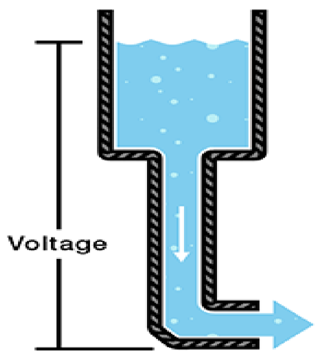
Electrical Charge

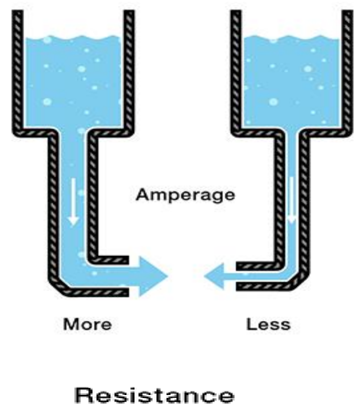
Electricity is the movement of electrons. Electrons create charge, which we can harness to do work. Your lightbulb, your stereo, your phone, etc., are all harnessing the movement of the electrons in order to do work.

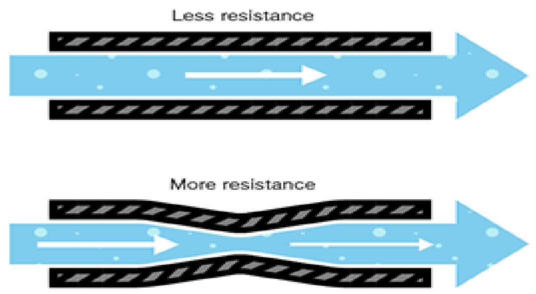
They all operate using the same basic power source: the movement of electrons.
The three basic principles for this tutorial can be explained using electrons, or more specifically, the charge they create:

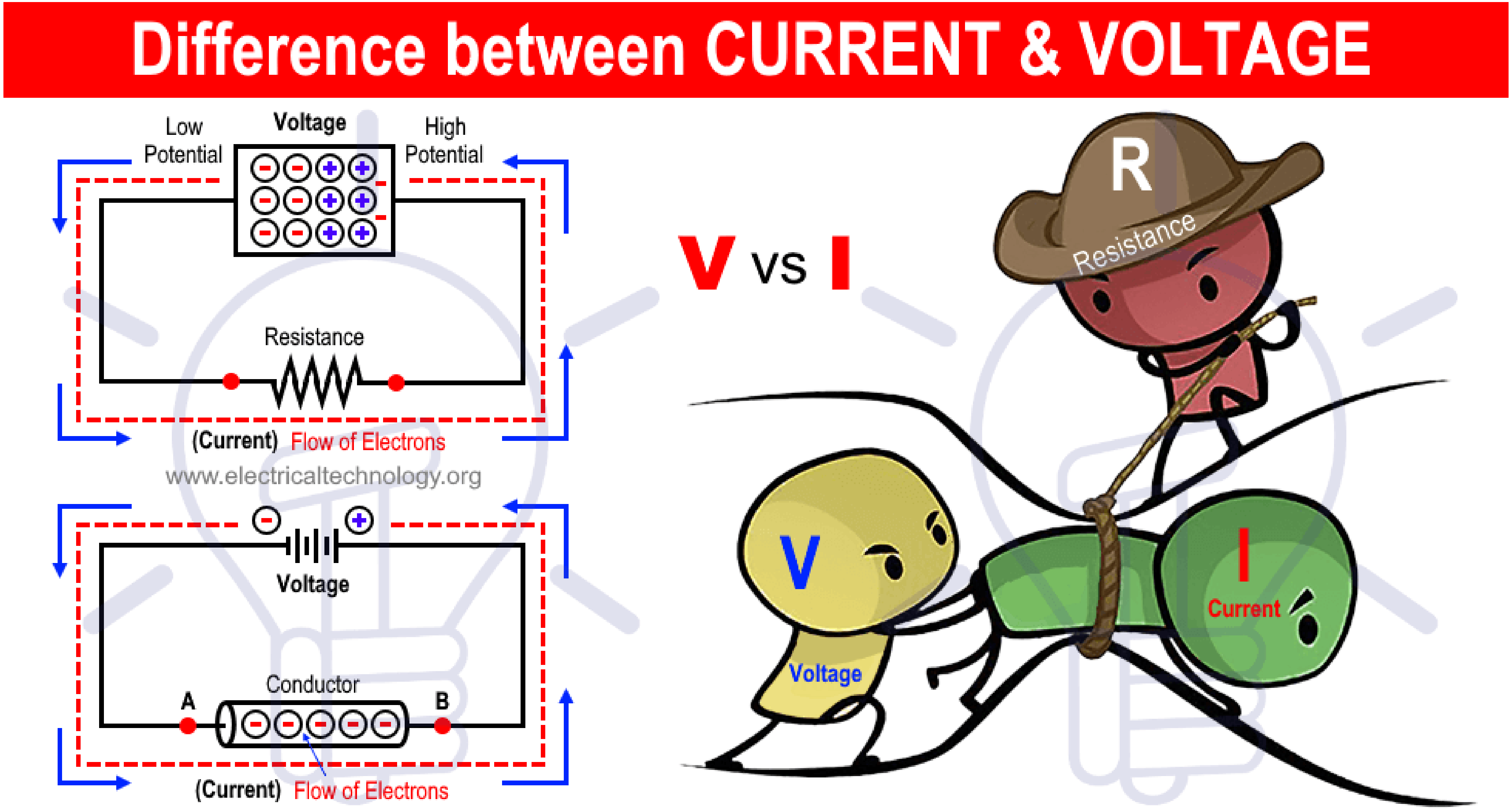
- **Voltage** is the difference in charge between two points.
- **Current** is the rate at which charge is flowing.
- **Resistance** is a material's tendency to resist the flow of charge (current).

- Water = Charge
- (measured in Coulombs)
- Pressure = Voltage
- (measured in Volts)
- Flow = Current
- (measured in Amperes,
- or "Amps" for short)
- **Hose Width = Resistance**








Difference between CURRENT & VOLTAGE
Low Potential
Voltage
High Potential
Resistance
(Current) Flow of Electrons
www.electricaltechnology.org
Voltage
Conductor
A
B
(Current) Flow of Electrons
V vs I
R
Resistance
V
Voltage
I
Current

Measuring Basic Parameters

Ohm’s law and Kirchhoff’s method are useful to analyze and design electrical circuits, providing you with the voltages across, the current through, and the resistance of the components that compose the circuit.

DC Voltmeters, Ammeters, Ohmmeter

Measuring Current with an Ammeter

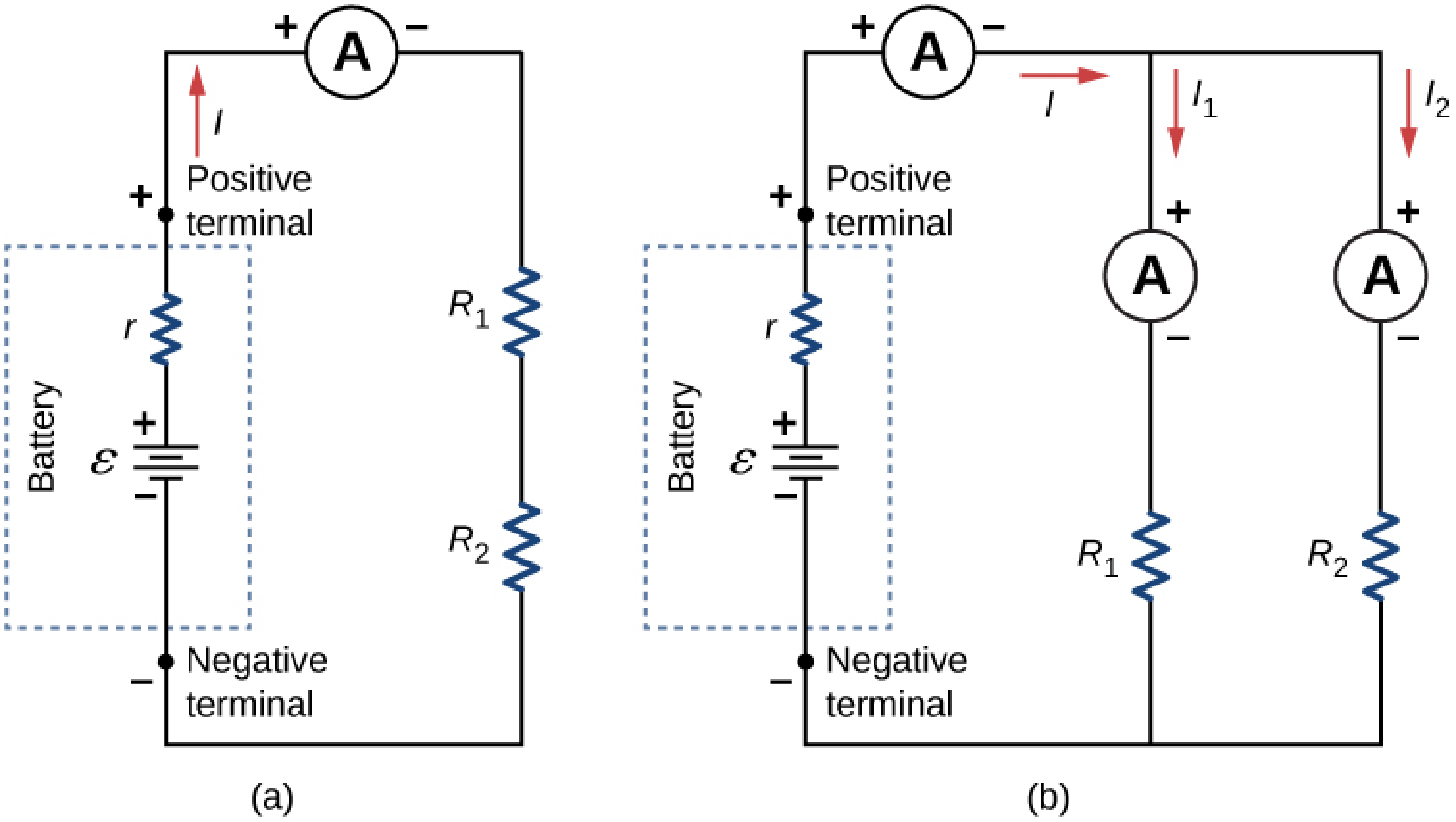
To measure the current through a device or component, the ammeter is placed in series with the device or component.

A series connection is used because objects in series have the same current passing through them. (See Figure, where the ammeter is represented by the symbol A.)

Ammeters need to have a very low resistance, a fraction of a milliohm

Ammeters normally contain a fuse to protect the meter from damage from currents which are too high.

