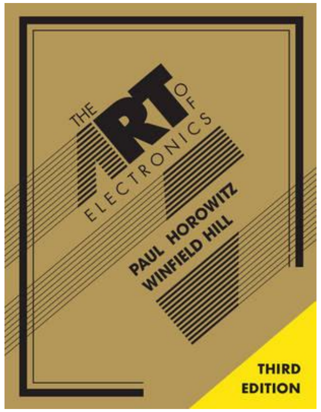
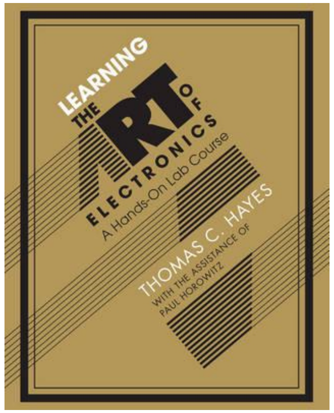
Analog electronics hands-on

- Analog – Digital?
- Recommended readings
  - for beginners
  - special topics
- How to proceed?
  - theory
  - modelling (simulations with LTspice IV)
  - experiments
- General topics
  - linear circuits – basic lows and tools
  - ideal operational amplifier
  - real operational amplifier - stability
  - basic circuits with operational amplifiers
  - comparators – discriminators
- Special topics for nuclear & high energy physicists
  - Pole/Zero correction and shaping amplifier
  - single channel analyzer
  - timing – leading edge, constant fraction discriminator

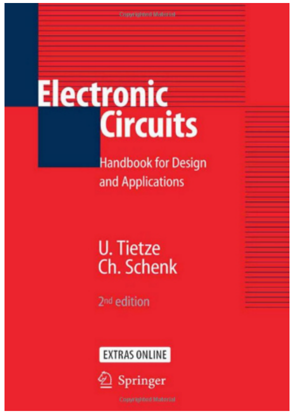
Recommended readings



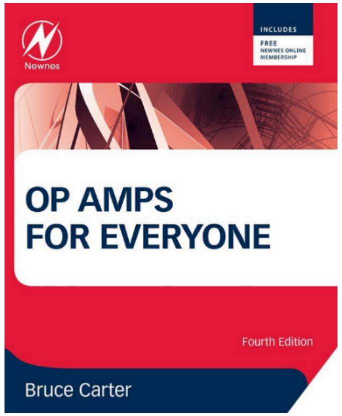
The Art of Electronics
Paul Horowitz, Winfield Hill
http://artofelectronics.net/
Learning the Art of Electronics
A Hands-On Lab Course
Thomas C. Hayes, Paul Horowitz



Halbleiter-Schaltungstechnik
Ulrich Tietze, Christoph Schenk,
Eberhard Gamm
http://www.tietze-schenk.de/tsbuch.htm
English version available:
Electronic Circuits: Handbook for Design and Application



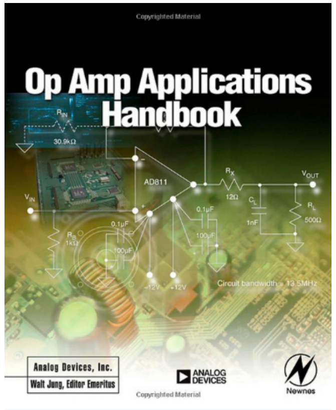
Online available readings

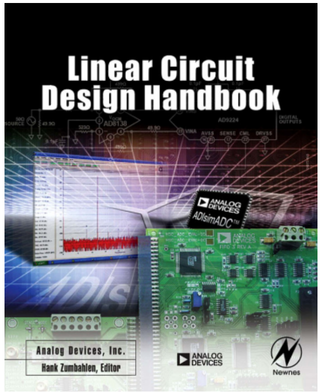


Op Amps for everyone (TI) – find it with google!

Handbook of Operational Amplifier Applications - Texas Instruments
www.ti.com/lit/an/sboa092a/sboa092a.pdf

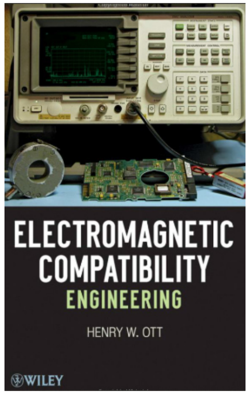
Op Amp Applications Handbook (AD)
http://www.analog.com/library/analogDialogue/archives/39-05/op_amp_applications_handbook.html



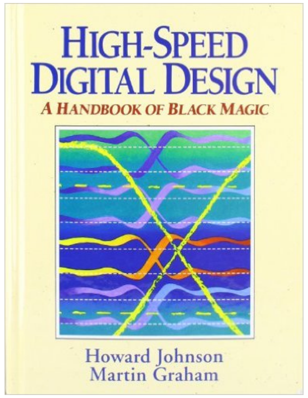


Linear Circuit Design Handbook (AD)
http://www.analog.com/library/analogDialogue/archives/43-09/linear_circuit_design_handbook.html

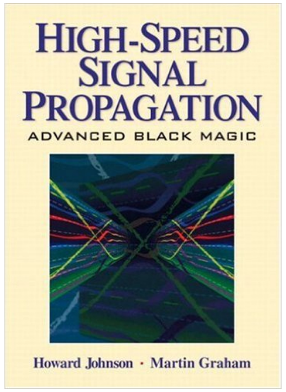
Special topics



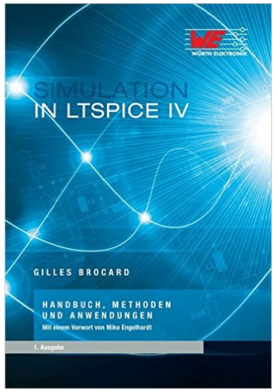
Electromagnetic Compatibility Engineering
Henry W. Ott
Everything about cabling, grounding, shielding, noise, PCB layout problems!

