Sensor Nodes Laboratory (SS 2019)

First Lecture

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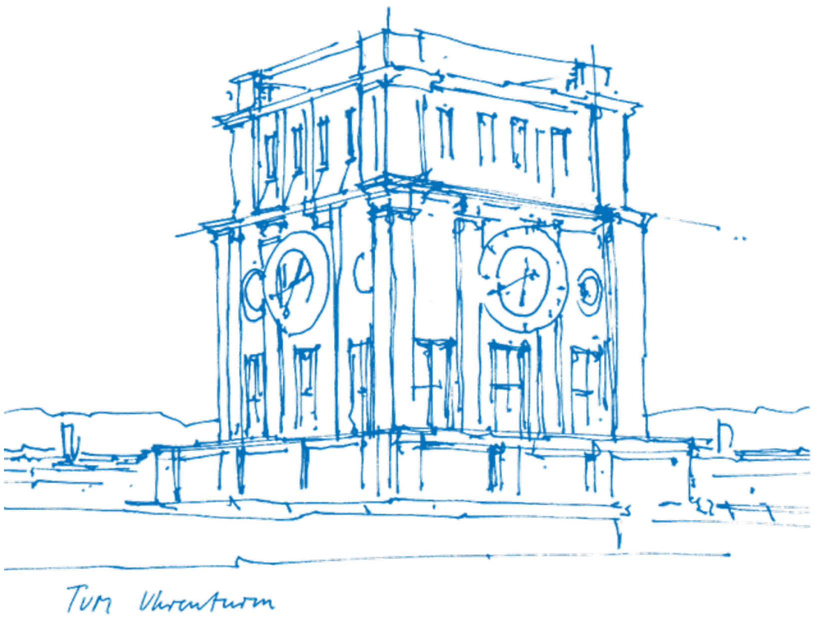

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Outline

Outline

Structure of the Course

- Kick-Off Meeting in the first week.
- Lecture-style meetings in the next few weeks, where we introduce the theoretical foundations required for the rest of this course, introducing the Hardware/Software framework, etc.
- Different sensors will be assigned to two different groups of students.
- The overall project is split into two tasks.

Task 1

1. Designing of an analog frontend circuit for the sensor provided to your group.
2. Using appropriate input filtering in order to have reasonable analog signals.
3. Digitize your signals using an analog to digital converter (ADC).
4. Transfer the digital data to a wireless front-end board.

Task 2

1. Package data with identifier/timestamp.
2. Communicate with gateway for sending the data to a server.
3. Retry/fallback strategy to be thought.

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Structure of the Course

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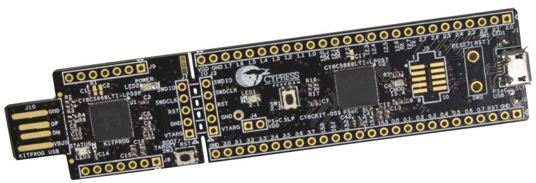

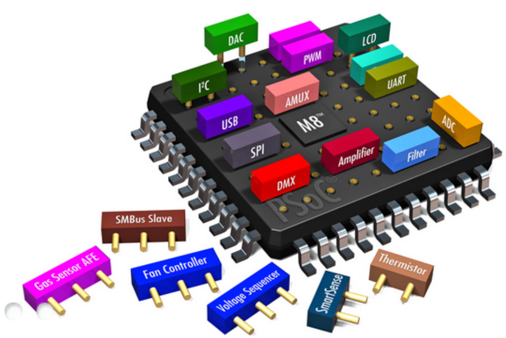

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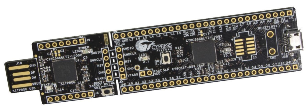
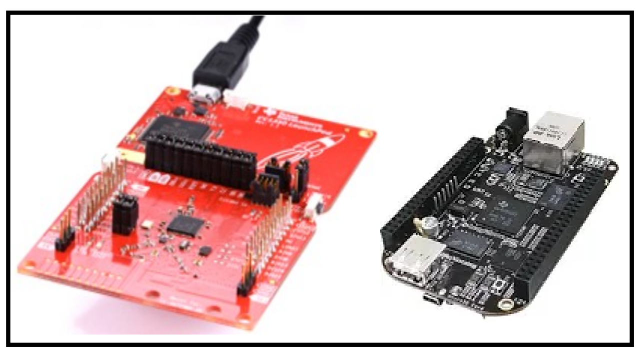


Task 2

1. Package data with identifier/timestamp.
2. Communicate with gateway for sending the data to a server.
3. Retry/fallback strategy to be thought.

