Capacitors and Inductors

W0TLM Tech Day 2023

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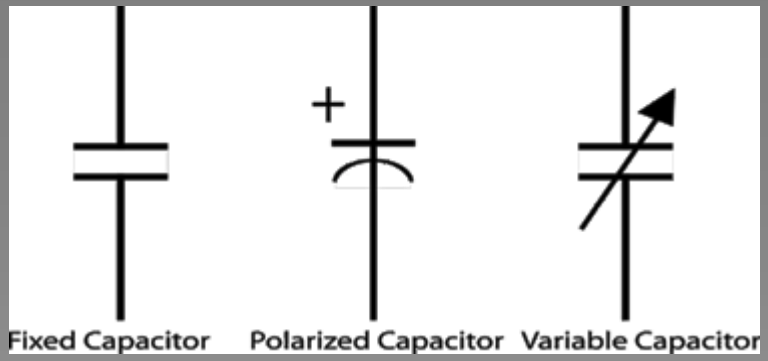
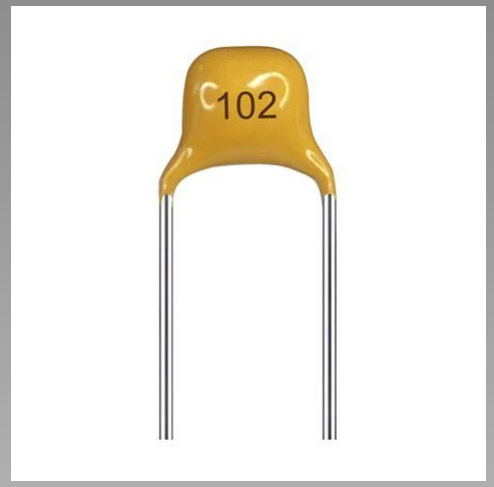
Why should you care about these?

- Don’t think that this is an attempt to turn you into circuit analysis experts! We are “***simply***” going to touch on some basics and show some illustrations.

- This is fundamental technology to virtually every element of a functioning radio
  - Power supplies
  - Receiver oscillators, filters, detectors, audio amplifiers
  - Transmitter oscillators, modulators, filters, power amplifiers
  - Antennas, feedlines, impedance matching networks (tuners, baluns, RF attenuators)

Capacitors


Fixed Capacitor
Polarized Capacitor
Variable Capacitor


102

SAMXON SAMXON
470uF25V

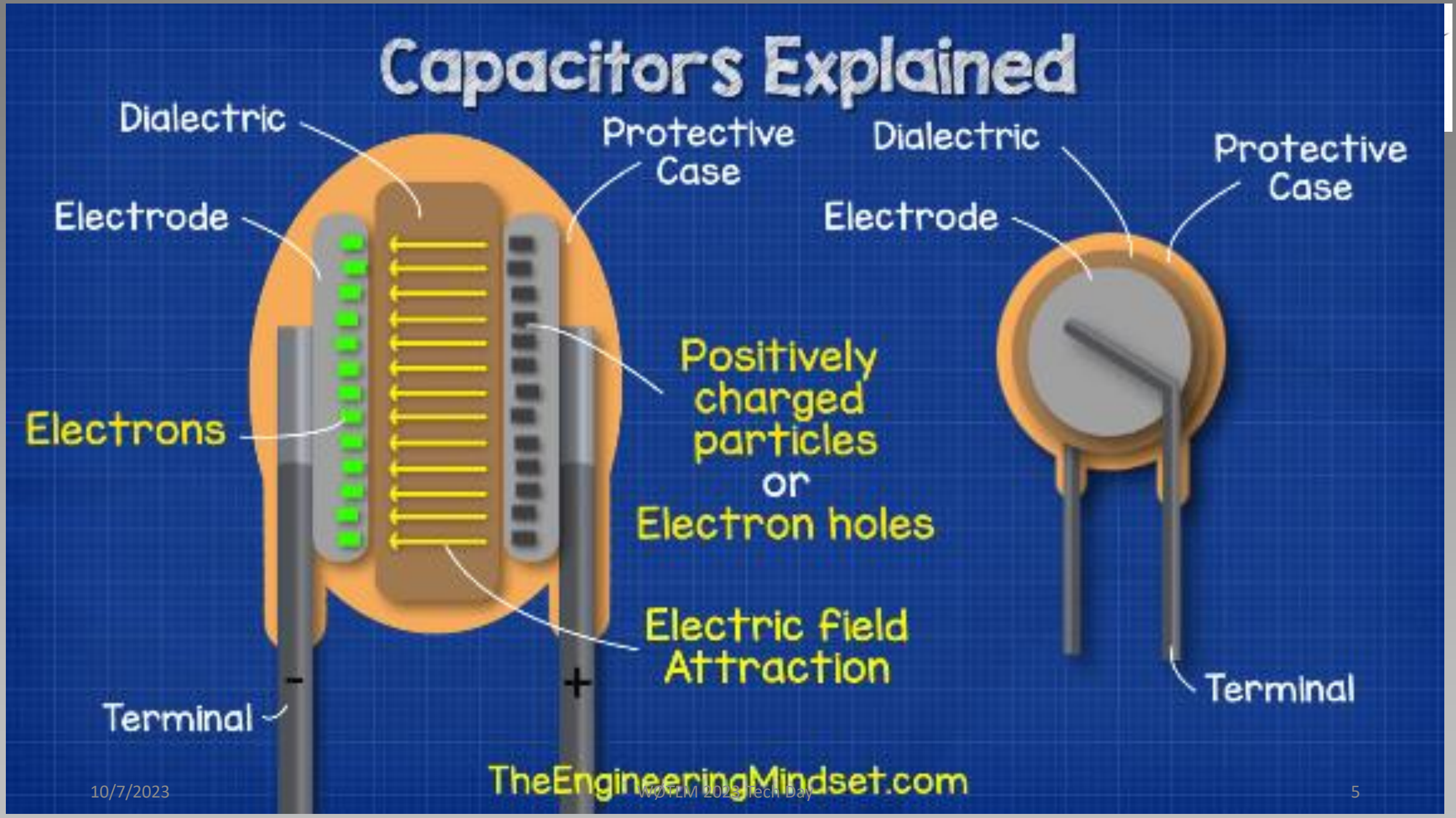
GTCAP
ULTRA CAPACITOR
2.7V
3000F
3.04Wh
WWW.GTCAPACITOR.COM

FT 5.5V
85°C 1.0F
SuperCapacitor
FT 5.5V

COMET

Characteristics of a Capacitor

- **Voltage cannot change instantaneously in a capacitor!**
- Looks like an open circuit to DC voltage
  - You may have seen the term “blocking capacitor”
- Capacitors store energy in the form of electrical charge that builds up on the capacitor’s plates
- The changing of the stored charge due when the voltage changes results in current flowing through the capacitor
  - This will be more apparent when we look at an AC circuit
- Capacitance value is a factor of the area of the plates and the *permittivity* value of the dielectric material (either air or insulating material)


Capacitors Explained
Dialectric
Protective Case
Electrode
Electrons
Positively charged particles or Electron holes
Electric field Attraction
Terminal
-
+
TheEngineeringMindset.com
Dialectric
Protective Case
Electrode
Terminal

RC Circuit

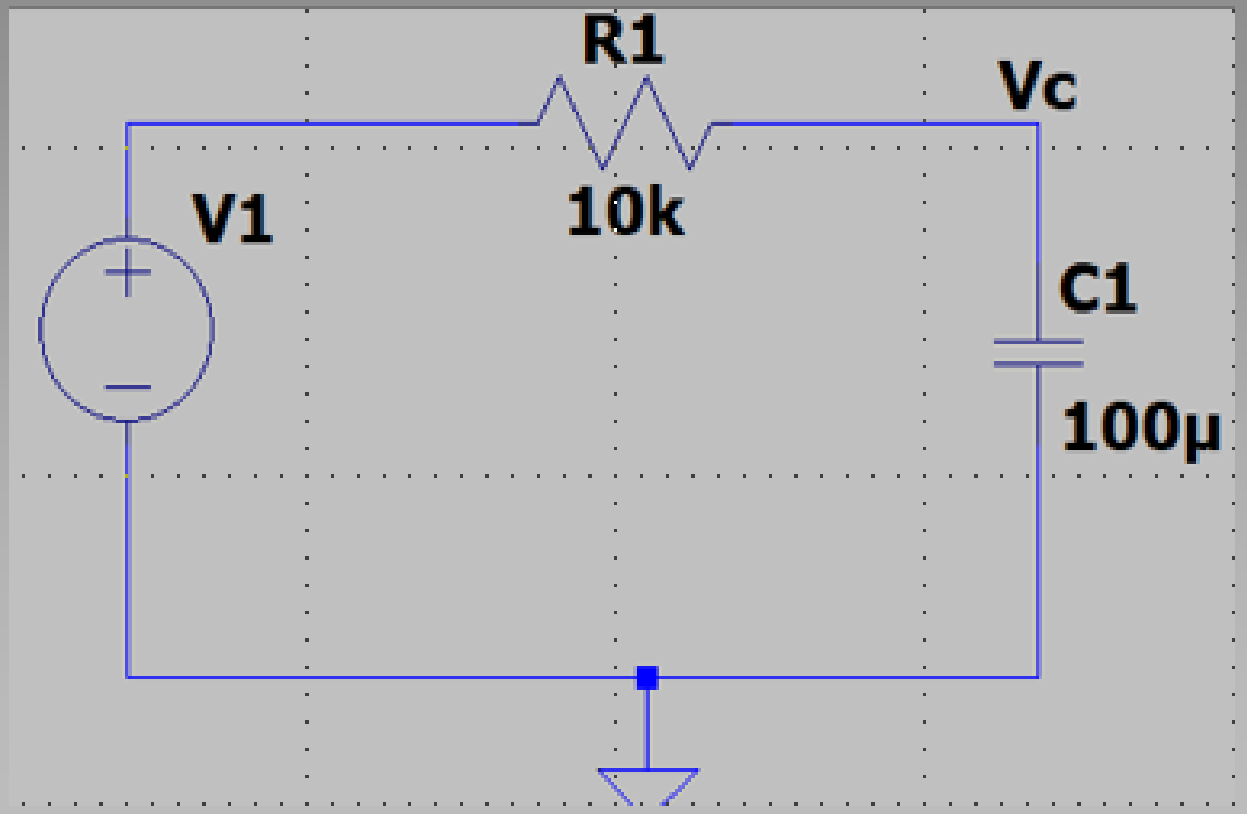
- Applications used for circuit analysis in this presentation are
- LTSpice

https://www.analog.com/en/design-center/design-tools-and-calculators/ltspice-simulator.html

and

- Qspice

https://www.qorvo.com/design-hub/design-tools/interactive/qspice



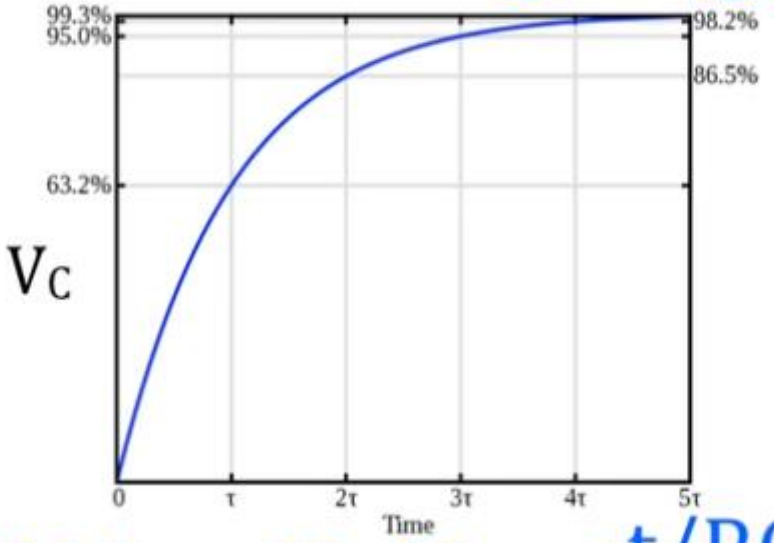
Quick Aside

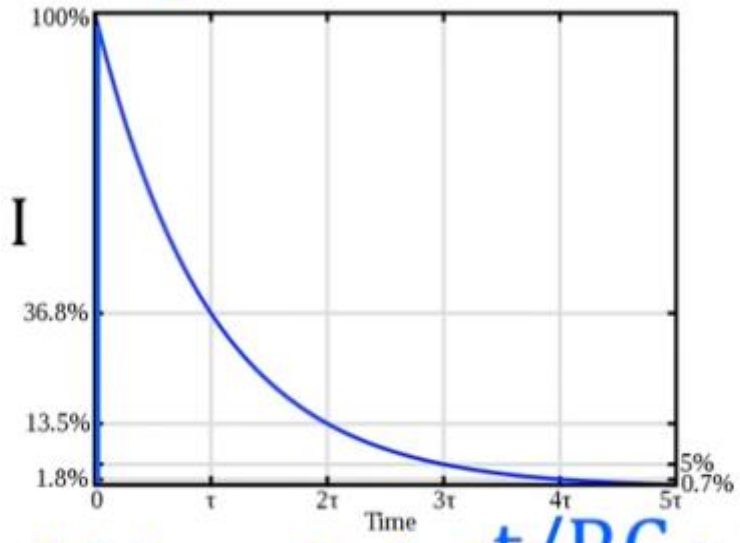
- The number ***e***, also known as **Euler's number**, like **π,** is a mathematical constant approximately equal to 2.71828
- ***e*** is the base for the natural logarithm (ln)
- **Euler's formula**

$$e^{jx} = \cos x + j \sin x$$

- Trust the math. We don't have time to explain why!

