Lab 10

Digital Technology

Introduction

In this lab you will learn about digital signals, and investigate some digital logic circuits.

- You will investigate the operation of AND, OR, NOT, and NAND logic gates.
- You will build a D type latch memory circuit, and use it in a simple burglar alarm circuit.

Before we can do these experiments, should learn about:

- What are digital signals.
- Digital communication and coding.
- Digital technologies in our everyday lives.
- Digital computation and digital logic.

Before Modern Electronics

Before there were computers, scientists and engineers still were able to build programmable and networked systems.

What are some examples?

Programmable Machines & Video Phones

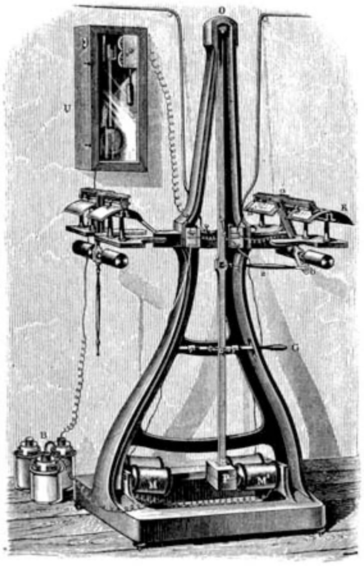
In 1801, the Jacquard loom was invented by Joseph Marie Jacquard (1752 - 1834).

- It was the first machine to use punch cards to control a sequence of operations.
- Each hole in a card corresponds to the motion of a weaving hook.

In 1936, the first public video telephone service was introduced in Germany.

- It was developed by the electrical engineer Oscar Georg Schubert (1900 - 1955).

The First Fax Machine



In 1861, the Italian physicist and priest Giovanni Caselli (1815 - 1891) invented the Pantelegraph.

- It used telegraph lines to transmit the electronic signals.
- In 1865, commercial telefax service was established between Paris and Lyon.

This was 11 years before Alexander Graham Bell received his patent for the telephone.

"Faxed" documents from 1861.

Digital Electronics In Our Modern World

Our Digital Lifestyle

Our modern society relies on digital technologies to function.

- Electrical and computer engineers work in many industries to design needed electronic systems.

Why Do We Use Digital Technology?

We use digital technology for a variety of reasons, such as:

- To control mechanical and electrical systems, often with complex behaviours.
- To gather data from sensors, for storage or to take appropriate actions.

We are so accustomed to electronics, that we often don't appreciate how high performing these systems are.

- This "simple" optical mouse uses a tiny camera to take 1000's of pictures per second of the table under the mouse.
- A microprocessor capable of ~ 20 million operations per second calculates movement.

You can use an optical mouse as a low resolution camera. Many web sites show examples of how to do this.

The Slowing of Time

This computer can do over 25 billion calculations per second.

- It will have finished 50 calculations before the light travels from the screen to your face (a distance of about 2 feet).

As an engineer, what could you do will all this data processing?

- How about monitoring an explosion? During the time a stick of dynamite explodes (about 25 microseconds), the above computer can do over 600,000 calculations.

A microsecond is a long time to an electrical or computer engineer.

Controlling Aircraft Systems

A commercial jet cruises ~ 900 km/h. This computer can do 1,000,000 calculations in the time it takes it to travel 1 cm.

- What could you do with all this power?

Airbus A380 cockpit

Picture from Wikipedia

Electronic systems are critical to the operation of modern aircraft.

- Uses: navigation, flight controls, radar, communications, engine systems, on-board sensors, the passenger entertainment system, and more.

Controlling Automotive Systems

A typical car may have 50 electronic control units, and execute millions of lines of software code, to analyze engine data, control safety systems, the radio, and more.

Within ~ 10 ms after a collision, electronics calculate the angle and force of impact, and decide the deployment of seat belt pre-tensioners, and/or which of the many airbags.

NHTSA

DaimlerChrysler AG

This S-Class Mercedes has almost as many electronic control units as the Airbus A380 (excluding the plane's entertainment system). 100 million lines of software code control the car's various systems.

Innovation in cars is now largely in electronic systems.

