

Chapter 3: Digital Circuitry and Interfacing

Now we turn our attention to the physical circuitry and electrical quantities that are used to represent and operate on the binary codes 1 and 0. In this chapter we begin by looking at how logic circuits are described and introduce the basic set of gates used for all digital logic operations. We then look at the underlying circuitry that implements the basic gates including digital signaling and how voltages are used to represent 1s and 0s. We then look at interfacing between two digital circuits and how to ensure that when one circuit sends a binary code, the receiving circuit is able to determine which code was sent. Logic families are then introduced and the details of how basic gates are implemented at the switch level are presented. Finally, interfacing considerations are covered for the most common types of digital loads (i.e., other gates, resistors, and LEDs). The goal of this chapter is to provide an understanding of the basic electrical operation of digital circuits.

Learning Outcomes—After completing this chapter, you will be able to:

- 3.1 Describe the functional operation of a basic logic gate using truth tables, logic expressions, and logic waveforms.
- 3.2 Analyze the DC and AC behavior of a digital circuit to verify that it is operating within specification.
- 3.3 Describe the meaning of a logic family and the operation of the most common technologies used today.
- 3.4 Determine the operating conditions of a logic circuit when driving various types of loads.

3.1 Basic Gates

The term *gate* is used to describe a digital circuit that implements the most basic functions possible within the binary system. When discussing the operation of a logic gate, we ignore the details of how the 1s and 0s are represented with voltages and manipulated using transistors. We instead treat the inputs and output as simply ideal 1s and 0s. This allows us to design more complex logic circuits without going into the details of the underlying physical hardware.

3.1.1 Describing the Operation of a Logic Circuit

3.1.1.1 The Logic Symbol

A logic symbol is a graphical representation of the circuit that can be used in a schematic to show how circuits in a system interface to one another. For the set of basic logic gates, there are uniquely shaped symbols that graphically indicate their functionality. For more complex logic circuits that are implemented with multiple basic gates, a simple rectangular symbol is used. Inputs of the logic circuit are typically shown on the left of the symbol and outputs are on the right. Figure 3.1 shows two example logic symbols.

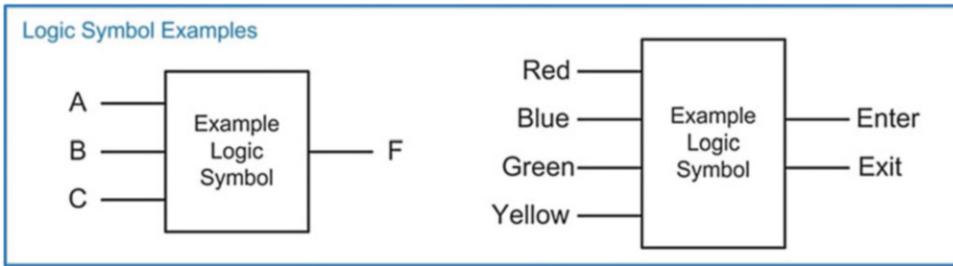


Fig. 3.1
Example logic symbols

3.1.1.2 The Truth Table

We formally define the functionality of a logic circuit using a *truth table*. In a truth table, each and every possible input combination is listed and the corresponding output of the logic circuit is given. If a logic circuit has n inputs, then it will have 2^n possible input codes. The binary codes are listed in ascending order within the truth table mimicking a binary count starting at 0. By always listing the input codes in this way, we can assign a *row number* to each input that is the decimal equivalent of the binary input code. Row numbers can be used to simplify the notation for describing the functionality of larger circuits. Figure 3.2 shows the formation of an example 3-input truth table.

| Truth Table Formation | | | | | |
|--|-----|---|---|---|---|
| | row | A | B | C | F |
| <p>Input codes are always listed in ascending order.</p> <p>Listing the input codes as a binary count allow each input's decimal equivalent to be used as the "row number"</p> | 0 | 0 | 0 | 0 | 0 |
| | 1 | 0 | 0 | 1 | 1 |
| | 2 | 0 | 1 | 0 | 1 |
| | 3 | 0 | 1 | 1 | 0 |
| | 4 | 1 | 0 | 0 | 1 |
| | 5 | 1 | 0 | 1 | 0 |
| | 6 | 1 | 1 | 0 | 0 |
| | 7 | 1 | 1 | 1 | 1 |

The corresponding output of the circuit is listed for each possible input code

Fig. 3.2
Truth table formation

3.1.1.3 The Logic Function

A *logic expression* (also called a *logic function*) is an equation that provides the functionality of each output in the circuit as a function of the inputs. The logic operations for the basic gates are given a symbolic set of operators (e.g., +, ·, ⊕), the details of which will be given in the next sections. The logic function describes the operations that are necessary to produce the outputs listed in the truth table. A logic function is used to describe a single output that can take on only the values 1 and 0. If a circuit contains multiple outputs, then a logic function is needed for each output. The input variables can be included in the expression description just as in an analog function. For example, "F(A,B,C) = ..." would state that "F is a function of the inputs A, B, and C." This can also be written as "F_{A,B,C} = ..." The input variables can also be excluded for brevity as in "F = ..." Figure 3.3 shows the formation of an example 3-input logic expression.

| Logic Expression Formation | | | |
|----------------------------|---|---|---|
| A | B | C | F |
| 0 | 0 | 0 | 0 |
| 0 | 0 | 1 | 1 |
| 0 | 1 | 0 | 1 |
| 0 | 1 | 1 | 0 |
| 1 | 0 | 0 | 1 |
| 1 | 0 | 1 | 0 |
| 1 | 1 | 0 | 0 |
| 1 | 1 | 1 | 1 |

$$F(A,B,C) = A \oplus B \oplus C$$

or

$$F_{A,B,C} = A \oplus B \oplus C$$

or

$$F = A \oplus B \oplus C$$

Fig. 3.3
Logic function formation

3.1.1.4 The Logic Waveform

A logic waveform is a graphical depiction of the relationship of the output to the inputs with respect to time. This is often a useful description of behavior since it mimics the format that is typically observed when measuring a real digital circuit using test equipment such as an oscilloscope. In the waveform, each signal can only take on a value of 1 or 0. It is useful to write the logic values of the signal at each transition in the waveform for readability. Figure 3.4 shows an example logic waveform.

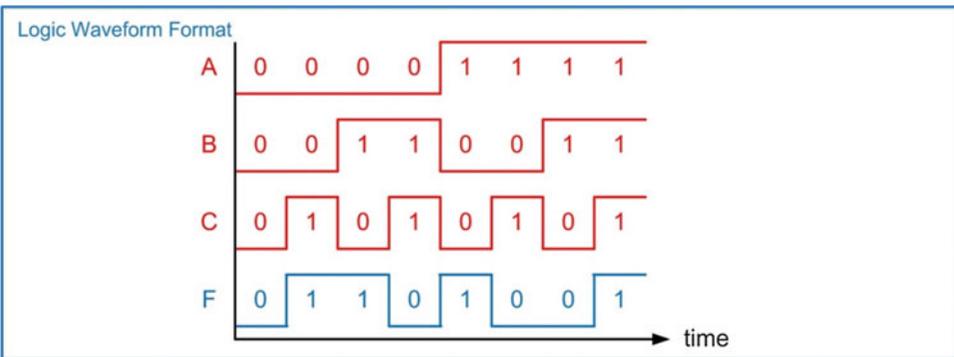


Fig. 3.4
Example logic waveform

3.1.2 The Buffer

The first basic gate is the *buffer*. The output of a buffer is simply the input. The logic symbol, truth table, logic function and logic waveform for the buffer are given in Fig. 3.5.

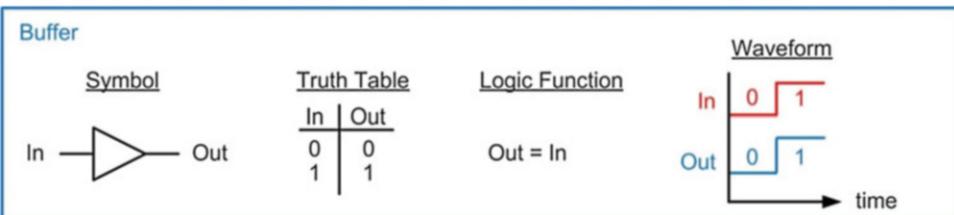


Fig. 3.5
Buffer symbol, truth table, logic function, and logic waveform

3.1.3 The Inverter

The next basic gate is the *inverter*. The output of an inverter is the complement of the input. Inversion is also often called the *not* operation. In spoken word, we might say “A is equal to *not* B”; thus this gate is also often called a *not* gate. The symbol for the inverter is the same as the buffer with the exception that an *inversion bubble* (i.e., a circle) is placed on the output. The inversion bubble is a common way to show inversions in schematics and will be used by many of the basic gates. In the logic function, there are two common ways to show this operation. The first way is by placing a prime (') after the input variable (e.g., $\text{Out} = \text{In}'$). This notation has the advantage that it is supported in all text editors but has the drawback that it can sometimes be difficult to see. The second way to indicate inversion in a logic function is by placing an *inversion bar* over the input variable (e.g., $\text{Out} = \overline{\text{In}}$). The advantage of this notation is that it is easy to see but has the drawback that it is not supported by many text editors. In this text, both conventions will be used to provide exposure to each. The logic symbol, truth table, logic function, and logic waveform for the inverter are given in Fig. 3.6.

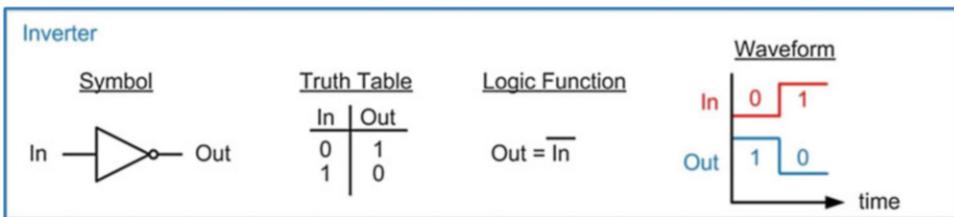


Fig. 3.6
Inverter symbol, truth table, logic function, and logic waveform

3.1.4 The AND Gate

The next basic gate is the *AND gate*. The output of an AND gate will only be true (i.e., a logic 1) if **all of the inputs are true**. This operation is also called a *logical product* because if the inputs were multiplied together, the only time the output would be a 1 is if each and every input was a 1. As a result, the logic operator is the dot (\cdot). Another notation that is often seen is the ampersand (&). The logic symbol, truth table, logic function, and logic waveform for a 2-input AND gate are given in Fig. 3.7.

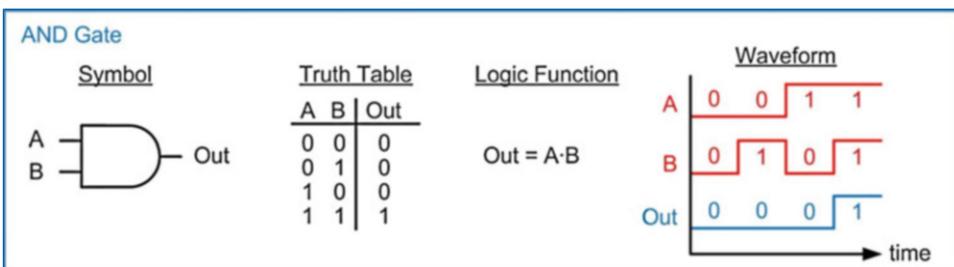


Fig. 3.7
2-Input AND gate symbol, truth table, logic function, and logic waveform

Ideal AND gates can have any number of inputs. The operation of an n-bit, AND gates still follows the rule that the output will only be true when all of the inputs are true. Later sections will discuss the limitations on expanding the number of inputs of these basic gates indefinitely.

3.1.5 The NAND Gate

The NAND gate is identical to the AND gate with the exception that the output is inverted. The “N” in NAND stands for “NOT,” which represents the inversion. The symbol for a NAND gate is an AND gate with an inversion bubble on the output. The logic expression for a NAND gate is the same as an AND gate but with an inversion bar over the entire operation. The logic symbol, truth table, logic function, and logic waveform for a 2-input NAND gate are given in Fig. 3.8. Ideal NAND gates can have any number of inputs with the operation of an n-bit, NAND gate following the rule that the output is always the inversion of an n-bit, AND operation.

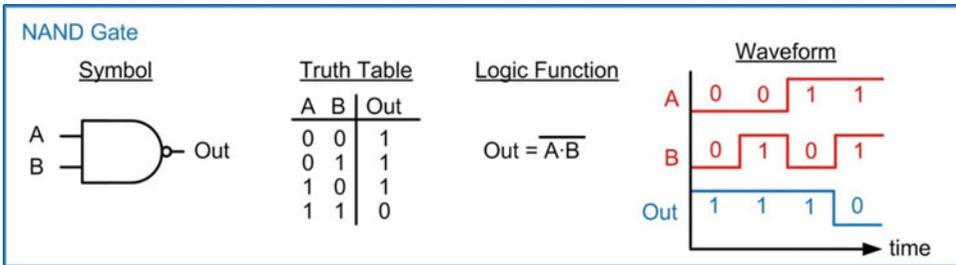


Fig. 3.8
2-Input NAND gate symbol, truth table, logic function, and logic waveform

3.1.6 The OR Gate

The next basic gate is the *OR gate*. The output of an OR gate will be true when **any of the inputs are true**. This operation is also called a *logical sum* because of its similarity to logical disjunction in which the output is true if *at least one* of the inputs is true. As a result, the logic operator is the plus sign (+). The logic symbol, truth table, logic function, and logic waveform for a 2-input OR gate are given in Fig. 3.9. Ideal OR gates can have any number of inputs. The operation of an n-bit, OR gates still follows the rule that the output will be true if any of the inputs are true.

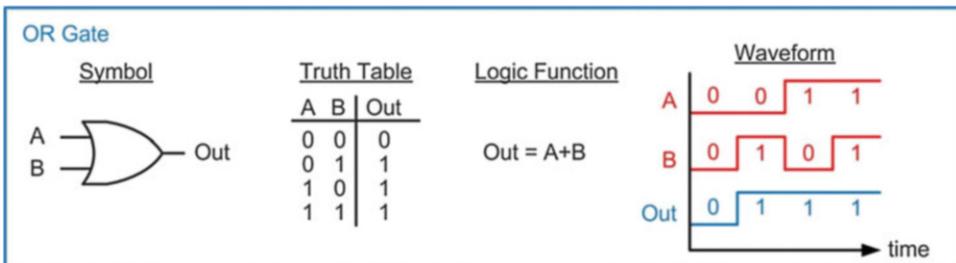


Fig. 3.9
2-Input OR gate symbol, truth table, logic function, and logic waveform

3.1.7 The NOR Gate

The NOR gate is identical to the OR gate with the exception that the output is inverted. The symbol for a NOR gate is an OR gate with an inversion bubble on the output. The logic expression for a NOR gate is the same as an OR gate but with an inversion bar over the entire operation. The logic symbol, truth table, logic function, and logic waveform for a 2-input NOR gate are given in Fig. 3.10. Ideal NOR gates can have any number of inputs with the operation of an n-bit, NOR gate following the rule that the output is always the inversion of an n-bit, OR operation.

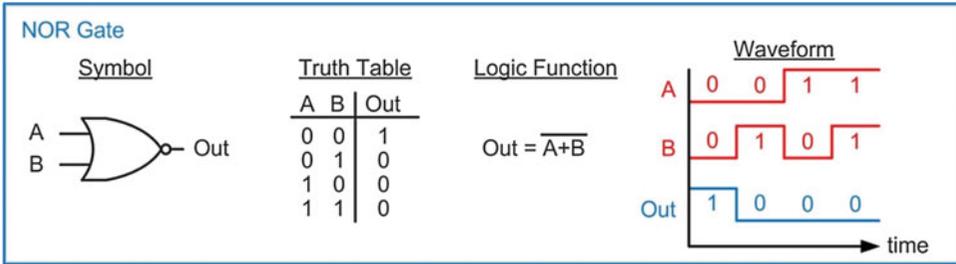


Fig. 3.10
2-Input NOR gate symbol, truth table, logic function, and logic waveform

3.1.8 The XOR Gate

The next basic gate is the *exclusive-OR gate*, or XOR gate for short. This gate is also called a *difference gate* because for the 2-input configuration, its output will be true when the **input codes are different from one another**. The logic operator is a circle around a plus sign (\oplus). The logic symbol, truth table, logic function, and logic waveform for a 2-input XOR gate are given in Fig. 3.11.

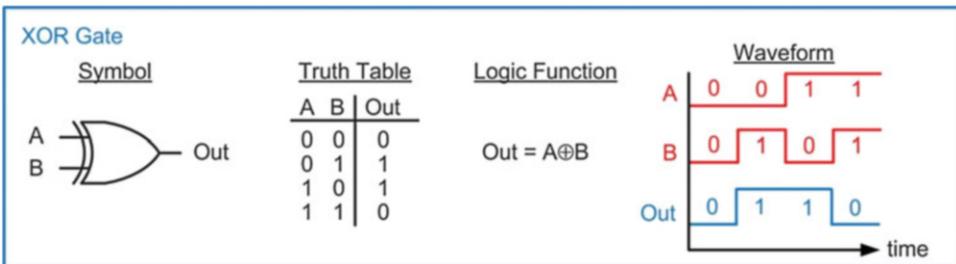


Fig. 3.11
2-Input XOR gate symbol, truth table, logic function, and logic waveform

Using the formal definition of an XOR gate (i.e., the output is true if any of the input codes are different from one another), an XOR gate with more than two inputs can be built. The truth table for a 3-bit, XOR gate using this definition is shown in Fig. 3.12. In modern electronics, this type of gate has found little use since it is much simpler to build this functionality using a combination of AND and OR gates. As such, XOR gates with greater than two inputs do not implement the *difference* function. Instead, a more useful functionality has been adopted in which the output of the n-bit, XOR gate is the result of a cascade of 2-input XOR gates. This results in an ultimate output that is true when there is **an ODD number of 1s on the inputs**. This functionality is much more useful in modern electronics for error correction codes and arithmetic. As such, this is the functionality that is seen in modern n-bit, XOR gates. This functionality is also shown in Fig. 3.12.

