Electrical and Electronic Measurements:

Digital Electronic Meters

1

Digital Signal

- Binary or two stages:
  "0" (Low voltage ➔ 0 - 3 V)
  "1" (High voltage ➔ 4 - 5 V)
- Binary digit is called "bit".
- Group of bits is called "word".
- 8-bit group is called "byte".
- For N-bit base-2 number = 2^N levels

2^{N-1} … 2^3 2^2 2^1 2^0

01…000111
N bits

Most Significant Bit (MSB)

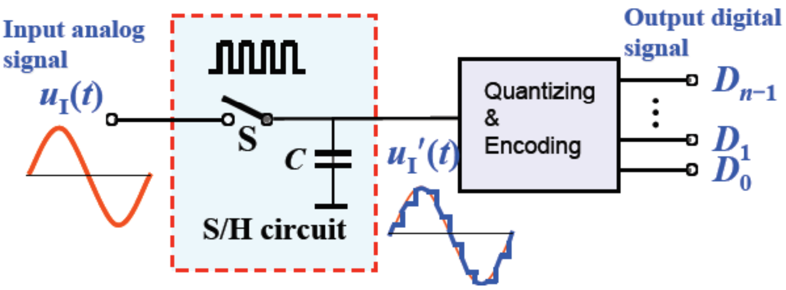
Least Significant Bit (LSB)

2

Analog-to-Digital Process

2 Steps

- Sampling and Holding (S/H)
- Quantizing and Encoding (Q/E)

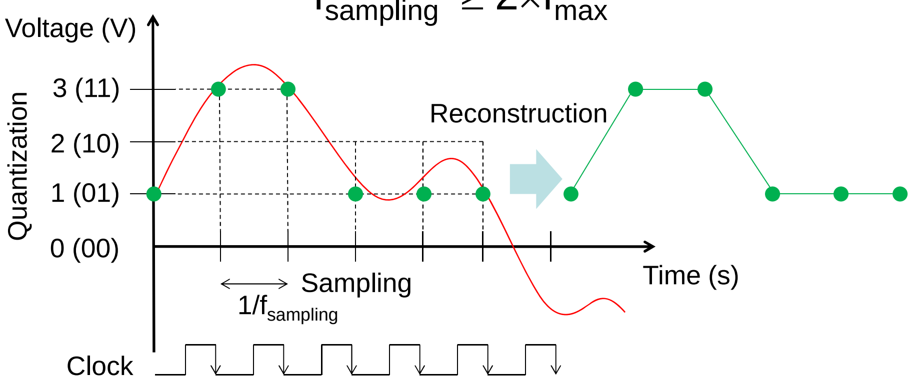


3

Shannon-Nyquist Sampling Theorem

- Discrete time enough to avoid aliasing

$$f_{sampling} \geq 2 \times f_{max}$$



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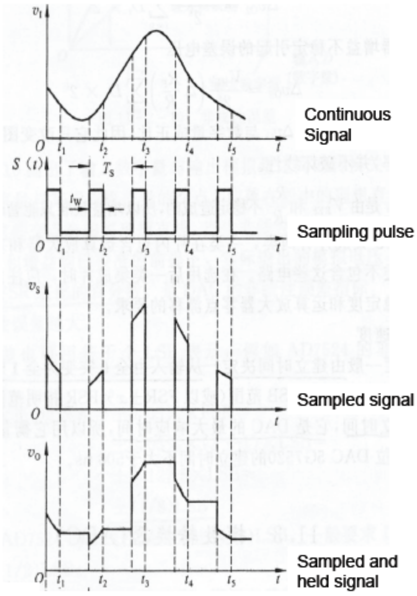
Sampling and Hold

- Holding signal benefits the accuracy of the A/D conversion.
- Minimum sampling rate should be at least twice the highest data frequency of the analog signal



Resolution

- Quantization error ➔ rounding

Input Voltage (V)	Binary Word (4 bits)	Digital Signal
0.0	0 0 0 0	
k 0.1	0 0 0 1	
k 0.2	0 0 1 0	

Step size for N-bit code, $k = V_{reference} / 2^N$

Resolution (Cont'd)

Ex Signal from 800-1500 mV may be converted to 8-bit binary codes starting from 01010000_2 (80_{10}) to 10010110_2 (150_{10}). In this case, the step size is equal to 10 mV.

$$V_{in} \approx k \times \text{digital output}$$

$$\text{Quantization error} = \frac{\text{step size}}{\text{full scale}} \times 100\ \%$$

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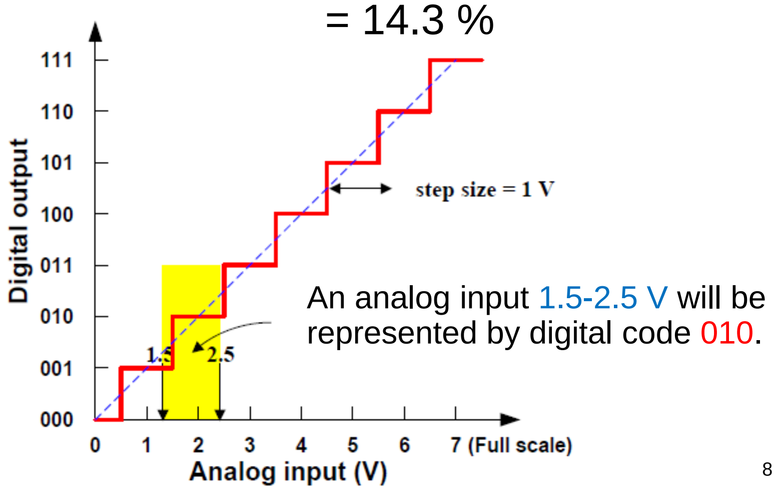
Resolution (Cont'd)

e.g. quantization error $= 1/(2^N - 1) \times 100\%$

$= 1/7 \times 100\%$

$= 14.3\ \%$



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Accuracy of A/D

There are two ways to best improve the accuracy of A/D conversion:

- Increasing the sampling rate which increases the maximum frequency that can be measured.
- Increasing the resolution which improves the accuracy in measuring the amplitude of the analog signal.

