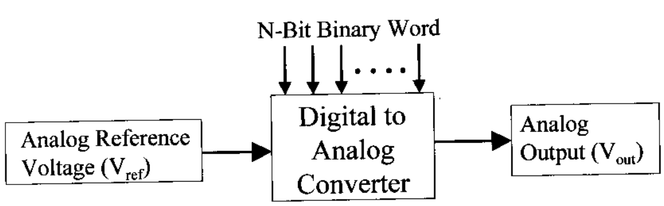
What is a DAC?
(Digital to Analog Converter)

- A digital to analog converter (DAC) is a device that converts n-bit (parallel) digital input into an analog voltage or current output.
- Primary output is a current which can be easily converted to a voltage

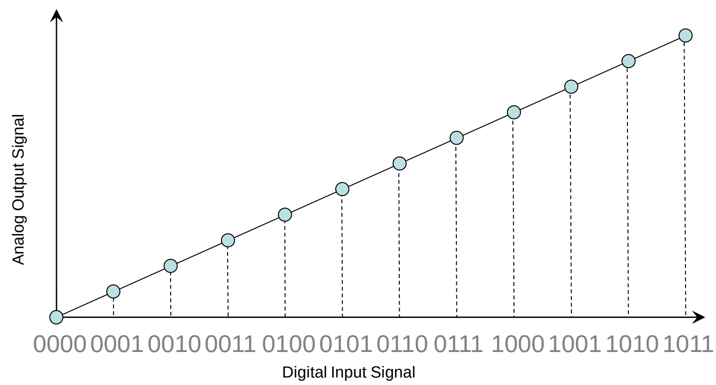
Principal components of DAC

- Consists off:
- Network of analog switches controlled by the input code
- Network of weighted resistors
- The switches control currents or voltages derived from a precise reference voltage
- Output current/voltage represents the ration of the input code to the full scale voltage of the reference source



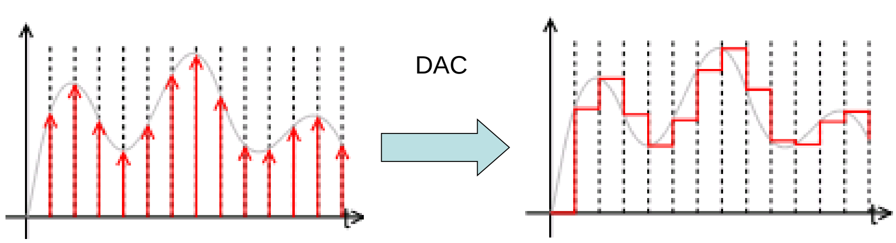
What is a DAC?

- Digital → Analog
- Each binary number sampled by the DAC corresponds to a different output level.



Typical Output

- DACs capture and hold a number, convert it to a physical signal, and hold that value for a given sample interval.
- This is known as a zero-order hold and results in a piecewise constant output.

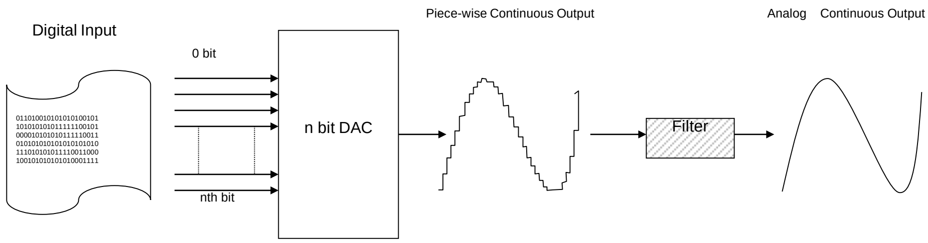


Ideally Sampled Signal

Output typical of a real, practical DAC due to sample & hold

Common Applications

- Used when a continuous analog signal is required.
- Signal from DAC can be smoothed by a Low pass filter



Common Applications:

- Digital Oscilloscopes
  - Digital Input
  - Analog Output
- Signal Generators
  - Sine wave generation
  - Square wave generation
  - Triangle wave generation
  - Random noise generation

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Applications – Video

- Video signals from digital sources, such as a computer or DVD must be converted to analog signals before being displayed on an analog monitor.
- Beginning on February 18th, 2009 all television broadcasts in the United States are in a digital format, requiring ATSC tuners (either internal or set-top box) to convert the signal to analog.