Ammeter

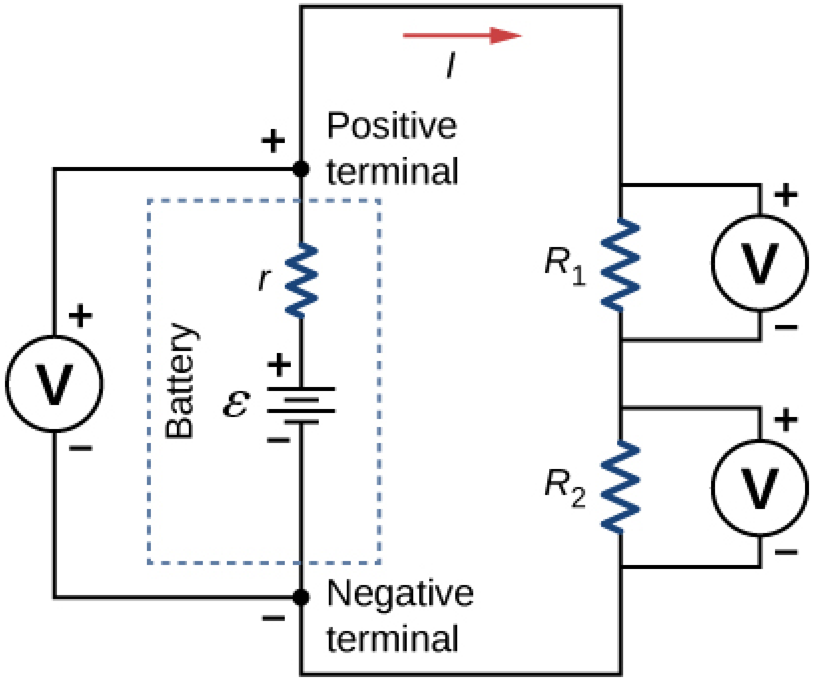


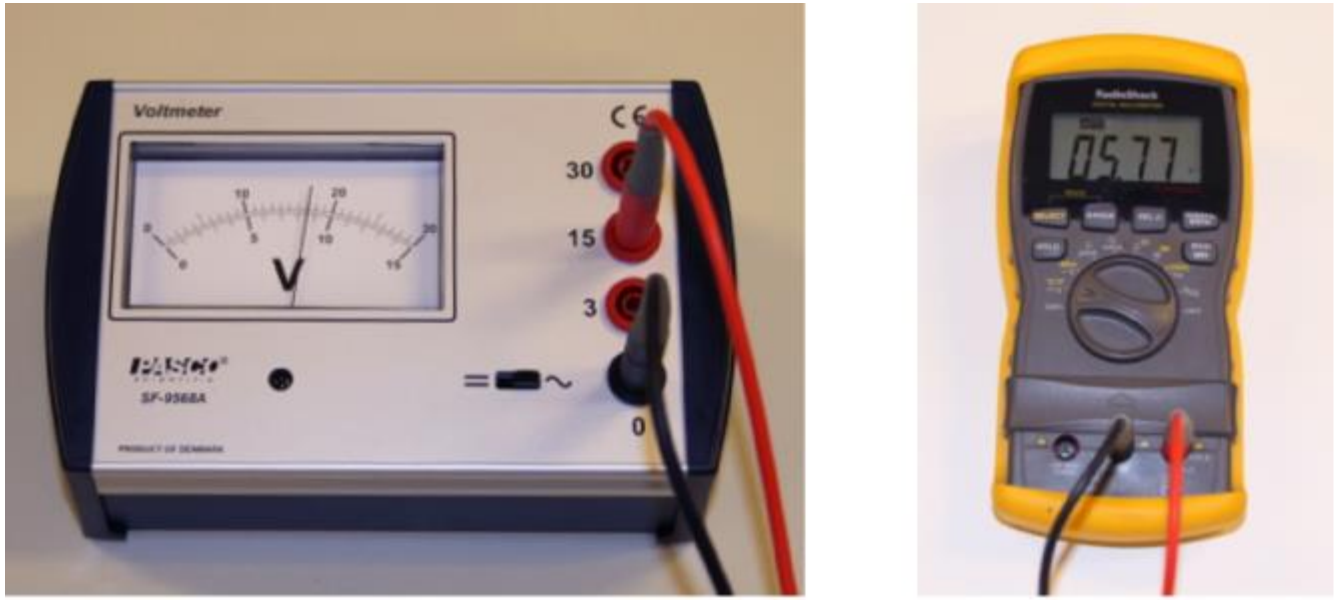
(a) When an ammeter is used to measure the current through two resistors connected in series to a battery, a single ammeter is placed in series with the two resistors because the current is the same through the two resistors in series. (b) When two resistors are connected in parallel with a battery, three meters, or three separate ammeter readings, are necessary to measure the current from the battery and through each resistor. The ammeter is connected in series with the component in question.

Measuring Voltage with a Voltmeter

- A voltmeter is connected in parallel with whatever device it is measuring. A parallel connection is used because objects in parallel experience the same potential difference.

Since voltmeters are connected in parallel, the voltmeter must have a very large resistance. Digital voltmeters convert the analog voltage into a digital value to display on a digital readout





(a)

(b)

Ohmmeters

An **ohmmeter** is an instrument used to measure the resistance of a component or device. The operation of the ohmmeter is based on Ohm's law.

Traditional ohmmeters contained an internal voltage source (such as a battery) that would be connected across the component to be tested, producing a current through the component.

A galvanometer was then used to measure the current and the resistance was deduced using Ohm's law.

The resistance is measured using Ohm's law $R=V/I$, where the voltage is known and the current is measured, or the current is known and the voltage is measured.

The component of interest should be isolated from the circuit; otherwise, you will be measuring the equivalent resistance of the circuit.

An ohmmeter should never be connected to a "live" circuit, one with a voltage source connected to it and current running through it. Doing so can damage the meter.

Analog and Digital Meters

Analog Meter

An **analog meter** uses a galvanometer, which is essentially a coil of wire with a small resistance, in a magnetic field, with a pointer attached that points to a scale. Current flows through the coil, causing the coil to rotate.

To use the galvanometer as an ammeter, a small resistance is placed in parallel with the coil. For a voltmeter, a large resistance is placed in series with the coil.

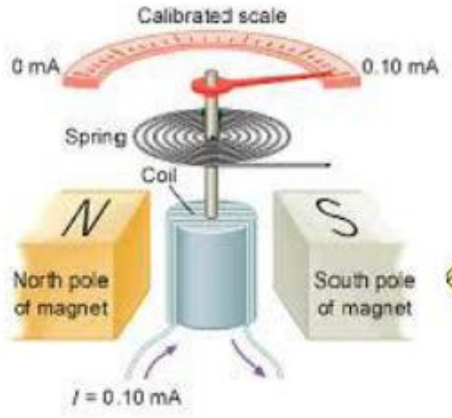
Digital Meter

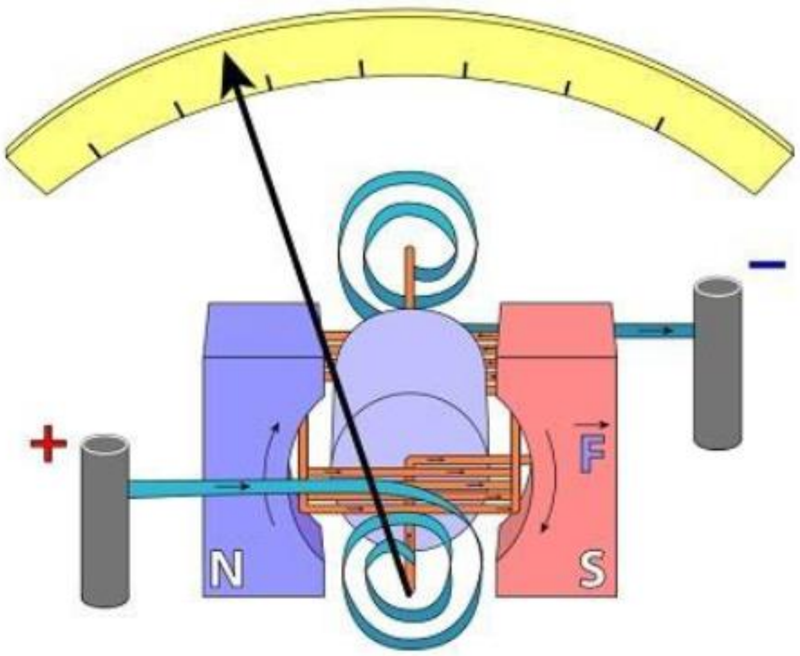
A **digital meter** uses a component called an analog-to-digital converter and expresses the current or voltage as a series of the digits (0) and (1) which are used to run a digital display. Most analog meters have been replaced by digital meters.

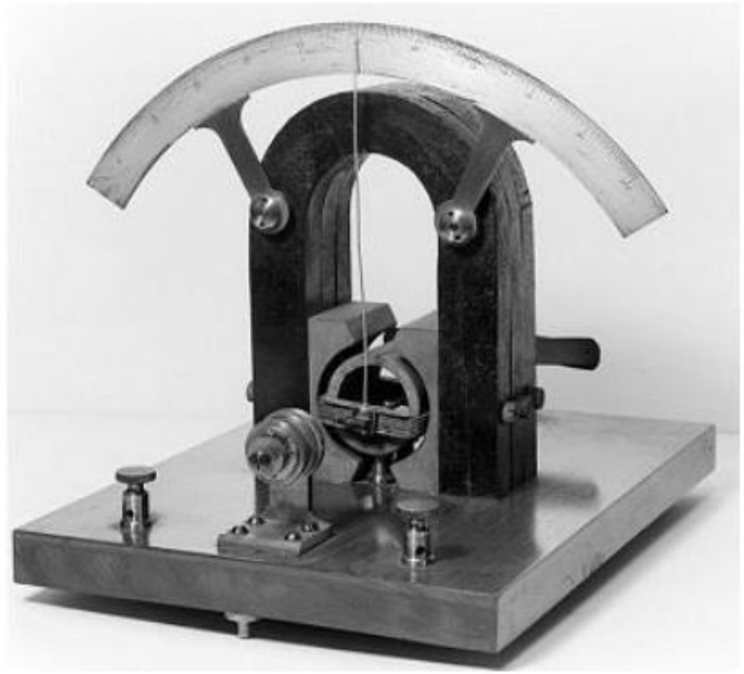
Analog Galvanometer

Analog Galvanometer

http://pediaa.com/difference-between-galvanometer-and-voltmeter/







Galvanometer is a device which has parts that move in response to an electric current

Analog Voltmeter

Analog Voltmeter

http://pediaa.com/difference-between-galvanometer-and-voltmeter/

A voltmeter is a device which,
when connected across two points on an electric circuit,
measures the potential difference between those two points

Galvanometers can be used to make voltmeters.
The needle of a galvanometer moves in response to *current*,
but if we know the resistance of the coil,
then we can use Ohm's law to determine
the corresponding potential difference
between the two ends of a voltmeter.

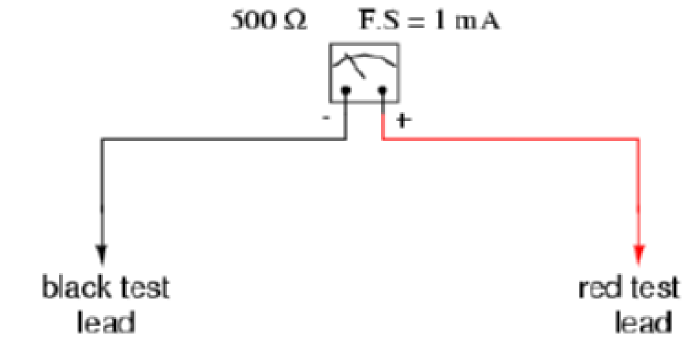
Voltmeter Calibration:
We could **set up** a scale next to the needle
that reads the values of potential difference
corresponding to the needle's position
+ Manual ZERO correction (rotate spring...)

Analog Voltmeter: Problems
Periodical Calibration is needed
Low accuracy
Values must be logged manually

Voltmeter

Galvanometer → Voltmeter

http://www.allaboutcircuits.com/textbook/direct-current/chpt-8/voltmeter-design/

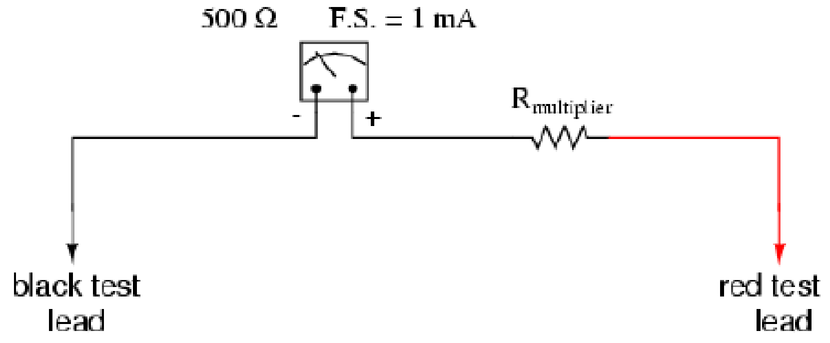


Using Ohm's Law (V=IR),
we can determine how much voltage will drive this meter movement directly to full scale:

V = I R

V = (1 mA)(500 Ω)

V = 0.5 volts



How to measure bigger voltages ?
Add additional resistor.