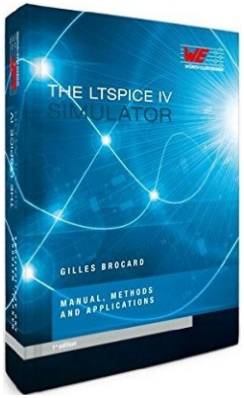


High Speed Digital Design: A Handbook of Black Magic and **High Speed Signal Propagation: Advanced Black Magic**
by Howard Johnson, Martin Graham



Simulation in LTspice IV
or
The LTspice IV Simulator
by Gilles Brocard Würth





Lets start with some known lows from the physics

… and some useful techniques to analyse electric circuits

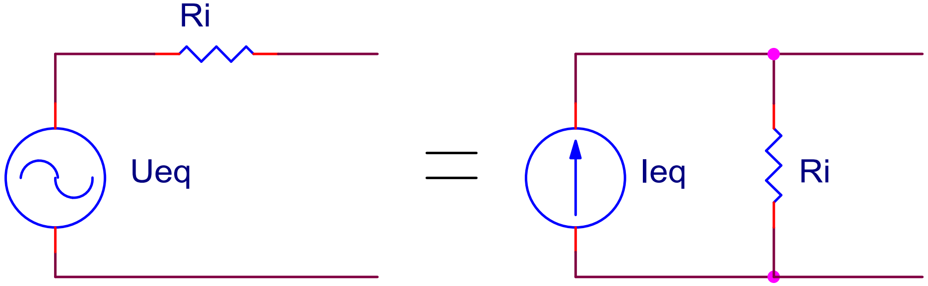
- Ohm‘s low
- Kirchhoff‘s laws
  - Algebraic sum of currents in and out of a node is 0
  - Algebraic sum of voltage drops in a closed loop is 0
- Mesh analysis
- **Only for linear circuits:**
  - **Norton and Thévenin theorems**
  - **Superposition**

Linear circuits

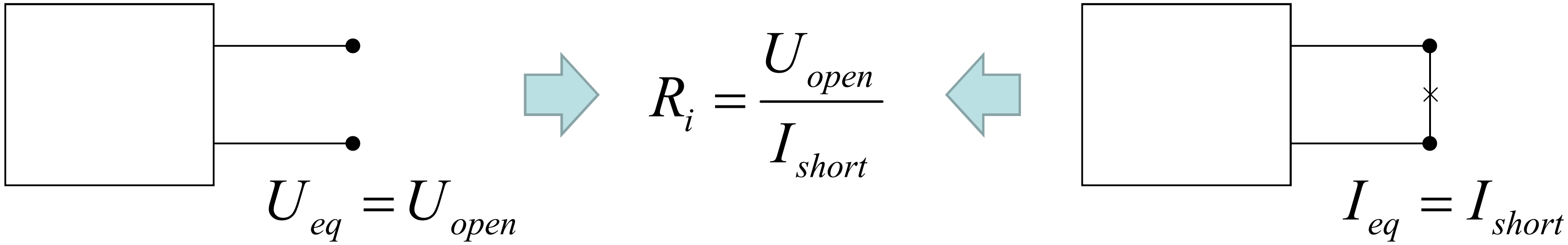
- Ideal and real voltage and current sources
    - Thévenin and Norton theorems
- Equivalent transformations
- Examples
- AC circuits
    - Low pass, high pass filter
- Impedance matching, termination (experimental)

Ideal and real sources, source transformations – Thévenin & Norton Theorems

- Ideal & real voltage/current sources, equivalence (Norton theorem)



- Thévenin-Theorem for a two terminal part of a circuit



$$R_i = \frac{U_{open}}{I_{short}}$$

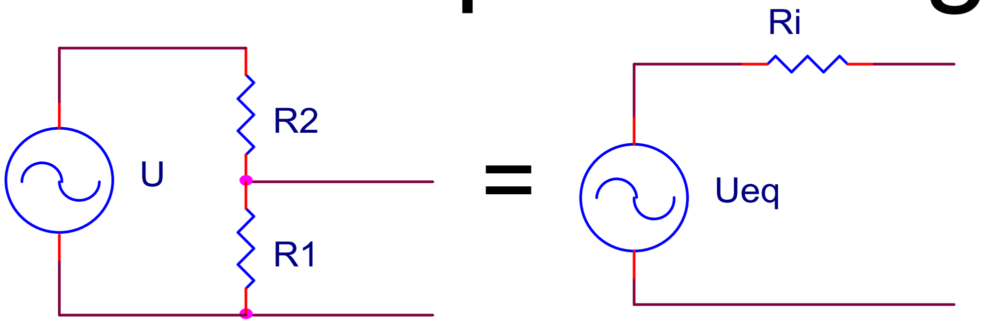
$$U_{eq} = U_{open}$$

$$I_{eq} = I_{short}$$

Not recommended as experimental method!!!

