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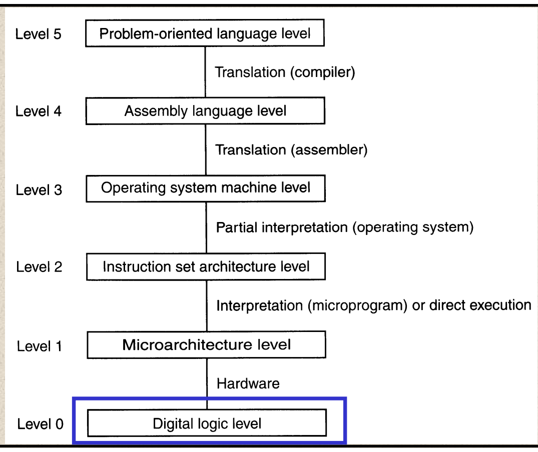
GATES

THE DIGITAL LOGIC LEVEL

At the bottom of the hierarchy chart we find the digital logic level, the computer's real hardware. In this chapter, we will examine many aspects of digital logic, as a building block for the study of higher levels in subsequent chapters. This subject is on the boundary of computer science and electrical engineering, but the material is self-contained, so no previous hardware or engineering experience is needed to follow it.



GATES AND BOOLEAN ALGEBRA

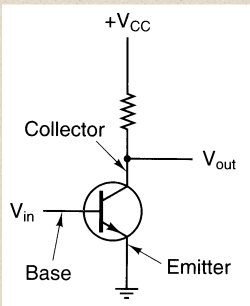
Digital circuits can be constructed from a small number of primitive elements by combining them in innumerable ways.
In the following sections we will describe these primitive elements, show how they can be combined, and introduce a powerful mathematical technique that can be used to analyze their behavior.

GATES

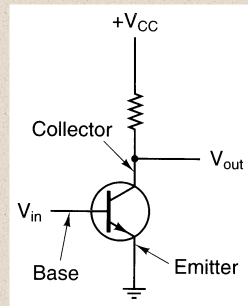
A digital circuit is one in which only two logical values are present.
Typically, a signal between 0 and 1 volt represents one value (e.g., binary 0) and a signal between 2 and 5 volts represents the other value (e.g., binary 1). Voltages outside these two ranges are not permitted.
Tiny electronic devices, called gates, can compute various functions of these two-valued signals.
These gates form the hardware basis on which all digital computers are built.

GATES

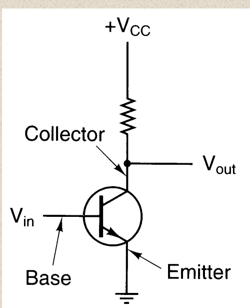
The details of how gates work inside is beyond the scope of this book, belonging to the device level, which is below our level 0.
Nevertheless, we will take a quick look at the basic idea, which is not difficult.
All modern digital logic ultimately rests on the fact that a transistor can be made to operate as a very fast binary switch.



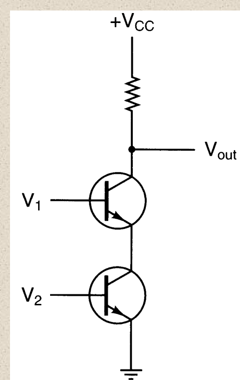
Here is a bipolar transistor (the circle) embedded in a simple circuit.
This transistor has three connections to the outside world: the collector, the base, and the emitter.
When the input voltage, Vin, is below a certain critical value, the transistor turns off and acts like an infinite resistance.



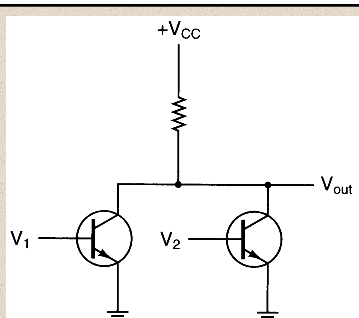
This causes the output of the circuit , Vout, to take on a value close to Vcc, an externally regulated voltage, typically +5 volts for this type of transistor.
When Vin, exceeds the critical value, the transistor switches on and acts like a wire, causing Vout to be pulled down to ground (by convention, 0 volts).



The important thing to notice is that when Vin is low, Vout is high, and vice versa.
This circuit is thus an inverter, converting a logical 0 to a logical 1, and a logical 1 to a logical 0.
The resistor (the jagged line) is needed to limit the amount of current drawn by the transistor so it does not burn out.
The time required to switch from one state to the other is typically a few nanoseconds.



Here two transistors are cascaded in series.
If both V1 and V2 are high, both transistors will conduct and Vout will be pulled low.
If either input is low, the corresponding transistor will turn off, and the output will be high.
In other words, Vout will be low if and only if both VI and V2 are high.



