E85: Digital Design and Computer Architecture

Lab 1: Electrical Characteristics of Logic Gates

Objective

The purpose of this lab is to become comfortable with logic gates as physical objects, to interpret datasheets, and to use test-and-measurement equipment to characterize their physical properties including voltage transfer characteristics, power consumption, and propagation delay. Specifically, you will use a breadboard, multimeter, and oscilloscope. You will connect gate inputs to switches and outputs to LEDs to visualize the behavior. You will explore the voltage transfer characteristics, delay, and power consumption of a 74HC04 inverter, a transistor-level inverter, and a ring oscillator. You will then design, build, and test a full adder with logic gates.

1. Tutorial: Test and Measurement Equipment

In this lab, you will use a breadboard, multimeter, and oscilloscope.

Breadboard

Familiarize yourself with the breadboards in the E85 lab. Use an ohmmeter and some bits of wire to check which rows in the breadboard are connected. You should confirm that horizontal rows of five holes are connected. Vertical columns are also connected and are intended for power and ground, but note that the top and bottom half of each column is not connected on this breadboard, making it easy to accidentally not power your circuits.

Check the voltage supplies with a voltmeter. Confirm that the 5V supply puts out the correct value and try adjusting the variable positive and negative supplies while monitoring their values.

Wire up a logic switch to an LED. Make sure the switch is in the +5 position, not the +V position (which uses the variable voltage). Check that you can toggle the LED on and off. Look at the voltage with a multimeter and check that it matches your expectations.

Taking the time to wire neatly will usually save you time in the long run because your circuit will be easier to debug. Never run a wire directly over a chip because you may find you need to remove and replace the chip.

When you are done building circuits, return the components to the supply drawers only if the circuit worked correctly. Use an IC extractor to carefully rock chips out without bending the pins. If you have reason to suspect a chip was damaged, throw it in the trash rather than making your classmates unhappy.

If you are concerned that a piece of equipment in the lab is not working correctly, please put a sheet of paper on it with the symptoms and notify the instructor immediately. Your classmates

will be grateful. Even if you are uncertain about whether the equipment is working, it is better to report it than ignore it.

Oscilloscope

An oscilloscope can be used to measure repetitive (periodic) signals or one-time events. AUTO mode is easy for periodic signals, but for one-time events you'll need NORMAL mode. Many interesting digital events thus require normal mode.

Sometimes folks leave the oscilloscope in a weird configuration. If you are bamboozled, hit the Setup button and choose Default Setup to get to a known reasonable state.

To measure a one-time event, press the Trigger Mode button and choose Single (on some scopes, Normal). Set the Trigger Source to the channel of interest (e.g channel 1). Set the Trigger Slope to rising, and adjust the trigger level knob to the midpoint of your expected event (e.g. 2.5 V). To measure a repetitive event, press the Trigger Mode button and choose Auto Lvl.

It is easy to misconfigure an oscilloscope and thus miss your signal. Always test your scope on a known signal before attempting to measure an unknown signal. Use AUTO mode to measure a 1.0 KHz TTL-level square wave clock signal coming from the function generator on your breadboard. The AutoScale button may be helpful here. Use the cursors or automatic measurement capability to find the amplitude and frequency. Use SINGLE mode to measure the waveform as you toggle a logic switch. The AutoScale button won't help you at all here. Do you observe any switch bounce?

2. Tutorial: Data Sheets

In this lab, you will use 74HC-series logic gates and TN2106/TP2104 transistors.

You can find the pinouts of common 74-series logic gates in Appendix A.2.1 of the textbook (online and on the class web site) and the 74HC04 datasheet in Appendix A.5. Read these sections and learn to interpret the 74HC04 datasheet.

The transistor datasheets are on the class web site.

3. Gates, Switches, and LEDs

The circuit shown below has a pushbutton switch, two light-emitting diodes (LEDs), and two inverters. Select appropriate resistor values for R1-R3.
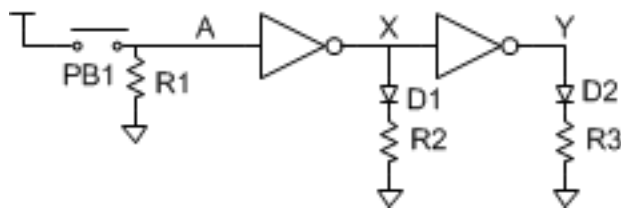
Build the circuit on a breadboard. Use switches and LEDs from the supply cabinet rather than the ones built into the board, so you become comfortable with how to wire them up. Use a multimeter to determine how the pushbutton switch pins are connected. Remember that an LED has polarity; the shorter leg is the cathode and goes to the lower voltage. Predict what the LEDs should do as you press and release the switch, then test your circuit and resolve any discrepancies.

