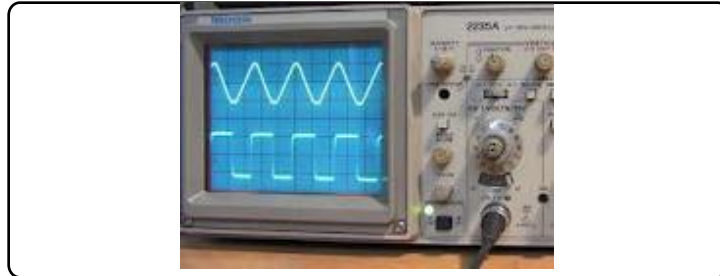


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UNIT 27: THE OSCILLOSCOPE AND AC CIRCUITS



First there was a generation of huge machines that relied on vacuum tubes; then there was one that used transistors; a third relied on the integrated circuits printed on silicon chips; and a fourth -- a generation only now emerging -- turns to very large scale integrated circuits (VLSI), with chips so compact they must be designed by another computer. The achievement of artificial intelligence would be the crowning effort, the fifth generation.

Richard Flaste

OBJECTIVES

1. To learn how to use a digital oscilloscope.
2. To investigate different AC (alternating current) wave forms using an oscilloscope. ¹

¹ The Reddy Kilowatt images taken from Wikipedia: http://en.wikipedia.org/wiki/Reddy_Kilowatt

OVERVIEW

This unit is intended to provide you with a brief introduction to alternating current (AC) circuits. In the first part of this unit you will learn to use an oscilloscope, which is one of the most basic measuring devices used in electronics to measure voltages that vary with time. In the second part of this unit you will explore AC circuits in detail. In particular we will observe Lissajous figures; use an oscilloscope to measure voltages and time intervals for alternating voltages; compare oscilloscope measurements with those from a digital multimeter (DMM), and use the dual channel feature to compare waveforms in a circuit with both resistance and capacitance.

An electrical voltage is much like water pressure: the more water pressure the greater the amount of water that flows through a pipe per second. Similarly, the greater the voltage, the more electrons flow through a resistor per second. So voltage is a kind of electrical pressure that forces electrons to flow.

You will be familiar with batteries as a source of voltage. Batteries supply a steady DC (direct current) voltage that remains relatively constant in time. B.C. Hydro generates and supplies us with a voltage that varies with time and is called AC (for alternating current). Hence, many of the voltages and currents we encounter in everyday life are alternating or varying. For example, the voltage used in our homes alternates 60 times every second. Thus, if the two live terminals (the third terminal is grounded) of a typical house outlet were connected across a load, one terminal would be positive relative to the other for a short time, in this case $1/120$ of a second, and then the situation reverses. The output voltage undergoes 1 complete cycle in $1/60$ sec and we say that the frequency is 60 cycles/sec or 60 Hz. A graph of the voltage of one terminal relative to the other is shown in Figure 27.1.

