

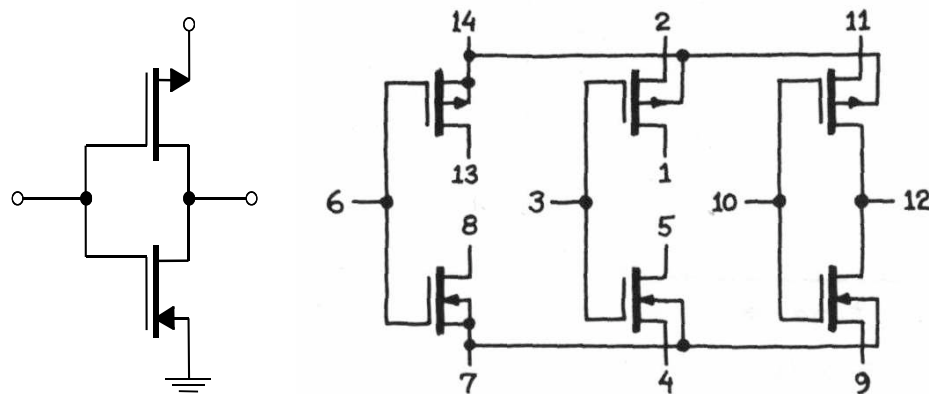
## Lab 8: Digital Circuit Elements

### Section A: CMOS Element and Watch Switching

The complementary MOSFET scheme (or CMOS) started the second revolution in computational machines. The limits of speed and density were conquered by the move to semiconductors and Very Large Scale Integration, but the power consumption and circuit cooling demands of bipolar transistors packed at extreme densities were formidable problems. The problem is that the transistors were always “on” (in other words drawing current and dissipating energy). CMOS circumvents this problem and allows bits to be stored without constant power consumption. A schematic of the CMOS inverter is given in the figure below. As discussed in class the device dissipates energy only when it is switched from high to low or back. Quiescent operation in either the high or the low state dissipates essentially no power. So cooling the circuit is much easier, and supplying power is much less of a problem. If you don’t believe me, just ask your calculator, digital watch or your laptop.

Connect  $V_{DD} = +5V$  and ground to the CD4007 pins as depicted below using only

$+V_{DD}$  in/out



one set of transistors. For example,  $V_{in} = \text{pin } 10$ ,  $V_{DD} = \text{pin } 11$ ,  $GND = \text{pin } 9$  and  $V_{OUT} = \text{pin } 12$ . Connect a  $500\Omega$  resistor between  $V_{DD}$  and pin 11 for better performance.

- Slowly ramp the input voltage from zero up through  $3.5V$ . At some point the output should switch from high to low. Note the voltage where the switch occurs.

Now connect a  $100\Omega$  resistor in series with pin 9 above the ground point.

- Try to measure the transient current with an ammeter (momentary voltage across the resistor) as you slowly ramp the input voltage up and down to make the output switch. If you can’t see the signal you can cheat by using the Miller effect by adding a medium sized capacitor between output and ground.
- Compare this value to a theoretical value by measuring the switching voltage and using Ohm’s law.

- Try to measure the intrinsic switching time and estimate the power consumption for such an inverter switched at 1MHz compared with a bipolar circuit where the devices is constantly passing current.
- Estimate the power consumption for switching at 1GHz.

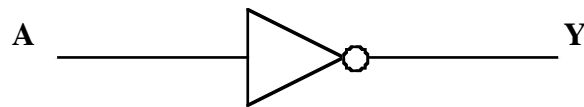
## Section B: Gates, Truth Tables, and Pull-up Resistors

### B-1 The Inverter

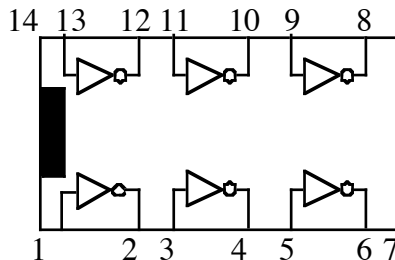
One of the simplest gates is the inverter. The Boolean equation for the inverter is:

$$Y = \bar{A}$$

The following is the diagrammatic representation of the inverter.