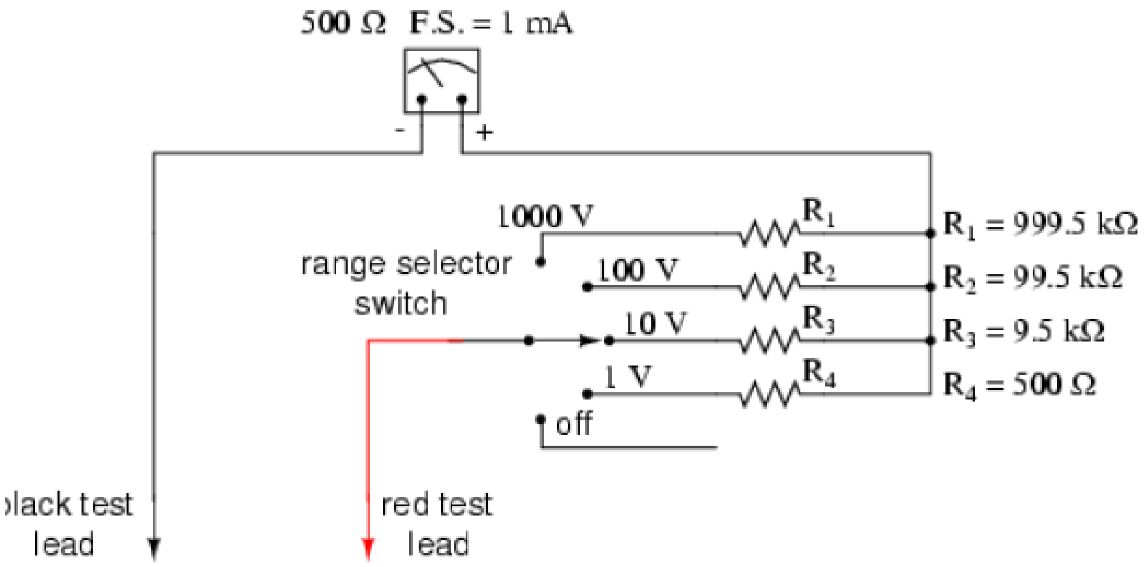
	Movement	$R_{multiplier}$	Total	
E	0.5	9.5	10	Volts
I	1m	1m	1m	Amps
R	500	9.5k	10k	Ohms

Sensitivity $=1/ I_{fd}$

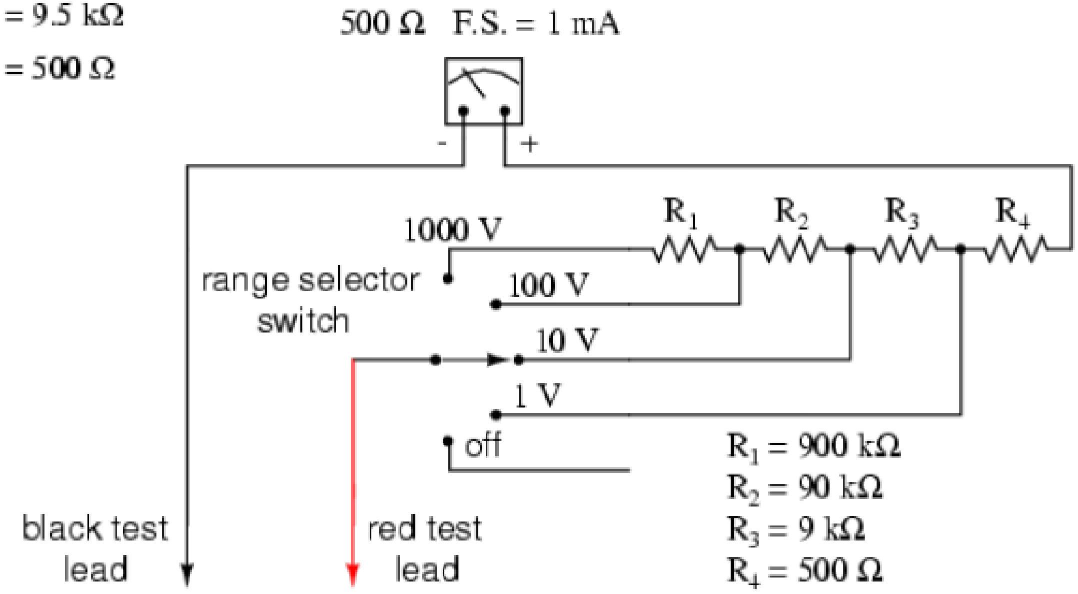
Multi range Voltmeter

Multi-Range Analog Voltmeter

http://www.allaboutcircuits.com/textbook/direct-current/chpt-8/voltmeter-design/



More practical design



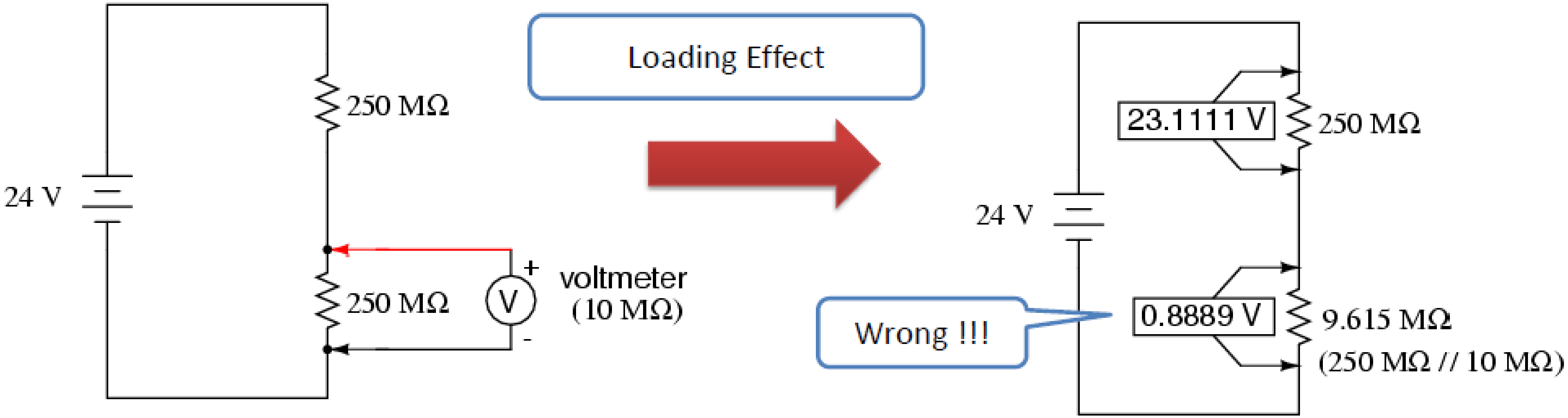
Multi range Voltmeter

Analog Voltmeter Impact on Measuring Circuit

http://www.allaboutcircuits.com/textbook/direct-current/chpt-8/voltmeter-design/

Every meter impacts the circuit it is measuring to some extent.
While some impact is inevitable, it can be minimized through good meter design.

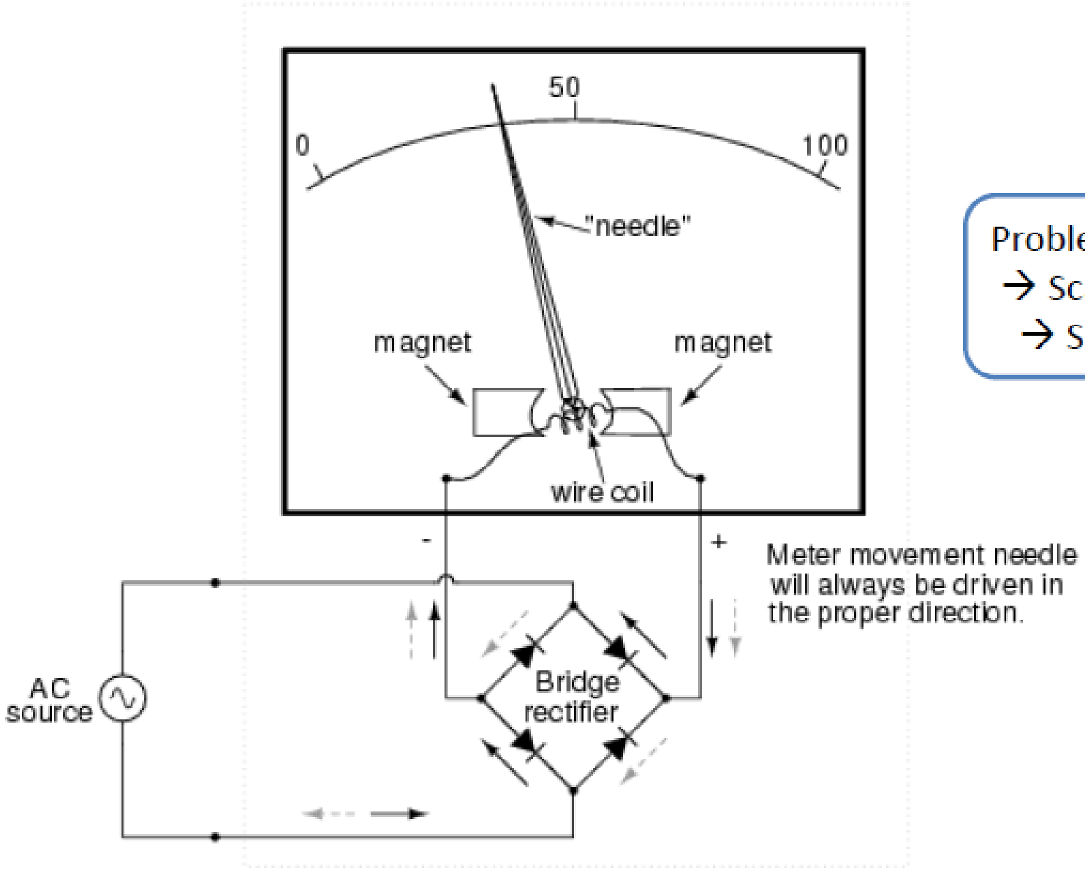
Voltmeters are **always** connected in parallel with the component under test.
A perfect voltmeter has infinite resistance, so that it draws no current from the circuit under test.
However, perfect voltmeters only exist in the pages of textbooks, not in real life!



AC Analog Ammeter design

AC Analog Ammeter design

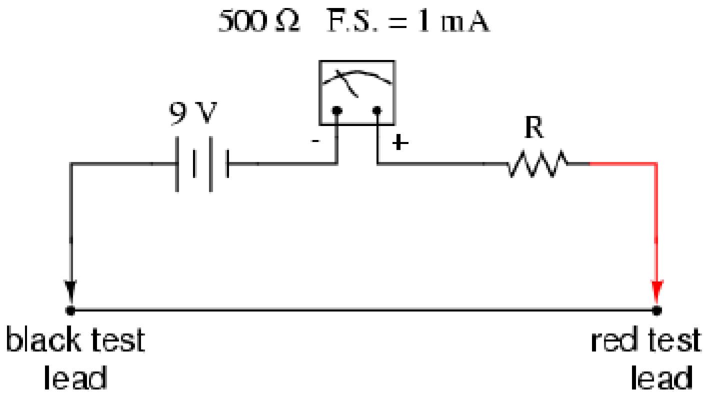
https://www.ibiblio.org/kuphaldt/electricCircuits/AC/AC_12.html



Problem: Diodes are NON LINEAR
→ Scale is not linear
→ Special Scale for AC must be printed