R_i can be found by removing all current sources and setting all voltage sources to 0, then it is the resistance seen at the two terminals.

Example: voltage divider



$$U_{eq} = U_{open} = U\frac{R_1}{R_1 + R_2}$$

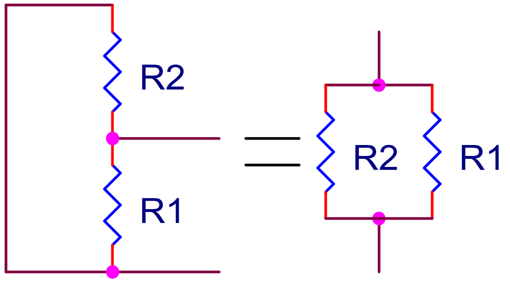
$$I_{short} = \frac{U}{R_2}$$

$$R_i = \frac{U_{open}}{I_{short}} = \frac{\dfrac{U \cdot R_1}{R_1 + R_2}}{\dfrac{U}{R_2}} =$$

$$= \frac{R_1 \cdot R_2}{R_1 + R_2} = R_1 \| R_2$$

Alternative:

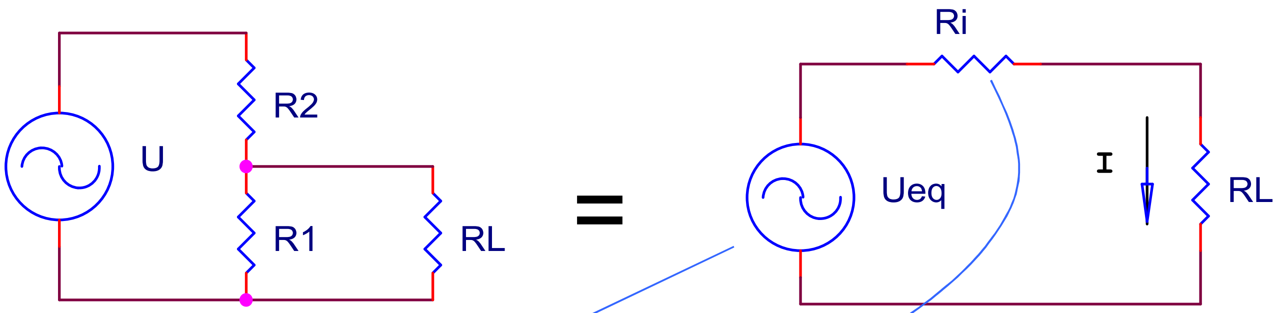
- set U=0
- calculate the resistance seen from outside:



$$R_i = R_1 \| R_2$$

Example: loaded voltage divider

- May I load the voltage divider?



$$U_{eq} = U \frac{R_1}{R_1 + R_2}$$

$$I = \frac{U_{eq}}{R_L + R_i}$$

$$R_i = R_1 \| R_2$$

$$U_{RL} = U_{eq} - I \cdot R_i$$

$$rel.err \approx R_i / R_L$$

Example

$U = 10\mathrm{V}, R_1 = 1\mathrm{k}, R_2 = 9\mathrm{k}$

$U_{eq} = 1\mathrm{V}, R_i = 0.9\mathrm{k}$

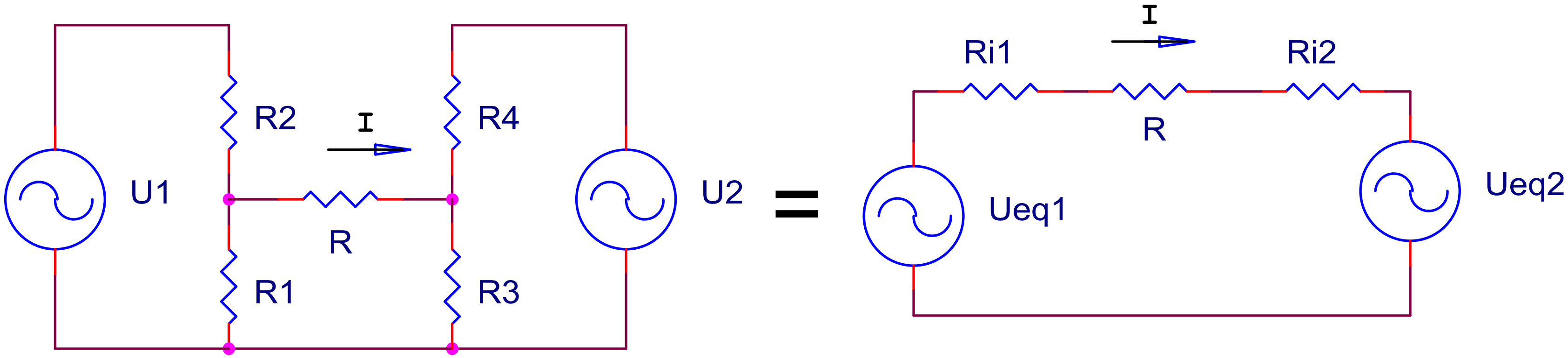
$R_L = 100\mathrm{k}, I = 1\mathrm{V}/100.9\mathrm{k} = 9.9\mu\mathrm{A}$