Common Applications

Motor Controllers

- Cruise Control
- Valve Control
- Motor Control

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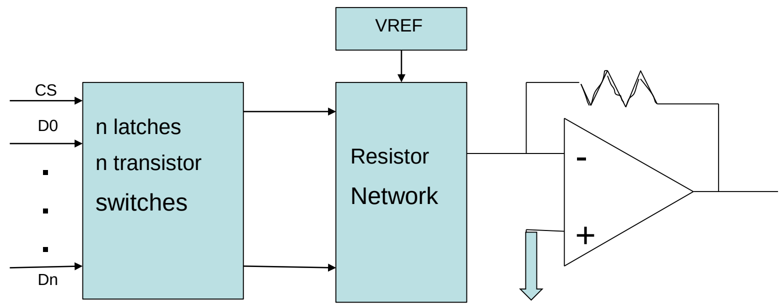
Typical DAC



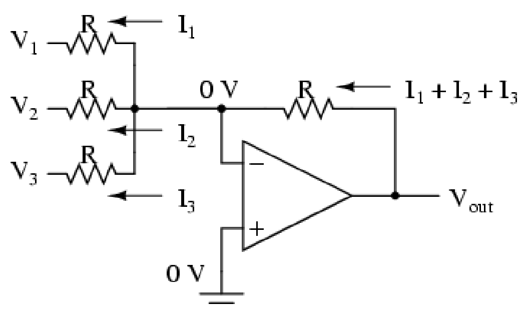
- N latches hold the binary number to be converted
- n transistors controlled by outputs of latches and control a particular resistor each
- VREF precision reference controls output voltage range
- Opamp provides summing function to add together the results of activating multiple switches simultaneously

Types of DAC implementations

- Binary Weighted Resistor
- R-2R Ladder

Binary Weighted Resistor

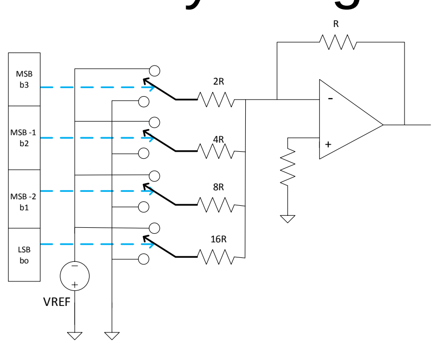
Inverting summer circuit



$$\mathbf{V_{out} = -(V_1 + V_2 + V_3)}$$

- Start with summing op-amp circuit
- Input voltage either high or ground
- Adjust resistor weighting to achieve desired Vout

Binary Weighted Resistor



- *Details*
  - Use transistors to switch between high and ground
  - Use resistors scaled by two to divide voltage on each branch by a power of two
  - V_1 is MSB, V_4 LSB in this circuit
- *Assumptions:*
  - Ideal Op-Amp
  - No Current into Op-Amp
  - Virtual Ground at Inverting Input

