Department of Experimental Physics
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3rd Year Electronics Laboratory

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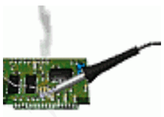
1 Introduction

The aim of the 3rd year electronics laboratory is to provide a solid hands-on foundation in analogue electronics. The course consists of a number of modules related to analogue electronics, including simple RC circuits, diodes, transistors and operational-amplifiers. You will be required build the circuits on bread-board and compare the performance to that of simulation and/or analytic calculation. The following symbols will indicate which is required:


- construction (on breadboard)


- simulation


- analytic calculation/derivation


- something for you to ponder (and reply to!)

Design and simulation will be done with the software package TINA (Toolkit for Interactive Network Analysis) PRO. This package allows circuits to be simulated and optimised using the industry standard SPICE (Simulation Program with Integrated Circuit Emphasis) system. TINA PRO includes models for 20,000 electronics components and has a large range of instruments which allow the performance of a circuit to be characterised before it is constructed. However, TINA PRO is just a simulation and there is no substitute for building and testing the real circuit.

For your report you should keep a ring-binder in which you keep all material related to the exercises. You must include schematics and the results of simulations from TINA PRO, oscilloscope traces (from the digital oscilloscopes, if possible) and the results of analytic derivation/calculation as appropriate. You should always include a brief discussion of the exercise and explain any decisions you made in completing the exercise.

The lab will require approximately 3 weeks to complete, with full attendance on 3 afternoons each week. If you feel that you are running our of time on any section, then you should move on to the next section with a view to returning to any missed exercises should time permit. Analytic derivations/calculation may be done as exercises outside of lab hours. As a guide, each of the 4 sections should take approximately two days to complete.

Some recommended books:

- *The Art of Electronics*, Horowitz and Hill, published by Cambridge University Press
- *Electronic Devices*, Floyd, published by Prentice Hall
- *Electronics for Today and Tomorrow*, Tom Duncan, Published by John Murray (Publishers) Ltd.

2 Resistor/Capacitor Circuits

Chapter 1 from Horowitz and Hill is compulsary reading for this section.

2.1 The Voltage Divider

The purpose of a voltage divider is to obtain a predictable output voltage that is a fraction of some input voltage. Consider the simple network of resistors:

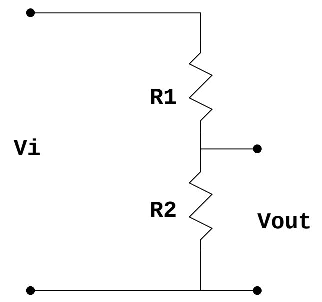


Figure 2.1: Simple Voltage Divider

The output voltage is given by

$$V_{out} = V_{in}\frac{R_2}{R_1 + R_2} \tag{2.1}$$

Exercise 1. What happens to V_{out} if a load resistor is inserted? Try different values of R_{load} (set $V_{in} = 5$ V, $R_1 = R_2 = 1$ kΩ).

To calculate what happens **Thévenin's theorem** of equivalent circuits can be used: *any two terminal network of resistors and voltage sources is equivalent to a single resistor R_{th} in series with a single voltage source V_{th}.*

V_{th} and R_{th} are calculated by:

$$V_{th} = V \text{ (open circuit)} \tag{2.2}$$

$$R_{th} = \frac{V_{th}}{I \text{ (short circuit)}} \tag{2.3}$$

For the voltage divider in figure 2.1:

$$V_{th} = V_{in}\frac{R_2}{R_1 + R_2} \tag{2.4}$$

$$I_{short} = \frac{V_{in}}{R_1} \tag{2.5}$$

$$\therefore R_{th} = \frac{R_1 R_2}{R_1 + R_2} \tag{2.6}$$

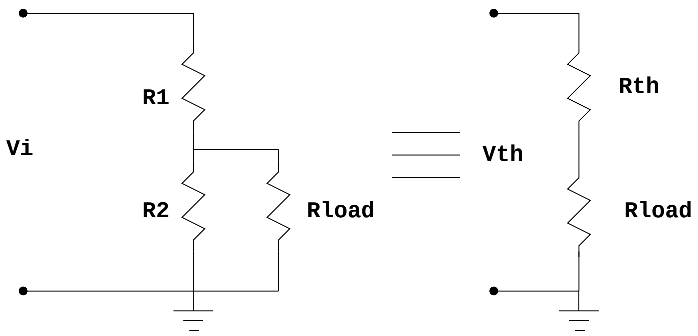


Figure 2.2: Simple Voltage Divider - Thévenin's equivalent circuit

Exercise 2. For the circuit shown in figure 2.1, with $V_{in} = 30$ V and $R_1 = R_2 = 10$ kΩ, find (a) the output voltage with no load attached, (b) the output voltage with a 10 kΩ load, (c) the Thévenin equivalent circuit, (d) as part b but with Thévenin circuit.

From the Thévenin equivalent circuit it can be seen that R_{load} must be significantly greater that R_{th} for the desired voltage to be delivered to the load.

Exercise 3. Select the load resistor using the *input* button and using the *DC transfer characteristic* from the *Analysis* → *DC analyis* menu, plot the output of the Thévenin circuit as a function of the load resistance.

2.2 RC Networks

Consider the following circuit:

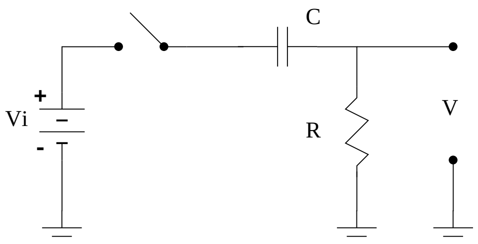


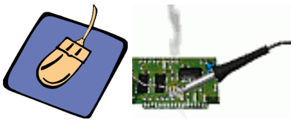
Figure 2.3: RC circuit

What happens to V when the swirch is closed?

Exercise 4. Show that the output is given by

$$V = V_i e^{-t/RC} \tag{2.7}$$

i.e. the output voltage decays exponentially to 0, with the rate of decay determined by the RC combination. At $t = RC$ the output will have decayed by 63% of its initial value. The numerical value of RC is known as the *time constant* of the circuit. The output voltage can be assumed to have reached zero (i.e. capacitor can be assumed to be completely charged) after $5RC$.



Exercise 5. Simulate an RC network as in figure 2.3 but being driven by a square wave. Choose $R = 1.0$ kΩ, $C = 1$ μF, $V_i = 5$ V. Then construct the circuit on breadboard and record the output. Compare the results of analytic calculation, simulation and measurement.

Note: In TINA PRO you will need to use *transient* mode to view the waveforms with the interactive oscilloscope. In addition, you should also use the full-featured virtual oscilloscope from the *T&M* menu, which allows the graphs exported and saved. As a guide to what you should aim for:

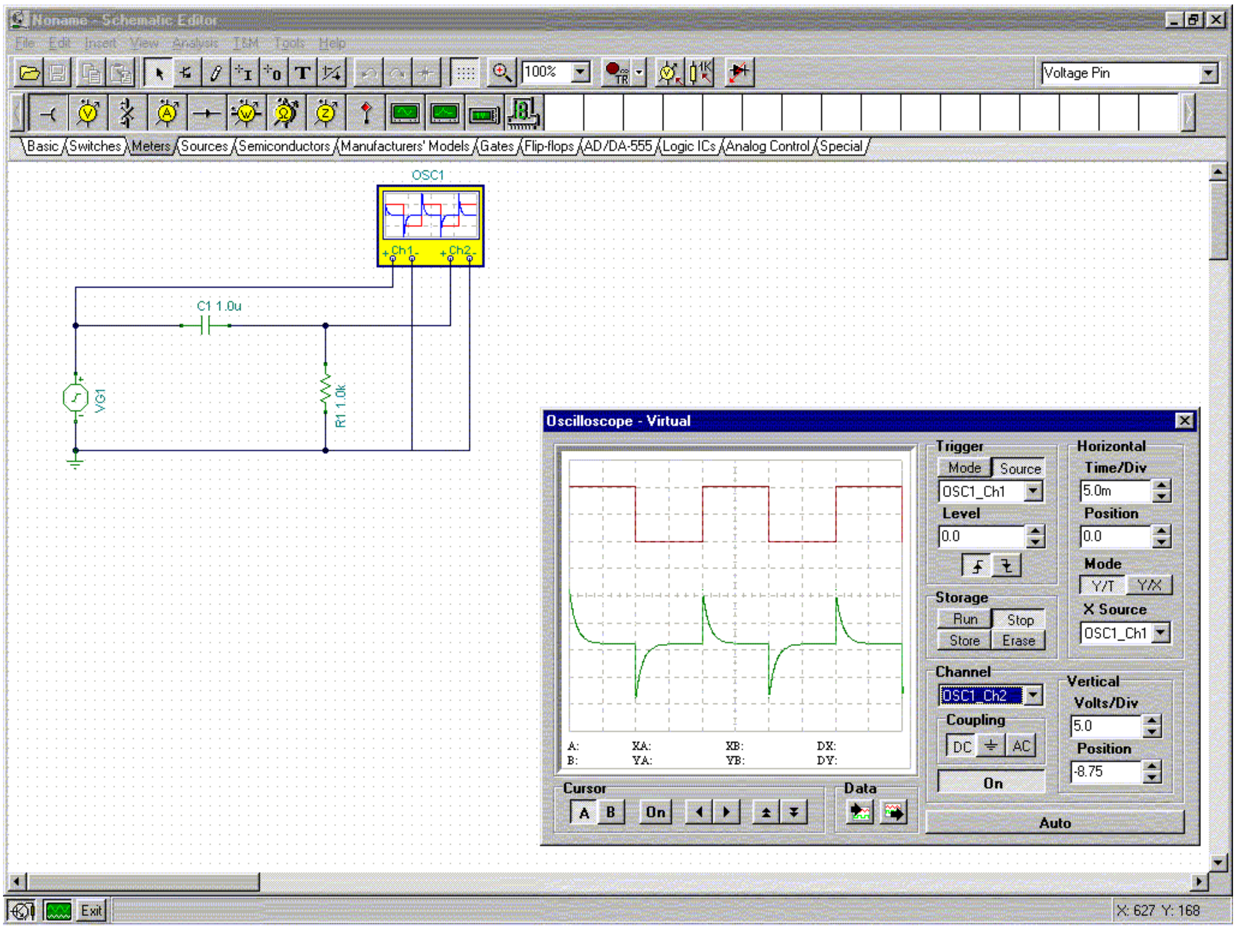


Figure 2.4: TINA PRO screenshot of RC simulation

What will the output from the RC network look like for an arbitrary input? (EXPH 3014 students take note!).