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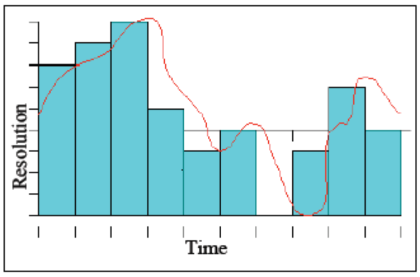
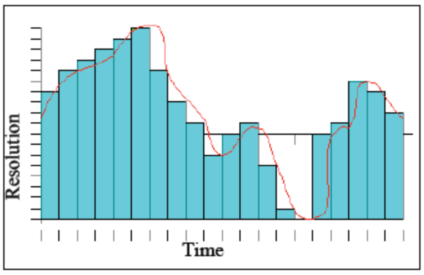
Accuracy of A/D (Cont'd)

- Low accuracy



- Improved



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Digital Electronic Basics

- Logic gate, e.g. AND, OR, NAND, NOR, NOT, XOR
- Adder and Subtractor
- Flip-Flop, e.g. RS-FF, JK-FF
- Shift Register
- Counter
- Digital display, e.g. LED, 7-Segment, LCD

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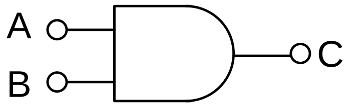
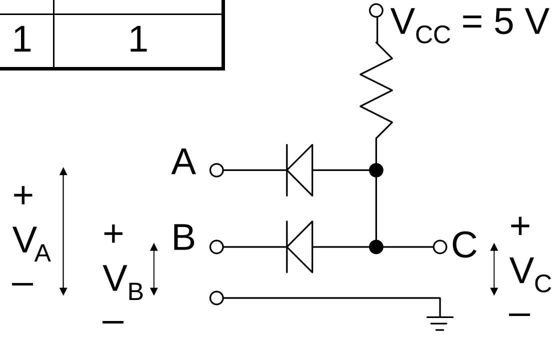
e.g. AND Gate

A	B	C = A·B
0	0	0
0	1	0
1	0	0
1	1	1





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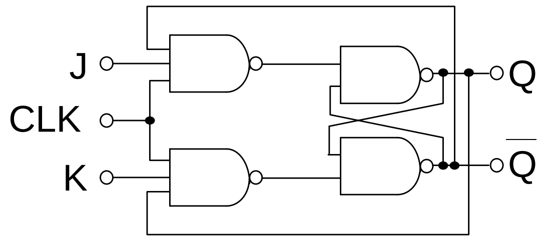
e.g. J-K Flip Flop

It is like a memory.

J	K	CLK	Q	
0	0	1	Q	Unchanged
0	1	1	0	Reset
1	0	1	1	Set
1	1	1	$\overline{Q}$	Toggle



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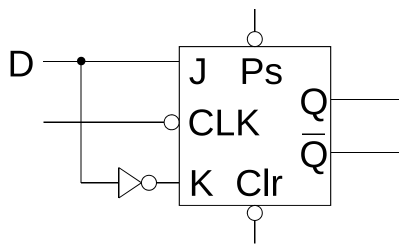
e.g. D Flip-Flop

CLK	D	Q	$\overline{Q}$
↓	1	1	0
↓	0	0	1



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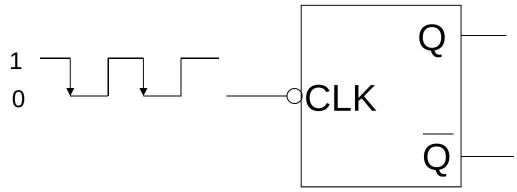
e.g. Toggle Flip-Flop

CLK	Q	$\overline{Q}$
↓	$\overline{Q}$	Q



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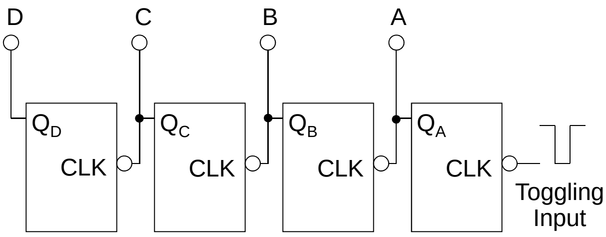
e.g. 16-Counter

Input Pulses	Q_D	Q_C	Q_B	Q_A
0	0	0	0	0
1	0	0	0	1
2	0	0	1	0
3	0	0	1	1
4	0	1	0	0
5	0	1	0	1
6	0	1	1	0
7	0	1	1	1
8	1	0	0	0
9	1	0	0	1
10	1	0	1	0
11	1	0	1	1
12	1	1	0	0
13	1	1	0	1
14	1	1	1	0
15	1	1	1	1