Gateway and demo on visualizing data sent to the gateway- will be provided!



Structure of the Course

Goal (tentative)

- ***Having a fully functional prototype of a wireless sensor node ready by the end of the semester.***
- *Ideally, this prototype should be able to demonstrate the working principle of a wireless sensor node.*
- *The prototype should consist of hardware provided by the institute, your own readout circuit, and software for handling the measured data.*

Deliverables: What constitutes your Grade?

- Paper: Write a paper (4 pages strict) in IEEE format.
- Presentation: 15-minutes oral presentation of your results at the end of the semester with subsequent Q&A session.
- Update: 10-minutes update discussions at the beginning of each appointment (evaluation of measurement results, discussion of software issues, literature research, etc.)
- Milestone Reports: We will have three milestones in the Sensor Nodes project. There should be a one page milestone report submitted after each project milestone. These milestones are:
  - Readout frontend including analog-to-digital conversion. (2-3 weeks)
  - Communication interface between readout circuit and wireless communication board. (2-3 weeks)
  - Data encapsulation and enqueuing. (1-2 weeks)

Read the literature in Moodle!

Templates, Literature, Instructions, etc. will be uploaded to Moodle. This Kick-Off slides will also follow...

Group Assignment

Group slots will be assigned as follows

G1 G2

G1 Group 1	Nagesh, Nitish	Thekkekara, Sebastian	
G2 Group 2	Lopez Cruz, Daniel	Lavin Vizcaino, Daniel	Vilkelyte, Zivile

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Outline

Dynamic Range Amplification and Attenuation

- An analog to digital converter (ADC), converts analog signals to digital data by comparing the analog input voltage to fixed reference voltages in multiple stages.
- The number of stages determines the resolution of the ADC, while the voltage span from minimum to maximum reference voltage determines the so called dynamic range.
- In practice, output voltages of sensor system never really meet the requirements for ADC dynamic ranges.
- Hence, one needs to design an analog interface, matching the expected voltages at the sensor output to the dynamic range of the ADC in use.

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Dynamic Range Amplification and Attenuation

- We distinguish two cases. One where the Sensor output span is smaller than the ADC input span and one where the Sensor output span is larger than the ADC input span.
- In the first case we need to amplify the signal, in the other case the signal voltage needs to be attenuated.
- Two examples, one for the first case and one for the second case are given in the figure below.