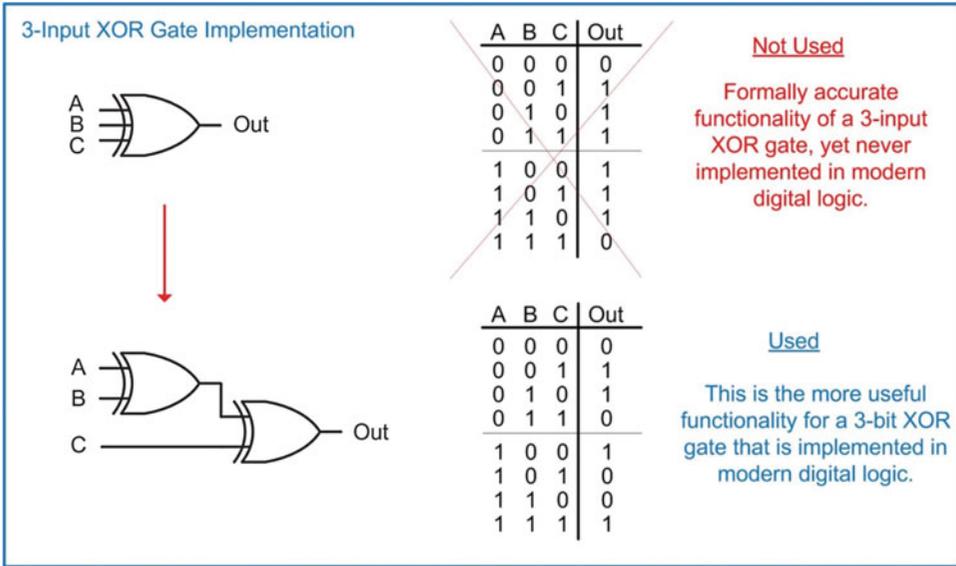


Fig. 3.12
3-Input XOR gate implementation

3.1.9 The XNOR Gate

The exclusive-NOR gate is identical to the XOR gate with the exception that the output is inverted. This gate is also called an *equivalence* gate because for the 2-input configuration, its output will be true when the **input codes are equivalent to one another**. The symbol for an XNOR gate is an XOR gate with an inversion bubble on the output. The logic expression for an XNOR gate is the same as an XOR gate but with an inversion bar over the entire operation. The logic symbol, truth table, logic function, and logic waveform for a 2-input XNOR gate are given in Fig. 3.13. XNOR gates can have any number of inputs with the operation of an n-bit, XNOR gate following the rule that the output is always the inversion of an n-bit, XOR operation (i.e., the output is true if there is an ODD number of 1s on the inputs).

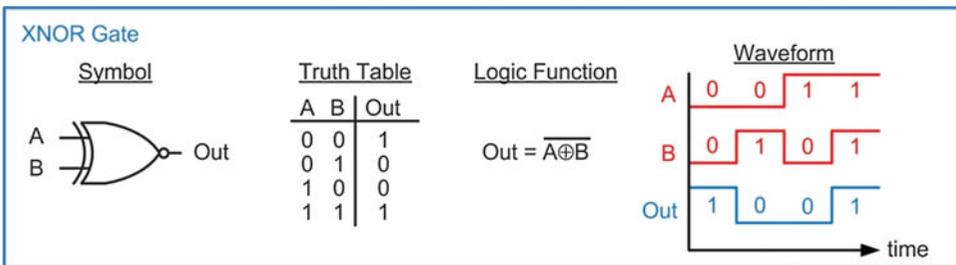
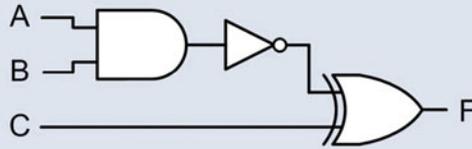


Fig. 3.13
2-Input XNOR gate symbol, truth table, logic function, and logic waveform

CONCEPT CHECK

CC3.1 Given the following logic diagram, which is the correct logic expression for F?



- A) $F = (A \cdot B)' \oplus C$
- B) $F = (A' \cdot B') \oplus C$
- C) $F = (A' \cdot B' \oplus C)$
- D) $F = A \cdot B' \oplus C$

3.2 Digital Circuit Operation

Now we turn our attention to the physical hardware that is used to build the basic gates just described and how electrical quantities are used to represent and communicate the binary values 1 and 0. We begin by looking at digital signaling. Digital signaling refers to how binary codes are generated and transmitted successfully between two digital circuits using electrical quantities (e.g., voltage and current). Consider the digital system shown in Fig. 3.14. In this system, the sending circuit generates a binary code. The sending circuit is called either the *transmitter* (Tx) or *driver*. The transmitter represents the binary code using an electrical quantity such as voltage. The receiving circuit (Rx) observes this voltage and is able to determine the value of the binary code. In this way, 1s and 0s can be communicated between the two digital circuits. The transmitter and receiver are both designed to use the same digital signaling scheme so that they are able to communicate with each other. It should be noted that all digital circuits contain both inputs (Rx) and outputs (Tx) but are not shown in this figure for simplicity.

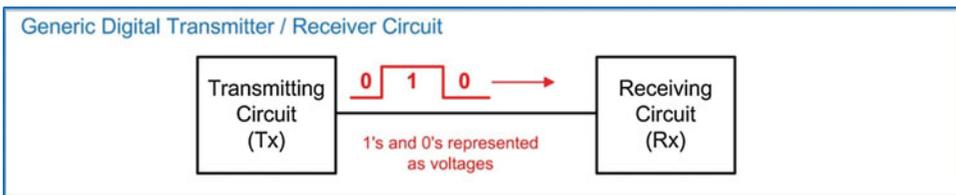


Fig. 3.14
Generic digital transmitter/receiver circuit

3.2.1 Logic Levels

A *logic level* is the term to describe all possible states that a signal can have. We will focus explicitly on circuits that represent binary values, so these will only have two finite states (1 and 0). To begin, we define a simplistic model of how to represent the binary codes using an electrical quantity. This model uses a voltage threshold (V_{th}) to represent the switching point between the binary codes. If the voltage of the signal (V_{sig}) is above this threshold, it is considered a *logic HIGH*. If the voltage is below this threshold, it is considered a *logic LOW*. A graphical depiction of this is shown in Fig. 3.15. The terms HIGH and LOW are used to describe which logic level corresponds to the *higher* or *lower* voltage.

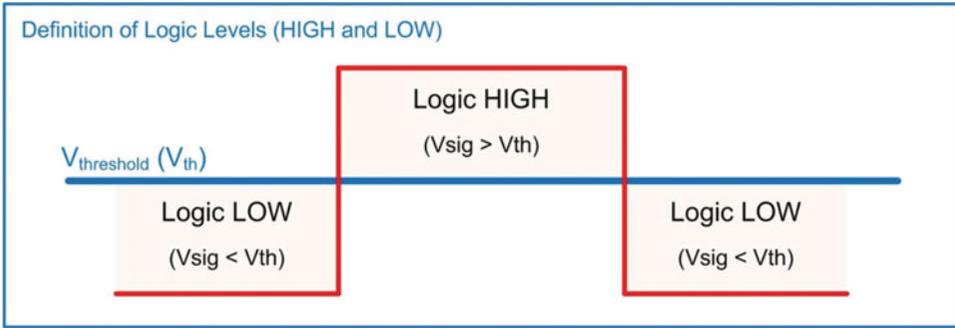


Fig. 3.15
Definition of logic HIGH and LOW

It is straightforward to have the HIGH level correspond to the binary code 1 and the LOW level correspond to the binary code 0; however, it is equally valid to have the HIGH level correspond to the binary code 0 and the LOW level correspond to the binary code 1. As such, we need to define how the logic levels HIGH and LOW map to the binary codes 1 and 0. We define two types of digital assignments: positive logic and negative logic. In **positive logic**, the logic HIGH level represents a binary 1 and the logic LOW level represents a binary 0. In **negative logic**, the logic HIGH level represents a binary 0 and the logic LOW level represents a binary 1. Table 3.1 shows the definition of positive and negative logic. There are certain types of digital circuits that benefit from using negative logic; however, we will focus specifically on systems that use positive logic since it is more intuitive when learning digital design for the first time. The transformation between positive and negative logic is straightforward and will be covered in Chap. 4.

Definition of Positive and Negative Logic

| Logic Level | Logic Value | |
|-------------|----------------|----------------|
| | Positive Logic | Negative Logic |
| LOW | 0 | 1 |
| HIGH | 1 | 0 |

Table 3.1
Definition of positive and negative logic

3.2.2 Output DC Specifications

Transmitting circuits provide specifications on the range of output voltages (V_O) that they are guaranteed to provide when outputting a logic 1 or 0. These are called the DC output specifications. There are four DC voltage specifications that specify this range: $V_{\text{OH-max}}$, $V_{\text{OH-min}}$, $V_{\text{OL-max}}$, and $V_{\text{OL-min}}$. The $V_{\text{OH-max}}$ and $V_{\text{OH-min}}$ specifications provide the range of voltages the transmitter is guaranteed to provide when outputting a logic HIGH (or logic 1 when using positive logic). The $V_{\text{OL-max}}$ and $V_{\text{OL-min}}$ specifications provide the range of voltages the transmitter is guaranteed to provide when outputting a logic LOW (or logic 0 when using positive logic). In the subscripts for these specifications, the “O” signifies “output” and the “L” or “H” signifies “LOW” or “HIGH,” respectively.

The maximum amount of current that can flow through the transmitter's output (I_O) is also specified. The specification I_{OH-max} is the maximum amount of current that can flow through the transmitter's output when sending a logic HIGH. The specification I_{OL-max} is the maximum amount of current that can flow through the transmitter's output when sending a logic LOW. When the maximum output currents are violated, it usually damages the part. Manufacturers will also provide a *recommended* amount of current for I_O that will guarantee the specified operating parameters throughout the life of the part. Figure 3.16 shows a graphical depiction of these DC specifications. When the transmitter output is providing current to the receiving circuit (a.k.a., the *load*), it is said to be **sourcing** current. When the transmitter output is drawing current from the receiving circuit, it is said to be **sinking** current. In most cases, the transmitter sources current when driving a logic HIGH and sinks current when driving a logic LOW. Figure 3.16 shows a graphical depiction of these specifications.

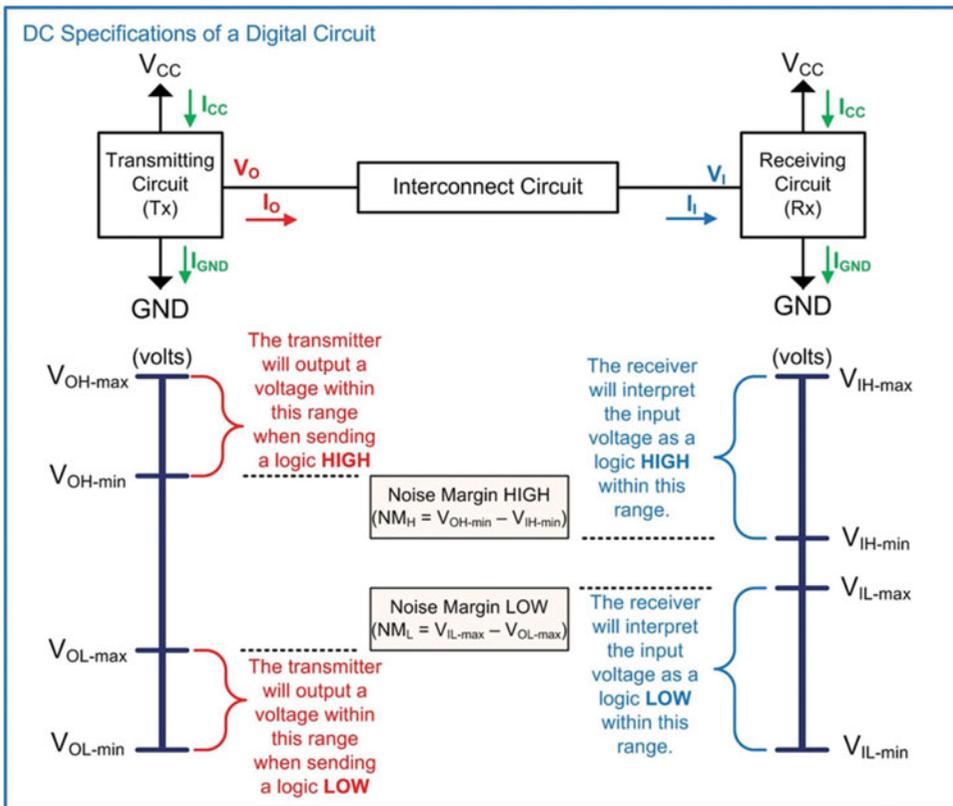


Fig. 3.16
DC specifications of a digital circuit

3.2.3 Input DC Specifications

Receiving circuits provide specifications on the range of input voltages (V_I) that they will interpret as either a logic HIGH or LOW. These are called the DC input specifications. There are four DC voltage specifications that specify this range: V_{IH-max} , V_{IH-min} , V_{IL-max} , and V_{IL-min} . The V_{IH-max} and V_{IH-min} specifications provide the range of voltages that the receiver will interpret as a logic HIGH (or logic 1 when using positive logic). The V_{IL-max} and V_{IL-min} specifications provide the range of voltages that the

receiver will interpret as a logic LOW (or logic 0 when using positive logic). In the subscripts for these specifications, the “I” signifies “input.”

The maximum amount of current that the receiver will draw, or take in, when connected is also specified (I_i). The specification I_{IH-max} is the maximum amount of current that the receiver will draw when it is being driven with a logic HIGH. The specification I_{IL-max} is the maximum amount of current that the receiver will draw when it is being driven with a logic LOW. Again, Fig. 3.16 shows a graphical depiction of these DC specifications.

3.2.4 Noise Margins

For digital circuits that are designed to operate with each other, the V_{OH-max} and V_{IH-max} specifications have equal voltages. Similarly, the V_{OL-min} and V_{IL-min} specifications have equal voltages. The V_{OH-max} and V_{OL-min} output specifications represent the *best-case* scenario for digital signaling as the transmitter is sending the largest (or smallest) signal possible. If there is no loss in the interconnect between the transmitter and receiver, the full voltage levels will arrive at the receiver and be interpreted as the correct logic states (HIGH or LOW).

The *worst-case* scenario for digital signaling is when the transmitter outputs its levels at V_{OH-min} and V_{OL-max} . These levels represent the furthest away from an *ideal* voltage level that the transmitter can send to the receiver and are susceptible to loss and noise that may occur in the interconnect system. In order to compensate for potential loss or noise, digital circuits have a predefined amount of margin built into their worst-case specifications. Let’s take the worst-case example of a transmitter sending a logic HIGH at the level V_{OH-min} . If the receiver was designed to have V_{IH-min} (i.e., the lowest voltage that would still be interpreted as a logic 1) equal to V_{OH-min} , then if even the smallest amount of the output signal was attenuated as it traveled through the interconnect, it would arrive at the receiver below V_{IH-min} and would not be interpreted as a logic 1. Since there will always be some amount of loss in any interconnect system, the specifications for V_{IH-min} are always less than V_{OH-min} . The difference between these two quantities is called the **noise margin**. More specifically, it is called the noise margin HIGH (or NM_H) to signify how much margin is built into the Tx/Rx circuit when communicating a logic 1. Similarly, the V_{IL-max} specification is always higher than the V_{OL-max} specification to account for any voltage added to the signal in the interconnect. The difference between these two quantities is called the noise margin LOW (or NM_L) to signify how much margin is built into the Tx/Rx circuit when communicating a logic 0. Noise margins are always specified as positive quantities, and thus the order of the subtrahend and minuend in these differences:

$$NM_H = V_{OH-min} - V_{IH-min}$$

$$NM_L = V_{IL-max} - V_{OL-max}$$

Figure 3.16 includes the graphical depiction of the noise margins. Notice in this figure that there is a region of voltages that the receiver will not interpret as either a HIGH or a LOW. This region lies between the V_{IH-min} and V_{IL-max} specifications. This is the **uncertainty region** and should be avoided. Signals in this region will cause the receiver’s output to go to an unknown voltage. Digital transmitters are designed to transition between the LOW and HIGH states quickly enough so that the receiver does not have time to react to the input being in the uncertainty region.

3.2.5 Power Supplies

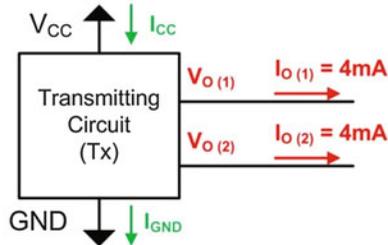
All digital circuits require a power supply voltage and a ground. There are some types of digital circuits that may require multiple power supplies. For simplicity, we will focus on digital circuits that only require a single power supply voltage and ground. The power supply voltage is commonly given the abbreviations of either V_{CC} or V_{DD} . The “CC” or “DD” have to do with how the terminals of the transistors inside of the digital circuit are connected (i.e., “collector to collector” or “drain to drain”). Digital circuits will specify the required power supply voltage. Ground is considered an ideal 0v. Digital circuits will also specify the maximum amount of DC current that can flow through the V_{CC} (I_{CC}) and GND (I_{GND}) pins before damaging the part.

