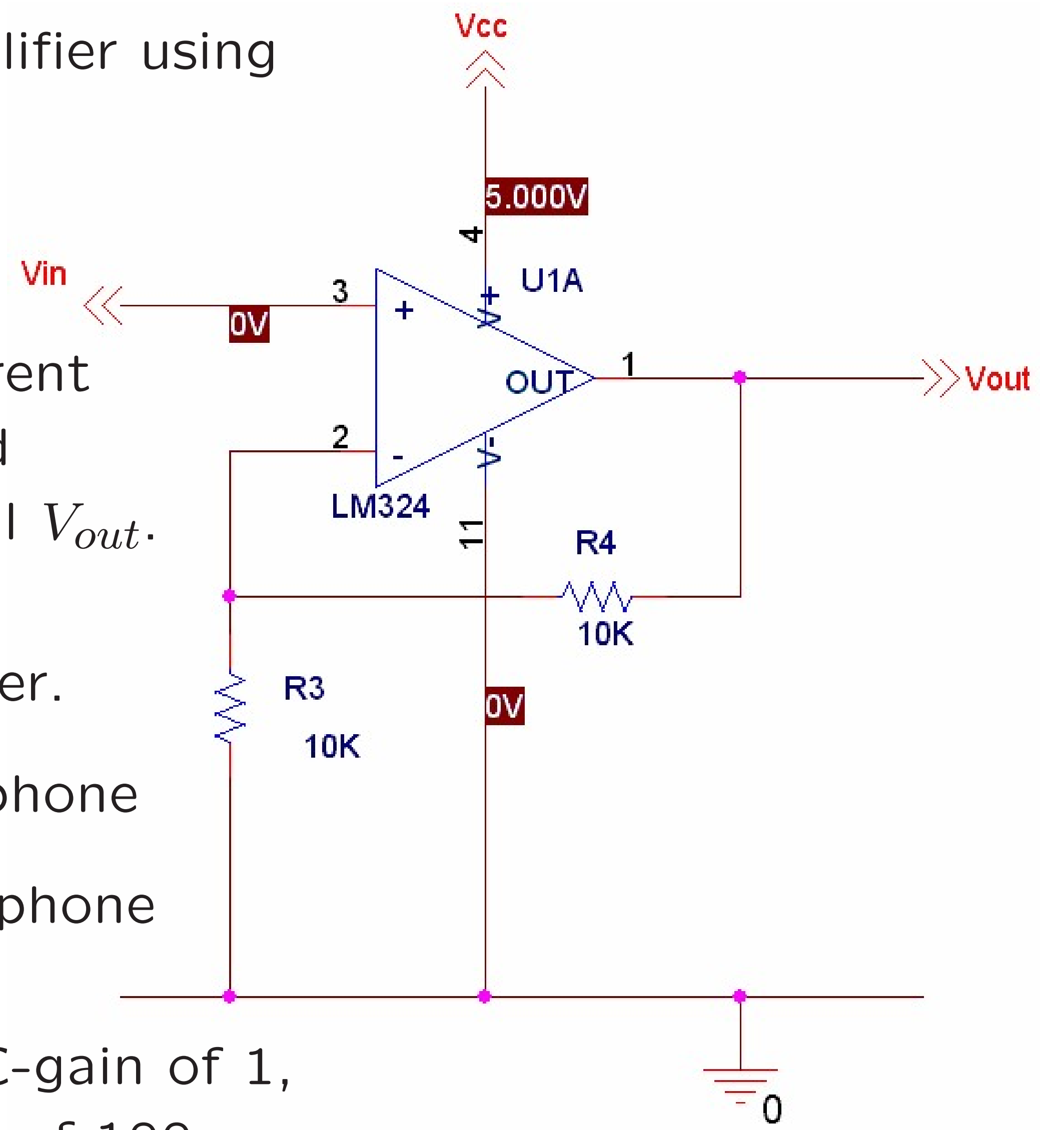
Laboratory Work - week 1

- Audio application: generate input signal via MIKE-74 electret microphone
- build a DC-bias circuit for the microphone to measure (sound) pressure variations
- Measure the DC-bias (offset) voltages
- Display and analyse the time plots generated by the microphone



Laboratory Work - week 1

- Build non-inverting amplifier using quad LM324 op-amp
- Measure bias voltages
- Experiments:
  determine gain for different resistor values and avoid clipping on output signal V_{out}.
- Measure the frequency response of your amplifier.

