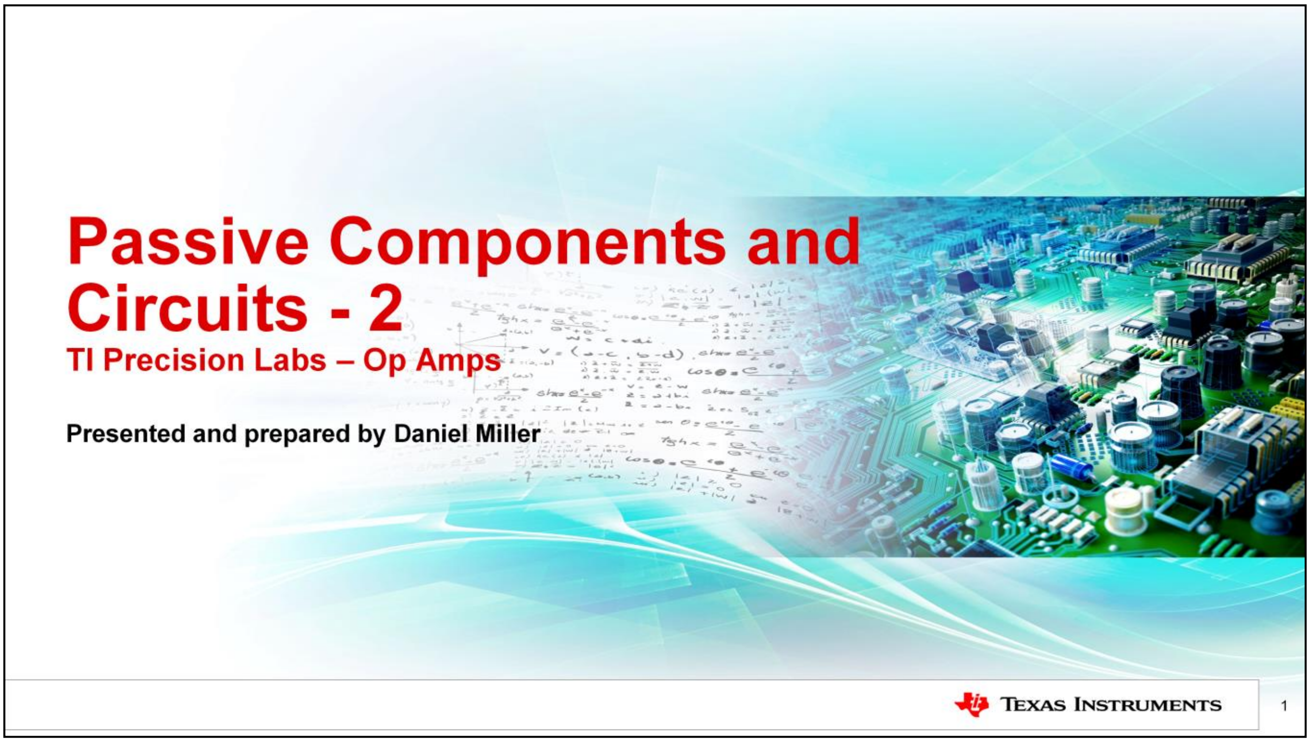
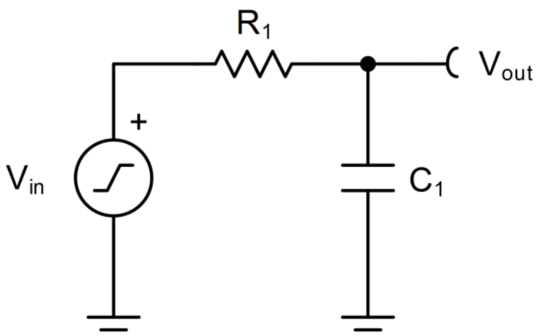


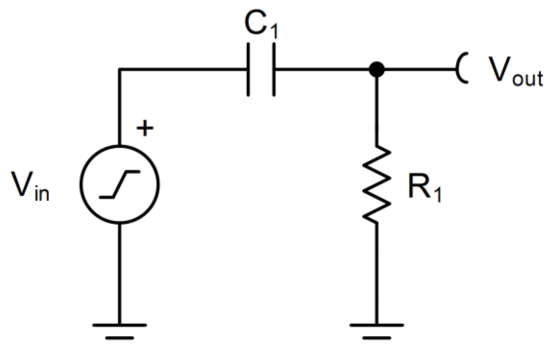
Hello and welcome to the TI precision labs series on passive components and circuits. Today we'll be discussing RC circuits.

RC circuits

Low pass RC filter



High pass RC filter



RC circuits are composed of resistive and capacitive elements. They can be formed in one of the two ways shown here. RC circuits can be both intentionally designed and occur parasitically. Because they are so commonly seen with op amps, understanding their function is important for analog designers. In this presentation, we will observe both the transient and AC response of RC circuits.