Ans:
$$V(t) = \frac{1}{RC}\int_{-\infty}^{t} V_i(\tau)\, e^{-t(t-\tau)/RC}\, d\tau$$

2.3 A Differentiator

The current in the circuit of figure 2.3 is:

$$I = C\,\frac{d}{dt}(V_{in} - V) = \frac{V}{R} \tag{2.8}$$

$$\therefore \frac{d\,V_{in}}{dt} = \frac{V}{RC} + \frac{dV}{dt} \tag{2.9}$$

If RC is made very small then $\frac{dV}{dt} << \frac{dV_{in}}{dt}$ and

$$\frac{dV_{in}}{dt} \approx \frac{V}{RC} \tag{2.10}$$

$$V \approx RC\frac{dV_{in}}{dt} \tag{2.11}$$

i.e. the output is the derivative of the input voltage.

Exercise 6. Choose appropriate values for R and C and differentiate a square-wave signal (save trace from virtual oscilloscope).

2.4 Sinusoidal Signals & Impedance

The most interesting signals are those which vary with time. However, rather than learning to treat arbitrary waveforms we will deal exclusively with sinusoidal signals as, from Fourier theory, any waveform can be decomposed into a sum of sinusoids.

In this section complex notation will be used extensively and you should be familiar with the use of complex numbers in treating oscillating phenomenon[1]. To recap, a wave may be written as:

$$\psi = A\,\cos(\omega t + \delta) \tag{2.12}$$

$$= A\;\mathcal{R}e(e^{i(\omega t+\delta)}) \tag{2.13}$$

$$= A\,e^{i(\omega t+\delta)} \tag{2.14}$$

Often in dealing with such signals a complex amplitude (written $\mathbf{A}$) is used. What does a complex amplitude mean?

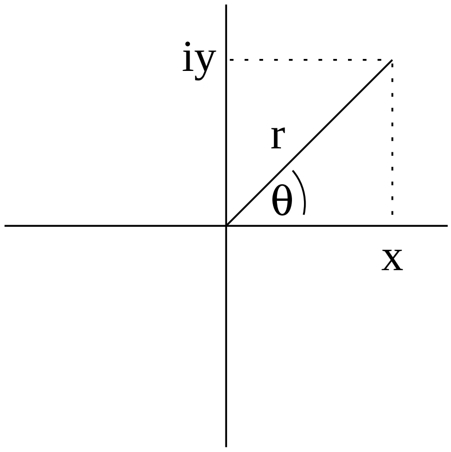
[1] good references: Feynman Vol I Ch 22-23, Horowitz & Hill Appendix B

Recall:

$$\mathbf{A} = x + iy \tag{2.15}$$

$$= r\,(\cos\theta + i\sin\theta) \tag{2.16}$$

$$= r\,e^{i\theta} \tag{2.17}$$



Hence, a wave of form $\psi = \mathbf{A}e^{\omega t}$ may also be written as:

$$\psi = \mathbf{A}e^{\omega t} \tag{2.18}$$

$$= r\,e^{i\theta}\,e^{i\omega t} \tag{2.19}$$

$$= r\,e^{i(\omega t+\theta)} \tag{2.20}$$

Hence, a complex amplitude contains not only the magnitude of the wave but also the phase.

For a resistor:

$$\mathbf{V} = V_0\,e^{i(\omega t+\delta)} \tag{2.21}$$

$$\mathbf{V} = R\mathbf{I} \tag{2.22}$$

$$\therefore \mathbf{I} = \frac{\mathbf{V}}{R} = \frac{V_0}{R}\,e^{i(\omega t+\delta)} \tag{2.23}$$

i.e., the current and voltage have the same phase.

Now consider a capacitor:

$$\mathbf{Q} = C\mathbf{V} \tag{2.24}$$

$$\mathbf{Q} = CV_0\,e^{i(\omega t+\delta)} \tag{2.25}$$

$$\mathbf{I} = \frac{d\mathbf{Q}}{dt} = i\omega CV_0 e^{i(\omega t+\delta)} \tag{2.26}$$

i.e., the amplitude is complex $\Rightarrow$ the current and voltage are not in phase. Since the amplitude is purely complex (i.e. no real part) the phase difference is 90°.

In analogy to the resistance for the d.c. case, the **Impedance** ($\mathbf{Z}$) may be defined to treat a.c. signals:

$$\mathbf{Z} = \frac{\mathbf{V}}{\mathbf{I}} \tag{2.27}$$

In general, the impedance will be complex. E.g. for a capacitor

$$\mathbf{Z} = \frac{V_0\, e^{i(\omega t+\delta)}}{i\omega C V_0\, e^{i(\omega t+\delta)}} = \frac{1}{i\omega C} = \frac{-i}{\omega C} \tag{2.28}$$

Since the impedance is purely imaginary there is only a phase angle change involved and no dissipation of energy.

Equation 2.27 is a generalisation of Ohm's Law. Similarly, Thévenin's theorem may be generalised to include impedances and the voltage divider equation (2.1) becomes:

$$\mathbf{V_{out}} = \mathbf{V_{in}} \frac{\mathbf{Z_2}}{\mathbf{Z_1} + \mathbf{Z_2}} \tag{2.29}$$

Exercise 7.Using the generalised voltage divider equation, calculate the output voltage from the circuit in figure 2.5 below. In MATHCAD plot the amplitude (on a log-log plot) and phase (on a log-linear plot) of the output for $V_0 = 1V$, $C = 1\ \mu$F, $R = 1$ kΩ for frequencies in the range 1 Hz to 1 MHz.

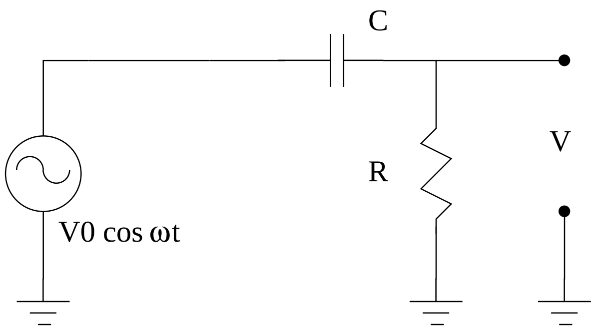
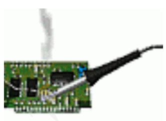


Figure 2.5: RC-network

Simulate this circuit and use the Signal Analysis instrument from the T&M menu to plot the amplitude and phase response (i.e. Bode plot).



Build and measure the amplitude and phase response for the following frequencies: 1 Hz, 10 Hz, 100 Hz, 1 kHz, 10 kHz, 100 kHz, 1 MHz.

The CR combination in figure 2.5 acts as a high-pass filter (figure 2.6). Frequencies below about 1 kHz are attenuated and also suffer phase changes. At a frequency of $1/RC$ the amplitude of the transmitted signal is ~ 0.707 ($= -3$ dB) that of the input with a phase angle change of $45°$. The intensity falls off at 20 dB per decade (change by a factor of 10 in frequency).

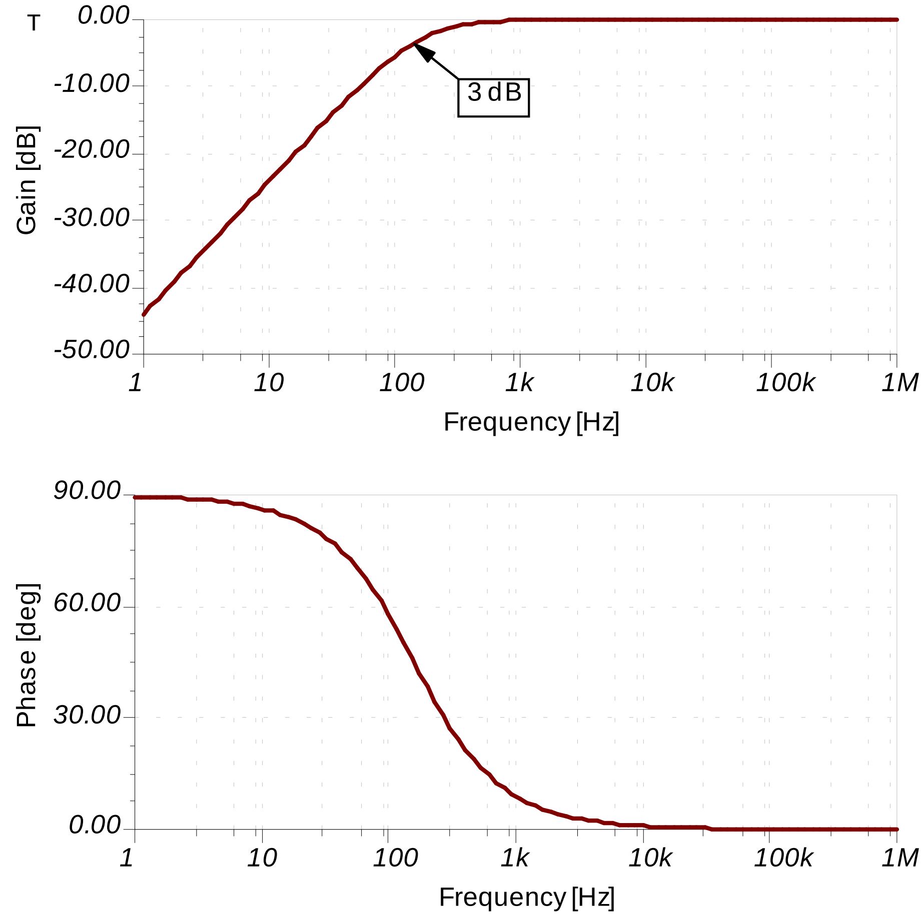


Figure 2.6: Bode Plot of High-Pass filter with $R = 1\text{k}\Omega$, $C = 1\mu$F

If the position of the capacitor and resistor in figure 2.5 are interchanged then the circuit acts as an integrator/low-pass filter. In your simulation of figure 2.5 swap the components and look at the output. In this case, after a time of $t = RC$ the capacitor will be 63% charged and the 3dB point is again at $\omega = 1/RC$.