$$I_3 = \frac{V_{REF}}{2R} \rightarrow V_{out3} = \frac{V_{REF}}{2}$$

$$I_2 = \frac{V_{REF}}{4R} \rightarrow V_{out2} = \frac{V_{REF}}{4}$$

$$I_1 = \frac{V_{REF}}{8R} \rightarrow V_{out1} = \frac{V_{REF}}{8}$$

$$I_0 = \frac{V_{REF}}{16R} \rightarrow V_{out0} = \frac{V_{REF}}{16}$$

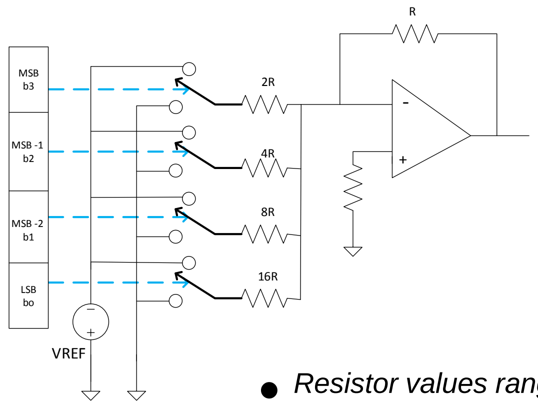
$$V_{out} = R\left(I_3 + I_2 + I_1 + I_0\right)$$

$$= R\left(\frac{V_{REF}}{2R} + \frac{V_{REF}}{4R} + \frac{V_{REF}}{8R} + \frac{V_{REF}}{16R}\right)$$

$$= V_{REF}\left(b_3.\frac{1}{2} + b_2.\frac{1}{4} + b_1.\frac{1}{8} + b_0.\frac{1}{16}\right)$$

$$= V_{REF}\left(b_3.2^{-1} + b_2.2^{-2} + b_1.2^{-3} + b_0.2^{-4}\right)$$

Binary Weighted Resistor



For a 12 bit DAC

$R = 5k\Omega$

$2^n R = 20.48M\Omega$

- *Resistor values range from R to 2^n*R which must be matched*
- *High value of resistance requires more silicon die area*
- *This results in higher cost*

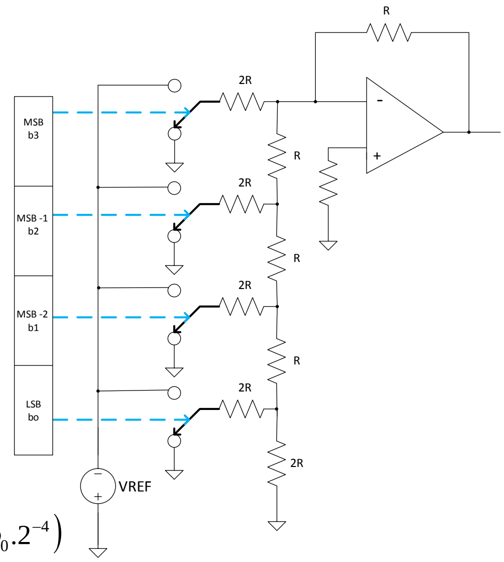
Ken Marek

Binary Weighted Resistor

- Advantages
  - Simple
  - Fast
- Disadvantages
  - Need large range of resistor values (2048:1 for 12-bit) with high precision in low resistor values
  - Need very small switch resistances
  - Op-amp may have trouble producing low currents at the low range of a high precision DAC

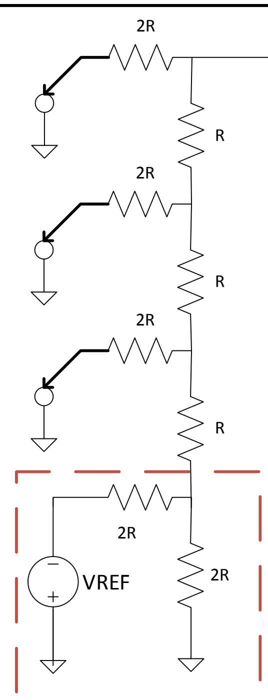
R-2R Ladder

- Each bit corresponds to a switch:
  - If the bit is high "1", the corresponding switch is connected to the reference voltage
  - If the bit is low "0" , the corresponding switch is connected to ground.