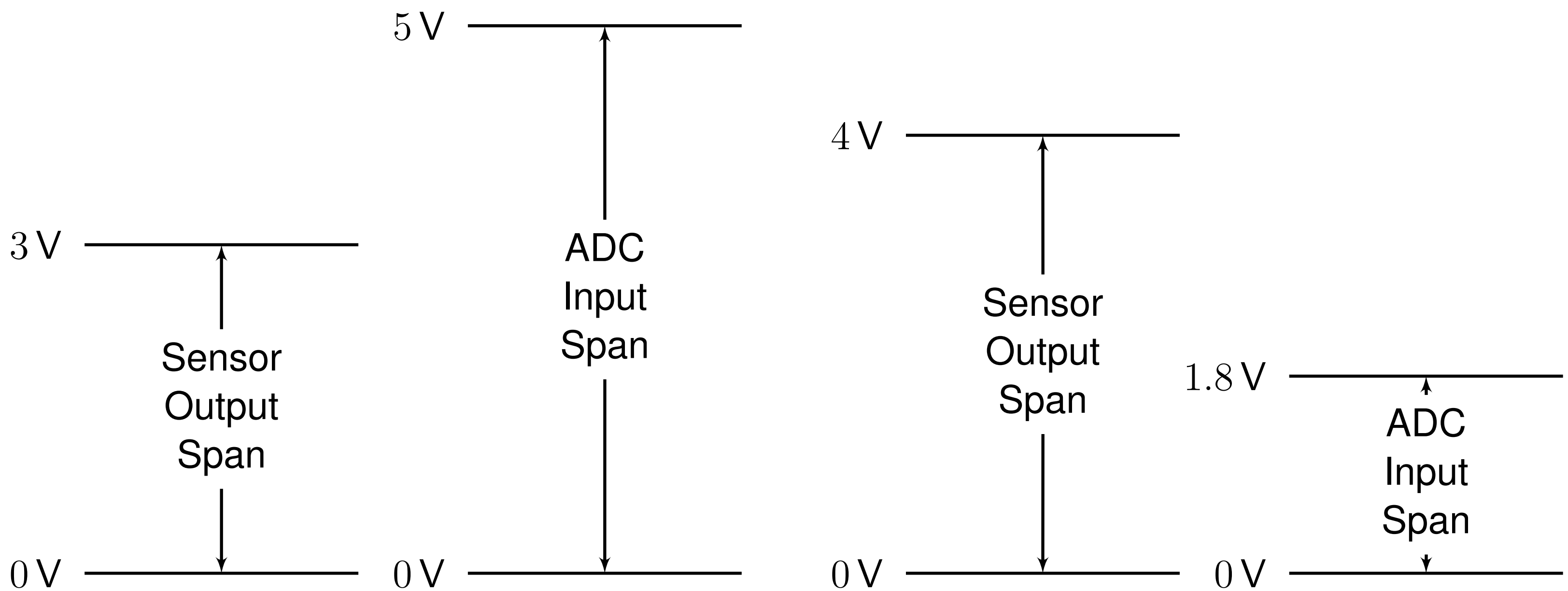

Figure: Voltage range missmatch between Sensor output and ADC input.

Dynamic Range Amplification and Attenuation

- For the first case, where the signal needs to be amplified, an operational amplifier is used as analog input stage.
- If the signal voltage needs to be attenuated, one can use a simple voltage divider network.

Read the literature in Moodle!

Designing an operational amplifier circuit with given input and output voltages is not scope of this lecture and should have been covered during your Bachelor's. Anyway, a whitepaper will be uploaded to Moodle for further reference.
The same holds for the design of a voltage divider circuit. This is elementary electronics and can be found everywhere on the internet.

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Outline

Filter Design

- In electronics and especially in signal processing, a filter is a device or process that extracts some parts or features out of a given signal.
- There are several different filter topologies. We distinguish between the following:
  - linear or non-linear
  - time-invariant or time-variant, also known as shift invariance.
  - causal or not-causal
  - analog or digital
  - discrete-time or continuous-time
  - passive or active

Filter Design

- Consider the following two-port.

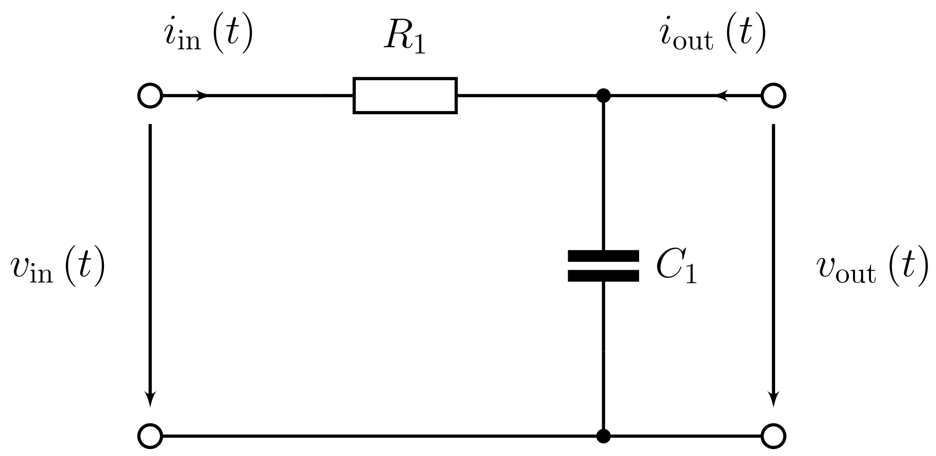

Figure: First order passive low-pass filter.

- Let us now calculate the input/output characteristic of this simple low-pass filter.
- The output voltage $v_{\text{out}}(t)$ is given by

$$v_{\text{out}}(t) = v_{\text{in}}(t) - R_1 i_{\text{in}}(t) \ .$$

Filter Design

- Furthermore, we have

$$i_{\mathrm{in}}\left(t\right) + i_{\mathrm{out}}\left(t\right) = C_1 \frac{\mathrm{d}}{\mathrm{d}t} v_{\mathrm{out}}\left(t\right) \ .$$

- As we are interested in the frequency characteristics of the low-pass filter, we perform a Fourier transform on our system of equations, resulting in

$$\begin{aligned} V_{\mathrm{out}}\left(\omega\right) &= V_{\mathrm{in}}\left(\omega\right) - R_1 I_{\mathrm{in}}\left(\omega\right) \ , \\ I_{\mathrm{in}}\left(\omega\right) + I_{\mathrm{out}}\left(\omega\right) &= \mathrm{i}\omega C_1 V_{\mathrm{out}}\left(\omega\right) \ . \end{aligned}$$

