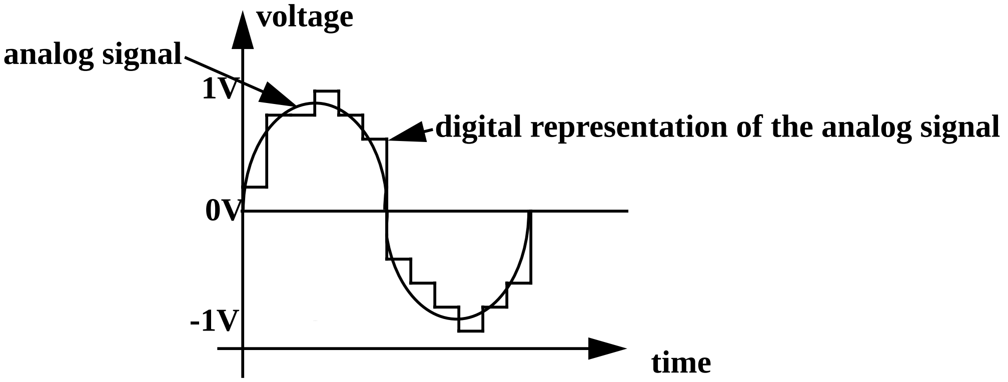
Binary Logic - Concepts and Circuits

To this point we have considered signals (voltages and currents) that could take on any value. These are referred to as analog signals. Analog signals are time continuous and can take on an infinite number of values.

Another kind of signal of great importance is one that can assume a strictly limited set of discrete values. These are called digital signals. Digital signals are time and value discrete. The values that a signal may take on at any time are finite, often consisting of only two logical values.

The figure below shows an analog voltage signal and its digital counterpart. The analog signal can take on an infinite number of values while the digital signal is quantized to 10 discrete voltage levels.

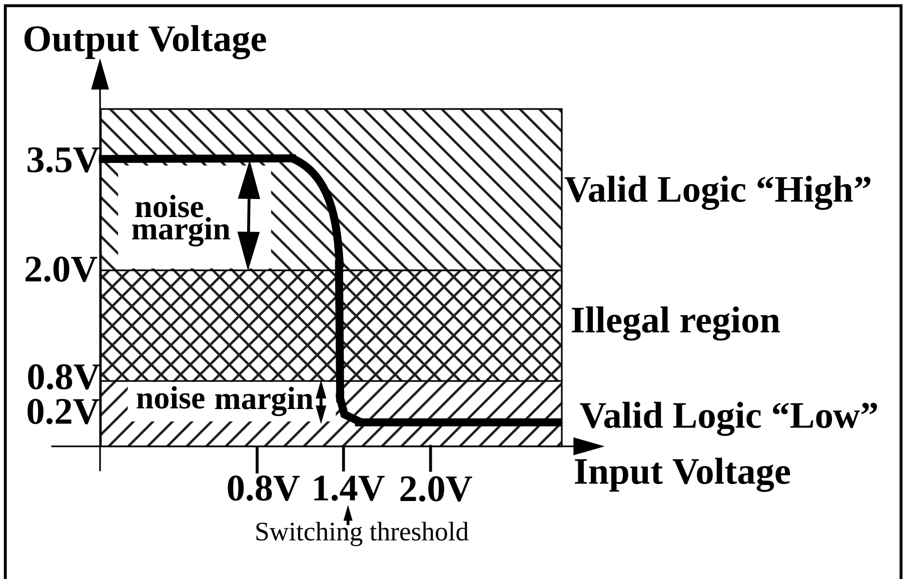


Analog versus Digital Signals

The most interesting system (and the easiest to implement with transistors) is one where a signal my take on only two possible values. These signals are called “binary” signals. We give different names to the binary signal levels; “1” and “0”; “true” and “false”; “on” and “off”. These names may represent any particular voltage or current level. Typically, we assign the logic value “1” to the higher output voltage and “0” to the lower output voltage.

Circuits built with real components actually operate with continuous voltages and currents. Thus cut-off values are chosen so that any voltage within a certain range is considered to be the value “1” and any number within a second, non-overlapping range is assigned the value “0”. Other values are considered illegal.

The input/output transfer function of a digital TTL (transistor to transistor) “inverter” below shows the valid “high”, “low” and illegal voltage values.