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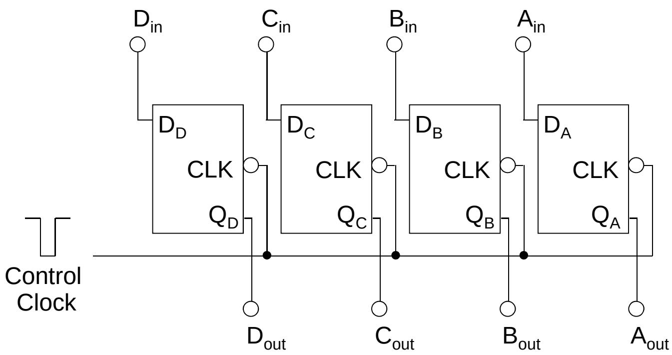
e.g. Parallel-In Parallel-Out Shift Register



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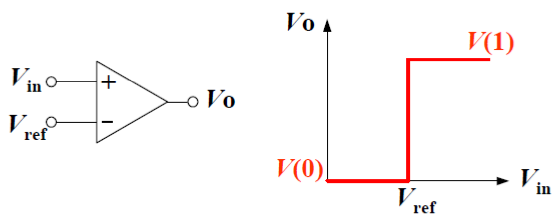
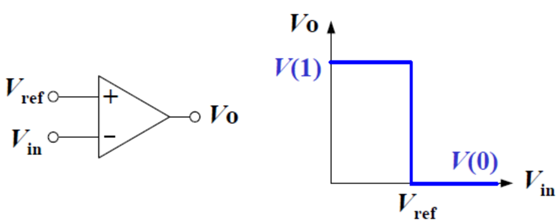
Comparator

V+ > V– $\rightarrow$ V_o = V(1)   Logic high



V+ < V– $\rightarrow$ V_o = V(0)   Logic low



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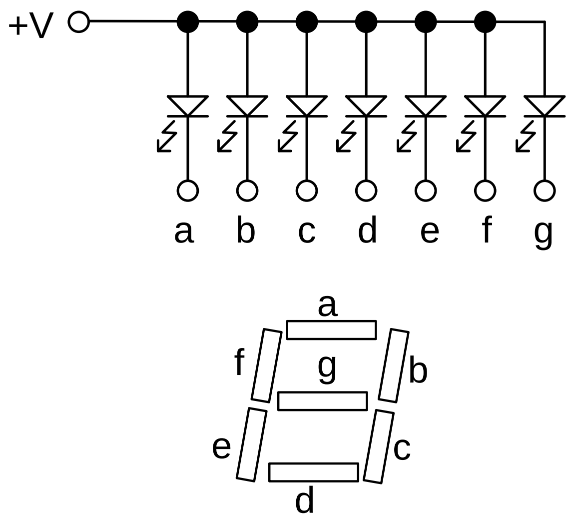
e.g. Common-Anode 7-Segment



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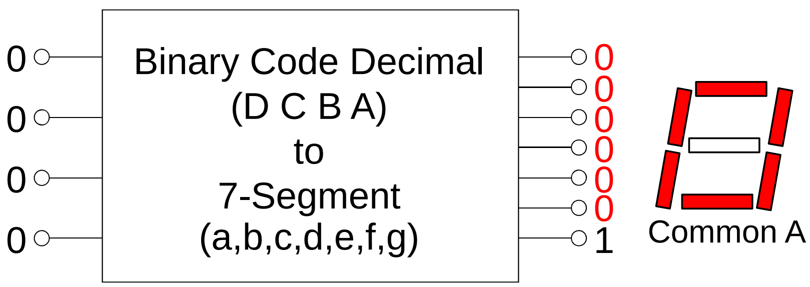
e.g. BCD to 7-Segment



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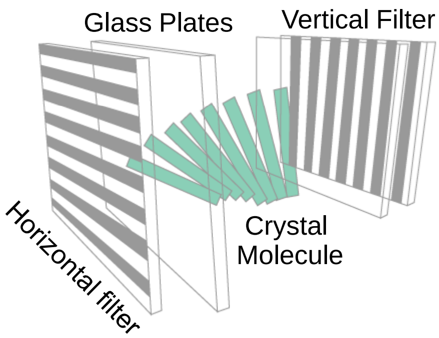
Liquid Crystal Display

- There is a set of two 90°-polarlized transparent panels with a liquid crystal solution between them.
- When electricity is applied to one of the segments, the crystals line up in such a way as to make the light twists through the panels and is visible on the other side.



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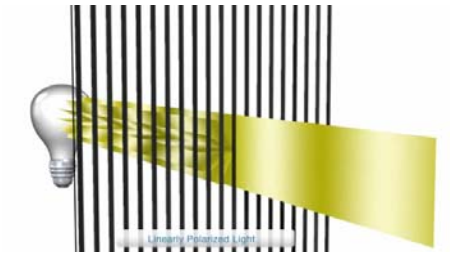
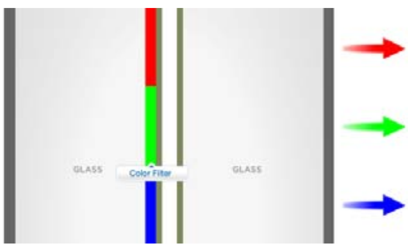
Liquid Crystal Display (Cont'd)

- Light is shined from behind the panels.



- Color filters are used in color LCD, where each color sub-pixel is controlled individually



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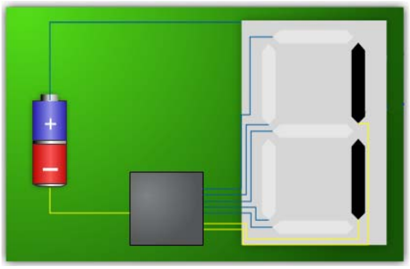
Direct Address Display

- When the display include limited variable components, e.g. watches or calculators
- Simple electronics is used to control the components
- Simple types of LCDs such as in pocket calculators are built without an internal light source, requiring external light sources to convey the display image to the user.