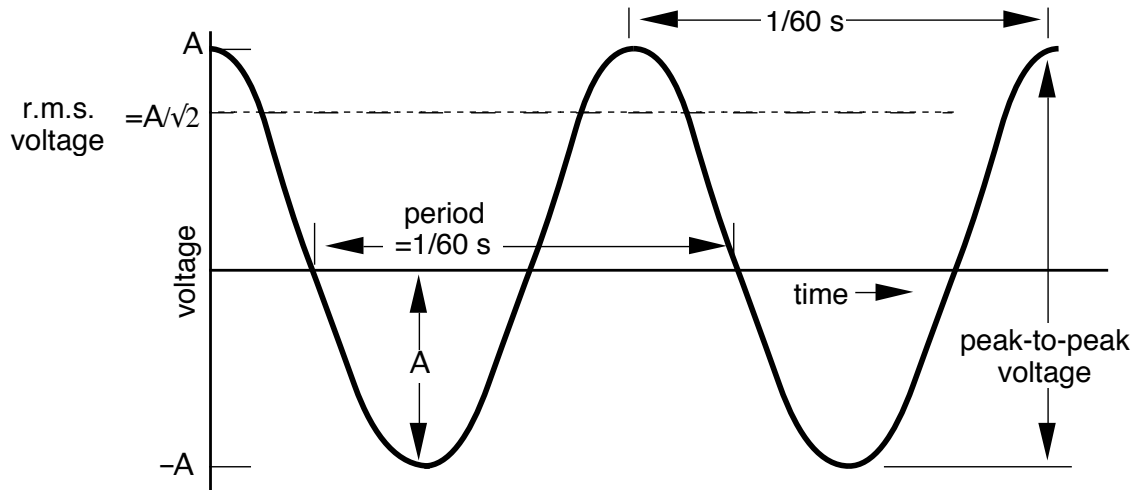


Fig 27-1: AC voltage

The amplitude A is half the peak-to-peak value of the voltage. The effective value of an alternating voltage is equal to the steady direct voltage that would produce the same heating in a resistor as does the alternating voltage. The effective value is also called the rms (root mean square) voltage, and it can be shown to equal $A/\sqrt{2}$ for a sinusoidal voltage. The digital multimeter has an AC function that reads the voltage $A/\sqrt{2}$, root mean square (rms) voltage that is indicated by the dashed line on Figure 27.1. An oscilloscope can also be used to measure AC and in this unit we will compare the relative capabilities of a multimeter and an oscilloscope. Before doing this, however, the oscilloscope will be discussed in some detail.

SESSION ONE: THE OSCILLOSCOPE

Using an Oscilloscope

Many scientists and engineers are interested in measuring voltages and visualizing how they change over time. Although these kinds of voltage measurements can also be made using newly developed computer systems, the oscilloscope is used by most physicists for making such measurements.

A *digital storage oscilloscope* (DSO), which is the type we will be using in this class, converts the measured voltage into numerical values with an analog-to-digital converter. The conversion is repeated at a uniform rate and the consecutive values are stored in memory while a microprocessor graphs the values on a display.

The face of an oscilloscope is shown in the figure below.