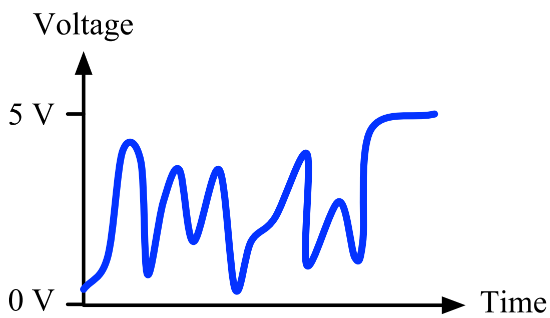
- By 2020, the cost of electronics is expected to be 50% of vehicle cost, and 80% in hybrid vehicles.

Digital Signals & Digital Data

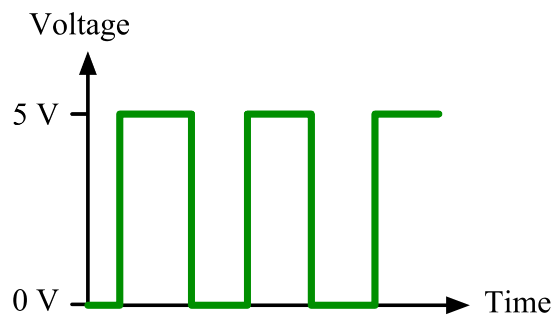
Digital Signals

In digital electronics, information is represented by discrete voltage levels, rather than continuous voltage levels. For example:

- An analog circuit might have a voltage that can be any value from 0 - 5 volts.
- While in a two state (binary) digital circuit, the voltage might only be allowed to be either 0 V or 5 V.



Analog Signal

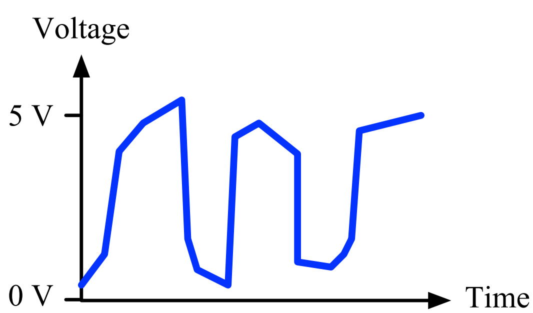


Digital Signal

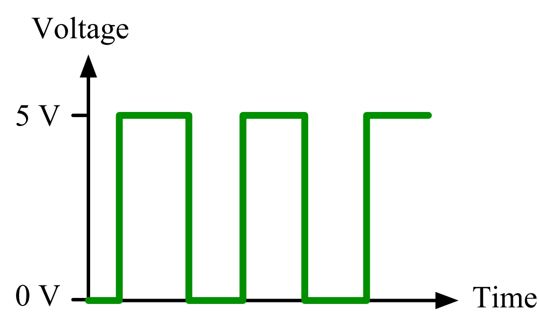
Noise Advantage of Digital Signals

Since only "***high***" and "***low***" voltages are used ***and expected***, digital signals can be transmitted without worry about electrical noise or interference. For example:

- A transmitter sends a 5 V "high" signal to a receiver a long distance away.
- But due to interference, the signal received was only 4 V.
- The receiver could safely assume that it was supposed to be a 5 V "high", since the received 4 V signal is closer to 5 V than to 0 V.



Poor quality signal received.



But the receiver knows it should be this.

Digital Information Storage

Since digital electronics will ignore small variations from the expected *high* and *low* voltages, digital storage of information is advantageous.

- Data can be stored for long periods, or read many times, without fear of degradation.
- For example, a vinyl record will degrade with repeated listening, while a music CD will not.

Picture from Wikipedia

Binary Digital Circuits

Digital electronics typically operate using two state, or binary, signals.

- But what if you need more than two data values?
- If you need more than two data values, then sequences of digital pulses are used to represent other possible numbers.

One method of coding number information using digital pulses is the binary number system.

Each binary digit is called a bit.

- For example, the binary number "1010" is a 4 bit number.

A group of 8 binary bits is called a byte.

Other coding methods can be used.

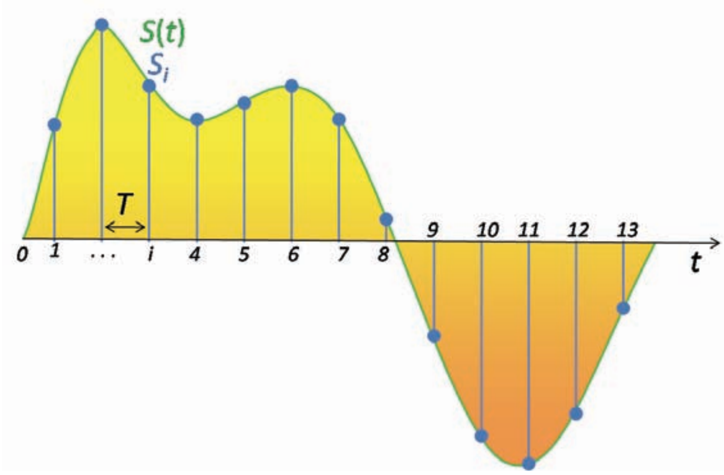
Decimal Number	Binary Number
0	0
1	1
2	10
3	11
4	100
5	101
6	110
7	111
8	1000
9	1001
10	1010
11	1011
12	1100
13	1101
14	1110
15	1111