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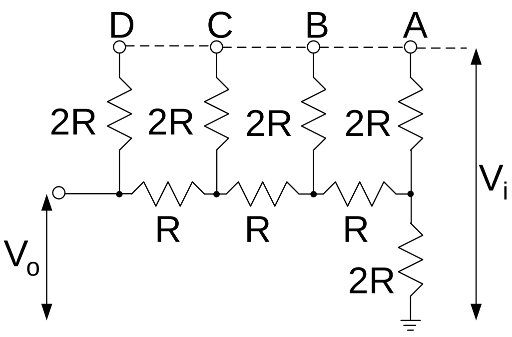
e.g. R/2R Network

V_i at each input				Analog Output (V_o)
D	C	B	A	
0	0	0	0	0
0	0	0	1	V_i / 16
0	0	1	0	2 (V_i / 16)
0	0	1	1	3 (V_i / 16)
0	1	0	0	4 (V_i / 16)
0	1	0	1	5 (V_i / 16)
0	1	1	0	6 (V_i / 16)
0	1	1	1	7 (V_i / 16)
1	0	0	0	8 (V_i / 16)
1	0	0	1	9 (V_i / 16)
1	0	1	0	10 (V_i / 16)
1	0	1	1	11 (V_i / 16)
1	1	0	0	12 (V_i / 16)
1	1	0	1	13 (V_i / 16)
1	1	1	0	14 (V_i / 16)
1	1	1	1	15 (V_i / 16)

Digital-to-analog converter



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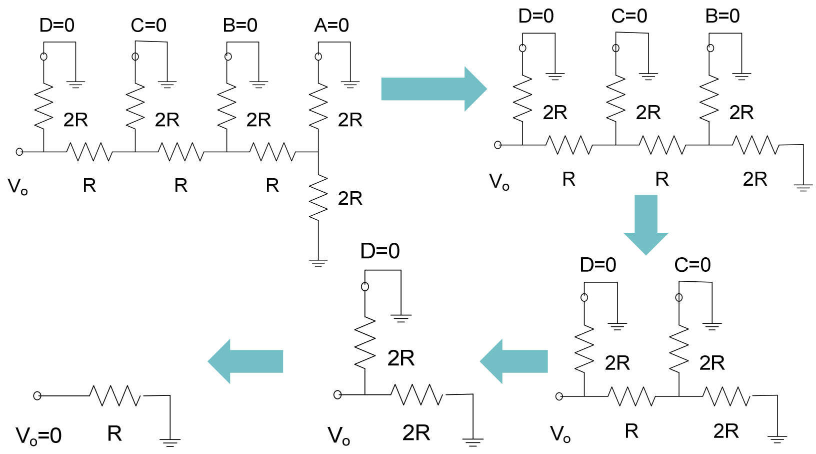
R/2R Network (Cont'd)

- 0000 ➔ $V_o = 0$



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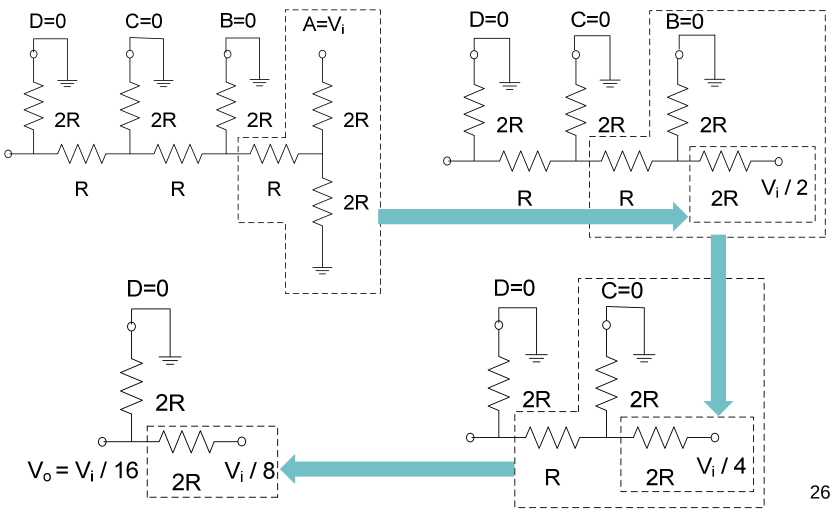
R/2R Network (Cont'd)

- 0001 ➔ $V_o=V_i/16$ using Thévenin's theorem



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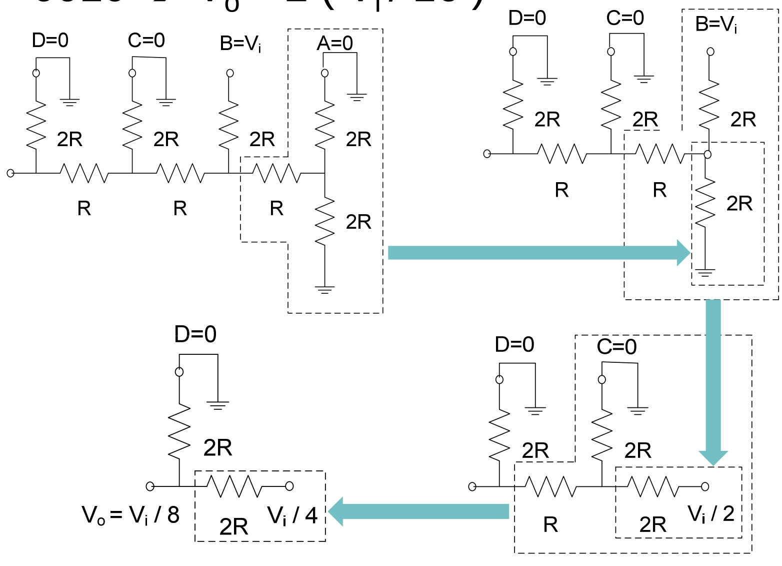
R/2R Network (Cont'd)

