

ENGG1000 Engineering Design and Innovation

Electrical Stream Laboratory Guide and Exercises

1.0 Laboratory Etiquette and Safety

To begin, please note that use of the EE&T laboratory facilities is conditional on adhering to the following rules:

- You may not smoke, eat or drink in the laboratories.
- Covered footwear must be worn at all times.
- Bags and loose clothing must be stored under the benches. The most common form of accident in laboratories is tripping, so this rule is much more important than you may think.
- You may not, under any circumstances, wire your own project directly to the mains. For this subject, all designs are to be powered either by batteries or from the power supplies provided in the labs.
- Please report any equipment failures or unsafe mains cords to laboratory technical staff or to one of the laboratory demonstrators.

In addition to the above safety guidelines, you should remember that the School's laboratories are a shared resource, to be treated with care and respect. Before leaving the laboratory, please

- turn off and unwire any equipment you have used;
- put all equipment, leads and components away; and
- store lab stools under the bench.

2.0 Laboratory Test Equipment

This provides a brief guide to the equipment you will see in the laboratory. These basic items of equipment are used throughout many (perhaps most) electrical engineering courses, and are found widely in industrial labs. If you have questions about the equipment, ask the demonstrators.

2.1 DC Power Supply

In general the DC power supply will provide a useful and more flexible alternative to using batteries for your project work. Note that some integrated circuits require positive and negative supply, e.g. $\pm 6V$, as well as ground. For this, ensure that the power supply is in series mode (the front face of the power supply should show which button combination is required for this), then use the left-most negative terminal as the negative supply, the right-most positive terminal as the positive supply, and either the left positive or the right negative terminal as ground. Once you have set this up, test it with the multimeter or oscilloscope and get help from a demonstrator if what you see is not what you expect.

2.2 Digital Multimeter

The digital multimeter is a simpler alternative to the oscilloscope for measuring voltages that do not change over time (or that change **very** slowly with time). Most voltages you will use in this course will be DC, so ensure that the AC/DC button is set accordingly. Also ensure that you have the leads connected to the correct sockets and the right voltage range set. Multimeters can also measure resistance and current, but this is rarely done, because the LCR bridge (one per lab) is more accurate for measuring resistance, and because current is usually measured in terms of voltage across a known resistance.

2.3 Signal Generator

In some instances, you will want to produce voltages that *vary with time* in order to test your circuits. **Note that any voltage/current that varies with time is not a DC voltage/current. DC voltages/currents are constant.** For example, you may want to turn an LED or a motor on once every second. For this purpose, the standard piece of test equipment is the signal generator, also known as a function generator. The signal generator can produce various types of waveforms, including square waves, sinusoids and triangular waves. For these laboratory exercises, we use a square wave – the main characteristics of this are as follows:

- The maximum voltage (known as amplitude, if the wave is symmetrical about zero Volts): Make sure you know how to control this on the signal generator.
- The minimum voltage: See if you can figure out how to control this. Note that there is an offset knob.
- The period T , measured in seconds — equivalently, the frequency $f = 1/T$, measured in Hz (cycles/second).
- The duty cycle, meaning the percentage of each period spent in the high voltage state — typically 50%.

Be careful not to use the “TTL output” – this output is designed to produce a fixed 0V / 5V square wave for use with logic circuits and this can easily cause confusion.

2.4 Oscilloscope (CRO)

Having generated periodic test signals like the square wave in section 5.1, we need a piece of equipment that allows us to visualize them. The oscilloscope does this, by locking on to a periodic signal (a process known as ‘triggering’) and displaying usually just a few periods of it.

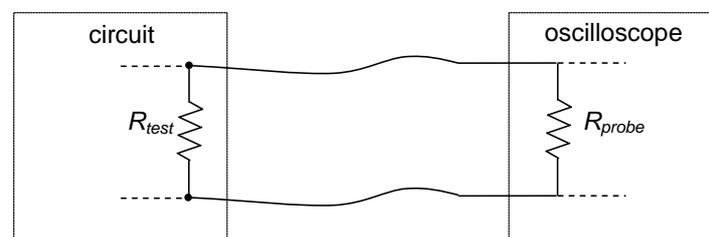
Early oscilloscopes used a cathode ray tube for the display, and were known as cathode ray oscilloscopes (CROs) - there are still a few of these in the labs. Nowadays most oscilloscopes are digital, although the principles of operation are similar.