and so on

Analog to Digital Conversion

Suppose you want to transmit the information in an analog signal (such as human voice), but using digital pulses. What do you need to do?

- First, the amplitude of the analog signal is sampled (measured) at specific time intervals. The rate that this is done is called the *sampling frequency*.
- Second, the amplitude value is converted to a binary number. The resolution of this conversion is called the *bit depth*.



Sampling Frequency

Sampling frequency is the number of times per second that you sample the analog signal.

- Compact disc music: The digital music on CD's is made by sampling the original analog sound at 44,100 times per second (44.1 kHz sampling).

Why is 44.1 kHz used?

- The Nyquist-Shannon sampling theorem guarantees that a signal can be reconstructed perfectly if the sampling rate is at least 2x the signal frequency.
- Since humans can hear up to 20 kHz sound, you need a sampling rate of at least 40 kHz to digitally encode all possible sounds that humans can hear.

Bit Depth

At each sampling time, the amplitude of the analog signal is measured, and converted to a digital number. Bit depth is the resolution of the amplitude measurement.

- The number of possible binary number values that can be assigned to the amplitude level is 2^n, where n is the bit depth.

Compact disc music: Sound is digitized at 16 bits. The number of possible amplitude levels is $2^{16} = 65{,}536$.

- 2^{16} amplitude levels converts to 96 dB on a decibel scale. This quality is higher than the signal-to-noise ratio of most consumer audio systems.

Decibel amplitude conversion: $20 \times \log(65{,}536) = 96.3$ dB

Signal-to-noise ratio (SNR) compares the amplitude of a desired signal to the amplitude of the background level of noise in the electronics. Most consumer quality audio systems have an SNR of ~ 90 dB.

- FYI: The range of human hearing is about 1 million times (2^{20} bits, or 120 dB).

Digital Images

Digital images have two ratings.

- The size of the image in pixels.
  - For example 1920 pixels wide and 1080 pixels tall is the size of a high definition video picture for television.
- The bit depth of the colour range of each pixel.
  - For example, JPEG images are 24 bit colour, sub-divided into 8 bits for red, 8 bits for green, and 8 bits for blue.
  - Thus, there are $2^8 = 256$ possible brightnesses levels for each colour, and the total possible number of colours is $2^{24} = 16{,}777{,}216$.

In 1861, the Scottish physicist James Clerk Maxwell (1831 - 1879) demonstrated that colour photographs could be formed by overlaying three pictures, separately taken using red, green, and blue filters over a camera lens.

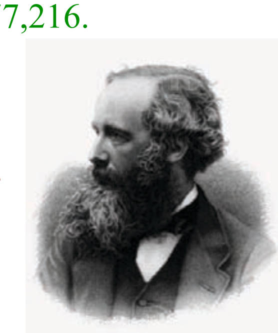
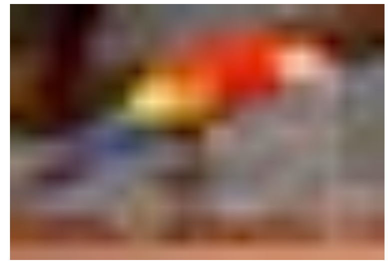


Image Resolution & Number of Colours

300 pixels wide
16 million colours

100 pixels wide
16 million colours



25 pixels wide
16 million colours

300 pixels wide
256 colours

300 pixels wide
50 colours

300 pixels wide
20 colours

Picture from Wikipedia

Data Compression

The above pictures of the bird at different qualities indicate that you can often discard data, or approximate it mathematically, without significant detriment.

For example, video can be heavily compressed without significant loss of quality.

- One frame of a standard definition video picture needs:

(720 pixels) x (480 pixels) x (24 bits) = 8.2944 Megabits *(1.0368 Mbytes)*

- What does a 2 hour movie playing at 30 frames per second need ?