- The input output relation of the two-port is given in terms of the impedance matrix $\boldsymbol{Z}$ by

$$\begin{bmatrix} V_{\mathrm{in}}\left(\omega\right) \\ V_{\mathrm{out}}\left(\omega\right) \end{bmatrix} = \begin{bmatrix} Z_{11}\left(\omega\right) & Z_{12}\left(\omega\right) \\ Z_{21}\left(\omega\right) & Z_{22}\left(\omega\right) \end{bmatrix} \begin{bmatrix} I_{\mathrm{in}}\left(\omega\right) \\ I_{\mathrm{out}}\left(\omega\right) \end{bmatrix} \ .$$

Filter Design

- Thus, we have

$$V_{\text{in}}(\omega) = \left(R_1 - \mathrm{i}\frac{1}{\omega C_1}\right) I_{\text{in}}(\omega) - \mathrm{i}\frac{1}{\omega C_1} I_{\text{out}}(\omega) \ ,$$
$$V_{\text{out}}(\omega) = -\mathrm{i}\frac{1}{\omega C_1} I_{\text{in}}(\omega) - \mathrm{i}\frac{1}{\omega C_1} I_{\text{out}}(\omega) \ .$$

- In matrix-vector notation, we can write

$$\begin{bmatrix} V_{\text{in}}(\omega) \\ V_{\text{out}}(\omega) \end{bmatrix} = \begin{bmatrix} R_1 - \mathrm{i}\frac{1}{\omega C_1} & -\mathrm{i}\frac{1}{\omega C_1} \\ -\mathrm{i}\frac{1}{\omega C_1} & -\mathrm{i}\frac{1}{\omega C_1} \end{bmatrix} \begin{bmatrix} I_{\text{in}}(\omega) \\ I_{\text{out}}(\omega) \end{bmatrix} \ .$$

- By rearranging the second row of the matrix for $I_{\text{in}}(\omega)$ and inserting the result in the first row, we obtain the transfer function of the filter

$$\frac{V_{\text{out}}(\omega)}{V_{\text{in}}(\omega)} = \frac{1}{\mathrm{i}\omega R_1 C_1 + 1 - \frac{R_1}{Z_{\text{out}}(\omega)}} \ ,$$

with $Z_{\text{out}}(\omega) = \frac{V_{\text{out}}(\omega)}{I_{\text{out}}(\omega)}$.

Filter Design

- Assuming a high output impedance $Z_{\text{out}} \to \infty$, the transfer function $H(\omega)$ of the low-pass filter is given by

$$H(\omega) = \frac{V_{\text{out}}(\omega)}{V_{\text{in}}(\omega)} = \frac{1}{\mathrm{i}\omega R_1 C_1 + 1},$$

- The cut-off frequency ω_c is the point, where the power magnitude has dropped to half the power in the pass-band. Since power depends on voltage squared, we are looking for the point

$$|H(\omega_c)| = \frac{1}{\sqrt{2}} = \left| \frac{1}{1 + \mathrm{i}\omega_c R_1 C_1} \right| = \sqrt{\frac{1}{1 + \omega_c^2 R_1^2 C_1^2}}.$$

- From this it follows for the cut-off frequency ω_c

$$\omega_c = \frac{1}{R_1 C_1}.$$

- Note that a finite output or load impedance influences the filter. Hence, there are other active filter topologies to get around this issue.

Filter Design

- The low-pass filter discussed so far is the simplest possible realization of the general Butterworth[1] filter family.
- The family of Butterworth filters is characterized by a transfer function with magnitude

$$|H(\omega)| = \frac{1}{\sqrt{1 + \left(\frac{\omega}{\omega_c}\right)^{2n}}} .$$

  where ω_c is the cut-off frequency, as before, and n is called the filter order.
- It is trivial to show that the simple RC low-pass filter with $\omega_c = \frac{1}{R_1 C_1}$, we derived before, can be characterized by this requirement to the transfer function with $n = 1$.
- A Butterworth filter type is the "maximally flat" filter in terms of the frequency behavior of the transfer function in the pass-band. The derivative of the transfer function magnitude is given by

$$\frac{\mathrm{d}|H(\omega)|}{\mathrm{d}\omega} = -n\,|H(\omega)|^3 \left(\frac{\omega}{\omega_c}\right)^{2n-1} ,$$

  which is a monotonically decreasing function since $|H(\omega)| \geq 0$. Hence, there is no ripple in the transfer function.