Charging a Capacitor



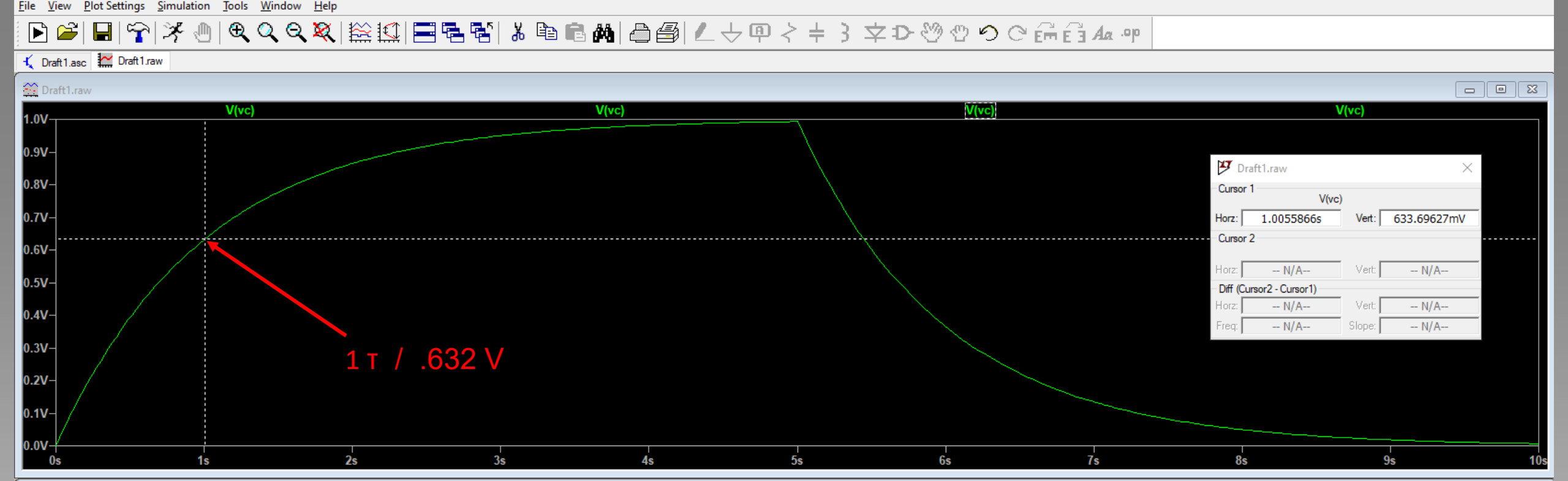


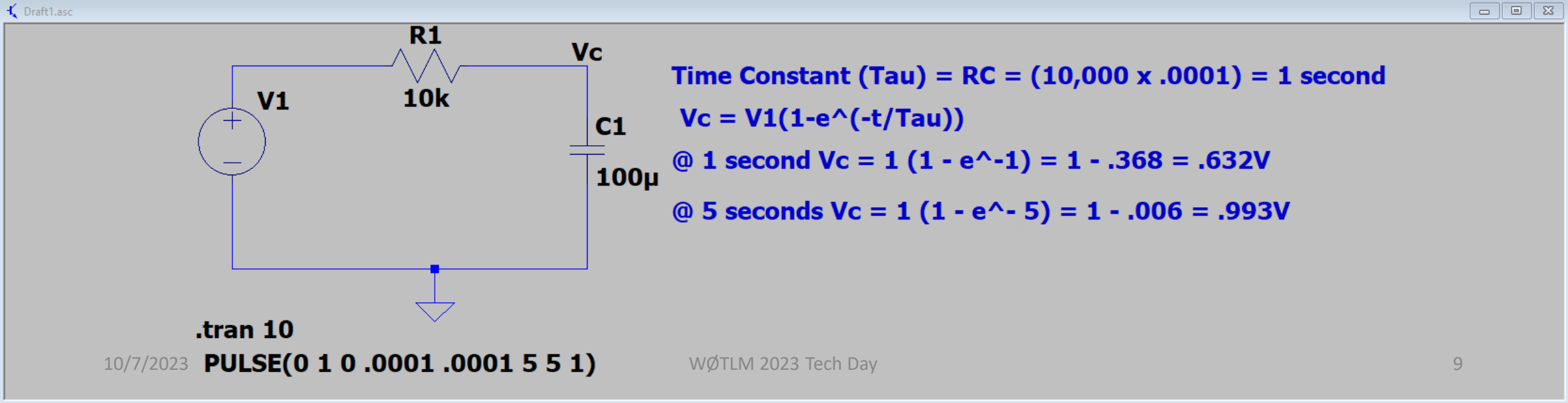
$$V(t) = V_B(1 - e^{-t/RC}) \qquad I(t) = I_0(e^{-t/RC})$$

$$\text{Time Constant } (\boldsymbol{\tau}) = RC$$

$$\boldsymbol{\tau} = 10\text{K}\Omega \cdot 470\mu\text{F}$$

$$\boldsymbol{\tau} = 4.7\,\text{s}$$



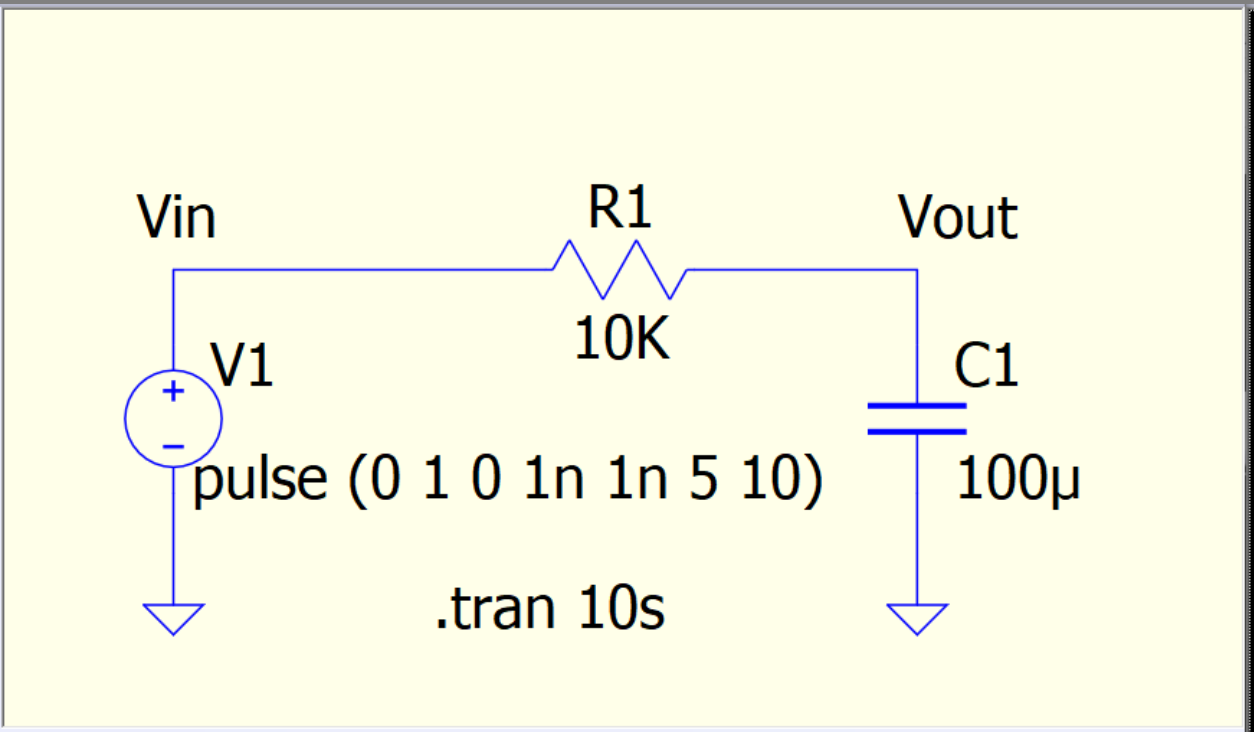


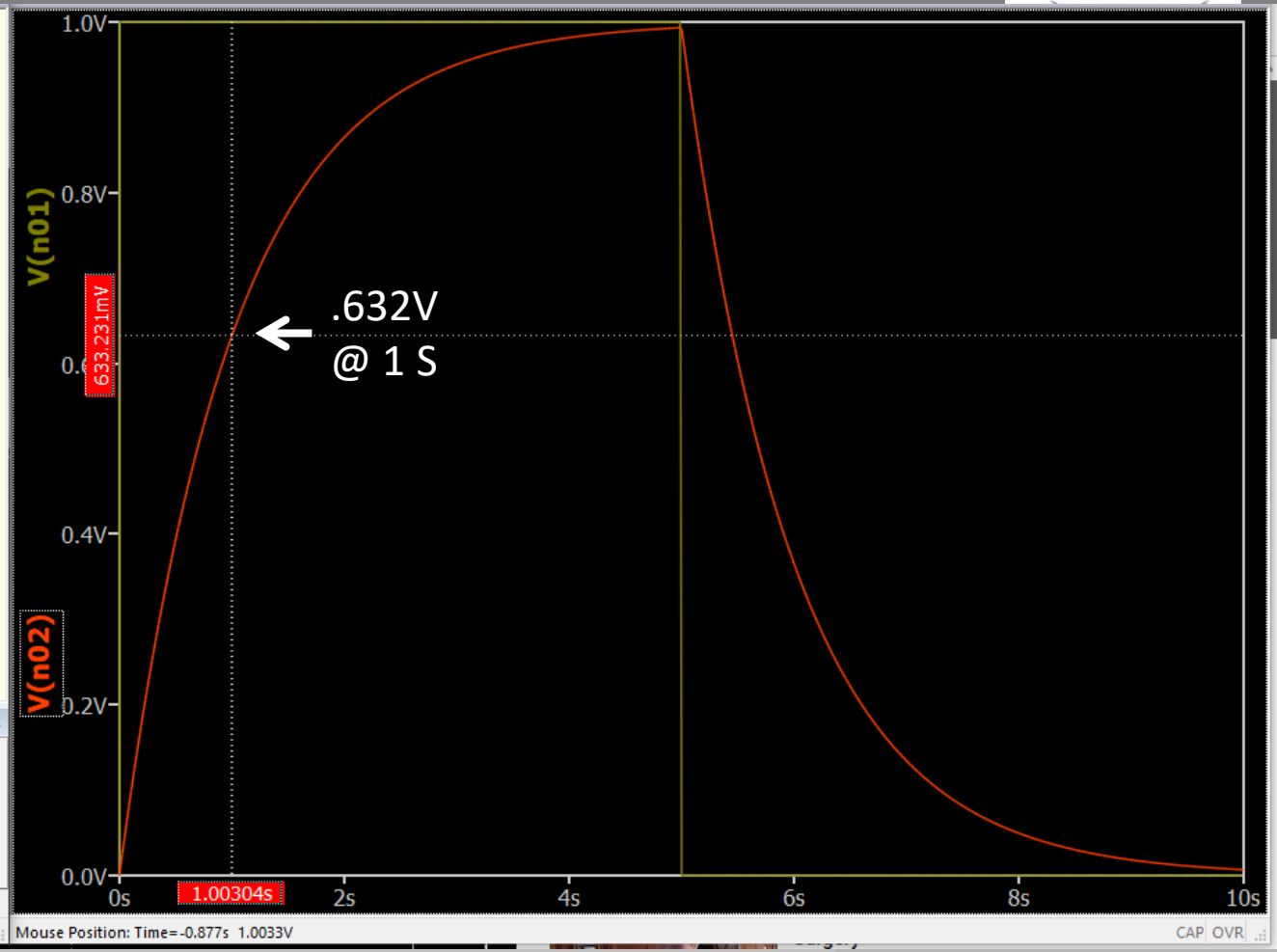
Time Constant (Tau) = RC = (10,000 x .0001) = 1 second