The key features of the oscilloscope are:

- You can adjust the horizontal time base of the oscilloscope manually. Make sure you know how.

- You can adjust the vertical (voltage) scale of the oscilloscope manually. Make sure you know how.
- Manual adjustment alone cannot be expected to yield an exact lock with the periodicity of the signal under test. For this reason, all oscilloscopes provide an electronic triggering mechanism which automatically adjusts the flyback period (by a small amount) so that the start of the trace is aligned with a defined event. Typically, this event is based upon the rate at which the input waveform rises (or falls). Play around with the triggering features on the oscilloscope.
- The oscilloscopes in the lab provide at least two separate channels, so you can observe and compare multiple signals together. Both channels share the same horizontal time base. For each channel, you can adjust the vertical gain, controlling the way in which input signal voltage is converted into vertical displacement on the screen. You can also adjust the vertical offset of each channel, allowing you to separate the channels on the screen. Make sure you know how to do these things.
- The oscilloscope has three important settings for each channel: GND, AC and DC. The GND setting will show a straight horizontal line at 0 V. This is handy for working out where 0 V is, but usually there is also some kind of indicator (e.g. a triangle or arrow) at the left of the screen for this. The DC setting will show time-varying waveforms **with** their DC (constant) offset. Think of the DC setting as showing the “true” voltage waveform. The AC setting will show time-varying waveforms **without** their DC (constant) offset. Think of the AC setting as showing the voltage waveform but with a mean of zero. Often the DC offset can be important, so we usually use the DC setting in preference to the AC unless the signal is small-amplitude with a large offset.

Before concluding this section, note carefully that the oscilloscope is itself an electronic circuit. Ideally, it would have absolutely no effect on the circuit being tested, however in practise, it needs to draw a small amount of current from the circuit in order to measure it. This might alter the circuit’s behaviour, particularly if the part of the circuit being measured has a very large resistance. To avoid this, ensure that $R_{probe} \gg R_{test}$, i.e. R_{probe} is much larger than the resistance being tested R_{test} . See whether you can find out what the oscilloscope’s probe resistance (impedance) is.



3.0 Common Errors in Circuit Construction or Testing

Try to avoid the following common errors:

- All black leads (assuming you are using black for the ground connection – this is conventional), from power supplies, function generators and test equipment,

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Acknowledgement: Parts of these notes, in particular lab exercises, developed by Prof D. Taubman

must be connected to the same point in the circuit. If you don't, you risk creating a ground at other points in your circuit (since the equipment may be grounded to a common point, so that the ground connections), and hence an unintended short circuit.

- An example of this is as follows: suppose you are asked to measure the voltage across R_1 in the circuit for Experiment 1. The temptation is to connect the red lead to the top of R_1 , and the black lead to the bottom of it. If you do this, you will be creating a ground at the bottom of R_1 , and a short-circuit across R_2 . Instead, keep the black lead at the ground point, and separately record the two voltages at the top and bottom of R_1 using the red lead.
- All current measurement should be done by measuring the voltage across a resistor. It is possible to place a DC multimeter in series with your circuit, however (i) this will not help if your circuit contains AC components (oscilloscopes cannot be connected in series with your circuit), and (ii) the multimeter does not have zero resistance, so including it in your circuit may change your circuit's behavior.
- A multimeter cannot be used to measure the voltage or current of a circuit that is not a DC circuit, i.e. if the voltage is varying at all, don't use a multimeter (multimeters can measure AC rms voltages, but this is not used in ENGG1000). In general, because oscilloscopes can measure both AC and DC voltages, use an oscilloscope first. If you're sure that the part of the circuit you're interested in is only DC, then connect a multimeter to it.

4.0 Some Practical Tips

Looking at a circuit on paper or in an equation is one thing. Building and testing it in the lab is another. Over this and future courses, you will learn a great deal about how to build, test and debug circuits and other kinds of engineering constructions (e.g. computer programs). Here is a small subset of practical tips that may help when things are not working.

4.1 Does my circuit match the diagram ?

What is the circuit diagram ? First of all, any circuit you build in this course (or any other) should exist as a circuit diagram – in your note book, in course notes, on the Internet, in a book etc. Try to understand as much as you can about the circuit before you start to build it.