$I_{R1,R2} = 1\mathrm{mA} = 1000\mu\mathrm{A}$

$rel.err. \approx 0.9\mathrm{k}/100\mathrm{k} \approx 1\%$

Example: circuit transformations

- Which is the current through R?



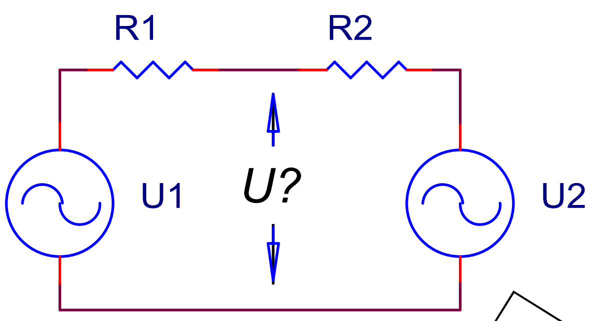
$$R_{i1} = R_1 \| R_2 \qquad R_{i2} = R_3 \| R_4$$

$$U_{eq1} = U_1 \frac{R_1}{R_1 + R_2} \qquad U_{eq2} = U_2 \frac{R_3}{R_3 + R_4}$$

$$I = \frac{\left(U_{eq1} - U_{eq2}\right)}{R_{i1} + R_{i2} + R}$$

Superposition principle

- What is the voltage in the middle?



Two contributions

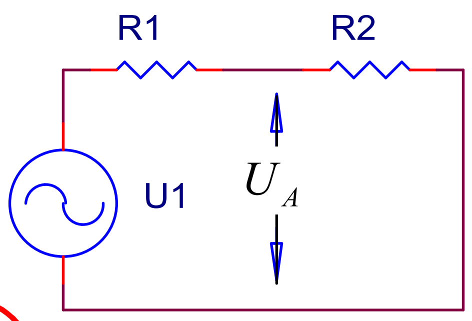
$$U = U_A + U_B$$

$$U_1 = 10\mathrm{V},\ R_1 = 4\mathrm{k}$$

$$U_2 = 5\mathrm{V},\ R_2 = 1\mathrm{k}$$

$$U = 10 \cdot 1/5 + 5 \cdot 4/5 = 2 + 4 = 6\mathrm{V}$$

A

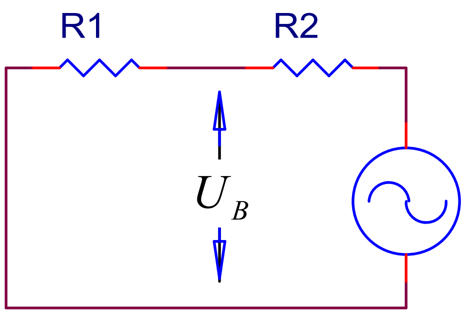


$$U_A = U_1 \frac{R_2}{R_1 + R_2}$$

U2=0 (short)

B

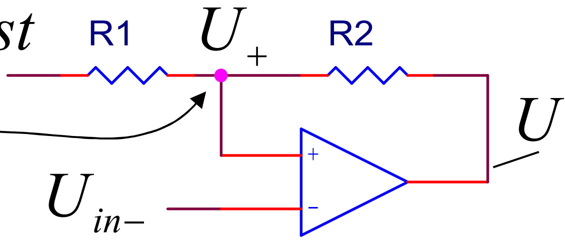
U1=0



$$U_B = U_2 \frac{R_1}{R_1 + R_2}$$

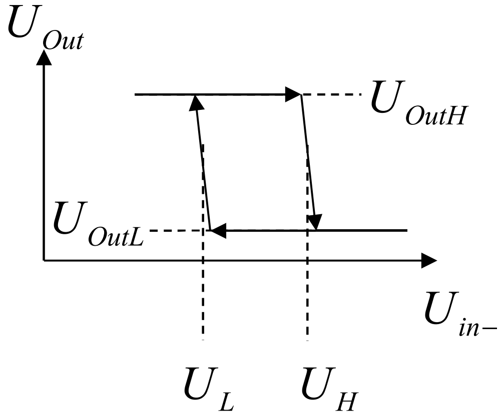
Superposition principle example - Comparator with Hysteresis