RC charging and discharging with DC source

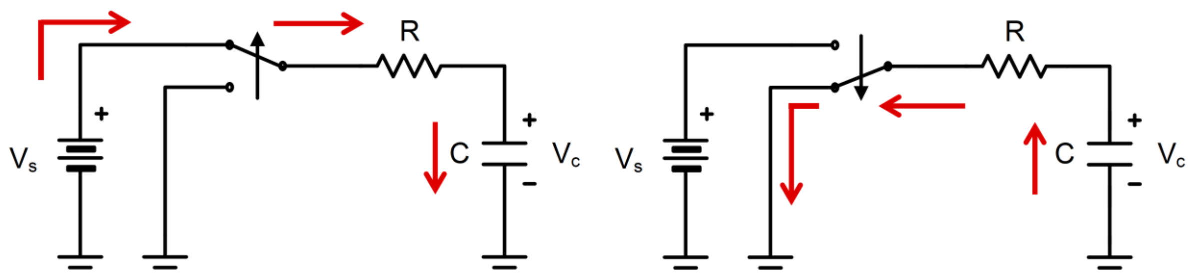
RC charging – Step response

$$V_c(t) = V_s + (V_i - V_s)e^{-t/RC}$$

$$V_c(t) = V_s\left(1 - e^{-t/RC}\right) \text{ if } V_i = 0$$

RC discharging – Natural response

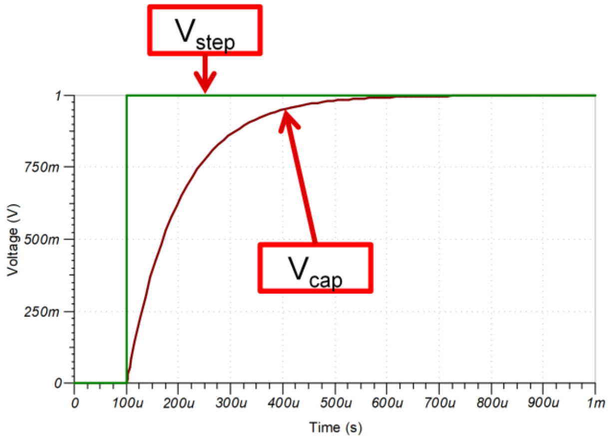
$$V_c(t) = V_i e^{-t/RC}$$

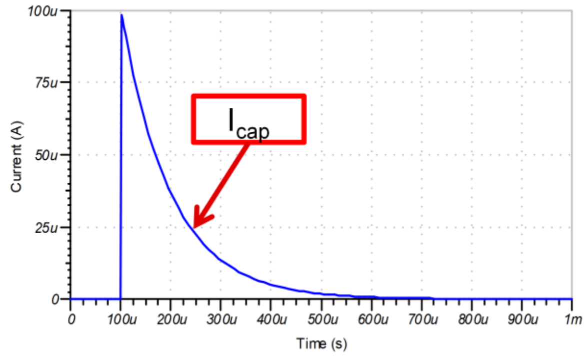


RC Time Constant $\boxed{\tau = RC}$

Recall that a capacitor stores energy in the form of an electric field created by the charge on two metallic plates. When a change in voltage is applied to a capacitor, current flows through the capacitor and the stored charge is changed. The same is true for an RC circuit. When a step voltage is suddenly applied to a discharged RC circuit, current through the circuit causes the capacitor to charge at an exponential rate. This is referred to as the "step response" of an RC circuit. Similarly, when an RC circuit with stored charge is suddenly tied to ground, a current is induced in the capacitor which causes it to discharge. This is referred to as the "natural response" of an RC circuit. For these equations, "V_C" refers to the voltage across the capacitor at a given moment in time; "V_S" refers to the supply voltage; "V_i" refers to the initial voltage across the capacitor; and "t" refers to time. Note that both responses are exponential and depend on the product of the resistance and capacitance. We refer to this important product as the "RC time constant" of the circuit and represent it with the Greek letter "tau."

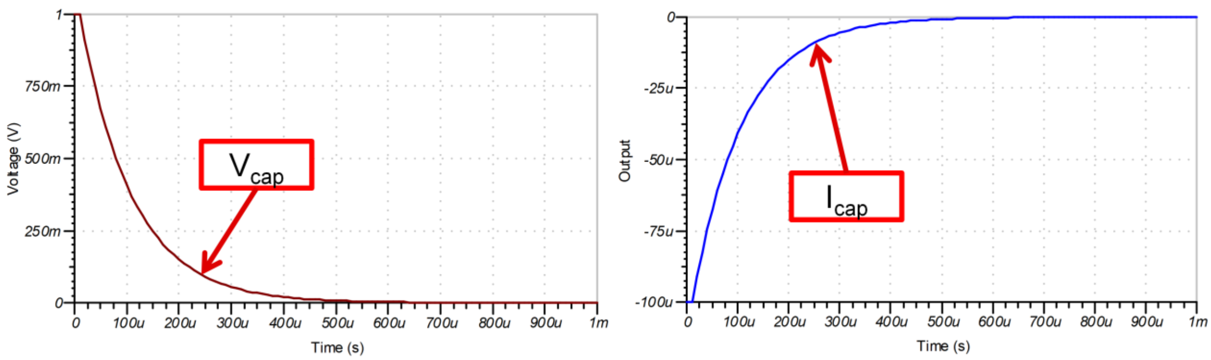
TINA-TI SPICE – RC charging, step response





To gain a better understanding of these equations, consider these plots for a charging RC circuit. These plots were obtained through a TINA-TI transient analysis. Note that, at time 100µs, a sudden step voltage is applied. This causes the voltage across the capacitor to rise exponentially from its initial voltage of 0V and asymptotically approach the final voltage of 1V, as predicted by the step response equation. The current through the capacitor at any given point in time is proportional to the derivative of the voltage across the capacitor.