Analog Ohmmeter design

http://www.allaboutcircuits.com/textbook/direct-current/chpt-8/voltmeter-design/



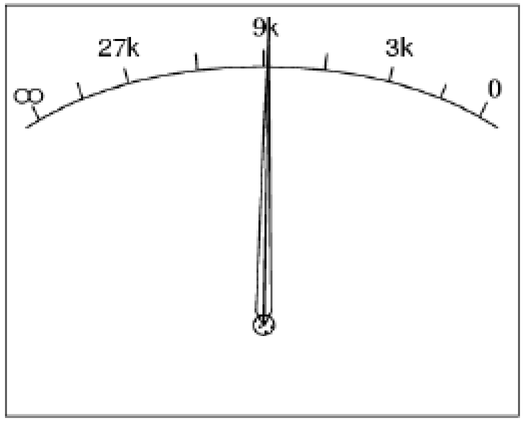
$$R_{total} = \frac{E}{I} = \frac{9\ V}{1\ mA}$$

$$R_{total} = 9\ k\Omega$$

$$R = R_{total} - 500\ \Omega = 8.5\ k\Omega$$

Current is a function of R + **Rx between black and red leads**

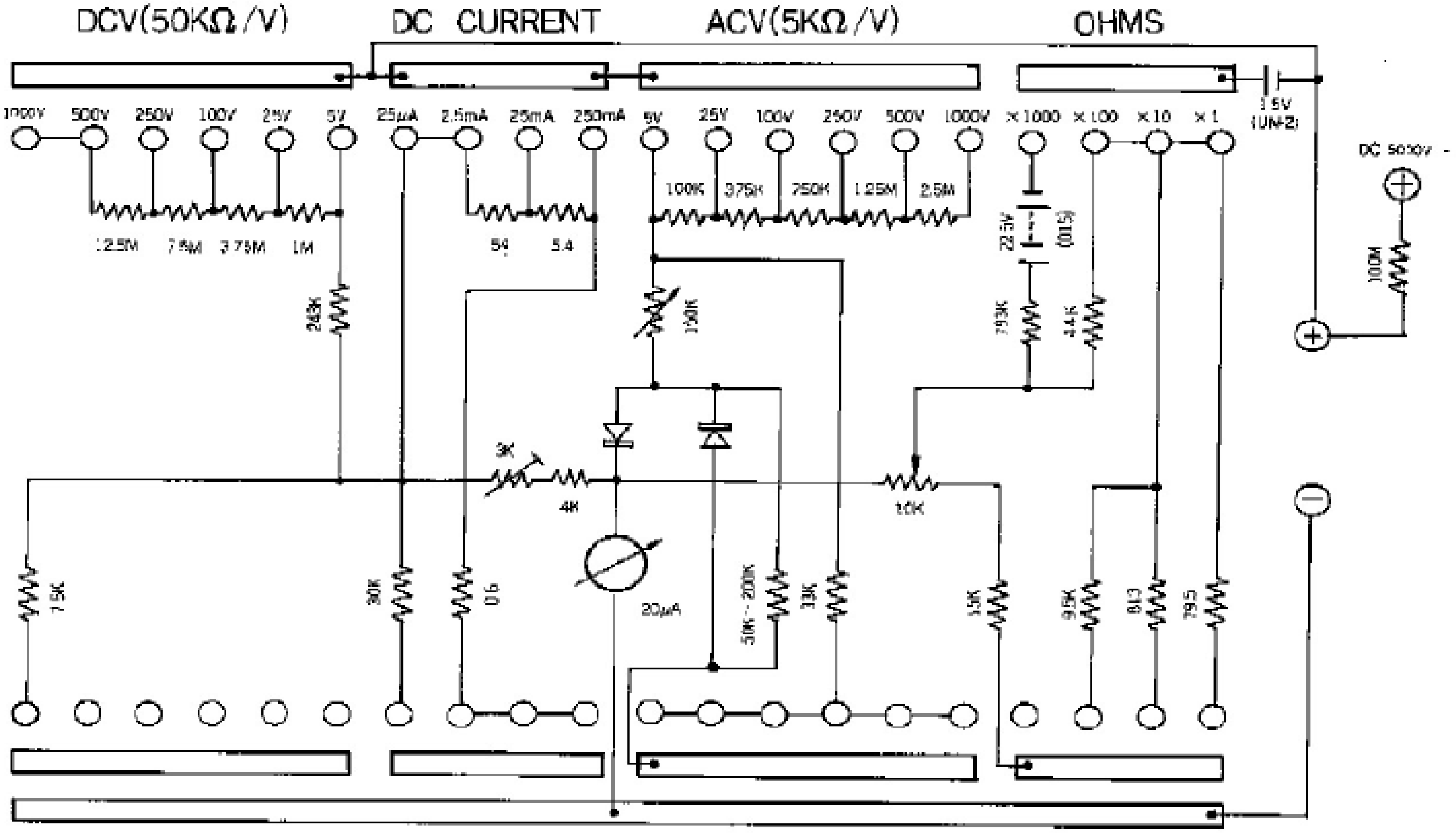
But scale is NOT Linear !!!
Example: if current of 0.5 mA then
R + Rx = 9V/0.5 mA = 18 k
→ Rx = 18 – 8.5 – 0.5 = 9 k



Q. Can EE measure resistance of the component **on the PCB** ?

Outdated Analog Multimeter design

Outdated Analog Multimeter design

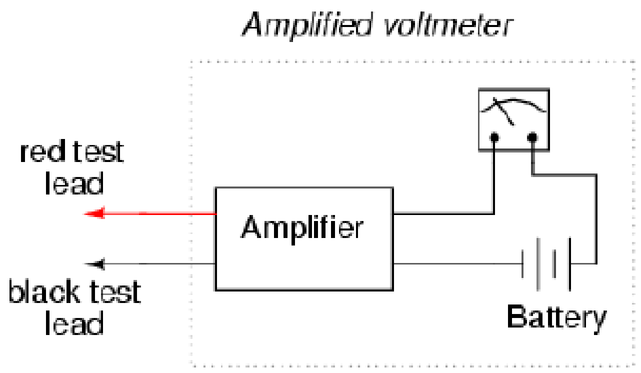


Analog Voltmeter with Analog Amplifier

http://www.allaboutcircuits.com/textbook/direct-current/chpt-8/voltmeter-design/

Amplifier can has nearly INFINITE input resistance. (FET, OA)

In case galvanometer is used, Voltage to Current converter must be used

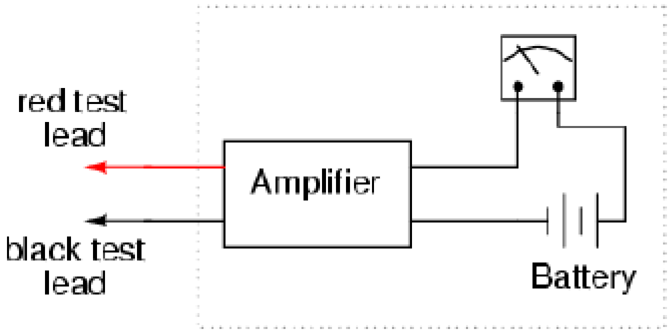


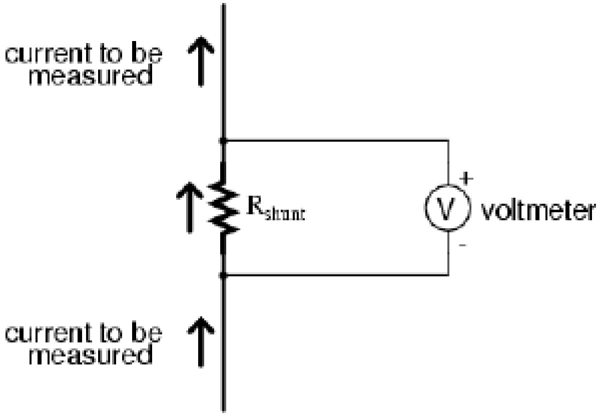
Analog Ammeter with Analog Amplifier

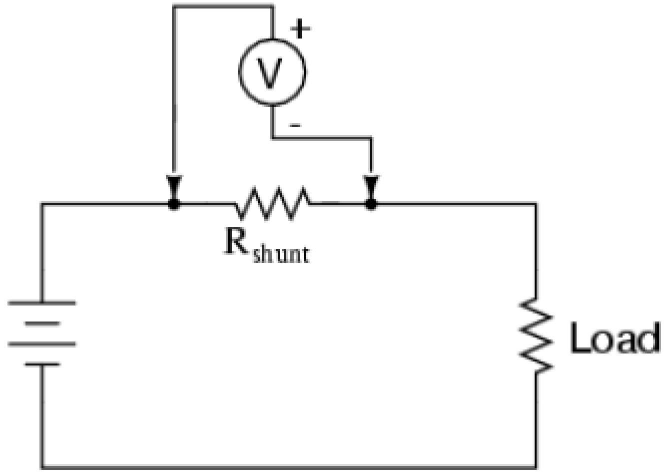
http://www.allaboutcircuits.com/textbook/direct-current/chpt-8/voltmeter-design/