$U_{in+} = const$



$$U_{Out} = \begin{cases} U_{OutH} \\ U_{OutL} \end{cases}$$

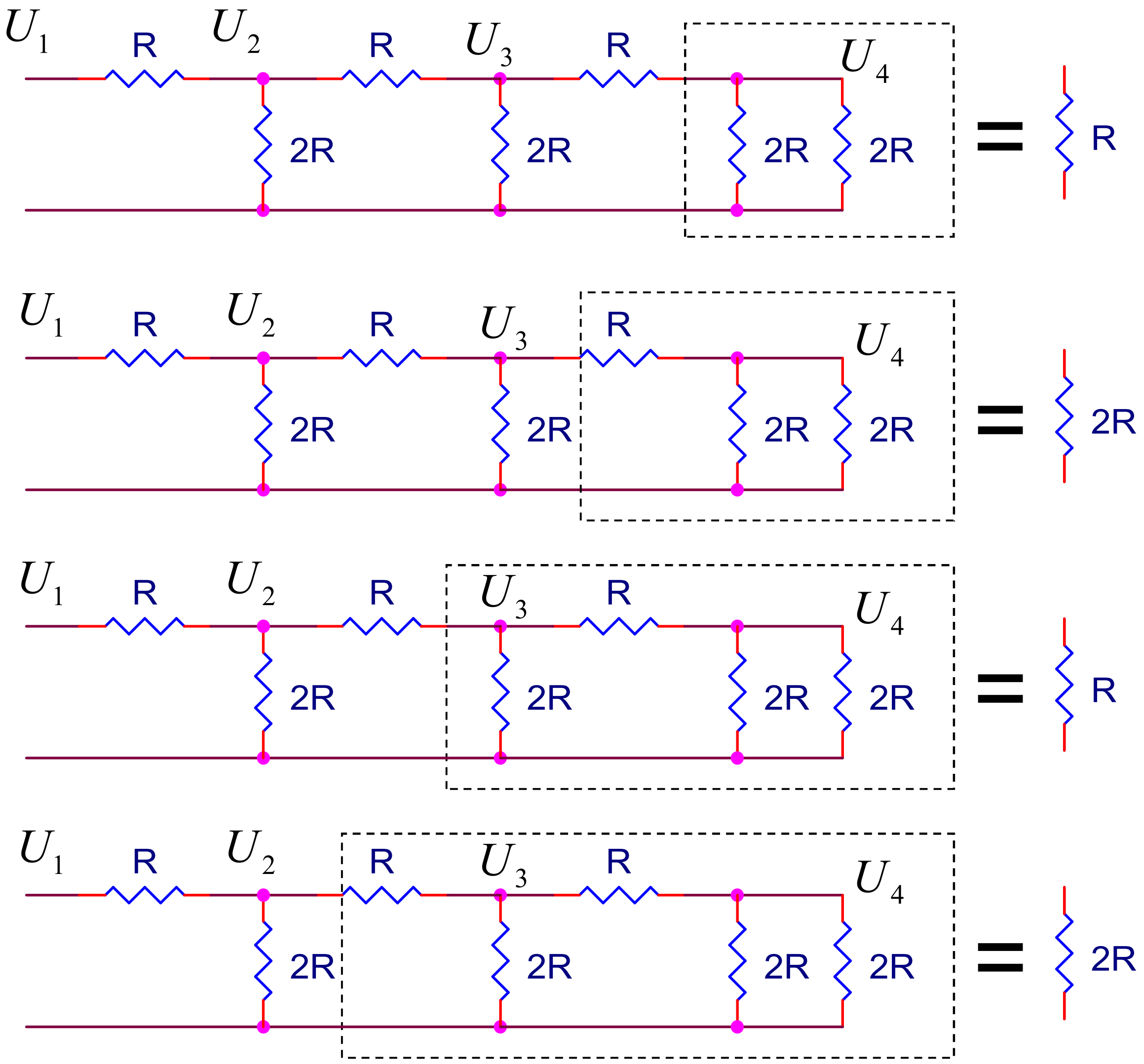
$$\begin{cases} U_H = U_{in+} \dfrac{R_2}{R_1 + R_2} + U_{OutH} \dfrac{R_1}{R_1 + R_2} \\ U_L = U_{in+} \dfrac{R_2}{R_1 + R_2} + U_{OutL} \dfrac{R_1}{R_1 + R_2} \end{cases}$$



$$Hysteresis = U_H - U_L = \left(U_{OutH} - U_{OutL}\right)\frac{R_1}{R_1 + R_2}$$

Example $R_1 = 1\text{k}, R_2 = 50\text{k}, U_{Out} = 0\,|\,5\text{V},\ Hyst. = (1/51)\cdot 5\text{V} = 98\text{mV} \approx 100\text{mV}$

Example - R-2R Network



$$U_4 = \frac{U_3}{2} = \frac{U_2}{2^2} = \frac{U_1}{2^3}$$

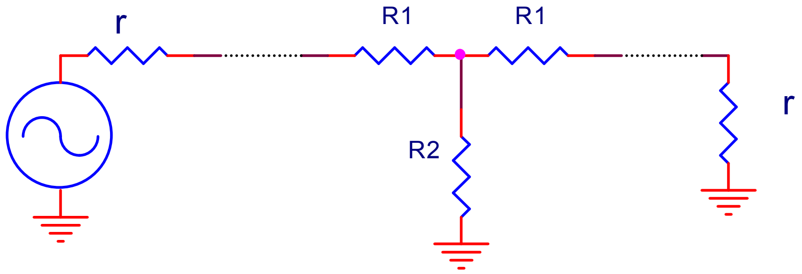
$$U_3 = \frac{U_2}{2} = \frac{U_1}{2^2}$$

$$U_2 = \frac{U_1}{2}$$

This technique is used in digital to analogue converter to divide the reference voltage using only two values of the resistors.

usw.