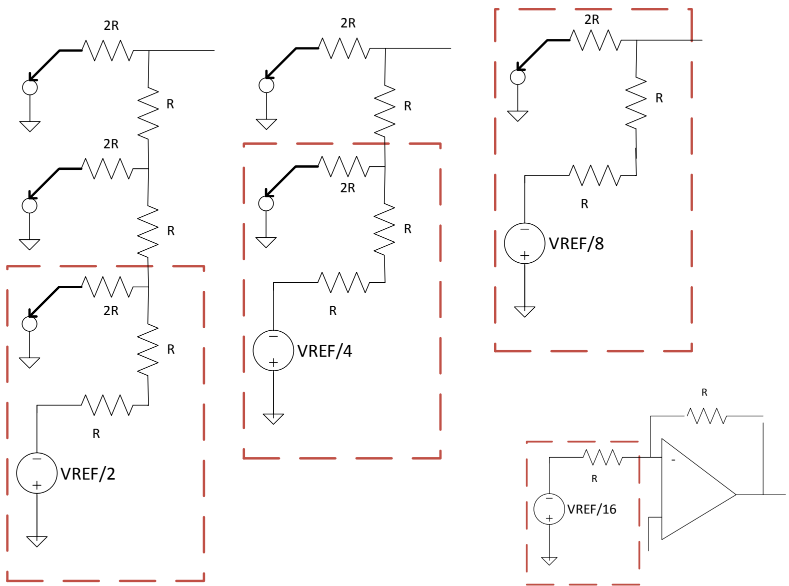


$$V_{out} = V_{REF}\left(b_3.2^{-1} + b_2.2^{-2} + b_1.2^{-3} + b_0.2^{-4}\right)$$

R-2R Ladder



- Circuit may be analyzed using Thevenin's theorem and superposition by considering one bit high at a time (replace network with equivalent voltage source and resistance)
- Consider input =0001



$$V_{out} = V_{REF}\left(0.2^{-1} + 0.2^{-2} + 0.2^{-3} + 1.2^{-4}\right) = \frac{V_{REF}}{16}$$

- Contribution of each input bit can be found in a similar fashion , by setting its value to 1 while all other bits are set to zero
- R-2R DAC resistor values are limited to two values only R or 2R which is less expensive
- Number of resistors is less: 2n+1 and lower precision is acceptable
- Conversion speed is lower

- Example: an 8 bit DAC with 5V reference has an input 10100111, what is the output?

$$V_{out} = \frac{167}{256} * 5 = 3.2617\ \text{V}$$

- Example: a 10 bit DAC with 10V reference, what input is required to get 6.5V output?

$$V_{out} = \frac{(\text{N})_{10}}{2^{10}} * 10 = 6.5\ \text{V}$$

$$(\text{N})_{10} = \frac{6.5 * 2^{10}}{10} = 665.6$$

$$\text{if N} = 665 ==> \text{V} = 6.494$$

$$\text{if N} = 666 ==> \text{V} = 6.504 \text{ (closer to required value)}$$

- Highest value of N:
- Unipolar DAC:

$$V_{o\max} = \frac{(\text{Nmax})_{10}}{2^n} * V_{FSR}; \text{where Nmax} = 2^{\text{n}} - 1$$

$$V_{o\max} = \frac{2^{\text{n}} - 1}{2^n} * V_{FSR}$$

- For Bipolar DAC:

$$V_o = \frac{(\text{N})_{10}}{2^n} * V_{FSR} - \frac{V_{FSR}}{2};$$

$$V_{o\max} = \frac{2^{\text{n}} - 1}{2^n} * V_{FSR} - \frac{V_{FSR}}{2}$$

$$V_{o\min} = -\frac{V_{FSR}}{2}$$

Examples

- A bipolar 10 bit DAC has V_{FSR}=5V and a hexadecimal input 2A4, what is the output? And at what input the output will be zero?
- Solution: 2A4 = 10 1010 0100 ==> $(512+128+32+4)_{10}=676_{10}$

$$V_o = \frac{676}{1024} * 5 - \frac{5}{2} = 0.80078 \text{ V}$$

- For Vo=0

$$0 = \frac{(\text{N})_{10}}{1024} * 5 - \frac{5}{2} \text{ ==>}$$

$$N = 512$$

$$0010\ 0000\ 0000 \text{ ==> } (200)_H$$

- Determine how many bits a DAC should have to provide an output voltage increment of 0.04V if V_{FSR}=10V?