TINA-TI SPICE – RC discharging, natural response



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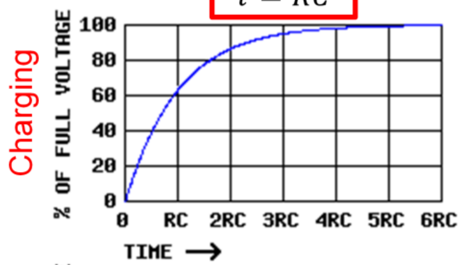
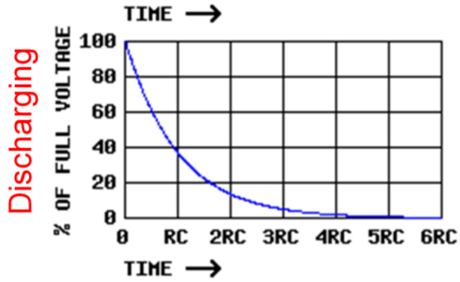
A similar SPICE analysis can be run for a discharging RC circuit. Here, an initial voltage of 1V is applied to the capacitor. Then at time 0, the RC circuit is suddenly switched to ground. The voltage across the capacitor decays exponentially, as expected, and the current through the capacitor corresponds to the change in voltage. Note that, in this case, the sign of the current direction is flipped because the current is set to flow in the opposite direction.

RC time constants

$$\tau = RC$$



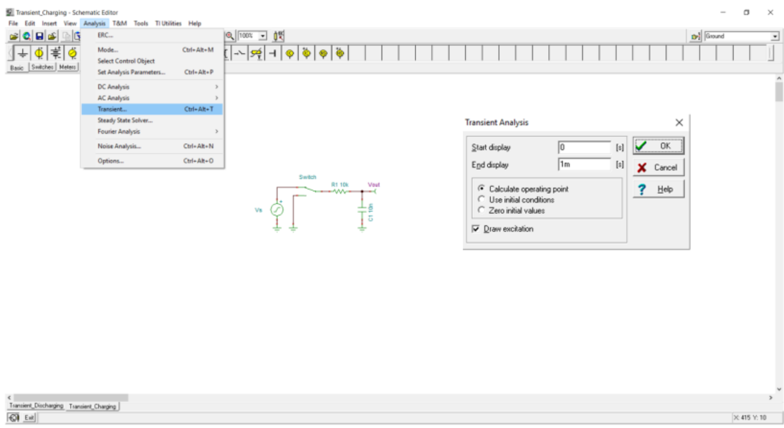


# of time constants	Charging % of final value	Discharging % of initial value
1	63.212%	36.788%
2	86.466%	13.534%
3	95.021%	4.979%
4	98.168%	1.832%
5	99.326%	0.674%
6	99.752%	0.248%
7	99.909%	0.091%
8	99.966%	0.034%
9	99.988%	0.012%
10	99.995%	0.005%

Regardless of the values of the resistor and capacitor in an RC circuit, the response will have the same exponential form. However, the resistor and the capacitor will determine the time it takes the capacitor to approach its final voltage level. This time is often measured in “RC time constants,” which are represented by the letter “tau.” For example, a charging RC circuit will take one RC time constant to reach 63% of its final charge value, 3 time constants to reach 95% of its final charge value, and 5 time constants to reach 99% of its final charge value. Time constants can similarly be used to determine the time an RC circuit will take to discharge. Let’s now look at some examples of this in TINA-TI.

Transient simulation setup – charging

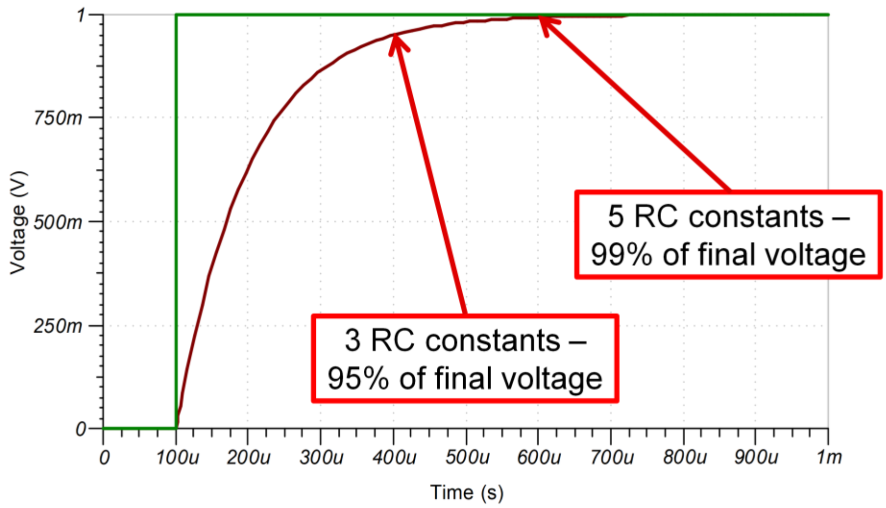
Click **Analysis** → **Transient** to show the RC response of this circuit. Run the analysis from 0ms to 1ms. The input is a 1Vpk step function.



Transient_Charging.TSC

Let’s first simulate a charging circuit. The TINA circuit is embedded in this presentation for your convenience. First, open the TINA circuit. Note, that the supply voltage is set to emulate a step function with an amplitude of 1V and a 100μs delay. Next, click “Analysis” and “Transient” to set up the simulation. We will run the sim for 1ms. Press “OK” to run the sim.