[1] Stephen Butterworth (*1885, †1958) was a British physicist who invented the filter that bears his name.

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Filter Design

- A Butterworth filter with order n can be realized by the Cauer topology.
- It is given by a network of capacitors and inductors as

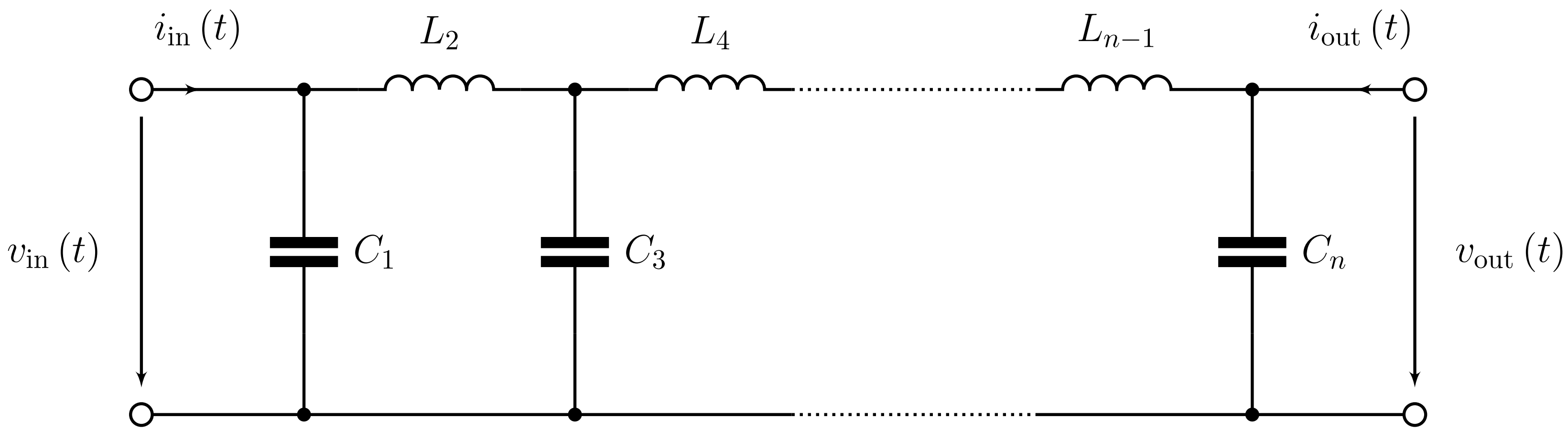

Figure: Cauer topology for n-th order Butterworth filer.

- The values for the capacitors C_k and inductors L_k are given by[2] (Proof $\rightarrow$ Homework)

$$C_k = 2\sin\left(\frac{2k-1}{2n}\cdot\pi\right), \qquad L_k = 2\sin\left(\frac{2k-1}{2n}\cdot\pi\right).$$

[2] W. R. Bennett (1932). "Transmission Network". US 1849656.

Filter Design

- The passive Cauer topology filter still depends on the output impedance $Z_{\mathrm{out}}(\omega)$. Previous investigations have only been valid by the assumption $Z_{\mathrm{out}}(\omega) \to \infty$.
- An active filter topology, where the transfer function is independent of the output impedance is given by the Sallen-Key filter topology using an operational amplifier.

