Electronics for Pedestrians
– Passive Components –

Ralph J. Steinhagen, CERN

“In theory, 'theory' and 'praxis' are the same, in praxis they aren't”

Introduction

- Why bother with electronics when dealing with accelerator physics?

Who doesn't want to be like MacGyver?*
… he's physicist, and he has a firm grasp of electronics.

*also: Farraday, Ampere, many Nobel prize winners (1956, 1964, 1973, 2000, 2009), Röntgen, Marconi, Braun, ...

Introduction – more serious

- Why bother with electronics when dealing with accelerator physics?
  - Most physics effects are invisible to naked eye
  - Electronics is not a fundamental element in our understanding of universe, but an essential tool in many experiments as are: problem-solving, scientific reasoning, math, computer science, …

- Most beam instrumentation/experiments "boil down" to electro-magnetic and optical signals that need to be pre-conditioned before they can be accurately measured, need to be able to distinguish between
  a) Model uncertainty (theory, particle tracking codes, ...)
  b) Machine uncertainties (multiple effects may contribute to your observations), and
  c) Beam measurement uncertainties → needs basic electronics knowledge

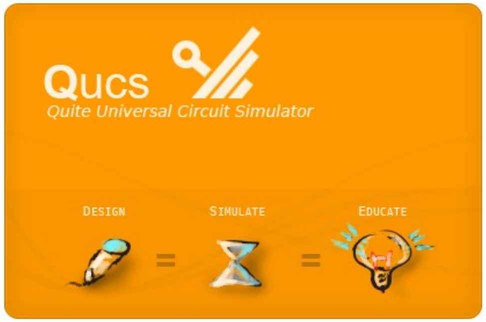
- As a physicist, (non-electronics) engineers or scientist, need to be able to:
  - distinguish between physics and instrumentation effects
  - interpret and communicate (simple) electronics schematics
  - communicate ideas to electronics engineer to guide & improve instrumentation

Examples

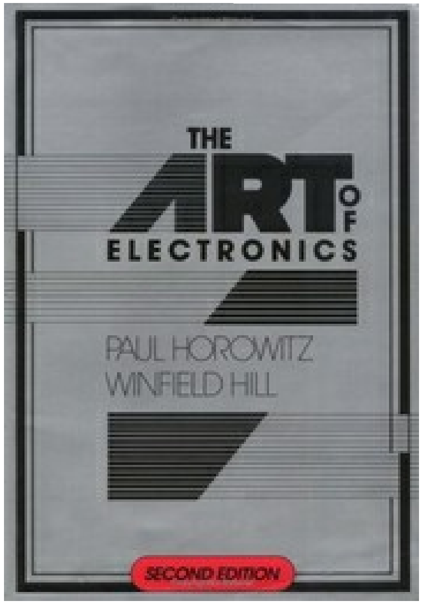
- Most beam properties can be easily converted into electric quantities:
  - Beam intensity
    - Faraday-cup → charges/very small currents
    - current transformer → small alternating voltages
  - Beam loss
    - Diodes or gas ionisation chamber → charges/very small currents
    - fibres/scintillators → photo-detector/multiplier → charges/very small currents
  - Beam position
    - Electro-magnetic fields → high alternating voltages
    - X-Ray BPMs → small photo-currents
  - Beam Profile
    - wire-scanner → scintilator → small charge pulses/current
    - Synchrotron-light monitor/OTR screens → photo-detector → small charge pulses/current

Tools, Literature and References

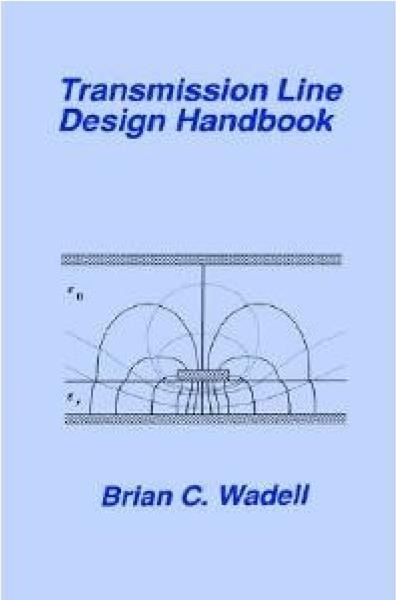
- QUCS – Quite universal circuit simulator:
  http://qucs.sourceforge.net/
  - similar to Spice™ & derivatives but open-source
  - DC, AC, S-parameter, harmonic balance analysis, noise analysis, RF structures, etc.



- Paul Horowitz & Windfield Hill:
  "The Art of Electronics", Cambridge Uni.-Press
  - The de-facto "electronics bible"



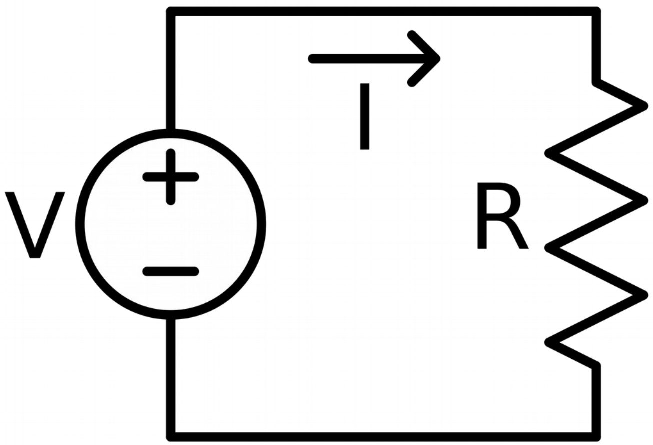
- Brian C. Wadell:
  "Transmission Line Design Handbook",
  - specialised RF structures
    microwave design



- Tutorial is inspired by K. Wille's lecture series "Elektronik 2013", TU-Dortmund:
  http://www.delta.tu-dortmund.de/cms/de/Studium/Homepage_Wille/ELEKTRONIK/index.html

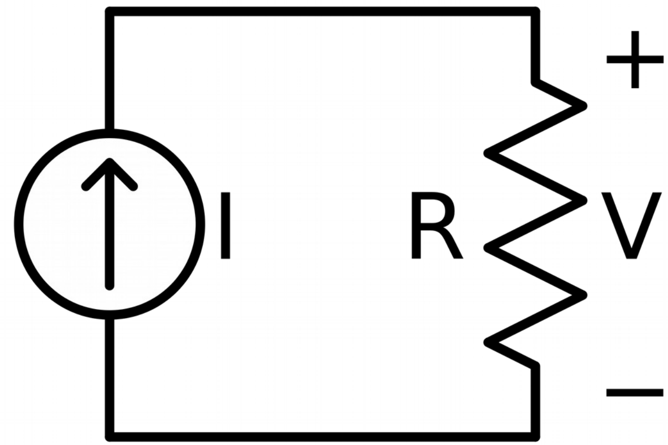
Voltage and Current Sources

- Ideal voltage source:



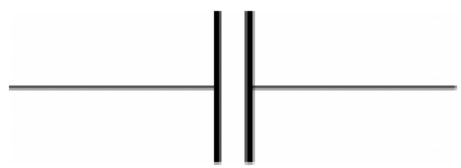
$$\frac{dU}{dI} = R_i = 0$$

- Ideal current source



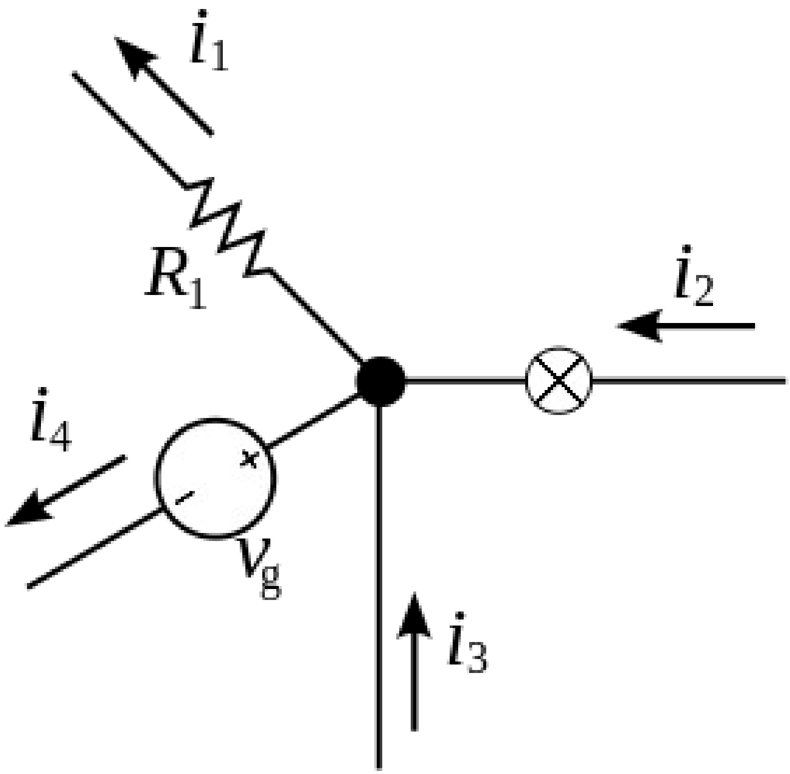
$$\frac{dU}{dI} = R_i \rightarrow \infty$$

Ideal Passive Components

ohmscher Widerstand ***R***		$U(t) = R\,I(t)$
Kondensator ***C***		$U(t) = \frac{1}{C}\int I(t)\,dt$
Spule ***L***.		$U(t) = L\frac{dI(t)}{dt}$

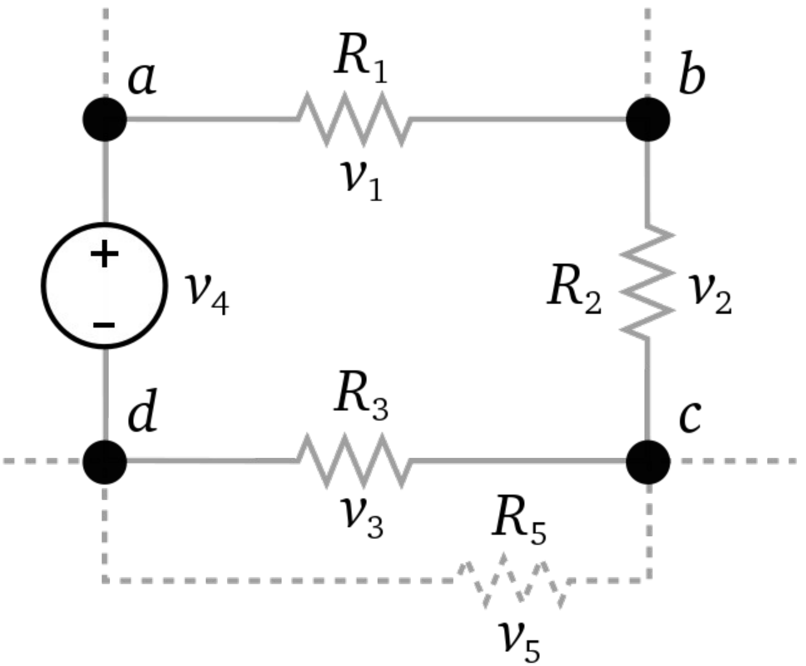
Kirchhoff's Circuit Laws

- Kirchhoff's current law (KCL)
  - conservation of charge



$$\sum_k I_k = 0$$

- Kirchhoff's voltage law (KVL)
  - conservation of energy



$$\sum_k V_k = 0$$

Fixed Frequency Oscillation & Phasor

- Steady-state frequency solution can be decomposed:

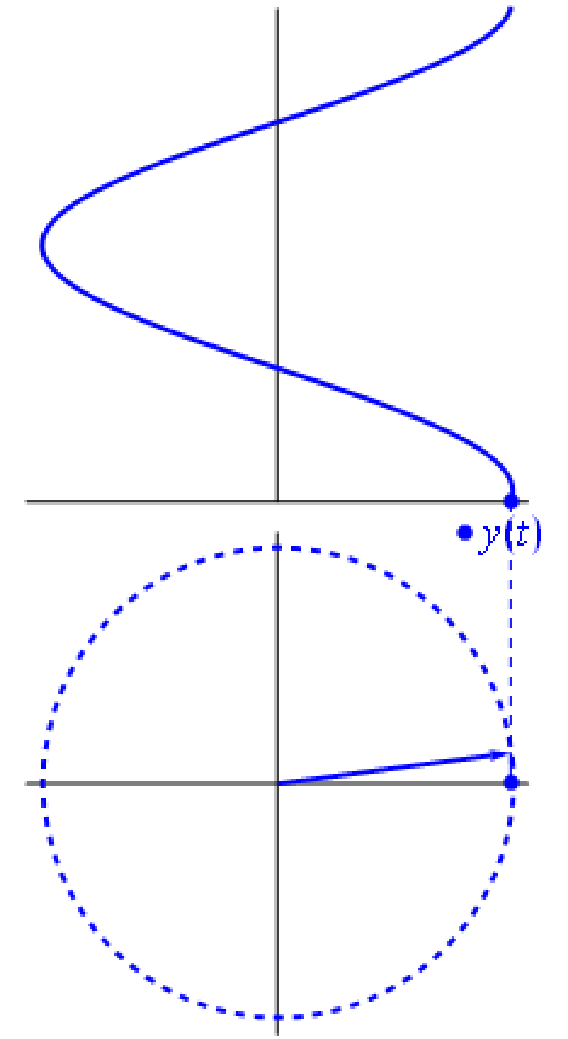
$$A\cos(\omega t - \varphi) = A\cos(\omega t)\cos(\varphi) + A\sin(\omega t)\sin(\varphi)$$

  – can be interpreted as the projection on the real axis of a circular motion in the complex plane.