TINA-TI SPICE – charging transient analysis



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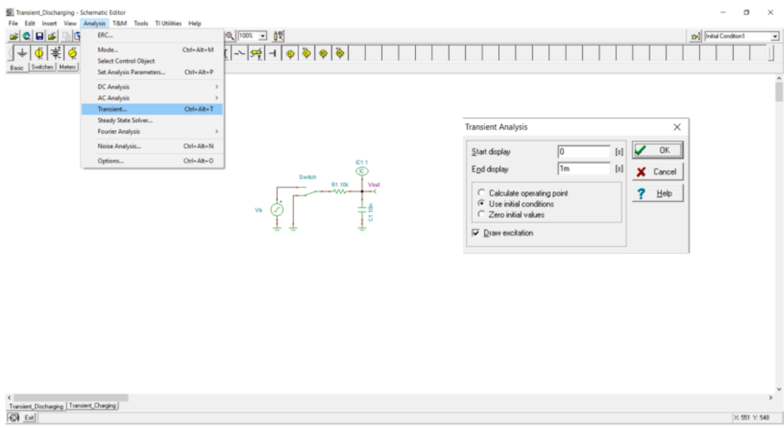
We can now see the transient response of this circuit for a 1V step function. For this simulation, we used a resistor of 10kΩ and a capacitor of 10nF. Multiplying these two together, we get a time constant of 100µs. From before, we know that a charging RC circuit should reach 95% of its final output voltage after 3 time constants. To find this point, we take the beginning of the step function at time 100µs and add 300µs. So we expect to see 95% of our final output level at 400µs and, similarly, 99% of the final output at 600µs. Considering that our initial voltage was 0V and our final voltage is 1V, we expect to see 950mV across the capacitor and 990mV across the capacitor at these points in time. This can be verified with a cursor in TINA-TI.

Transient simulation setup – discharging

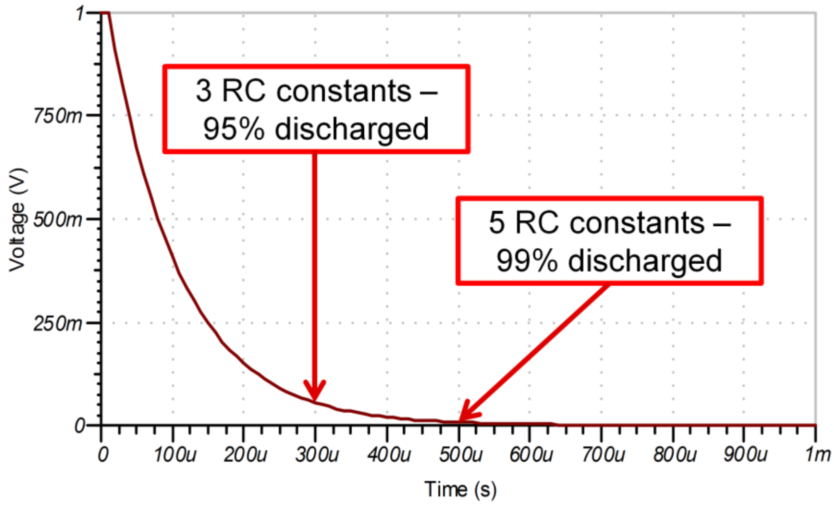
Click **Analysis** → **Transient** to show the RC response of this circuit. Run the analysis from 0ms to 1ms. There is an initial condition of 1V on the capacitor.



Transient_Discharging.TSC

The transient response of a discharging RC circuit can be found in the same manner. This time, the voltage supply is disconnected and an initial condition of 1V is placed across the capacitor. The circuit is now tied to ground. The TINA file for the circuit used is embedded on this slide.

TINA-TI SPICE – discharging transient analysis

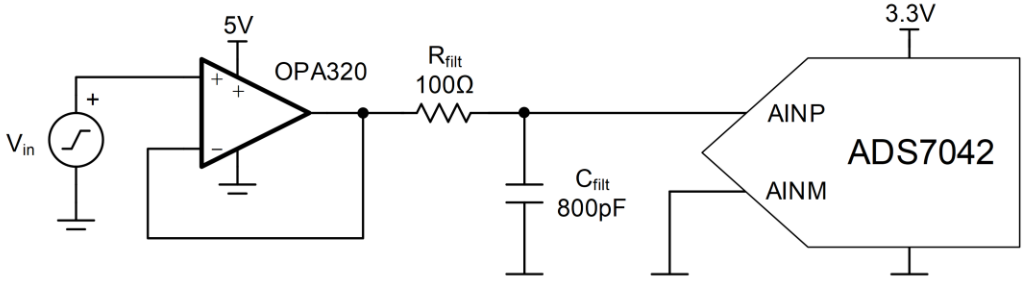


The natural response of the simulated RC circuit shows an exponential decay asymptotically approaching zero, as expected. After 3 time constants, or 300µs, 95% of the original charge is lost and the voltage level has fallen to 5% of the initial voltage level. In this case, that would be 50mV. Similarly, allowing 5 time constants, or 500µs, to pass will leave only 1% of the original voltage across the capacitor.