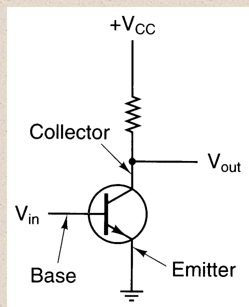
Here the two transistors are wired in parallel instead of in series.
In this configuration, if either input is high, the corresponding transistor will turn on and pull the output down to ground.
If both inputs are low, the output will remain high.

GATES

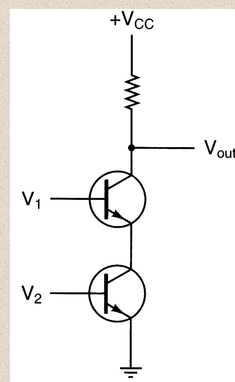
These three circuits, or their equivalents, form the three simplest gates.
They are called

NOT
NAND
NOR

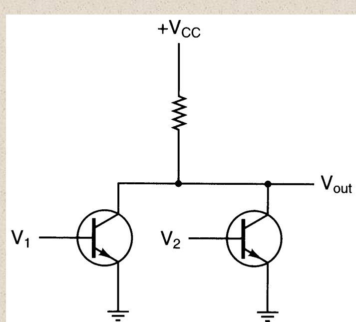
NOT gates are often called inverters; we will use the two terms interchangeably.



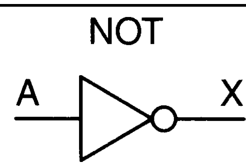
NOT INVERTOR



NAND



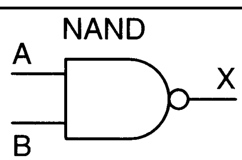
NOR



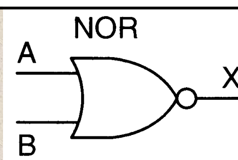
input output

A	X
0	1
1	0

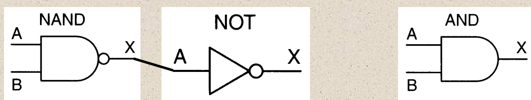
If we now adopt the convention that "high" (Vcc volts) is a logical 1, and that "low" (ground) is a logical 0, we can express the output value as a function of the input values.



A	B	X
0	0	1
0	1	1
1	0	1
1	1	0



A	B	X
0	0	1
0	1	0
1	0	0
1	1	0

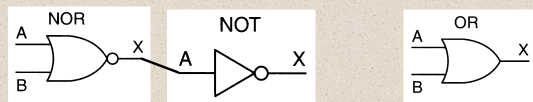


A	B	X
0	0	1
0	1	1
1	0	1
1	1	0

A	X
0	1
1	0

A	B	X
0	0	0
0	1	0
1	0	0
1	1	1

If the output signal of the NAND is fed into an inverter circuit, we get another circuit with precisely the inverse of the NAND gate- namely, a circuit whose output is 1 if and only if both inputs are 1. Such a circuit is called an AND gate.

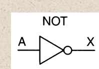


A	B	X
0	0	1
0	1	0
1	0	0
1	1	0

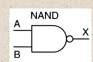
A	X
0	1
1	0

A	B	X
0	0	0
0	1	1
1	0	1
1	1	1

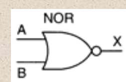
Similarly, the NOR gate can be connected to an inverter to yield a circuit whose output is 1 if either or both inputs is a 1 but 0 if both inputs are 0. The symbol and functional description of this circuit, called an OR gate, are given above.



A	X
0	1
1	0



A	B	X
0	0	1
0	1	1
1	0	1
1	1	0



A	B	X
0	0	1
0	1	0
1	0	0
1	1	0

The small circles used as part of the symbols for the inverter, NAND gate, and NOR gate are called inversion bubbles. They are often used in other contexts as well to indicate an inverted signal.

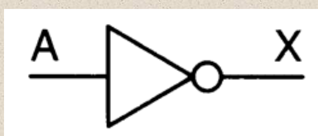
GATES

The five gates shown are the principal building blocks of the digital logic level.
From the foregoing discussion, it should be clear that the NAND and NOR gates require two transistors each, whereas the AND and OR gates require three each.
For this reason, many computers are based on NAND and NOR gates rather than the more familiar AND and OR gates. (In practice, all the gates are implemented somewhat differently, but NAND and NOR are still simpler than AND and OR.)

GATES

In passing it is worth noting that gates may have more than two inputs.
In principle, a NAND gate, for example, may have arbitrarily many inputs, but in practice more than eight inputs is unusual.