Voltmeter with Amplifier
→ Input Resistance can be set as HUGE

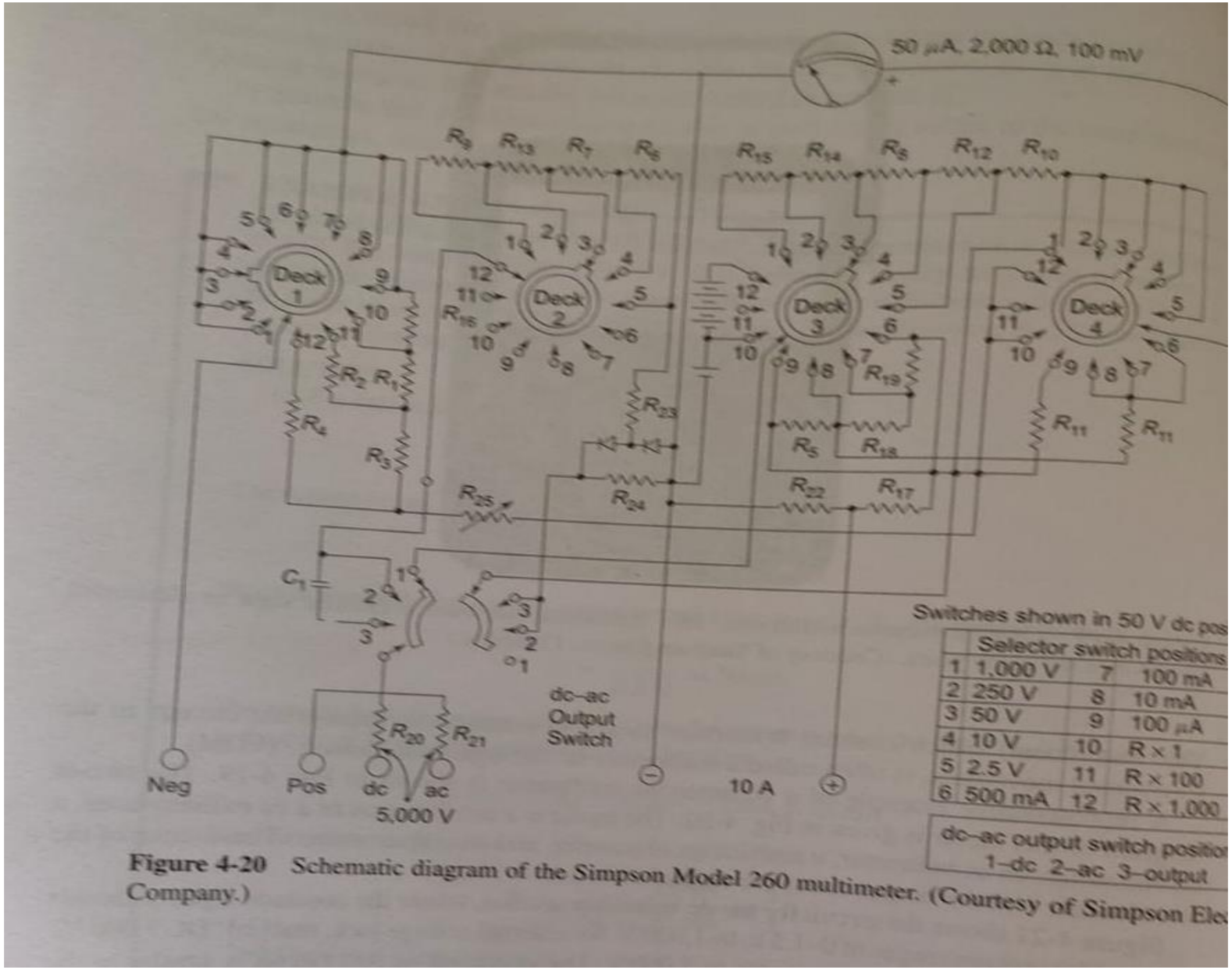
Amplified voltmeter







Analog multimeter



DC voltmeter section

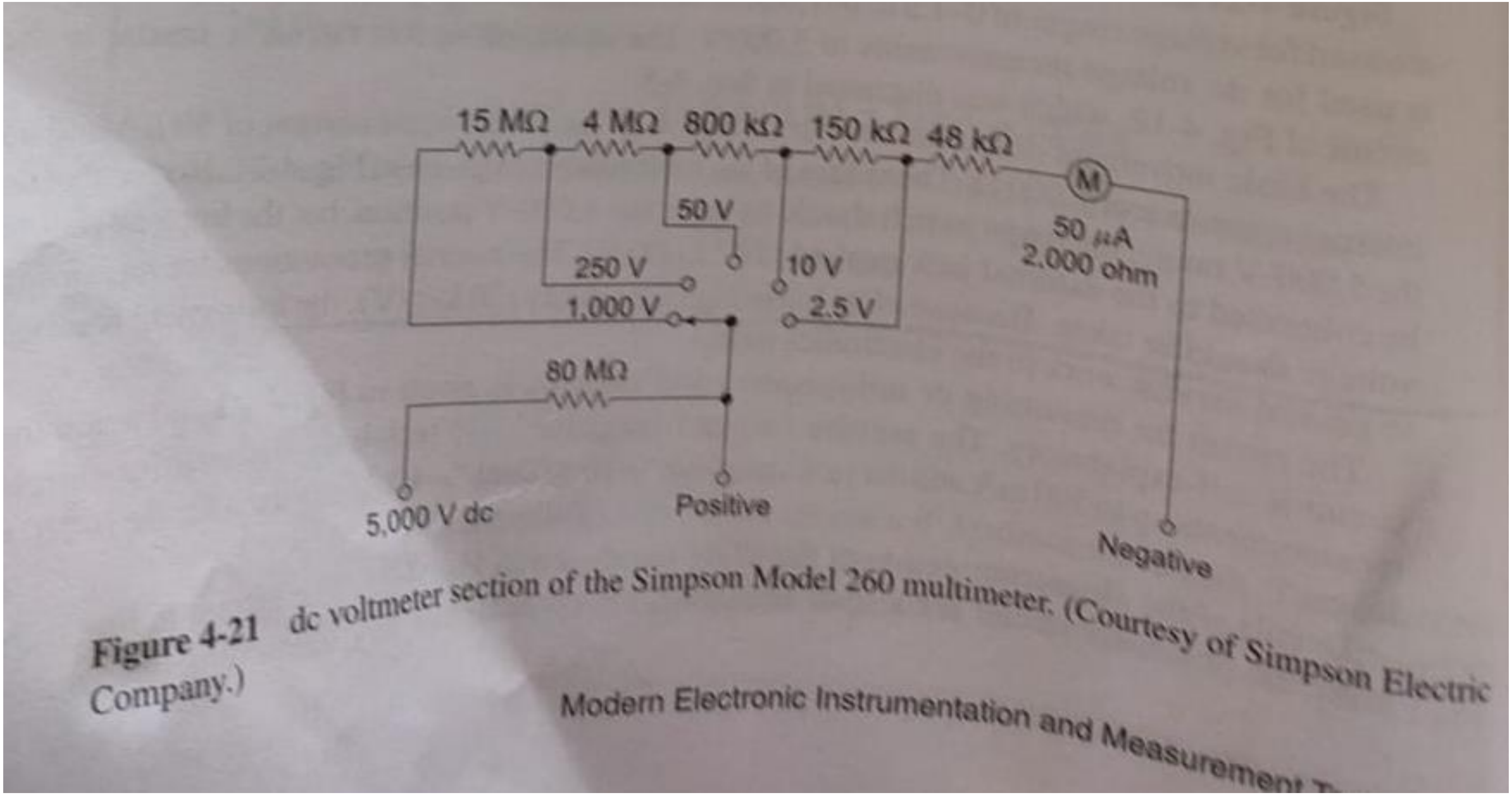


Figure 4-21 dc voltmeter section of the Simpson Model 260 multimeter. (Courtesy of Simpson Electric Company.)

DC ammeter section

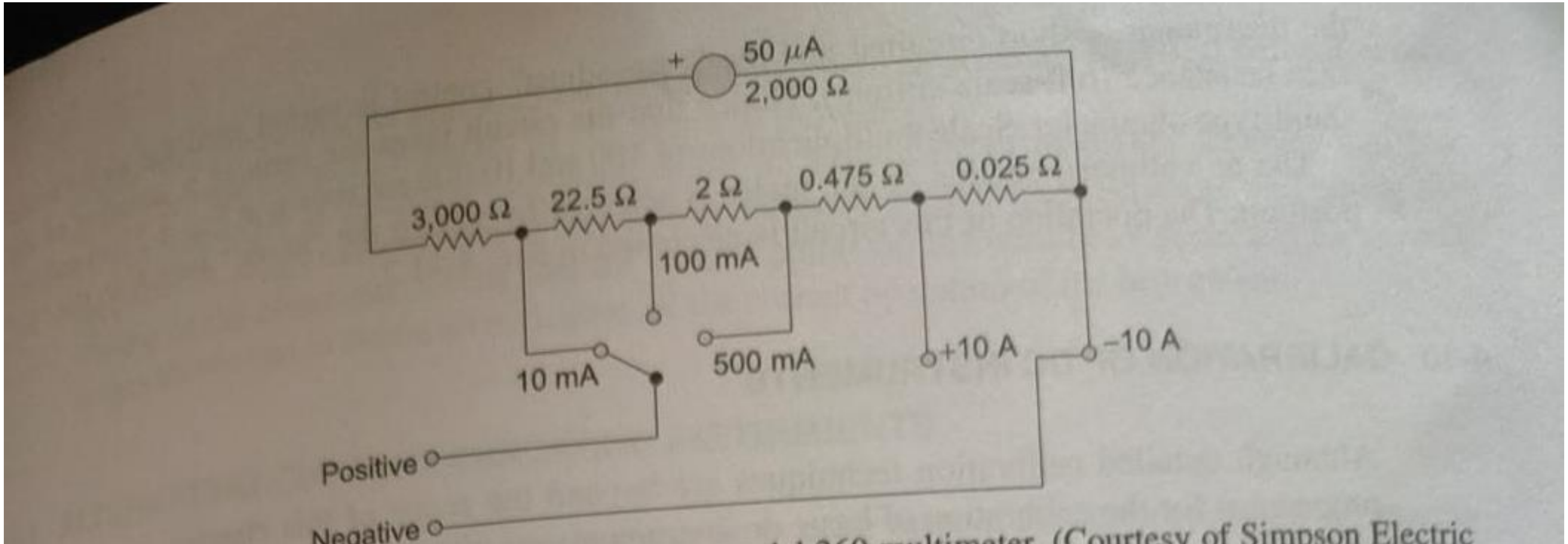


Figure 4-22 dc ammeter section of the Simpson model 260 multimeter. (Courtesy of Simpson Electric Company.)

Ohmmeter section

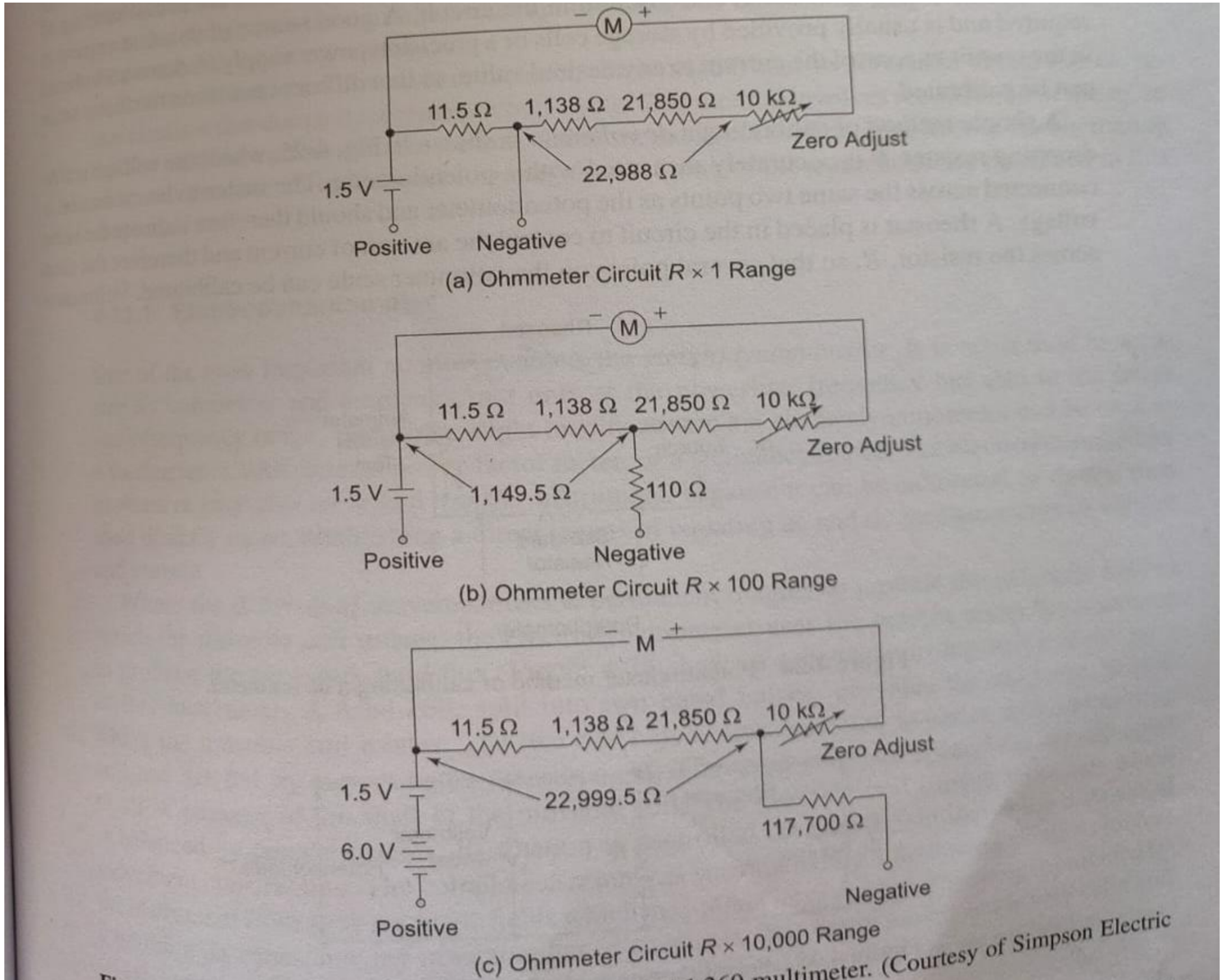


Figure 4-23 Ohmmeter section of the Simpson Model 260 multimeter. (Courtesy of Simpson Electric Company.)

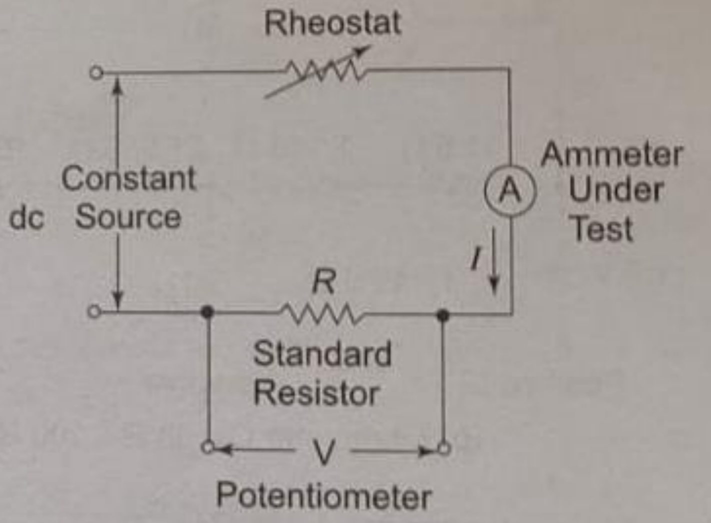


Figure 4-24 Potentiometer method of calibrating a dc ammeter.