Charging input capacitor of an ADC

- RC filter often placed before SAR ADC
- Also known as a “charge bucket”
- Helps ADC capture input signal quickly

Number of bits	½ LSB	Time Constants
10	0.0488281%	8
12	0.0122070%	9
14	0.0030518%	11
16	0.0007629%	12
18	0.0001907%	14
20	0.0000477%	15
22	0.0000119%	17
24	0.0000030%	18



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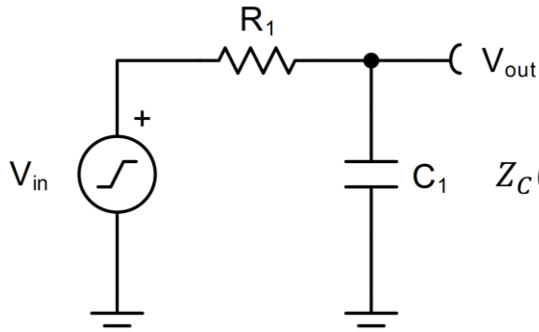
To conclude our discussion on the transient response of an RC circuit, we provide a real-world example. In general, RC filters are placed at the output of op amps and before certain types of ADCs, notably “SAR” ADCs. The RC circuit acts as a “charge bucket,” storing charge in an electrical field to provide current to the ADC during the acquisition phase. This is critical to ensuring an accurate and fast conversion of an analog signal to a digital signal and more accurate ADCs will require more time constants for the capacitor to settle. This topic is covered in much more detail in the TI Precision Labs series on ADCs.

RC filter in frequency domain

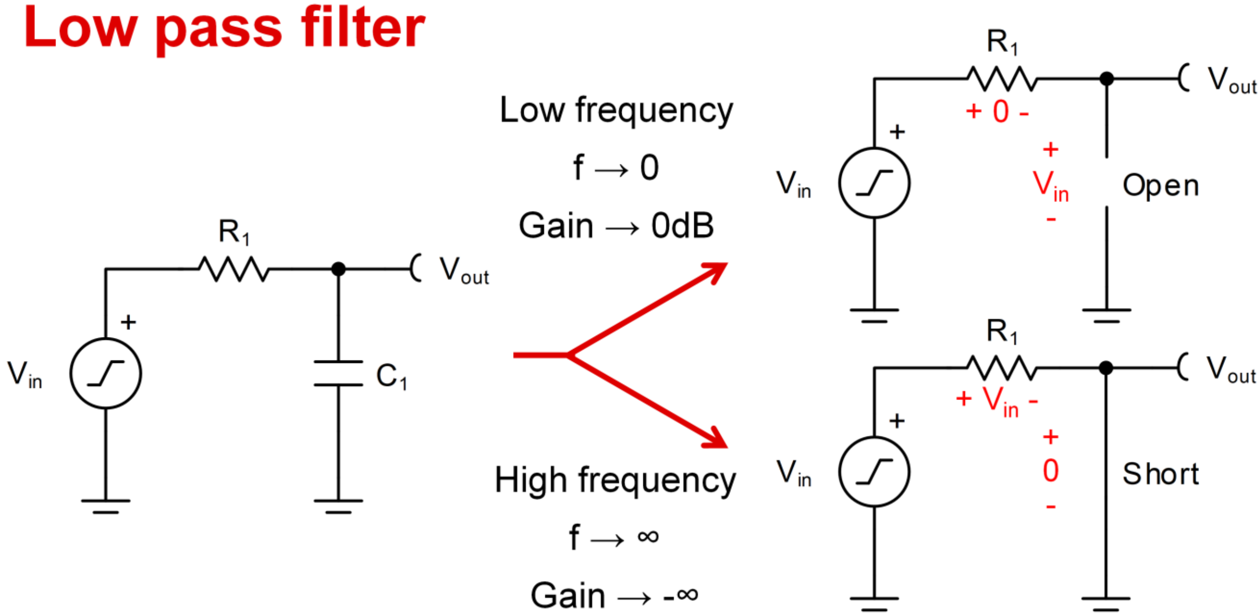
$$Z_R(j\omega) = R_1$$



$$Z_C(j\omega) = \frac{1}{j\omega C_1}$$

Having covered the time domain, let's move on to the frequency domain. Recall that a resistor has an impedance that is independent of frequency while a capacitor has an impedance that is inversely proportional to frequency. Analog engineers make use of these properties to design frequency filters with RC circuits.

Low pass filter



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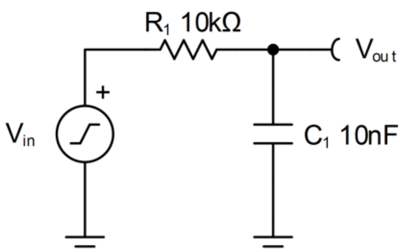
Let's begin by discussing the low pass filter. A low pass RC filter is created by placing a resistor followed by a capacitor down to ground. The output is taken between the two components. An intuitive understanding of this circuit's AC behavior can be obtained by considering the behavior of the capacitor at low and high frequencies. From the previous presentation on passive components, we know that at very low frequencies approaching DC, a capacitor will act as an open. If this is done for the low pass filter, the low frequency signal will effectively see an open circuit, current will stop flowing, and the input voltage will appear at the output. Thus, the gain will be of 0dB. On the other hand, a capacitor will act as a short circuit at very high frequencies. In the case of the low pass filter, this will effectively short the output to ground. Thus, the gain will approach negative infinity on a decibel scale.