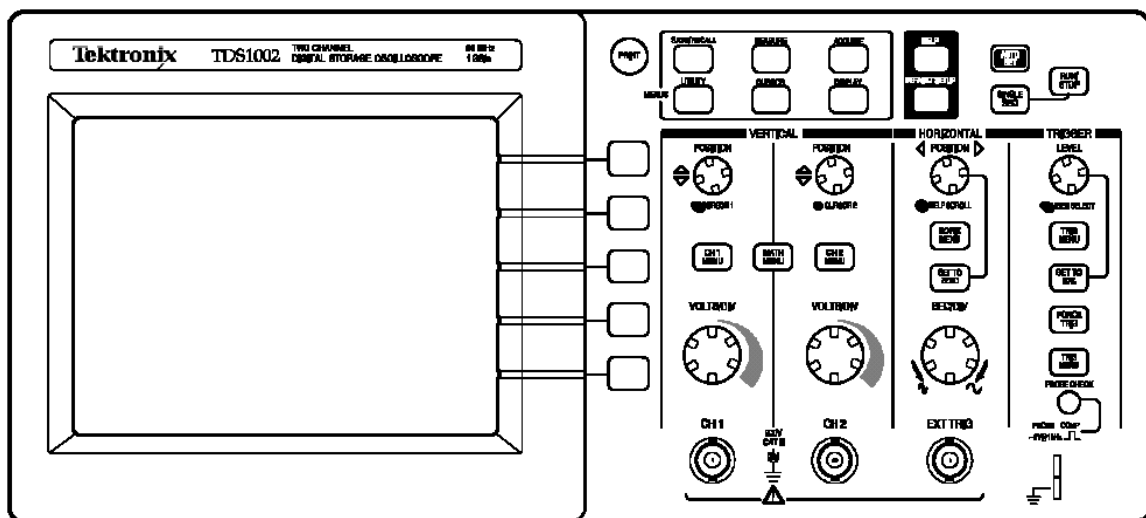


Figure 27-2: An Oscilloscope Face

The oscilloscope (and most electronic equipment) is supplied with a 3-pin ac plug for safety. The chassis (i.e., the part you can touch) is always grounded to the round ground pin of the ac plug which goes to earth ground. The shields of both channel 1 (CH1) and channel 2 (CH2) inputs are both grounded to the oscilloscope's chassis and earth ground as well. Thus the grounds of both channels are electrically connected together and you must be careful to ground both channels at the same point in your circuits, otherwise you will short out circuit elements. The grounds of any other instruments must also be connected to the same ground point unless you know that the instrument

has a "floating ground", i.e., a negative terminal not connected to the instrument's chassis and to earth ground.

Using a Digital Storage Oscilloscope

The many controls on the oscilloscope can be grouped into three types:

- The vertical system

The vertical system controls the attenuation or amplification of the signal. Use the volts/div knobs to adjust the amplitude of the signal to the desired measurement range.

- The timebase, or horizontal system

Use the sec/div control to set the amount of time per division represented horizontally across the screen. The time base control knob is marked in units of time/div, e.g. 5 $\mu\text{s}/\text{div}$. This means that each horizontal division on the screen represents 5 μs .

- The triggering system

The trigger level stabilizes a repeating signal. The signal being measured is repeatedly displayed on the screen in real time. If different parts of the signal are displayed each time the picture is refreshed then it will be jittery and appear unstable. Looking at such a jittery and unstable image could cause annoyance and even psychological harm! A stable clear picture can be produced by establishing a trigger voltage and slope. The the trigger setting ensures that signal is always displayed so that the same voltage is shown at the same place on the screen each time. Not only that! The voltage can be either rising or falling. The trigger slope ensures that not only the voltage level is displayed at that point, but that the slope is always going in the same direction, either up or down, at that point. If the same voltage level and the same slope are always positioned at the same point on the screen then the repetitive displays seem to form a stable image. This method of stabilization is called triggering. The trigger circuit can also be used to start the digitization of a single event when the input reaches a predetermined voltage level and slope.

- Measuring

Suppose an alternating square wave voltage is applied to the input of the oscilloscope so that it produces a pattern on the screen like that on Fig. 27-3. The peak-to-peak value of the applied voltage may be obtained by measuring the vertical height of the pattern seen on the screen and multiplying this number of screen divisions by the setting on the volts/div control.

Period (or time for one cycle) can be determined by multiplying the horizontal length on the screen (6.0 divisions in Fig. 27-3) by the time/div setting.

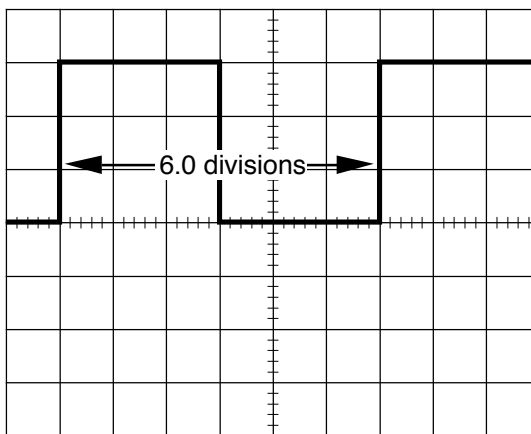


Figure 27-3: Measuring the period on the oscilloscope screen.

Suppose the latter was set at 2 ms/division. Then the period for this (Fig. 27-3) waveform would be

$$T = (6.0 \text{ div}) (2.0 \text{ ms/div}) = 12 \text{ milliseconds}$$

$$\text{frequency } f = 83 \text{ cycles/s} = 83 \text{ Hz} .$$

Thus an oscilloscope allows us to visualize a rapidly varying electrical signal, and also to measure its amplitude and frequency.