(1.0368 MB) x (30 frames/sec) x (7200 seconds) = 224 GB

But you can fit this on an 8 GB DVD and most people are happy with the quality !!

Data compression concepts are taught in various electrical and computer engineering courses.

Digital Communication
&
Digital Coding

Historical Digital Coding

Before telephones, information was transmitted by telegraph. How many wires do you need to install between cites to send a message?

- You could use 1 wire for each letter of the alphabet, each number, and punctuation. But this would cost a lot of money.

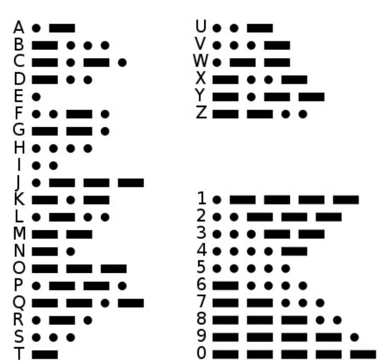
Samuel Morse

Many coding systems were developed. One of them, Morse code, only needed 1 wire, and was also a binary system.

- It was developed between 1837 and 1844, by the Americans Samuel Morse (1791 - 1872) and Alfred Vail (1807 - 1859).

Alfred Vail

International Morse Code



Over 160 years later, Morse code is still in use.

Pictures from Wikipedia

Information As Numbers

On a computer, the binary number system is used to code letters of the alphabet.

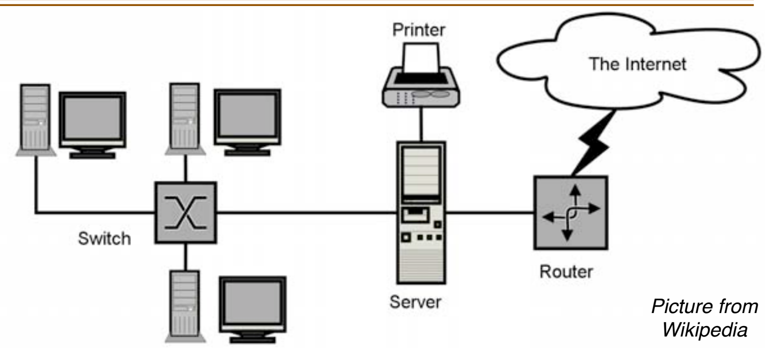
- An early method used by computers to recognize keyboard input was the ASCII code system.
- ASCII code used a 7 bit binary number assigned to each input value. And so there are 2^7 or 128 possible letters, numbers, punctuation marks, or other special characters that can be supported.

Part of the ASCII code.

Key Press	Decimal Number Assigned	Binary Number
A	65	100 0001
B	66	100 0010
C	67	100 0011
D	68	100 0100
E	69	100 0101
...		
a	97	110 0001
b	98	110 0010
c	99	110 0011
d	100	110 0100
e	101	110 0101

Networked Communication

When communicating on a network, digital messages must be “addressed” so that they arrive at the correct person/computer.



Picture from Wikipedia

On the Internet, a 32 bit (four 8 bit numbers) Internet Protocol (IP) address was initially used to identify all devices. A typical 32 bit address might look like:

In binary: 11011000 . 00011011 . 00111101 . 10001001

In Decimal: 216 . 27 . 61. 137

32 bit IP addresses provide only 2^{32} = 4.3 billion possible addresses. With so many devices connected to the internet, available addresses are rapidly becoming used up.

- A larger 128 bit addressing system is now being implemented. It provides:

$2^{128} = 3.4 \times 10^{38}$ possible addresses

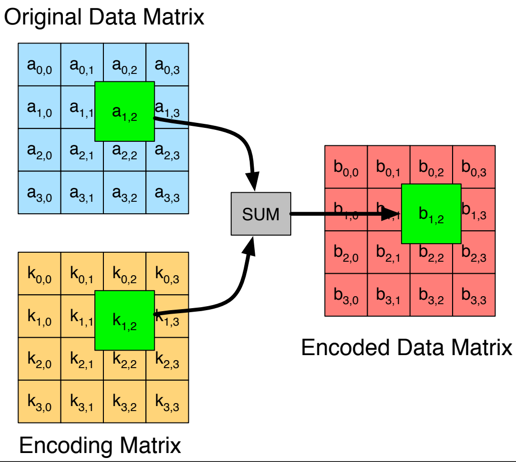
Encryption

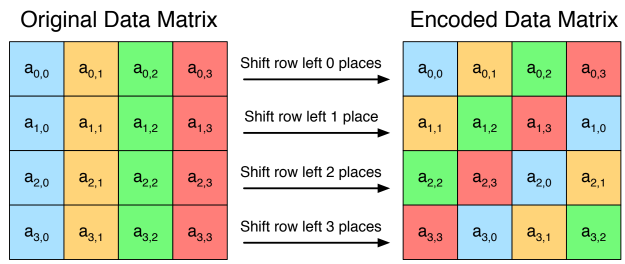
In an encrypted message the digital "bits" are scrambled so that someone listening cannot read the message being sent.