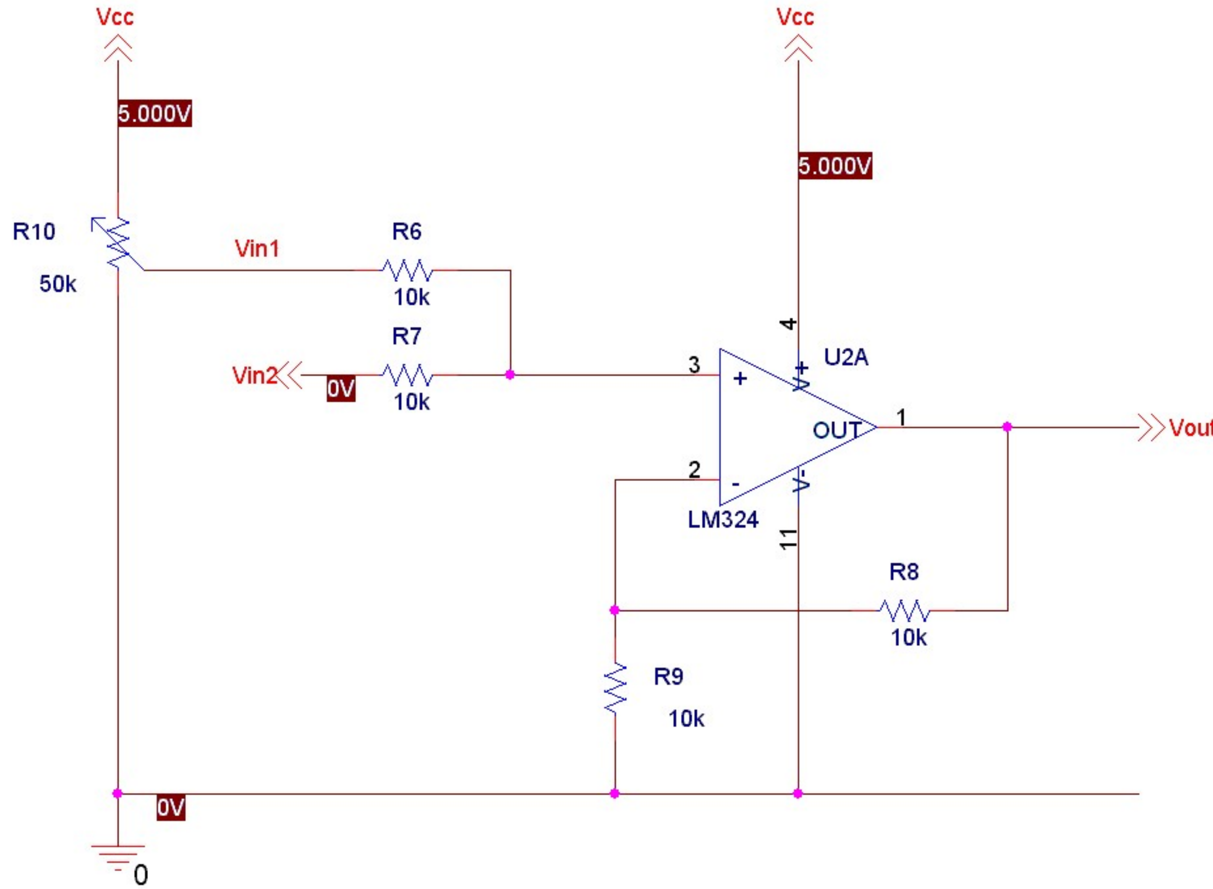


Connect amplifier to microphone

- Provide off-set of microphone signal to avoid clipping
- Create lead filter for DC-gain of 1, and high frequency gain of 100.