Note: Definition of the decibel (dB):

The decibel is a measure of the relative intensities of two signals and is defined as[2]

$$\text{number of decibels} = 10\log_{10}\frac{I_2}{I_1} \tag{2.30}$$

Since the intensity $\propto$ amplitude^2 (e.g. power in a circuit = V^2/R from Ohm's law) then

$$\text{number of decibels} = 10\log_{10}\frac{V_2^2}{V_1^2} \tag{2.31}$$

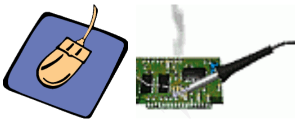
$$= 20\log_{10}\frac{V_2}{V_1} \tag{2.32}$$

The *bandwidth* of a circuit/device is defined as the range over which the response does not drop by more than 3 dB[3] (= 50% drop in intensity = 70.7% drop in voltage),

[2]see section 10-2 in Floyd

[3]see p. 36 Horowitz & Hill

e.g. a 300 MHz Oscilloscope has the upper 3 dB point at 300 MHz and frequencies > 300 MHz are attenuated).



Exercise 8. Design and build a filter comprised of Rs and Cs to give the response shown in figure 2.7 below (with ω_0 corresponding to 1.5kHz). Check the performance with TINA PRO before construction. In your report explain the reasoning behind your design - trial and error is not acceptable!

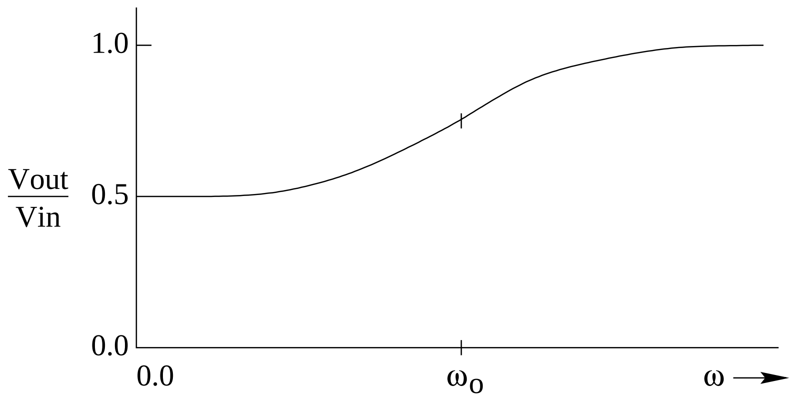


Figure 2.7: Desired response of RC network.

?

Exercise 9. What does the following circuit do and what effect does each component have on the output?

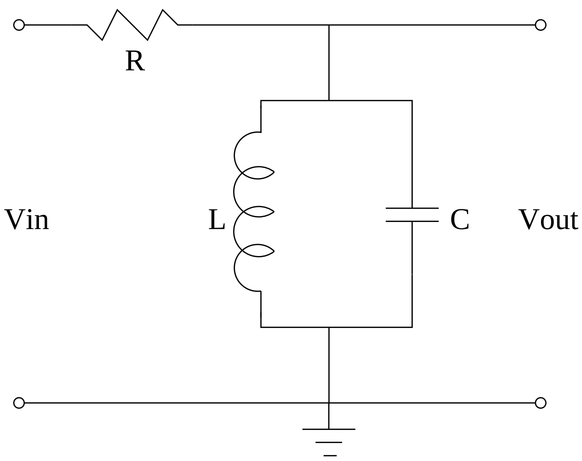


Figure 2.8: A resistor-capacitor-inductor network.

3 Diodes

3.1 Introduction

The diode is a PN junction device as shown below:

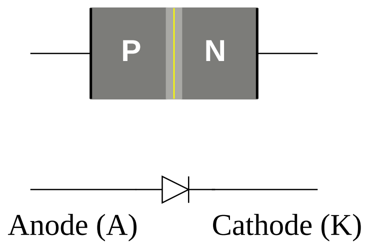


Figure 3.1: The diode and its schematic symbol.

The "arrow" points in the direction of current flow.

A diode is *forward biased* when a voltage source is connected so that the anode is made positive w.r.t. the cathode. If the potential difference is sufficient a current will flow.

When *reversed biased*, the cathode is positive w.r.t. the anode and no (well, negligible) current will flow. Note: if the reverse voltage becomes excessive the diode will break down, current will flow and the diode will be permanently damaged. The breakdown voltage depends on the material and doping level of the diode. A special diode, the Zener diode, is designed to breakdown at a specific voltage and and is operated at this voltage to provide a stable voltage source.

3.2 Electrical Properties

The Practical Diode Model provides a simplified description of the diode's electrical properties and is applicable in most circumstances:

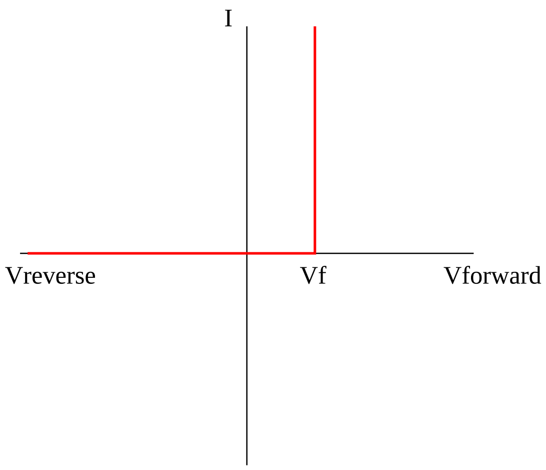


Figure 3.2: The Practical Diode Model - when the forward bias voltage reaches Vf the diode switches on and becomes a perfect conductor, in reverse-bias mode no current flows.

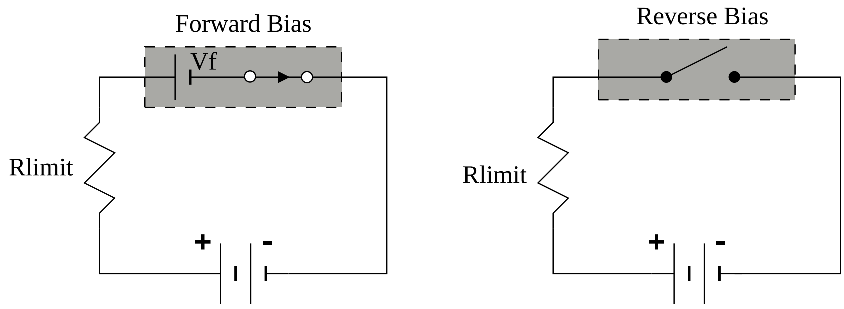


Figure 3.3: The Practical Diode Model - in forward bias mode the diode may be considered as an opposing voltage in series with a current source., in recerse bias mode it may be considered as an open connection..

Vf is equal to the barrier potential produced across the forward-biased PN junction. For silicon this is ∼0.7 V and for germanium is ∼0.3 V.

The forward current is

$$I_f = \frac{Vbias - V_f}{R_{limit}} \tag{3.1}$$

The maximum and average allowed forward currents for a diode, along with a host of other parameters, are available in its data-sheet, which should always be checked to make sure a diode is suitable for a given application.

The Practical Diode Model is quite suitable for the majority of applications but, naturally, more complex and elaborate models exist. The SPICE models (as used by TINA PRO) are quite realistic (just look at the number of parameters describing a diode) and even include temperature dependance.

Exercise 10. Use the Practical Diode Model to calculate the voltages developed across the diode and the resistor and the current through the diode in the circuit below.

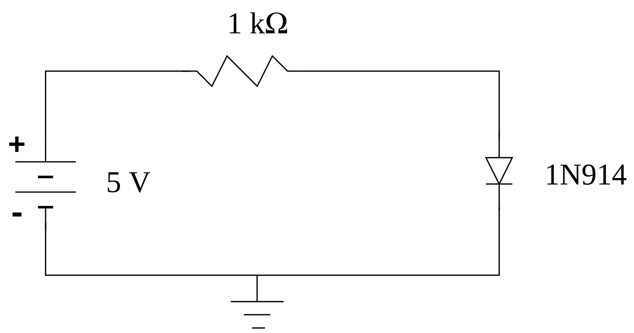
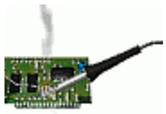


Figure 3.4: An application of the Practical Diode Model.

3.3 Measurements of real diodes

Let us look at the 1N914 diode. The data sheet on this diode is avaliable in an appendix and should be examined.

Exercise 11. Using the DC-Transfer-Characteristic option in TINA-PRO plot the I-V curve for the 1N914 diode in the range -1 to 1 V. (Use only the diode, a voltage source and an ammeter). Look at two different temperatures (say 10°C and 30°C) and plot them on one graph in your report. How does the simulation agree with the values calculated from the Practical Diode Model in the last exercise?