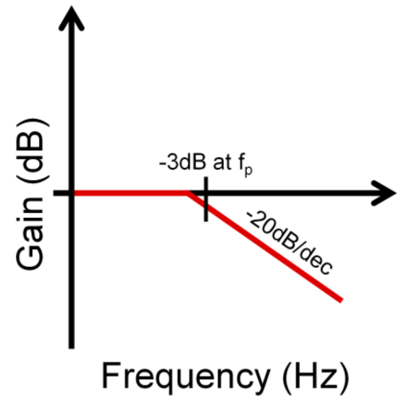
Low pass filter AC response example

$$f_p = \frac{1}{2\pi R_1 C_1}$$

$$f_p = \frac{1}{2\pi(10k\Omega * 10nF)}$$

$$f_p \approx 1.59kHz$$

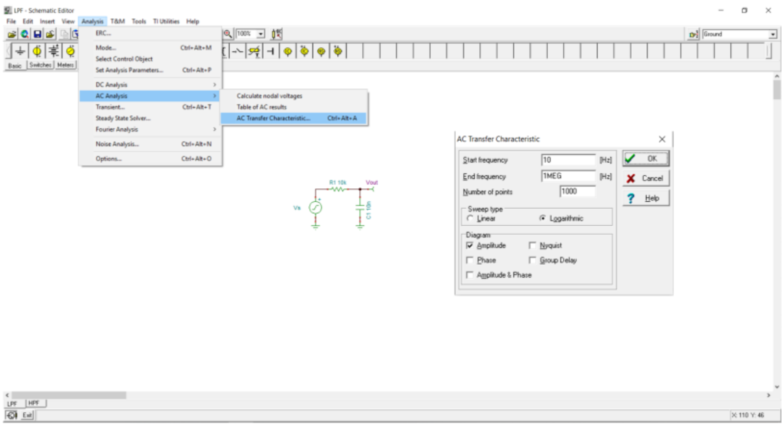




The behavior of the low pass filter can be understood using the equation of its pole. At low frequencies where the capacitor acts as an open circuit, the filter has a gain of 0dB. But at higher frequencies, the capacitor has a lesser and lesser impedance causing the gain to drop by 20dB per decade. The key transition point between these two regions is referred to as the “pole.” At the pole frequency, the gain of the circuit reaches -3dB and begins to fall rapidly. Being able to determine this frequency is key to a successful filter design. For this RC circuit, the pole can be found using the equation “f_p equals 1 over 2 pi RC,” where f_p is the pole frequency in hertz. For a low pass filter of 10kΩ and 10nF, we expect to see a pole frequency of 1.59kHz. Poles and their plots are covered in much more detail in the TI Precision Labs series on op amps.

AC analysis simulation setup – LPF

Click **Analysis** → **AC Analysis** → **AC Transfer Characteristic** to see the AC response of the HPF. Run the analysis from 10Hz to 1MHz.




LPF.TSC

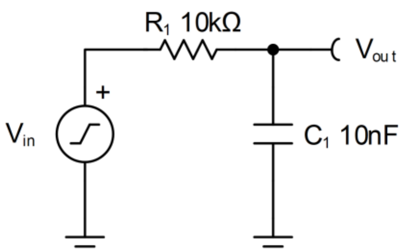
Let's now validate our analysis by running a TINA-TI simulation! The TINA file used is embedded in this presentation for your convenience. After opening the file, we can now run an AC sim. This can be done clicking "Analysis," then "AC Analysis," and finally "AC Transfer Characteristic." The simulation settings box will then pop up. We will sweep our input signal from 10Hz to 1Mhz. When you're ready, hit "OK" to run the sim.