C. Probes

Oscilloscope probes are recommended for many measurements because they provide several useful features:

1. They have a little clip that can be hooked on to bare wires in a circuit. The clip can be slipped off to expose a pointed tip that can probe small electrical contacts.


2. There is another clip for attaching to a ground point in the circuit being measured.

3. Most probes are “times-ten” (10X) probes and increase the input impedance of the oscilloscope by a factor of 10. This increase of the input impedance means that the act of making a measurement has less effect on the circuit’s operation. If the scope has a $1\text{ M}\Omega$ input impedance, using a 10X probe would increase that to $10\text{ M}\Omega$. If you were measuring the voltage across a $1\text{ M}\Omega$ resistor, connecting the scope without a 10X probe would decrease the voltage to half its value. Using a 10X probe would only decrease its value by one-tenth. There is also a compensation adjustment that can eliminate the effect of the small input capacitance of the oscilloscope (i.e., the imaginary part of its input impedance) which can cause the shape of the input signal to be distorted.

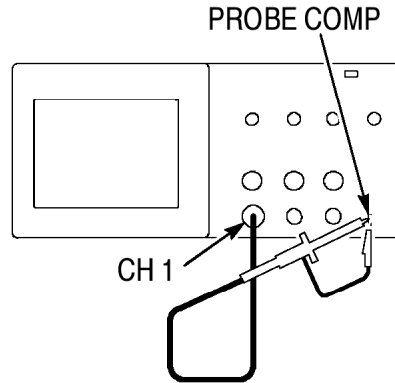
The 10X probe provides the oscilloscope input with only 1/10 of the voltage it is measuring. One must compensate when reading the value. There is a setting under the “vertical menu” which will automatically adjust for the use of a probe. On startup it assumes that measurements are made with a 10X probe and multiplies measurements by 10 and the vertical V/div value by 1/10 before displaying them.

To begin with we will examine the oscilloscope probe calibration signal. You will need the following equipment:

- A digital oscilloscope
- a 10X probe

 Activity 27-1: Measuring the internal calibration signal (PROBE COMP) and using the Vertical Menu


(a) Attach a probe to the CH1 input and connect it to the calibration signal which is labelled “PROBE COMP”. The ground clip should be clipped to the bottom tab of the signal output and the probe hook should be hooked on the top part.



- (b) Slide the 1X/10X switch on the probe to 10X.
 (c) Press the Autoset button. The scope attempts to find the best settings to display the signal

You should now see a “square wave” signal on the screen:



If the signal looks like this 

or like this 

then the compensation of the probe needs adjusting. The adjustment requires a special little screwdriver so ask an instructor or a technician to do it.

- (d) Find the following information on the screen display and record it below:

Vertical V/div scale:

Horizontal sec/div scale:

Number of vertical divisions between bottom and top of signal:

Number of horizontal divisions in one complete period:

- (e) From these values you can calculate the peak-to-peak amplitude and frequency of the signal. Show your calculations in the space below.

(f) The readout also displays direct measurements of these values, thus obviating the need to actually think about what you're doing. Find these values on the readout:

Peak-to-peak amplitude of the signal:

Frequency of the signal:

Compare with the values you got by calculating in (e). Do they agree?

(f) A little 1 on the left-hand side of the screen shows the zero voltage level for channel 1. A little arrow on the right-hand side shows the trigger voltage and a downward pointing arrow on the top shows the trigger point. Try to find these features. Record the trigger voltage value below and trigger point location below.

(g) Turn the Volts/div knob for CH1 a few click clockwise and counterclockwise. What display changes do these adjustments cause?

Try adjusting the position knobs too. Notice that the little "1" on the left-hand side of the screen moves as you change the position knob for CH1.

(h) Similarly, turn the sec/div scale clockwise and counterclockwise. What happens to the signal's display?