Exercise 12. Experimentally measure the I-V curve for the 1N914 diode. First, design a circuit in TINA PRO which uses a limiting resistor and a potentiometer to vary the voltage across the diode and to ensure that the maximum forward current through the diode (see spec. sheet in an appendix) is not exceeded. (design your circuit conservatively so that half the maximum rated current is not exceeded).By reversing the polarity of the voltage source the reverse-biased I-V curve can be determined. Once you are happy with your design construct the circuit and experimentally measure the I-V curve. Plot the forward current in mA and the reverse current in μA and compare to simulation.

3.4 Diode Applications

In this section we will look at one of the main applications of diodes - rectification. Rectification is the process of converting an ac voltage to a dc voltage.

3.4.1 Half-wave rectifier

Since a diode allows current to flow only in one direction and blocks current in the other direction, it may be used as a simple half-wave recitifier:

Exercise 13. Simulate the circuit shown below. Assume R_{load}=1 kΩ, V_{in}= 50 Hz, 10 V peak-to-peak. Compare the output to the input.

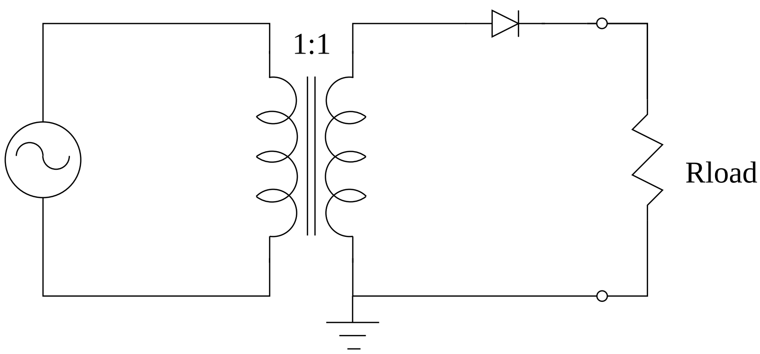


Figure 3.5: The diode as a half-wave rectifier.

The output from the above circuit is far from ideal as a constant voltage source is generally required to power the load. The situation can be improved dramatically by inserting a filter capacitor into the output stage of the circuit as shown below. Naturally, the time constant of the RC network should be such that the capacitor discharges much more slowly than the change in the input voltage.

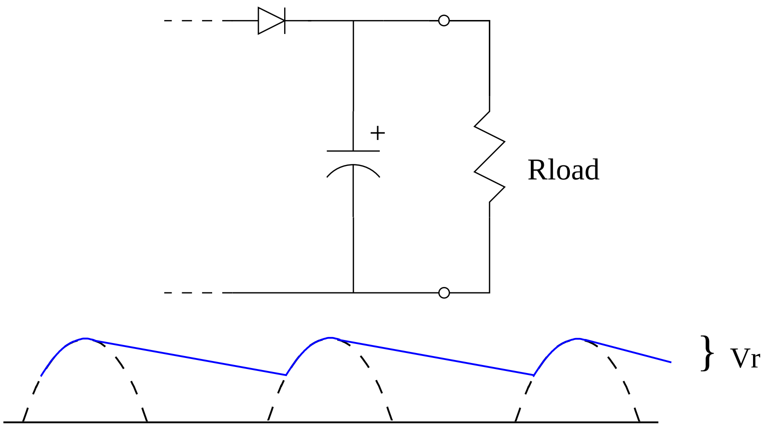


Figure 3.6: Half-wave rectifier with filter capacitor and the effect on its output.

Exercise 14. Show that the peak-to-peak ripple voltage for the half-wave rectifier may be approximated by:

$$\Delta V = \frac{V_0}{f\, R_{load}\, C} \tag{3.2}$$

Hint[4]: assume that RC is sufficiently large so that $\Delta V = \dfrac{I}{C}\Delta t$

3.4.2 Fill-Wave rectifier

Four diodes may be placed in a *bridge* to form a full-wave rectifier:

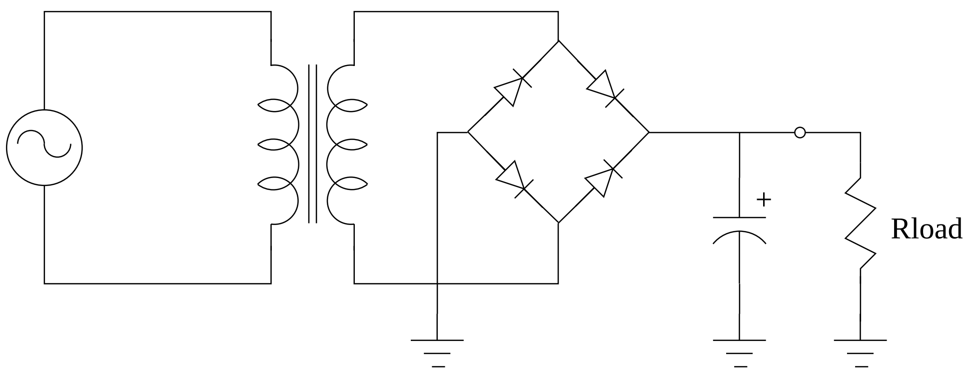
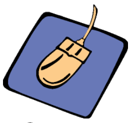
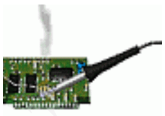


Figure 3.7: Full-wave rectifier, including filter capacitor, made with a *diode bridge*.

[4] see section 1.27, Horrowitz and Hill for an explanation for why higher accuracy is not needed.

Exercise 15. How does the above circuit work? How does the peak output voltage compare to the peak input voltage?

Exercise 16. Design and construct a a full-wave bridge rectifier to deliver 10 V DC with less than 0.1 V (pk-pk) into a load drawing 10 mA. Choose the appropriate ac voltage of the 50Hz sinusoidal input signal. Discuss your design in your report.

The above circuit forms the basis of most power supplies. Additional components needed include a surge resistor, to limit the current through the filter capacitor when the circuit is first powered, and possibly a regulator, to provide an even smoother voltage output.

3.4.3 Diode Clamp

The diode clamp, which is also known as a dc restorer, adds a dc level to an ac voltage. Conisder the following circuit:

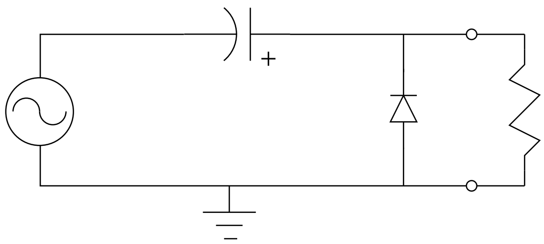


Figure 3.8: Diode clamp, for effective operation $RC \gtrsim 10$ input frequency.

Exercise 17. Simulate the above circuit and compare input to output (say, amplitude of input=10 V). What happens if the direction of the diode is changed? Explain how the circuit works.

Exercise 18. What do the following circuits do, how do they do it and can you think of an application?

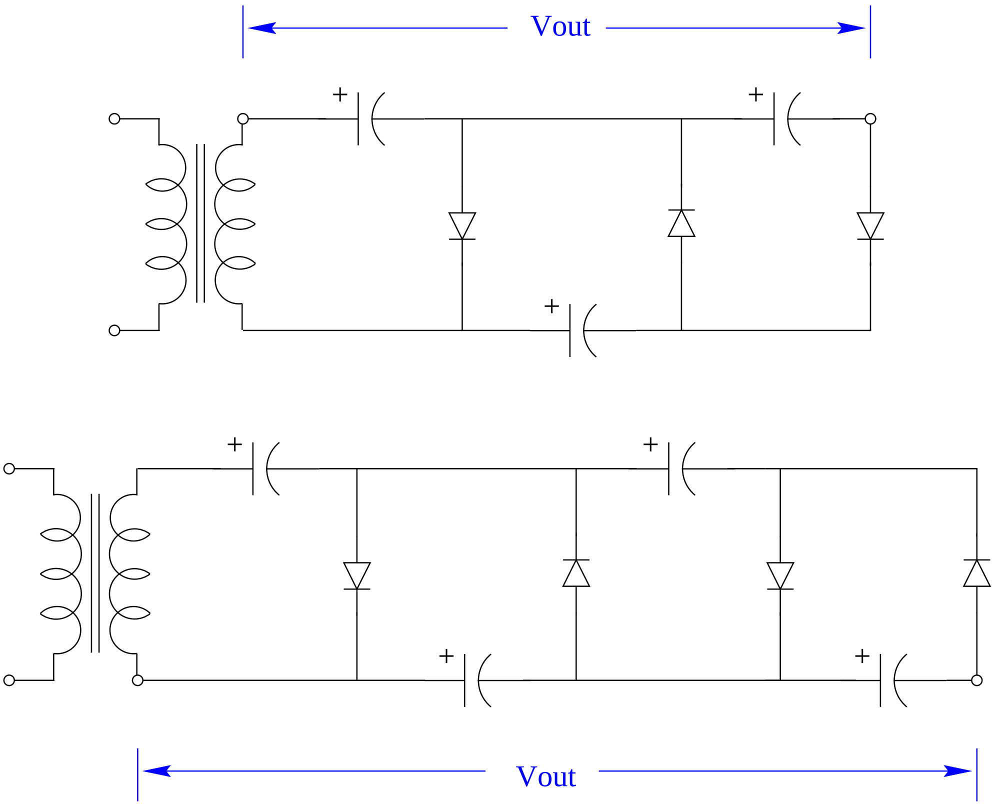
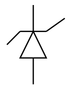
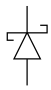
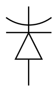
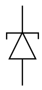
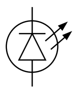
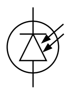


Figure 3.9: Diode applications.