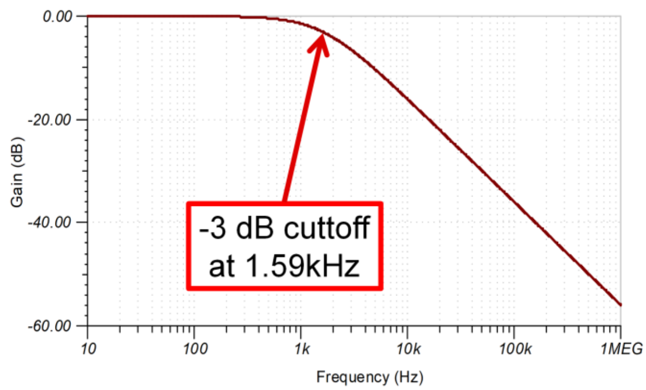
TINA-TI SPICE – AC analysis for LPF

$$f_p = \frac{1}{2\pi R_1 C_1}$$

$$f_p = \frac{1}{2\pi(10k\Omega * 10nF)}$$

$$f_p \approx 1.59kHz$$





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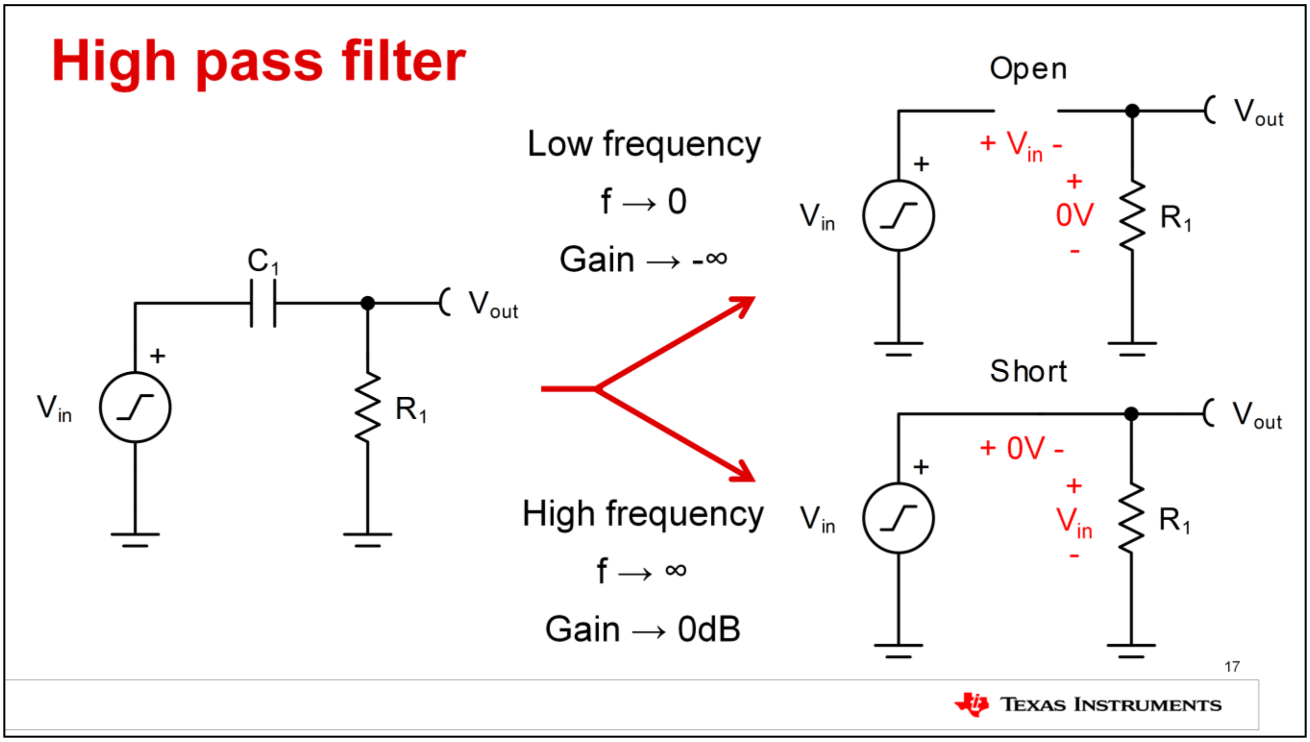
On the right we can see our simulation results. Indeed, the overall response of the circuit matches our expectations. There is a low frequency segment of 0dB of gain followed by a pole frequency and a region of -20dB/decade of gain. True to its name, the low pass filter passes signals of lower frequency and attenuates those at higher frequency. Using TINA's cursor function, we can place a cursor on the -3dB point to double check our calculation and indeed find that our pole comes in at 1.59kHz.



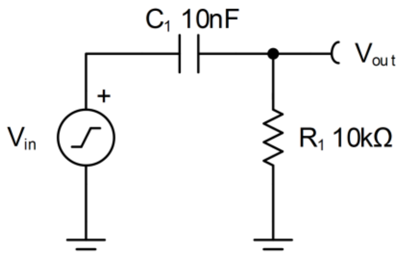
The complement of the low pass filter is the high pass filter. This can be created by simply flipping the position of the capacitor and resistor. Given that they look so similar, it can be hard to remember which is a low pass filter and which is a high pass filter. To aid your memory, simply look at the location of the capacitor. If the capacitor comes first in the signal path, it's a high pass filter. If it comes second, then it's a low pass filter. The high pass filter has the opposite behavior of the low pass filter. At low frequencies, the capacitor acts as an open such that the output is disconnected from the input and pulled down to ground. The gain approaches negative infinity on the decibel scale. At high frequencies, the capacitor acts as a short circuit and shorts the input to the output. In this scenario, the gain approaches 0dB.

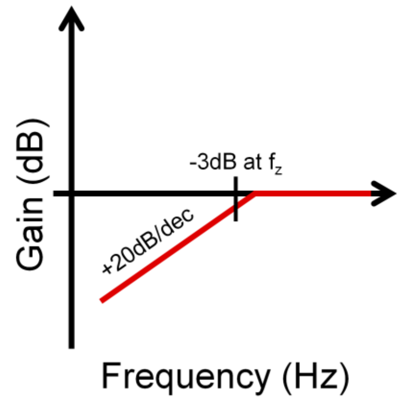
High pass filter AC response example

$$f_z = \frac{1}{2\pi R_1 C_1}$$

$$f_z = \frac{1}{2\pi(10k\Omega * 10nF)}$$

$$f_z \approx 1.59kHz$$

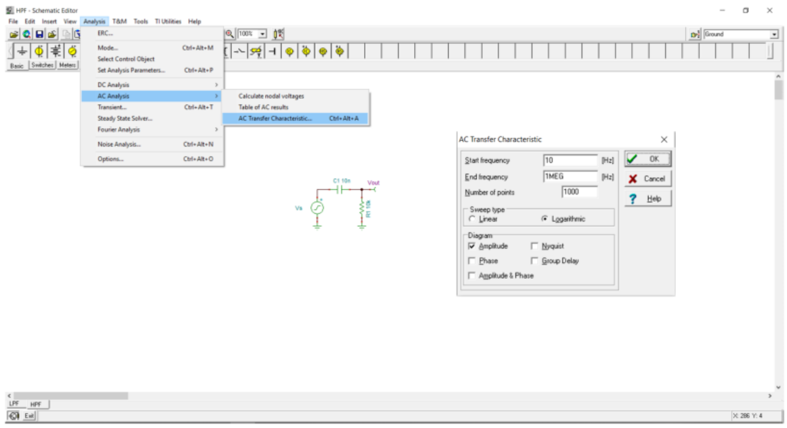




Just as a low pass filter has a critical frequency called a “pole,” the high pass filter has a critical point called a “zero.” Prior to this frequency, the circuit attenuates the input. As the zero frequency is approached, the attenuation is lessened by 20dB/dec. The zero frequency has a gain of -3dB and the frequencies above this point show a gain of about 0dB. Note that the zero frequency equation is the same as the pole frequency equation. However, we now use “f_z” to denote the zero frequency. For this high pass filter, we use the same component values as before. However, we now expect to see a zero at 1.59kHz rather than a pole. Zeroes and their plots are covered in much more detail in the TI Precision Labs series on op amps.