There are two components of power supply current. The first is the current that is required for the functional operation of the device. This is called the *quiescent current* (I_q). The second component of the power supply current is the output currents (I_O). Any current that flows out of a digital circuit must also flow into it. When a transmitting circuit sources current to a load on its output pin, it must bring in that same amount of current on another pin. This is accomplished using the power supply pin (V_{CC}). Conversely, when a transmitting circuit sinks current from a load on its output pin, an equal amount of current must exit the circuit on a different pin. This is accomplished using the GND pin. This means that the amount of current flowing through the V_{CC} and GND pins will vary depending on the logic states that are being driven on the outputs. Since a digital circuit may contain numerous output pins, the maximum amount of current flowing through the V_{CC} and GND pins can scale quickly and care must be taken not to damage the device.

The quiescent current is often specified using the term I_{CC} . This should not be confused with the specification for the maximum amount of current that can flow through the V_{CC} pin, which is often called I_{CC-max} . It is easy to tell the difference because I_{CC} (or I_q) is much smaller than I_{CC-max} for CMOS parts. I_{CC} (or I_q) is specified in the μA to nA range while the maximum current that can flow through the V_{CC} pin is specified in the mA range. Example 3.1 shows the process of calculating the I_{CC} and I_{GND} currents when sourcing multiple loads.

Example: Calculating I_{CC} and I_{GND} when Sourcing Multiple Loads

Given: The driver is specified to have a quiescent current of 1mA and is driving a logic HIGH on two of its output pins. Each of the two loads on the output pins is being sourced with 4mA of current from the driver.



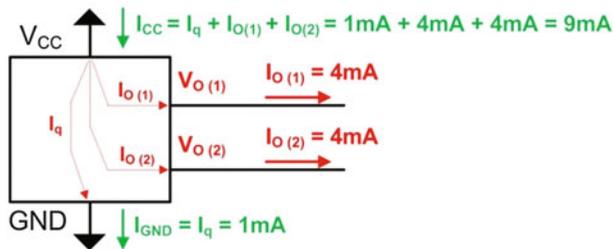
Find: I_{CC} and I_{GND}

Solution: The current into the device must equal the current out of the device. The quiescent current of 1mA is used for the functional operation of the transistors within the transmitter and will flow into the device through the V_{CC} pin and out of the device on the GND pin. The output currents that are being sourced by the driver exit the circuit on the two output pins $V_{O(1)}$ and $V_{O(2)}$. An equal amount of current must also flow into the device ($I_{O(1)} + I_{O(2)} = 8\text{mA}$), which enters the device on the V_{CC} pin. This means the total amount of current flowing into the circuit on the V_{CC} pin is:

$$I_{CC} = I_q + I_{O(1)} + I_{O(2)} = 1\text{mA} + 4\text{mA} + 4\text{mA} = 9\text{mA}$$

The total amount of current flowing out of the circuit on the GND pin is simply the quiescent current I_q .

$$I_{GND} = I_q = 1\text{mA}$$



Check: Does the total amount of current entering the circuit equal the total amount of current exiting the circuit?

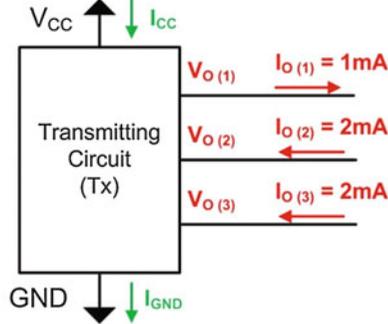
Yes, there is 9mA entering the circuit through the V_{CC} pin. There is also 9mA exiting the circuit using the $V_{O(1)}$, $V_{O(2)}$ and GND pins.

Example 3.1 Calculating I_{CC} and I_{GND} When Sourcing Multiple Loads

Example 3.2 shows the process of calculating the I_{CC} and I_{GND} currents when both sourcing and sinking loads.

Example: Calculating I_{CC} and I_{GND} When Both Sourcing and Sinking Loads

Given: The driver is specified to have a quiescent current of 0.5mA and is driving a logic HIGH on one of its output pins and a logic LOW on two of its output pins. The driver is sourcing 1mA when driving a HIGH and sinking 2mA when driving a LOW.



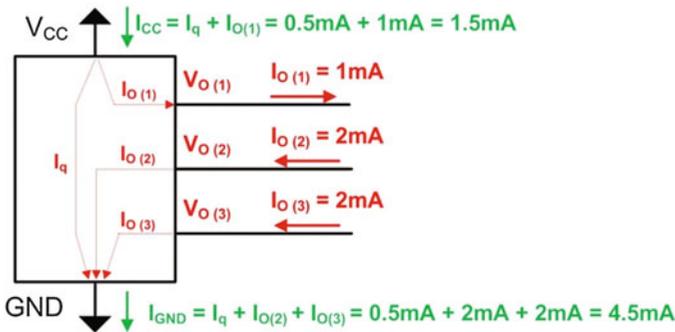
Find: I_{CC} and I_{GND}

Solution: The current into the device must equal the current out of the device. The quiescent current of 0.5mA enters the circuit on the V_{CC} pin and exits on the GND pin. The output current for $V_{O(1)}$ enters the circuit on the V_{CC} pin and exits the circuit on the $V_{O(1)}$ pin. The output current for $V_{O(2)}$ and $V_{O(3)}$ enters the circuit on the $V_{O(2)}$ and $V_{O(3)}$ pins and exits the circuit on the V_{CC} pin is:

$$I_{CC} = I_q + I_{O(1)} = 0.5\text{mA} + 1\text{mA} = 1.5\text{mA}$$

The total amount of current flowing out of the circuit on the GND pin is the quiescent current I_q plus the current being sunk from the pins $V_{O(2)}$ and $V_{O(3)}$:

$$I_{GND} = I_q + I_{O(2)} + I_{O(3)} = 0.5\text{mA} + 2\text{mA} + 2\text{mA} = 4.5\text{mA}$$



Example 3.2

Calculating I_{CC} and I_{GND} When Both Sourcing and Sinking Loads

3.2.6 Switching Characteristics

Switching characteristics refer to the transient behavior of the logic circuits. The first group of switching specifications characterize the *propagation delay* of the gate. The propagation delay is the time it takes for the output to respond to a change on the input. The propagation delay is formally defined as the time it takes from the point at which the input has transitioned to 50 % of its final value to the point at which the output has transitioned to 50 % of its final value. The initial and final voltages for the input are defined to be GND and V_{CC} , while the output initial and final voltages are defined to be V_{OL} and V_{OH} . Specifications are given for the propagation delay when transitioning from a LOW to HIGH (t_{PLH}) and from a HIGH to LOW (t_{PHL}). When these specifications are equal, the values are often given as a single specification of t_{pd} . These specifications are shown graphically in Fig. 3.17.

The second group of switching specifications characterize how quickly the output switches between states. The *transition time* is defined as the time it takes for the output to transition from 10 to 90 % of the output voltage range. The *rise time* (t_r) is the time it takes for this transition when going from a LOW to HIGH, and the *fall time* (t_f) is the time it takes for this transition when going from a HIGH to LOW. When these specifications are equal, the values are often given as a single specification of t_t . These specifications are shown graphically in Fig. 3.17.

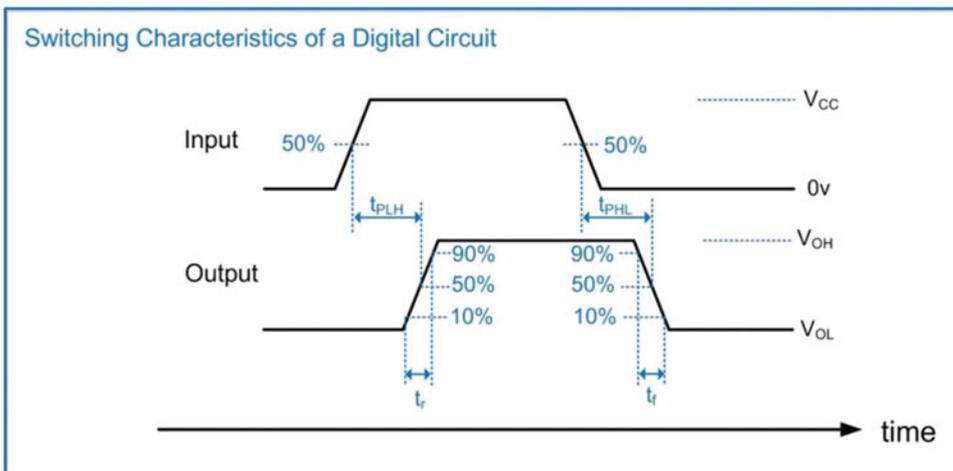


Fig. 3.17
Switching characteristics of a digital circuit

3.2.7 Data Sheets

The specifications for a particular part are given in its **data sheet**. The data sheet contains all of the operating characteristics for a part, in addition to functional information such as package geometries and pin assignments. The data sheet is usually the first place a designer will look when selecting a part. Figures 3.18, 3.19, and 3.20 show excerpts from an example data sheet highlighting some of the specifications just covered.

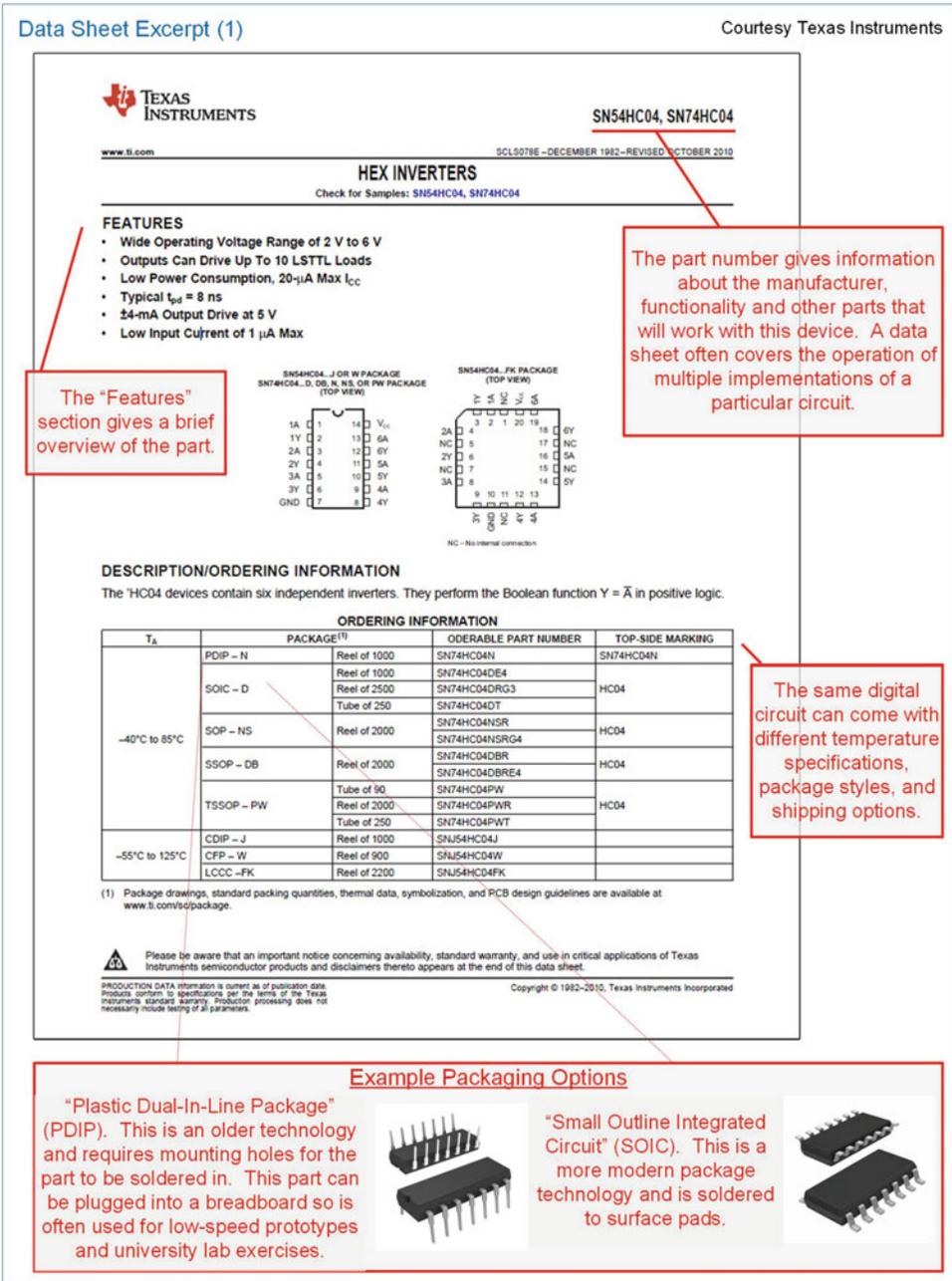


Fig. 3.18 Example data sheet excerpt (1)

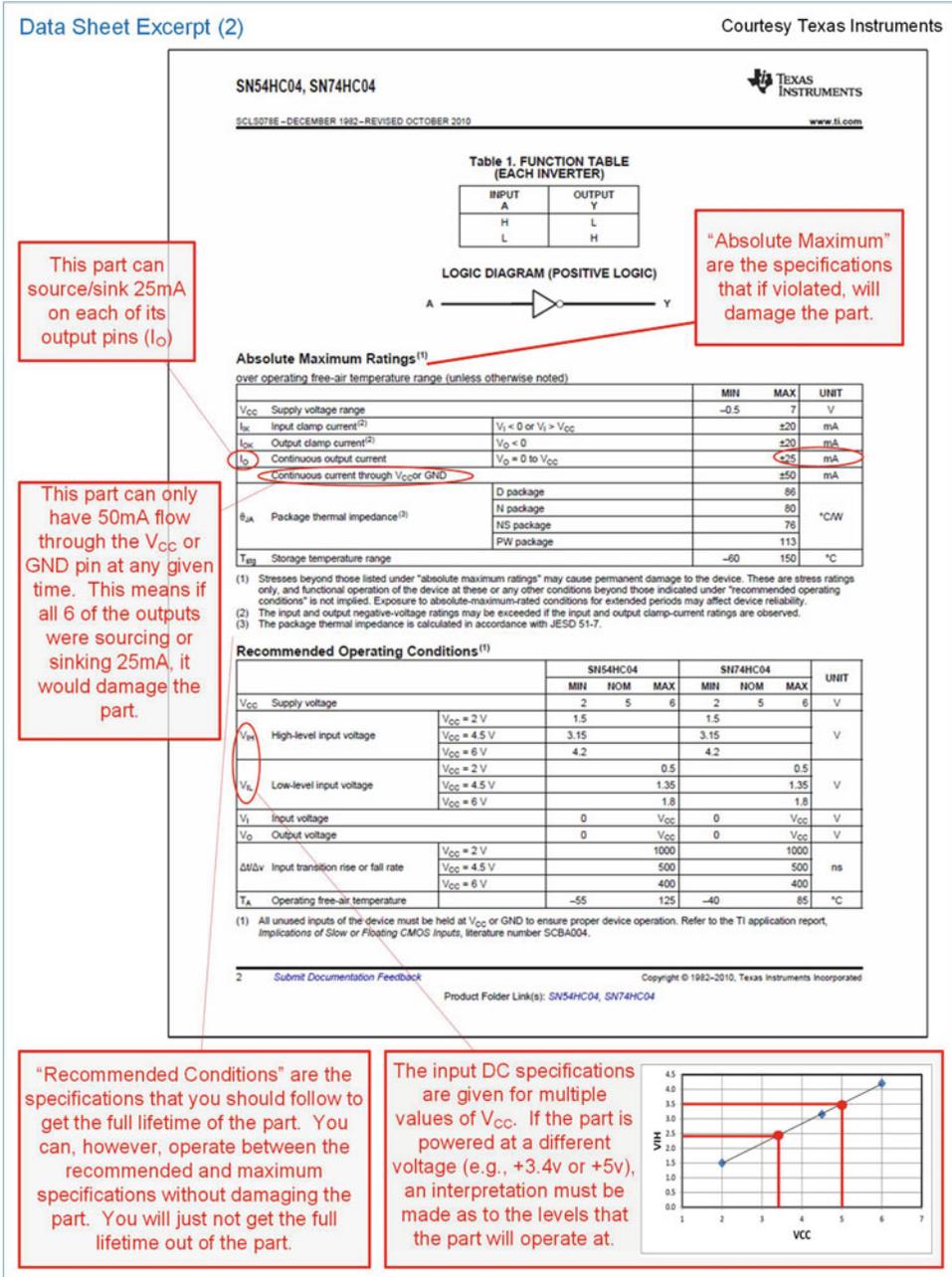


Fig. 3.19 Example data sheet excerpt (2)