- For example, a simple code would be to swap every two consecutive bits.

  01 01 11 10 would be 10 10 11 01

- More complex methods might include adding or multiplying blocks of data by number sequences, or more complex data reorganizing methods.

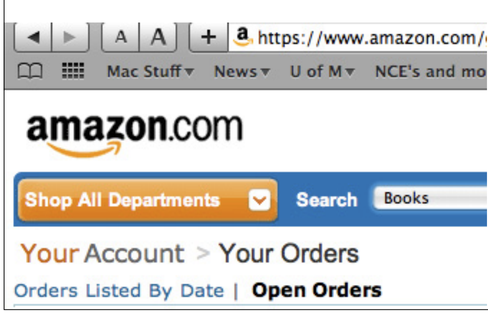




How Much Encryption Do You Need?

If you want a secure password, how long should it be?

- A 6 character password is 48 bits long (8 bits/character), or $2^{48} = 2.8 \times 10^{14}$ combinations.
- A fast graphics processor (GPU) in a PC can perform 500 billion calculations per second. If this card could test 500 billion passwords per second, it would crack a 6 character password in: $$\frac{2.8 \times 10^{14}}{500 \times 10^{9}} = 563 \text{ seconds}$$
- An 8 character password is 64 bits long, or $2^{64} = 1.8 \times 10^{19}$ combinations. The above graphic card would need: $$\frac{1.8 \times 10^{19}}{500 \times 10^{9}} = 416.7 \text{ days}$$



The fastest supercomputers are 1000's of times faster, and so an 8 character password would be broken in only a few hours. This is why secure web communications (https) use 128 bit (or larger) encryption.

Computer Logic

Let's now learn about logical electronic gates for today's lab project.

Boolean Logic

Boolean logic is a two state logic system.

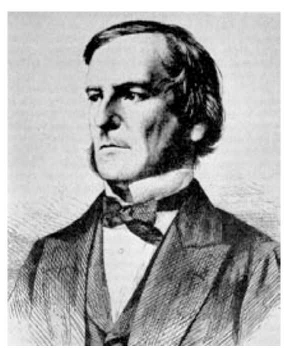
- For example, the answer to a question could be either "True" or "False".

Computers operate using boolean logic.

- For example, boolean logic statements can be implemented in a digital circuit using 0 V for a logical "False", and 5 V for a logical "True".

The British mathematician and philosopher George Boole (1815 - 1864) invented Boolean logic.

- These logic concepts form the basis of modern digital computer logic.



Boolean Logic Functions

Boolean logic functions are similar to functions in algebra. One, two, or more binary inputs can be evaluated to generate a binary output.

- Examples of logic decision functions are AND, OR, and NOT.

A "truth table" shows the output of a function for every possible combination of inputs.

- On a truth table, "1" means "True", and "0" means "False".

Inputs		Output
x	y	x AND y
0	0	0
0	1	0
1	0	0
1	1	1

Output is "1" only when both inputs are "1".

Inputs		Output
x	y	x OR y
0	0	0
0	1	1
1	0	1
1	1	1

Output is "1" when any input is "1".

Input	Output
x	NOT x
0	1
1	0

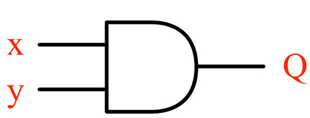
Output is the opposite of the input.

Digital Logic Gates

Digital logic gates are electronic devices which implement binary logic functions.

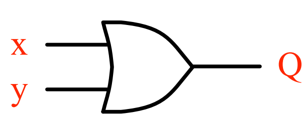
- You will learn how build logic gates from transistors in upper years of electrical and computer engineering.