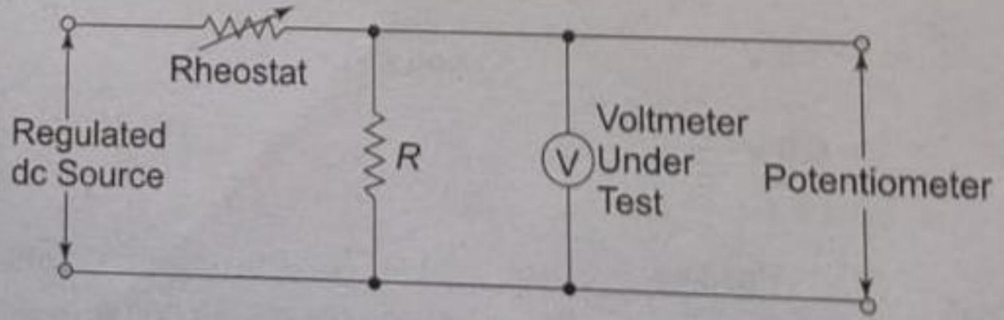
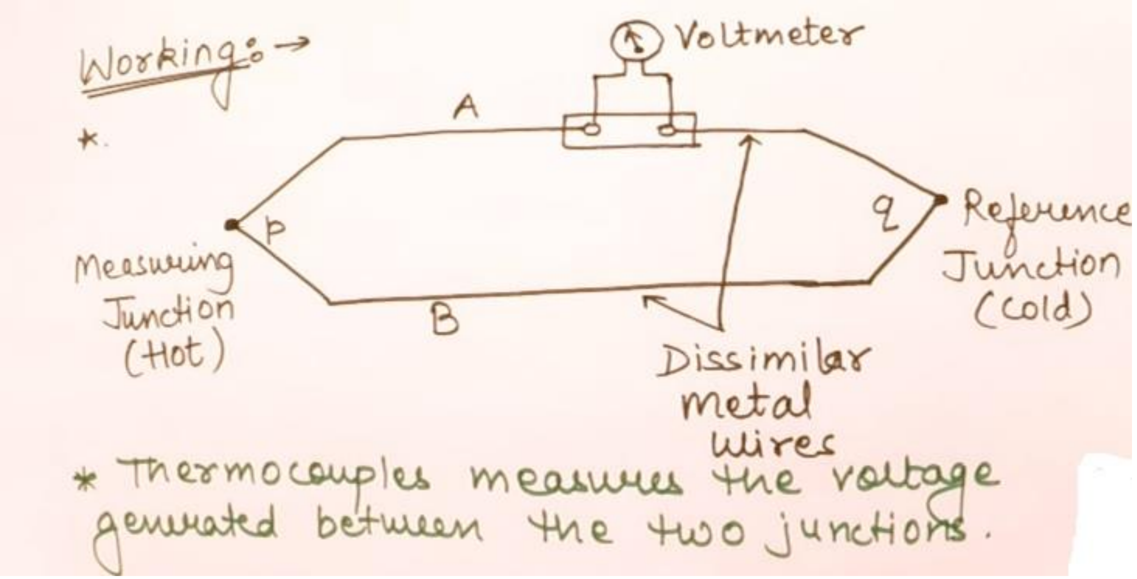
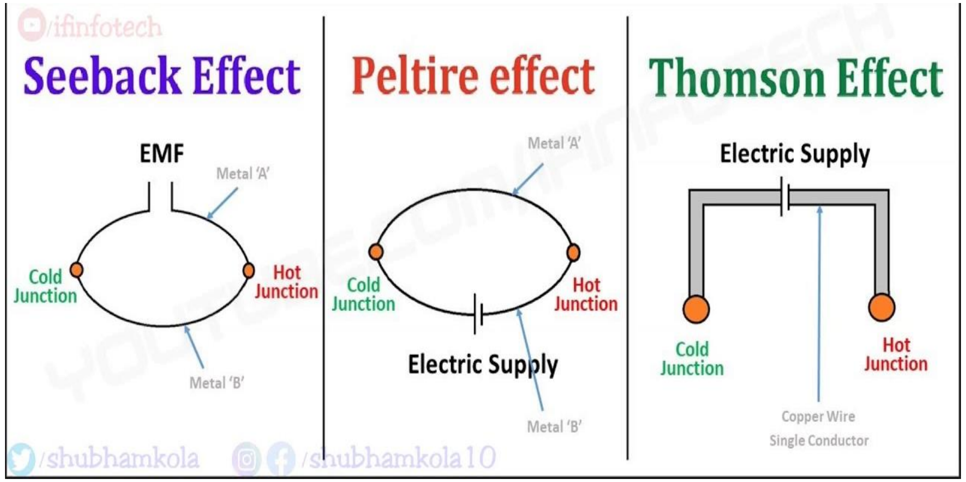


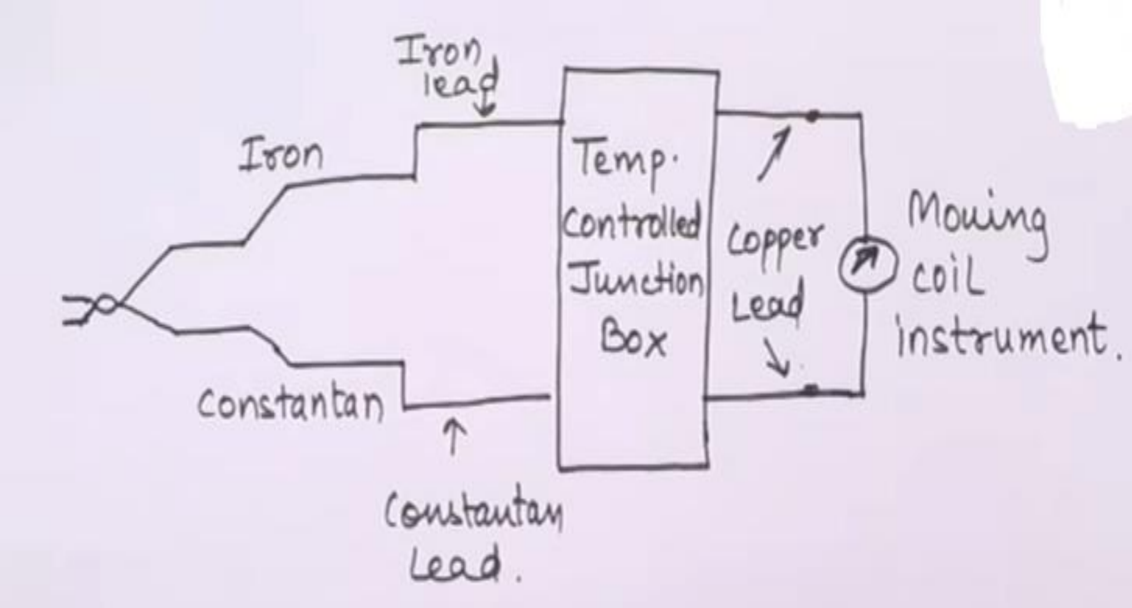
Figure 4-25 Potentiometer method of calibrating a dc voltmeter.

Thermo Instruments





$$V = \alpha \Delta T$$



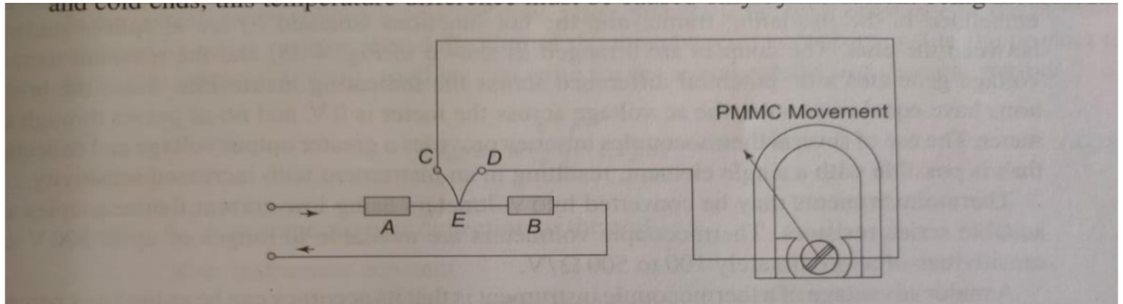


Figure 4-33 Schematic representation of a basic thermocouple instrument using thermocouple CDE and a PMMC movement.

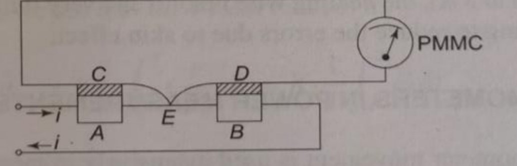


Figure 4-34 Compensated thermocouple to measure the thermo voltage produced by current i alone. Couple terminals C and D are in thermal contact with heater terminals A and B, but are electrically insulated from them.

Digital Voltmeter

- A digital voltmeter (DVM) is an instrument which measures the AC/DC voltage and displays the value directly in numeric form instead of pointer deflection.

Advantages : (over an Analog type VM)

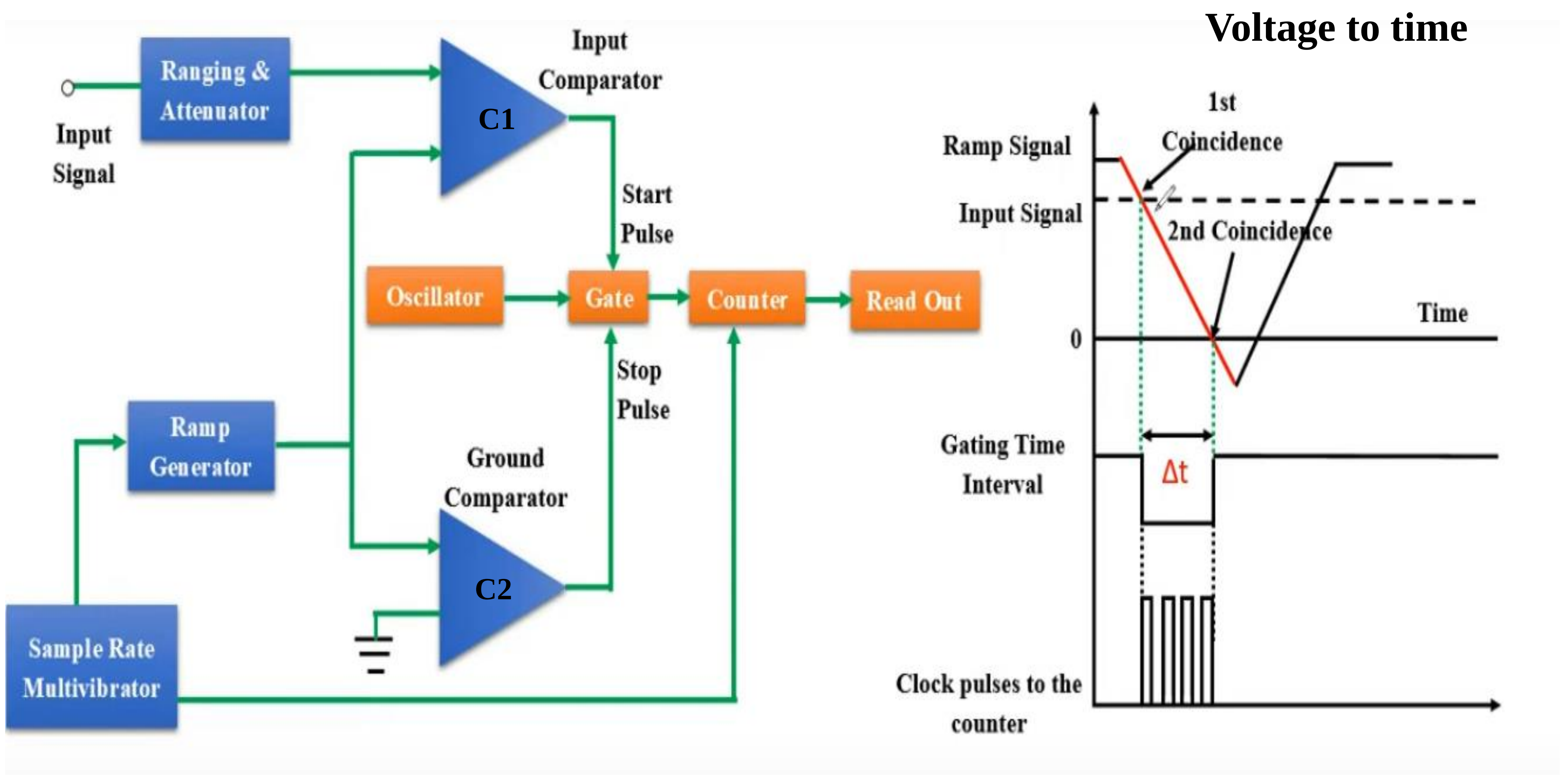
- Accuracy ⬆️
- Speed ⬆️
- Sensitivity ⬆️
- Observational Error ⬇️
- Power Requirement ⬇️
- Cost ⬇️
- Size ⬇️
- Storage

Digital Voltmeter

- DVM displays measurements of dc or ac voltages as discrete numerals instead of a pointer deflection on a continuous scale as in analog devices.
- Types of DVM

1. Ramp type DVM
2. Integrating DVM
3. Continuous-balance DVM
4. Successive-approximation DVM

Ramp Digital Voltmeter



Ramp Digital Voltmeter

- Ramp-type ADC can be divided into two sections as follows:
  1. Voltage to time conversion section
  2. Time measurement section
- The analog input voltage is fed to the attenuation circuit. The attenuated signal is compared with the the ramp signal generated by the ramp generator given in the block diagram by the input comparator 'C1'.
- Similarly, The ramp signal generated is compared with 0V via a zero-crossing detector 'C2'.
- A sample rate multivibrator is connected to the ramp generator whose purpose is to provide an initiating pulse for the ramp generator to start the next ramp voltage for the next measurement.
- It is also used to reset the counter before generating the next ramp voltage.