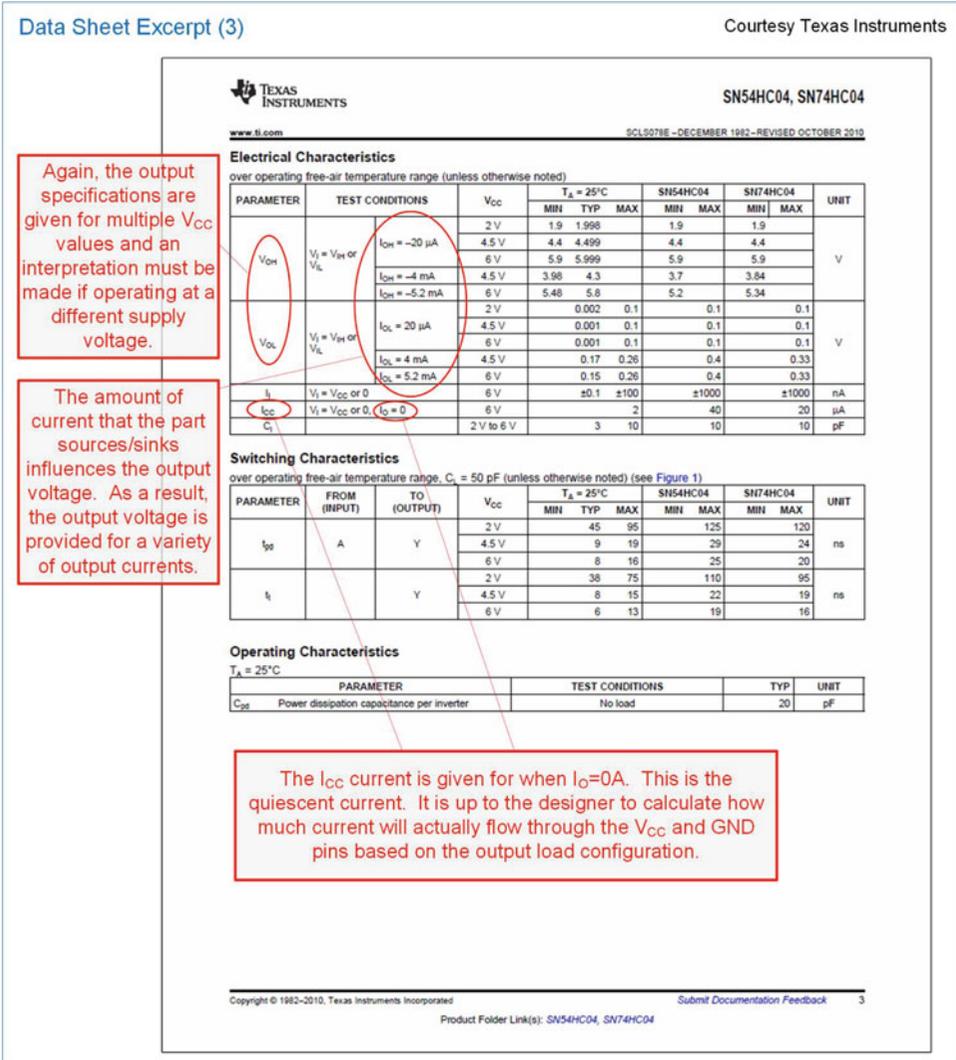


Fig. 3.20 Example data sheet excerpt (3)

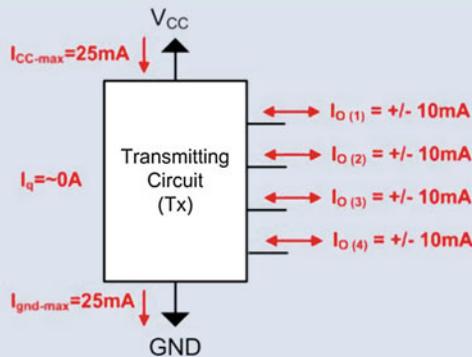
CONCEPT CHECK

CC3.2(a) Given the following DC specifications for a driver/receiver pair, in what situation *may* a logic signal transmitted not be successfully received?

| | |
|----------------------|----------------------|
| $V_{OH-max} = +3.4v$ | $V_{IH-max} = +3.4v$ |
| $V_{OH-min} = +2.5v$ | $V_{IH-min} = +2.5v$ |
| $V_{OL-max} = +1.5v$ | $V_{IL-max} = +2.0v$ |
| $V_{OL-min} = 0v$ | $V_{IL-min} = 0v$ |

- A) Driving a HIGH with $V_o=+3.4v$
- B) Driving a HIGH with $V_o=+2.5v$
- C) Driving a LOW with $V_o=+1.5v$
- D) Driving a LOW with $V_o=0v$

CC3.2(b) For the following driver configuration, which of the following is a valid constraint that could be put in place to prevent a violation of the maximum power supply currents (I_{CC-max} and $I_{GND-max}$)?



- A) Modify the driver transistors so that they can't provide more than 5mA on any output.
- B) Apply a cooling system (e.g., a heat sink or fan) to the driver chip.
- C) Design the logic so that no more than half of the outputs are HIGH at any given time.
- D) Drive multiple receivers with the same output pin.

CC3.2(c) Why is it desirable to have the output of a digital circuit transition quickly between the logic LOW and logic HIGH levels?

- A) So that the outputs are not able to respond as the input transitions through the uncertainty region. This avoids unwanted transitions.
- B) So that all signals look like square waves.
- C) To reduce power by minimizing the time spent switching.
- D) Because the system can only have two states, a LOW and a HIGH.

3.3 Logic Families

It is apparent from the prior discussion of operating conditions that digital circuits need to have comparable input and output specifications in order to successfully communicate with each other. If a transmitter outputs a logic HIGH as +3.4v and the receiver needs a logic HIGH to be above +4v to be successfully interpreted as a logic HIGH, then these two circuits will not be able to communicate. In order to address this interoperability issue, digital circuits are grouped into *logic families*. A logic family is a group of parts that all adhere to a common set of specifications so that they work together. The logic family is given a specific name and once the specifications are agreed upon, different manufacturers produce parts that work within the particular family. Within a logic family, parts will all have the same power supply requirements and DC input/output specifications such that if connected *directly*, they will be able to successfully communicate with each other. The phrase “connected directly” is emphasized because it is very possible to insert an interconnect circuit between two circuits within the same logic family and alter the output voltage enough so that the receiver will not be able to interpret the correct logic level. Analyzing the effect of the interconnect circuit is part of the digital design process. There are many logic families that exist (up to 100 different types!) and more emerge each year as improvements are made to circuit fabrication processes that create smaller, faster, and lower power circuits.

3.3.1 Complementary Metal Oxide Semiconductors

The first group of logic families we will discuss is called complementary metal oxide semiconductors, or CMOS. This is currently the most popular group of logic families for digital circuits implemented on the same integrated circuit (IC). An **integrated circuit** is where the entire circuit is implemented on a single piece of semiconductor material (or chip). The IC can contain transistors, resistors, capacitors, inductors, wires, and insulators. Modern integrated circuits can contain billions of devices and meters of interconnect. The opposite of implementing the circuit on an integrated circuit is to use **discrete components**. Using discrete components refers to where every device (transistor, resistor, etc.) is its own part and is wired together externally using either a printed circuit board (PCB) or jumper wires as on a breadboard. The line between ICs and discrete parts has blurred in the past decades because modern discrete parts are actually fabricated as an IC and regularly contain multiple devices (e.g., four logic gates per chip). Regardless, the term *discrete* is still used to describe components that only contain a *few* components where the term IC typically refers to a much larger system that is custom designed.

The term CMOS comes from the use of particular types of transistors to implement the digital circuits. The transistors are created using a metal oxide semiconductor (MOS) structure. These transistors are turned on or off based on an electric field, so they are given the name metal oxide semiconductor *field effect* transistors, or MOSFETs. There are two transistors that can be built using this approach that operate *complementary* to each other, thus the term *complementary metal oxide semiconductors*. To understand the basic operation of CMOS logic, we begin by treating the MOSFETs as ideal switches. This allows us to understand the basic functionality without diving into the detailed electronic analysis of the transistors.

3.3.1.1 CMOS Operation

In CMOS, there is a single power supply (V_{CC} or V_{DD}) and a single ground (GND). The ground signal is sometimes called V_{SS} . The maximum input and output DC specifications are equal to the power supply ($V_{CC} = V_{OH-max} = V_{IH-max}$). The minimum input and output DC specification are equal to ground ($GND = 0v = V_{OL-min} = V_{IL-min}$). In this way, using CMOS simplifies many of the specifications. If you state that you are using “CMOS with a +3.4v power supply,” you are inherently stating that $V_{CC} = V_{OH-max} = V_{IH-max} = +3.4v$ and that $V_{OL-min} = V_{IL-min} = 0v$. Many times the name of the logic

family will be associated with the power supply voltage. For example, a logic family may go by the name “+3.3v CMOS” or “+2.5v CMOS.” These names give a first-level description of the logic family operation, but more details about the operation must be looked up in the data sheet.

There are two types of transistors used in CMOS. The transistors will be closed or open based on an input logic level. The first transistor is called an N-type MOSFET, or **NMOS**. This transistor will turn on, or close, when the voltage between the gate and source (V_{GS}) is greater than its *threshold voltage*. The threshold voltage (V_T) is the amount of voltage needed to create a conduction path between the drain and the source terminals. The threshold voltage of an NMOS transistor is typically between 0.2v and 1v and much less than the V_{CC} voltage in the system. The second transistor is called a P-type MOSFET, or **PMOS**. This transistor turns on, or closes, when the voltage between the gate and the source (V_{GS}) is less than V_T , where the V_T for a PMOS is a negative value. This means that to turn on a PMOS transistor, the gate terminal needs to be at a lower voltage than the source. The type of transistor (i.e., P-type or N-type) has to do with the type of semiconductor material used to conduct current through the transistor. An NMOS transistor uses negative charge to conduct current (i.e., Negative-Type) while a PMOS uses positive charge (i.e., Positive-Type). Figure 3.21 shows the symbols for the PMOS and NMOS, the fabrication cross sections, and their switch-level equivalents.

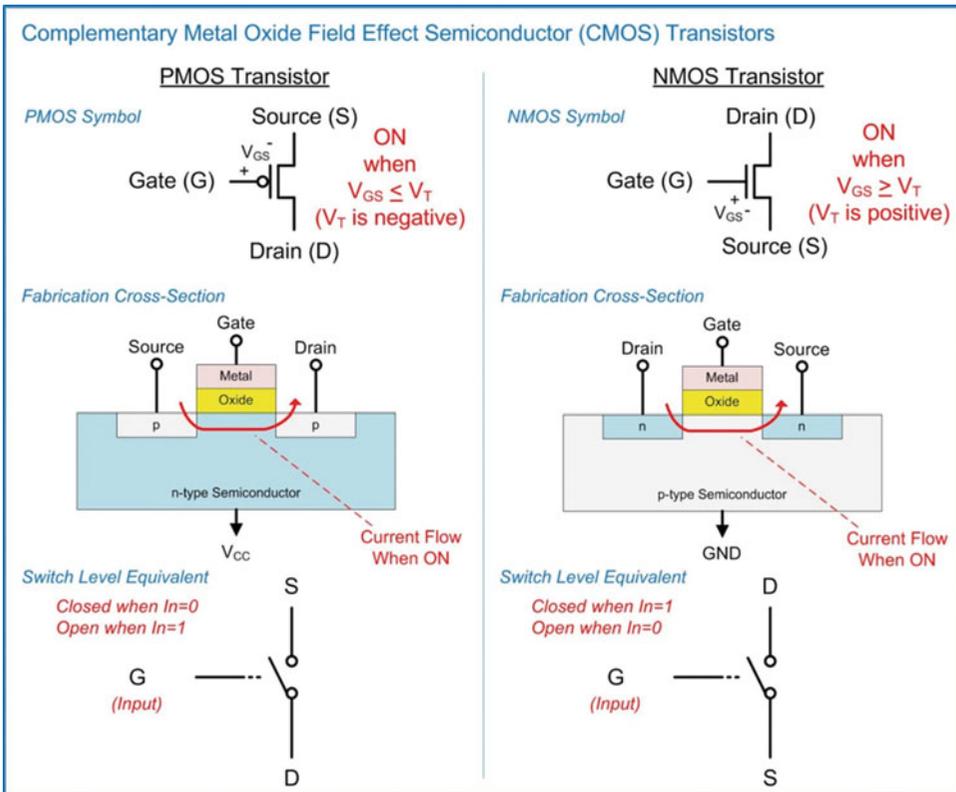


Fig. 3.21
CMOS transistors

The basic operation of CMOS is that when driving a logic HIGH the switches are used to connect the output to the power supply (V_{CC}), and when driving a logic LOW the switches are used to connect the output to GND. In CMOS, V_{CC} is considered an ideal logic HIGH and GND is considered an ideal logic LOW. V_{CC} is typically much larger than V_T , so using these levels can easily turn on and off the transistors. The design of the circuit must never connect the output to V_{CC} and GND at the same time or else the device itself will be damaged due to the current flowing directly from V_{CC} to GND through the transistors. Due to the device physics of the MOSFETS, PMOS transistors are used to form the network that will connect the output to V_{CC} (a.k.a., the pull-up network), and NMOS transistors are used to form the network that will connect the output to GND (a.k.a., the pull-down network). Since PMOS transistors are closed when the input is a 0 (thus providing a logic HIGH on the output) and NMOS transistors are closed when the input is a 1 (thus providing a logic LOW on the output), CMOS implements negative logic gates. This means that CMOS can implement inverters, NAND, and NOR gates but not buffers, AND, and OR gates directly. In order to create a CMOS AND gate, the circuit would implement a NAND gate followed by an inverter and similarly for an OR gate and buffer.

3.3.1.2 CMOS Inverter

Let's now look at how we can use these transistors to create a CMOS inverter. Consider the transistor arrangement shown in Fig. 3.22.

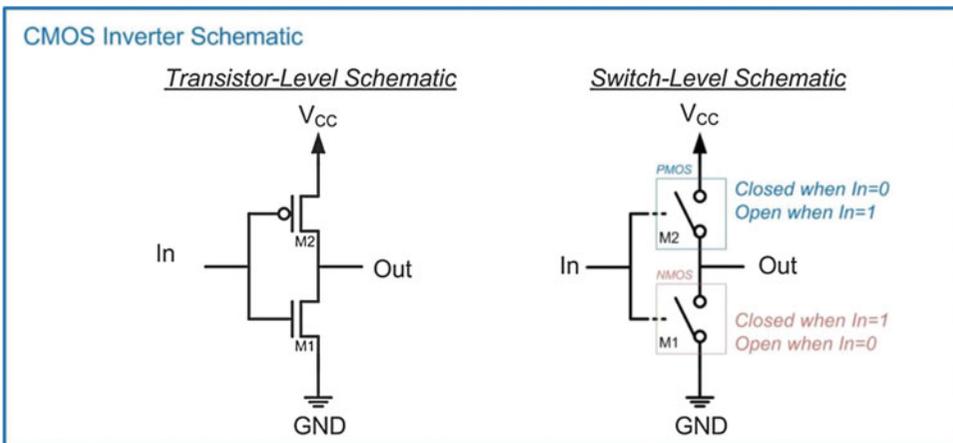


Fig. 3.22
CMOS inverter schematic

The inputs of both the PMOS and NMOS are connected together. The PMOS is used to connect the output to V_{CC} and the NMOS is used to connect the output to GND. Since the inputs are connected together and the switches operate in a complementary manner, this circuit ensures that both transistors will never be on at the same time. When $In = 0$, the PMOS switch is closed and the NMOS switch is open. This connects the output directly to V_{CC} , thus providing a logic HIGH on the output. When $In = 1$, the PMOS switch is open and the NMOS switch is closed. This connects the output directly to GND, thus providing a logic LOW. This configuration yields an inverter. This operation is shown graphically in Fig. 3.23.

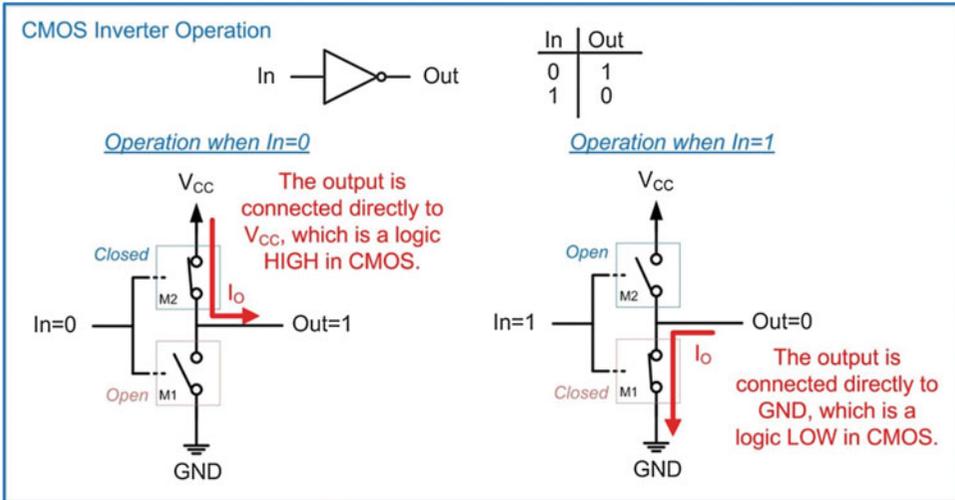


Fig. 3.23
CMOS inverter operation

3.3.1.3 CMOS NAND Gate

Let's now look at how we use a similar arrangement of transistors to implement a 2-input NAND gate. Consider the transistor configuration shown in Fig. 3.24.