Is everything connected ? Check every point in the circuit, and ensure that all components are connected. On your prototyping board, not all rows of holes are connected: make sure that where you have assumed two components are connected, that they actually are. Once you have a power supply in your circuit, you can check this by testing the voltages at the component leads that are to be connected (should be identical).

Have I double-checked ? Constructing circuits with more than a few components can easily result in a mistake. Double-check everything, or get a team member to check it for you.

4.2 Why isn't something happening ?

Do I know what I should be seeing ? The purpose of any test is to determine whether a circuit or component is behaving the way you expect. *You need to have an expectation about how the circuit or component should behave before you test.* If you don't, read any relevant notes you have and/or talk with your lab demonstrator.

Why is everything zero ? Check that the power supply is plugged in and switched on. Very occasionally, a connector lead may be faulty. In this case, be an engineer: swap it with another one (without changing anything else) and work out if the lead is actually the cause of the problem.

4.3 Everything is OK, but the circuit doesn't work

Do you have any test equipment connected to your circuit ? Don't expect help from a lab demonstrator until you do.

Which part of the circuit doesn't work ? The first question when debugging is: "can I test something simpler ?" If your circuit consists of a voltage divider followed by an op-amp amplifier, then test the voltage divider on its own and the op-amp amplifier on its own. If your test signal is complex, disconnect it and replace it by something simple and known, like a sinusoid from the function generator.

Test the voltages of the circuit at all the nodes. Are they what you expect ? If not, or if you don't know what to expect, ask your demonstrator.

Why is the oscilloscope display wrong ? Make sure that the problem is not with your oscilloscope settings. If you are using a signal generator as input, attach the channel 1 leads to the signal generator output, and fix all the settings for this input (why? You know what to expect from the signal generator, and it's independent of your circuit). *Then*, attach the channel 2 leads to the part of your circuit you want to test.

4.4 Everything was OK, but I bumped my circuit and now it doesn't work

It is tempting to just plug a whole lot of components into the prototyping board to get something working. To achieve a robust implementation that is also easier to see and to test, do the following:

- Cut all the leads back (you may need pliers for this) so there is just enough length to position them securely in the prototyping board holes. Then your components and connecting wires will be flat on the board, which means that they won't touch other component leads and e.g. cause unwanted short circuits.
- Use as few connecting wires as you can.

- Color-code your connecting wires, so you can easily understand what each wire is for.
- Securely attach the alligator clips to your circuit, when using test equipment.

5.0 Experiments

Please note that these experiments are not compulsory, nor will attendance be marked. It will be assumed that you use these laboratory exercises to familiarize yourself with constructing and testing circuits, for two reasons:

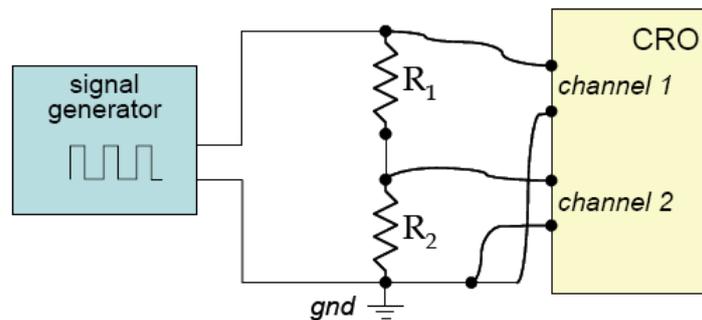
- You will need this knowledge in order to build and test the electrical parts of your design
- Your understanding **will be assessed in the lab skills test**.

5.1 Experiment 1: Voltage Divider

In this experiment, you will select two resistors R_1 and R_2 and use them to construct and measure a voltage divider circuit, as shown in Figure 7. The symbol marked “gnd” in the figure is not an explicit connection. Instead, this symbol is used to indicate a (ground) wire that we think of as the reference for all our signals and measurements. This reference wire is understood as having an electric potential of 0 volts. The signal generator output and oscilloscope input channels also have one wire identified as the ground — this is the wire which is connected to the external metal ring on the BNC connector. While not always necessary, it is good practice to connect the ground lines together on all instruments. This is true of the configuration shown in Figure 7. One reason for sticking to this practice is that the “gnd” connections on the oscilloscope are usually all connected internally to the metal case of the instrument (if there is one), which is also connected to the “earth” lead in the mains power cord. Other instruments may also connect their “gnd” terminals to earth, depending on how they are configured.