Vc = V1(1-e^(-t/Tau))

@ 1 second Vc = 1 (1 - e^-1) = 1 - .368 = .632V

@ 5 seconds Vc = 1 (1 - e^- 5) = 1 - .006 = .993V





Output Window

```
Total elapsed time: 0.0041499 seconds.
```

Simulation | Post Process

CAP OVR

Time Constant (Tau) = RC = (10,000 x .0001) = 1 second

Vc = V1(1-e^(-t/Tau))

@ 1 second Vc = 1 (1 - e^-1) = 1 - .368 = .632V

@ 5 seconds Vc = 1 (1 - e^-5) = 1 - .006 = .993V

Practical uses of an RC Circuit

- AC coupling (aka DC blocking)
- Bypass (aka decoupling)
- Low pass filter
- High pass filter
- Phase shift networks
- Timing (delay) circuits
- Square wave generator (RC circuit for timing)

Capacitor values – component marking

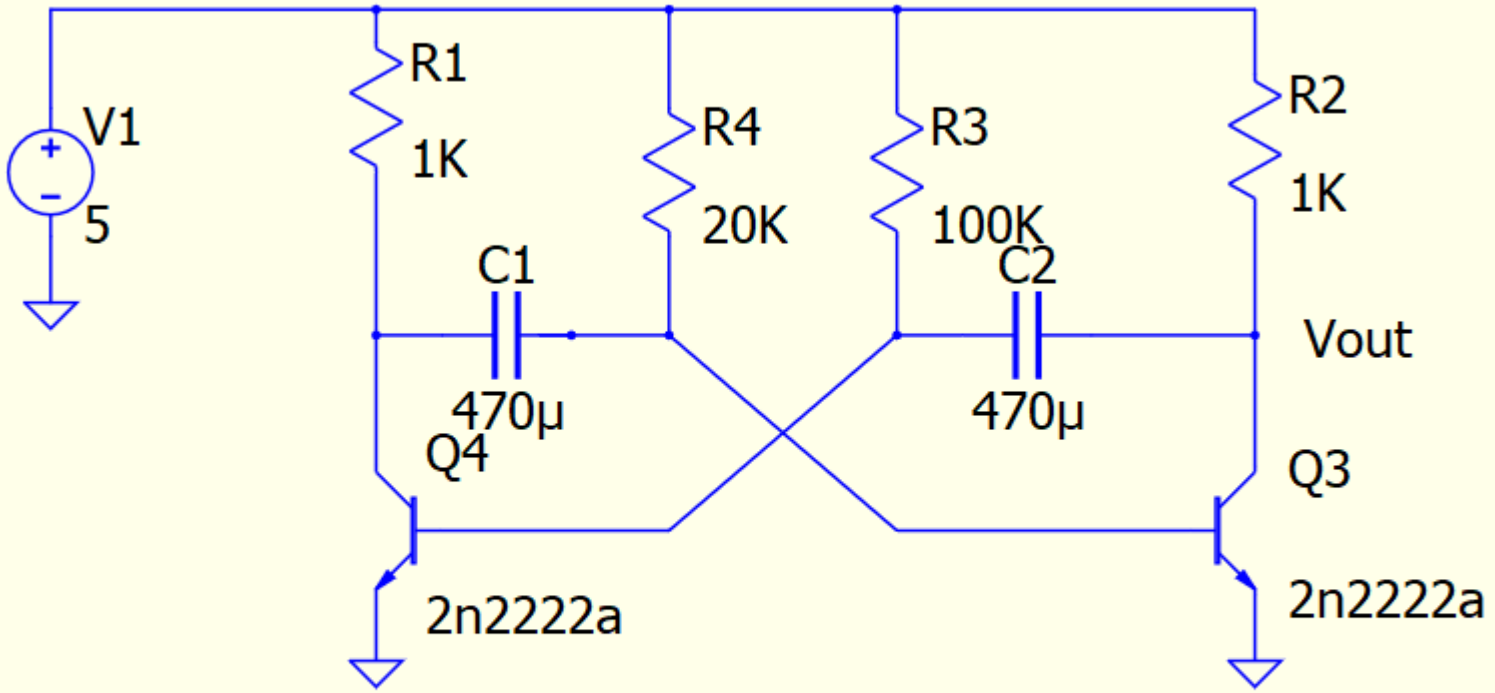
- If a 3-digit number is present the third, non-zero number is the number of zeros that will make the number C x 10^ -12 (picofarads)
  - A capacitor marked 103 would be 10000 x 10^-12 or 10000 picofarads (pf) or more commonly, .01 microfarads (.01 µf)
  - A capacitor marked 472 would be 4700 pf or .0047 µf
- If the 3-digit number ends with 0 the value is picofarads
  - A capacitor marked 220 is 220 pf

Capacitor values – on schematics

- If a polarized capacitor is required, its polarity will be marked. If not indicated assume the value to be microfarads (µf)
- Non-polarized capacitors marked with no decimal point assume to be picofarads (pf)
- Non-polarized capacitors with a decimal point assume to be microfarads (µf)

Square Wave Generator

Astable Multivibrator



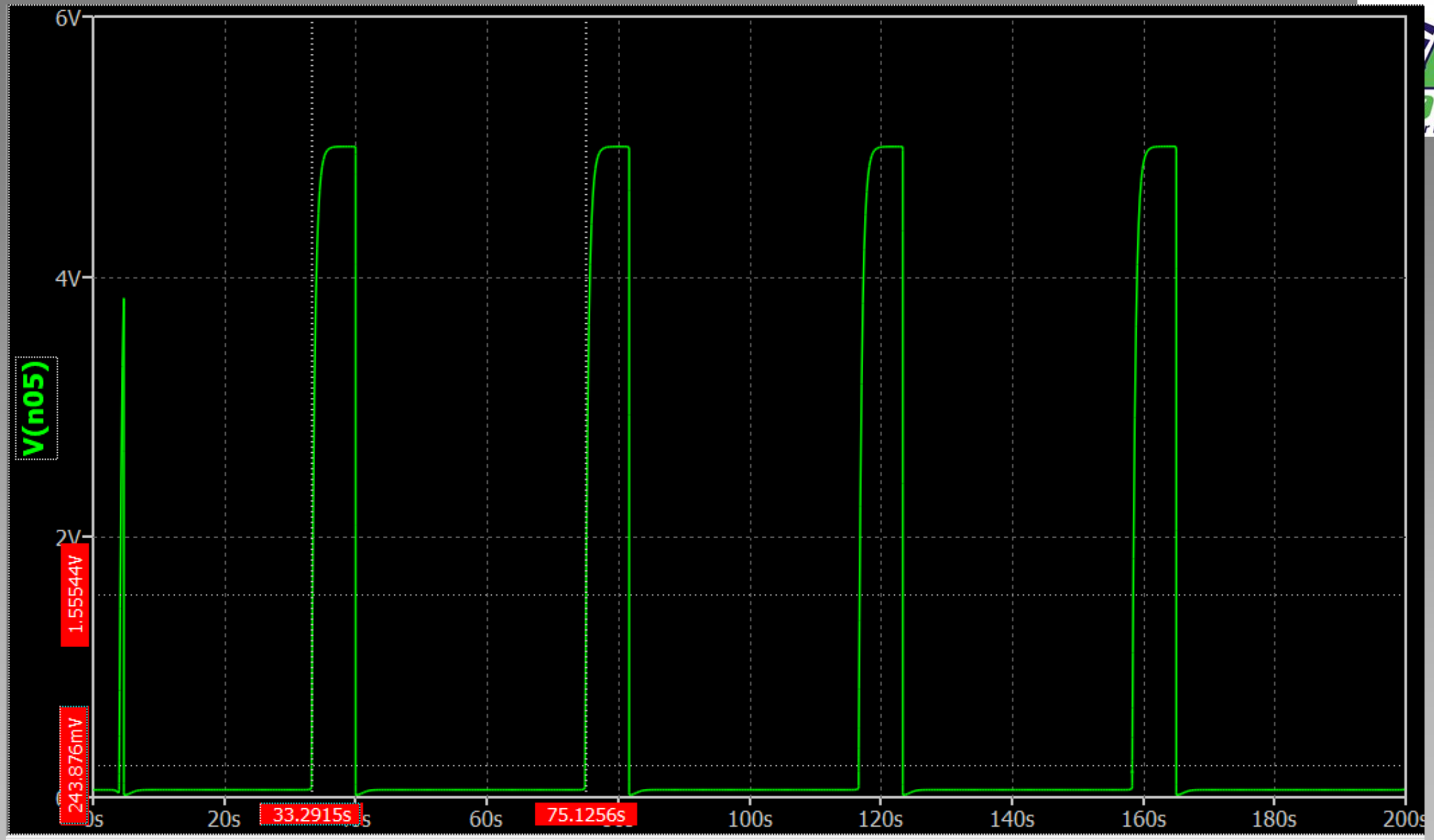
.tran 200

$\tau_{(R4\&C1)}$ = RC = 20k * .00047

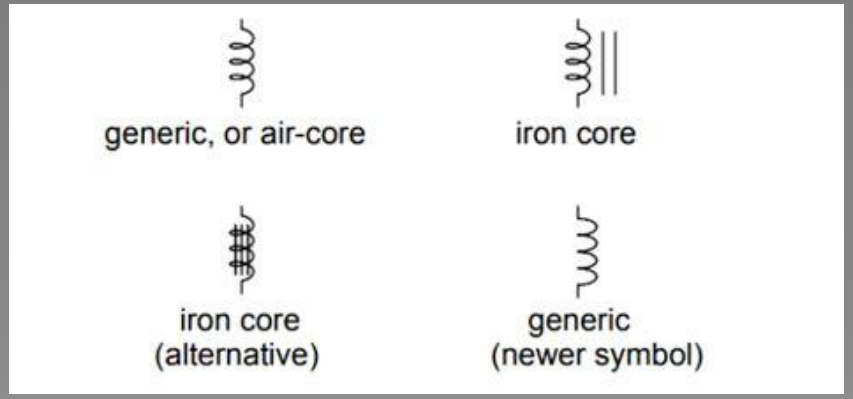
= 9.4 seconds

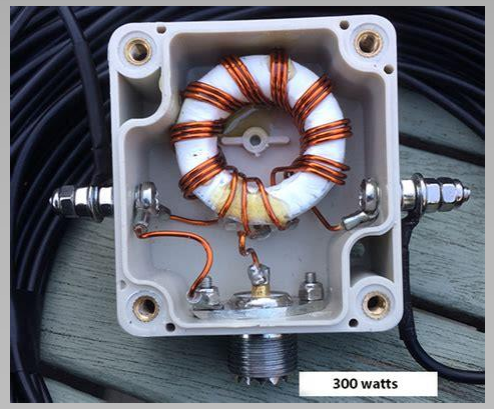
$\tau_{(R3\&C2)}$ = RC = 100k * .00047

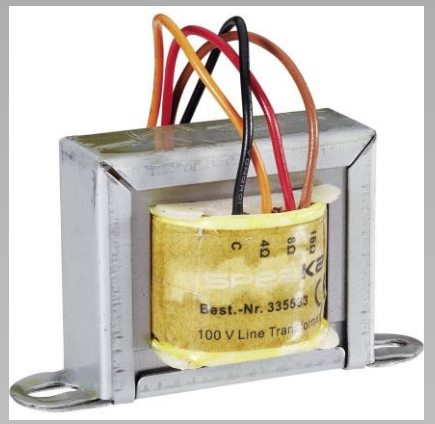
= 47 seconds


6V
4V
2V
V(n05)
1.55544V
243.876mV
20s
33.2915s
60s
75.1256s
100s
120s
140s
160s
180s
200s
Drag to move the cursor attached to "V(n05)"