(i) Press the CH1 MENU button. The Vertical Menu is displayed beside the signal display. From top to bottom the following options can be adjusted by pressing the button beside them:

Input Coupling: DC/AC/GND. Change to AC and observe the change. What happened?

The signal should now be centred about the zero-volt level. On AC a high-pass filter takes out the DC component and reduces the low frequency components of the signal. On GND the signal is zero. Normally one uses DC coupling unless it's necessary to suppress a large DC offset in the signal.

BW Limit: 20MHz/Off. Set this to 20 MHz to reduce noise on the signal display. The calibration signal has no noise so it won't make any difference this time.

Volts/div: Coarse/Fine. Fine allows fine control of the vertical scale. Set this to Fine and try adjusting the Volts/div.

Probe: 1X/10X/100X/1000X. Set this to agree with the probe you are using. If you are connecting a signal directly to the input, choose 1X. By default it's on 10X. Set it to 1X and observe how that changes the display. Describe what happened below.

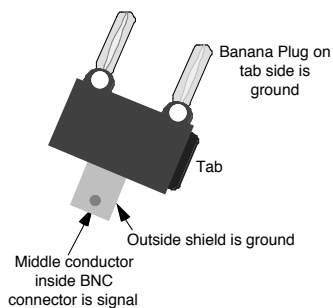
Invert On/Off: Turns the signal display upside down: Positive becomes negative and vice versa. Try it. What happens?

For the following activities you will need:

- digital oscilloscope
- function generator
- 2 BNC cables
- BNC to banana plug converter
- AC voltage divider
- DMM

Activity 27-2: Measuring an Alternating Sine Wave Voltage

(a) Use the digital multimeter (DMM) to measure the AC voltage output of the voltage divider in the grey metal box that plugs into an AC outlet. This thing cuts down the line voltage by a factor of ten so you can study the AC line voltage without killing yourself. The voltage divider does not affect the frequency. Record the r.m.s. voltage given by the meter below.



(b) Connect the output of the voltage divider to the CH1 input using a direct BNC-to-BNC cable and a banana-to-BNC adapter. (Make sure the ground is properly connected.) Adjust the “Probe” setting on the CH1 vertical menu to 1X.

The DSO allows three ways to measure amplitude and period of a signal: automatic, cursors and visual.

(c) Automatic measurement:

Press the “Measurement” button. Choose “Pk-Pk” option to measure the peak-to-peak amplitude: the absolute difference between maximum and minimum points in the signal. The value is displayed on the screen. Record this value below.

(d) Cursors

Press “Cursors”. Choose “Voltage”. Use the cursor knobs to position the two dotted horizontal lines (the cursors) at the top and bottom of the signal. Press the button beside the “Delta” menu option. The voltage difference is displayed. Record this value below.

(e) Visual

Many oscilloscopes do not have cursors or automated measurement, so you should learn how to measure values by reading directly from the screen. Use the knob with the up-down arrow to position the minimum signal point on a major division line. Read the voltage of the major division line just below the signal maximum. (For example, if the top of the wave is a little over three divisions above the bottom of the wave and the vertical setting is 5 V/div, then count 5..10..15 V.) Next, estimate the exact voltage of the maximum. (For

example, if it's just over half way to the next division, estimate 18 V.) Record this value below.

(f) Compare these peak-to-peak amplitude measurements to each other and to the value from the DMM. **You will have to convert the r.m.s. value from the DMM into a peak-to-peak value.** Do your four values agree?

(f) The period of the signal can be measured the same three ways and the frequency is just $1/\text{period}$ in each case. Direct measurement of the frequency is also available under the "Measurement" menu. Record your values for the frequency below and compare them to each other and to the direct measurement value.

The Function Generator

You will use a function generator (pictured below) to produce voltages that change with time in a regular pattern.