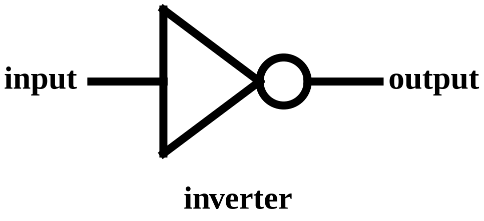


TTL I/O Thresholds

When digital logic has an output voltage of two volts or above its output is considered to be logic “1”. An output voltage 0.8 volts or less is considered to be logic “0”. Voltages between 0.8 volts and 2.0 volts are considered illegal. The binary logic circuits should never encounter signals within this region except for a quick transition through it when switching states.

In real implementations of these circuits, electrical noise may exist. Therefore the typical output levels are well in excess of the points at which the “1” or “0” decision is made. The distance by which the input voltage exceeds the switching threshold is called the *noise margin.* Noise levels of up to 0.6 volts may be injected on an input signal and the inverter shown above will still operate correctly.

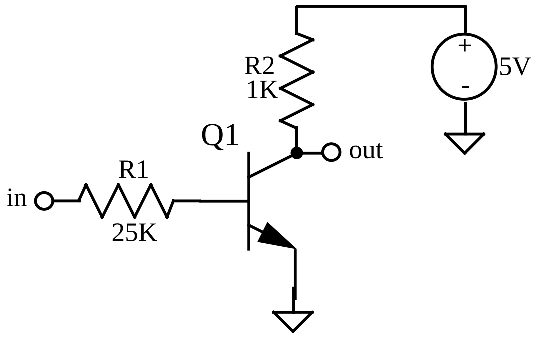
The inverter is the most simple logic gate. Its function is simply to invert whatever signal is present on its input. If the input is a “1”, the output is “0”. If the input is “0”, the output is “1”. The symbol for the inverter and its truth table is shown below. Note that the “bubble” on the output of a gate indicates a logical inversion. Thus, an inverter without a “bubble” would not invert the signal. The output would be identical to the input.



input	output
0	1
1	0

The use of a binary coded signaling system is intentional. First of all, it allows simple implementation with transistor switches that are either “on” or “off”. Additionally, the binary system allows us to leverage the work of George Boole and Claude Shannon pertaining to rules for manipulating boolean (logic) variables and thus perform binary arithmetic.

A simple inverter can be made from a single transistor. Lets return to our old transistor amplifier and see how it can work as an inverter.



Transistor Logic Inverter

We will adopt the convention that voltages between 2 and 5 volts constitute logic “one” and voltages between 0 and 0.8 volts are logic “zero”. Also, assume a transistor beta of 100.

Logic 0 input case:

If we apply a logic zero (0.5 volt or less) to the input of the circuit, we know that no base current will flow because the base-emitter junction cannot be forward biased by less than 0.7 volt. Thus the collector current will be zero and the voltage at “out” will be 5 volts.

Logic 1 input case:

If we apply an input signal of a minimum of 2 volts to the input, what happens? Writing the KVL equation at the base-emitter loop:

$-2 + 25000Ib + .7 = 0$
$25000Ib = 1.3$
$Ib = 52uA$, thus
$Ic = 5.2mA$

The voltage drop across the 1k resistor would be 5.2 volts. We know that at most it will be 5 - Vce_{sat}. Therefore we know that the transistor is in saturation. Output “out” will be at 0.2 volts which corresponds to logic “zero” with the input at logic “one”. Our transistor amplifier can indeed function as a primitive inverter.

So, what is the threshold of the inverter we just created? Lets define that the input voltage which causes the output to be at exactly one half the supply voltage (half way between power and ground) to mark the switching threshold. This will occur when Ic = 2.5mA or when Ib = 25uA. Thus we will solve for Vin when Ib = 25uA.

Writing the KVL equation at the base-emitter loop with a known Ib:

$-Vin + 25000(25uA) + .7 = 0$
$Vin = 1.3V$

Therefore we see that the common emitter amplifier can act as primitive inverter. The inverter determines if the input voltage is above or below 1.3 volts. If above, the output voltage is zero volts (logic zero). If below 1.3 volts, the output is five volts (logic one). The accuracy of the switching threshold is strongly dependent however on Vbe and Beta.