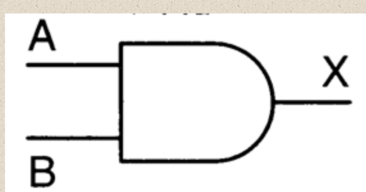
GATES



A	X
0	1
1	0

NOT

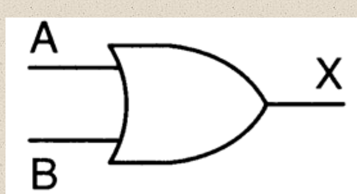
GATES



A	B	X
0	0	0
0	1	0
1	0	0
1	1	1

AND

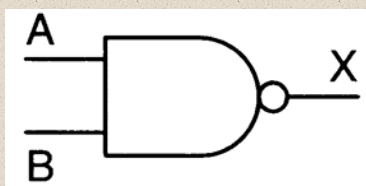
GATES



A	B	X
0	0	0
0	1	1
1	0	1
1	1	1

OR

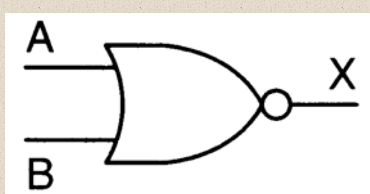
GATES



A	B	X
0	0	1
0	1	1
1	0	1
1	1	0

NAND

GATES



A	B	X
0	0	1
0	1	0
1	0	0
1	1	0

NOR

GATES

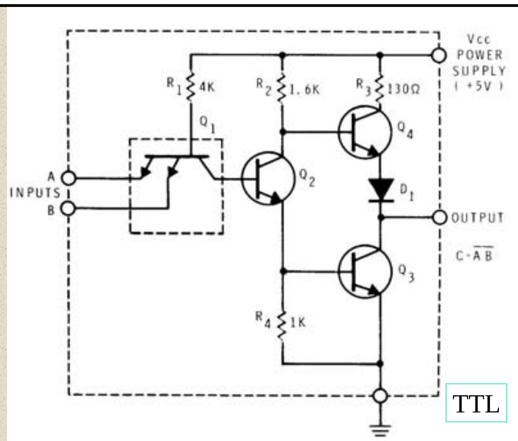
Although the subject of how gates are constructed belongs to the device level, we would like to mention the major families of manufacturing technology because they are referred to frequently.
The two major technologies are bipolar and MOS (Metal Oxide Semiconductor).

GATES

The major bipolar types are

TTL (TransistorTransistor Logic), which has been the workhorse of digital electronics for years, and

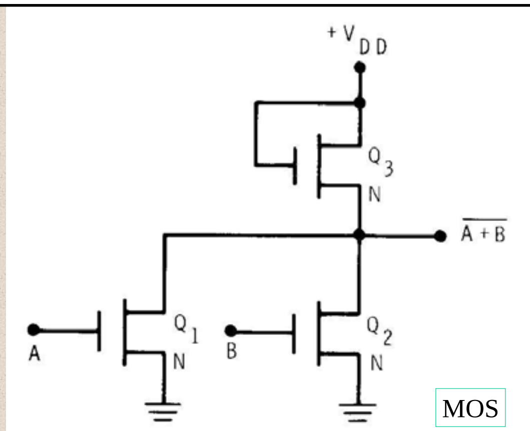
ECL (Emitter-Coupled Logic), which is used when very high-speed operation is required.



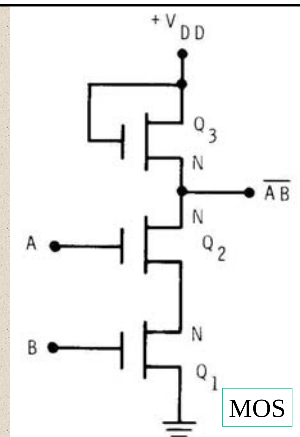
TTL

GATES

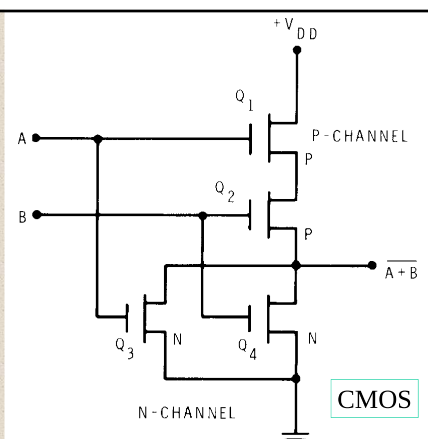
MOS gates are slower than TTL and ECL but require much less power and take up much less space, so large numbers of them can be packed together tightly.
MOS comes in many varieties, including PMOS, NMOS, and CMOS.
While MOS transistors are constructed differently from bipolar transistors, their ability to function as electronic switches is the same.
Most modern CPUs and memories use CMOS technology, which runs on +3.3 volts.



MOS



MOS



CMOS