Laboratory Work - week 2

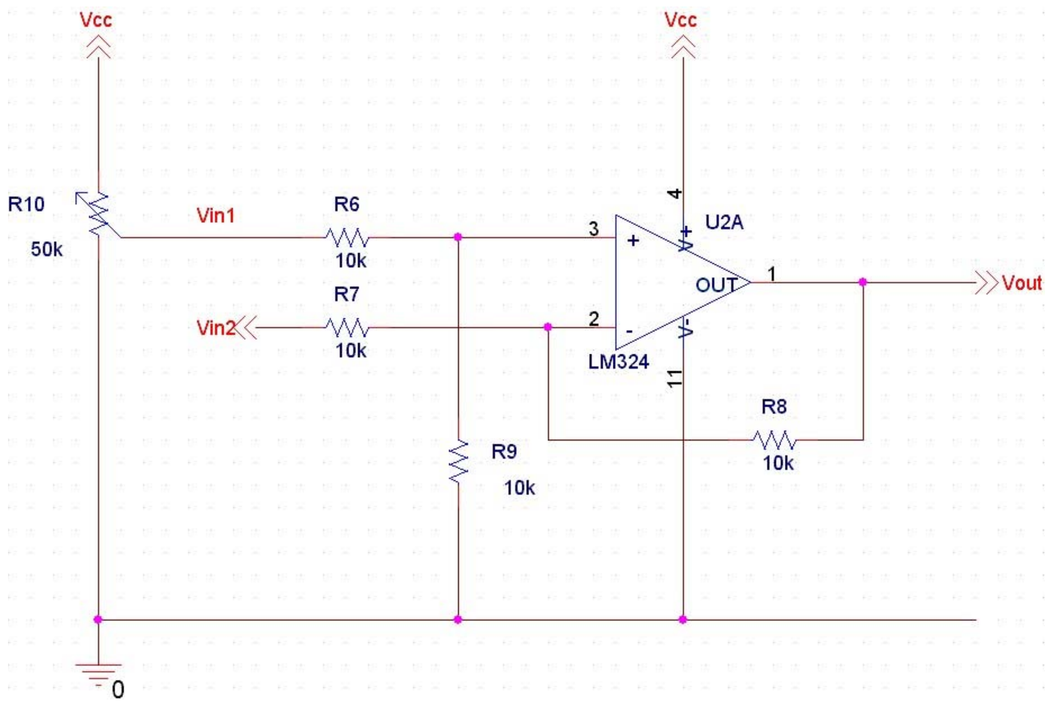
- Build none inverting summing amplifier
- Experiments: verification of operation (adding of signals)
- Bias voltage adjustment
- Experimental verification of bias effects.