- 0010 ➔ $V_o = 2\ (V_i / 16)$



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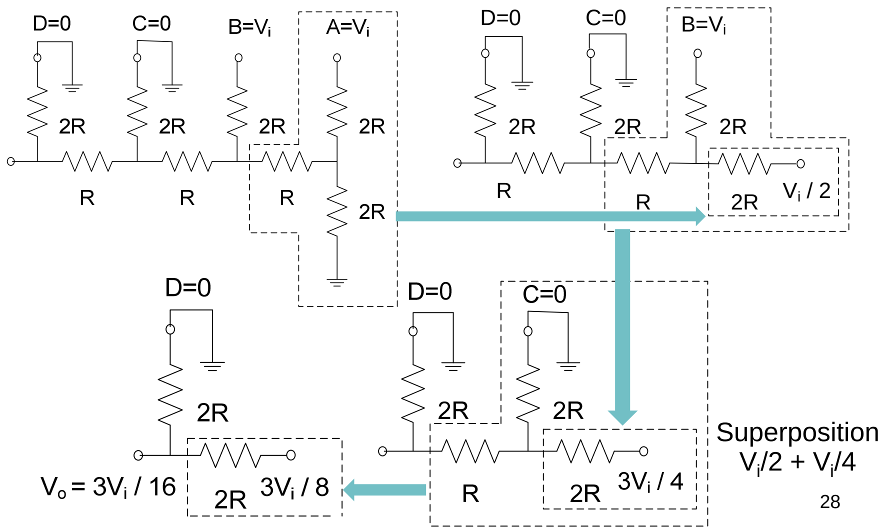
R/2R Network (Cont'd)

- 0011 ➔ $V_o = 3\ (V_i / 16)$



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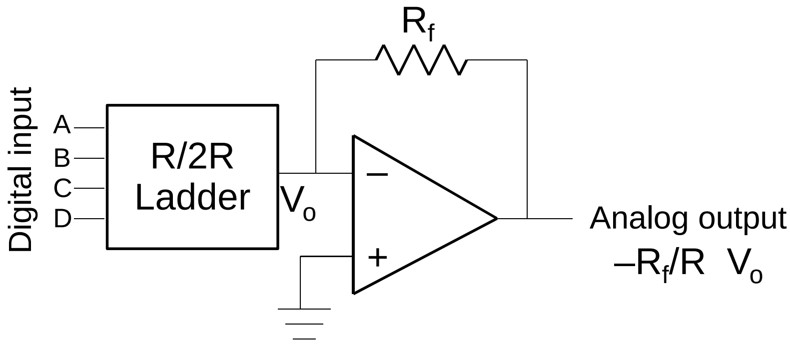
R/2R Network (Cont’d)

- The speed of the converter is limited by the output amplifier slew rate (the maximum rate of change of the output voltage).



Inverting Amplifier

Digital Multimeter (DMM)

Digital multimeter is an electronic volt-ohm-milliammeter with digital display.

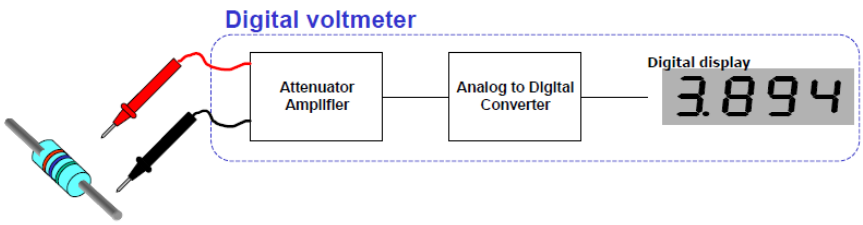
Portable Analog Multimeter

Hand-held DMM

Bench-top DMM

Digital Voltmeter

Digital voltmeter (DVM) is essentially an analog to digital converter (A/D) with a digital display.



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Digital Voltmeter (Cont'd)

- Analogue voltage is sampled at some instant of time (sampled and hold) and converted to digital signals (series of pulses).
- Number of pulses related to the voltage is counted and displayed as digits.

Analogue Input → Analogue-to-Digital Converter → Digital Signal → Counter → Display

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Advantages over Analog Meters

- The numerical readout reduces the human reading error, many readers read the same value, and makes no parallax error
- Faster reading
- The accuracy is much higher e.g. the best tolerance of analog meters is about $\pm$0.5%, while it is about $\pm$0.005% for digital meters
- Higher precision (repeatability) and also contain automatic ranging
- No moving part, life will be long
- Digital signal processing is possible e.g. hold, max, min, polarity or peak

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Disadvantages

- Battery needed for electronic circuits
- Cannot show trend and continuous changing number not easy to be interpreted (bar graph may be optional added)
- Cannot measure very high frequency signals (not more than Nyquist rate of sampling)

In spite of above mentioned disadvantages, the digital meters are gaining popularity and are most widely used.