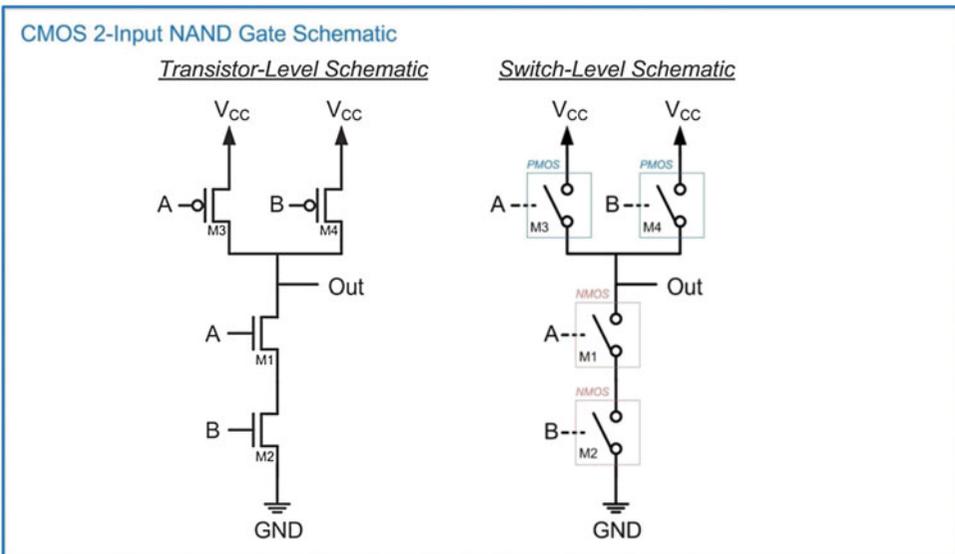


Fig. 3.24
CMOS 2-input NAND gate schematic

The pull-down network consists of two NMOS transistors in series (M1 and M2) and the pull-up network consists of two PMOS transistors in parallel (M3 and M4). Let's go through each of the input conditions and examine which transistors are on and which are off and how they impact the output. The first input condition is when $A = 0$ and $B = 0$. This condition turns *on* both M3 and M4 creating two parallel paths between the output and V_{CC} . At the same time, it turns *off* both M1 and M2 preventing a path between the output and GND. This input condition results in an output that is connected to V_{CC} resulting in a logic HIGH. The second input condition is when $A = 0$ and $B = 1$. This condition turns *on* M3 in the pull-up network and M2 in the pull-down network. This condition also turns *off* M4 in the pull-up network and M1 in the pull-down network. Since the pull-up network is a parallel combination of PMOS transistors, there is still a path between the output and V_{CC} through M3. Since the pull-down network is a series combination of NMOS transistors, both M1 and M2 must be on in order to connect the output to GND. This input condition results in an output that is connected to V_{CC} resulting in a logic HIGH. The third input condition is when $A = 1$ and $B = 0$. This condition again provides a path between the output and V_{CC} through M4 and prevents a path between the output and ground by having M2 open. This input condition results in an output that is connected to V_{CC} resulting in a logic HIGH. The final input condition is when $A = 1$ and $B = 1$. In this input condition, both of the PMOS transistors in the pull-up network (M3 and M4) are off preventing the output from being connected to V_{CC} . At the same time, this input turns on both M1 and M2 in the pull-down network connecting the output to GND. This input condition results in an output that is connected to GND resulting in a logic LOW. Based on the resulting output values corresponding to the four input codes, this circuit yields the logic operation of a 2-input NAND gate. This operation is shown graphically in Fig. 3.25.

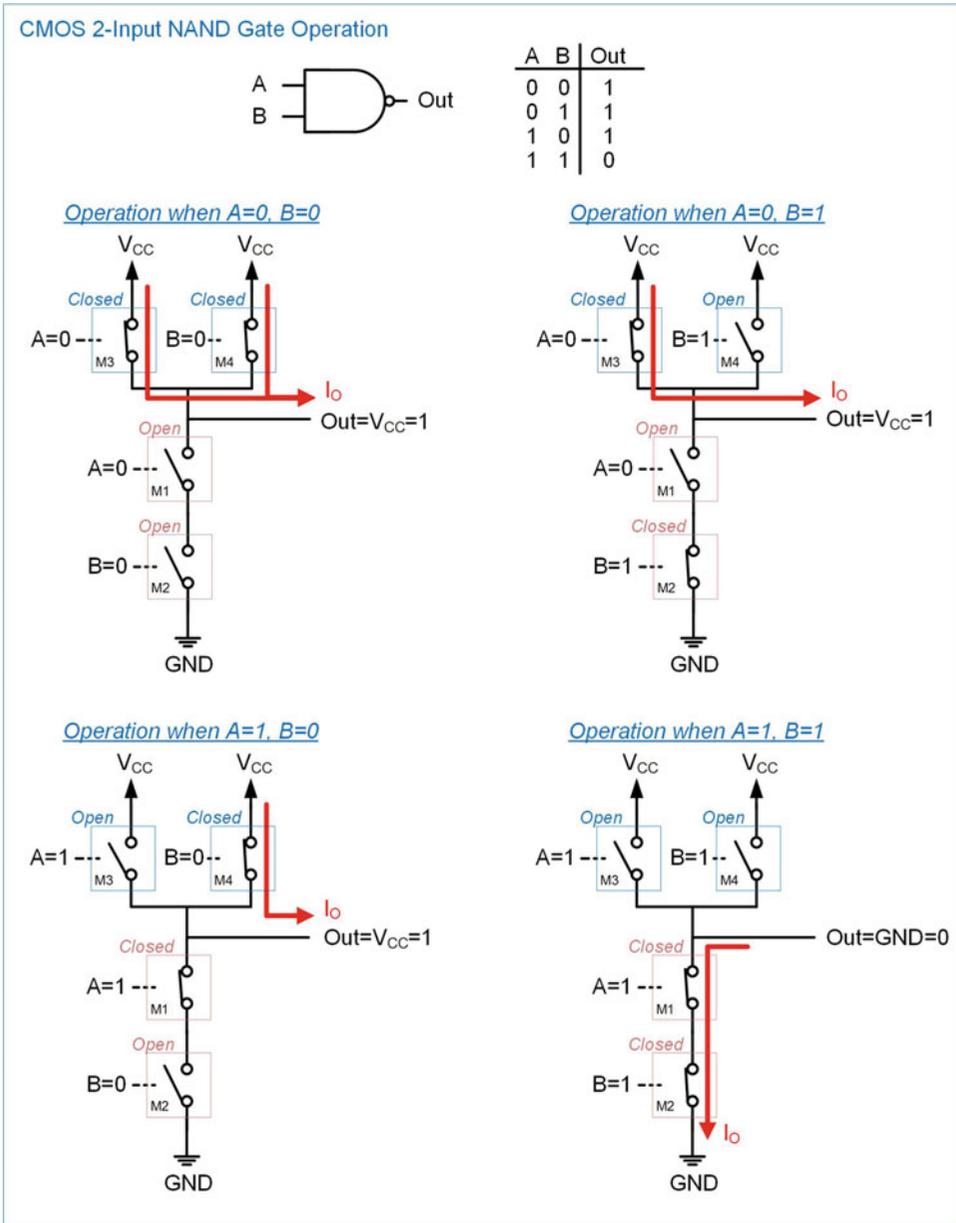


Fig. 3.25
CMOS 2-input NAND gate operation

Creating a CMOS NAND gate with more than two inputs is accomplished by adding additional PMOS transistors to the pull-up network in parallel and additional NMOS transistors to the pull-down network in series. Figure 3.26 shows the schematic for a 3-input NAND gate. This procedure is followed for creating NAND gates with larger numbers of inputs.

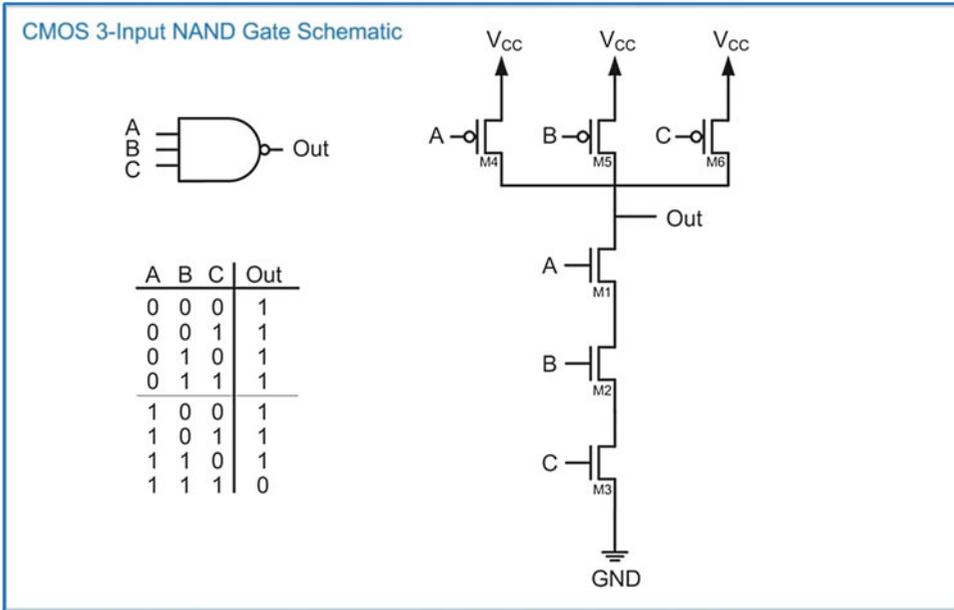


Fig. 3.26
CMOS 3-input NAND gate schematic

If the CMOS transistors were ideal switches, the approach of increasing the number of inputs could be continued indefinitely. In reality, the transistors are not ideal switches and there is a limit on how many transistors can be added in series and continue to operate. The limitation has to do with ensuring that each transistor has enough voltage to properly turn on or off. This is a factor in the series network because the drain terminals of the NMOS transistors are not all connected to GND. If a voltage develops across one of the lower transistors (e.g., M3), then it takes more voltage on the input to turn on the next transistor up (e.g., M2). If too many transistors are added in series, then the uppermost transistor in the series may not be able to be turned on or off by the input signals. The number of inputs that a logic gate can have within a particular logic family is called its **fan-in** specification. When a logic circuit requires a number of inputs that exceeds the fan-in specification for a particular logic family, then additional logic gates must be used. For example, if a circuit requires a 5-input NAND gate but the logic family has a fan-in specification of 4, this means that the largest NAND gate available only has 4-inputs. The 5-input NAND operation must be accomplished using additional circuit design techniques that use gates with 4 or less inputs. These design techniques will be covered in Chap. 4.

3.3.1.4 CMOS NOR Gate

A CMOS NOR gate is created using a similar topology as a NAND gate with the exception that the pull-up network consists of PMOS transistors in series and the pull-down network that consists of NMOS transistors in parallel. Consider the transistor configuration shown in Fig. 3.27.

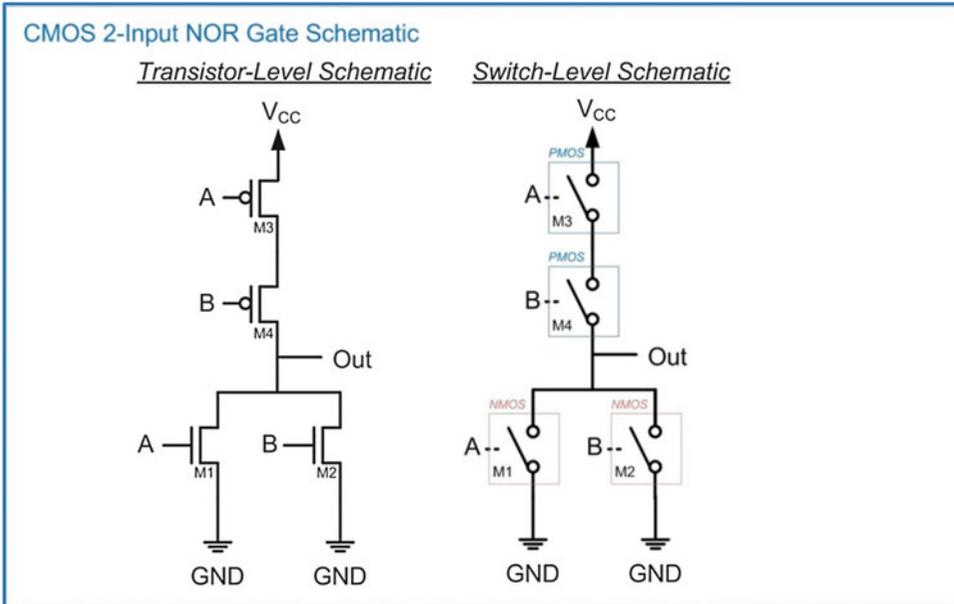


Fig. 3.27
CMOS 2-input NOR gate schematic

The series configuration of the pull-up network will only connect the output to V_{CC} when both inputs are 0. Conversely, the pull-down network prevents connecting the output to GND when both inputs are 0. When either or both of the inputs are true, the pull-up network is off and the pull-down network is on. This yields the logic function for a NOR gate. This operation is shown graphically in Fig. 3.28. As with the NAND gate, the number of inputs can be increased by adding more PMOS transistors in series in the pull-up network and more NMOS transistors in parallel in the pull-down network.

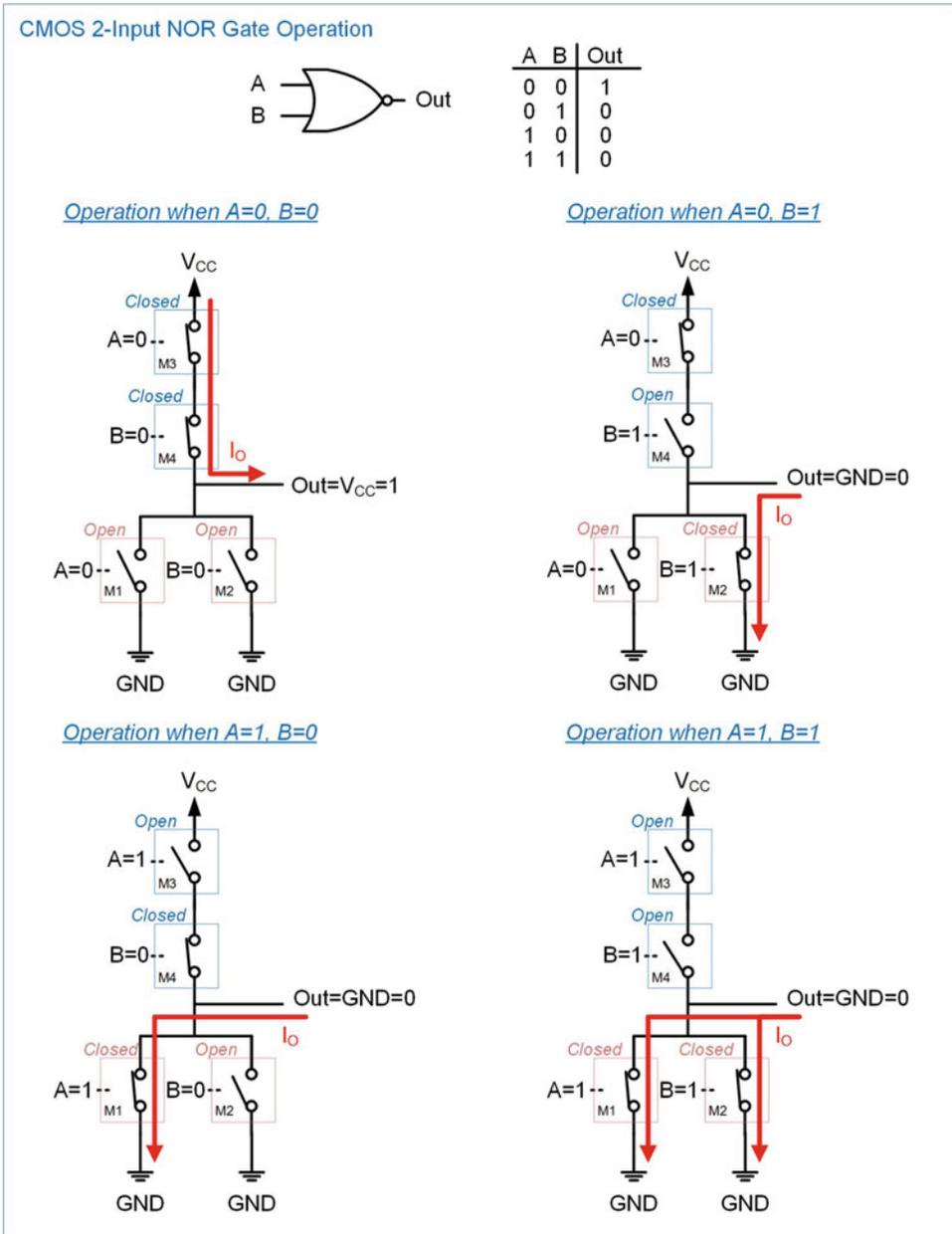


Fig. 3.28
CMOS 2-input NOR gate operation

The schematic for a 3-input NOR gate is given in Fig. 3.29. This approach can be used to increase the number of inputs up until the fan-in specification of the logic family is reached.