$$\Delta = \frac{V_{FSR}}{2^n} = 0.04$$

$$2^n = \frac{10}{0.04} = 250$$

$$n \ln n = \ln 250$$

$$n = \frac{\ln 250}{\ln 2} = 7.966 \text{ ==> } n = 8$$

Ken Marek

General comments

- Circuits as shown produce only unipolar output
- Replacing ground with $–V_{ref}$ will allow V_{out} to be positive or negative

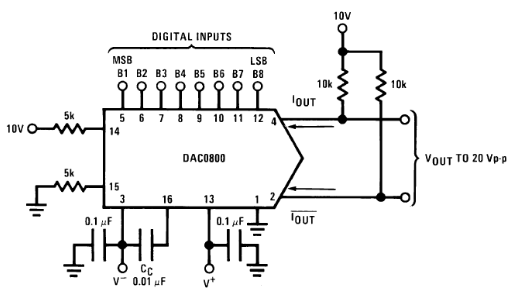
Other Types of DAC

A) DAC's with current output (DAC0800)

- Used in many applications
- Can be used in applications requiring voltage output by converting current to voltage using any of the known techniques

DAC080x

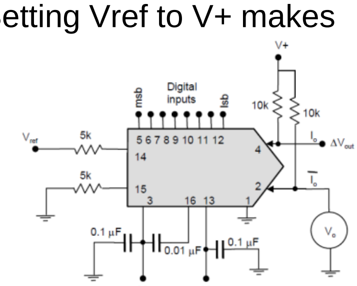
- A popular all-purpose 8-bit D to A converter IC is the DAC080x series.
- The settling time is in the order of 100 ns.

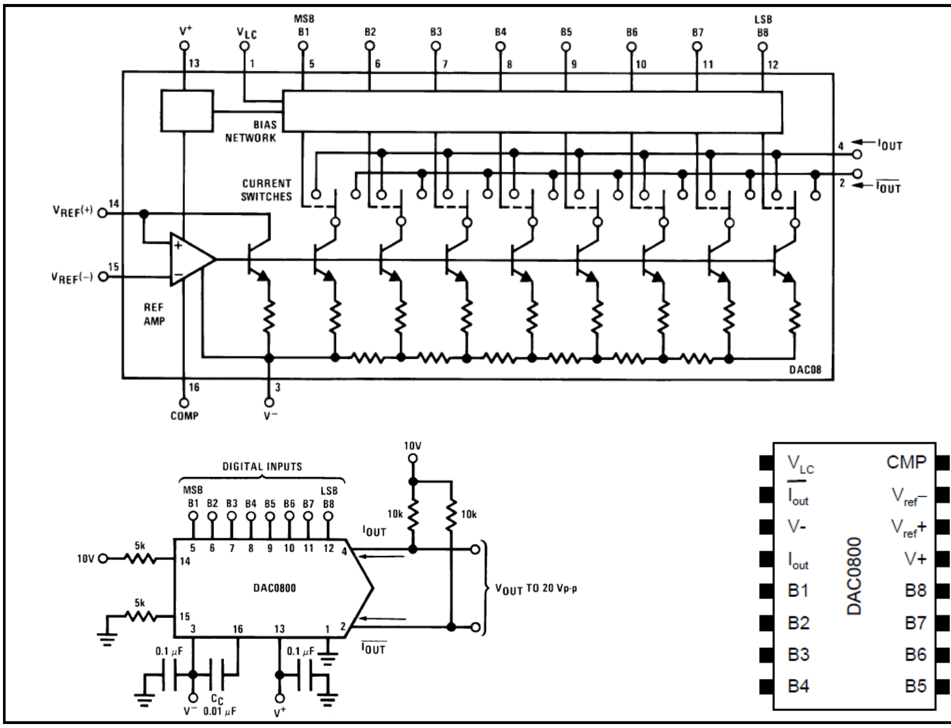


- The output for this IC is in the form of two **complementary currents** I_o and I_o'.
- In the diagram above, these current outputs are connected to a V+ supply through two 10K resistors