AND Gate



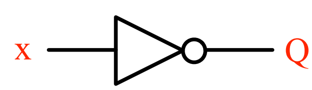
Input		Output
x	y	Q
0	0	0
0	1	0
1	0	0
1	1	1

OR Gate



Input		Output
x	y	Q
0	0	0
0	1	1
1	0	1
1	1	1

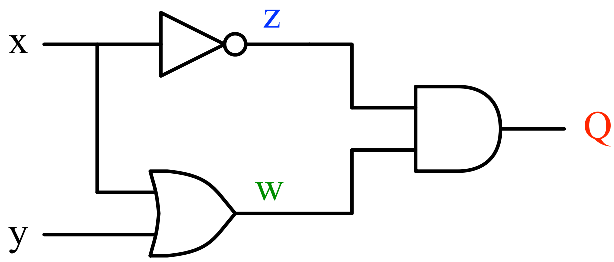
NOT Gate



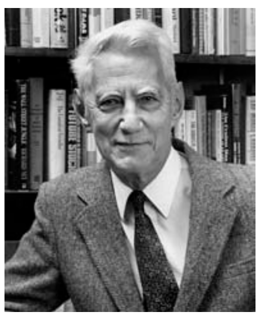
Input	Output
x	Q
0	1
1	0

A Logic Function Construction

You can make more complex logic functions by assembling many logic gates together.



x	y	z	w	Q
0	0	1	0	0
0	1	1	1	1
1	0	0	1	0
1	1	0	1	0



Picture from http://landley.net/history/mirror/pre/shannon.html

In 1937, the American electrical engineer and mathematician Claude Shannon (1916 - 2001) demonstrated how Boolean functions could be solved by electrical switches.

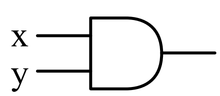
Shannon was well known for his diverse interests. He once rode his unicycle down the halls at Bell Labs while juggling.

Example: Adding Two Binary Digits

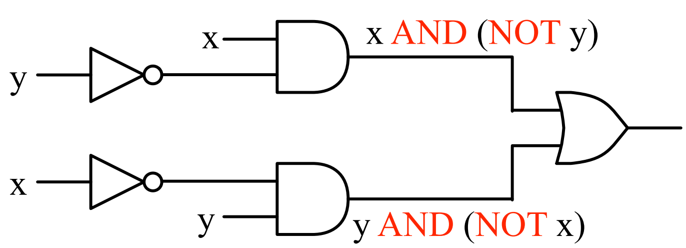
What logic circuit is needed to add two binary digits?

x + y = ?

x	y	Decimal Answer	Binary Answer	Carry Digit	Sum Digit
0	0	0	0 0	0	0
0	1	1	0 1	0	1
1	0	1	0 1	0	1
1	1	2	1 0	1	0



Carry = x AND y



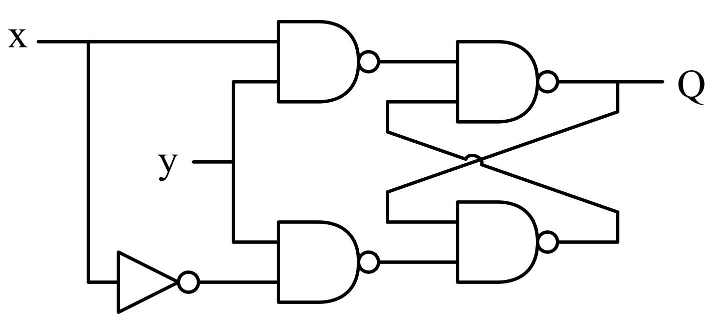
Sum = [x AND (NOT y)]
OR [y AND (NOT x)]

Digital Circuit with Memory

A Simple Digital Memory Circuit

In today's lab you will build a logic memory circuit called a D latch. You will use this circuit to remember when a burglar alarm has been tripped.

- You will build your D latch using one NOT gate, and four NAND gates.
- The NAND function (meaning NOT-AND) is the inverse of the AND function.



x	y	Q
0	0	no change
0	1	0
1	0	no change
1	1	1

In this circuit, the output Q will follow the value of x, only if y = True.

- If y = False, then the output will not change, even if x changes.

Important Things To

Remember

Important Points

When converting an analog signal into a digital signal:

- Sampling frequency is how often the amplitude of an analog signal is measured.
- Bit depth is the binary resolution (2^n possible values) that the amplitude of an analog signal is measured.

You should know how to count in binary up to 15.

You should know the Truth Tables for the AND, OR, NOT, and NAND logic functions, and the circuit symbols for these logic gates.

AND Gate OR Gate NOT Gate NAND Gate