Example – T-attenuator



$$Z_{IN} = Z_{OUT} = \left(r + R_1\right) \| R_2 + R_1 = r$$

The attenuation only of the T-net is

$$\frac{R_2}{r + R_1 + R_2}$$

- The signal source has output impedance r=50Ω and should “see” the rest of the circuit as r=50Ω
- The output impedance of the attenuator should be 50Ω
- The load is r=50Ω
- The desired attenuation is G

Note that the attenuation without the T-net is ½, so the total attenuation with proper termination is

$$G = \frac{1}{2} \cdot \frac{R_2}{r + R_1 + R_2}$$

AC - circuits

- AC analysis of circuits containing capacitors and inductors

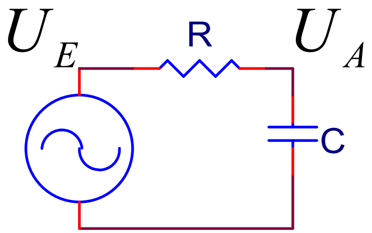
$$I = C\frac{dV}{dt} \qquad U = L\frac{dI}{dt}$$

- Using complex numbers in electronics
  - Impedance $Z_C = \frac{1}{j\omega C}$ $\quad Z_L = j\omega L$
  - Voltages and currents

$$U = U_0 e^{j(\omega t+\varphi)},\ U_{MEASURED} = \mathrm{Re}(U_0 e^{j(\omega t+\varphi)}) = U_0 \cos(\omega t+\varphi)$$

$$I = U/Z,\ \ldots$$

Low pass filter

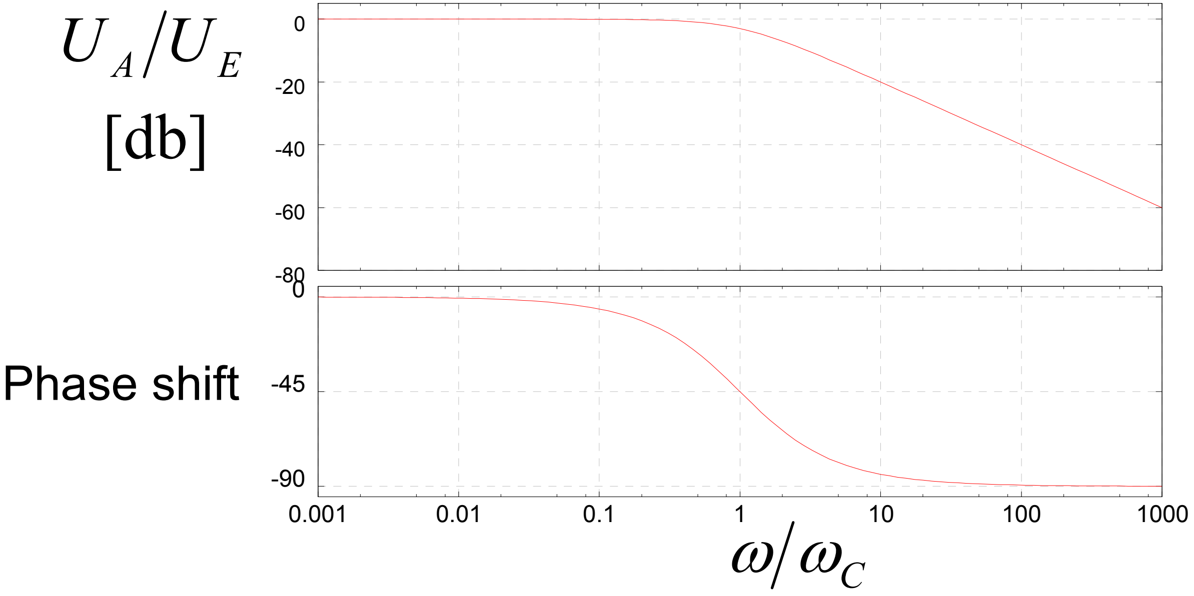


$$\frac{U_A}{U_E}=\frac{Z_C}{R+Z_C}=\frac{1/j\omega C}{R+1/j\omega C}=\frac{1}{1+j\omega RC}=\frac{1}{\boxed{1+j\omega\tau}}$$