$$\Re\left\{A\left[\cos(\phi) + j\sin(\phi)\right]\cdot e^{j\omega t}\right\}$$

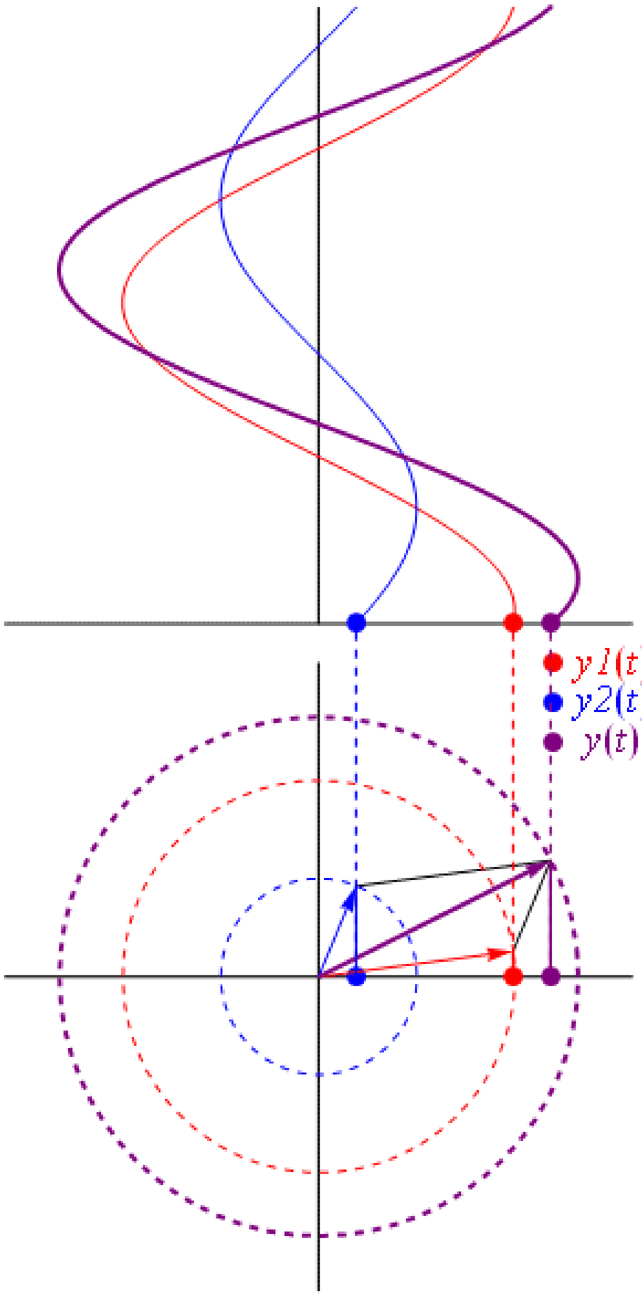
- The complex amplitude is called "phasor";

$$\tilde{A} = A\left[\cos(\phi) + j\sin(\phi)\right]$$



Calculus with Phasors

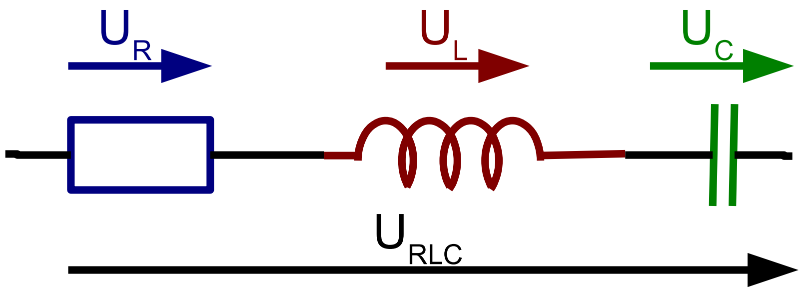
- Why this seeming “complication”?:
  - Because things become easier!
- Using $d/dt \equiv j\omega$, one may now forget about the rotation with ω and the projection on the real axis, and do the complete analysis making use of complex algebra!
- Importantly, using Fourier theorem: Any arbitrary signal can be decomposed into sum of sine and cosine waves
  - You'll hear more of this in the RF lectures



Phasors – Example 1: RLC Series Resonator

- Applying Kirchhoff's voltage law (KVL):

$$U_{RLC} = \underbrace{\left(R + \frac{1}{j\omega C} + j\omega L \right)}_{=:Z} \cdot I$$



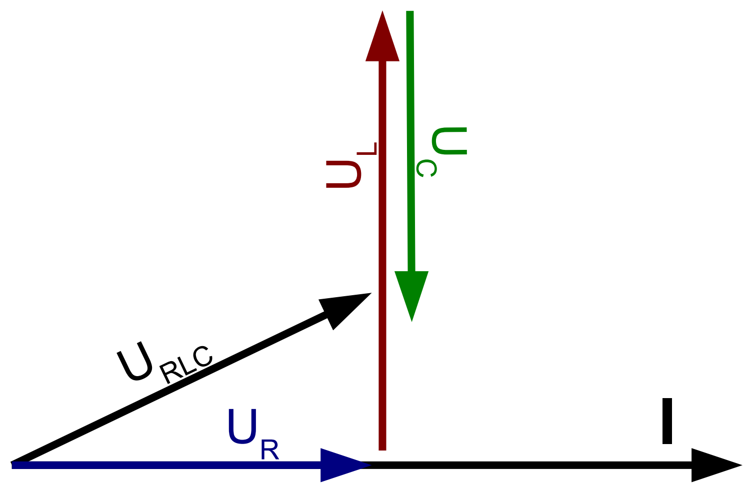
- We are interested in magnitude only

$$Z_{series} = \left| R - \frac{j}{\omega C} + j\omega L \right| = \left| R + j\left(\omega L - \frac{1}{\omega C} \right) \right|$$

… some arithmetic and beer

$$= \sqrt{\left(1 - (\omega/\omega_0)^2\right)^2 + (2\zeta\omega/\omega_0)^2}$$

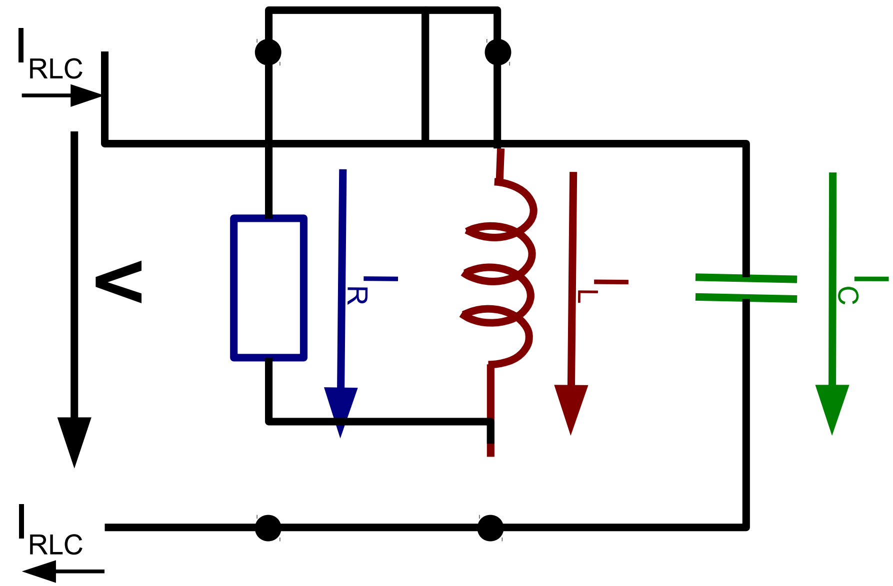
$$with: \quad \zeta = \frac{R}{2}\sqrt{\frac{C}{L}} \quad \wedge \quad \omega_0 = 1/\sqrt{LC}$$



Phasors – Example 2: RLC Parallel Resonator

- Applying Kirchhoff's current law (KCL):

$$I_{RLC} = \underbrace{V \cdot \left(\frac{1}{R} + j\omega C + \frac{1}{j\omega L} \right)}_{=:\frac{1}{Z}}$$



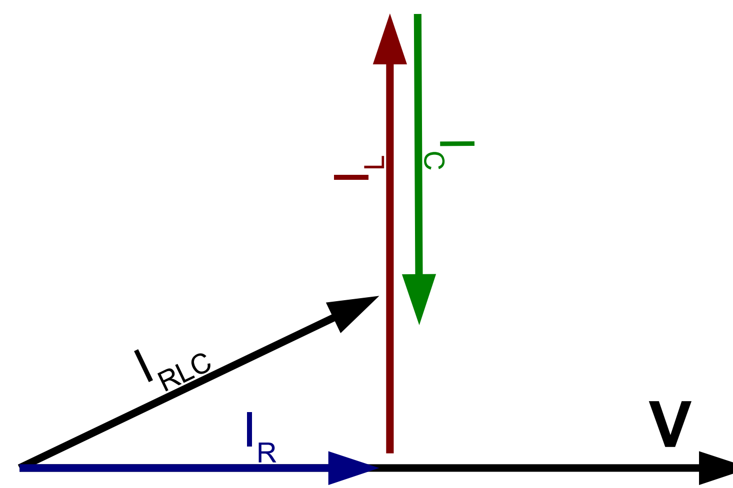
- We are interested in magnitude only

$$Z_{series} = \left| R - \frac{j}{\omega C} + j\omega L \right| = \left| R + j\left(\omega L - \frac{1}{\omega C} \right) \right|$$

… some arithmetic and more beer

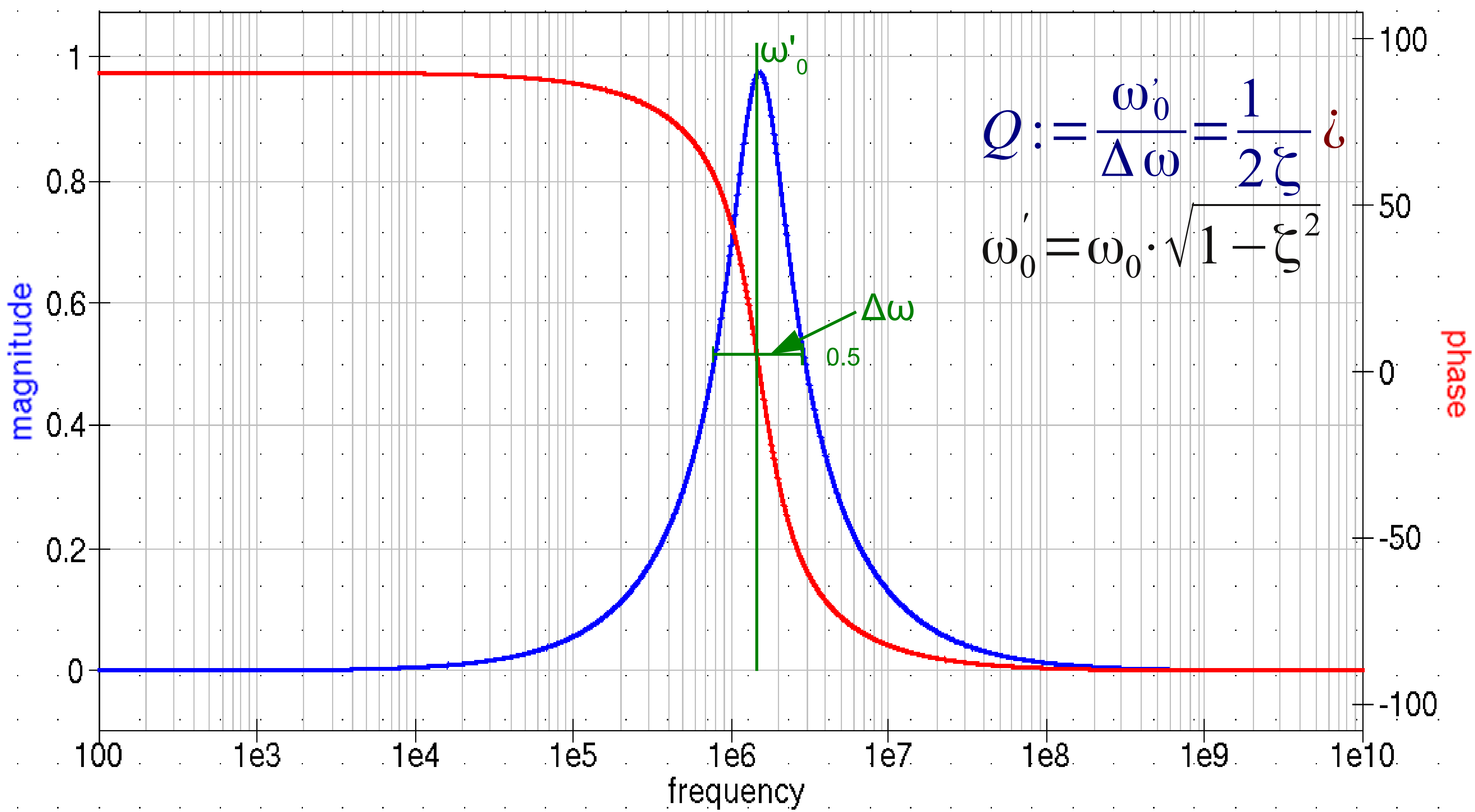
$$= \sqrt{\left(1 - \left(\omega/\omega_0\right)^2\right)^2 + \left(2\zeta\,\omega/\omega_0\right)^2}$$

$$with: \quad \zeta = \frac{1}{2R}\sqrt{\frac{L}{C}} \quad \wedge \quad \omega_0 = 1/\sqrt{LC}$$



Bode Plot: Magnitude/Phase vs. log. Frequency

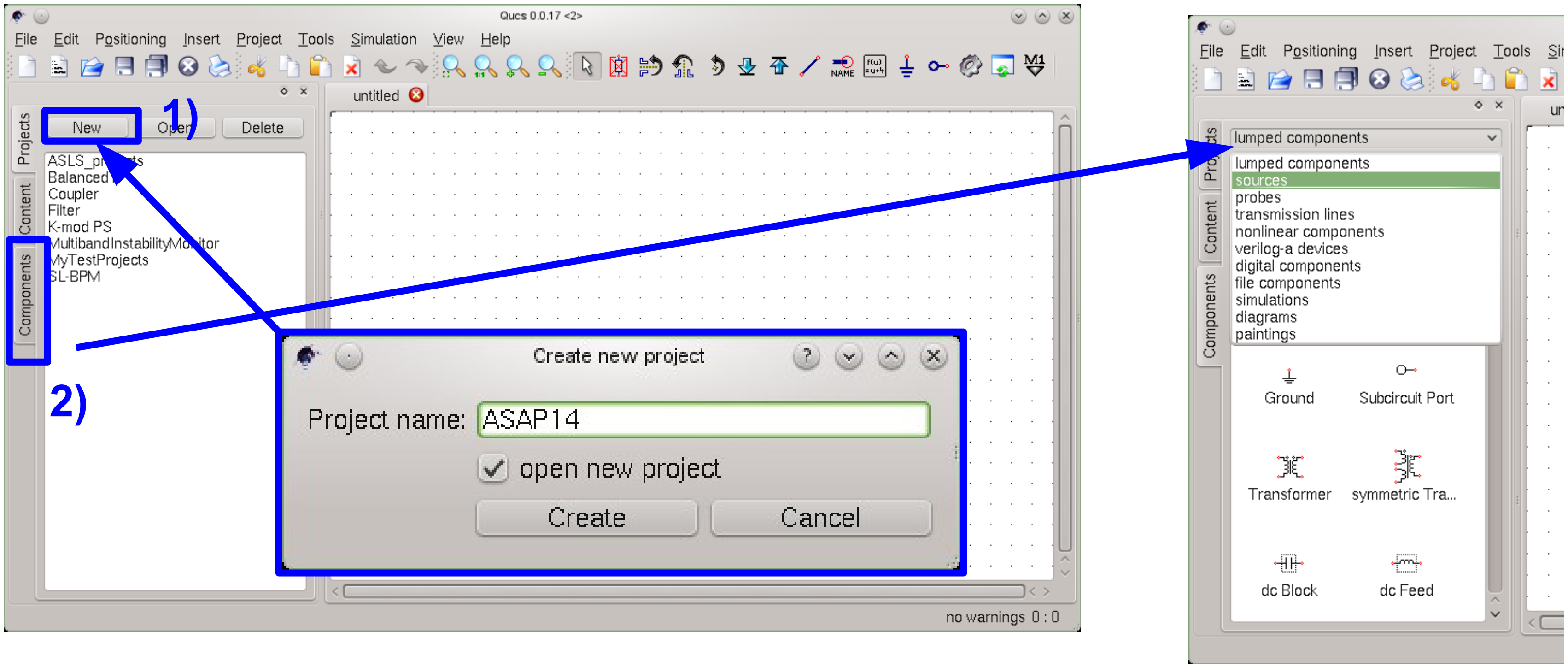
- Definition of '*quality factor*' Q → very important for cavities
  - ability to store energy, transient response, ...