AC analysis simulation setup – HPF

Click **Analysis** → **AC Analysis** → **AC Transfer Characteristic** to see the AC response of the HPF. Run the analysis from 10Hz to 1MHz.



HPF.TSC

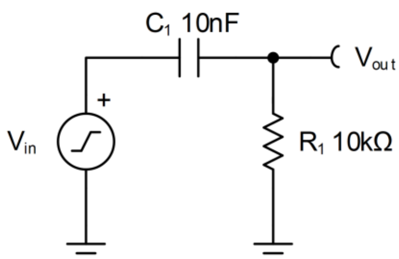
Let’s again validate our analysis by running a TINA-TI simulation! Download the embedded TINA file and open it. Run an AC sim as before by clicking “Analysis,” then “AC Analysis,” and “AC Transfer Characteristic.” The simulation settings box will pop up. Sweep the input signal from 10Hz to 1Mhz and hit “OK” to run the sim.

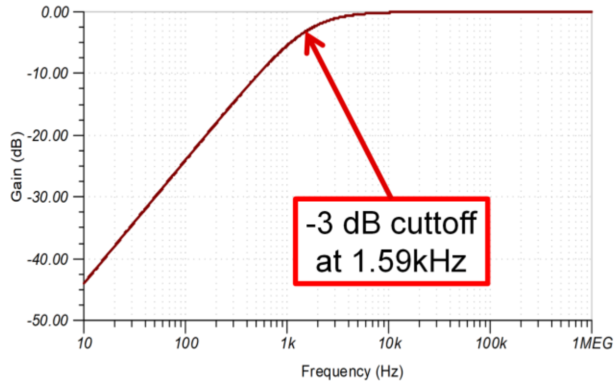
TINA-TI SPICE – AC analysis for HPF

$$f_z = \frac{1}{2\pi R_1 C_1}$$

$$f_z = \frac{1}{2\pi(10k\Omega * 10nF)}$$

$$f_z \approx 1.59kHz$$





Again, the overall response of the circuit matches our expectation. The high pass filter attenuates signals at low frequencies and allows the higher frequency signals to pass. Using TINA's cursor function, we can place a cursor on the -3dB point to double check our calculation and indeed find that our zero comes in at 1.59kHz.

Thanks for your time!
Please try the quiz.

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That concludes this lesson! Thanks for your time and please try the quiz.

Questions: Passive components and circuits - 2

1. The natural response of an RC circuit involves a _______ capacitor and is described by the equation: ________.
   a) Charging, $V_c = V_i e^{-t/RC}$
   b) Discharging, $V_c = V_i e^{-t/RC}$
   c) Charging, $V_c = V_s\left(1 - e^{-t/RC}\right)$ if $V_i = 0$
   d) Discharging, $V_c = V_s\left(1 - e^{-t/RC}\right)$ if $V_i = 0$

Question 1. Fill in the blank. The natural response of an RC circuit involves a ______ capacitor and is described by the equation: _________. The correct answer is “B.” The “natural response” of an RC circuit refers to its ability to discharge and is described by the equation “$V_C = V_i$ times ‘e’ to the –t/RC.”

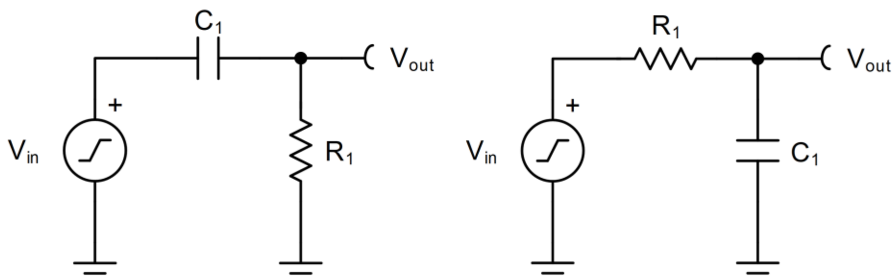
Questions: Passive components and circuits - 2

2. Assume a capacitor in an RC charge bucket has no charge stored and begins at zero volts across its nodes. Suddenly, a step voltage is applied. How many time constants will it take to reach 95% and 99% of its final voltage level, respectively?
   a) 1 and 2
   b) 1 and 3
   c) 2 and 3
   d) 3 and 5

Question 2. Assume a capacitor in an RC charge bucket has no charge stored and begins at zero volts across its nodes. Suddenly, a step voltage is applied. How many time constants will it take to reach 95% and 99% of its final voltage level, respectively? The correct answer is “D.” It will take 3 and 5 constants for the capacitor to reach 95% and 99% of its final voltage level, respectively.

Questions: Passive components and circuits - 2

3. True or False: The circuit on the left is a high pass, RC filter and the circuit on the right is a low pass, RC filter.
   a) True
   b) False



Question 3. True or False: The circuit on the left is a high pass, RC filter and the circuit on the right is a low pass, RC filter. The correct answer is true. Remember that for a high pass filter the current first passes through the capacitor and then the resistor while the opposite is true for the low pass filter.

Thanks for your time!

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That's all for now! Thanks again for your time.

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