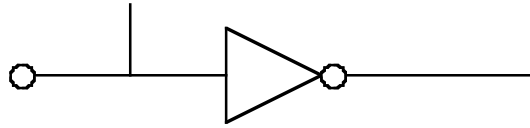
The 7404 chip contains 6 inverters and can be schematically represented as follows:



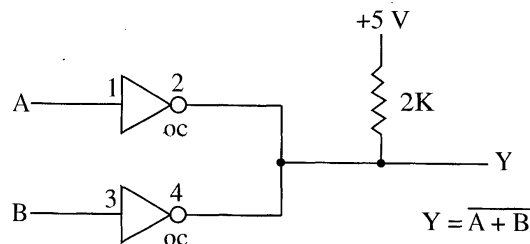
The diagram of the chip is drawn as if you are viewing it from above. Note the thick black line that is used as an orientation mark, located at the left end of the chip. Also note that pins 14 and 7 are not connected to an inverter, they are the power supply connections for the chip. Pin 14 must be held at +5 volts with respect to pin 7. No pin may be held at a voltage greater than that at pin 14 or less than that at pin 7. So if pin 14 is held at +5V then nothing can be greater than +5V and if pin 7 is grounded then you cannot have a voltage to the chip that is less than 0V. This supply pin assignment is common for 7400 series TTL. If you have a question about the wiring of a particular chip, refer to the TTL cookbook; a copy will be kept in the lab. You may also use the websites linked to the course homepage.

**Procedure**

1. Wire a 7404 inverter, on the Digi-Designer as follows:  
S1LEDLED12



2. Apply a clock signal from the clock on the Digi-Designer Box to the input of one of the inverters in the 7404 IC chip. Simultaneously look at the input and output on the oscilloscope and also the LED's on the Digi-Designer for a range of clock frequencies from 1kHz to 100kHz.
  - Comment on the input and output of the circuit. Are there any timing problems with this circuit?
3. Wire 6 inverters from the 7404 IC chip in series. Connect the Digi-Designer clock to the first inverter.
  - Observe the input of the 1st and the output of the last inverter simultaneously on the oscilloscope. Determine the "Propagation delay" through a single inverter.
4. Wire the following circuit using an open-collector inverter (7404). The  $2K\Omega$  "pull-up" resistor is necessary for speed and noise immunity when driving a TTL input. The numbers that you see on the diagram are to distinguish the input pins on the 7404 IC chip. So the 1 means that the input A should be connected to pin 1 on the 7404 IC chip and so on. The equation at the bottom right is the algebraic representation of the logical NOR function.
  - Verify that the circuit performs the logical NOR function.



- How does the inverter output differ from an inverting Op-amp that you worked with in Lab 6?

### B-2 Translating Boolean Equations Into Electronic Circuits

In many cases, translation of Boolean equations into electronic logic can be accomplished by a straightforward, one-for-one replacement of a term or group of terms in the equation by a gate. As an illustration, we will consider the 4-input data selector or "multiplexer".

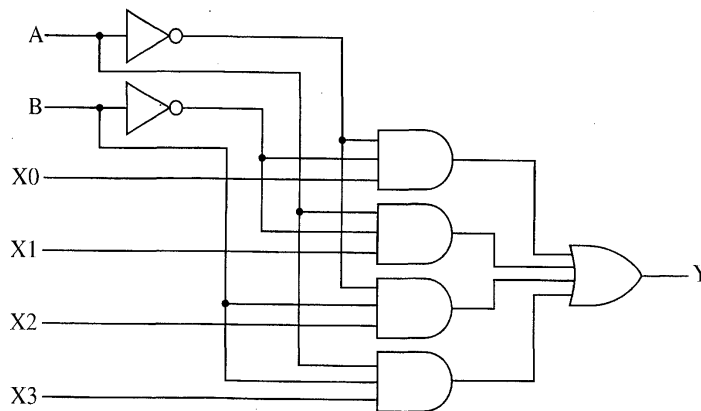
We have 4 digital signals that we would like to be able to send over a single wire. We need logic that defines the output Y of a circuit to be the *n*th input signal  $X_n$ , where the number, *n*, is given. Since *n* can take on 4 values, it must be a 2-digit binary number, which we will call BA. In other words, BA selects the input  $X_n$ , which will appear on the output. The truth table expressing this circuit is:

B	A	Y(output)
0	0	X0
0	1	X1
1	0	X2
1	1	X3

From this, a Boolean equation can be written by inspection.