Quick getting started with Qucs I/II

1) Project → New Project → <*type and confirm project name*>

- This creates a new projects and switches to '**Content**' tab



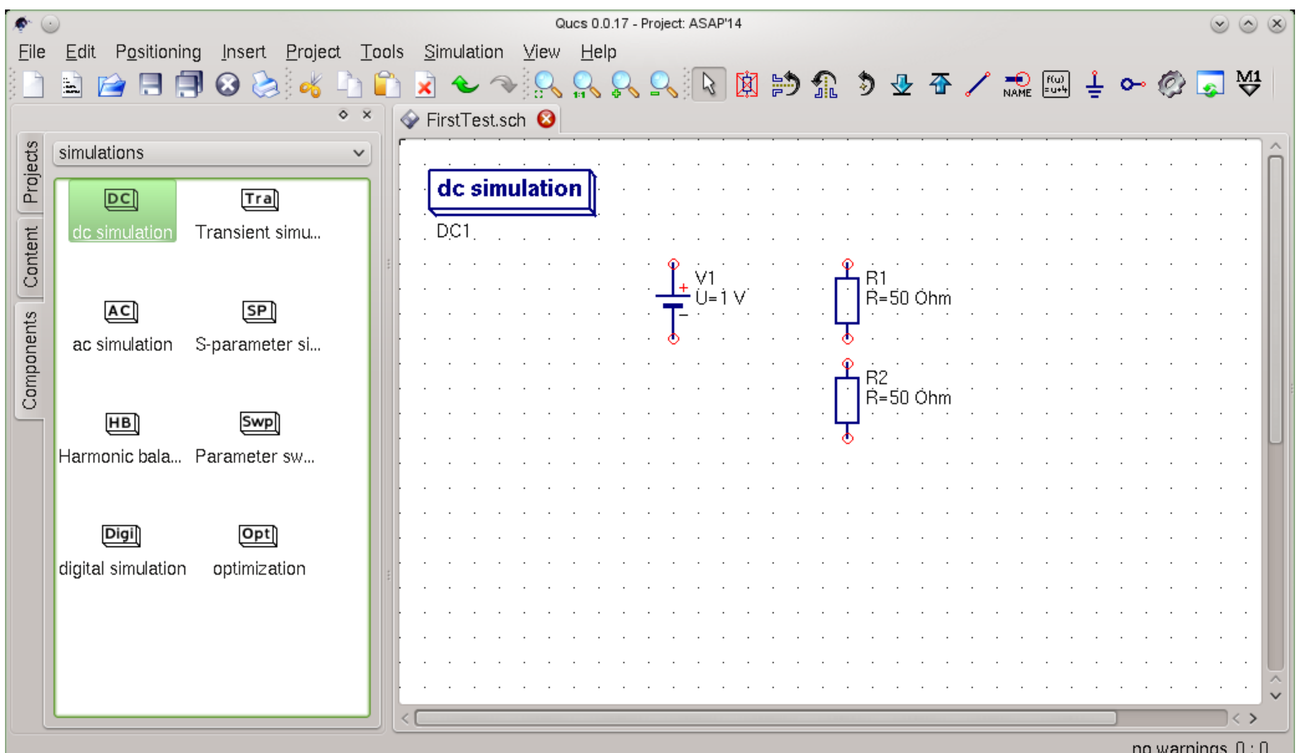
2) Now you can start editing your schematic. The available components can be found in the '**components**' tab.

- there is a sub-menu for different categories of components → feel free and encouraged to browse
- more precise parts and pre-configured elements can be found in: Tools → 'Component Library' (or via 'Ctrl + 4')

Quick getting started with Qucs

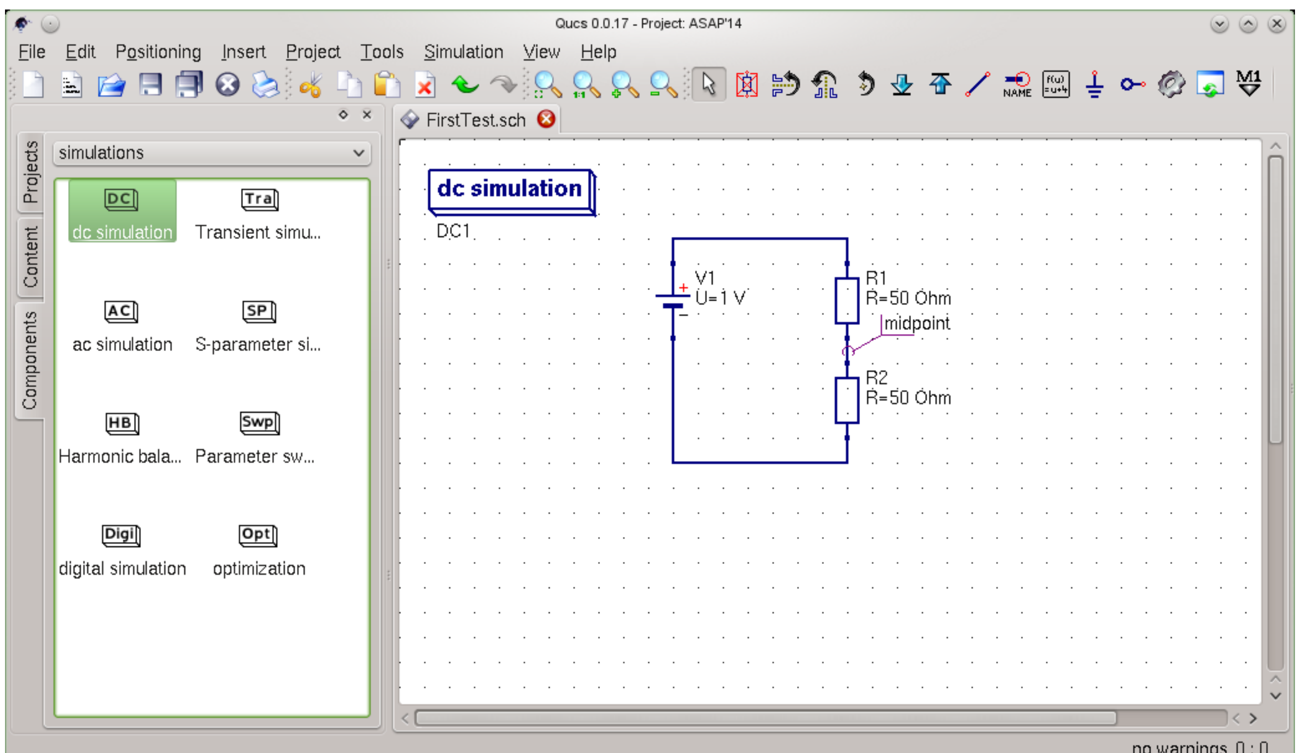
Design and simulate a simple voltage divider:

- Place two resistors (i.e. drag-and drop) onto the schematic:
  Components → lumped components → resistor
  - N.B. You can rotate the components via 'Ctrl+R'
- Place a dc voltage onto the schematic:
  Components → sources → dc Voltage Source



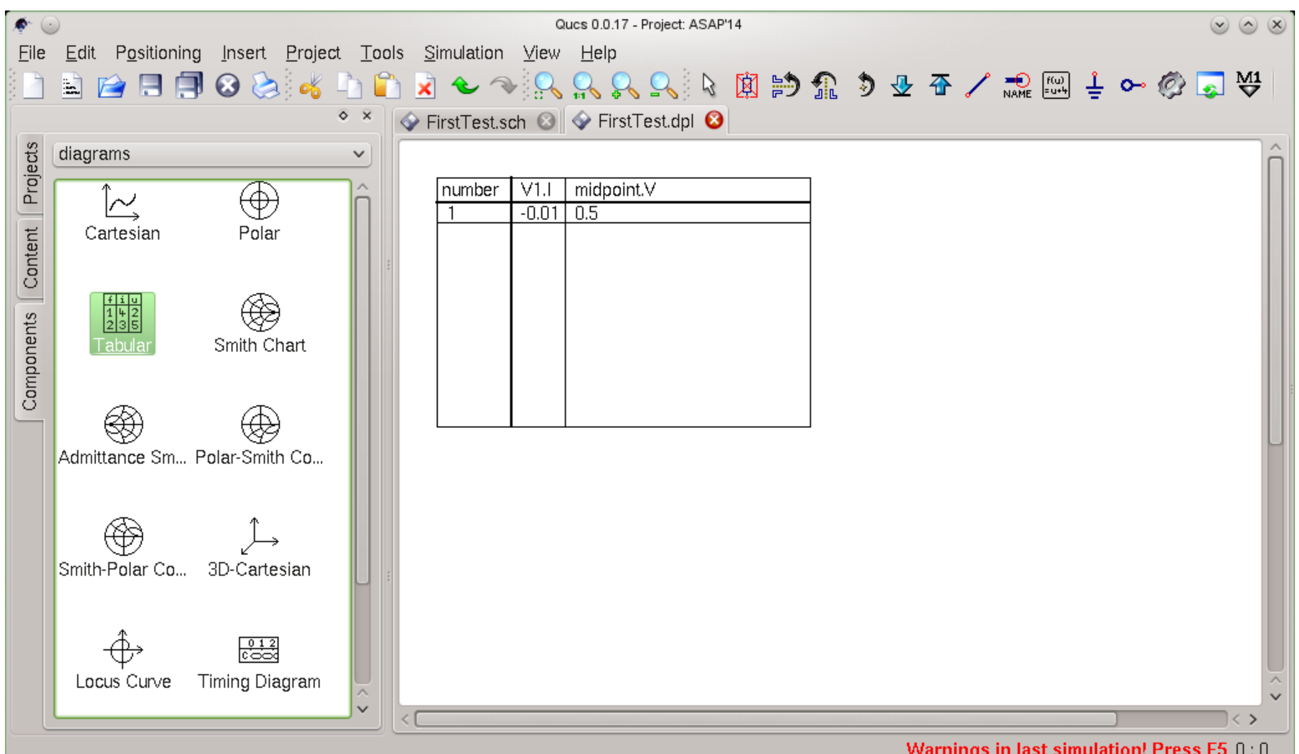
Quick getting started with Qucs

- Wire the parts either using the 'wire' button, or 'Ctrl+E')
- Place a simulation block – in our case 'DC':
  Components → simulations → dc simulation
- Label wires to calculate voltages of give nodes:
  Insert → Wire Label (or 'Ctrl+L') – <type/confirm name>
- N.B. if you haven't already → save the schematic:
  File → Save (as) (or 'Ctrl+S')→ <type descriptive name>



Quick getting started with Qucs

- Issue a Simulation: *Simulation → Simulate* (or 'F2')
  - This opens a new panel (<name>.dpl) which can house the results and opens the 'Components→diagrams' sub-panel on the left (you can switch back and forth with 'F4') (you may change this via 'File → Document Settings → 'open data display …' check-box)
- You can add e.g. a table and select (double-click) the nodes for which the currents and voltages have been calculated (here: 'V1.I' & 'midpoint.V')