Inductors

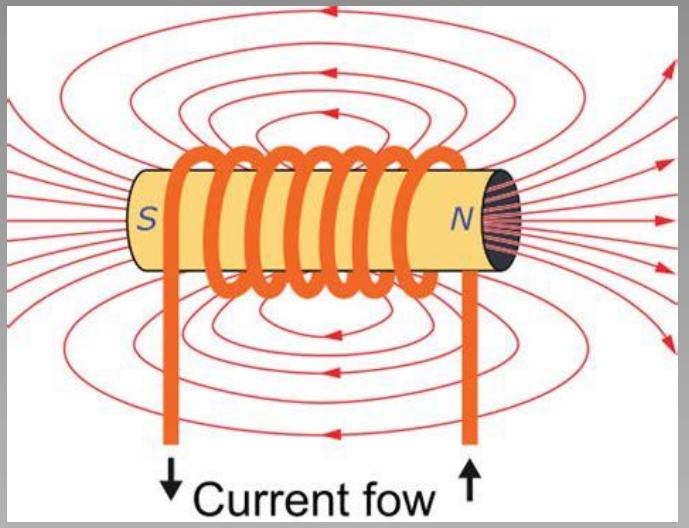

generic, or air-core
iron core
iron core
(alternative)
generic
(newer symbol)


300 watts

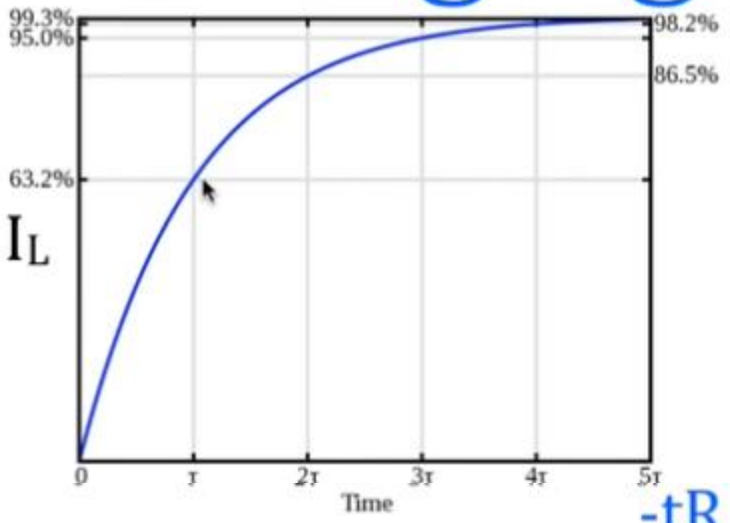


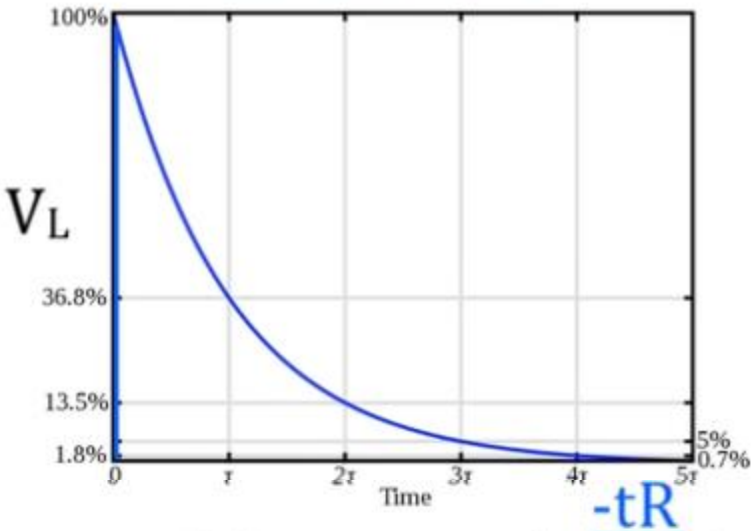
Characteristics of an Inductor

- **Current cannot change instantaneously in an inductor!**
- Inductor looks like a open circuit to DC voltage
  - Internal resistance is very low
- Inductors store energy in the form of magnetic field that occurs due to current flow
  - Inductor may or may not have a magnetic core to increase inductance (*permeability* factor)
- Voltage changes across the inductor in a circuit with changing voltage as the magnetic field changes



Charging an Inductor





$$I(t) = I_{max}(1 - e^{\frac{-tR}{L}})$$

$$V(t) = V_B(e^{\frac{-tR}{L}})$$

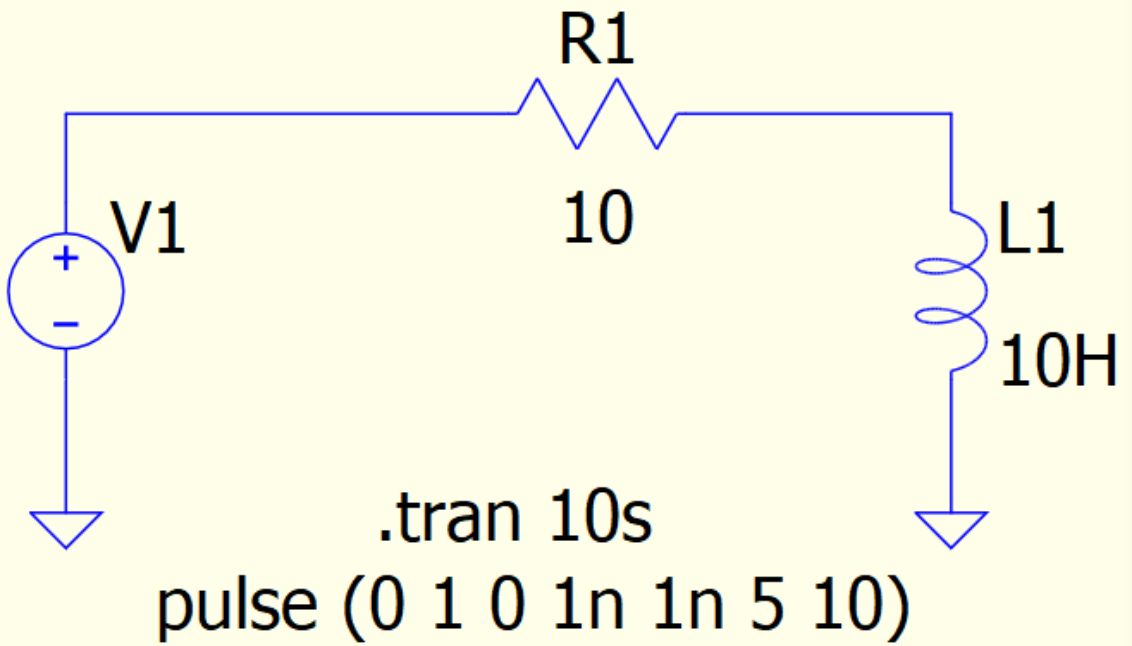
$$\text{Time Constant } (\boldsymbol{\tau}) = \frac{L}{R}$$

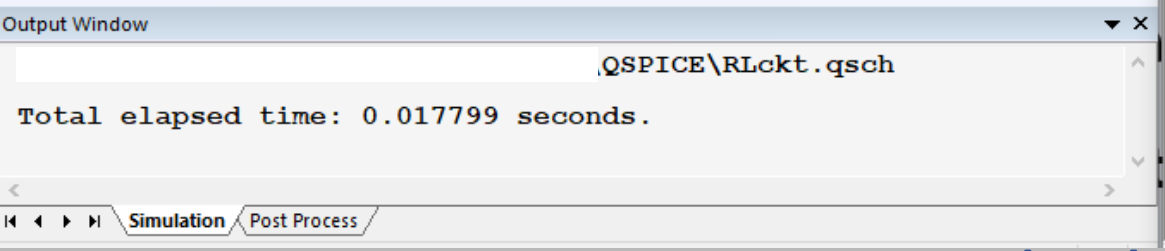
$$\boldsymbol{\tau} = 15\text{H} / 10\ \Omega$$

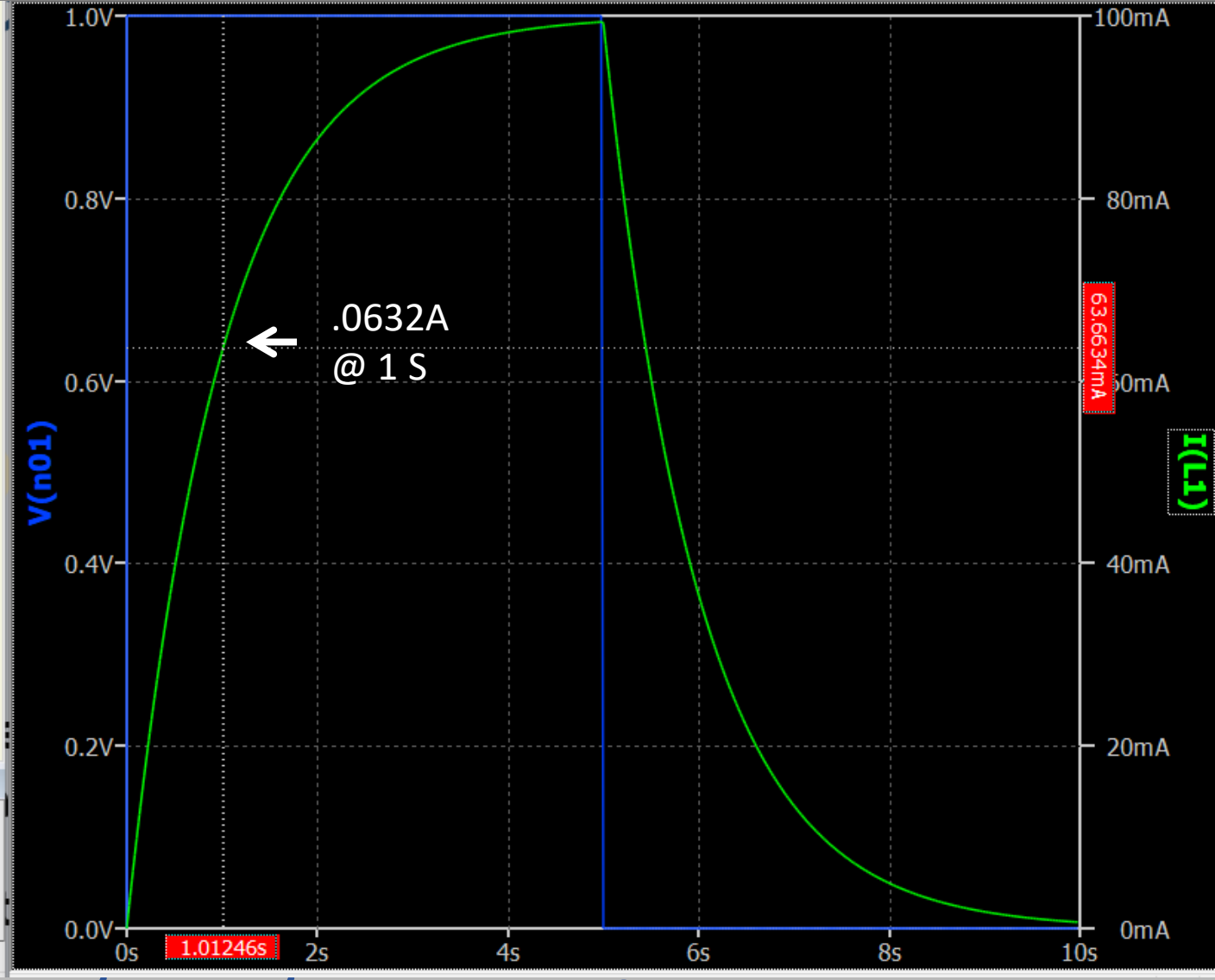
$$\boldsymbol{\tau} = 1.5\ \text{s}$$

Practical Uses for RL Circuits

- Low pass filters
- High pass filters
- Oscillator circuits
- Phase shift networks
- Voltage or current transformation
  - Baluns and transformers







Time Constant (Tau) = L / R = 10 / 10 = 1 second

I_L = (V1/R1) * (1 - e*(-t / Tau))

@ 1 second I_L = .1 * (1 – e^-1) = .1 - .0368 = .0632A

@ 5 seconds I_L = .1 * (1 – e^-5) = .1 - .0006 = .0993A

Winding Inductors

- The permeability of air is ~1
- Toroids used by Hams are typically either powdered iron or ferrite
  - Ferrite is a ceramic material that is magnetic but non-conductive
  - Permeability is determined by the “Mix”
- The permeability of powdered iron and ferrite mixes ranges from 10 – 20,000
- The number of turns required is determined by the size of the toroid and the mix
  - The larger the toroid the more turns required for the same inductance value
  - Typically, the higher the mix number the fewer turns required
- Care must be taken to ensure the mix will support the required frequency range!