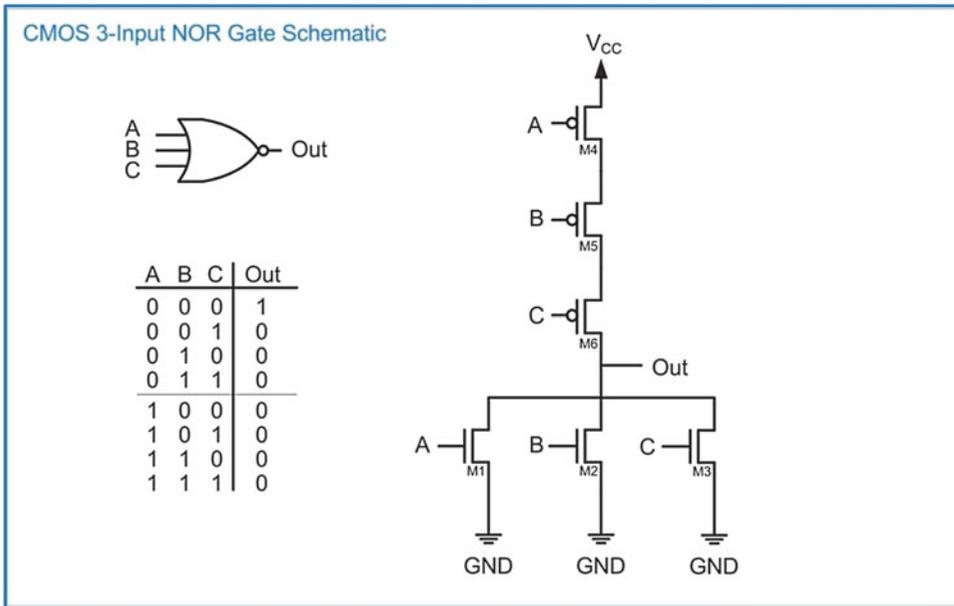


Fig. 3.29
CMOS 3-input NOR gate schematic

3.3.2 Transistor-Transistor Logic

One of the first logic families that emerged after the invention of the integrated circuit was transistor-transistor logic (TTL). This logic family uses bipolar junction transistor (BJT) as its fundamental switching item. This logic family defined a set of discrete parts that contained all of the basic gates in addition to more complex building blocks. TTL was used to build the first computer systems in the 1960s. TTL is not widely used today other than for specific applications because it consumes more power than CMOS and cannot achieve the density required for today's computer systems. TTL is discussed because it was the original logic family based on integrated circuits, so it provides a historical perspective of digital logic. Furthermore, the discrete logic pin-outs and part-numbering schemes are still used today for discrete CMOS parts.

3.3.2.1 TTL Operation

TTL logic uses BJT transistors and resistors to accomplish the logic operations. The operation of a BJT transistor is more complicated than an MOSFET; however, it performs essentially the same switch operation when used in a digital logic circuit. An input is used to turn the transistor on, which in turn allows current to flow between two other terminals. Figure 3.30 shows the symbol for the two types of BJT transistors. The PNP transistor is analogous to a PMOS and the NPN is analogous to an NMOS. Current will flow between the Emitter and Collector terminals when there is a sufficient voltage on the Base terminal. The amount of current that flows between the Emitter and Collector is related to the current flowing into the Base. The primary difference in operation between BJTs and MOSFETs is that BJTs require proper voltage biasing in order to turn on and also draws current through the BASE in order to stay on. The detailed operation of BJTs is beyond the scope of this text, so an overly simplified model of TTL logic gates is given.

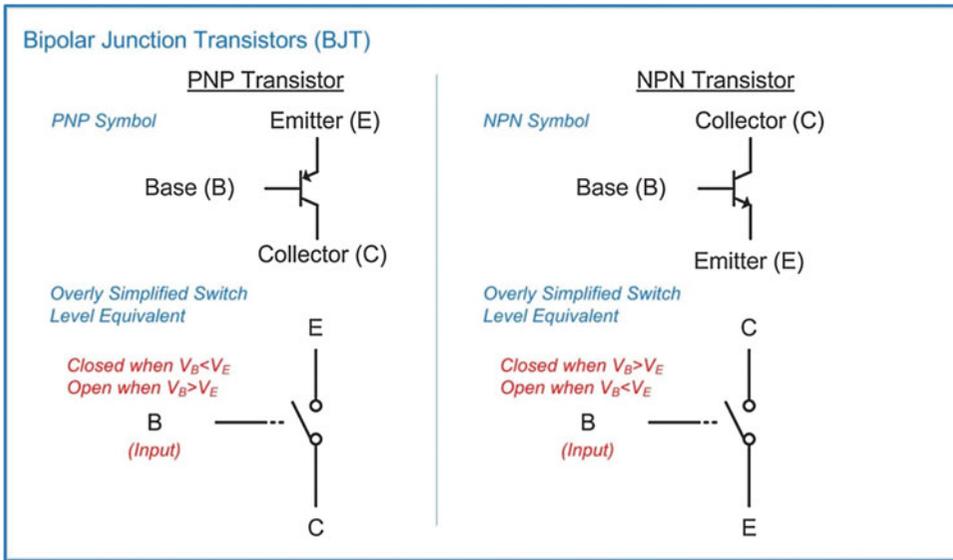


Fig. 3.30
PNP and NPN transistors

Figure 3.31 shows a simplified model of how TTL logic operates using BJTs and resistors. This simplified model does not show all of the transistors that are used in modern TTL circuits but instead is intended to provide a high-level overview of the operation. This gate is an inverter that is created with an NPN transistor and a resistor. When the input is a logic HIGH, the NPN transistor turns on and conducts current between its collector and emitter terminals. This in effect closes the switch and connects the output to GND providing a logic LOW. During this state, current will also flow through the resistor to GND through Q1, thus consuming more power than the equivalent gate in CMOS. When the input is a logic LOW, the NPN transistor turns off and no current flows between its collector and emitter. This, in effect, is an open circuit leaving only the resistor connected to the output. The resistor pulls the output up to V_{CC} providing a logic HIGH on the output. One drawback of this state is that there will be a voltage drop across the resistor, so the output is not pulled fully to V_{CC} .

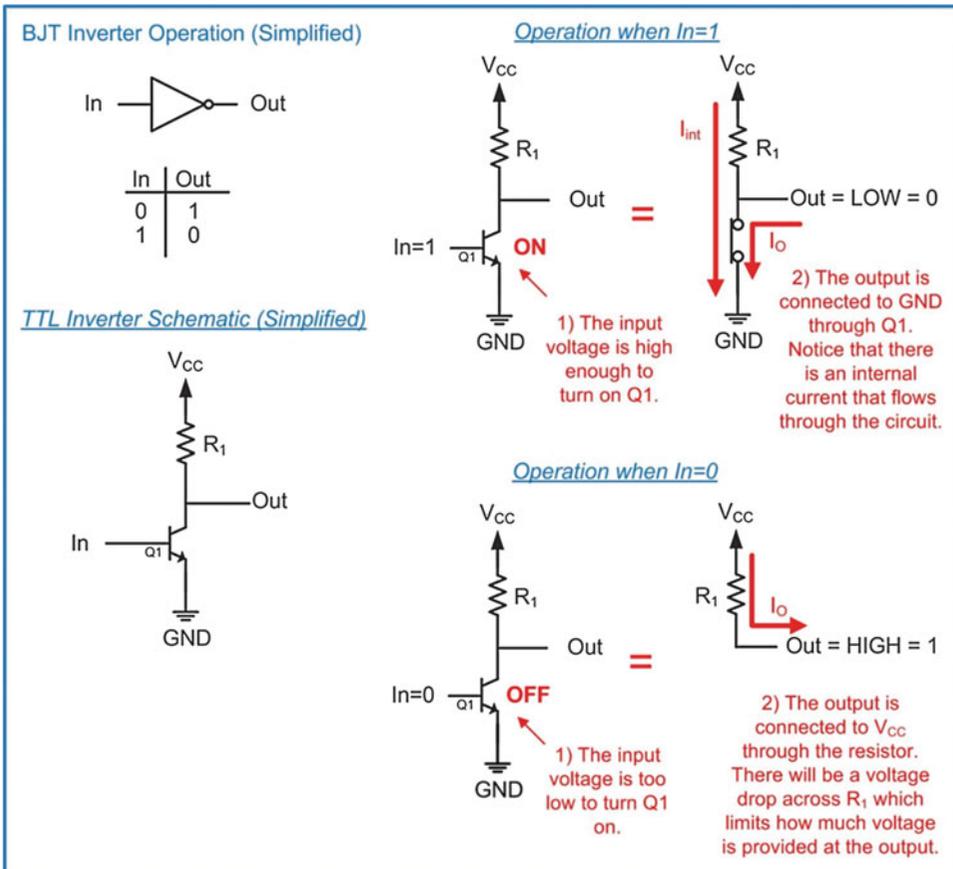


Fig. 3.31
TTL inverter

3.3.3 The 7400 Series Logic Families

The 7400 series of TTL circuits became popular in the 1960s and 1970s. This family was based on TTL and contained hundreds of different digital circuits. The original circuits came in either plastic or ceramic Dual-In-Line packages (DIP). The 7400 TTL logic family was powered off of a +5v supply. As mentioned before, this logic family set the pin-outs and part-numbering schemes for modern logic families. There were many derivatives of the original TTL logic family that made modifications to improve speed and reliability, decrease power, and reduce power supplies. Today's CMOS logic families within the 7400 series still use the same pin-outs and numbering schemes as the original TTL family. It is useful to understand the history of this series because these parts are often used in introductory laboratory exercises to learn how to interface digital logic circuits.

3.3.3.1 Part-Numbering Scheme

The part numbering scheme for the 7400 series and its derivatives contains five different fields: (1) manufacturer, (2) temperature range, (3) logic family, (4) logic function, and (5) package type. The breakdown of these fields is shown in Fig. 3.32.

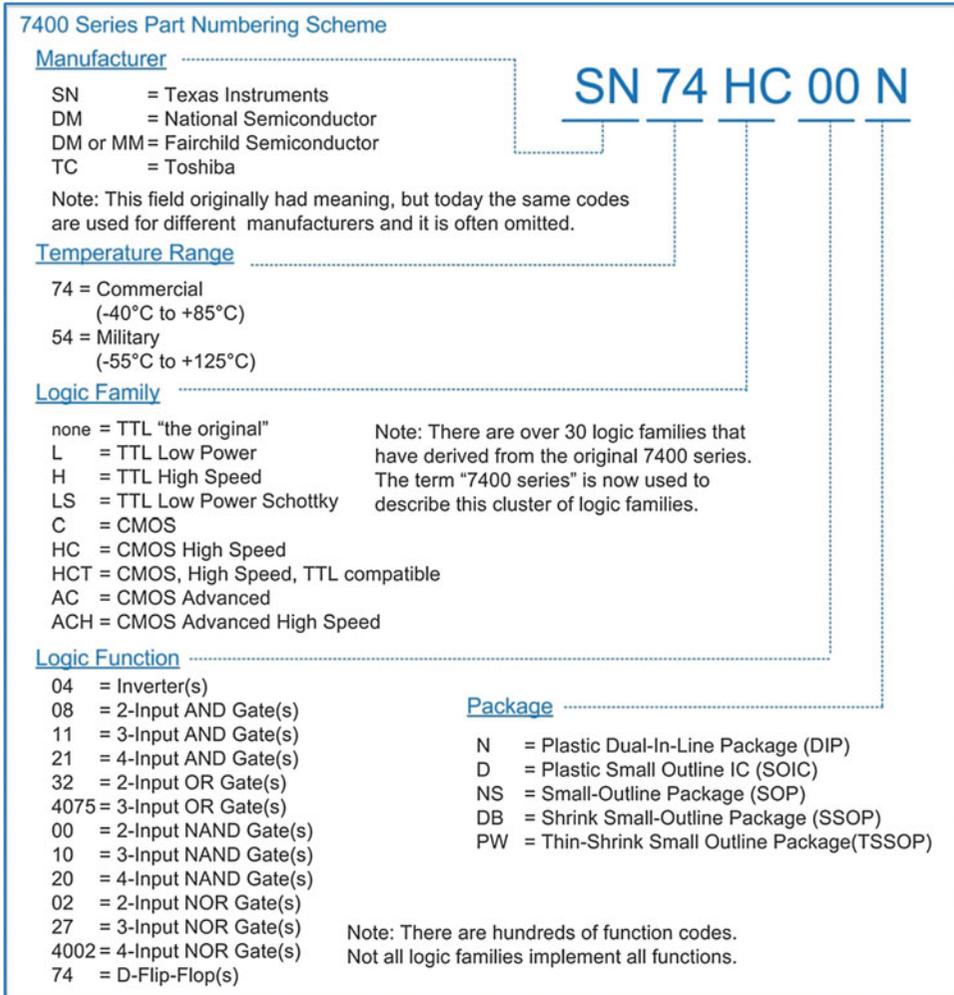


Fig. 3.32
7400 series part-numbering scheme

3.3.3.2 DC Operating Conditions

Table 3.2 gives the DC operating conditions for a few of the logic families within the 7400 series. Notice that the CMOS families consume much less power than the TTL families. Also notice that the TTL output currents are asymmetrical. The differences between the I_{OH} and I_{OL} within the TTL families have to do with the nature of the bipolar transistors and the resistors used to create the pull-up networks within the devices. CMOS has symmetrical drive currents due to using complementary transistors for the pull-up (PMOS) and pull-down networks (NMOS).

| Logic Family | Year | DC Operating Condition | | | | | | | | | | | Speed (MHz) |
|--------------|------|------------------------|-------------|--------------------|-------------|-------------|-------------|--------------------|--------------------|-------------|----------|------------------|-------------|
| | | V_{CC} | V_{OHmax} | V_{OHmin} | V_{OLmax} | V_{OLmin} | V_{IHmax} | V_{IHmin} | V_{ILmax} | V_{ILmin} | I_{CC} | $I_{Omax (H/L)}$ | |
| Orig. (TTL) | 1964 | +5 | +5 | +2.4 | +0.4 | GND | +5 | +2 | +0.8 | GND | 40m | -4/+16m | 25 |
| LS (TTL) | 1976 | +5 | +5 | +2.4 | +0.4 | GND | +5 | +2 | +0.8 | GND | 8.8m | -4/+8m | 40 |
| HC (CMOS) | 1982 | +2-6 | V_{CC} | $0.8 \cdot V_{CC}$ | 0.33 | GND | V_{CC} | $0.7 \cdot V_{CC}$ | $0.3 \cdot V_{CC}$ | GND | 40u | +/-25m | 50 |
| AC (CMOS) | 1985 | +2-6 | V_{CC} | $0.8 \cdot V_{CC}$ | 0.33 | GND | V_{CC} | $0.7 \cdot V_{CC}$ | $0.3 \cdot V_{CC}$ | GND | 80u | +/-50m | 125 |

Note 1: All voltage specifications have units of volts. All current specifications have units of amps.

Note 2: The V_O and V_I specifications for the AC and HC logic families are worst case and vary depending on the V_{CC} selection and the output current.

Note 3: All specifications are given for the commercial temperature range (74 series).

Table 3.2
DC operating conditions for a sample of 7400 series logic families

3.3.3.3 Pin-Out Information for the DIP Packages

Figure 3.33 shows the pin-out assignments for a subset of the basic gates from the 74HC logic family in the Dual-In-Line package form factor. Most of the basic gates within the 7400 series follow these assignments. Notice that each of these basic gates comes in a 14-pin DIP package, each with a single V_{CC} and single GND pin. It is up to the designer to ensure that the maximum current flowing through the V_{CC} and GND pins does not exceed the maximum specification. This is particularly important for parts that contain numerous gates. For example, the 74HC00 part contains four, 2-input NAND gates. If each of the NAND gates was driving a logic HIGH at its maximum allowable output current (i.e., 25 mA from Fig. 3.19), then a total of $4 \cdot 25 \text{ mA} + I_q = \sim 100 \text{ mA}$ would be flowing through its V_{CC} pin. Since the V_{CC} pin can only tolerate a maximum of 50 mA of current (from Fig. 3.19), the part would be damaged since the output current of $\sim 100 \text{ mA}$ would also flow through the V_{CC} pin. The pin-outs in Fig. 3.33 are useful when first learning to design logic circuits because the DIP packages plug directly into a standard breadboard.