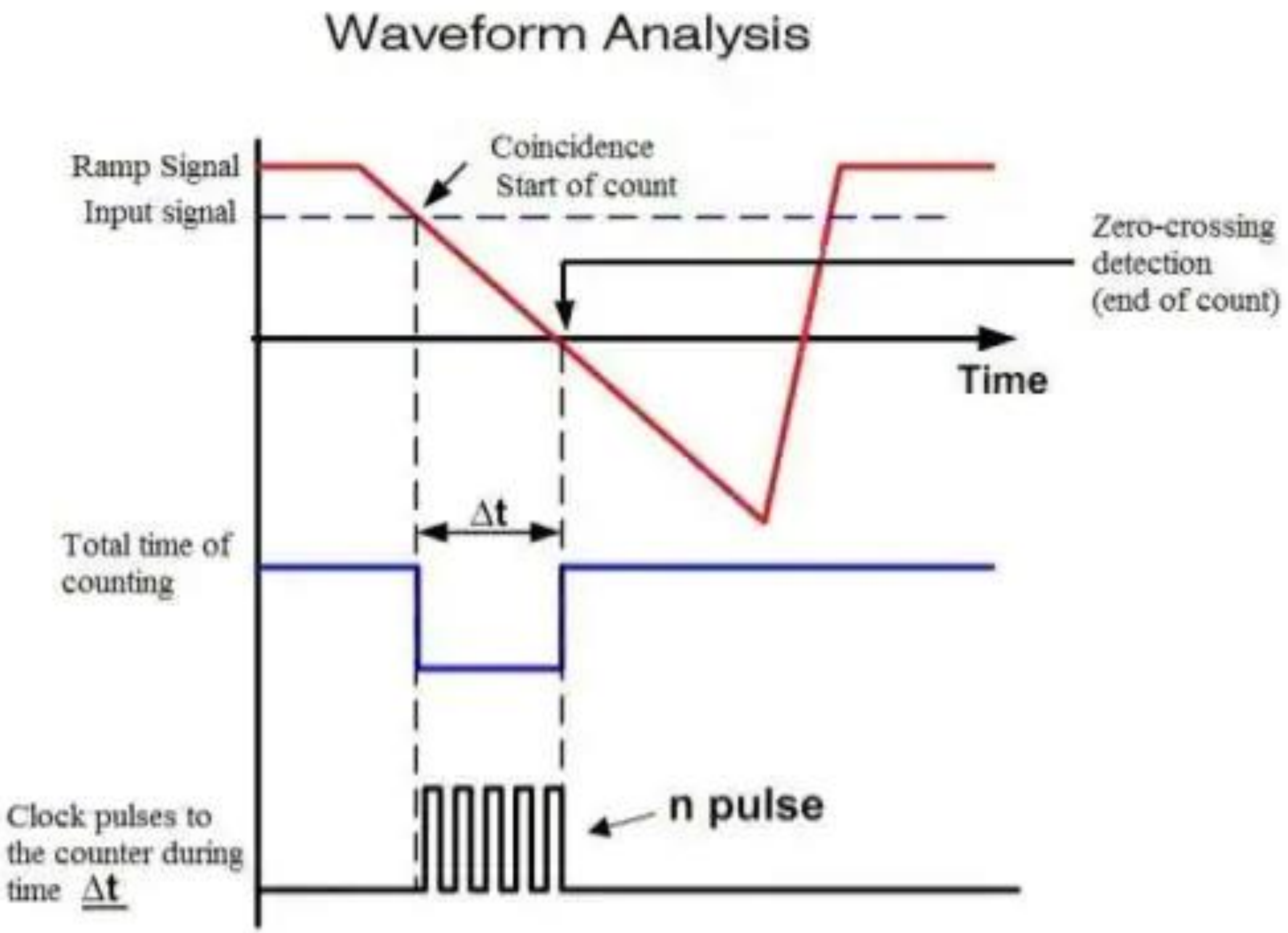
Ramp Digital Voltmeter

- In the time measurement section, there is counter which is triggered by a gating pulse.
- The inputs of the gating pulse are (i) Output of 'C1' (ii) Output of 'C2' (iii) Clock pulse from the oscillator.
- The counter is reset after each successful completion of time measurement by a control signal from the sample rate multivibrator.
- The count produced is displayed by connecting suitable display device.

Ramp Digital Voltmeter

- The attenuated signal is compared with a negative going ramp signal generated by the ramp generator.
- When the ramp voltage coincides with the input signal, the output of 'C1' becomes low. This point is called coincidence point. This initiates the counting process (start of count).
- The counter continues to count until the ramp voltage reduces and crosses zero (0V). This is detected by zero crossing detector 'C2'.
- The output of 'C2' becomes high which ends the counting process (end of count).

Ramp Digital Voltmeter



- **Equations:**

  $t = t2 - t1 = Vin/m = nT$;
  Hence, $Vin = nmT$;

  where
  t1-> start of count
  t2-> end of count
  Vin-> input analog voltage
  m-> slope of the ramp curve
  n-> number of clock pulses to counter
  T-> clock period

Ramp Digital Voltmeter

- Merits:
  * low cost
  * simple, easy to design
  * long distance transmission of output pulse is possible

  Demerits:
  * accuracy of output greatly depends on linearity of the ramp.
    (since only one ramp is used)
  * input filter are needed for filtering noise from input signal.

Dual slope integrating type DVM

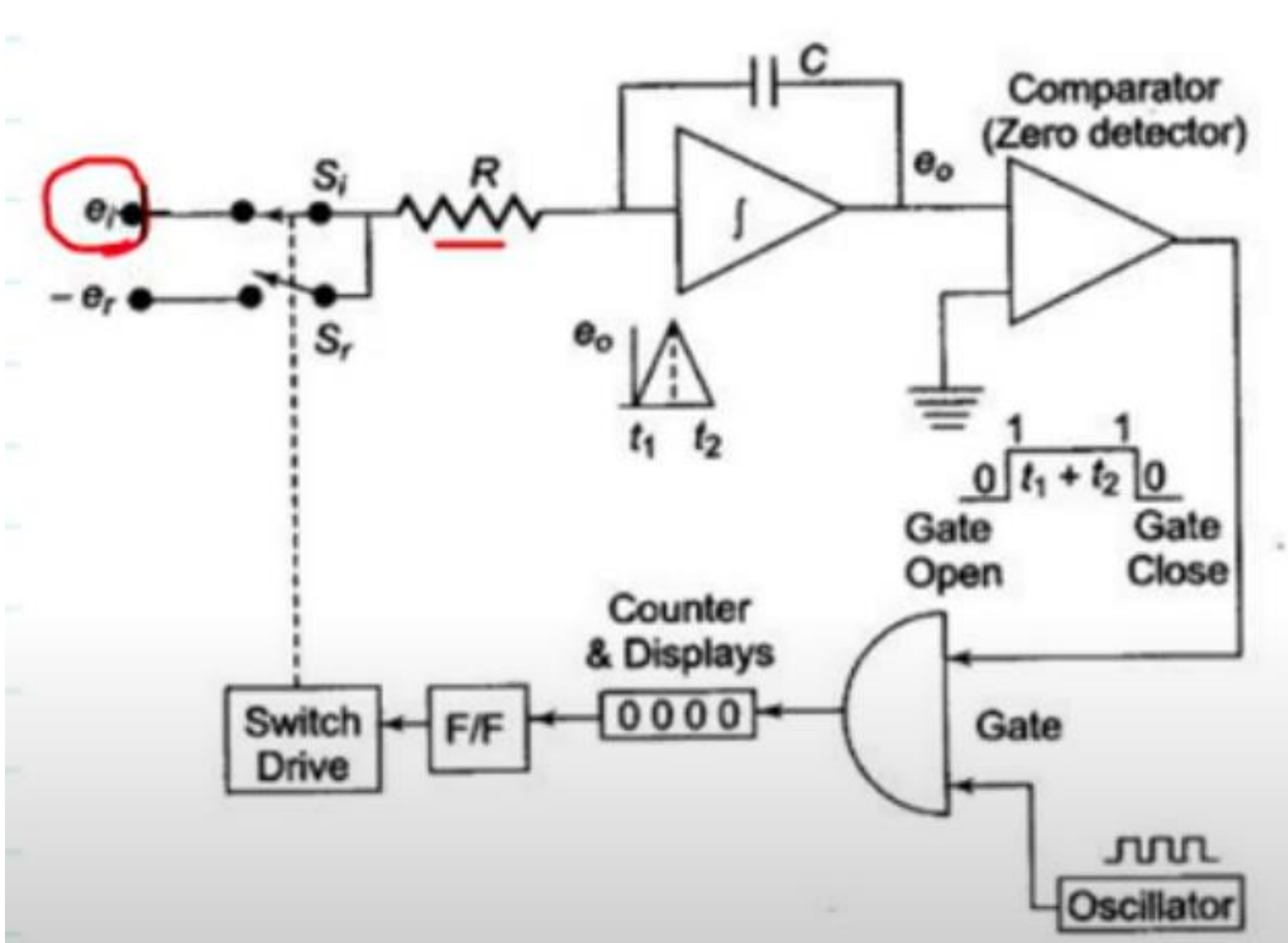


Fig. 5.4 Block Diagram of a Dual Slope Type DVM

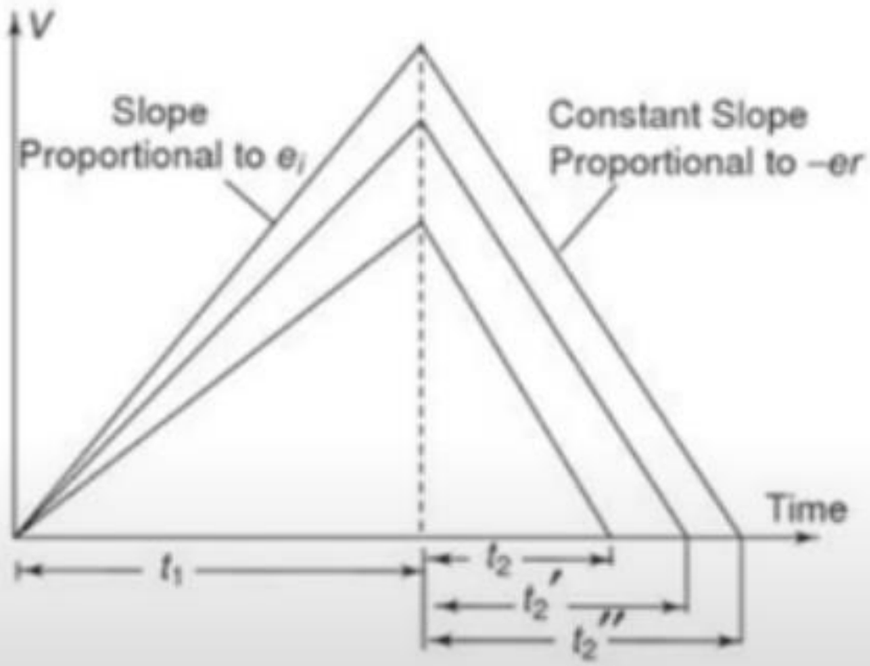


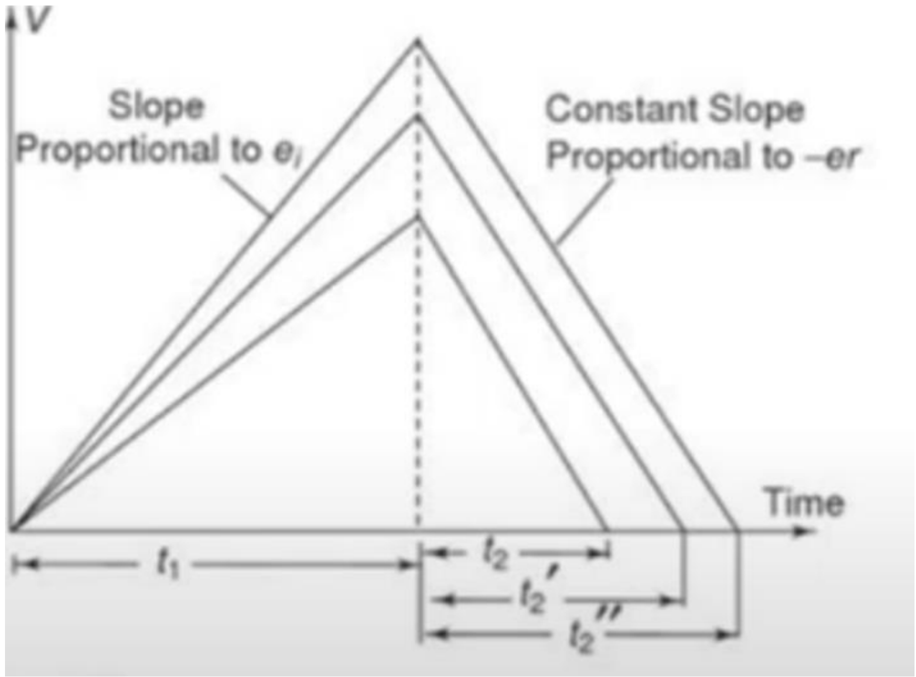
Fig. 5.3 Basic principle of dual slope type DVM