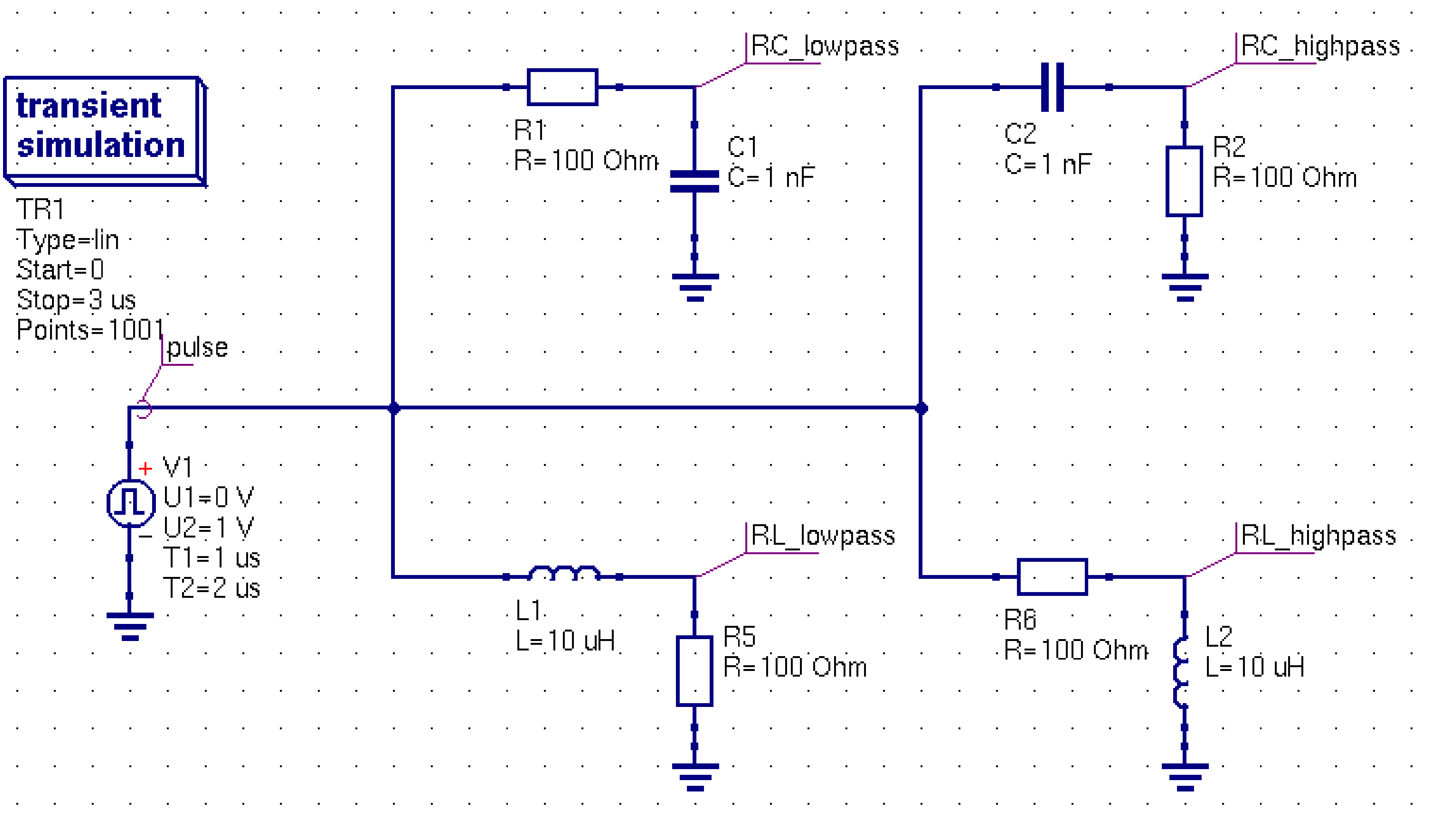


Quick getting started with Qucs

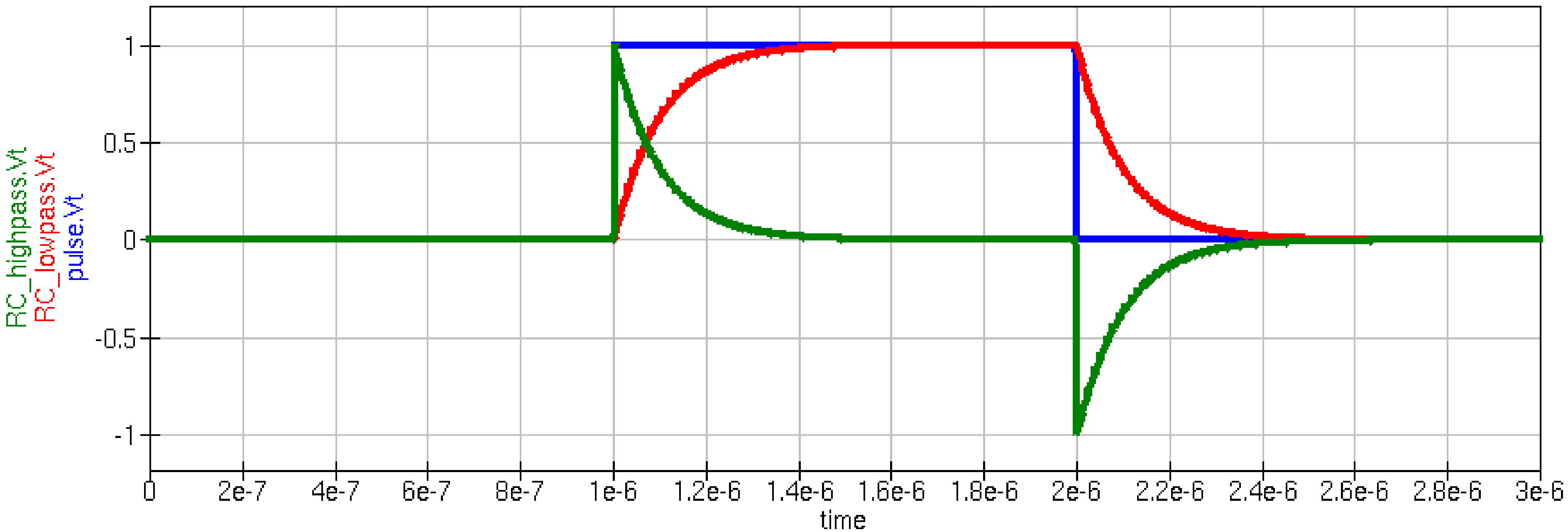
Available dataset items

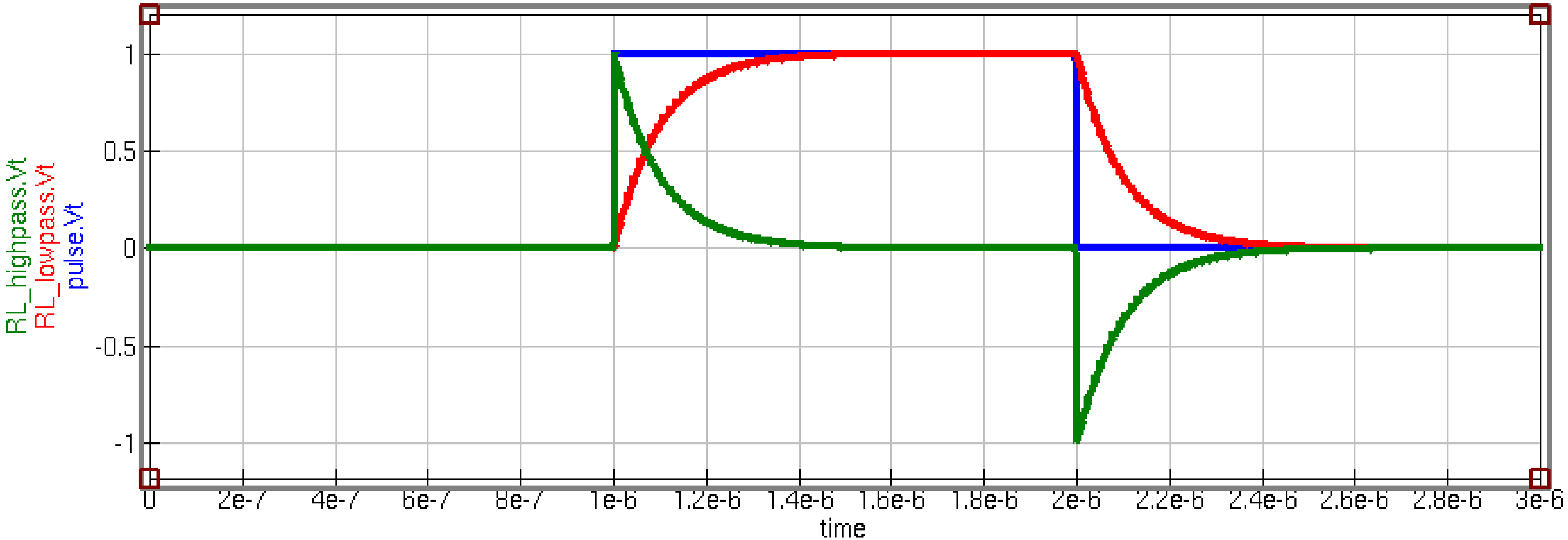
- Depending on the type of simulation performed you find the following types of items in the dataset:
  - *node*.V – DC voltage at node *node*
  - *name*.I – DC current through component *name*
  - *node*.v – AC voltage at node *node*
  - *name*.i – AC current through component *name*
  - *node*.vn – AC noise voltage at node *node*
  - *name*.in – AC noise current through component *name*
  - *node*.Vt – transient voltage at node *node*
  - *name*.It – transient current through component *name*
  - S[1,1] – S-parameter value
- N.B. Please note that all voltages and currents are peak values and all noise voltages are RMS values at 1Hz bandwidth

Simple RC/RL High- and Low-Pass Filter I/II

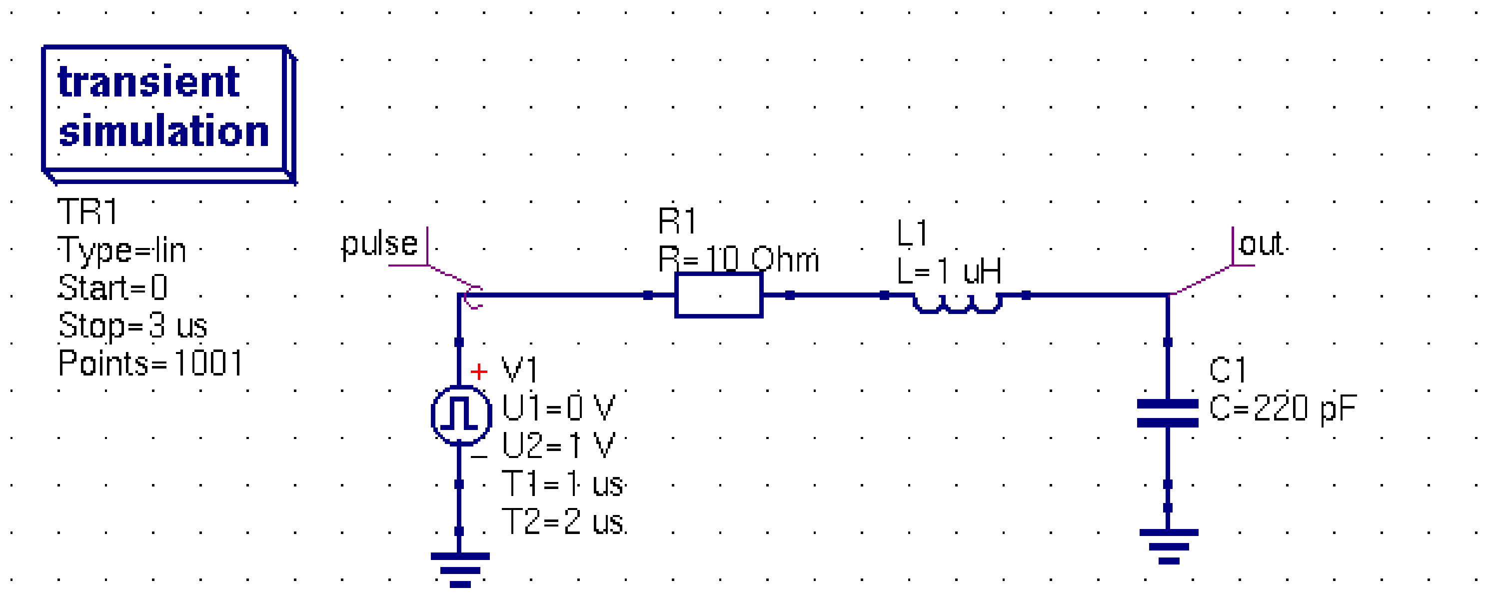


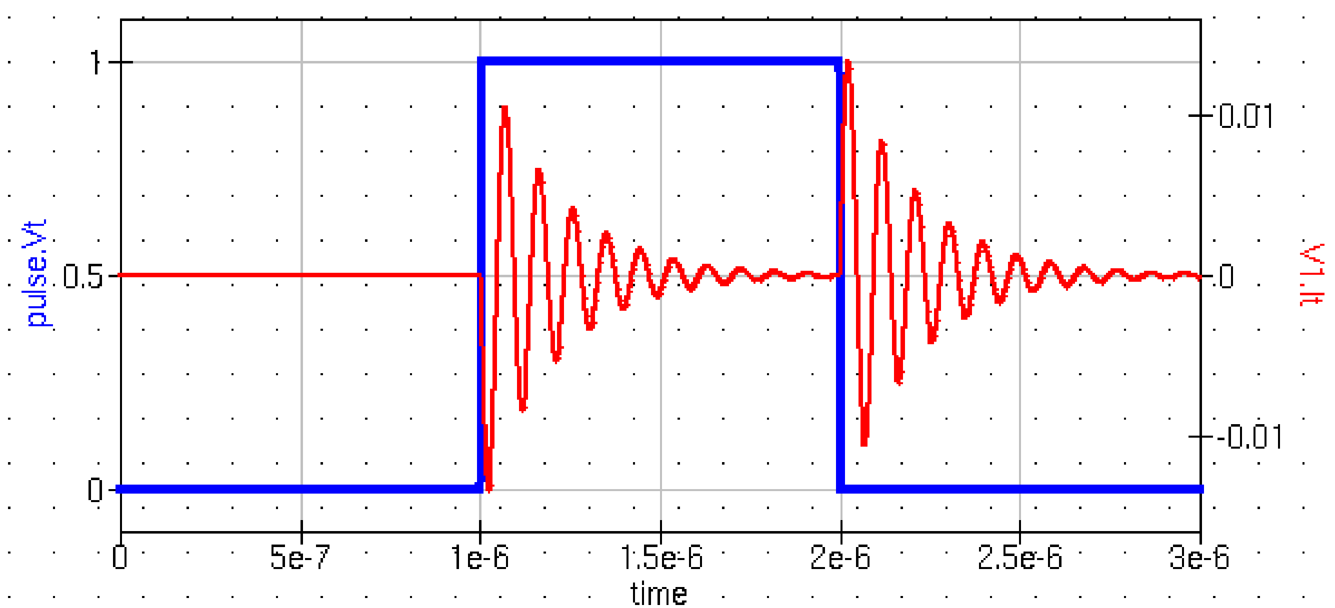
Simple RC/RL High- and Low-Pass Filter II/II