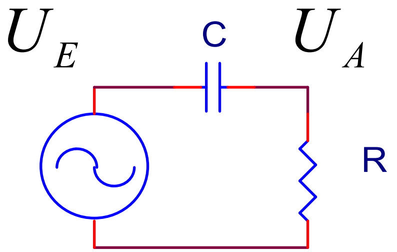
pole

$$\left|\frac{U_A}{U_E}\right|=\frac{1}{\sqrt{1+\omega^2\cdot\tau^2}}=\frac{1}{\sqrt{1+(\omega/\omega_C)^2}}=\frac{1}{\sqrt{1+(f/f_C)^2}}$$

where $\tau=R\cdot C,\ \omega_C=1/\tau,\ f_C=\omega_C/2\pi=\dfrac{1}{2\pi RC}$



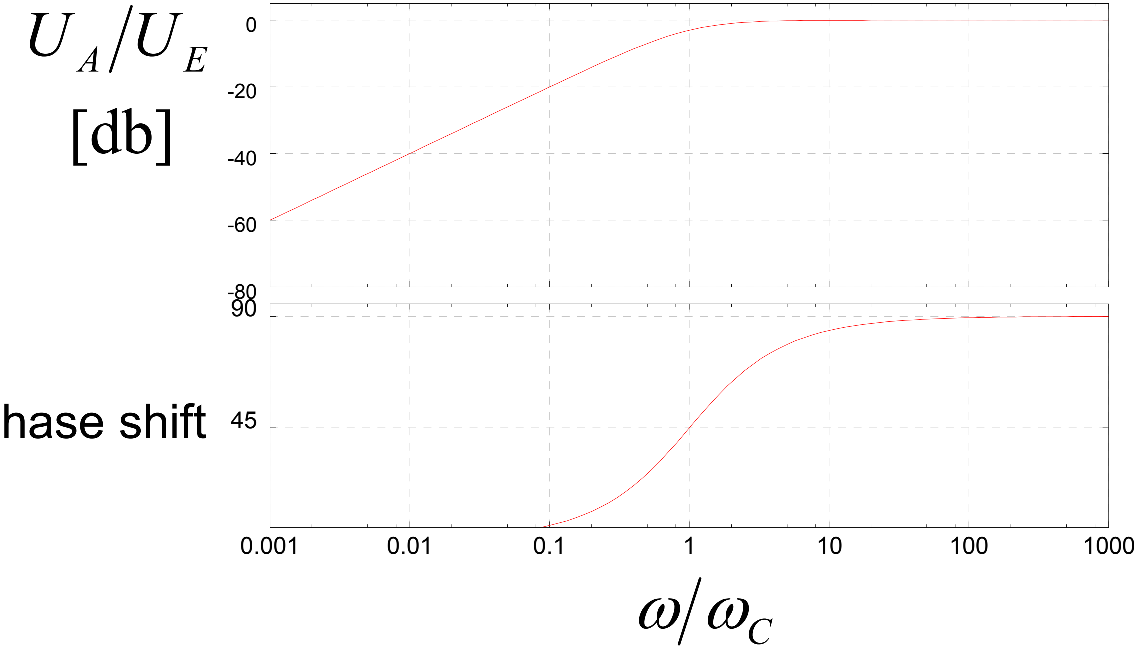
High pass filter



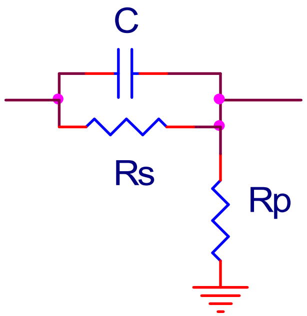
$$\frac{U_A}{U_E}=\frac{R}{R+Z_C}=\frac{R}{R+1/j\omega C}=\frac{j\omega RC}{1+j\omega RC}=\frac{j\omega\tau}{1+j\omega\tau}$$

$$\left|\frac{U_A}{U_E}\right|=\frac{\omega\tau}{\sqrt{1+\omega^2\cdot\tau^2}}=\frac{\omega/\omega_C}{\sqrt{1+\left(\omega/\omega_C\right)^2}}=\frac{f/f_C}{\sqrt{1+\left(f/f_C\right)^2}}$$