3.4.4 Special Diodes

Name	Symbol	Description
Zener		Has a carefully controlled breakdown voltage and is operated in reverse-bias mode at this voltage to maintain a constant dc voltage.
Schottky		Metal-to-semiconductor rather than PN junction and operated only with majority carriers. Characterised by very fast switching times which make it suitable for high frequency and high-speed digital applications.
Varactor		Variable capacitance diode where the capacitance is controlled by the reverse bias voltage. Used in tuning systems in electronic communication systems.
Tunnel		Pver a limited range has *negative resistance* where a decrease in voltage leads to an increase in current. Used in oscillator and microwave amplification appliications.
Light Emitting (LED)		When forward-biased emit light whose intenisty is directly porportional to the current. Have barrier potentials much higher than for silicon diodes (1.2-3.2 V) and breakdown reverse-bias voltages which are much less. (Note: same symbol is used for laser diode).
Photo-Diode		Operated in reverse-bias mode where the reverse current is proportional to the intensity of the light falling on the PN junction.

4 Transistors

4.1 Introduction

Transistors are tiny semiconductor devices which revolutionised electronics (see http://www.lucent.com/minds/transistor for a historical overview from the inventors). Their usefulness arises from their ability to act as current, voltage and power amplifiers and high-speed switches.

There are two types of transistor - the bipolar (juction) transistor, which is most common, and the unipolar or *field-effect* transistor (FET). The bipolar transistor consists of two PN junctions back-to-back, as indicated in the figure below. The p-type layer is very thin and lightly doped while the n-type is heavily doped.

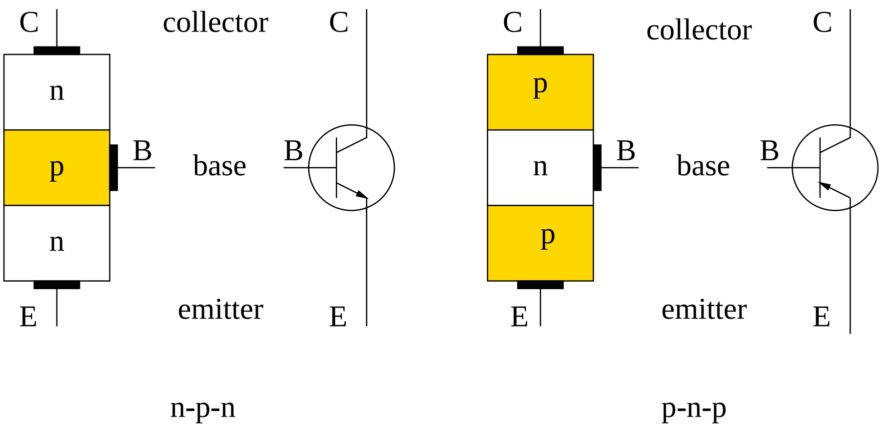


Figure 4.1: npn and pnp bipolar transistors with their schematic symbols.

The npn transistor must be operated with the collector and base positive w.r.t. the emitter while for a pnp transistor they must be negative w.r.t. the emitter. Silicon is preferred over germaniun since it can work at higher temperatures and has lower leakage current. In addition, silicon npn transistors are easier to mass produce than the pnp variety and, so, are more common in circuits.

4.2 Transistor Action

The bipolar transistor is operated most frequently in *common emitter* mode, where the currents flowing through the transistor are the base-emitter and collector-emitter currents. The usefulness of the transistor arises from the ability of the base-emitter current to control the collector-emitter current. Consider the following cases for an npn transistor (you should simulate each stage in TINA as you go along):

- a voltage of +5 V is applied across the emitter-collector (making the collector positive w.r.t. the emitter) with no connection to the base. No current flows through the device since the base-collector junction is reverse-biased.
- now forward-bias the base-emitter by applying a potential difference V_{BE} of 0.7 V. This allows electrons to enter the p-type material, from which they flow into the base (I_B) or into the collector (I_C), with $I_B << I_C$.

- As V_{BE} is increased the I_B increases and so does I_C. Therefore,
  - the transistor is a switch, since I_B turns on I_C.
  - the transistor is a current amplifier since I_B controls I_C.
- the d.c. current gain (h_{fe}) depends on the model of transistor and is typically 10 to 1000. This important property of a transistor is defined by

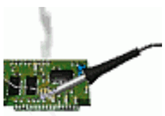
  $$h_{fe} = \frac{I_C}{I_B} \tag{4.1}$$

  Although h_{fe} is approximately constant for a transistor over a limited range if I_C, it varies from transistor to transistor of the same type due to the manufacturing process.
- the sum of the base and emitter current must equal the collector current,

  $$I_c = I_b + I_e \tag{4.2}$$

4.3 Transistor as a current amplifier

Here we will examine the current amplification properties of a real transistor, the 2N4400, whose spec. sheet is in an appendix and should be examined. As can be seen in the spec. sheet, the maximum collector current (sustained) is 1 amp, but the device is recommended for applications up to 500 mA.

Exercise 19. Compare the current amplification of the model in TINA PRO to the measured gain of a real 2N4400 transistor using the circuit below. Take care not to exceed an emitter current of 500 mA.

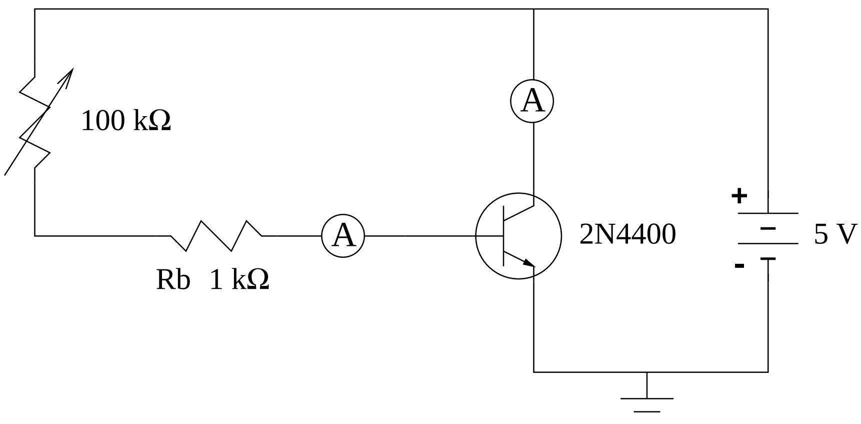


Figure 4.2: The 2N4400 transistor as a current amplifier..

Base Resistor: The base-emitter junction of a transistor is a forward-biased PN junction. A large voltage ($\gtrsim 0.7$ V) would cause an excessive current through the junction and the transistor would be destroyed through overheating. The base resistor, R_b in the above figure, limits the current through the junction and prevents damage. A base resistor *should always be present*.

4.4 Transistor as a switch

Transistors have many advantages over other electrically operated switches such as relays. They are small, cheap, reliable, have no moving parts, their life is almost indefinite (in properly designed circuits!) and they can switch millions of times a second.

Consider the following circuit:

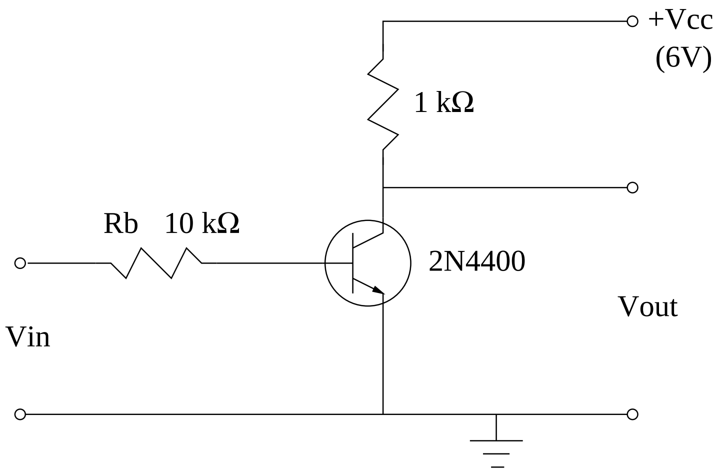


Figure 4.3: The 2N4400 transistor as a switch.

Simulate this circuit and examine how the output changes as the input voltage ranges from 0 to $+6$ V. A response-curve like the one shown below should be obtained:

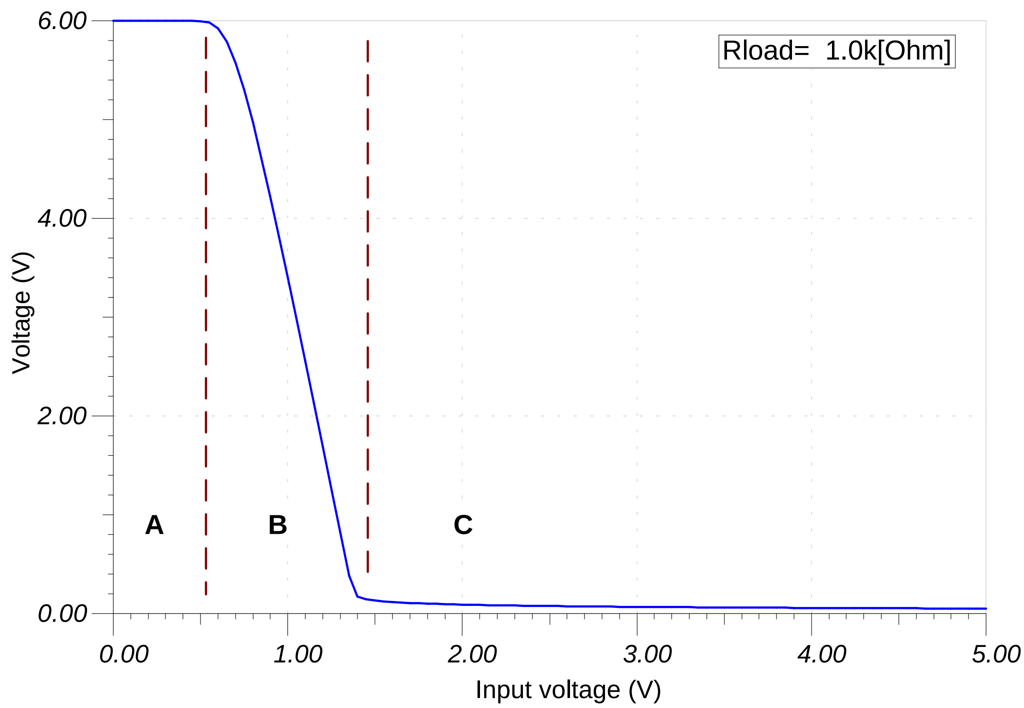


Figure 4.4: The 2N4400 transistor as a switch.