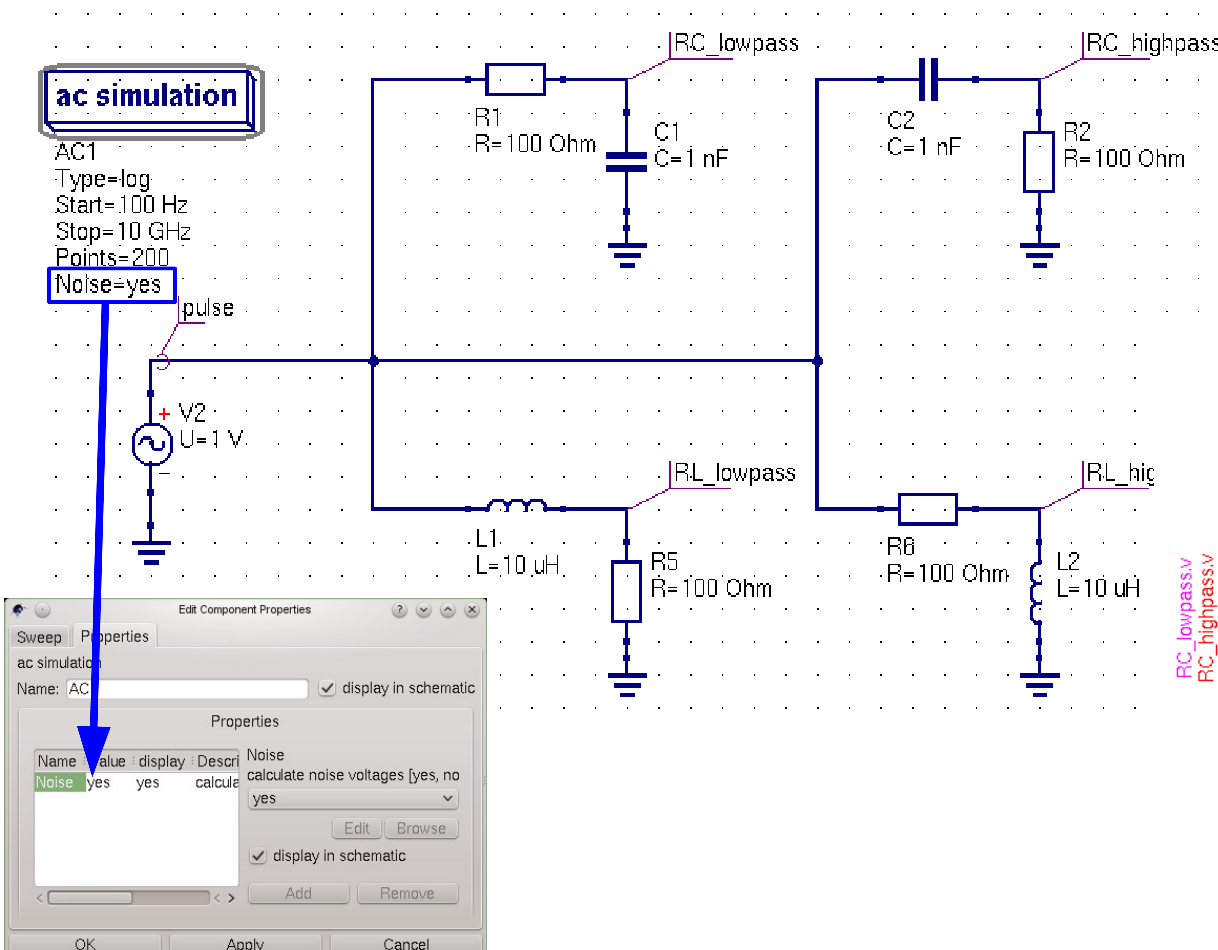
Qucs – Resonant Circuit

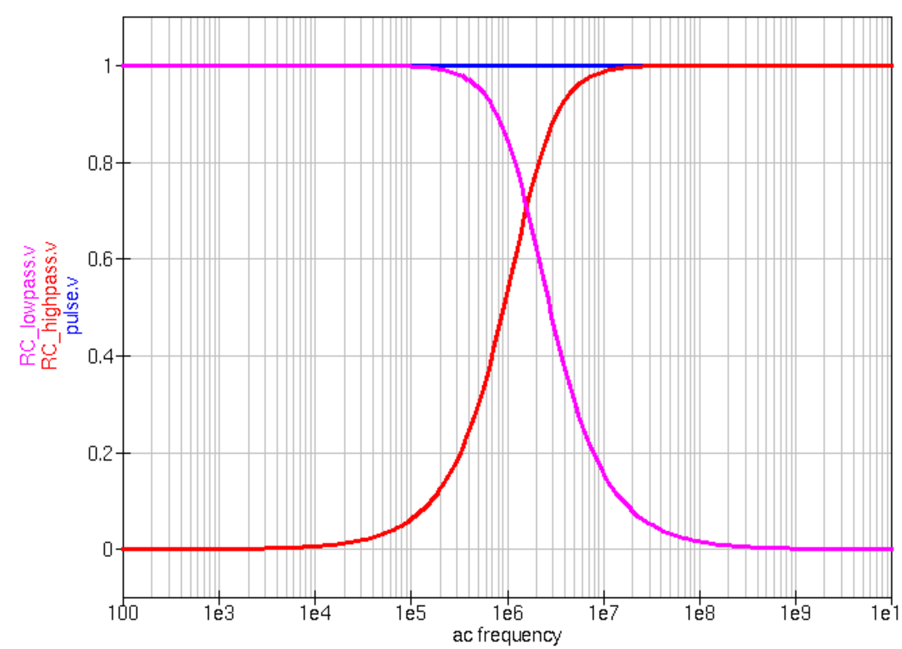




Qucs – AC Simulation

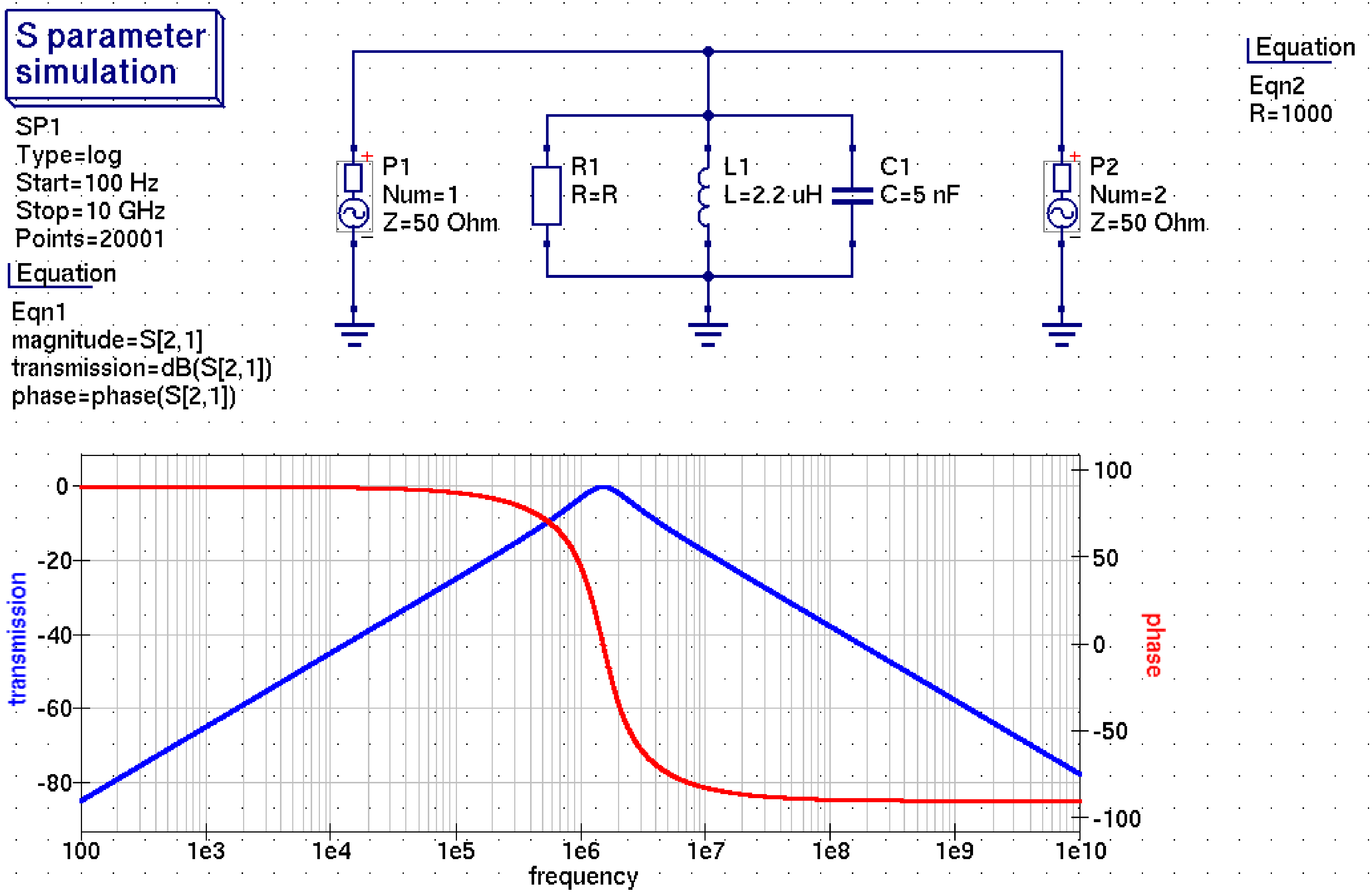
- … going to be used more frequently during RF tutorial
  - N.B. Noise simulation needs to be manually enabled:
    ac simulations → 'Properties' tab → Noise = <yes/no> (optional: 'display in schematic')





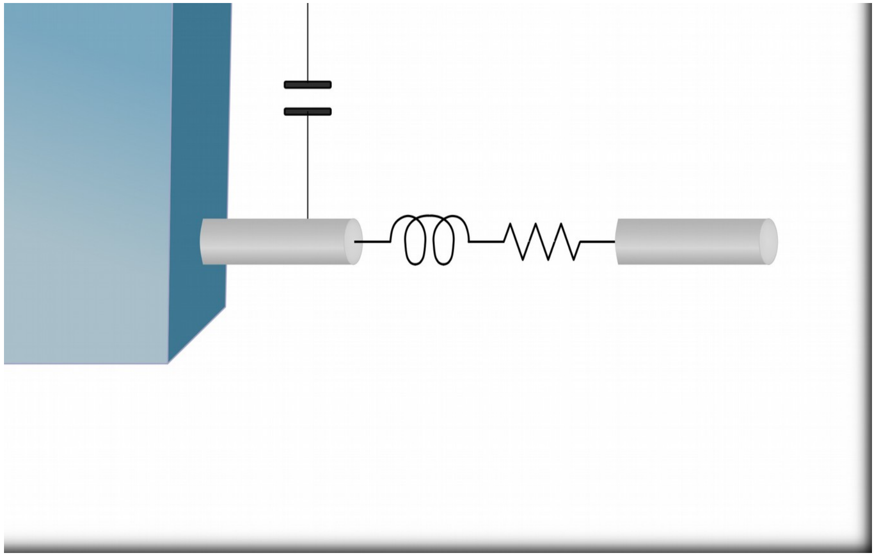
S-Parameter Simulation

- This will be more discussed during the RF tutorial

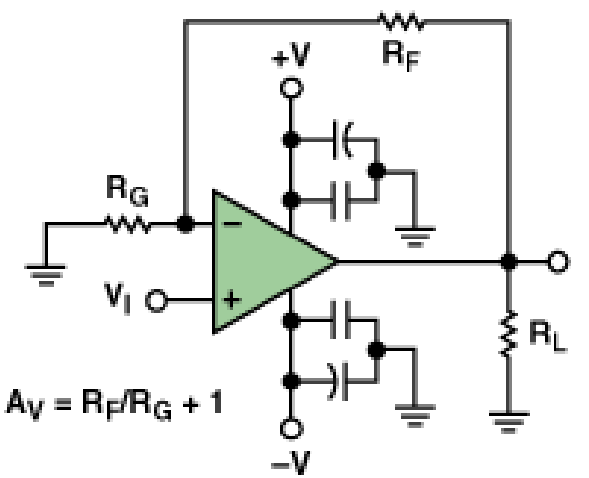


Between Theory and Reality I/II

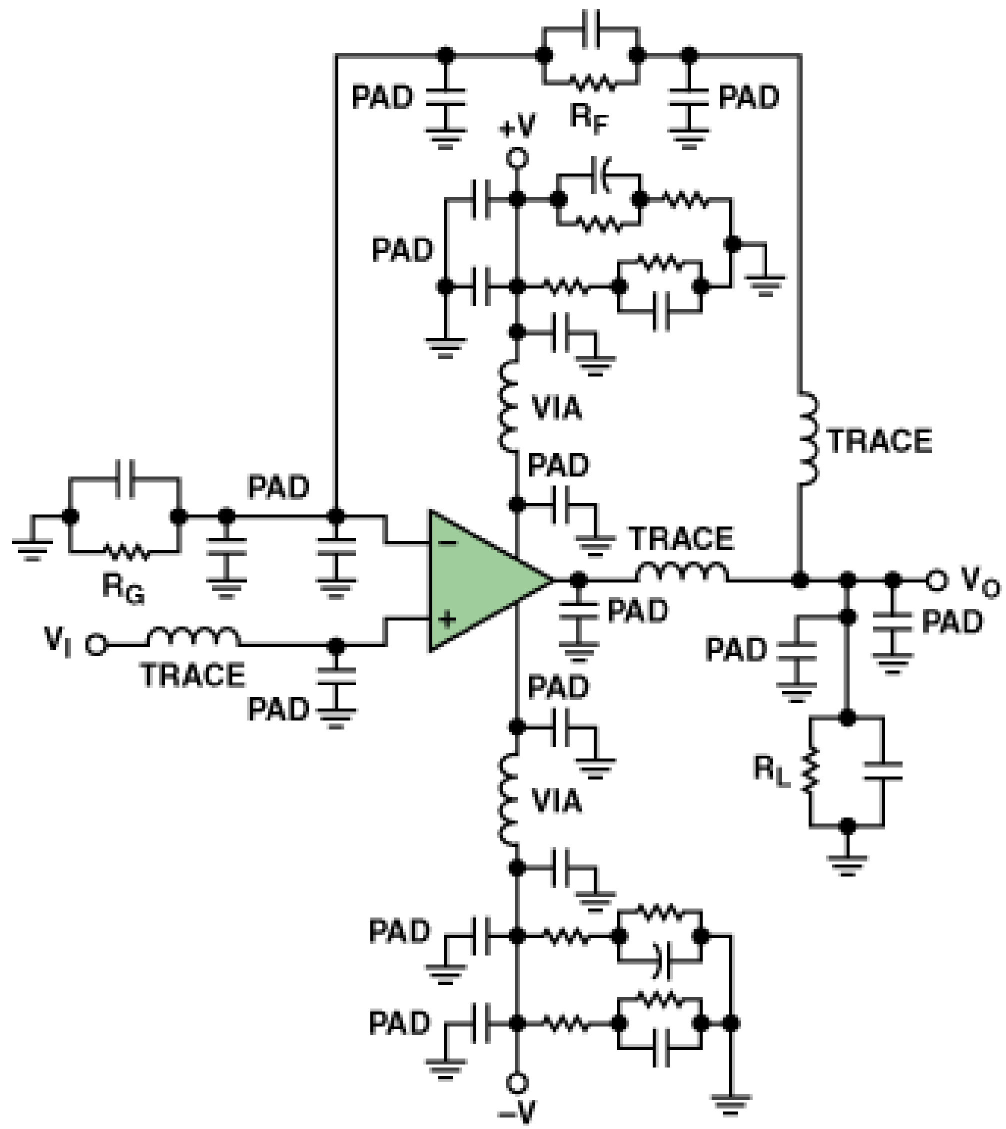
- Real resistances, capacitors and coils deviate from their nominal behaviour in particularly for high frequencies due to parasitic ohmic losses, parasitic capacities and inductances.
  - Often doesn't matter – i.e. for many low-frequency
  - … but can become <pain in the neck> for high-frequency & accuracy applications → identify early if your measurement might be affected by this



Between Theory and Reality II/II



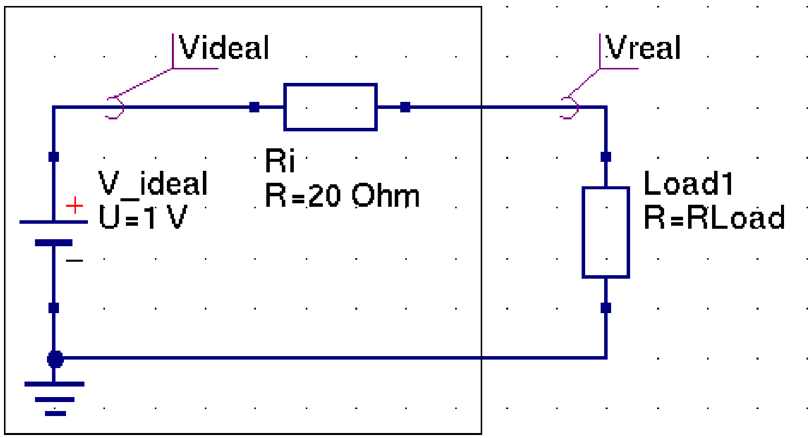
what you design...