In this experiment you use both channels of the oscilloscope. Think of channel 1 as the input channel; it is monitoring the square wave voltage source provided by the signal generator. Think of channel 2 as the output channel; it monitors the reduced voltage waveform produced across resistor R_2 . This is the output of the voltage divider.

- Sketch the voltage divider circuit in your lab notebook.
- Derive a simple formula to express the voltage at the output of the voltage divider in terms of its input (also in your lab notebook) — this is an important formula to remember!
- Play around with various values for the resistors and check that you understand what you see on the oscilloscope.



Experiment 1 configuration.

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5.2 Experiment 2: Driving an LED

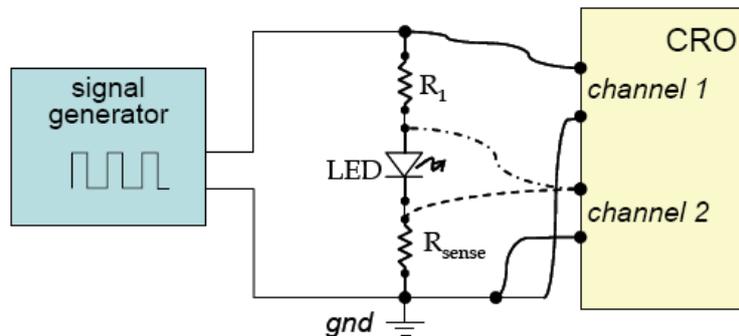
In this experiment, you use the signal generator to drive a Light Emitting Diode (LED). Unlike a resistor, the relationship between voltage and current in a diode is not linear. As a first order approximation, assuming the diode is forward-biased, you may think of diodes as devices which like to maintain a constant voltage between their two terminals, regardless of the amount of current which flows through the diode. An LED is a special type of diode which emits light as electrons move across the electric potential between the terminals. Current will flow through a diode only in one direction, from the anode to the cathode, which means that they can only consume power.

Note: The anode is always the longer of the two leads, unless of course you have cut them, in which case you can look for the small “flat” side on the LED, together with the device’s datasheet (found via <http://engg1000.ee.unsw.edu.au/components.html>)

In this experiment, we are interested in measuring the current flowing through the LED, as well as the voltage across the LED. Figure 8 shows an appropriate configuration. To begin the experiment, you might like to omit the sensing resistor R_{sense} altogether, connecting the LED’s cathode directly to ground and using oscilloscope channel 2 to measure the voltage across the LED.

- Select resistor R_1 and a signal generator output voltage so that the current through the LED is on the order of 10 mA. If you don’t know how, ask!!
- Start with a very low frequency square wave so that you can see the LED turn on and off with your naked eye.
- Now choose a current sensing resistor R_{sense} , which is sufficiently small that it does not interfere with the circuit. Use oscilloscope channel 2 to measure the voltage across R_{sense} , and hence the current flowing in the LED.
- How small should R_{sense} be? If you don’t know, ask, but think about it first!!
- Can you still measure the voltage across the LED while R_{sense} is in place?
- What happens to the voltage across the LED and to the current as the signal generator output voltage is adjusted?

- See if you can find out (not by experiment) how much current can be passed through the LED before it burns out — make sure you know where to find this information.



Configuration for experiment 2.

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5.3 Experiment 3: Introduction to Transistors

In this section, we will take a look at a three terminal device known as the bipolar junction transistor (BJT), whose principle purpose is to amplify current. This will allow us to build something which behaves like a current source — i.e., a sub-circuit which acts to maintain a constant flow of current, regardless of the potential across which the current flows. This is the dual of the more familiar voltage source (battery or signal generator). The transistor also allows us to make electronic switches, digital logic (e.g., computers) and a great deal else that is useful.

The configuration for this experiment is shown in Figure 9. From now on, we no longer explicitly show the signal generator or oscilloscope, but we identify the inputs and outputs of the circuit through V_{in} and V_{out} . As before, drive V_{in} with the signal generator and measure the input and output together, using oscilloscope channels 1 and 2. This experiment calls for a separate power supply of $V_{CC} = 12$ volts, for which you will use the lab's bench-top power supplies. If you are using a breadboard, it is customary to attach the power supply via the red (+) and black (-) terminals.