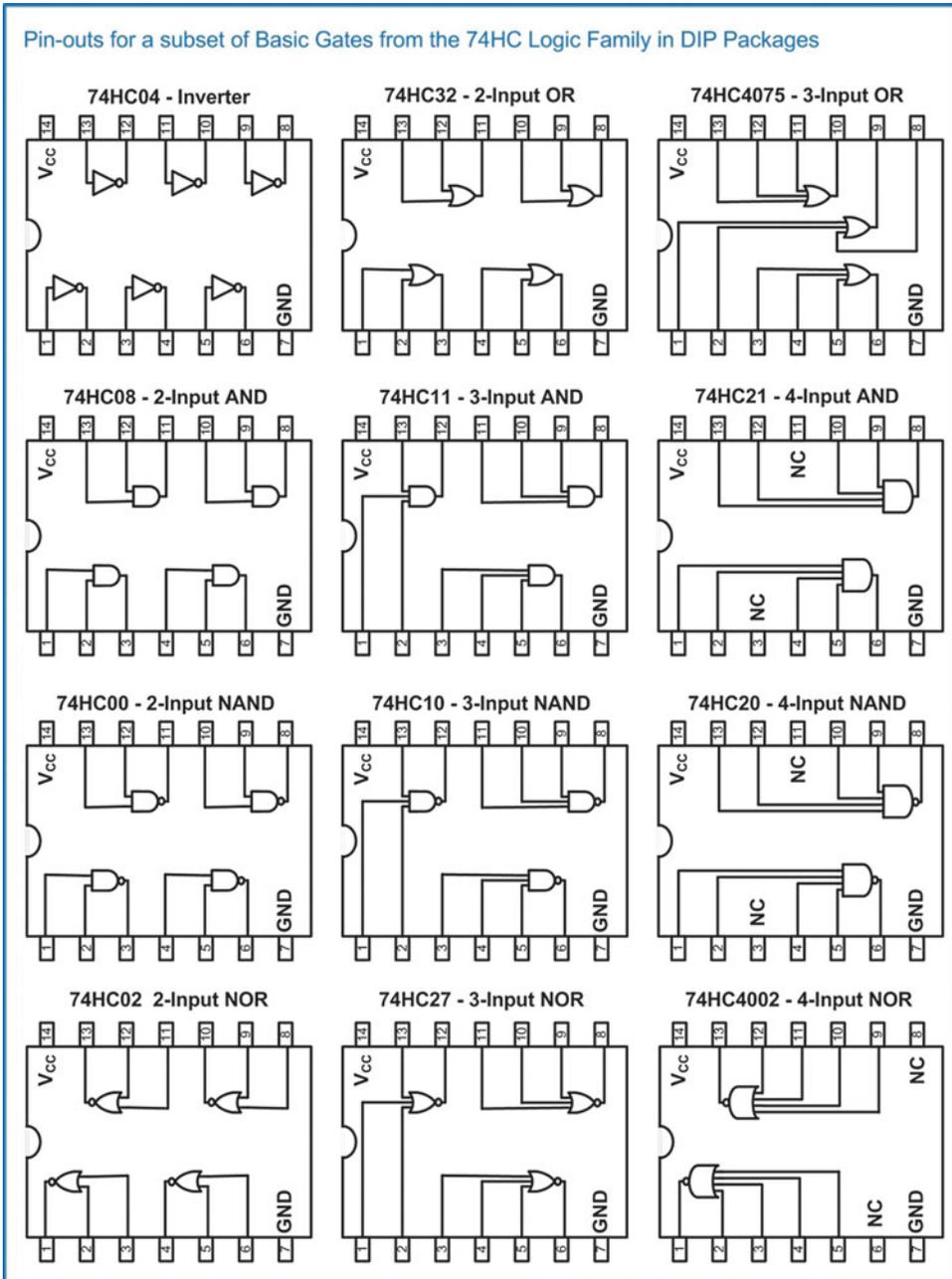
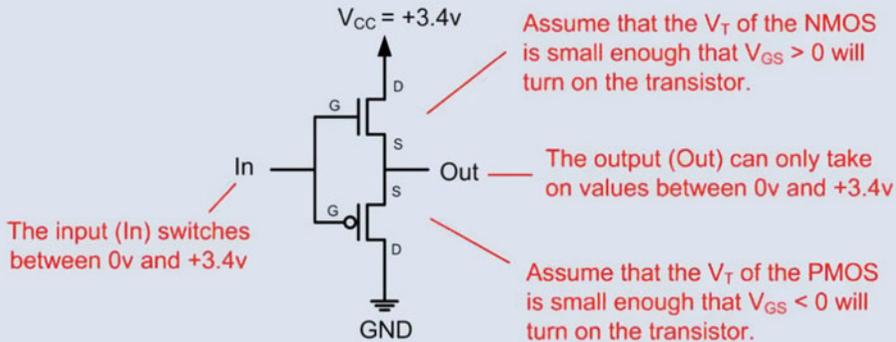


Fig. 3.33 Pin-outs for a subset of basic gates from the 74HC logic family in DIP packages

CONCEPT CHECK

CC3.3 Why doesn't the following CMOS transistor configuration yield a buffer?



- In order to turn on the NMOS transistor, V_{GS} needs to be greater than zero. In the given configuration, the gate terminal of the NMOS (G) needs to be driven above the source terminal (S). If the source terminal was at +3.4v, then the input (In) would never be able to provide a positive enough voltage to ensure the NMOS is on because "In" doesn't go above +3.4v.
- There is no way to turn on both transistors in this configuration.
- The power consumption will damage the device because both transistors will potentially be on.
- The sources of the two devices can't be connected together without causing a short in the device.

3.4 Driving Loads

At this point we've discussed in depth how proper care must be taken to ensure that not only do the output voltages of the driving gate meet the input specifications of the receiver in order to successfully transmit 1s and 0s, but that the output current of the driver does not exceed the maximum specifications so that the part is not damaged. The output voltage and current for a digital circuit depend greatly on the load that is being driven. The following sections discuss the impact of driving some of the most common digital loads.

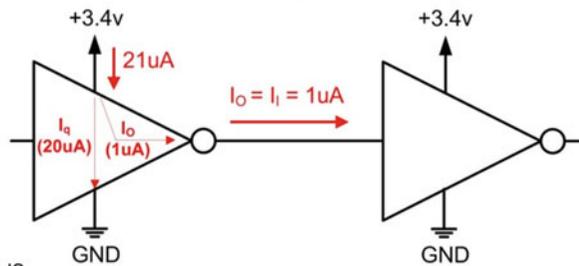
3.4.1 Driving Other Gates

Within a logic family, all digital circuits are designed to operate with one another. If there is minimal loss or noise in the interconnect system, then 1s and 0s will be successfully transmitted and no current specifications will be exceeded. Consider the example in Example 3.3 for an inverter driving another inverter from the same logic family.

Example: Determining if Specifications are Violated When Driving Another Gate as a Load

Given: 74HC04 Specifications

$$\begin{aligned} I_{I-\max} &= 1\mu\text{A} \\ I_q &= 20\mu\text{A} \\ I_{O-\max} &= 25\text{mA} \\ I_{CC-\max} &= 50\text{mA} \end{aligned}$$



Find: Were $I_{O-\max}$ or $I_{CC-\max}$ violated?

Solution: The maximum input current of the load (e.g., the receiving inverter) is $1\mu\text{A}$. This means that the I_o for the driver will be $1\mu\text{A}$ because the load sets the output current. This is far below the maximum output current of 25mA so the $I_{O-\max}$ specification is not violated.

The driver will draw I_q through its V_{CC} pin to power its functional operation. In addition to I_q , the driver will also pull a current equal to I_o through the V_{CC} pin while driving a logic HIGH. This means the maximum current pulled through the V_{CC} pin is $I_q + I_o = 20\mu\text{A} + 1\mu\text{A} = 21\mu\text{A}$. Again, this is well below the specification for the maximum amount of current that can flow through the V_{CC} pin (50mA) so the $I_{CC-\max}$ specification is also not violated.

Example 3.3

Determining if Specifications Are Violated When Driving Another Gate as a Load

From this example, it is clear that there are no issues when a gate is driving another gate from the same family. This is as expected because that is the point of a logic family. In fact, gates are designed to drive multiple gates from within their own family. Based solely on the DC specifications for input and output current, it could be assumed that the number of other gates that can be driven is simply $I_{O-\max}/I_{I-\max}$. For the example in Example 3.3, this would result in a 74HC gate being able to drive 25,000 other gates (i.e., $25\text{ mA}/1\ \mu\text{A} = 25,000$). In reality, the maximum number of gates that can be driven is dictated by the switching characteristics. This limit is called the **fan-out** specification. The fan-out specification states the maximum number of other gates from within the same family that can be driven. As discussed earlier, the output signal needs to transition quickly through the uncertainty region so that the receiver does not have time to react and go to an unknown state. As more and more gates are driven, this transition time is slowed down. The fan-out specification provides a limit to the maximum number of gates from the same family that can be driven while still ensuring that the output signal transitions between states fast enough to avoid the receivers from going to an unknown state. Example 3.4 shows the process of determining the maximum output current that a driver will need to provide when driving the maximum number of gates allowed by the fan-out specification.

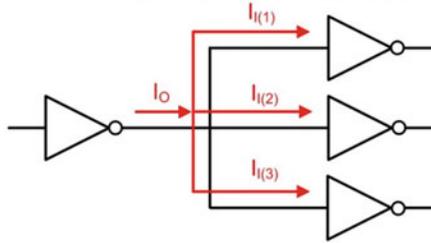
Example: Determining the Output Current When Driving Multiple Gates as the Load

Given: 74HC04 Specifications

Fan-out = 3

$I_{i\text{-max}} = 1\mu\text{A}$

Driving the maximum gates allowed by fan-out.



Find: I_O

Solution: The fan-out specification is 3, which means that the transmitting inverter can drive up to 3 other gates from its own logic family. Each of the receivers will draw their input current of $I_i = 1\mu\text{A}$, which will be provided by the driver. The total amount of output current from the driver is $3 \cdot 1\mu\text{A} = 3\mu\text{A}$.

Example 3.4

Determining the Output Current When Driving Multiple Gates as the Load

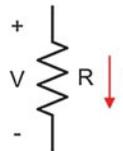
3.4.2 Driving Resistive Loads

There are many situations where a resistor is the load in a digital circuit. A resistive load can be an actual resistor that is present for some other purpose such as a pull-up, pull-down, or for impedance matching. More complex loads such as buzzers, relays, or other electronics can also be modeled as a resistor. When a resistor is the load in a digital circuit, care must be taken to avoid violating the output current specifications of the driver. The electrical circuit analysis technique that is used to evaluate how a resistive load impacts a digital circuit is **Ohm's law**. Ohm's law is a very simple relationship between the current and voltage in a resistor. Figure 3.34 gives a primer on Ohm's law. For use in digital circuits, there are only a select few cases that this technique will be applied to, so no prior experience with Ohm's law is required at this point.

A Primer on Ohm's Law

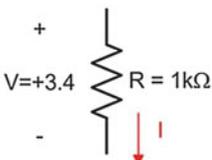
Ohm's Law describes the relationship between current and voltage in a resistor. This simple equation is used in nearly all electrical circuit analysis. The equation is as follows:

$$V = I \cdot R$$



A resistor is characterized by its *resistance*, which describes how much current will flow when a voltage is present across its two terminals. The units for resistance are Ohms ($\Omega = \text{Volts} / \text{Amp}$). The current in Ohm's Law is defined to flow from the + to - of the voltage.

Example: Use Ohm's Law to find the current flowing through the following resistor.



Solution: Plugging the parameters directly into Ohm's Law we find:

$$\begin{aligned} V &= I \cdot R \\ 3.4 &= I \cdot (1\text{k}) \\ I &= 0.0034 \text{ A} = 3.4 \text{ mA} \end{aligned}$$

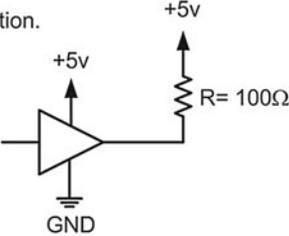
Fig. 3.34

A primer on Ohm's law

Let's see how we can use Ohm's law to analyze the impact of a resistive load in a digital circuit. Consider the circuit configuration in Example 3.5 and how we can use Ohm's law to determine the output current of the driver. The load in this case is a resistor connected between the output of the driver and the power supply (+5v). When driving a logic HIGH, the output level will be approximately equal to the power supply (i.e., +5v). Since in this situation both terminals of the resistor are at +5v, there is no voltage difference present. That means when plugging into Ohm's law, the voltage component is 0v, which gives 0 amps of current. In the case where the driver is outputting a logic LOW, the output will be approximately GND. In this case, there is a voltage drop of +5v across the resistor (5v-0v). Plugging this into Ohm's law yields a current of 50 mA flowing through the resistor. This can become problematic because the current flows through the resistor and then into the output of the driver. For the 74HC logic family, this would exceed the I_O max specification of 25 mA and damage the part. Additionally, as more current is drawn through the output, the output voltage becomes less and less ideal. In this example, the first order analysis uses $V_O = \text{GND}$. In reality, as the output current increases, the output voltage will move further away from its ideal value and may eventually reach a value within the uncertainty region.

Example: Determining the Output Current When Driving a Pull-Up Resistor as the Load

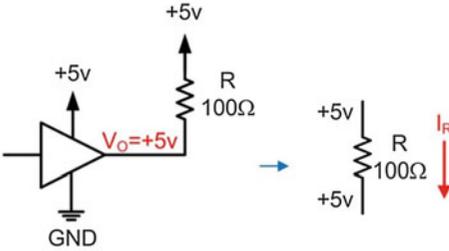
Given: The following circuit configuration.



Find: I_O

Solution: We need to solve for when the driver outputs both a HIGH and LOW.

Equivalent Circuit When Driving a HIGH



The voltage across the resistor is the difference between the voltages on its two terminals. In this situation, it is (5-5 = 0v). Plugging into Ohm's Law we get:

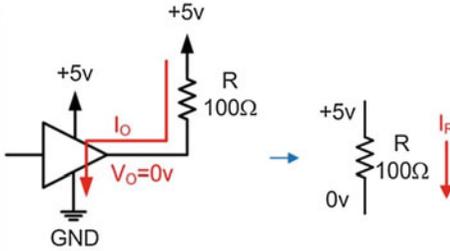
$$V = I \cdot R$$

$$0 = I \cdot (100)$$

$$I = 0 \text{ A}$$

Since there is no voltage across the resistor, there is no current flowing.

Equivalent Circuit When Driving a LOW



The voltage across the resistor is the difference between the voltages on its two terminals. In this situation, it is (5-0 = 5v). Plugging into Ohm's Law we get:

$$V = I \cdot R$$

$$5 = I \cdot (100)$$

$$I = 0.05 \text{ A} = 50\text{mA}$$

This 50mA will flow through the resistor and into the driver's output pin and then through the GND pin. Care must be taken that this current does not exceed the I_O specifications for the driver.

Example 3.5
Determining the Output Current When Driving a Pull-Up Resistor as the Load

A similar process can be used to determine the output current when driving a resistive load between the output and GND. This process is shown in Example 3.6.

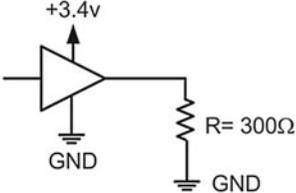
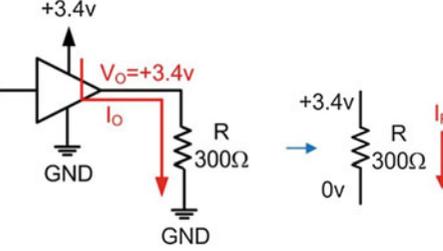
Example: Determining the Output Current When Driving a Pull-Down Resistor as the Load

Given: The following circuit configuration.

Find: I_o

Solution: We need to solve for when the driver outputs both a HIGH and LOW.

Equivalent Circuit When Driving a HIGH

The voltage across the resistor is $(3.4 - 0 = 3.4\text{v})$. Plugging into Ohm's Law we get:

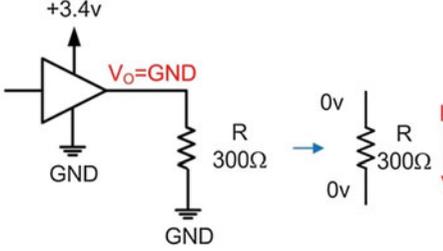
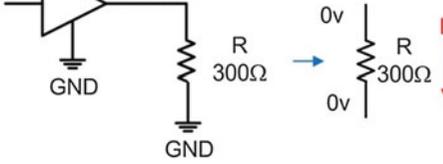
$$V = I \cdot R$$

$$3.4 = I \cdot (300)$$

$$I = 0.011 \text{ A} = 11\text{mA}$$

This current flows from the power supply of the driver through the output pin and then through the resistor to GND.

Equivalent Circuit When Driving a LOW

The voltage across the resistor is $(0 - 0 = 0\text{v})$. Plugging into Ohm's Law we get:

$$V = I \cdot R$$

$$0 = I \cdot (300)$$

$$I = 0 \text{ A}$$

No current flows through the resistor in this situation.

Example 3.6

Determining the Output Current When Driving a Pull-Down Resistor as the Load

3.4.3 Driving LEDs

A light-emitting diode (LED) is a very common type of load that is driven using a digital circuit. The behavior of diodes is typically covered in an analog electronics class. Since it is assumed that the reader has not been exposed to the operation of diodes, the behavior of the LED will be described using a highly simplified model. A diode has two terminals, the anode and cathode. Current that flows from the anode to the cathode is called the *forward current*. A voltage that is developed across a diode from its anode to cathode is called the *forward voltage*. A diode has a unique characteristic that when a forward voltage is supplied across its terminal, it will only increase up to a certain point. The amount is specified as the LED's forward voltage (V_f) and is typically between 1.5v and 2v in modern LEDs. When a power supply circuit is connected to the LED, no current will flow until this forward voltage has been reached. Once it has been reached, current will begin to flow and the LED will prevent any further voltage from developing across it. Once current flows, the LED will begin emitting light. The more current that flows, the more light that will be emitted up until the point that the maximum allowable current through the LED is reached and then the device will be damaged. When using an LED, there are two specifications of interest: the forward voltage and the recommended forward current. The symbols for a diode and an LED are given in Fig. 3.35.