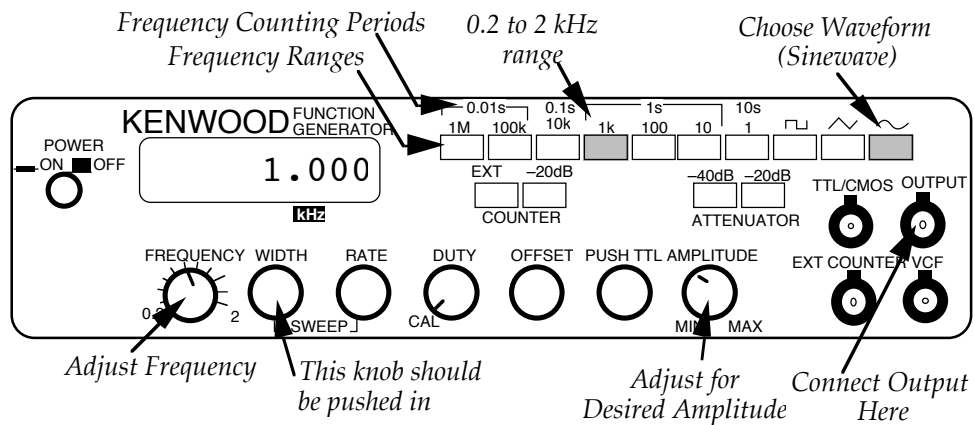


Figure 27-4: A Function Generator

Activity 27-3: Using Both Channels to Compare Waveforms

(a) Connect the function generator output to the CH2 input of the oscilloscope using a BNC cable. This is a direct connection so CH2 "Probe" must be set to 1X—remember that it is 10X by default. Adjust the settings on the function generator and on the oscilloscope so that the CH2 wave looks the same as the CH1 signal. Draw a sketch of the oscilloscope screen below. **Note:** You may not be able to get both signals to stop moving across the screen. This is ok.

Lissajous Figures

Lissajous figures can be observed on the screen when sinusoidal voltages are applied to both channels of the oscilloscope. The patterns that result depend on the relative frequency, amplitude and phase of the two sinusoidal signals.

Activity 27-4: Lissajous Figures

(a) Press the DISPLAY button and choose XY format so that it shows CH1 vs CH2 instead of both CH1 vs t and CH2 vs t. The display you get will not be stable because the function generator is not synchronized with the line voltage frequency. You can play with the function generator's frequency adjustment to try to get a stable circular display. Sketch it below.

(b) Repeat for other frequencies. The function generator output is not very stable, so each time the impression will be of a closed curve which gradually alters its form. Record the frequency ratio $f_1:f_2$ when you can observe an ellipse, an approximate figure eight (8) and a double loop (∞). The frequency ratios should be in terms of the nearest small whole numbers (e.g. 1:2). Sketch the waveforms you got below.

🔧 Activity 27-5: Learning About Triggering.

(a) Return to YT format so you can see both channels vs time. The “Autoset” function adjusts the triggering so that a stable waveform is displayed. Try manually adjusting the trigger level and watching how the display changes. The trigger level is indicated by an arrow on the right-hand side of the screen. Describe what you see below.

(b) Go to the trigger menu and change from rising edge trigger to falling edge trigger. Describe what happens. How is this different from the “Invert” option of the “Vertical” menu?

(c) Change the trigger source. This option chooses which input signal is used to synchronize the display. Switch between CH1 and CH2 source. Choosing “Line” synchronizes with the AC line frequency, so in this setup it is the same as CH1 because CH1 is displaying the voltage-divided line voltage. What happens when you change the trigger source?

(d) Investigate the Normal/Auto modes. Put the trigger level above the maximum of the signal or below its minimum. What happens? Explore what happens when you change between from “auto” to “normal”.

SESSION TWO: AC CIRCUITS

Examining the charge and discharge of a capacitor in an AC circuit

Now we're going to investigate the relationship between the input and output of an AC circuit with both a resistor R and capacitor C , with the output being taken across the capacitor. In this circuit the function generator switches between charging and discharging the capacitor.