where $\tau=R\cdot C,\ \omega_C=1/\tau,\ f_C=\omega_C/2\pi=\dfrac{1}{2\pi RC}$



Pole/Zero correction



$$\tau_1 = R_S \cdot C, \quad \tau_2 = \left(R_S \| R_P\right) \cdot C$$

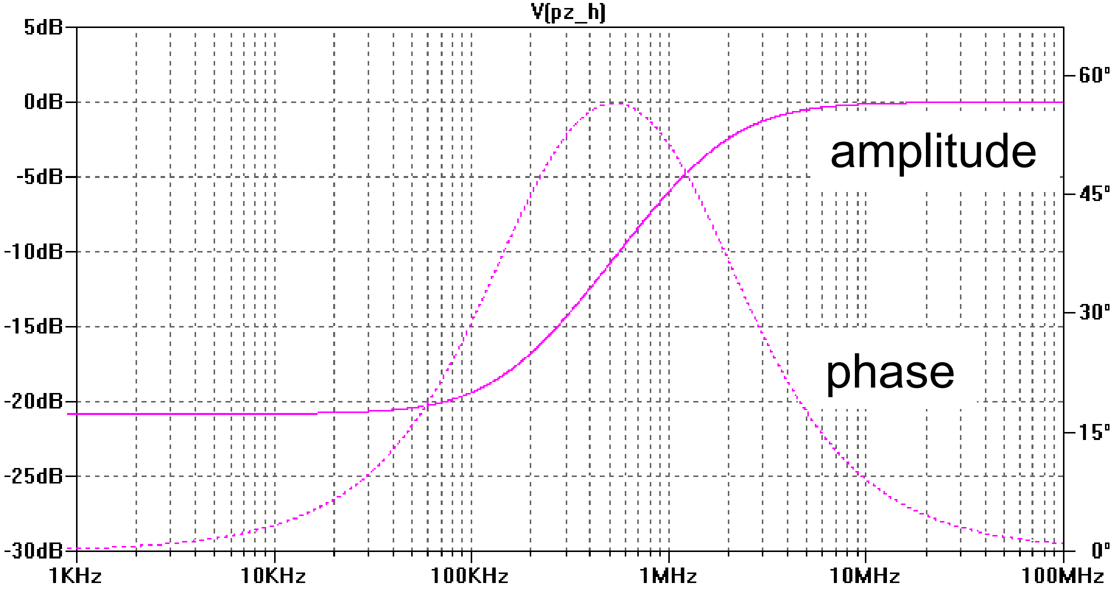
$$\frac{U_{OUT}}{U_{IN}} = K_0 \cdot \frac{\boxed{1 + j\omega\tau_1}}{\boxed{1 + j\omega\tau_2}},$$

← zero

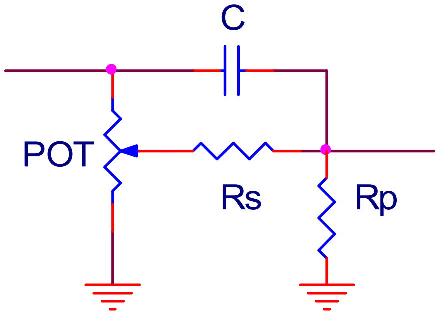
← pole

$$K_0 = \frac{R_P}{R_S + R_P}$$

$$\boxed{\tau_2 < \tau_1}$$!



Practical realisation

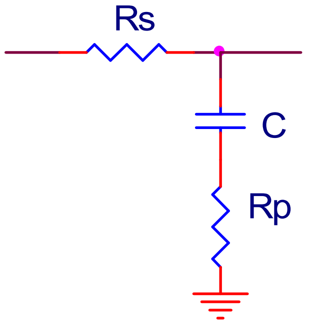


when $POT << R_S$

$$\tau_1 = R_S \cdot C \ldots \infty$$

$$\tau_2 = \left(R_S \| R_P\right) \cdot C$$

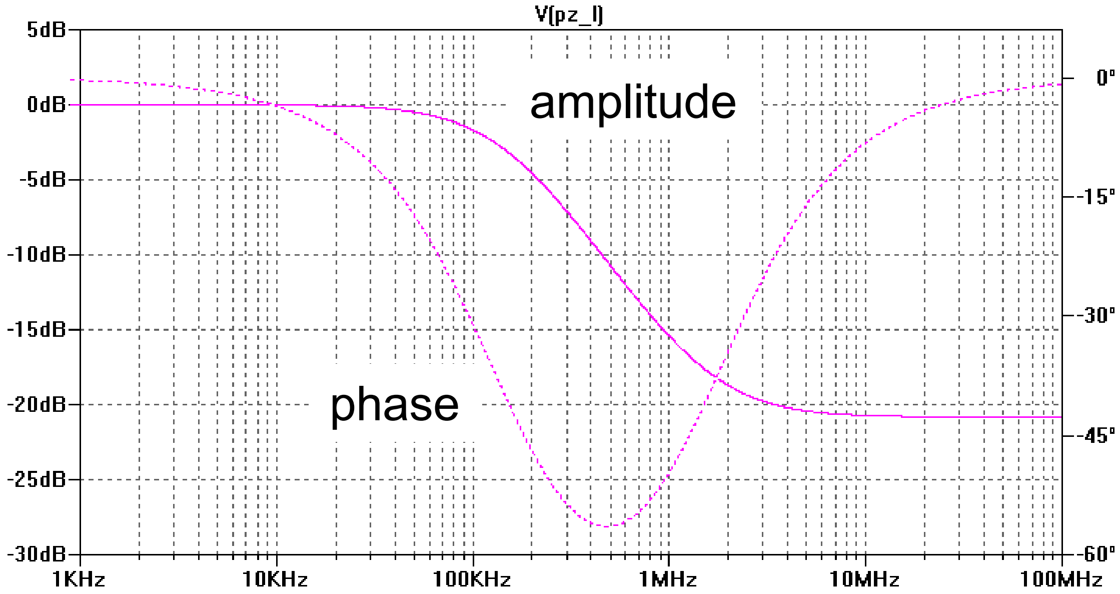
Pole/Zero correction



$$\tau_1 = R_P \cdot C, \quad \tau_2 = \left(R_S + R_P\right) \cdot C$$

$$\frac{U_{OUT}}{U_{IN}} = K_0 \cdot \frac{1 + j\omega\tau_1}{1 + j\omega\tau_2}, \quad K_0 = 1$$

$\boxed{\tau_2 > \tau_1}$!



Uni-Heidelberg, HighRR, Sept. 2016