Winding Inductors

For powdered-iron cores:

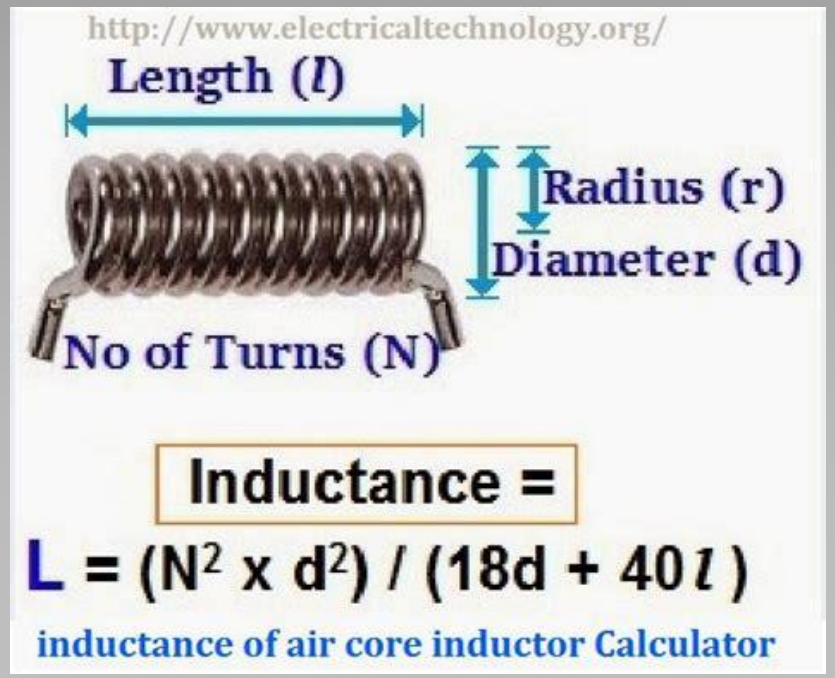
$$N = 100\frac{\sqrt{L_{\mu H}}}{A_L}$$

For ferrite cores:

$$N = 1000\sqrt{\frac{L_{mH}}{A_L}},$$

where

N = the number of turns
$L_{\mu H}$ = inductance in microhenrys (μH)
L_{mH} = inductance in millihenrys (mH)
A_L is a property of the core material.



Toroid Coil Winding Calculator

Use this online tool to calculate the number of winding turns required to achieve the desired inductance

Material Type:
Iron Powder ○ **Ferrite** ◉

Inductance
.1 mH

Core Size
FT-23

Material Number
43

Calculate
<

https://66pacific.com/calculators/toroid-coil-winding-calculator.aspx

INDUCTANCE
Desired: .1 mH
Calculated: 0.1 mH (99% of desired) **Turns required:** 23

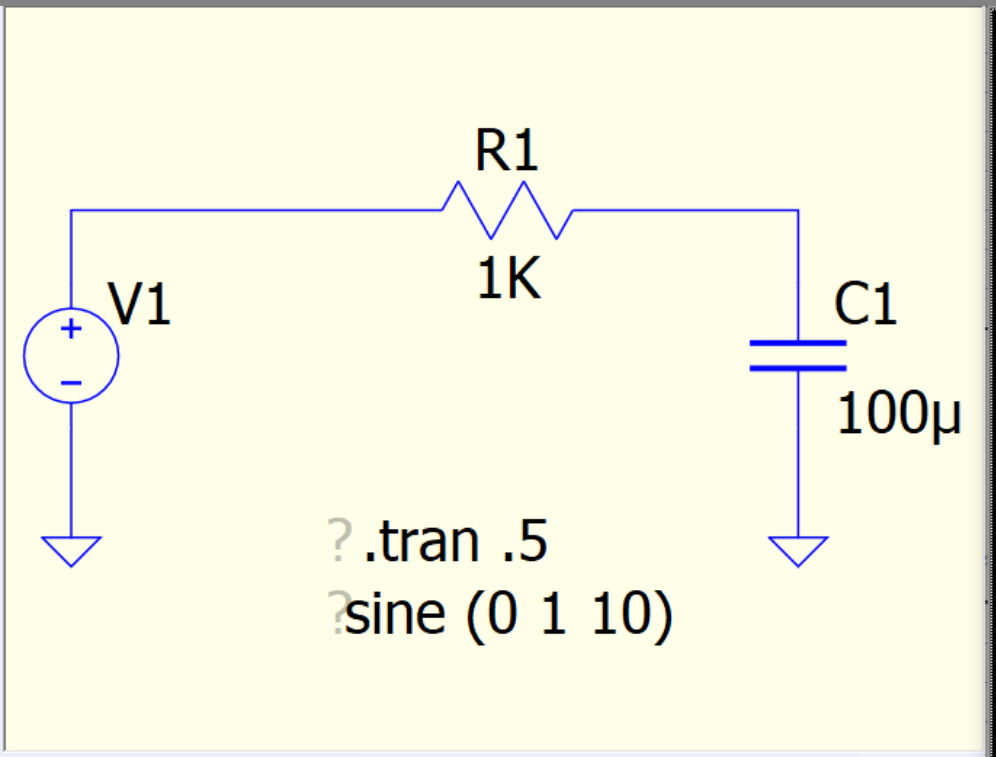
CORE
Part number: FT-23-43
Frequency Range:
u: 850
A_L: 188 mH/1000 turns

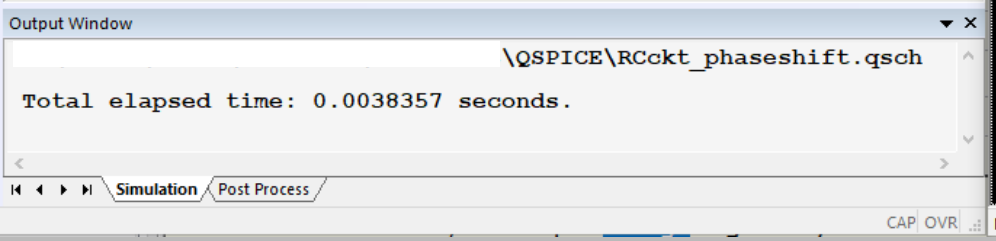
What About Phase?

Who is ELI the ICE man?

- We saw from the previous waveforms of the RC and RL circuits that the voltage across the capacitor or the current in the inductor did not change at the same time as the current or voltage changed across those components
- If the voltage source for the circuit is an AC source, regardless of frequency
  - Voltage (E) leads the current (I) in the inductor (L) (ELI)
  - Current (I) leads the voltage (E) in the capacitor (C) (ICE)
  - The amount of lead or lag depends on the frequency

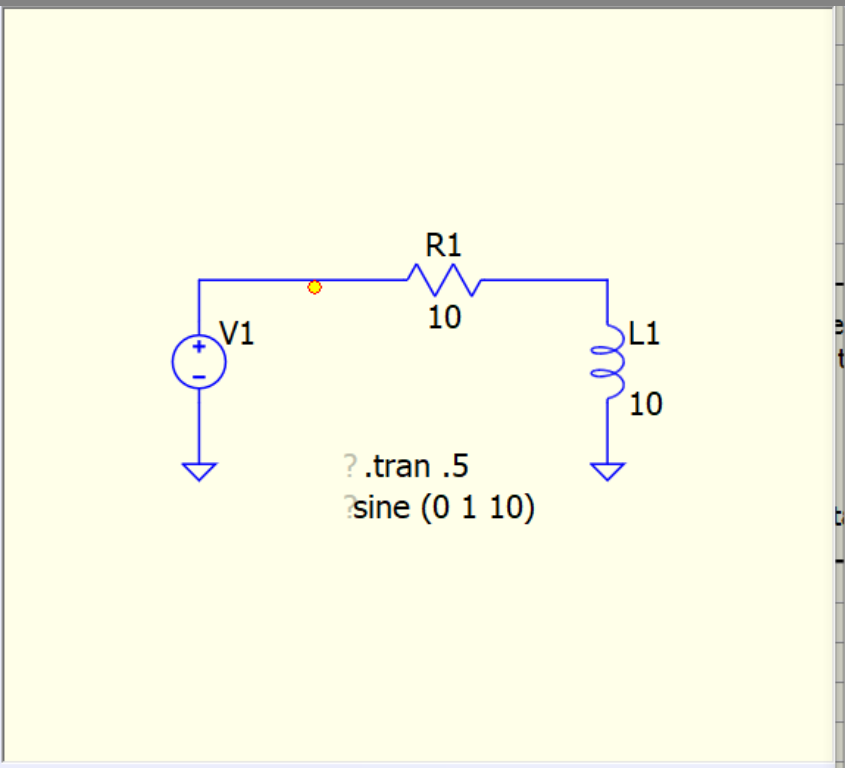
Capacitor's phase shift

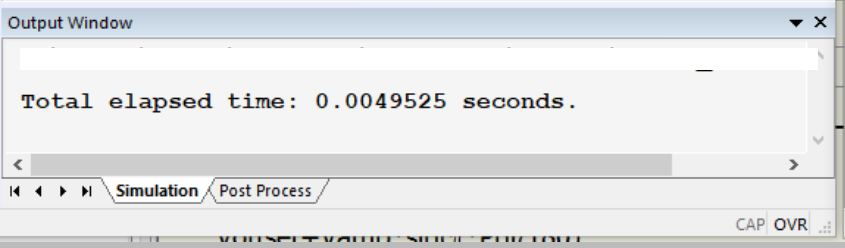


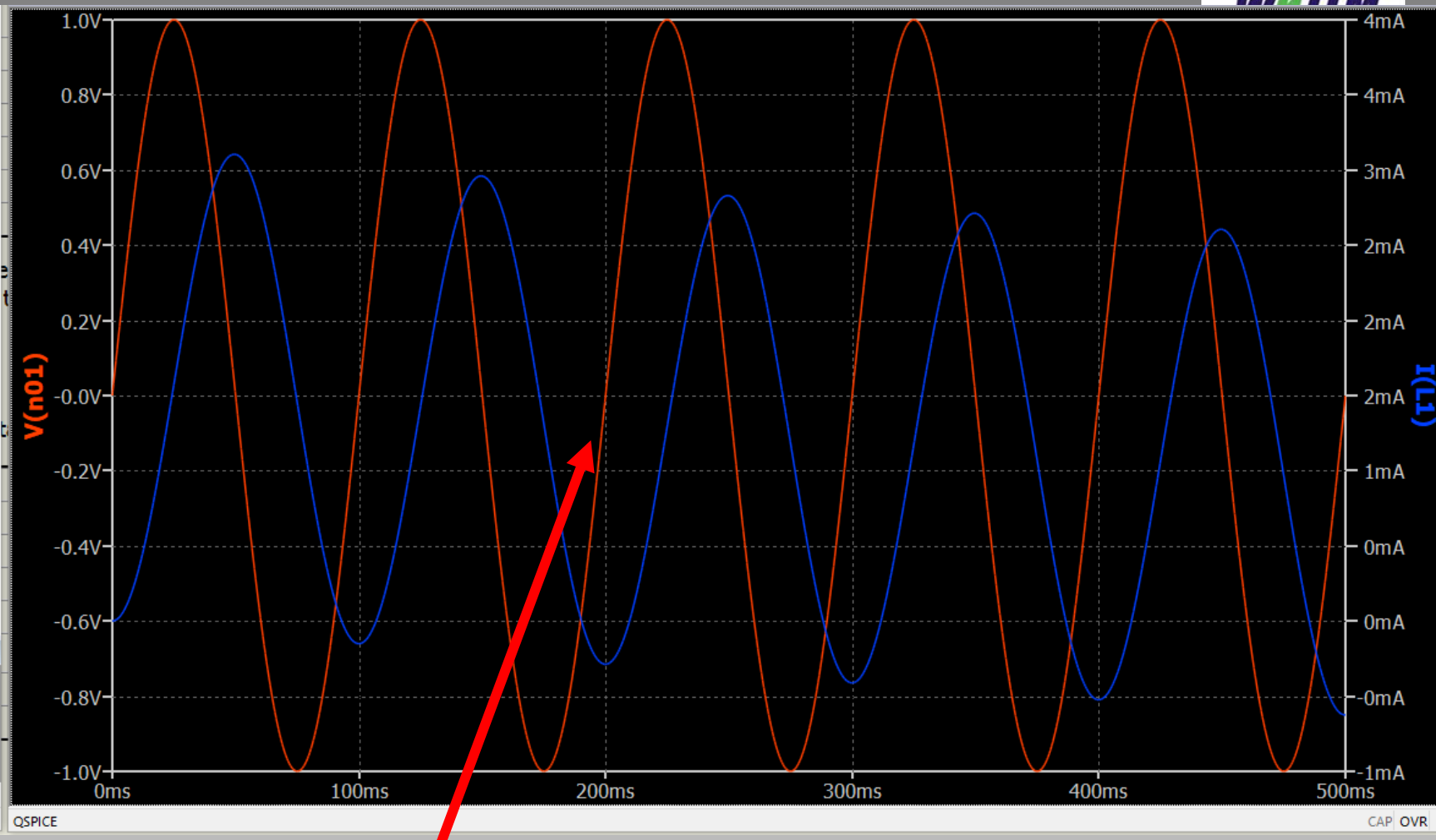


Note that the current in R1 leads the C1 voltage (ICE)