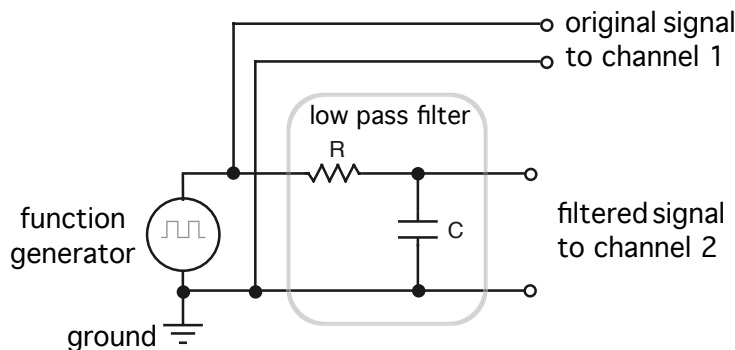


Figure 27-5: A low pass filter circuit.

For the following activities you will need:

- a digital oscilloscope
- a function generator
- 1 BNC cable
- 1 BNC T-barrel connector
- 2 male BNC to female banana plug connectors
- 4 banana plug to alligator clip wires, 1 alligator wire
- 1 $10.0\text{ k}\Omega$ resistor
- 1 $0.01\text{-}0.10\text{ }\mu\text{F}$ capacitor
- a DMM with appropriate capacitance range

Activity 27-6: The RC Time Constant (Again)

(a) Measure the resistance and capacitance values and calculate the time constant, $\tau = RC$.

(b) Set the function generator for square wave output and select a frequency *whose period is many times longer than τ* . Connect the above circuit. The signal from the function generator (V_{in}) should be connected to CH1, and the output signal across the capacitor (V_{out}) connected to CH2. Turn on the function generator and adjust the

oscilloscope so you can see the signals from both channels. You should see an exponential rising and falling of the output signal on channel 2 synchronized with the square wave of channel one. Trigger SOURCE should be on CH1. Sketch what you see on the screen below.

Note: Be careful to connect the grounded (black) terminals of the oscilloscope inputs to the same point in the circuit. Make sure you use the same output from the function generator to feed both Ch. 1 input and the filter.

(c) Adjust the function generator peak-to-peak output voltage to a convenient voltage, V_0 and its period to be several times RC . The peak-to-peak output voltage across the capacitor should also be about V_0 . If it is less you probably need to decrease the frequency. Use the oscilloscope to measure the time it takes the voltage on the capacitor to fall from V_0 to V_0/e . This measured time is the time constant τ . For convenience you may choose $V_0 = 2.71$ V. Then $V_0/e = 1$ V. Compare the measured time constant to the one you calculated.

(d) Increase the frequency of the function generator so that the period is about RC . Sketch the waveform across the capacitor, **indicating the time and voltage scales. Note the relative magnitudes of the input and output voltages.**

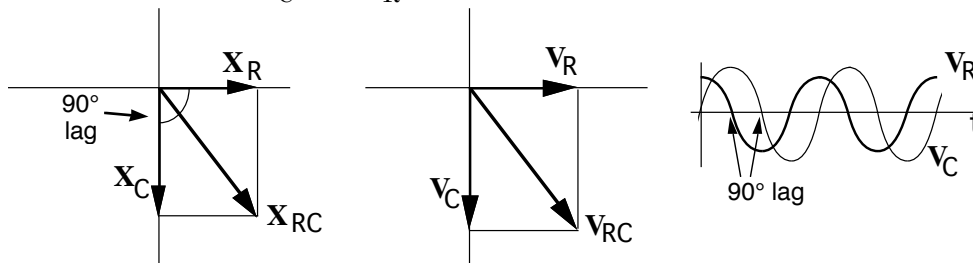
(e) Increase the frequency further until RC is many times the period. Sketch the output **indicating the time and voltage scales** and **note the relative magnitudes of the input and output voltages**.