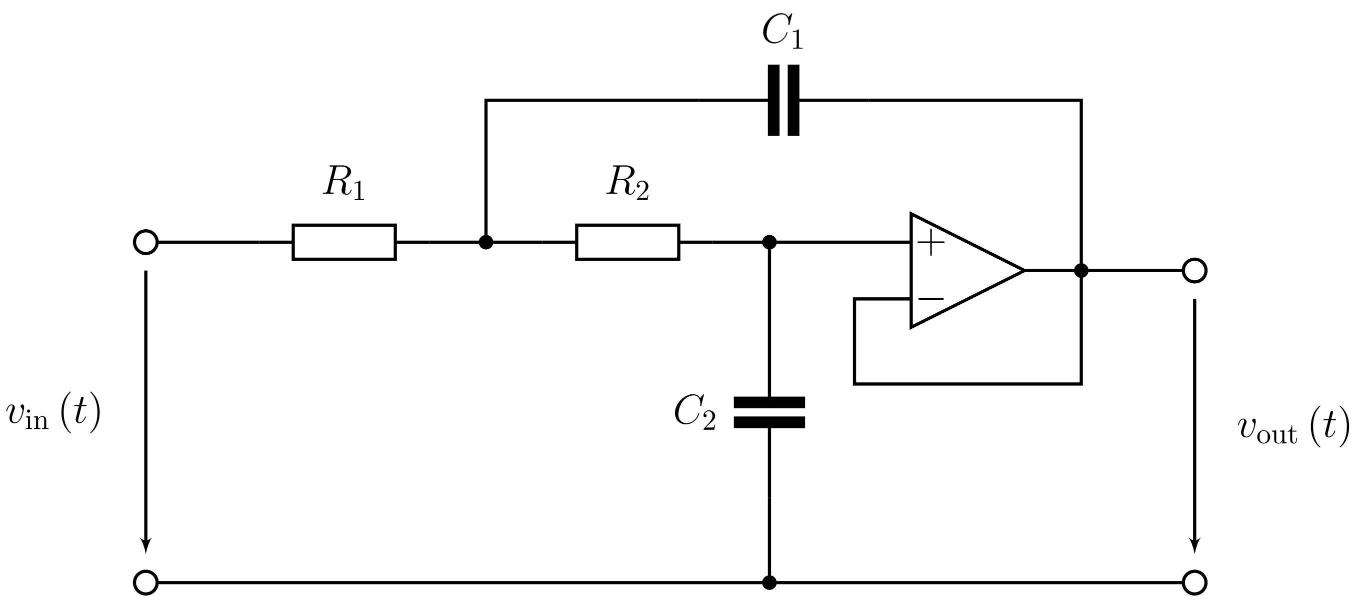

Figure: Sallen-Key topology for second order Butterworth filer.

Filter Design

- Let us analyze the second order Butterworth filter in Sallen-Key topology in frequency domain, by modeling the ideal operational amplifier input as a Nullator and the output as a Norator.
- Thus, we have with the helper node voltage $V_{\mathrm{x}}(\omega)$ between R_1 and R_2

$$\frac{V_{\mathrm{in}}(\omega) - V_{\mathrm{x}}(\omega)}{R_1} = \mathrm{i}\omega C_1 \left(V_{\mathrm{x}}(\omega) - V_{\mathrm{out}}(\omega)\right) + \frac{V_{\mathrm{x}}(\omega) - V_{\mathrm{out}}(\omega)}{R_2},$$
$$\frac{V_{\mathrm{x}}(\omega) - V_{\mathrm{out}}(\omega)}{R_2} = \mathrm{i}\omega C_2 V_{\mathrm{out}}(\omega).$$

- From here it follows for the transfer function $H(\omega)$

$$H(\omega) = \frac{V_{\mathrm{out}}(\omega)}{V_{\mathrm{in}}(\omega)} = \frac{1}{1 - R_1 R_2 C_1 C_2 \omega^2 + \mathrm{i}\omega C_2 (R_1 + R_2)}$$

- Comparing the transfer function to the second order Butterworth function yields

$$\frac{1}{1 - R_1 R_2 C_1 C_2 \omega^2 + C_2 (R_1 + R_2)\,\mathrm{i}\omega} = \frac{1}{1 - \frac{1}{\omega_c^2}\omega^2 + \frac{\sqrt{2}}{\omega_c}\mathrm{i}\omega}.$$

Filter Design

- From there it follows, that for a given cut-off frequency ω_c we have

$$R_1 R_2 C_1 C_2 = \frac{1}{\omega_c^2}\,,$$

  and that

$$C_2\left(R_1 + R_2\right) = \frac{\sqrt{2}}{\omega_c}\,.$$

- We express the values for the components R_1, R_2, C_1, and C_2 by the parameters

$$R_1 = mR\,, \qquad R_2 = \frac{R}{m}\,,$$
$$C_1 = nC\,, \qquad C_2 = \frac{C}{n}\,.$$

- The design procedure for a second order Butterworth low-pass filter is as follows:
  - Choose more or less arbitrary values for C and n.
  - Values for R and m are then calculated by

$$\frac{1}{\sqrt{2}} = \frac{mn}{m^2+1}\,.$$

Outline

1 Recap of last Meeting

2 Dynamic Range Amplification and Attenuation

3 Filter Design

4 Introduction to PSoC Creator

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Introduction to PSoC Creator

- Enough theory for today!
- Let us now make an LED blink using actual Hardware...