The response curve is characterised by three distinct sections:
(A) the transistor is *off*, no collector current flows and so V_{out} is 6 V.

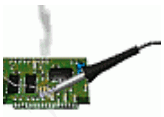
(B) the transistor is partly on. As the current increases the voltage developed across R_{load} increases and hence the output drops.
(C) the transistor is fully *on*. Although I_{ce} may not be at the maximum possible for the transistor, it cannot go any higher (even as V_{BE} is increased) as this would require a larger voltage than is available to power the load resistor. The transistor is said to be saturated.

Action:

V_{in}	V_{out}
low, < 0.6 V	*high*, 6 V
high, > 1.4 V	*low*, 0 V

Note: power is only used by the transistor when it is partly *on*, none is used in the when it is fully *on* or fully *off*. Therefore it is important to ensure that the transistor is either fully *on* or fully *off* and that the transition between the two states is rapid.

Exercise 20. Look at the effect of R_l on the switching action (try values of $10\ \Omega$, $100\ \Omega$, $1\ k\Omega$, $10\ k\Omega$). Note: TINA PRO can do this automatically if you select the load resistor using the *select control target* button: 



Exercise 21. Choose appropriate values for the components in the figure below to create a light sensitive alarm. The diode (our *lamp*) should switch on in darkness and switch off in brightness (Note: for the red LEDs in the lab, the reverse-bias voltage is approximately 1.8 V and a current of ~ 5 mA will produce a reasonably bright output). First, measure the resistance of the LDR (light dependant resistor) in brightness and darkness. Explain your choices of component values in your report.

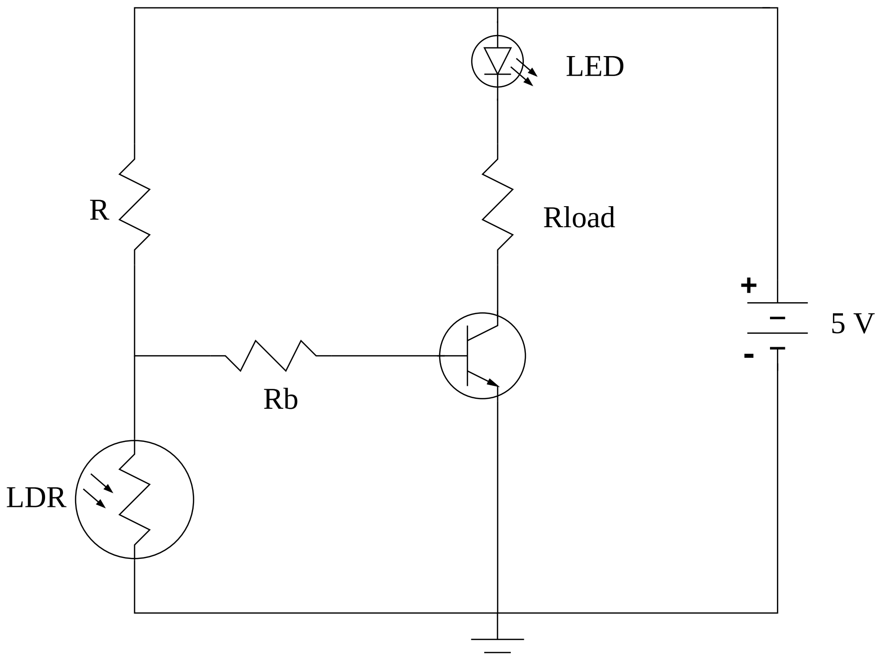


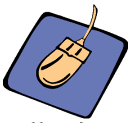
Figure 4.5: Light senistive switch.

4.5 Transistor as a Voltage Amplifier

The transistor as a switch circuit (figure 4.3) may be used as a voltage amplifier by operating it in region B (of figure 4.4).

Re-generate figure 4.4 but with $R_l = 500\ \Omega$. From the resulting plot you should see that the input voltage should be between 0.6 V and 1.8 V for amplification to occur.

For best amplification of an ac signal it can be seen that the input should vary around (i.e. have a d.c. off set of) ~ 1.2 V (midway between 0.6 V and 1.8 V), and amplitude less than 0.6 V ($(1.8 - 0.6)/2$).



Exercise 22. Simulate the circuit of figure 4.3 but with $R_l = 500\ \Omega$ and input signals as sinewaves of 1 kHz with (A) amplitude=0.3 V, d.c. offset: 1.2 V, (B) amplitude=0.3 V, d.c. offset: 0.6 V, (C) amplitude=0.8 V, d.c. offset: 1.2 V. (Note: include only the oscilloscope traces in your report).

The d.c. level is known as the *bias*.
Distortion occurs when the bias level is wrong and/or the the amplitude of the input voltage is too large.

Naturally, the above amplifier is not ever used as a voltage amplifier due to the need to bias the input voltage and because the output is biased by some different amount.

The circuit shown below is a more practical version of a simple transistor voltage amplifier:

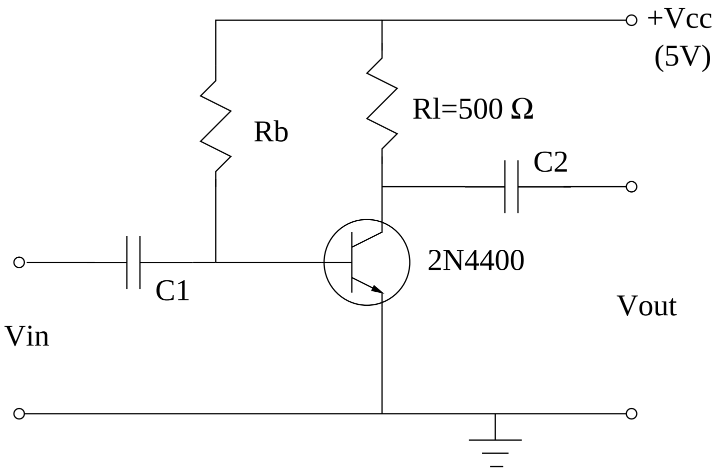


Figure 4.6: Voltage transistor amplifier.

In the above circuit the capacitors remove d.c. from the input and the output and the bias is provided by R_b.

Exercise 23. Simulate the amplifier in the above circuit. First, you must determine values for the capacitors and R_b, based on the assumption that h_{fe} for the 2N4400 amplifier is a constant 100 and that the input signal is of frequency 100 Hz $- 20$ kHz. Plot the frequency response of you amplifier.

The gain of the transistor voltage amplifier is highly dependand on h_{fe}, which varies from transistor to transistor of the same type and whose value depends on the collector current. Stability can be dramatically improved by using *feedback*, which we will see in the next section on operational amplifiers.

5 Operational Amplifiers

5.1 Introduction

Operational amplifiers (op-amps) are integrated circuit devices which contain $20+$ transistor in addition to resistors, capacitors and diodes. It is much easier to construct amplifiers and other circuits using op-amps than transistors. Op-amps generally contain internal circuit protection and so are more robust than transistors.

Op-amps have two inputs and one output and are generally represented in circuits by one of the following two symbols. Additional pins on op-amp chips are provided so that resistors and capacitors may be connected to modify the performance of the op-amp in a given application. The $-$ connection is the *inverting input* while the $+$ connection is the *non-inverting input*.

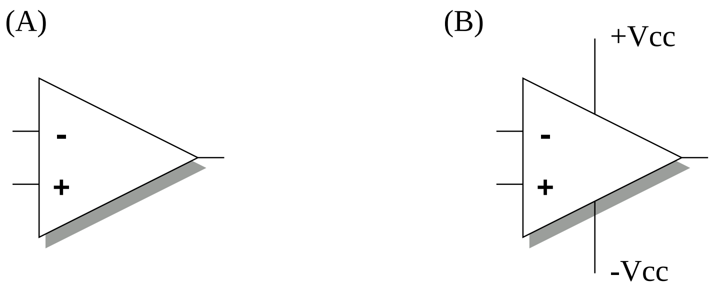


Figure 5.1: Op-Amp schematic symbols - without (A) and with (B) the power connections.

Op-amps are characterised by the following properties:

- very high gain, A_{ol} (also sometimes called the *large-signal voltage gain*), typically $\sim 10^5$ or higher. This falls off as the frequency of the input increases. It may also vary from op-amp to op-amp of the same type.
- very high input impedance, typically $\sim 10^6\ \Omega$, so that little current is drawn from the input source and the input voltage is transferred with little loss.
- low output impedance, typically $\sim 100\Omega$ so that the output voltage is easily transferred to loads with $R \gtrsim 1$ kΩ.

5.2 Op-amp action

In its simplest form, the op-amp acts as a differential amplifier and produces an output

$$V_{out} = A_{ol}(V_+ - V_-) \tag{5.1}$$

Given that op-amps have such high gains the output will be saturated (i.e. either at $+Vcc$ or $-Vcc$) unless the inputs are within a few μV of each other. The sign of the output is:

$$\begin{array}{rl} +\text{ive} & \text{if } V_+ > V_- \\ 0 & \text{if } V_+ = V_- \\ -\text{ive} & \text{if } V_+ < V_- \end{array}$$

The usefulness of the op-amp is limited in this mode but with negative feedback it can be made into a very flexible amplifier.

