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

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

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

But why (always) infinite gain \(G\)? Obviously:

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

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 $V_\text{out} = KV_\text{out}$ we obtain $V_\text{out} = \frac{G}{1 + GK} V_+$

![Diagram showing op-amp circuit](image)

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

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

- 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 $V_\text{out}$ by $1/K$
Background Theory - op-amp

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

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

$$V_{\text{out}} = KV_{\text{out}}$$

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

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

and with ideal high gain op-amp we get

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

\[ R_1 = \infty \text{ (not present) and } R_2 = 0 \]

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 \( V_- = \frac{R_1}{R_1 + R_2} V_{out} \)
- 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:

\[ V_{\text{out}} = -\frac{R_2}{R_1}V_{\text{in}} \]

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

- With \( V_- = V_+ = 0 \) and \( i_- = 0 \), Kirchhoff’s Current Law indicates

\[ \frac{V_{\text{in}}}{R_1} + \frac{V_{\text{out}}}{R_2} = 0 \]

- Hence

\[ \frac{V_{\text{out}}}{R_2} = -\frac{V_{\text{in}}}{R_1} \Rightarrow V_{\text{out}} = -\frac{R_2}{R_1}V_{\text{in}} \]
**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

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

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

\[ V_{in}(t) = a \sin(2\pi ft) \]

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**

\[ V_{in}(t) = a \sin(2\pi ft) + a \]

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:

\[ \frac{R_2}{R_1} = \frac{R_4}{R_3} \]

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 \( R_{\text{var}} \), makes

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

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

Instrumentation amplifiers are made & sold as a single chip.
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:

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

Hence

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

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 amplification 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 built 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 order RC-filter with voltage follower op-amp.

Due to \( i_+ = 0 \) we have

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

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

\[
R_1 + \frac{1}{j C_1 \omega}
\]

Application of gain formula for non-inverting amplifier yields:

\[
V_{out}(j\omega) = \left( 1 + \frac{R_2}{R_1 + \frac{1}{j C_1 \omega}} \right) V_{in}(j\omega)
\]

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 studied better by writing $V_{out}(s) = G(s)V_{in}(s)$ where $G(s)$ is a transfer function.

This allows us to write

$$V_{out}(s) = \left(1 + \frac{R_2}{R_1 + \frac{1}{C_1s}}\right)V_{in}(s)$$

as

$$V_{out}(s) = \left(1 + \frac{R_2C_1s}{R_1C_1s + 1}\right)V_{in}(s) = \frac{(R_1 + R_2)C_1s + 1}{R_1C_1s + 1}V_{in}(s)$$

making

$$G(s) = \frac{(R_1 + R_2)C_1s + 1}{R_1C_1s + 1}$$
**Background Theory** - filtering

The transfer function

\[ G(s) = \frac{(R_1 + R_2)C_1s + 1}{R_1C_1s + 1} \]

has the following properties:

- single pole at \( p_1 = -\frac{1}{R_1C_1} \) and found by solving \( R_1C_1s + 1 = 0 \).
- single zero at \( z_1 = -\frac{1}{(R_1 + R_2)C_1} \) and found by solving \((R_1 + R_2)C_1s + 1 = 0\).
- 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

\[ G(s) = \frac{(R_1 + R_2)C_1s + 1}{R_1C_1s + 1} \]

is a first order system where zero \( z_1 = \frac{1}{(R_1 + R_2)C_1} < p_1 = -\frac{1}{R_1C_1} \).

This indicates \( G(s) \) is a lead filter.

Easy to study in Matlab:

```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

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

with \( \omega_n = 2\pi \cdot 1000 \), \( \beta = \sqrt{\frac{1}{2}} \approx 0.707 \) means:

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

\[
\begin{align*}
\text{>> } & [\text{num,den}]=\text{butter}(2,2*\pi*1000,'s'); \\
\text{>> } & G=\text{tf(num,den);} \\
\text{>> } & \text{bode}(G)
\end{align*}
\]

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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 debugging
• 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