The three terminals of the transistor are known as the collector (C), emitter (E) and base (B). In this experiment, we are using an NPN transistor, which is schematically identified by an arrow pointing out of the emitter, as shown in the figure. Before hooking up this experiment, here is a brief summary of the properties of the NPN BJT.

The two-terminal device formed by the base and emitter terminals of the transistor acts exactly like a diode (actually, it is a diode). The base is the anode and the emitter is the cathode. This means that current flows into the base and out of the emitter. As with any diode, the base-emitter junction acts to maintain a roughly constant voltage across its terminals. Silicon transistors exhibit a base-emitter voltage drop of $V_{BE} \approx$

0.6V to 0.7V depending on the amount of current that flows. This is the same voltage drop that you will encounter with silicon diodes (i.e. the turn-on voltage V_{on}).

Current also enters the collector and flows out of the emitter. All current entering the collector must exit via the emitter, just as all current entering the base must also leave via the emitter. We can write this as:

$$I_E = I_B + I_C$$

The presence of a small current flowing in the base induces a much larger current to flow in the collector. The current gain of the transistor is usually expressed through the symbol β (also known as the H_{FE}), where

$$\beta = I_C / I_B$$

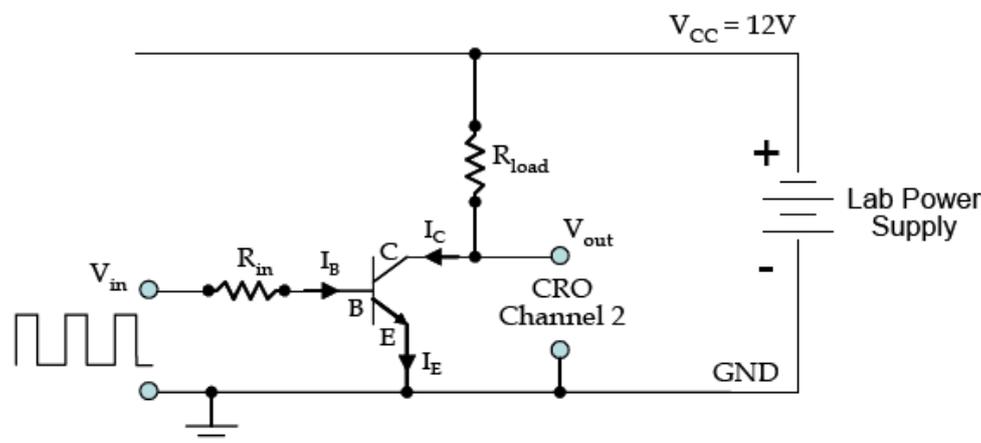
Small signal transistors (i.e., not power transistors) typically have β (H_{FE}) values in the range 50 to 1000.

Now you are ready to experiment with the NPN transistor with which you have been supplied in the lab. These have the following properties:

- Part Number = BC-549
- Package Type = TO-92h — looking from the bottom, with the flat edge on your left, the pins from top to bottom are E, B then C.
- Max forward current, $I_{C(max)} = 100$ mA. For more information, consult the datasheets via <http://engg1000.ee.unsw.edu.au/components.html>

As a starting point, select $R_{load} = 100 \Omega$ and $R_{in} = 10$ k Ω and adjust the output of the signal generator to supply a maximum signal of only a few volts (make sure $V_{in} \leq V_{CC} = 12V$), since otherwise the base-collector junction may become forward biased, causing current to flow from the base into the collector (not desirable).

- Use the observed V_{out} waveform to deduce the current flowing in R_{load} .
- Verify that the V_{BE} is essentially independent of the amount of current flowing in the base by adjusting the signal generator input V_{in} , while using the oscilloscope to monitor the base voltage.
- Calculate the base current, using the observed V_{in} and V_{BE} values. Hence, calculate the current gain. Repeat the current gain calculation at a few different input voltage levels.
- Verify that the collector current does not depend on the load resistance R_{load} . How can you do this? Ask a demonstrator if you are not sure!!



Configuration for experiment 3.

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5.4 Experiment 4: Introduction to Digital Logic

Digital logic, and hence computers, can be constructed from any switching elements which have power gain, meaning that the power required to drive the switch is less than the power which can be switched. This property allows the switch to drive multiple downstream switches, which turns out to be all that is required. Switches can be constructed from electron tubes (valves), mechanical relays, superconducting quantum interference devices (SQUIDS) and a host of other devices, all of which offer the potential to build computers. In this experiment, we will use either the switching and amplifying properties of transistors to construct two logic devices (option A) or digital logic integrated circuits (option B - recommended).