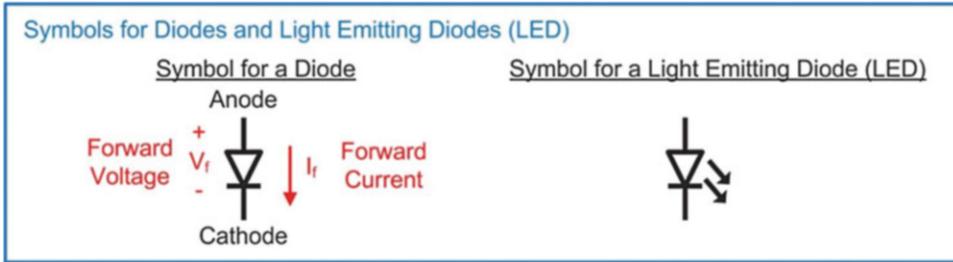
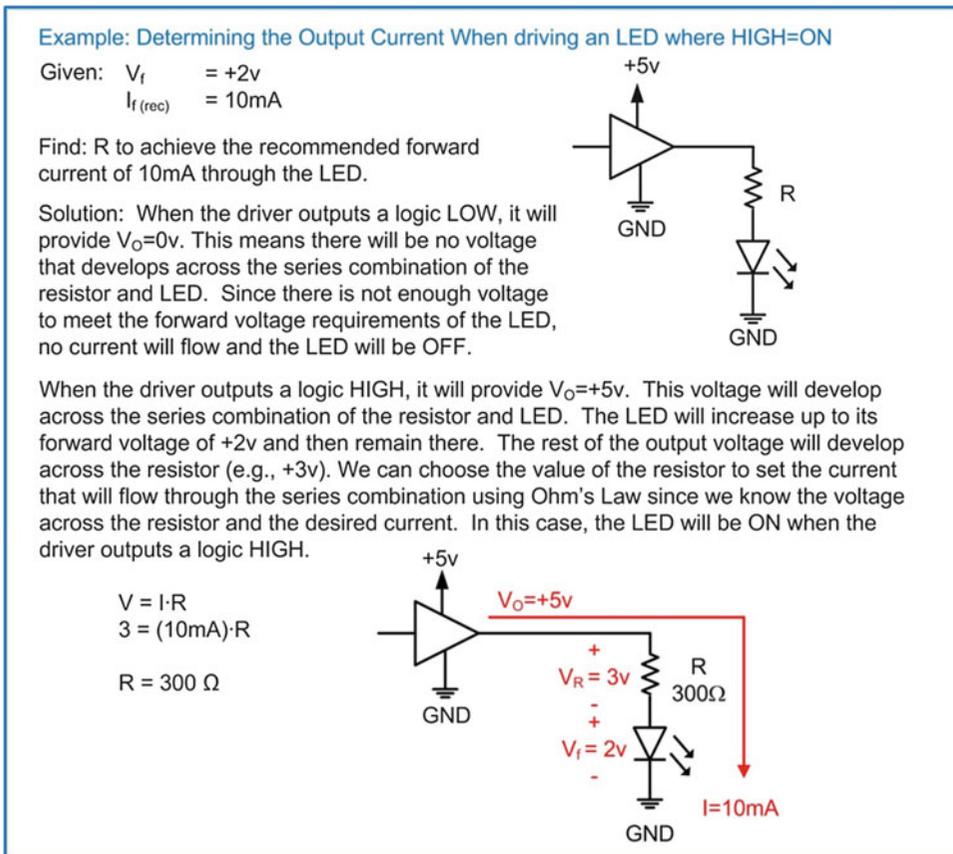


Fig. 3.35
Symbols for a diode and a light-emitting diode

When designing an LED driver circuit, a voltage must be supplied in order to develop the forward voltage across the LED so that current will flow. A resistor is included in series with the LED for two reasons. The first reason is to provide a place for any additional voltage provided by the driver to develop in the situation that $V_o > V_f$, which is most often the case. The second reason for the resistor is to set the output current. Since the voltage across the resistor will be a fixed amount (i.e., $V_o - V_f$), then the value of the resistor can be chosen to set the current. This current is typically set to an optimum value that turns on the LED to a desired luminosity while also ensuring that the maximum output current of the driver is not violated. Consider the LED driver configuration shown in Example 3.7 where the LED will be turned on when the driver outputs a HIGH.



Example 3.7
Determining the Output Current When Driving an LED where HIGH = ON

Example 3.8 shows another example of driving an LED, but this time using a different configuration where the LED will be on when the driver outputs a logic LOW.

Example: Determining the Output Current When Driving an LED where LOW=ON

Given: $V_f = +1.8\text{v}$
 $I_{f(\text{rec})} = 4\text{mA}$

Find: R to achieve the recommended forward current of 4mA through the LED.

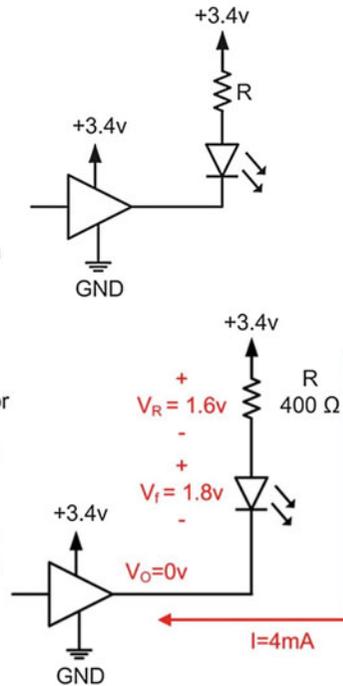
Solution: When the driver outputs a logic HIGH, it will provide $V_o = +3.4\text{v}$. This means there will be no voltage that develops across the series combination of the resistor and LED since the other end of the combination is also at +3.4. This means when driving a logic HIGH, the LED will be OFF.

When the driver outputs a logic LOW, it will provide $V_o = 0\text{v}$. Since the resistor is tied to +3.4v, this voltage will develop across the series combination of the resistor and LED. The LED will increase up to its forward voltage of +1.8v and then remain there. The rest of the output voltage will develop across the resistor (e.g., +1.6v). We can choose the value of the resistor to set the current that will flow through the series combination using Ohm's Law since we know the voltage across the resistor and the desired current. In this case, the LED will be ON when the driver outputs a logic LOW.

$$V = I \cdot R$$

$$1.6 = (4\text{mA}) \cdot R$$

$$R = 400 \Omega$$



Example 3.8
 Determining the Output Current When Driving an LED where HIGH = OFF

CONCEPT CHECK

CC3.4 A fan-out specification is typically around 6-12. If a logic family has a maximum output current specification of $I_{O-\text{max}} = 25\text{mA}$ and a maximum input current specification of only $I_{I-\text{max}} = 1\mu\text{A}$, a driver could conceivably source up to 25,000 gates ($I_{O-\text{max}}/I_{I-\text{max}} = 25\text{mA}/1\mu\text{A} = 25,000$) without violating its maximum output current specification. Why isn't the fan-out specification then closer to 25,000?

- The fan-out specification has significant margin built into it in order to protect the driver.
- Connecting 25,000 loads to the driver would cause significant wiring congestion and would be impractical.
- The fan-out specification is in place to reduce power, so keeping it small is desirable.
- The fan-out specification is in place for AC behavior. It ensures that the AC loading on the driver doesn't slow down its output rise and fall times. If too many loads are connected, the output transition will be too slow and it will reside in the uncertainty region for too long leading to unwanted switching on the receivers.

Summary

- ❖ The operation of a logic circuit can be described using either a logic symbol, a truth table, a logic expression, or a logic waveform.
- ❖ Logic *gates* represent the most basic operations that can be performed on binary numbers. They are BUF, INV, AND, NAND, OR, NOR, XOR, and XNOR.
- ❖ XOR gates that have a number of inputs greater than two are created using a cascade of 2-input XOR gates. This implementation has more practical applications such as arithmetic and error detection codes.
- ❖ The logic *level* describes whether the electrical signal representing one of the two states is above or below a switching threshold region. The two possible values that a logic level can be are HIGH or LOW.
- ❖ The logic *value* describes how the logic levels are mapped into the two binary codes 0 and 1. In positive logic a HIGH = 1 and a LOW = 0. In negative logic a HIGH = 0 and a LOW = 1.
- ❖ Logic circuits have DC specifications that describe how input voltage levels are interpreted as either HIGHs or LOWs (V_{IH-max} , V_{IH-min} , V_{IL-max} , and V_{IL-min}). Specifications are also given on what output voltages will be produced when driving a HIGH or LOW (V_{OH-max} , V_{OH-min} , V_{OL-max} , and V_{OL-min}).
- ❖ In order to successfully transmit digital information, the output voltages of the driver that represent a HIGH and LOW must arrive at the receiver within the voltage ranges that are *interpreted* as a HIGH and LOW. If the voltage arrives at the receiver outside of these specified input ranges, the receiver will not know whether a HIGH or LOW is being transmitted.
- ❖ Logic circuits also specify maximum current levels on the power supplies (I_{VCC} , I_{gnd}), inputs (I_{I-max}), and outputs (I_{O-max}) that may not be exceeded. If these levels are exceeded, the circuit may not operate properly or be damaged.
- ❖ The current exiting a logic circuit is equal to the current entering.
- ❖ When a logic circuit *sources* current to a load, an equivalent current is drawn *into* the circuit through its power supply pin.
- ❖ When a logic circuit *sinks* current from a load, an equivalent current flows *out of* the circuit through its ground pin.
- ❖ The type of load that is connected to the output of a logic circuit dictates how much current will be drawn from the driver.
- ❖ The *quiescent current* (I_q or I_{CC}) is the current that the circuit always draws independent of the input/output currents.
- ❖ Logic circuits have AC specifications that describe the delay from the input to the output (t_{PLH} , t_{PHL}) and also how fast the outputs transition between the HIGH and LOW levels (t_r , t_f).
- ❖ A *logic family* is a set of logic circuits that are designed to operate with each other.
- ❖ The *fan-in* of a logic family describes the maximum number of inputs that a gate may have.
- ❖ The *fan-out* of a logic family describes the maximum number of other gates from within the same family that can be driven simultaneously by one gate.
- ❖ CMOS logic is the most popular family series in use today. CMOS logic uses two transistors (NMOS and PMOS) that act as complementary switches. CMOS transistors draw very low quiescent current and can be fabricated with extremely small feature sizes.
- ❖ In CMOS, only inverters, NAND gates, and NOR gates can be created directly. If it is desired to create a buffer, AND gate, or OR gate, an inverter is placed on the output of the original inverter, NAND, or NOR gate.

Exercise Problems

Section 3.1: Basic Gates

- 3.1.1 Give the truth table for a 3-input AND gate with the input variables A, B, and C and output F.
- 3.1.2 Give the truth table for a 3-input OR gate with the input variables A, B, and C and output F.
- 3.1.3 Give the truth table for a 3-input XNOR gate with the input variables A, B, and C and output F.
- 3.1.4 Give the logic expression for a 3-input AND gate with the input variables A, B, and C and output F.

- 3.1.5 Give the logic expression for a 3-input OR gate with the input variables A, B, and C and output F.
- 3.1.6 Give the logic expression for a 3-input XNOR gate with the input variables A, B, and C and output F.
- 3.1.7 Give the logic waveform for a 3-input AND gate with the input variables A, B, and C and output F.
- 3.1.8 Give the logic waveform for a 3-input OR gate with the input variables A, B, and C and output F.
- 3.1.9 Give the logic waveform for a 3-input XNOR gate with the input variables A, B, and C and output F.

Section 3.2: Digital Circuit Operation

- 3.2.1 Using the DC operating conditions from Table 3.2, give the noise margin HIGH (NM_H) for the 74LS logic family.
- 3.2.2 Using the DC operating conditions from Table 3.2, give the noise margin LOW (NM_L) for the 74LS logic family.
- 3.2.3 Using the DC operating conditions from Table 3.2, give the noise margin HIGH (NM_H) for the 74HC logic family with $V_{CC} = +5v$.
- 3.2.4 Using the DC operating conditions from Table 3.2, give the noise margin LOW (NM_L) for the 74HC logic family with $V_{CC} = +5v$.
- 3.2.5 Using the DC operating conditions from Table 3.2, give the noise margin HIGH (NM_H) for the 74HC logic family with $V_{CC} = +3.4v$.
- 3.2.6 Using the DC operating conditions from Table 3.2, give the noise margin LOW (NM_L) for the 74HC logic family with $V_{CC} = +3.4v$.
- 3.2.7 For the driver configuration in Fig. 3.36, give the current flowing through the V_{CC} pin.

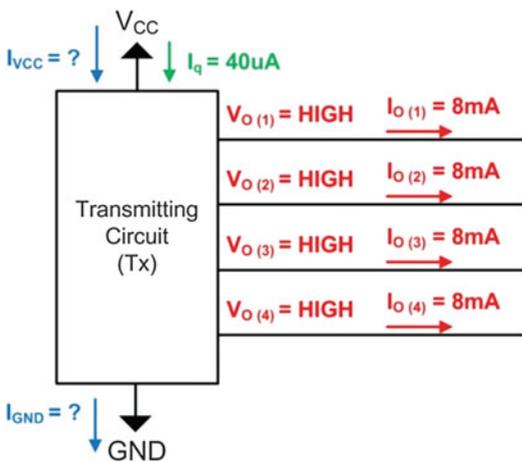


Fig. 3.36
Driver Configuration 1

- 3.2.8 For the driver configuration in Fig. 3.36, give the current flowing through the GND pin.
- 3.2.9 For the driver configuration in Fig. 3.37, give the current flowing through the V_{CC} pin.

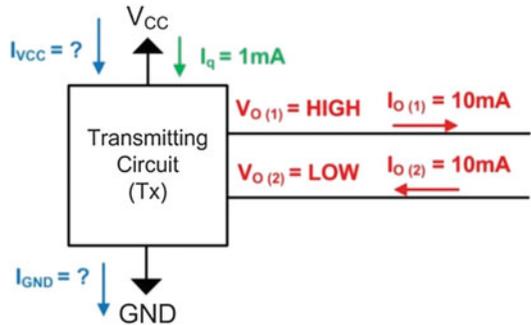


Fig. 3.37
Driver Configuration 2

- 3.2.10 For the driver configuration in Fig. 3.37, give the current flowing through the GND pin.
- 3.2.11 Using the data sheet excerpt from Fig. 3.20, give the maximum propagation delay (t_{pd}) for the 74HC04 inverter when powered with $V_{CC} = +2v$.
- 3.2.12 Using the data sheet excerpt from Fig. 3.20, give the maximum propagation delay from low to high (t_{PLH}) for the 74HC04 inverter when powered with $V_{CC} = +2v$.
- 3.2.13 Using the data sheet excerpt from Fig. 3.20, give the maximum propagation delay from high to low (t_{PHL}) for the 74HC04 inverter when powered with $V_{CC} = +2v$.
- 3.2.14 Using the data sheet excerpt from Fig. 3.20, give the maximum transition time (t_t) for the 74HC04 inverter when powered with $V_{CC} = +2v$.
- 3.2.15 Using the data sheet excerpt from Fig. 3.20, give the maximum rise time (t_r) for the 74HC04 inverter when powered with $V_{CC} = +2v$.
- 3.2.16 Using the data sheet excerpt from Fig. 3.20, give the maximum fall time (t_f) for the 74HC04 inverter when powered with $V_{CC} = +2v$.

Section 3.3: Logic Families

- 3.3.1 Provide the transistor-level schematic for a 4-input NAND gate.
- 3.3.2 Provide the transistor-level schematic for a 4-input NOR gate.
- 3.3.3 Provide the transistor-level schematic for a 2-input AND gate.
- 3.3.4 Provide the transistor-level schematic for a 2-input OR gate.
- 3.3.5 Provide the transistor-level schematic for a buffer.

Section 3.4: Driving Loads

3.4.1 In the driver configuration shown in Fig. 3.38, the buffer is driving its maximum fan-out specification of 6. The maximum input current for this logic family is $I_i = 1 \text{ nA}$. What is the maximum output current (I_o) that the driver will need to source?

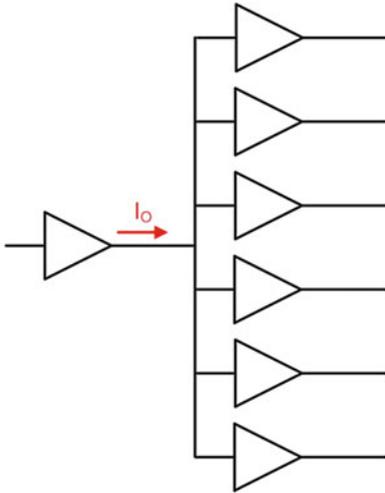


Fig. 3.38
Driver Configuration 3

3.4.2 For the pull-down driver configuration shown in Fig. 3.39, calculate the value of the pull-down resistor (R) in order to ensure that the output current does not exceed 20 mA.

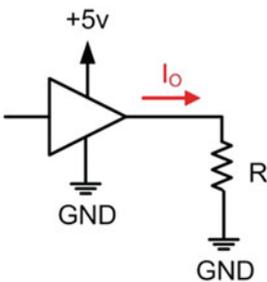


Fig. 3.39
Driver Configuration 4

3.4.3 For the pull-up driver configuration shown in Fig. 3.40, calculate the value of the pull-up resistor (R) in order to ensure that the output current does not exceed 20 mA.

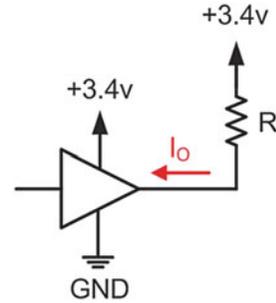


Fig. 3.40
Driver Configuration 5

3.4.4 For the LED driver configuration shown in Fig. 3.41 where an output of HIGH on the driver will turn on the LED, calculate the value of the resistor (R) in order to set the LED forward current to 5 mA. The LED has a forward voltage of 1.9v.

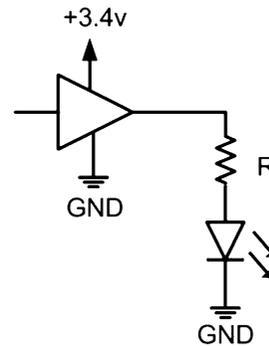


Fig. 3.41
Driver Configuration 6

3.4.5 For the LED driver configuration shown in Fig. 3.42 where an output of LOW on the driver will turn on the LED, calculate the value of the resistor (R) in order to set the LED forward current to 5 mA. The LED has a forward voltage of 1.9v.

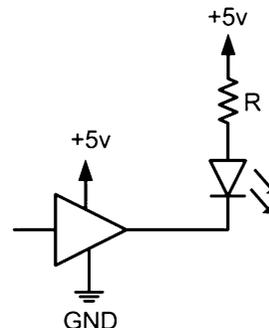


Fig. 3.42
Driver Configuration 7