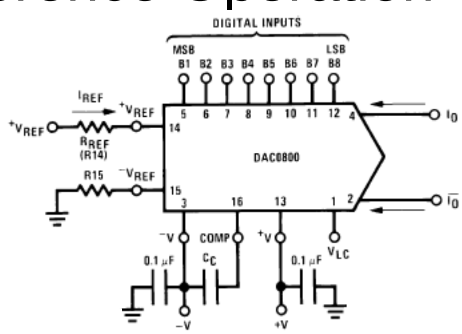
DAC080x

- A voltage output can be obtained by measuring the voltage between the two output terminals or measuring the voltage of one of the outputs with respect to ground.
- As the binary value of the digital inputs increases, Io increases and Io' decreases. A decrease in Io' means an decrease in the voltage drop across the 10k resistor and an increase in Vo measured w.r.t. ground.
- Vref provides a current reference. Setting Vref to V+ makes Vo swing positive and negative.
- Setting Vo to V+/2 gives a 0 to V+ analog output.





Positive Reference Operation



$$I_{FS} \approx \frac{+V_{REF}}{R_{REF}} \times \frac{255}{256}$$

$I_O + \overline{I_O} = I_{FS}$ for all logic states

For fixed reference, TTL operation, typical values are:

V_{REF} = 10.000V

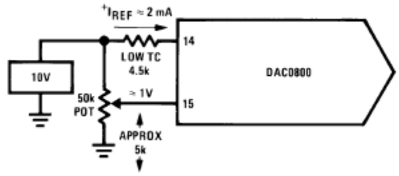
R_{REF} = 5.000k

R15 ≈ R_{REF}

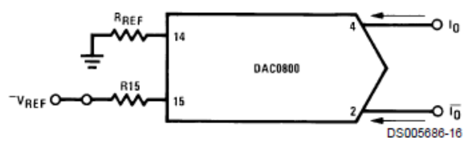
C_C = 0.01 µF

V_{LC} = 0V (Ground)

Recommended Full Scale Adjustment Circuit

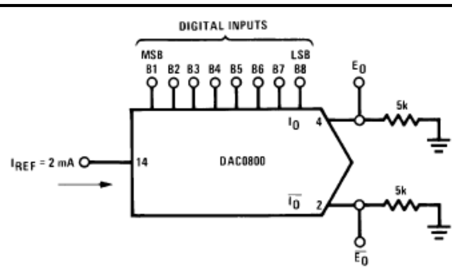


Basic Negative Reference Operation



$$I_{FS} \approx \frac{-V_{REF}}{R_{REF}} \times \frac{255}{256}$$

Note. R_{REF} sets I_{FS}; R15 is for bias current cancellation



	B1	B2	B3	B4	B5	B6	B7	B8	I_O mA	$\bar{I}_O$ mA	E_O	$\bar{E}_O$
Full Scale	1	1	1	1	1	1	1	1	1.992	0.000	−9.960	0.000
Full Scale−LSB	1	1	1	1	1	1	1	0	1.984	0.008	−9.920	−0.040
Half Scale+LSB	1	0	0	0	0	0	0	1	1.008	0.984	−5.040	−4.920
Half Scale	1	0	0	0	0	0	0	0	1.000	0.992	−5.000	−4.960
Half Scale−LSB	0	1	1	1	1	1	1	1	0.992	1.000	−4.960	−5.000
Zero Scale+LSB	0	0	0	0	0	0	0	1	0.008	1.984	−0.040	−9.920
Zero Scale	0	0	0	0	0	0	0	0	0.000	1.992	0.000	−9.960

Basic Unipolar Negative Operation

B) Frequency to voltage converter (LM2917)