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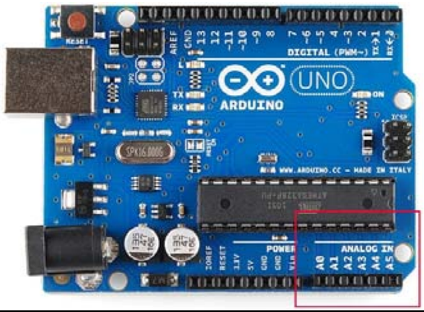
Relating ADC Value to Voltage

- Not every pin on a microcontroller has the ability to do analog to digital conversions. On the Arduino board, these pins have an ‘A’ in front of their label (A0 through A5) to indicate these pins can read analog voltages.



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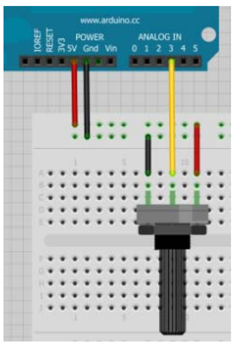
Relating ADC Value to Voltage (Cont’d)

- The ADC on the Arduino is a 10-bit ADC meaning it has the ability to detect 2^{10} or 1,024 discrete analog levels (0-1,023).



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Ratiometric Value

- Analog to digital conversions are dependant on the system voltage.
- For example, the 10-bit ADC of the Arduino on a 5V system, if the analog voltage is 2.12V what will the ADC report as a value?

$$\frac{Resolution\ of\ the\ ADC}{System\ Voltage} = \frac{ADC\ Reading}{Analog\ Voltage\ Measured}$$

$$\frac{1023}{5.00V} = \frac{x}{2.12V}$$

- The ADC should report 434.

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Analogue-to-Digital Converter

1. Ramp converter
2. Successive approximation
3. Flash converter
4. Voltage-to-frequency converter
5. Dual-slope DVM
6. Delta-sigma converter

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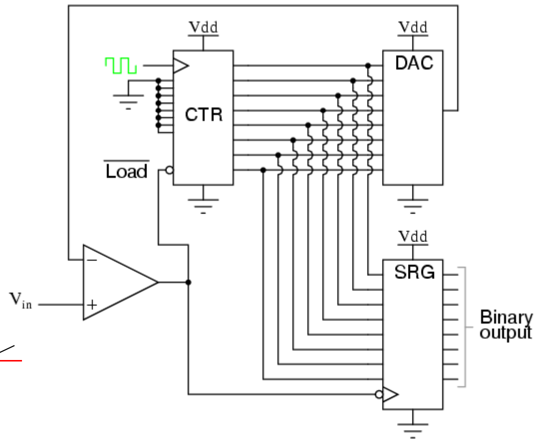
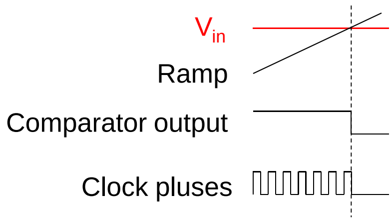
Ramp Converter

- The most simple A/D
- Ramp voltage climbs from 0 V to the input voltage.
- Counting the clock pulses during no "load" (Active-low).





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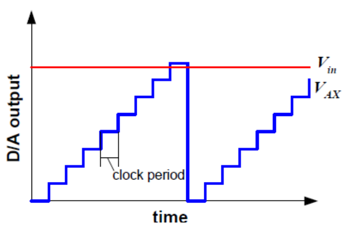
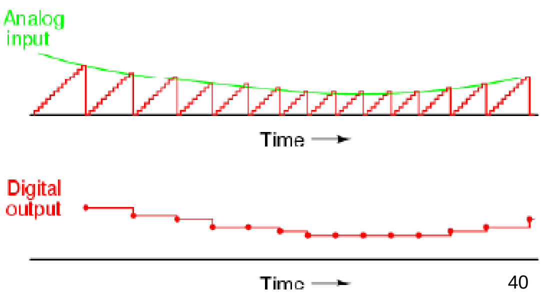
Ramp Converter (Cont'd)

- Slow conversion and conversion time depends on the magnitude of input signal.

$$T_{conversion,\ max} = (2^N - 1) \times \text{clock period}$$





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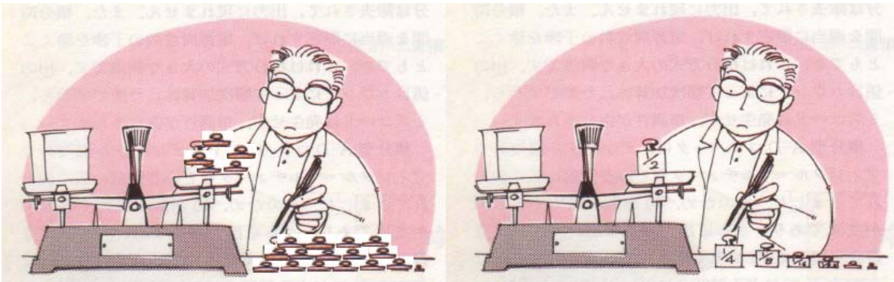
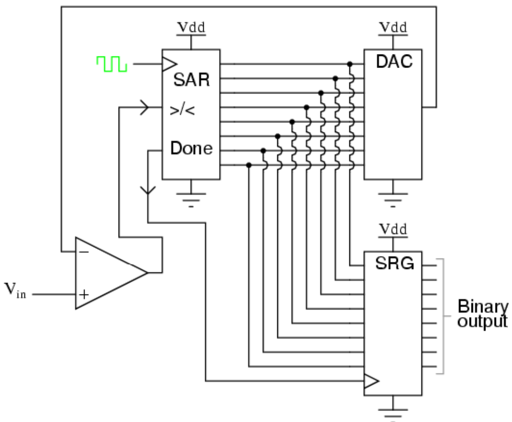
Successive Approximation

Ramp converter Vs. Successive approximation



Successive Approximation (Cont'd)

- Input voltage is compared to the voltage increased until it reaches the input voltage.
- Trying all values starting with MSB to LSB.