(f) Use the capacitor charging and discharging model to explain in a brief sentence why the relative output voltage is nearly the same as the input voltage at frequencies much less than $1/\tau$ but diminishes to zero as the frequency increases above $1/\tau$.

Sinusoidal Signals: Low-pass filters

AC circuits are usually analyzed in terms of their response to sine-wave inputs because any arbitrary input signal can be represented as a sum of sine waves. The circuit of the last part can be viewed as an AC voltage divider where the input voltage is divided by the resistor and capacitor. The concept of electrical resistance is generalized for AC signals and called *impedance*. The impedance of a resistor is its resistance. For a capacitor, the impedance is frequency-dependent and is called *reactance*. The reactance of a capacitor is $X_C = 1/(2\pi fC)$. The factor $2\pi f$ is the frequency in radians per second and is written ω . Therefore we also can write $X_C = 1/(\omega C)$.

The voltage across the capacitor can be calculated using Kirchhoff's laws, if we allow for a 90° phase shift between V_C and V_R as shown in the phasor diagram below.



This phase shift is a result of the fact that the voltage across the capacitor is a maximum when the current is zero and zero when the current is a maximum. The voltage across the resistor is on the other hand proportional to the current. The amplitude of V_C compared to the voltage applied across both resistor and capacitor V_{RC} is given by

$$\frac{V_C}{V_{RC}} = \frac{IX_C}{I\sqrt{R^2 + X_C^2}} = \frac{1}{\sqrt{(2\pi fRC)^2 + 1}}$$

Where the total impedance Z_{RC} of the series resistor and capacitor is then given by:

$$Z_{RC} = \sqrt{R^2 + X_C^2}$$

For very low frequencies, $f \approx 0$ and the voltage across the capacitor, V_C , is about the same as the voltage from the function generator, V_{RC} . This means that the capacitor is essentially an open circuit with nearly infinite impedance.

At high frequencies as $f \rightarrow \infty$ the voltage across the capacitor approaches zero as $1/f$ because a capacitor acts like a short circuit (a wire) at high frequencies.

The critical frequency, f_c , marks the division between high- and low-frequency behaviour. It is defined as the frequency at which $X_C = R$ so that $V_C/V_{RC} = 1/\sqrt{2}$. Therefore $f_c = 1/(2\pi RC)$.

Activity 27-7: A Low Pass Filter

(a) Calculate the critical frequency for the capacitor and resistor combination used in your circuit and record the value below.

(b) Set the function generator to produce a sine wave. Adjust the function generator to give a frequency equal to the critical frequency and measure the peak-to-peak voltage across the capacitor with an input voltage of about 1 V peak-to-peak. Record the value below. Also draw a sketch of the output signal **indicating the time and voltage scales** below.

(c) Calculate the ratio of the capacitor voltage to the input voltage from your measurements in (b). Does your result agree with what the theory predicts it should be? Show your theory calculation below.

(d) Note the phase of V_C relative to V_{RC} . Is the phase difference you see consistent with theory? Sketch a phasor diagram of the voltages below indicating the phase angle at this frequency.

(e) Now set the frequency to about 10X the critical frequency and measure the peak-to-peak capacitor voltage. Record the value below. How does this value compare with the input voltage? Draw a sketch of the input signal and the output signal **indicating the time and voltage scales** below.

(f) Now set the frequency to about 1/10 the critical frequency and measure the peak-to-peak capacitor voltage. Record the value below. How does this value compare with the input voltage? Draw a sketch of the input signal and the output signal **indicating the time and voltage scales** below.

(g) Given your results in (e) and (f), why might this circuit be called a “Low Pass Filter”? (**Hint:** How does the output for a low frequency (less than the critical frequency), both amplitude and phase, compare with the output for a higher frequency?)