Inductor's phase shift







Note that the volage leads the L1 current (ELI)

Ohm's Law applies to RLC Circuits

- Most of us are familiar with

  E = I x R -> Electromotive Force (Voltage) equals Current times Resistance

- We can also write this equation as

  E = I x Z -> Voltage equals Current times Impedance

  - Impedance takes into consideration resistance plus the reactance of the circuit

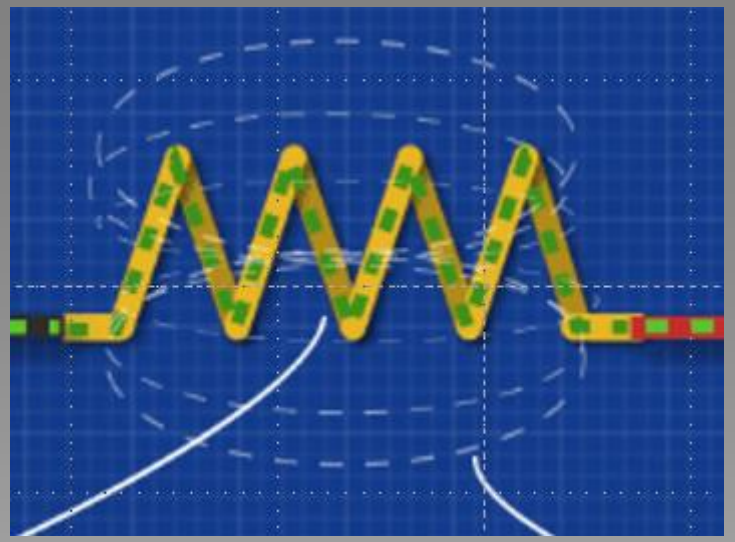
    Z = R + jX (+j means inductive reactance, -j means capacitive)

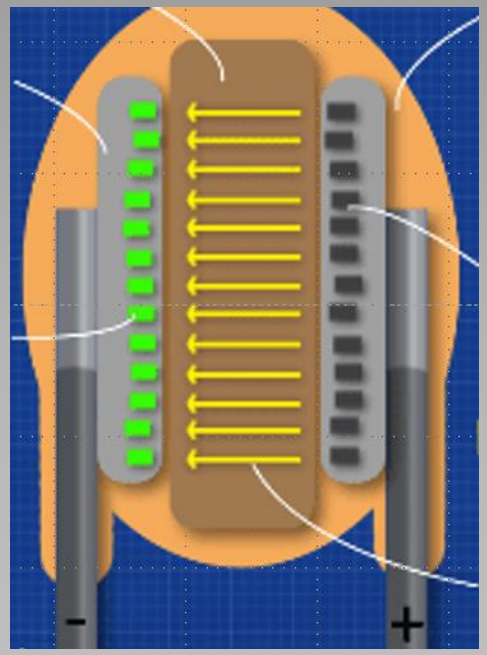
- Unlike resistors, ideal capacitors and inductors don't dissipate any energy (for our purposes we'll ignore the small amounts of energy dissipated in actual devices).
- But they do have impact on circuit behavior, so we treat reactance (X) values as imaginary numbers designated by "***j***". Mathematicians use "***i***" but in electronics we don't want to confuse this with current.

What Causes Reactance?

- Inductive Reactance is caused by an opposition to alternating current (AC) due to an induced EMF caused by an inductor's changing magnetic field.

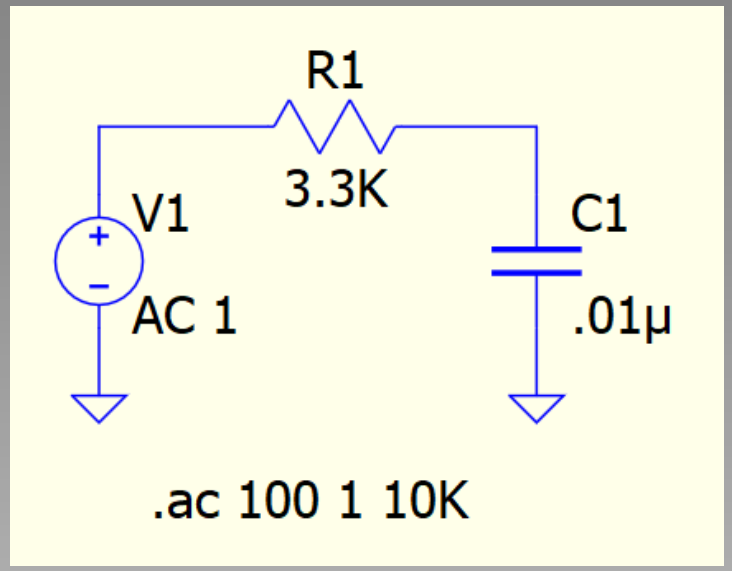
- Capacitive Reactance is an opposition to AC due to the EMF caused by the build up of charge across the capacitor.



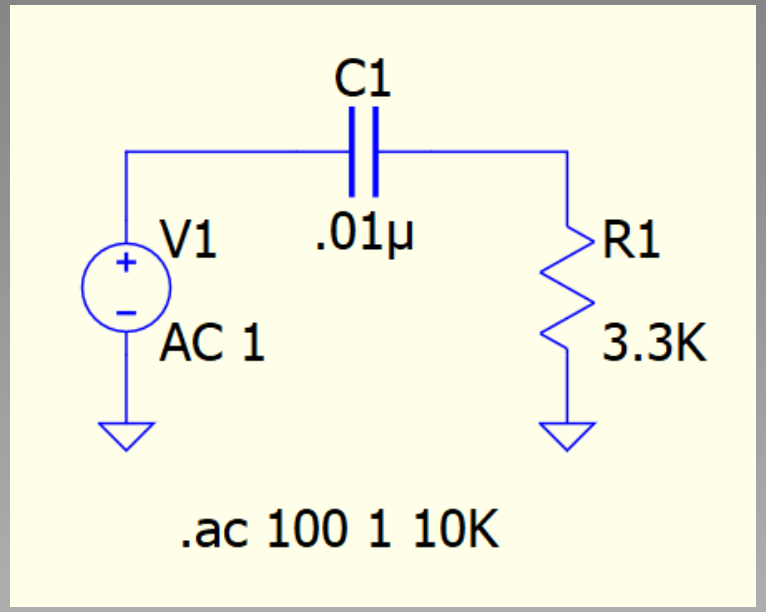


Single Pole Filters

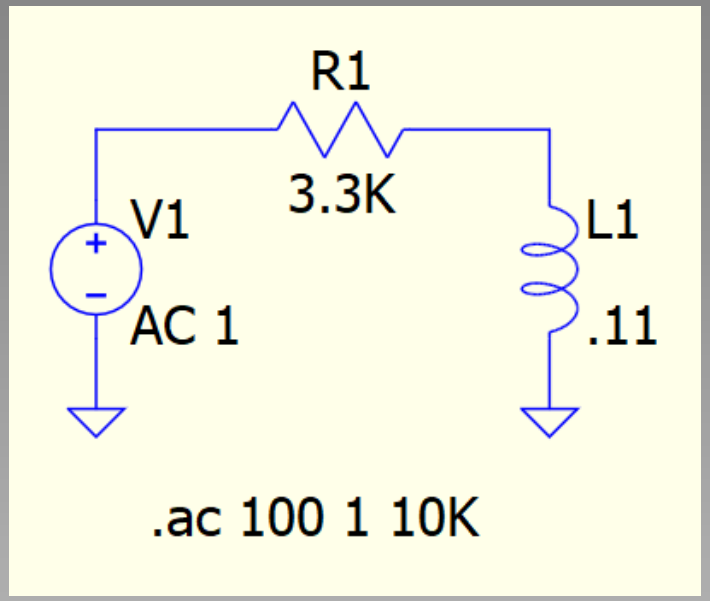
Low-Pass Filter



High-Pass Filter



High-Pass Filter



Break point of filter is identified as frequency at which output power is reduced by 3 dB (half-power point).
Think of this circuit as a divider. Half power will be at the frequency where X_C is equal to R.