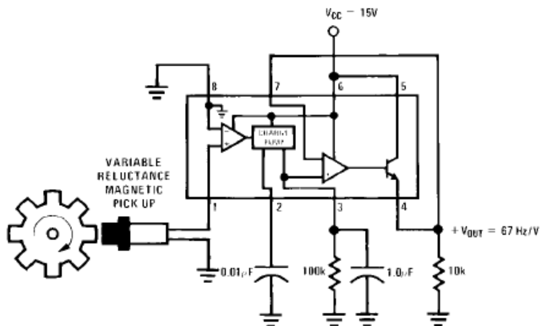
Accepts a signal and converts its frequency to a corresponding analog voltage level as an alternative of counting pulses for certain time , then converting the count via D/A methods

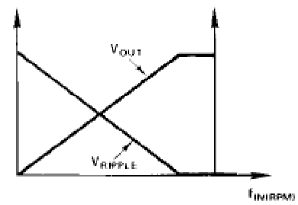
- The LM2907, LM2917 series are monolithic frequency to voltage converters with a high gain op amp/comparator designed to operate a relay, lamp, or other load when the input frequency reaches or exceeds a selected rate.
- The tachometer uses a charge pump technique and offers frequency doubling for low ripple, full input protection in two versions (LM2907-8, LM2917-8) and its output swings to ground for a zero frequency input.

Advantages

- Output swings to ground for zero frequency input
- Easy to use; $V_{OUT} = f_{IN} \times V_{CC} \times R_1 \times C_1$
- Only one RC network provides frequency doubling
- Zener regulator on chip allows accurate and stable frequency to voltage or current conversion (LM2917)

Minimum Component Tachometer





- Following the input stage is the charge pump where the input frequency is converted to a dc voltage. To do this requires one timing capacitor, one output resistor, and an integrating or filter capacitor.
- When the input stage changes state (due to a suitable zero crossing or differential voltage on the input) the timing capacitor is either charged or discharged linearly between two voltages whose difference is VCC/2
- Then in one half cycle of the input frequency or a time equal to 1/2 f_{IN} the change in charge on the timing capacitor is equal to VCC/2 x C1.

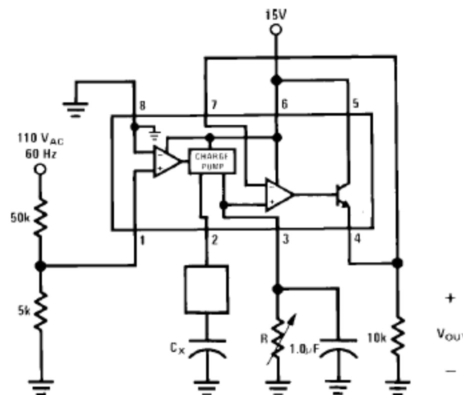
- The average amount of current pumped into or out of the capacitor then is:

$$\frac{\Delta Q}{T} = i_{c(AVG)} = C1 \times \frac{V_{CC}}{2} \times (2f_{IN}) = V_{CC} \times f_{IN} \times C1$$

- The output circuit mirrors this current very accurately into the load resistor R1, connected to ground, such that if the pulses of current are integrated with a filter capacitor, then
- V_O = ic x R1, and the total conversion equation becomes: $V_O = V_{CC} \times f_{IN} \times C1 \times R1 \times K$
- Where K is the gain constant - typically 1.0

Capacitance Meter

Capacitance Meter
V_{OUT} = 1V–10V for C_X = 0.01 to 0.1 mFd
(R = 111k)



- C) Pulse width modulation
- The digital input code is used to generate a train of pulses of fixed frequency and variable width proportional to the input count, LPF is used to generate an output proportional to the average time spent in the high state, i.e. proportional to the input code
- D) Multiplying DACs (AD7541,7548,7845 and DAC 1230) : in these DACs , the output equal to the product of an input (voltage or current) and the input digital code

Types of DAC

- Multiplying DAC*
  - Reference source external to DAC package
- Nonmultiplying DAC
  - Reference source inside DAC package

*Multiplying DAC is advantageous considering the external reference.

- These DACs open the possibility for ratiometric measurements and conversions
- If a sensor is powered from the reference voltage that supplies the DAC or ADC , then variations in this voltage will not affect the measurement which relaxes requirements on references and power supplies