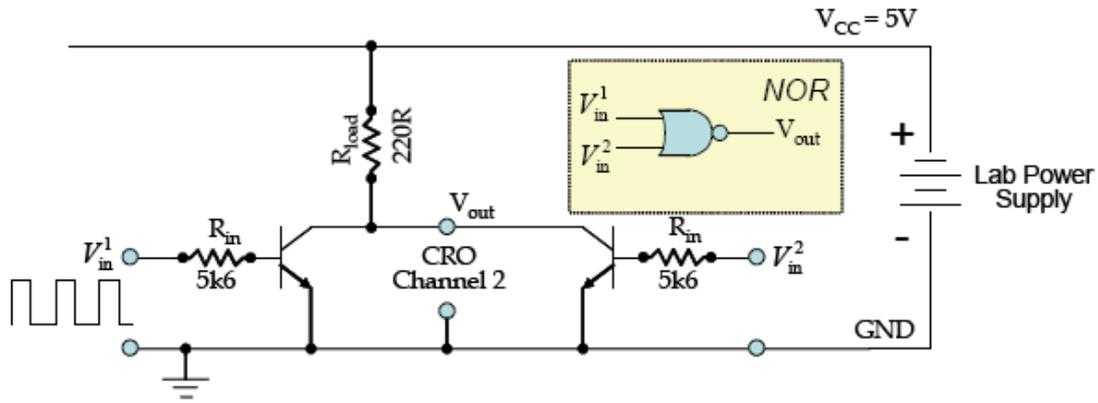
Option A: NOR Gate Using Transistors

The figure below shows an elementary logic gate constructed from two NPN transistors. The gate has two inputs, V_{1in} and V_{2in} and one output, V_{out} . The supply rails to the logic circuit are $GND = 0V$ and $V_{CC} = 5V$ in this experiment. Other values could easily be selected here, although the packaged (TTL) logic devices you will be using all require $V_{CC} = 5V$ for their power source. Each input to the gate is interpreted as taking one of two possible states:

- Low state (logical 0): This corresponds to an input voltage close to $0V$ — in our circuit, anything less than $V_{BE} \approx 0.6V$ is interpreted as a low state.
- High state (logical 1): This corresponds to an input voltage close to V_{CC} — in our circuit, voltages of $1V$ or more should be sufficient to turn the relevant NPN transistor on, producing enough collector current to pull the output voltage down close to GND .

When each of the inputs is in one of these two states, the output of the gate will also be in one of the low or high states and is thus able to drive the inputs to other gates. Cascading simple gates in this way can result in complex logical functions. The logic gate implemented in the figure is known as a NOR gate, which is a contraction of NOT-OR. An OR gate produces a logical 1 (high) output if either or both of its inputs are 1's (high). The NOR gate provides an inverted output, which is 0 (low) when either or both of the inputs are 1 (high).

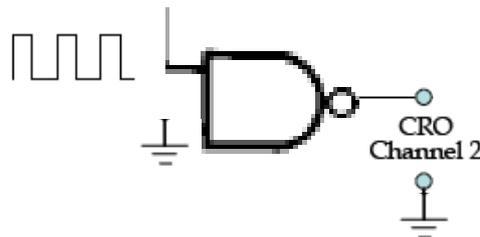
- Test the behaviour of the NOR gate by applying the signal generator to one of the inputs and tying the other input alternately to V_{CC} and GND , while using the oscilloscope to monitor both the signal generator's signal and the gate's output voltage.
- Find out the thresholds associated with low and high input states. How do these depend upon the resistors in the circuit?



Implementing a NOR gate using two NPN BJT's.

Option B: NAND Gate Using Integrated Circuits

Connect a 74LS00 integrated circuit carefully to the power, then implement a single NAND gate as shown below. Test the behaviour of the NAND gate by applying the signal generator to one of the inputs and tying the other input alternately to V_{CC} (=5V) and GND, while using the oscilloscope to monitor both the signal generator's signal and the gate's output voltage (CRO channel 2). The input voltage waveform (square wave) should have a minimum voltage of 0V, and a maximum voltage of 5V.



Check that the observed voltages at the output match those predicted by the truth table for a NAND gate.

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