Laboratory Work - week 2

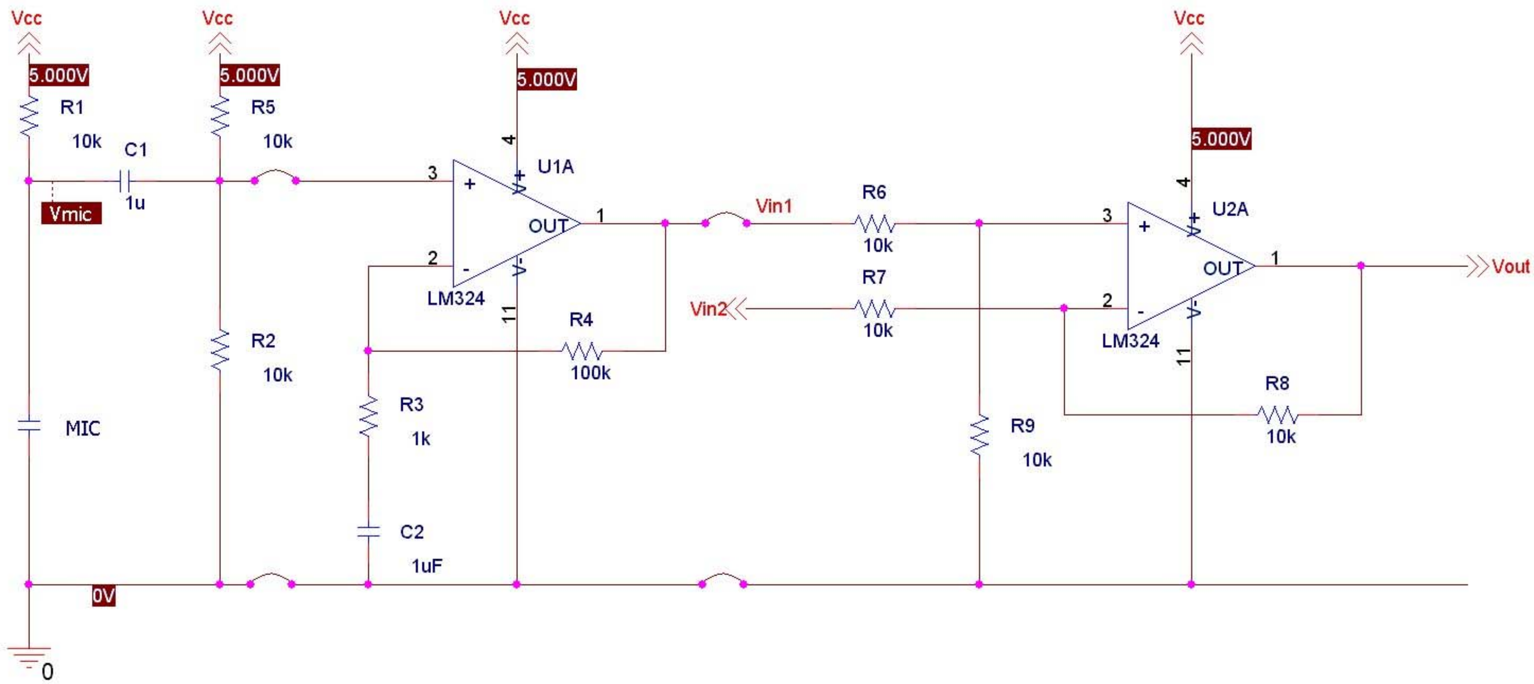
- Build differential/difference amplifier
- Experiments: verification of operation (difference of signals)
- Bias voltage adjustment
- Gain adjustments and experimental verification

Combine microphone & amplifier circuit from week 1 with difference amplifier to allow mixing of signals.



- Measure bias voltages
- Demonstrate mixing of sine wave signal and microphone signal without distortions

Laboratory Work - week 3



Starting point of week 3: completed amplified/mixed microphone signal.

V_{out} will now be filtered and (optional) power boosted for speaker output.

Laboratory Work - week 3

- Create active low pass filter with cutt-off frequency of 1kHz.
- Demonstrate filter by measuring amplitude of output signal for sine wave excitation of different frequencies
- Connect filter to circuit of week 2 (microphone, amplifier and differential amplifier for mixing)
- Demonstrate filter by measuring microphone and filtered microphone signal
- Optional: add power boost to circuitry and connect speaker.

Summary

- (relatively simple) signal conditioning algorithms: *amplification*, *adding/difference* and basic (most 2nd order) *filtering*
- Challenge: single source power supply of 5 Volt. Avoid clipping/distortion of amplified, mixed and filtered signal.
- insight in op-amp based linear circuits by building and debuging
- compare theory (ideal op-amp) with practice (build and test)
- experimentally verify gain of circuitry
- for error/statistical analysis: measure gain for different resistor (of the same value)
- audio application on a single voltage power supply shows amplification of small signals and careful filter design to maintain DC (off-set)

GOOD LUCK