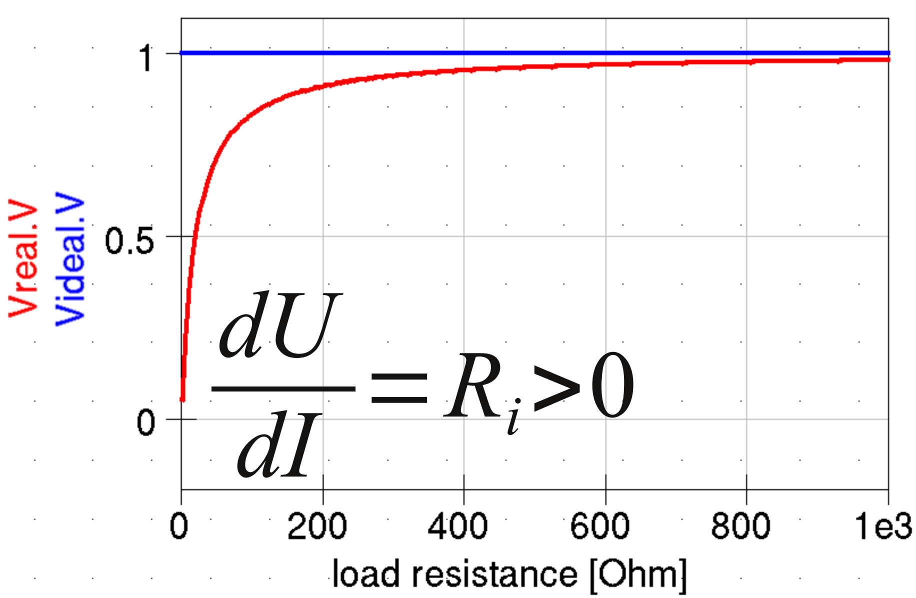


… what you get

Voltage and Current Sources

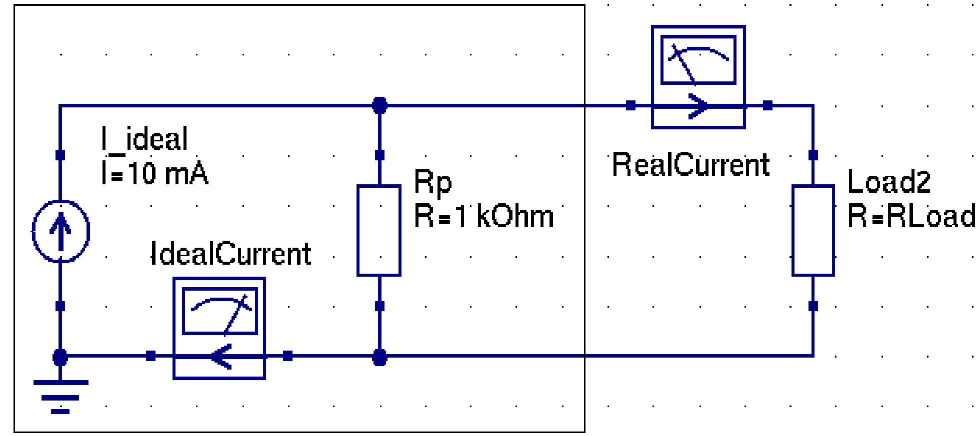
- real voltage source

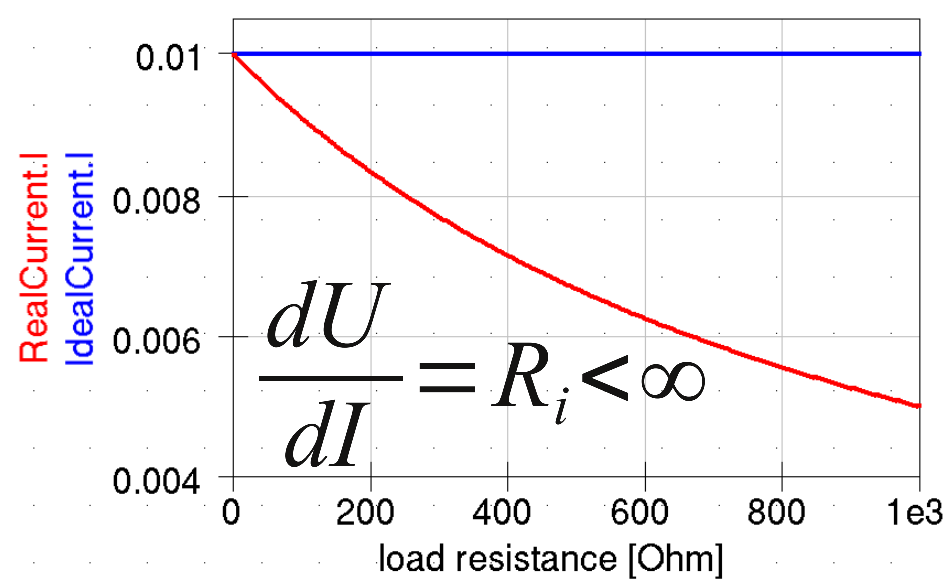




$$\frac{dU}{dI} = R_i > 0$$

- real current source



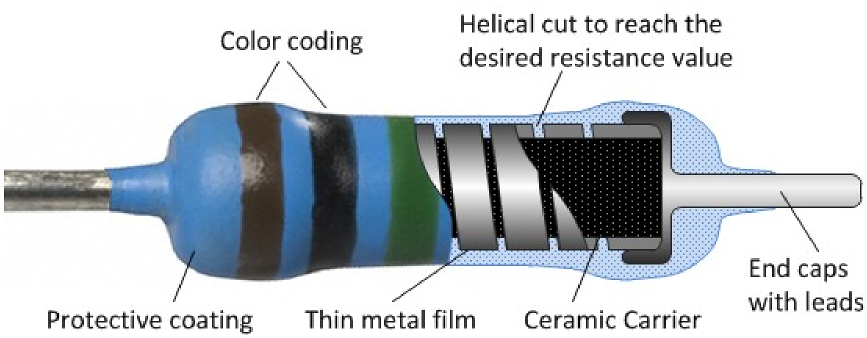


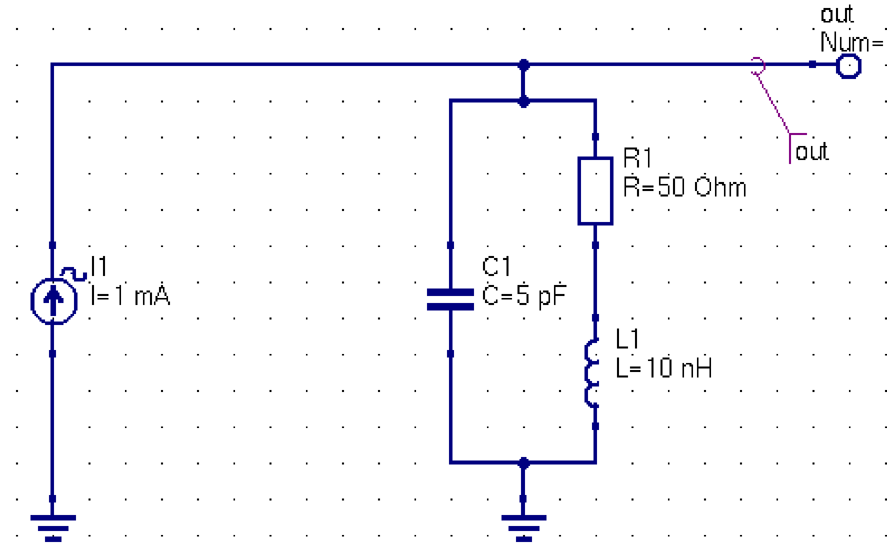
$$\frac{dU}{dI} = R_i < \infty$$

→ reproduce plots in tutorials

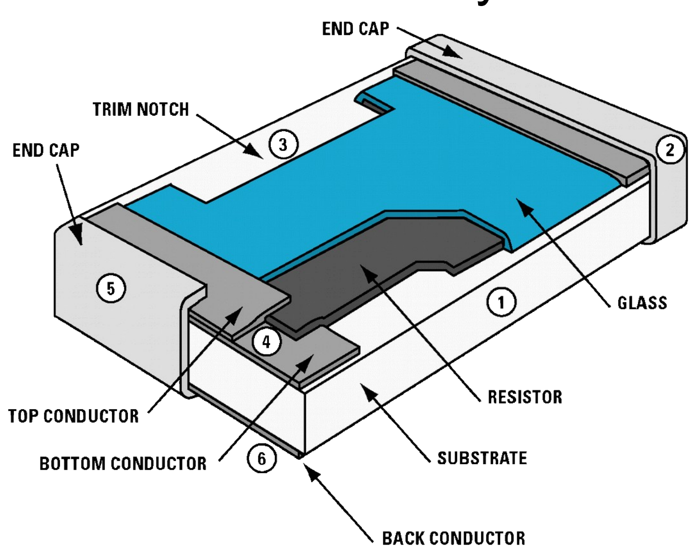
Real Resistance

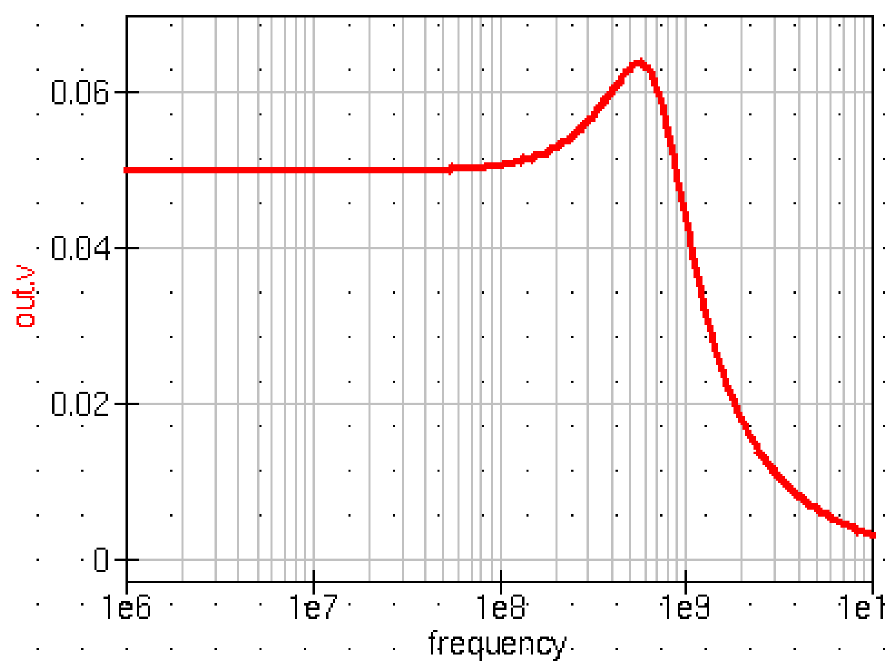
- technical realisation
  - "historic": part-through-hole (PTH) not common these days:





  - Surface-mount-style:

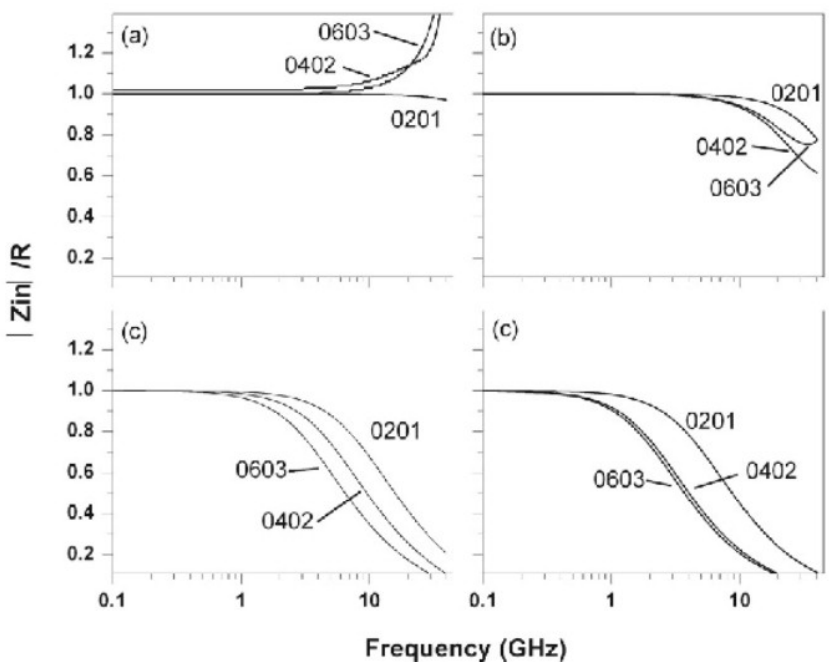


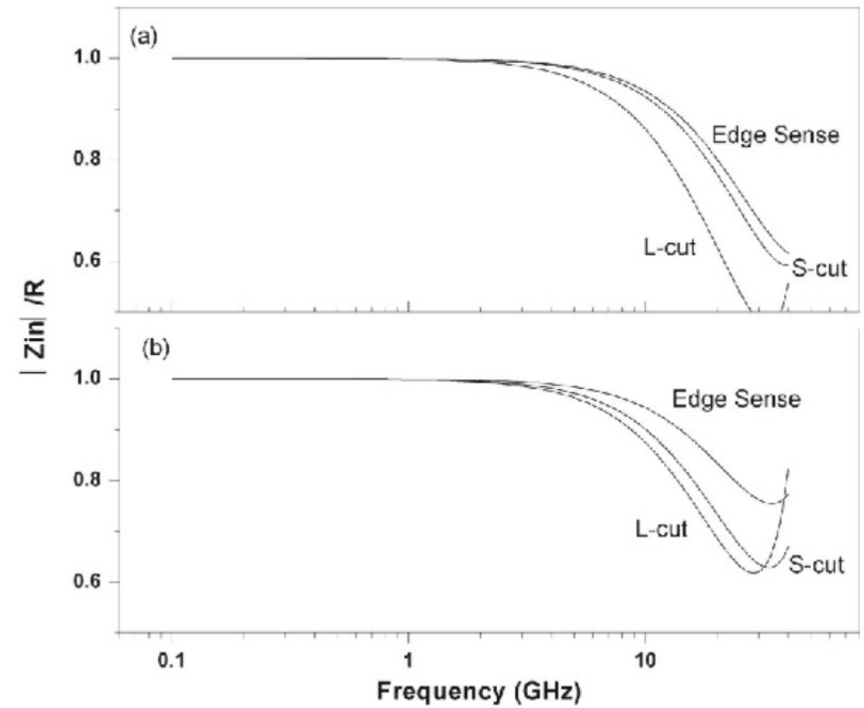


Capacitance – A glimpse on Pandora's Box

TABLE 1 - PARAMETERS FOR DIFFERENT CASE SIZES UTILIZED

CASE SIZE	LENGTH (inch/ mm)	WIDTH (inch/ mm)	RESISTOR AREA (inch²/ mm²)	MODEL INTERNAL COEFFICIENTS	
				C (pF)	L (nH)
0201	0.02/ 0.51	0.01/ 0.25	0.00004/ 0.02581	0.0206	1.73×10^{-5}
0402	0.04/ 1.02	0.02/ 0.51	0.000352/ 0.22710	0.0262	1.89×10^{-3}
0402 (wrap)	0.04/ 1.02	0.02/ 0.51	0.000352/ 0.22710	0.0392	0.1209
0603	0.064/ 1.626	0.032/ 0.813	0.000816/ 0.52645	0.0403	0.0267