5.3 Op-amps and Negative Feedback

Feedback, as the name implies, involves feeding a fraction of the output back to the input. If the feedback goes to the non-inverting input then the output of the op-amp will increase and saturation occurs (positive feedback is used in oscillator applications). However, if the feedback goes to the inverting input then the o/p is reduced and a stable equilibrium situation occurs.

The following Golden Rules may be used to understand op-amp circuits with negative feedback:

1. the output attempts to do whatever is necessary to make the difference between the voltage difference between the inputs zero.
2. the inputs draw no current.

By using negative feedback the gain of the amplifier may be controlled by the external feedback network and is independant of the open loop gain (A_{ol}) of the amplifier. The gain of the amplifier with feedback is known as the *closed loop gain*, A_{cl}. The use of negative feedback produces an A_{cl} less than A_{ol} but increases the bandwidth, as can be seen in the figure below. The product of bandwidth and gain is approximately constant for a given op-amp. The input and output impedances may also be controlled with negative feedback.

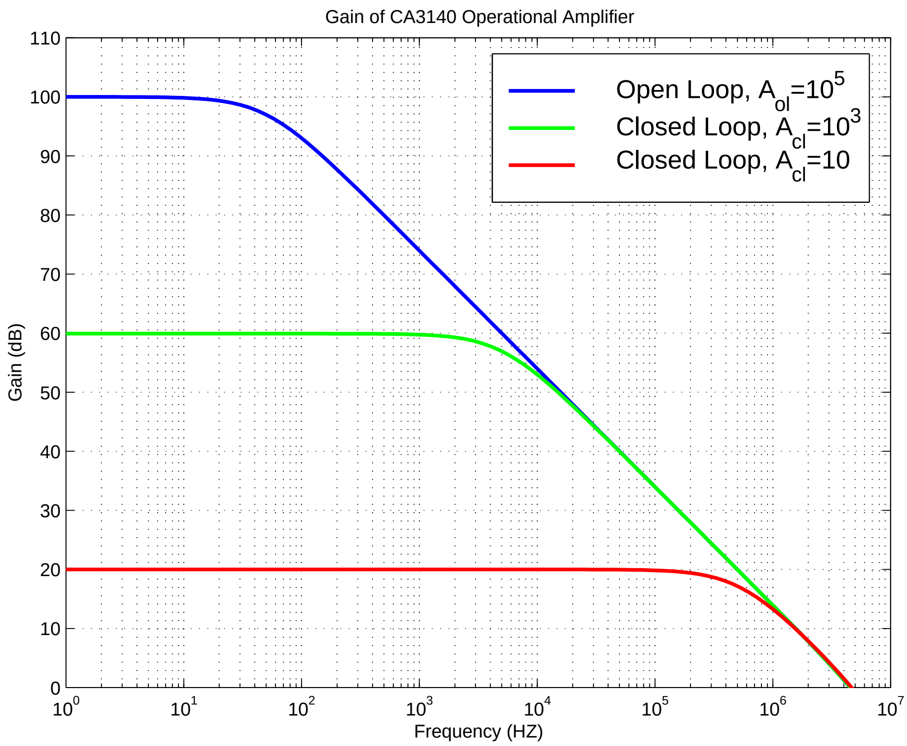


Figure 5.2: Frequency response of the CA3140 op-amp for open loop and non-inverting configurations with two different feedback fractions. The product of bandwidth and gain is 4.5 MHz for this op-amp (see spec. sheet in appendix)

5.4 Real Opamps

Real op-amps are not perfect and are characterised by a number of parameters which describe how their behaviours depart from ideal. Chapter 12 in the Floyd book should be read as an introduction. In addition, the data sheet on the op-amp which will be used, the CA3140, is included in an appendix and should be examined.

In all exercises in this section assume $Vcc = \pm 12$ V. In addition, noise on the power supply lines can result in op-amp circuits producing unexpected outputs and oscillations, especially in high gain circuits. A way to reduce the effect of a noisy power supply is to add decoupling capacitors (of about $0.1\ \mu$ F) as shown below. All of the circuits you build should have provision for adding them, or even better, include them from the start.

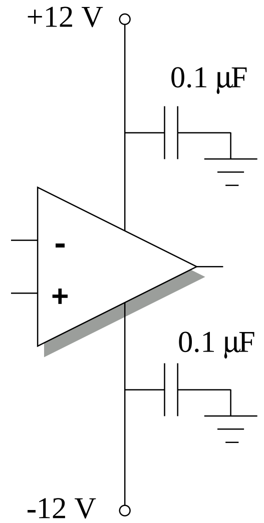


Figure 5.3: Power connections, with de-coupling capacitors, to a real op-amp. The above connections are implied on all op-amp circuits to be constructed.

5.5 The Non-Inverting Amplifier

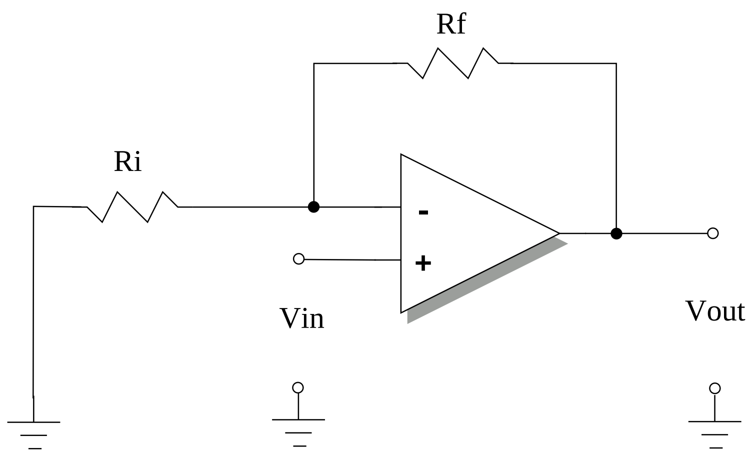


Figure 5.4: Non-Inverting amplifier using negative feedback

To analyse this circuit use the two golden rules.

The first implies that the voltage at the inverting input is equal to the voltage at the non-inverting input, so

$$V_- = V_{in} \tag{5.2}$$

Therefore, the current flowing I_i through R_i must be

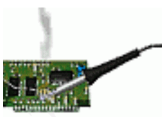
$$I_i = \frac{V_{in}}{R_i} \tag{5.3}$$

From the second rule, since the inputs draw no current, all of I_i must flow through R_f and so $I_i = I_f$. Hence, the output voltage must be

$$\begin{aligned} V_{out} &= V_- + I_f R_f && (5.4) \\ &= V_{in} + I_i R_f && (5.5) \\ &= V_{in} + \frac{V_{in}}{R_i} R_f && (5.6) \\ &= V_{in}\left(1 + \frac{R_f}{R_i}\right) && (5.7) \\ \therefore A_{cl} = \frac{V_{out}}{V_{in}} &= \left(1 + \frac{R_f}{R_i}\right) && (5.8) \end{aligned}$$

i.e. the gain is always greater than unity, is independant of A_{ol} and is controllable by the feedback network.

Exercise 24. Simulate the circuit of figure 5.4. Use the *!OPAMP* op-amp from the *Semiconductor→Operational Amplifier* menu of TINA. For a d.c. input of 0.1 V look at the gain for a range (say 5) of different feedback fractions and compare the results to the prediction of equation 5.8. Next, pick one configuration and change A_{ol} (in the *Properties→Type ...* menu) for the opamp and verify that A_{cl} is independant of A_{ol}.



Exercise 25. Construct the circuit of figure 5.4. Use the CA3140 op-amp and choose components to give a gain of 20 dB. (Note: do not solder the op-amp into the board but use an 8-pin IC holder). Drive the circuit with a 1 kHz sine-wave and compare the input to the output. Measure the frequency response and compare to figure 5.2. Insert a 1 μF capacitor across R_f and look at the effect on the bandwidth. Explain why the capacitor has this effect on the output.

5.6 The Inverting Amplifier

Consider the following circuit:

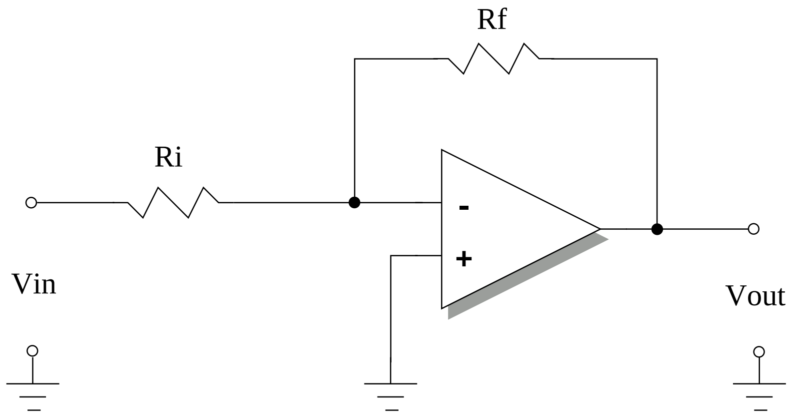


Figure 5.5: Inverting amplifier using negative feedback.

The non-inverting input is held at 0 V and is often referred to as a *virtual ground*. Hence, the current through R_i is

$$I_f = \frac{V_{in} - 0}{R_i} \tag{5.9}$$

All of this current flows through R_f and so the gain is:

$$A_{cl} = \frac{V_{out}}{V_{in}} = \frac{R_f}{R_i} \tag{5.10}$$

Exercise 26. Simulate the circuit of figure 5.5 and verify that it performs as expected.