If your measurements reveal suspicious behavior, make sure that power and ground are attached to the chip. It is possible to damage chips, especially by shorting an output to power or ground or another output.

4. 74HC04 Inverter Electrical Characteristics

Wire up a 74HC04 inverter on a breadboard. Use $V_{DD} = 5V$. Connect one input to an adjustable voltage. Measure the input and output voltages on the oscilloscope.

Adjust the input voltage and record the output, then enter your data into a spreadsheet or Matlab or your favorite plotting program and generate a plot of the voltage transfer characteristic (VTC). Be sure to take enough data points at the interesting parts of the curve to capture it faithfully, and to show your actual data points in your graph. Determine V_{IH}, V_{IL}, V_{OH}, and V_{OL}. Are they within the specifications of the datasheet? Explain any discrepancies.

With all of the inputs grounded, measure the quiescent power consumption of the 74HC04 chip with an ammeter. Is it within the specification of the datasheet? Explain any discrepancies.

## 5. CMOS Inverter Electrical Characteristics

Sketch a schematic of an CMOS inverter built from TN2106 and TP2104 nMOS and pMOS transistors.

Build your circuit on a breadboard. Beware that discrete MOS transistors are particularly static sensitive. Ground yourself by touching a large metal object before handling your transistors.

Set $V_{DD} = 5$ V. Measure and plot the VTC. Determine V_{IH}, V_{IL}, V_{OH}, and V_{OL}.

6. Ring Oscillator

Draw a schematic for a 5-stage ring oscillator, as shown below. Label the pin numbers of each inverter input and output using a 74HC04 chip. Build your circuit on a breadboard. Think about the circuit and predict what it should do. Then capture the output on the oscilloscope and compare with your expectations. Measure the period and frequency of the output. From this measurement, calculate the average propagation delay of an individual inverter. Also measure the power consumption of the circuit. Why is it higher than the quiescent power consumption from Part 4?
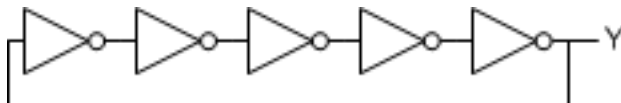
7. Full Adder

Design a *full adder*. The inputs are A, B, and C_{in}. The outputs are S and C_{out}. The full adder computes $\{C_{out}, S\} = A + B + C_{in}$. In other words, it sums the three inputs to produce a two-bit result, with S being the least significant bit and C_{out} being the most significant bit. C_{in} and C_{out} are called the carries. For example, if A = 1, B = 0, and Cin = 1, the result is $1 + 0 + 1 = 2_{10} = 10_2$. Thus the sum is 0 and the carry out is 1. Although the logic for a full adder is in the textbook and many other places, please work it out yourself from first principles.
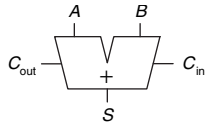
Write the truth table below for your full adder. Sketch a schematic using 74-series components. Label each gate with the part number (e.g. 04 for a 74HC04 inverter) and label each gate's inputs and output with the pin number as described in Appendix A.7. Build your circuit on the breadboard. Connect the inputs to logic switches and outputs to LEDs. Try all eight inputs and check that the outputs match your truth table. Debug any discrepancies.

Inputs			Outputs	
C_{in}	B	A	C_{out}	S
0	0	0		
0	0	1		
0	1	0		
0	1	1		
1	0	0		
1	0	1		
1	1	0		
1	1	1		

Table 1. Full Adder Truth Table

What to Turn In

1. Please indicate how many hours you spent on this lab. This will be helpful for calibrating the workload for next time the course is taught.

2. Gates, Switches, and LEDs

    a) What resistor values did you choose? Why?

    b) Did your circuit function correctly?

3. 74HC04 Inverter

    a) Plot of VTC

    b) Input and output logic levels. Are they within the specifications of the datasheet?

    c) Measured power consumption, compared to data sheet value.

4. Transistor-level Inverter

    a) Plot of VTC

    b) Input and output logic levels

5. Ring oscillator

    a) Photo of oscilloscope trace of switching output, annotated with the period and frequency.

    b) Compute the average delay of a single inverter from the ring

    c) Measured power consumption

6. Full adder

    a) Truth table

    b) Schematic

    c) Do your measured outputs match your truth table in all eight cases?

If you have suggestions for further improvements of this lab, you're welcome to include them at the end of your lab.