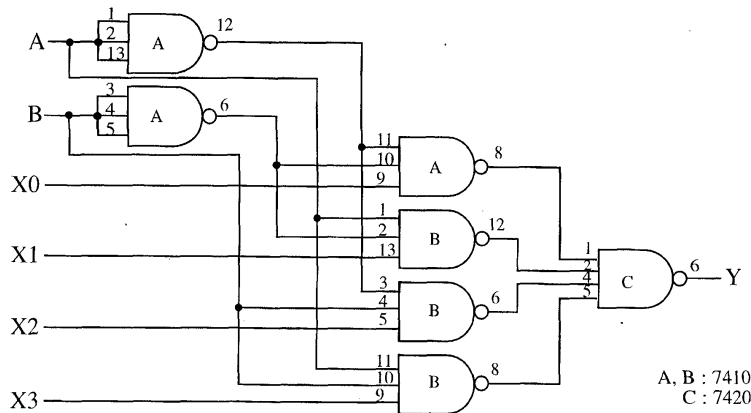
$$Y = (\bar{B} \cap \bar{A} \cap X0) \cup (\bar{B} \cap A \cap X1) \cup (B \cap \bar{A} \cap X2) \cup (B \cap A \cap X3)$$

From the Boolean equation above, the following schematic that describes the equation can be drawn.



In implementing the logic displayed in this diagram, we are slightly hampered by the fact that a 7400 series 4-input OR gate does not exist. The elegant solution to this problem involves DeMorgan's theorem and some common sense.

- Show that the circuit above is equivalent to the one below by writing the Boolean equations for both and using DeMorgan's Theorem to transform one into the other.

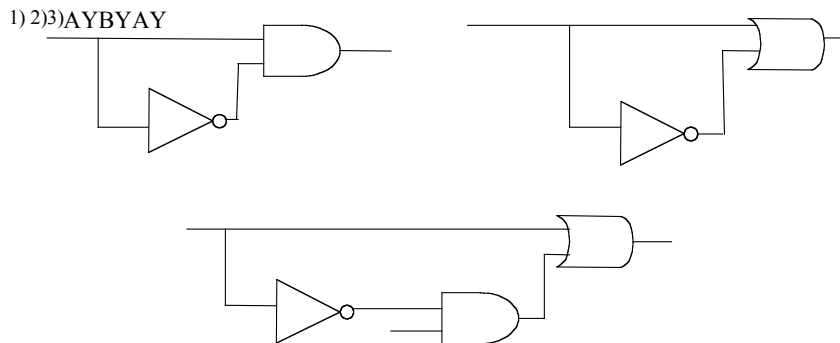


- Build the above circuit on your Digi-Designer and write out the truth table for the circuit. (Isn't this a real pain to build? Now imagine building the Pentium with its 50 million switches. That's why computers do all of the layout and wiring in foundries.)
- Verify that your circuit is working properly for 5 of the combinations in your truth table.

- Now, explain what sense - if any - can be made of the statement:

*+5V enables a NAND, forces a NOR. 0V enables a NOR, forces a NAND*

- Using other Boolean theorems, or common sense, simplify the following three circuits. Draw the simplified circuit, assuming that propagation delay can be ignored.



- Now, what happens if the propagation delay cannot be ignored? Draw a timing diagram for each original and simplified circuit. It's easiest to use graph paper for this. Are they still equivalent?

- Finally, connect five gates in series and then connect those gates to your neighbor's five gates and measure the propagation delay of the combined circuits. You and your neighbor should agree on the type of gates you wish to connect, but beyond that you are free to choose the type of gate you wish to study.
- Determine from your measurement what the propagation delay is for a single gate.