Successive Approximation (Cont'd)

D (MSB)	C	B	A (LSB)	V_{ref}
0	0	0	0	0
0	0	0	1	1
0	0	1	0	2
0	0	1	1	3
0	1	0	0	4
0	1	0	1	5
0	1	1	0	6
0	1	1	1	7
1	0	0	0	8
1	0	0	1	9
1	0	1	0	10
1	0	1	1	11
1	1	0	0	12
1	1	0	1	13
1	1	1	0	14
1	1	1	1	15

e.g. V_{in} = 9 V

- V_{ref1} = 8 V (<u>1</u>000)
  if $V_{in} > V_{ref1}$ ➔ D = "1"
- V_{ref2} = 12 V (**1<u>1</u>**00)
  if $V_{in} < V_{ref2}$ ➔ C = "0"
- V_{ref3} = 10 V (**10<u>1</u>**0)
  if $V_{in} < V_{ref3}$ ➔ B = "0"
- V_{ref4} = 9 V (**100<u>1</u>**)
  if $V_{in} = V_{ref4}$ ➔ A = "1"
  V_{in} = **1001**

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Successive Approximation (Cont'd)

<u>Ex</u> To determine a number between 0-511 (9-bit binary), given the number to be determined is 301.

No.	Estimate		Results
1	256	1 0000 0000	$V_{in} > V_{AX}$
2	256+128 = 384	1 1000 0000	<
3	256+64 = 320	1 0100 0000	<
4	256+32 = 288	1 0010 0000	>
5	288+16 = 304	1 0011 0000	<
6	288+8 = 296	1 0010 1000	>
7	296+4 = 300	1 0010 1100	>
8	300+2 = 302	1 0010 1110	<
9	300+1 = 301	1 0010 1101	Finished

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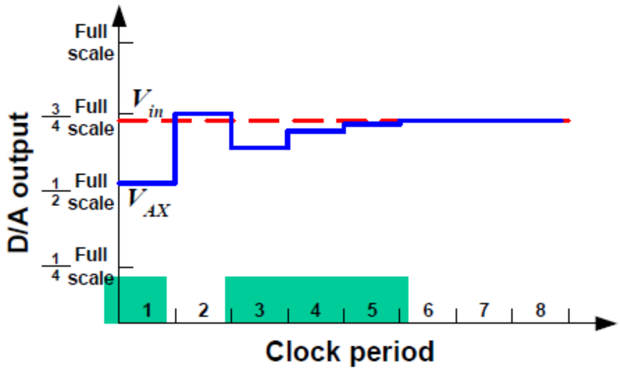
Successive Approximation (Cont'd)

- The most common A/D for general applications
- Conversion time is fixed (not depend on the signal magnitude) and relatively fast.

$$T_{conversion} = N \times \text{clock period}$$



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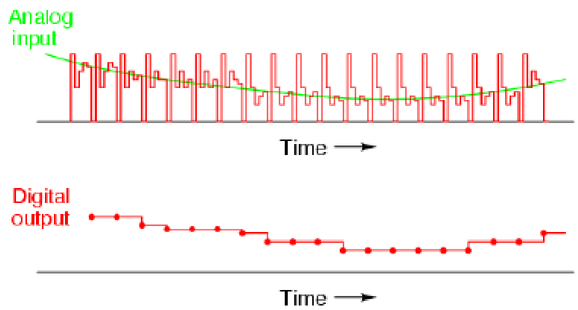
Successive Approximation (Cont'd)

- When you require higher resolution and do not require high sampling rate



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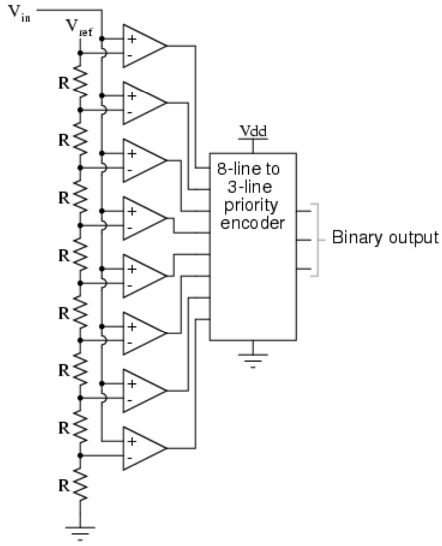
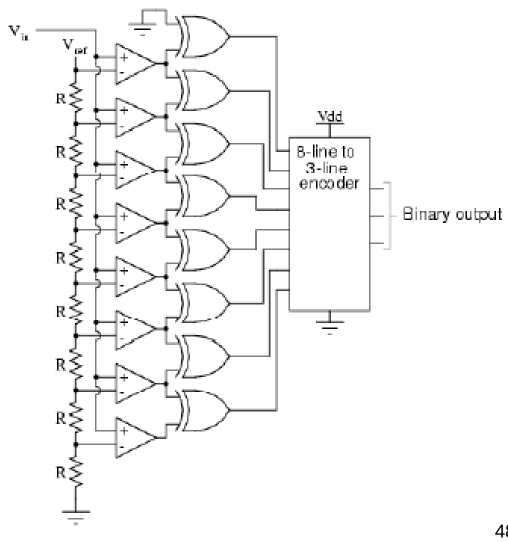
Flash Converter