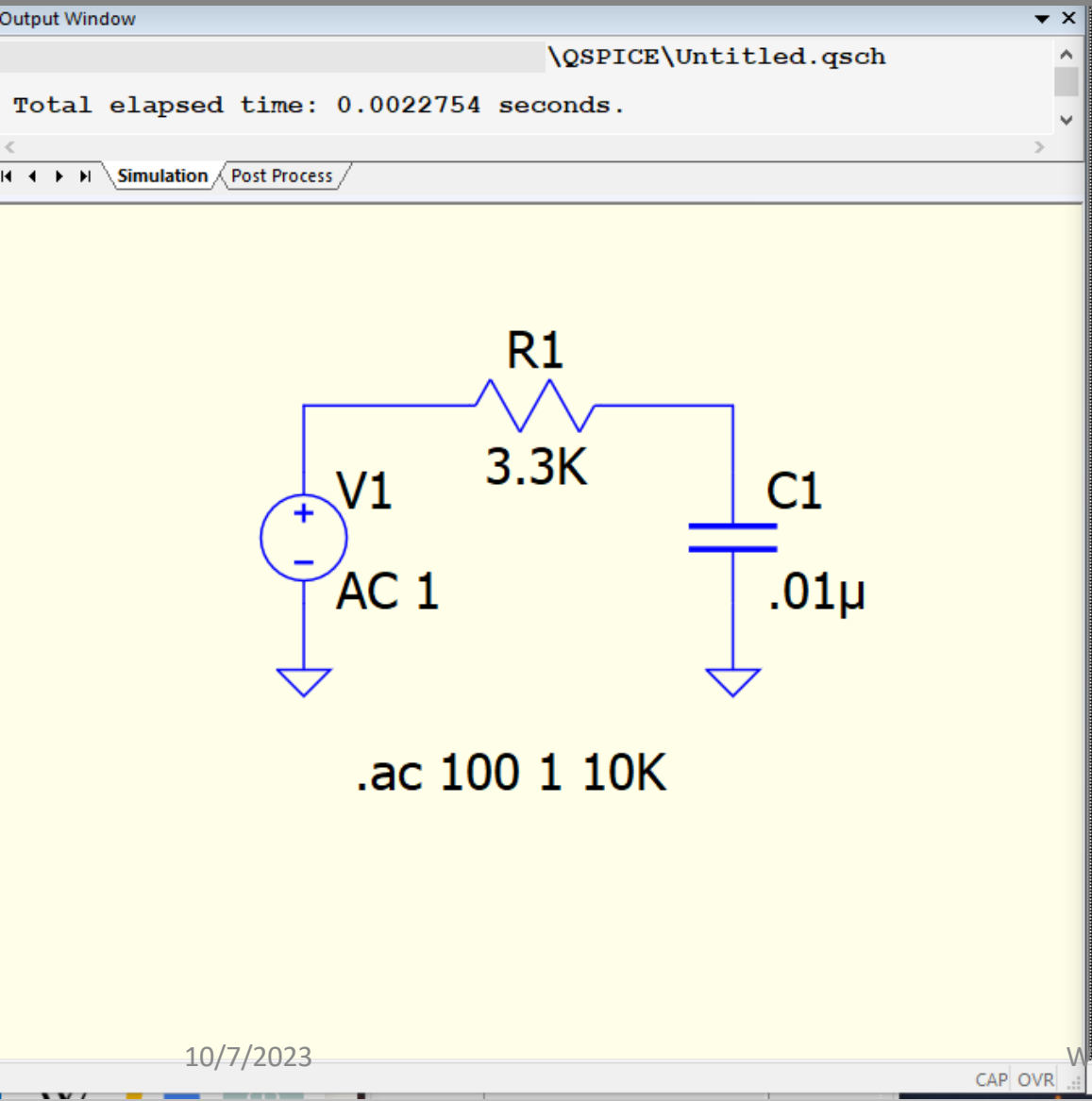
$$X_C = \frac{1}{2\pi f C} = -j3.3k$$

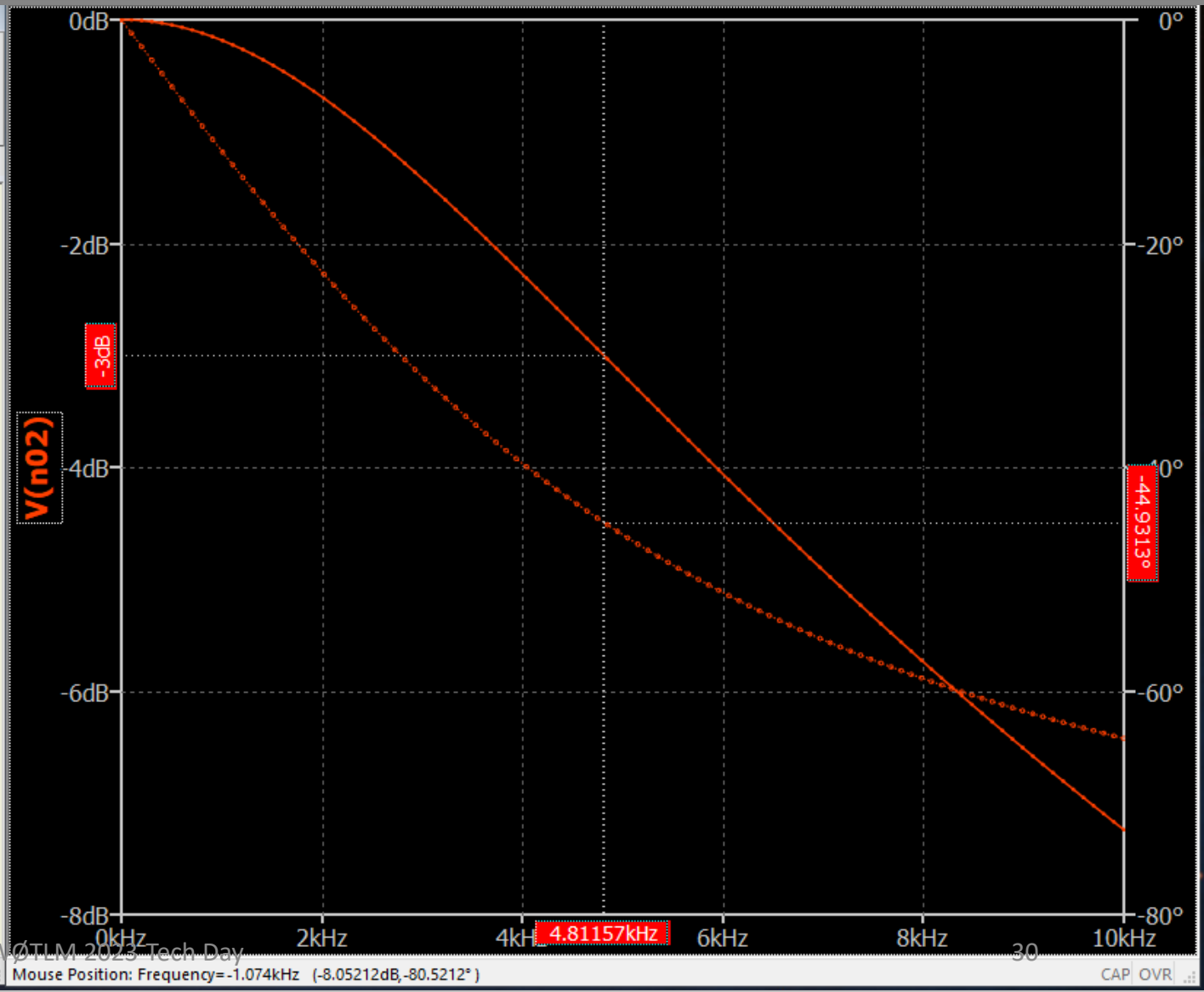
@f = 4.823kHz

$$X_L = 2\pi f L = j3.3k$$

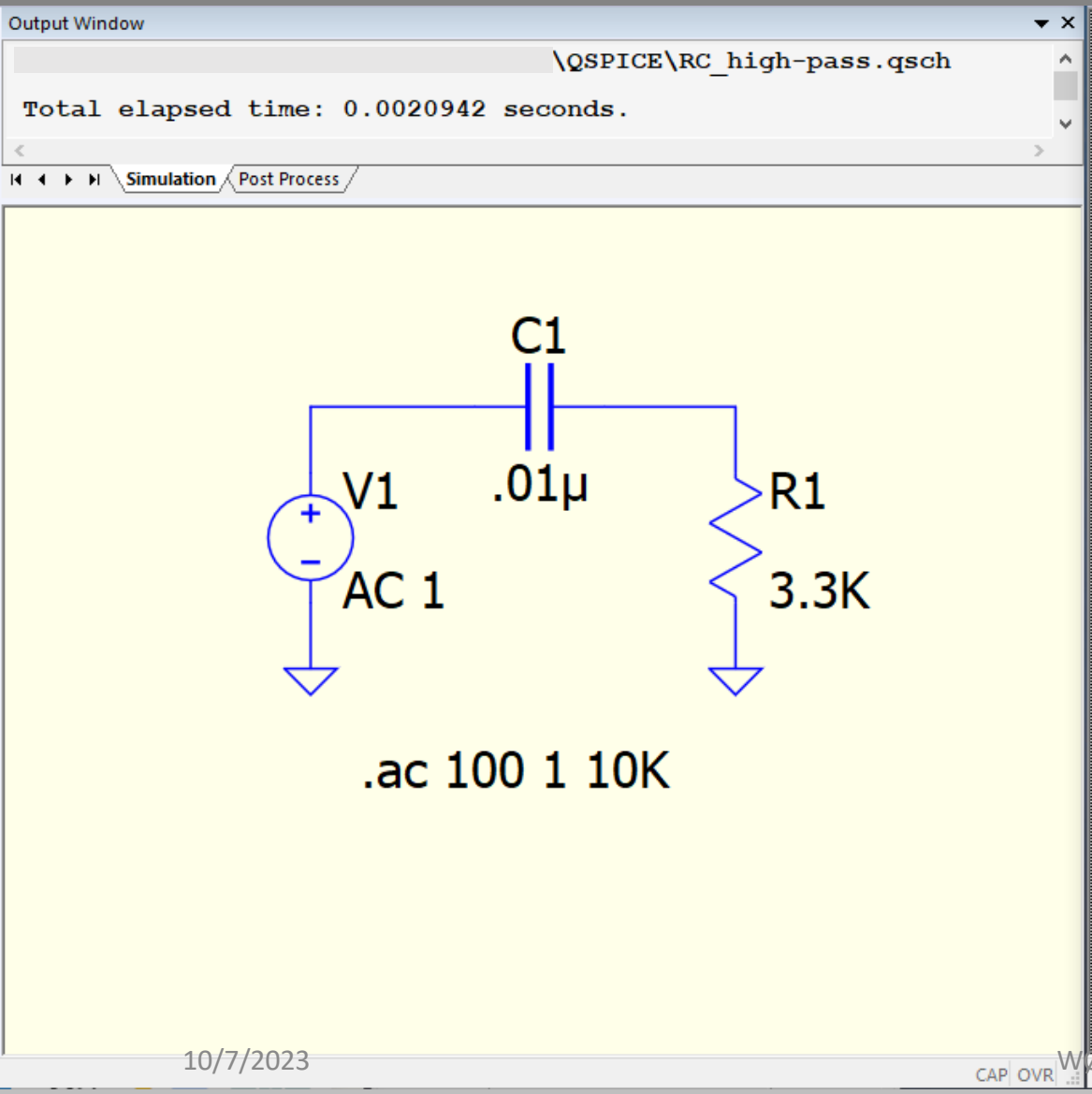
@f = 4.823kHz

Low-pass Filter

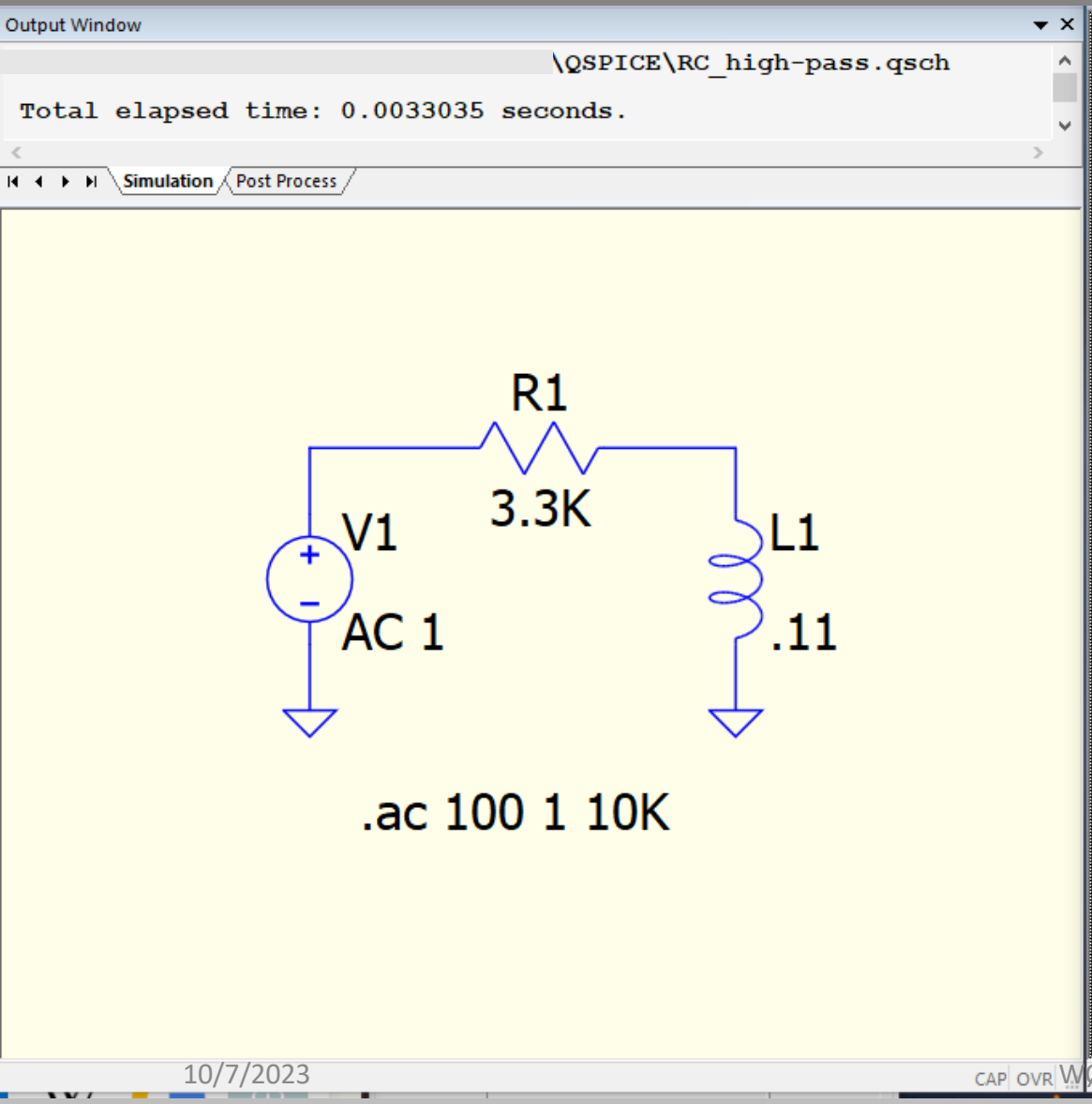


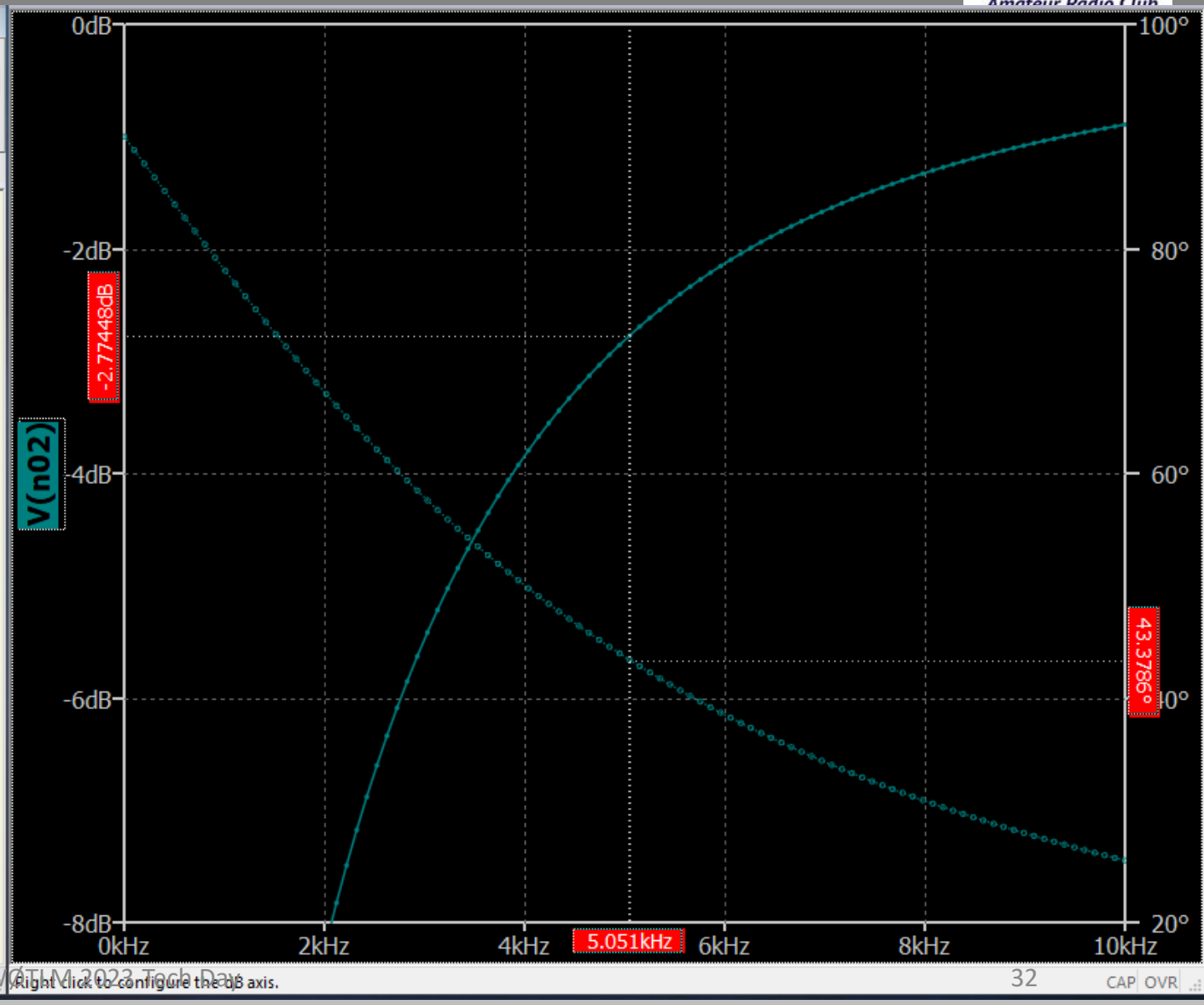


High-pass Filter



High-pass Filter

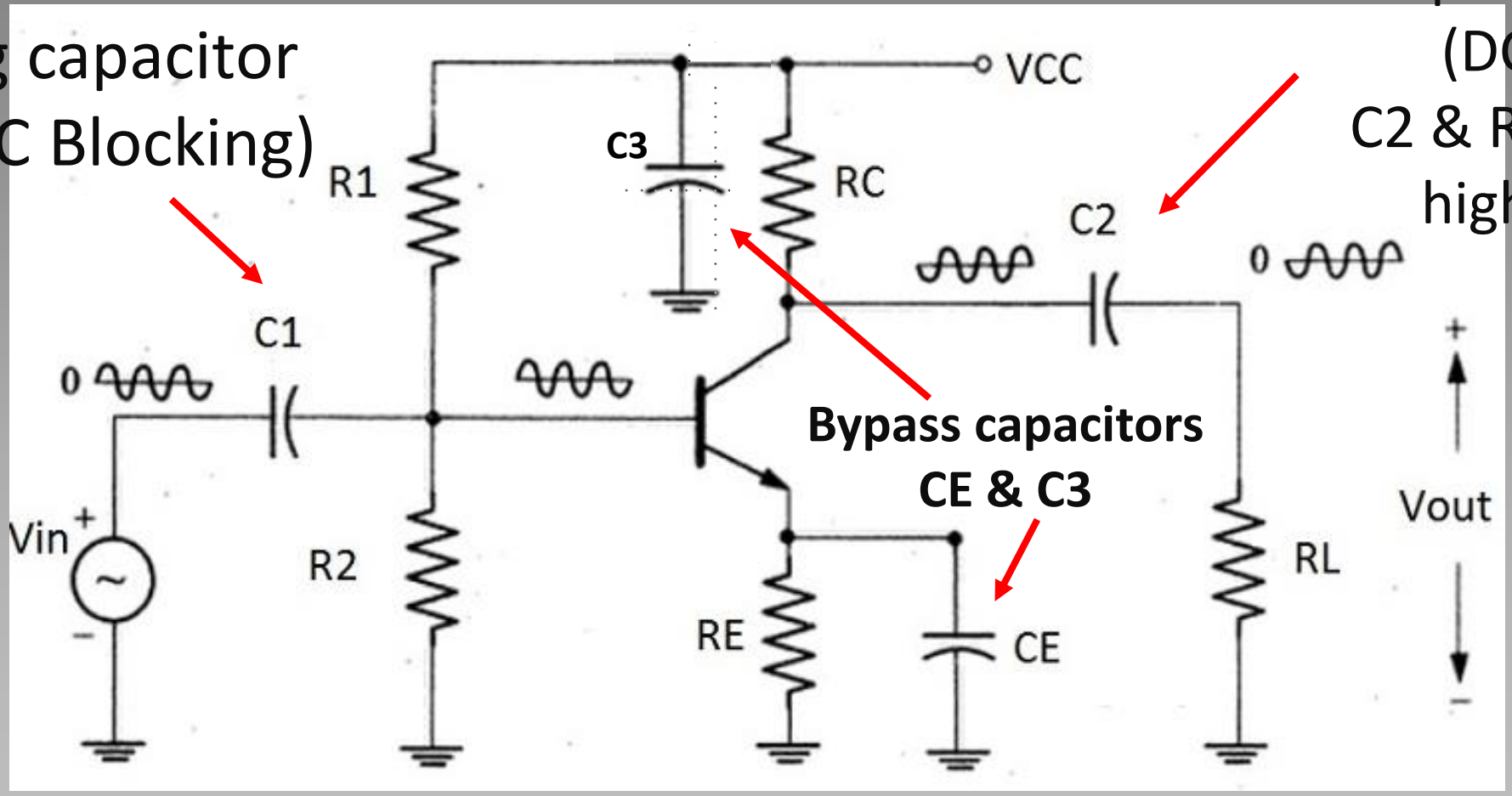




Coupling & Bypass Capacitors

Coupling capacitor
(C1) - (DC Blocking)

Coupling capacitor
(DC Blocking)
C2 & RL also act as a
high-pass filter



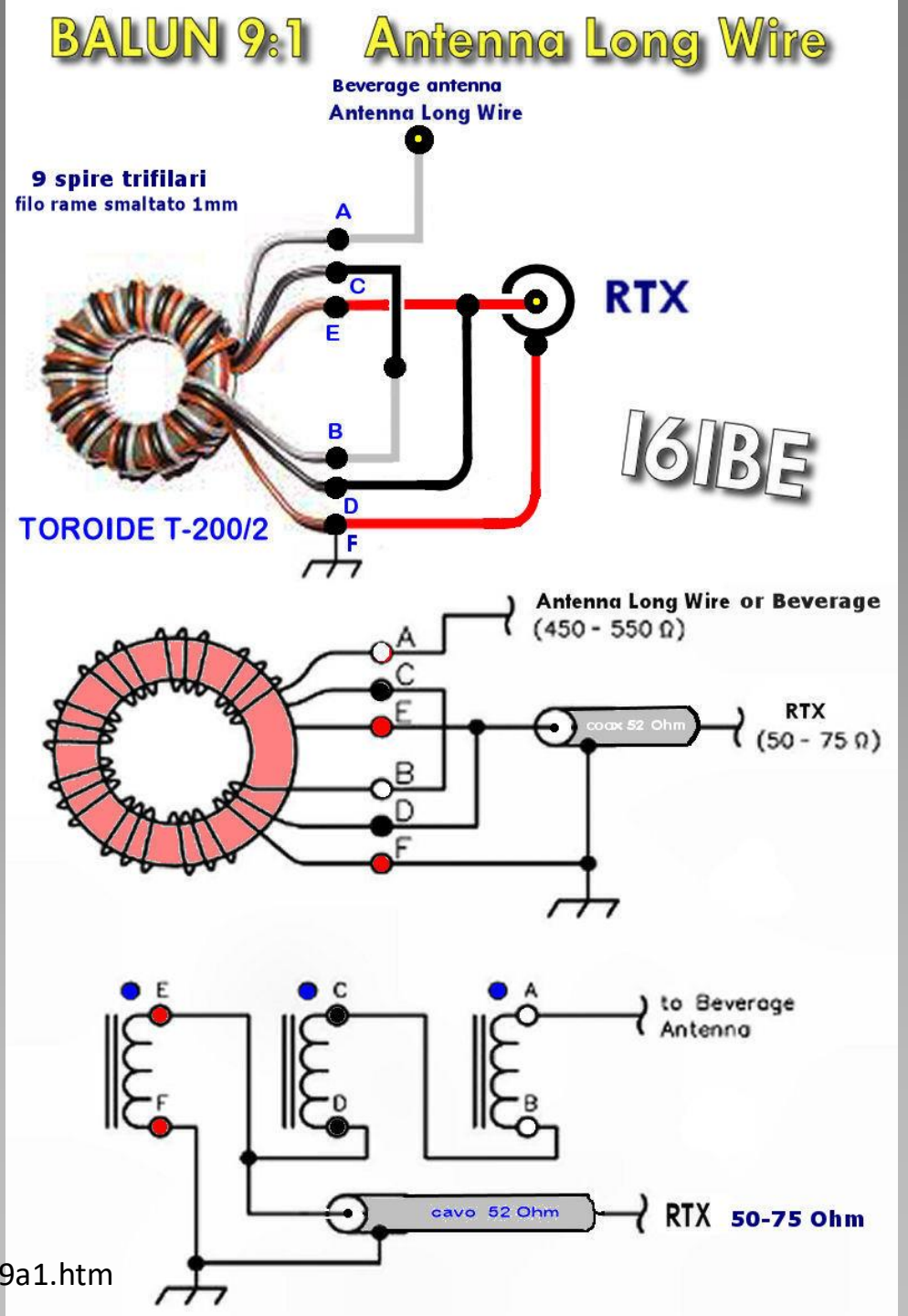
https://www.electronicshub.org/bypass-capacitor-tutorial/

Coupling and Bypass Capacitors

- Bypass Capacitor - A capacitor employed to conduct AC around a component or group of components. Regularly an AC is removed from an AC/DC combination; the DC is free to pass through the bypassed component.
  - Filters AC ripple from a power source
  - Increases the AC gain in a common-emitter amplifier
- Coupling/Blocking Capacitor - A coupling capacitor is a capacitor which is used to couple or link together only the AC signal from one circuit element to another. The capacitor blocks the DC signal from entering the second element and, thus, only passes the AC signal.
  - Allows stages to have different bias voltages

Baluns/Transformers

- These are inductors configured to magnetically couple energy from a primary to secondary winding
- From Primary to Secondary
  - The voltage transformation equals the turns ratio
  - The current transformation equals the inverse of the turns ratio
  - The impedance transformation is equal to the square of the turns ratio
- In Balun (or Unun) with 1:3 turns ratio the impedance transform is 1:9 (or 50Ω:450Ω)
- There is some power lost due to heat in the toroid but most of the power is transferred.



http://www.radioamatoripeligni.it/i6ibe/balun9a1/balun9a1.htm

Capacitors and Inductors in AC circuits

- Analysis becomes more complicated because reactance, unlike resistance, is frequency dependent

$$X_C = -\frac{1}{\omega C} = -\frac{1}{2\pi f C}$$

$$X_L = \omega L = 2\pi f L$$

- In an RC circuit $Z = R - jX_C$
- In an RL circuit $Z = R + jX$