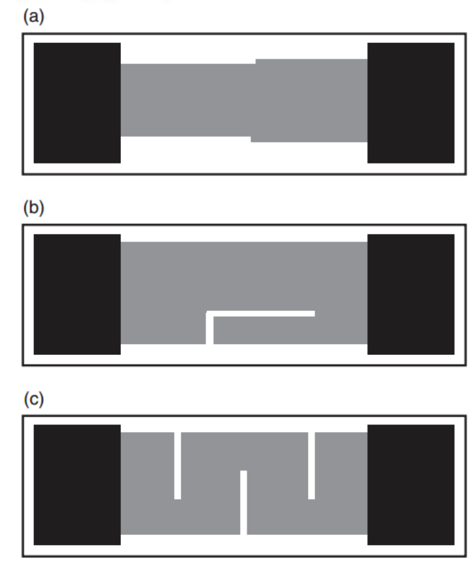
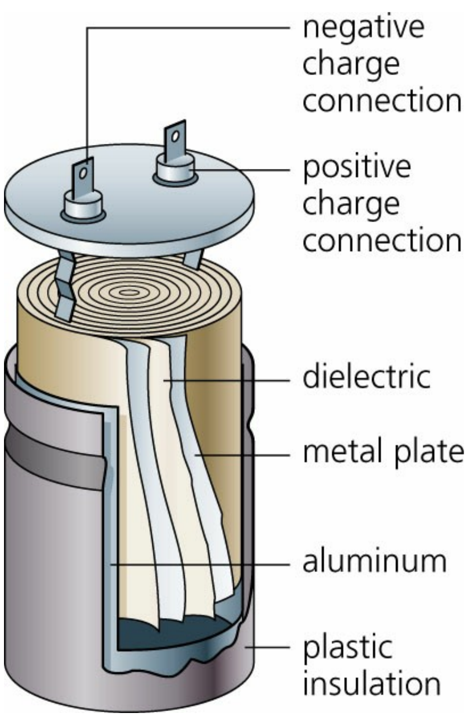


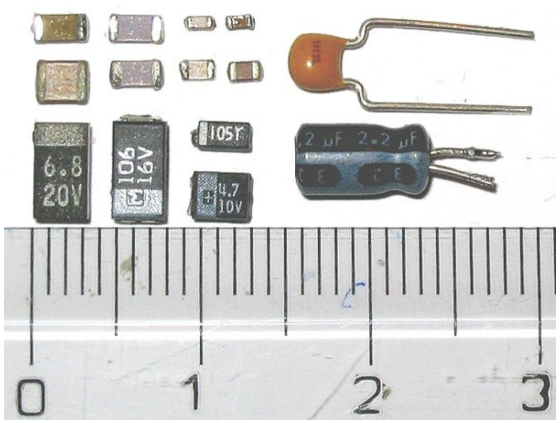
Fig. 11 - Trim methods: (a) balanced edge sense, (b) L-cut, and (c) S-cut

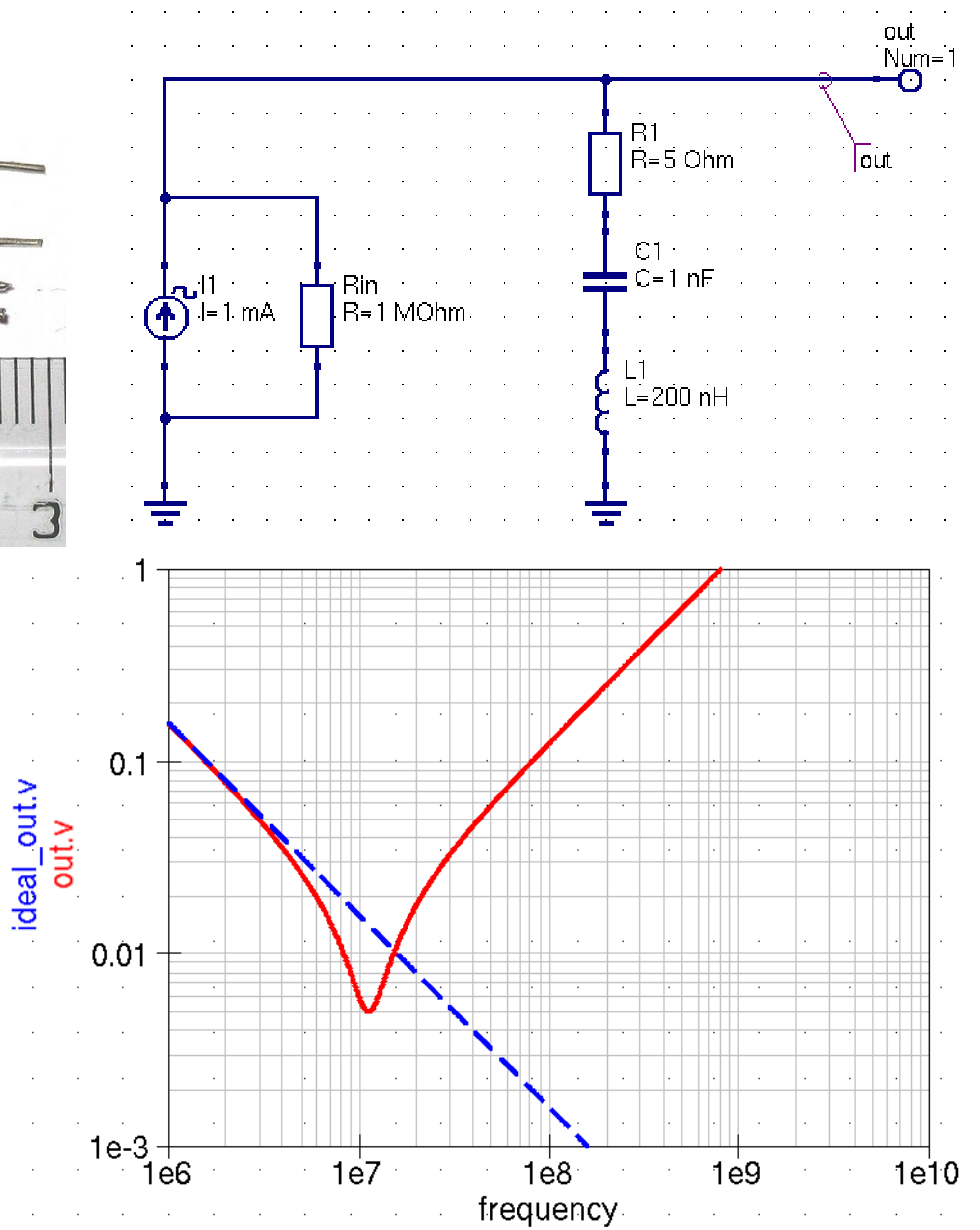
Source: Vishay

Real Capacitance

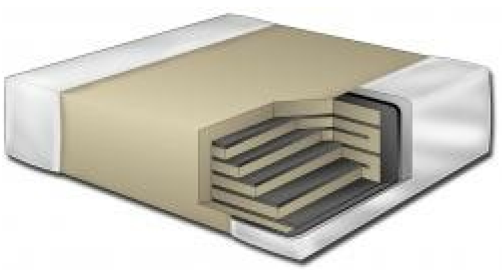
- Zoo of implementations:





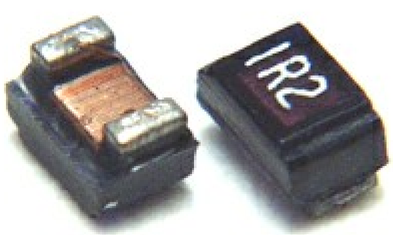


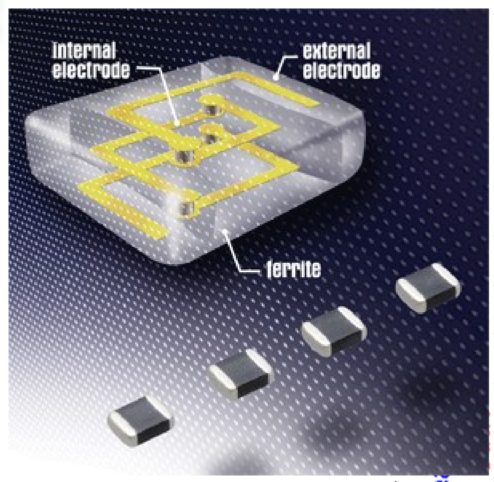
- Most common – SMD:

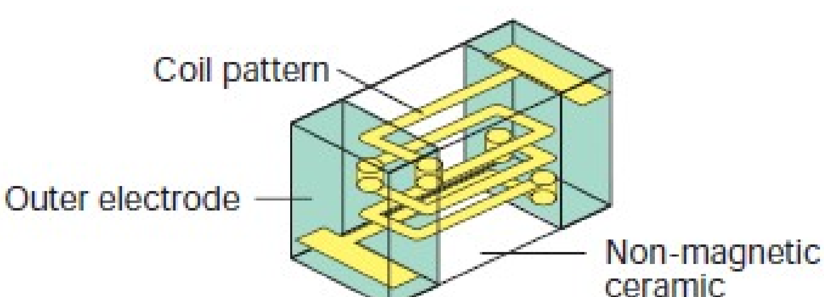


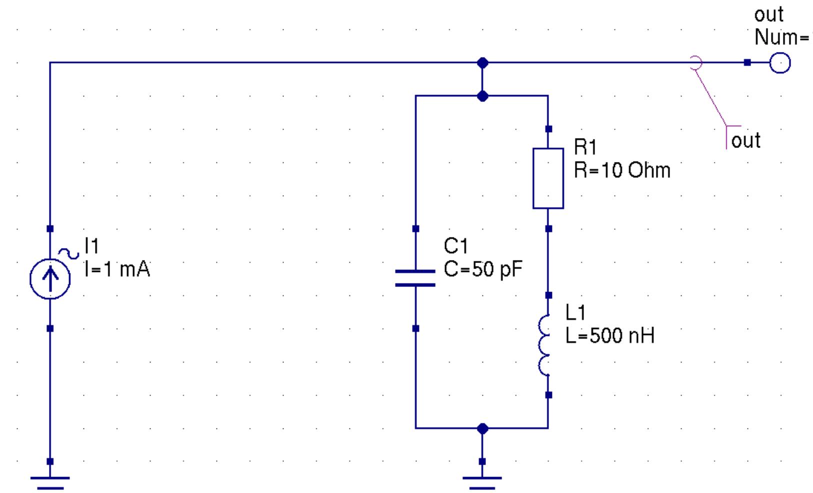
Real Inductor

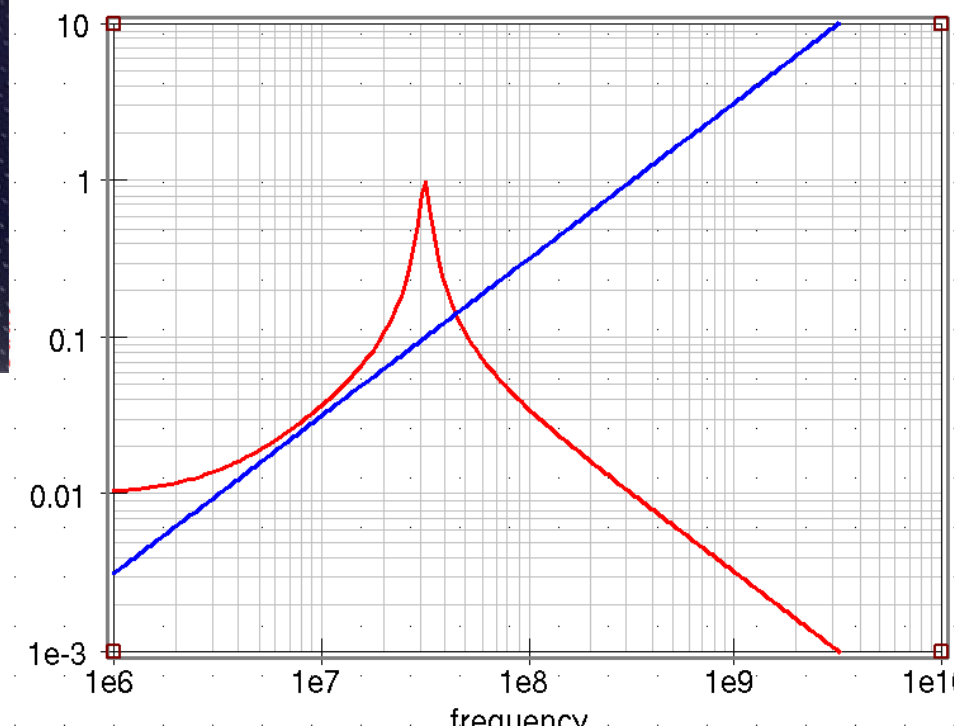
- technical realisation



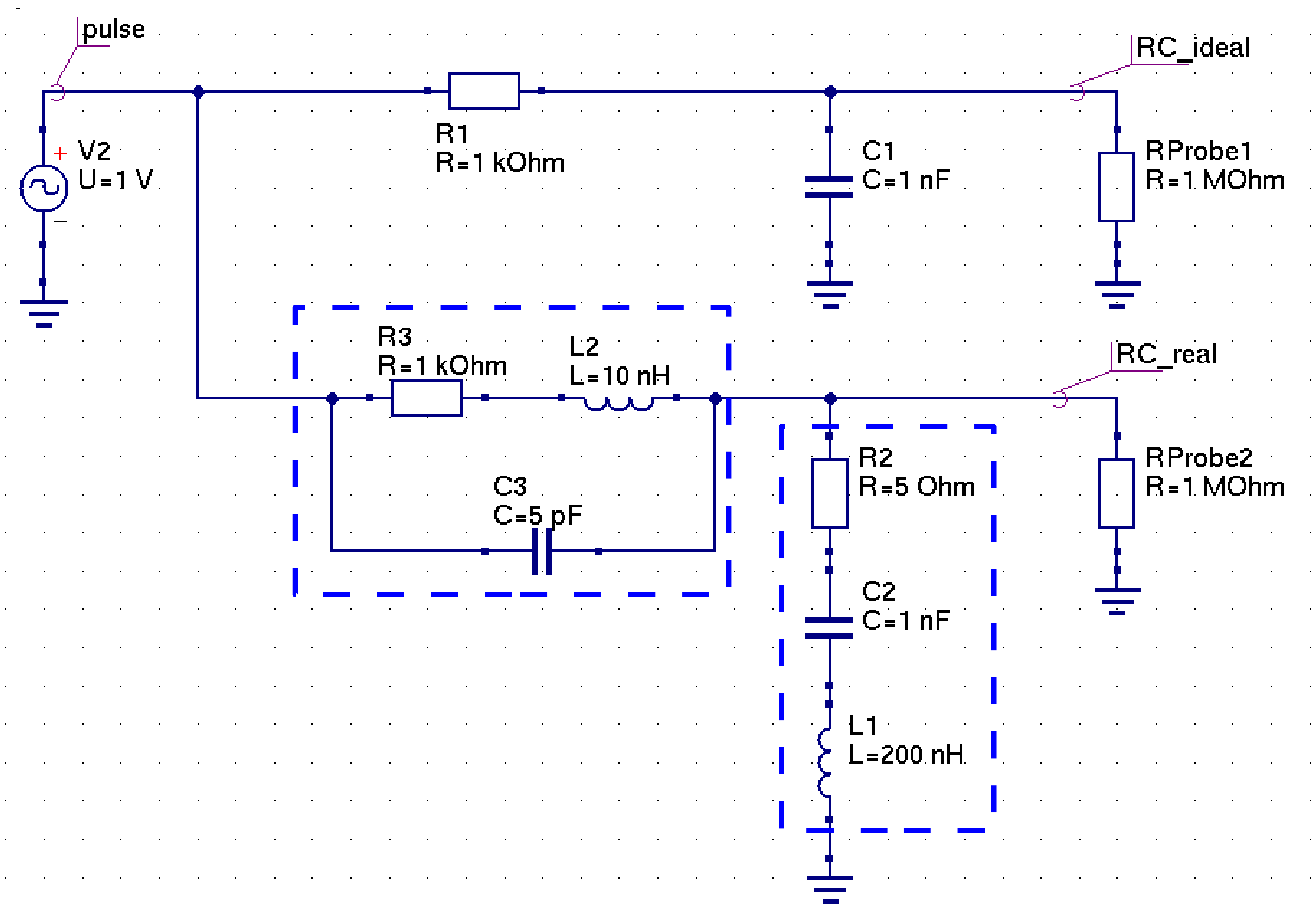




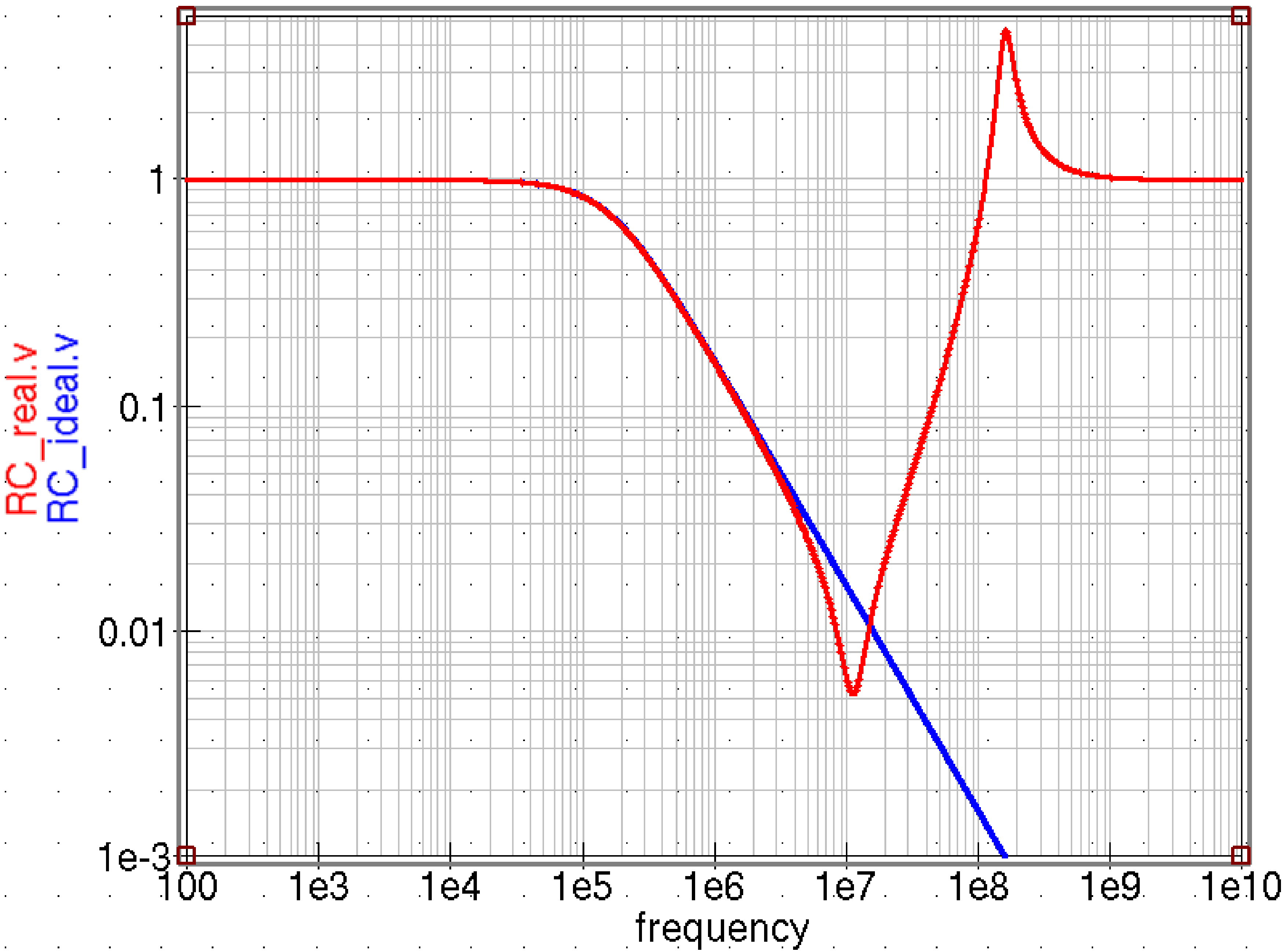




Ideal vs. Real RC Low-Pass Filter I/II

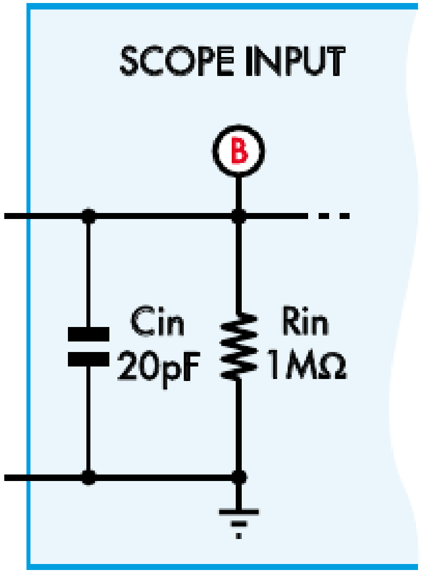


Ideal vs. Real RC Low-Pass Filter II/II



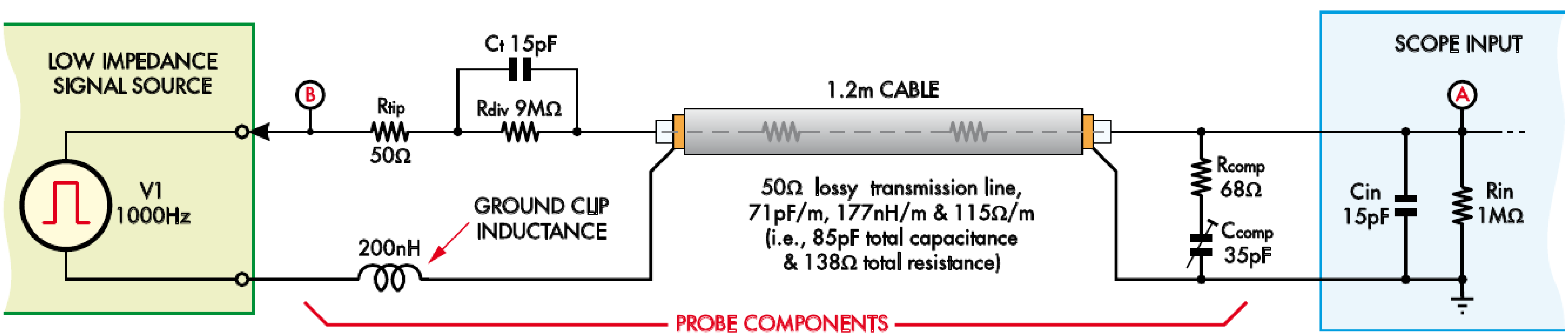
Ideal vs. Real Voltage Measurements I/II

- "How" you measure may affect what you measure – circuit loading:
  - Application dependent: R_{in} typ. 50Ω (HF-RF), 10kΩ (cheapo), 1 MΩ (multimeter/mid-range oscilloscopes), up to few GΩ (specialised HW)

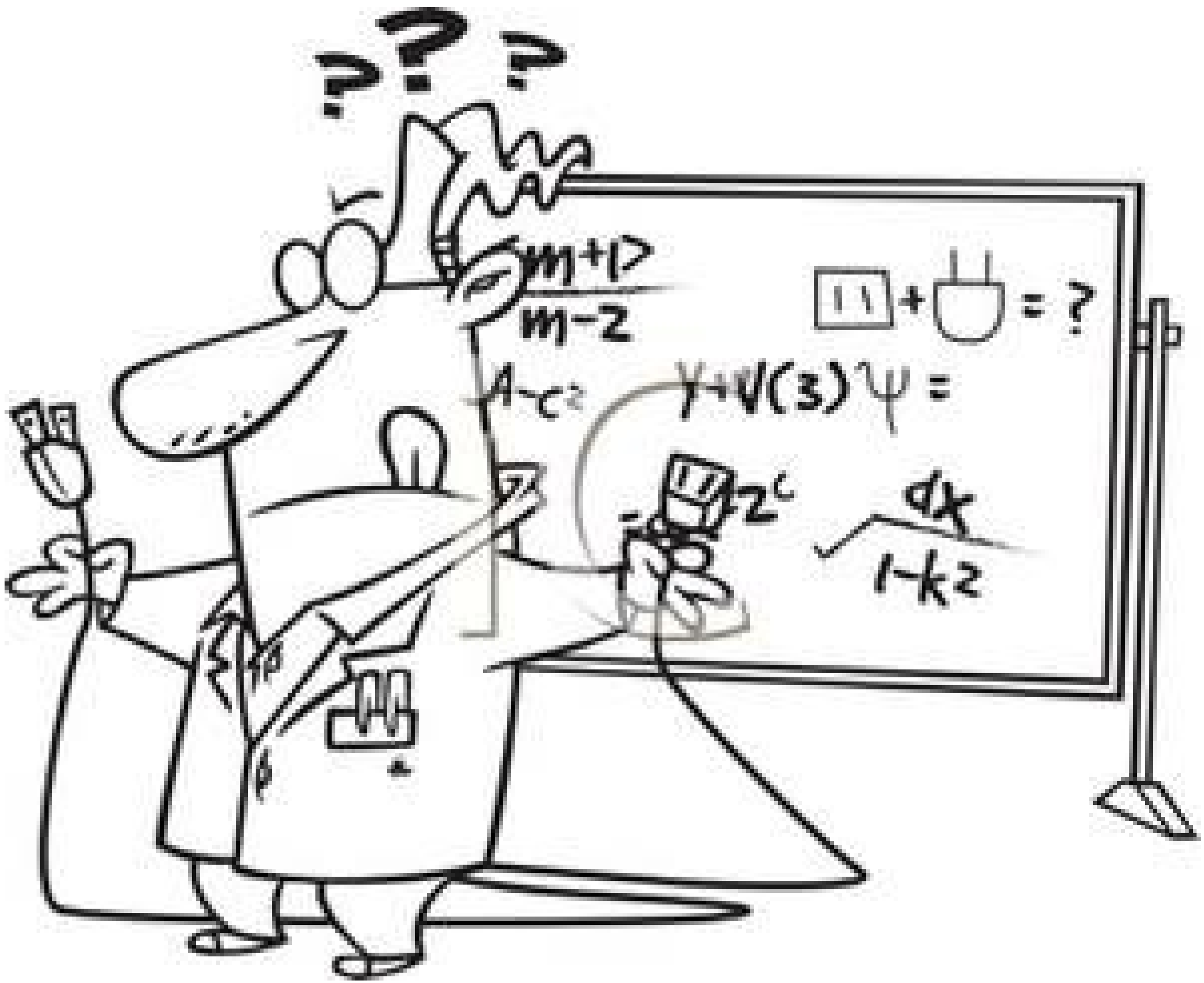


Ideal vs. Real Voltage Measurements II/II

- Voltage probes – a ~~full~~ more detailed story:
  - Joe Weber,"Oscilloscope Probe Circuits", 062-1146-00, Nov'69, Tektronix Inc.
  - Doug Ford: "The secret World of Oscilloscope Probes", Silicon Chip, Oct'09 (www.siliconchip.com.au)



Questions?



Quick getting started with Qucs

- Parameter sweeps – can be also cascaded