5.7 The Summing Amplifier

The summing amplifier is a variation on the inverting amplifier:

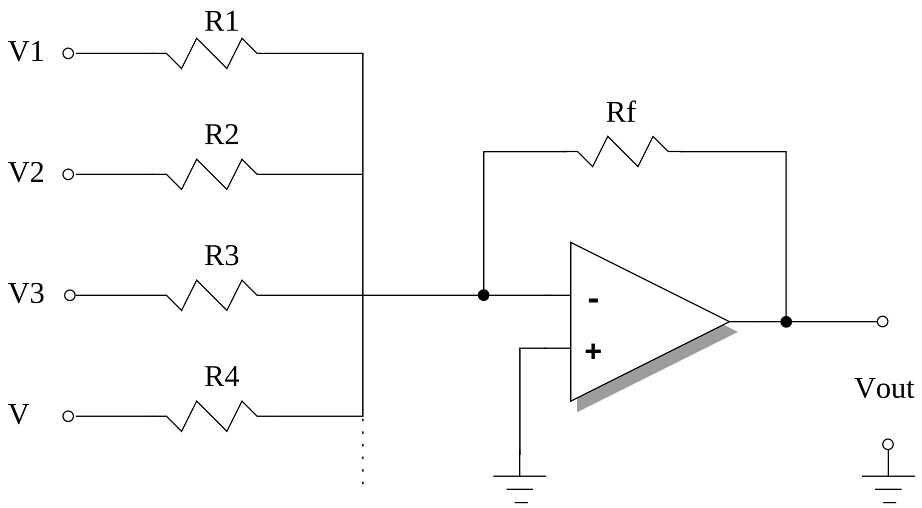


Figure 5.6: Inverting Summing Amplifier using negative feedback.

This circuit basically sums the currents from each of the input branches and the resulting current flows through R_f. The output voltage is a linear combination of the input voltages, with resistors $R_1 \ldots R_N$ determining the relative contribution of each of the input voltages $V_1 \ldots V_N$, and R_f determining the amplification. The ouput voltage is given by

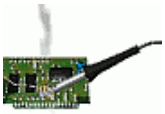
$$V_{out} = -R_f \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \ldots + \frac{V_N}{R_N} \right) \tag{5.11}$$

Exercise 27. Design a 4-bit Digital-to-Analogue Convertor (DAC) which produces an output in the range 0 V to -3 V. Inputs are either digital 'high' ($+5$ V) or digital 'low' (0 V). In TINA use switches to select between the two possible states for each input bit and either digital or analogue sources may be used. Explain your design and include a plot of input (decimal) -vs- output.

Exercise 28. How could an op-amp with feedback be configured so that it would supply a constant current to some load, even if the resistance of the load changed.

5.8 Current-to-Voltage Convertor

An op-amp with negative feedback can be used as current-to-voltage convertor by replacing R_i in the inverting amplifier circuit with the current source. Since V_- is a virtual ground, all the current flows through R_f, which can be chosen to give the appropriate output voltage. The CA3140 op-amp is a good choice for such applications as it has a very high input impedance.



Exercise 29. Build the infra-red detector shown below. The BPW 34 infra-red photodiode (data sheet in appendix) is operated in reverse-bias mode and produces a current proportional to the infra-red light level falling on it. Illuminate the photodiode with an infra-red signal (e.g. from a remote control) and look at the output on the oscilloscope.

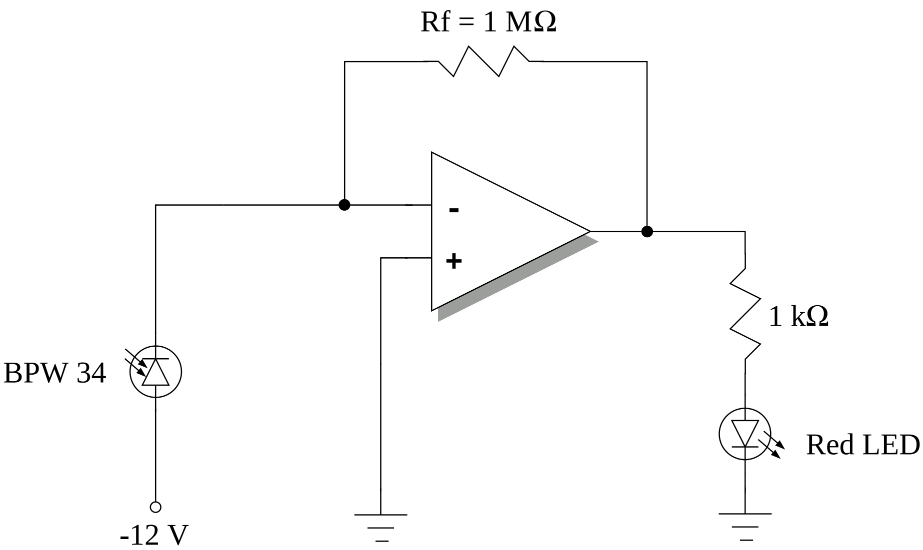


Figure 5.7: Current-to-voltage convertor using and infra-red photodiode as current source.

5.9 Comparators

Comparators are used to compare two input voltages and produce an output depending on whether one voltage is greater or less than another. In its simplest configuration a comparator made from an op-amp is as shown below.

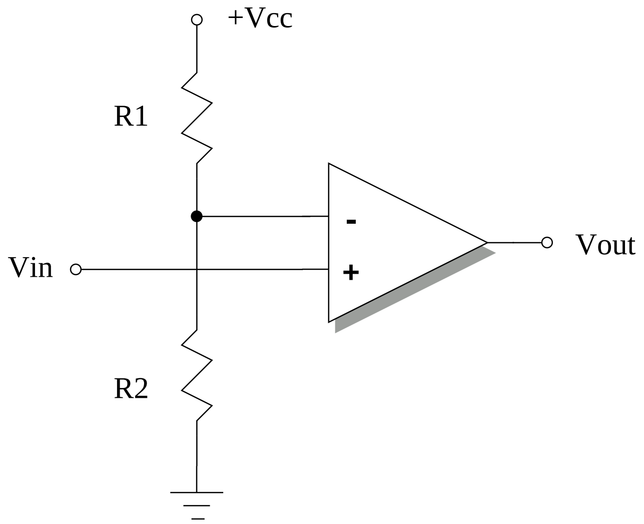


Figure 5.8: Op-amp as a comparator.

Exercise 30. Simulate the above comparator with $R_1 = 6$ kΩ, $R_2 = 3$ kΩ and drive with an input sine wave of amplitude 5 V and frequency 1 kHz and look at the output. Vary the relative values of the resistors and look at the effect on the output.

5.10 Integrators and Differentiators

Integrators and differentiators can also be constructed using op-amps, as shown in the figure below.

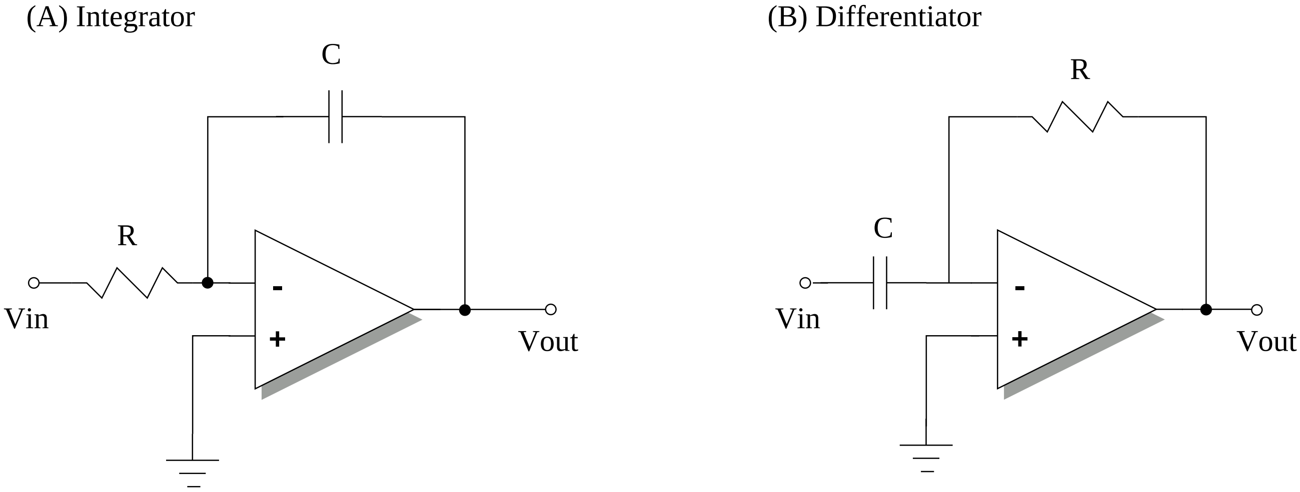


Figure 5.9: Op-amp integrator and differentiator.

In the integrator circuit a current, ($I = V_{in}/R$) flows through the resistor and the feedback capacitor (until saturation occurs). Since $Q = -VC$ and $Q = It$ for a capacitor, the voltage dropped across the capacitor must be

$$V_{out} = \frac{Q}{C} = \frac{It}{C} = -\frac{1}{RC}V_{in}\,t \tag{5.12}$$

i.e. the output increases linearly with time, until saturation occurs. This is useful for generating triangular waveforms - check in TINA by driving an integrator ($R = 10$ kΩ, $C = 0.01$ μF) with a 5 V, 100 μs square wave.

A more general derivation reveals that

$$V_{out} = -\frac{1}{RC}\int V_{in}t \tag{5.13}$$

If $RC = 1$ then

$$V_{out} = -\int V_{in}dt \tag{5.14}$$

Exercise 31. Use two op-amp integrators to solve the differential equation for an object falling under the force of gravity

$$\frac{d^2y}{dt^2} = 10 \tag{5.15}$$