- Simultaneous comparison between the analogue input and the reference signals.
- N-bit conversion needs 2^{N-1} comparators.
- Consumes power (many op-amps)
- Fast! up to 20 G Samples / second



Flash Converter (Cont'd)

- Implementation of a priority encoder can be simple circuitry.
- 8-line to 3-line priority encoder, e.g.
  00000001 $\Rightarrow$ 001
  00000011 $\Rightarrow$ 010
  00000111 $\Rightarrow$ 011



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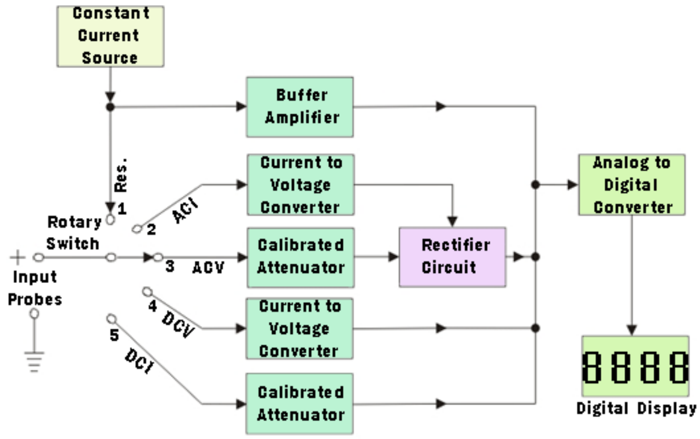
Digital AC Voltmeter

- Using rectifier in a similar way to analogue meter.
- The average value from rectifier is scaled to RMS value.



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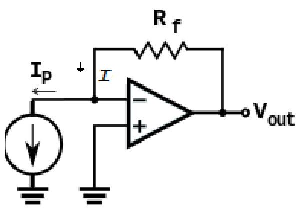
Digital Ammeter

- Current can be measured by using digital voltmeter to measure the potential difference across a standard resistor.
- Current-to-voltage converter, e.g.



$$V_{out} - V^{-} = I\,R_f$$

$$V_{out} = I_p R_f \quad , V^{-} = V^{+} = 0$$

$$I_p = V_{out} / R_f$$

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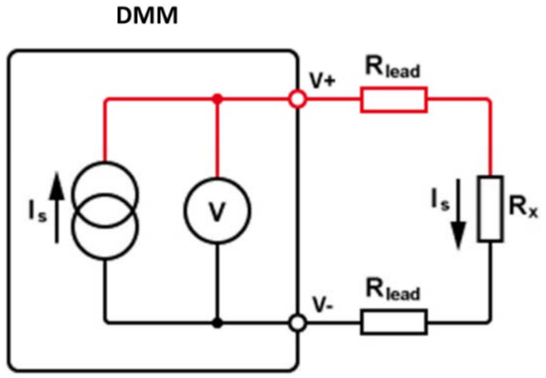
Digital Ohmmeter

- The DMM supplies a constant current source to the resistor and the meter measures the voltage across it, the voltage being proportional to the resistance.



$V = I_s(2R_{lead} + R_x)$
$R_x = V/I_s - 2R_{lead}$

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Reading Resolution

- For the fixed resolution of .001 V (step size)
  Range 0 - 1 V ➔ 3 digits (.999) 1,000 steps
  Range 0 - 10 V ➔ 4 digits (9.999) 10,000 steps
  Range 0 - 100 V ➔ 5 digits (99.999) 100,000 steps
  Number of digit = log(step)

- How many digit for the range 0 - 3 V ?
  It is 3½ digits (log(3000) ≈ 3.477 digits)

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Reading Resolution (Cont'd)

- 3½ digit display 0000 ➔ 1999 (e.g. full scale 2 V if enable the 1st decimal point, 0.000 ➔ 1.999)
- MSB can only be "0" or "1" (usually not visible when the reading is less than 999), whereas all the other can be "0", "1", "2", "3", …, "9"
- e.g. 1V range, resolution is 1V/1999 ≈ 0.001 V (0.000, 0.001, 0.002, …, 0.999)
- For 3¾ digit for the range 5 V, MSB can be "0" to "4"

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Range Changing

Auto ranging by using frequency divider circuit to change clock frequency.

- e.g. 3½ digit display (fixed digit),
  change step size
  Range 1V (0.999) ➔
  1/1999 ≈ 0.001 V/step (1,000 steps)
  Range 10V (09.99) ➔
  10/1999 ≈ 00.01 V/step (1,000 steps)
  Range 100V (099.9) ➔
  100/1999 ≈ 000.1 V/step (1,000 steps)

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Accuracy

- $\pm$ (0.5% Reading + 1 Digit LSB)
- e.g. when you read a voltage 1.8 V

error = $\pm$ (0.5% of 1.8V + 0.001V)

= $\pm$ 0.01V

$\approx \pm$ 0.56% of reading

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Reference

- https://learn.sparkfun.com/tutorials/analog-to-digital-conversion
- http://en-us.fluke.com/training/training-library/test-tools/digital-multimeters/digital-multimeter-fundamentals.html
- https://www.electrical4u.com/digital-multimeter/
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