Dual slope integrating type DVM

$$e_0 = \frac{-1}{RC}\int_0^{t_1} e_i \, dt$$

$$= \frac{-e_1 t_1}{RC} \quad \text{--- (1)}$$

$$e_0 = \frac{1}{RC}\int_0^{t_2} -e_r \, dt = \frac{-e_r t_2}{RC} \quad \text{--- (2)}$$



Dual slope integrating type DVM

$$\frac{-e_i t_1}{\cancel{RC}} = \frac{-e_r t_2}{\cancel{RC}}$$

$$t_2 = n_2 T$$

$$e_i = \frac{e_r t_2}{t_1}$$

$$t_1 = n_1 T$$

$n_2 \rightarrow$ counter shown count

$$= e_r \frac{n_2 T}{n_1 T} = e_r \left(\frac{n_2}{n_1}\right)$$

T = Time for each count

Voltage to frequency Integrating

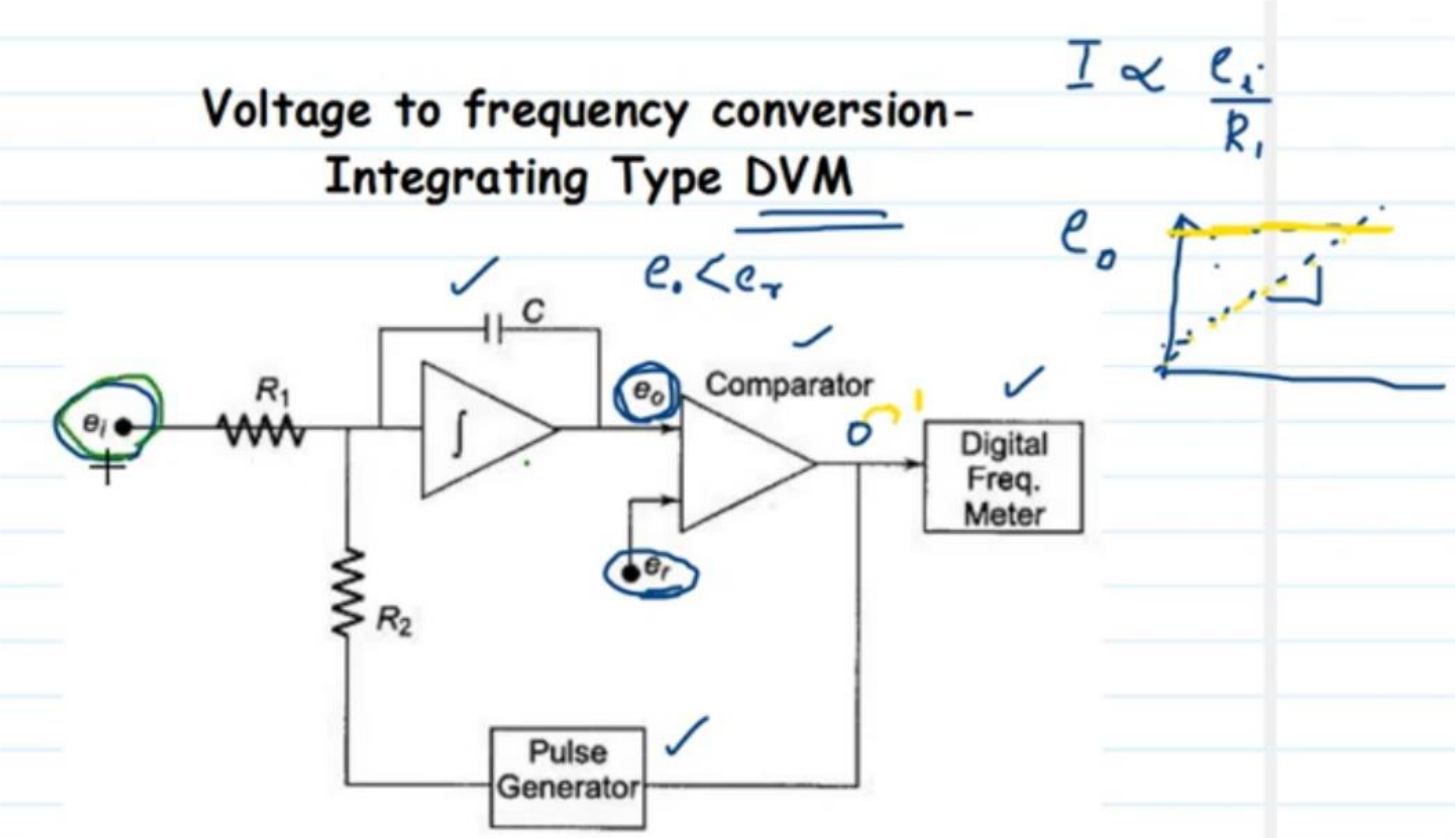


Fig. 5.6 Block Diagram of an Integrating Type DVM

Voltage to frequency Integrating

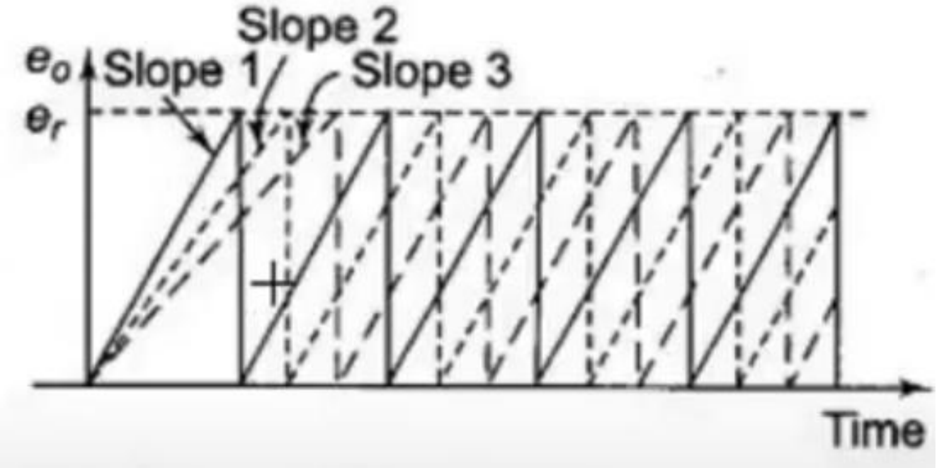
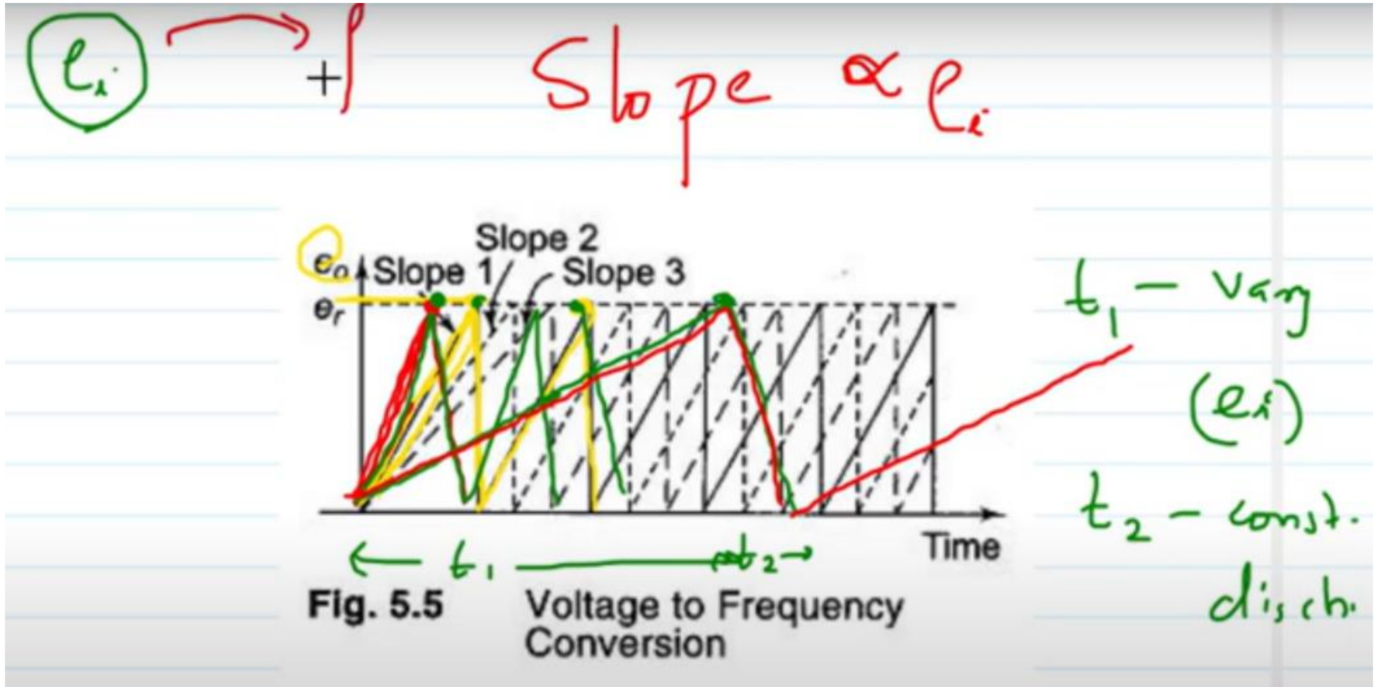


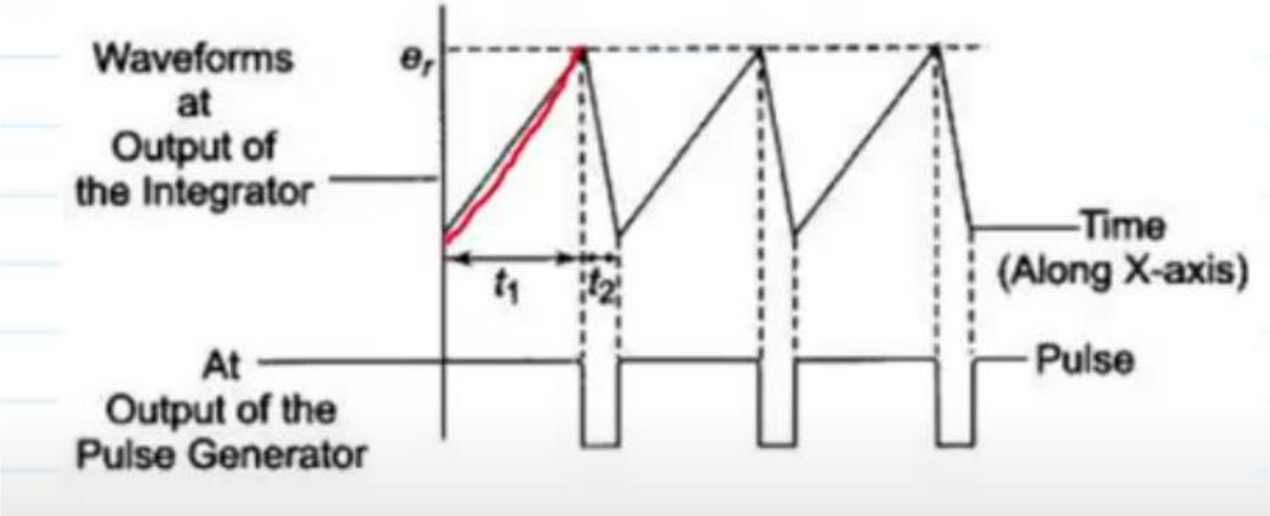
Fig. 5.5 Voltage to Frequency Conversion



V → f

high V → high f

low V → low f



Voltage to frequency Integrating

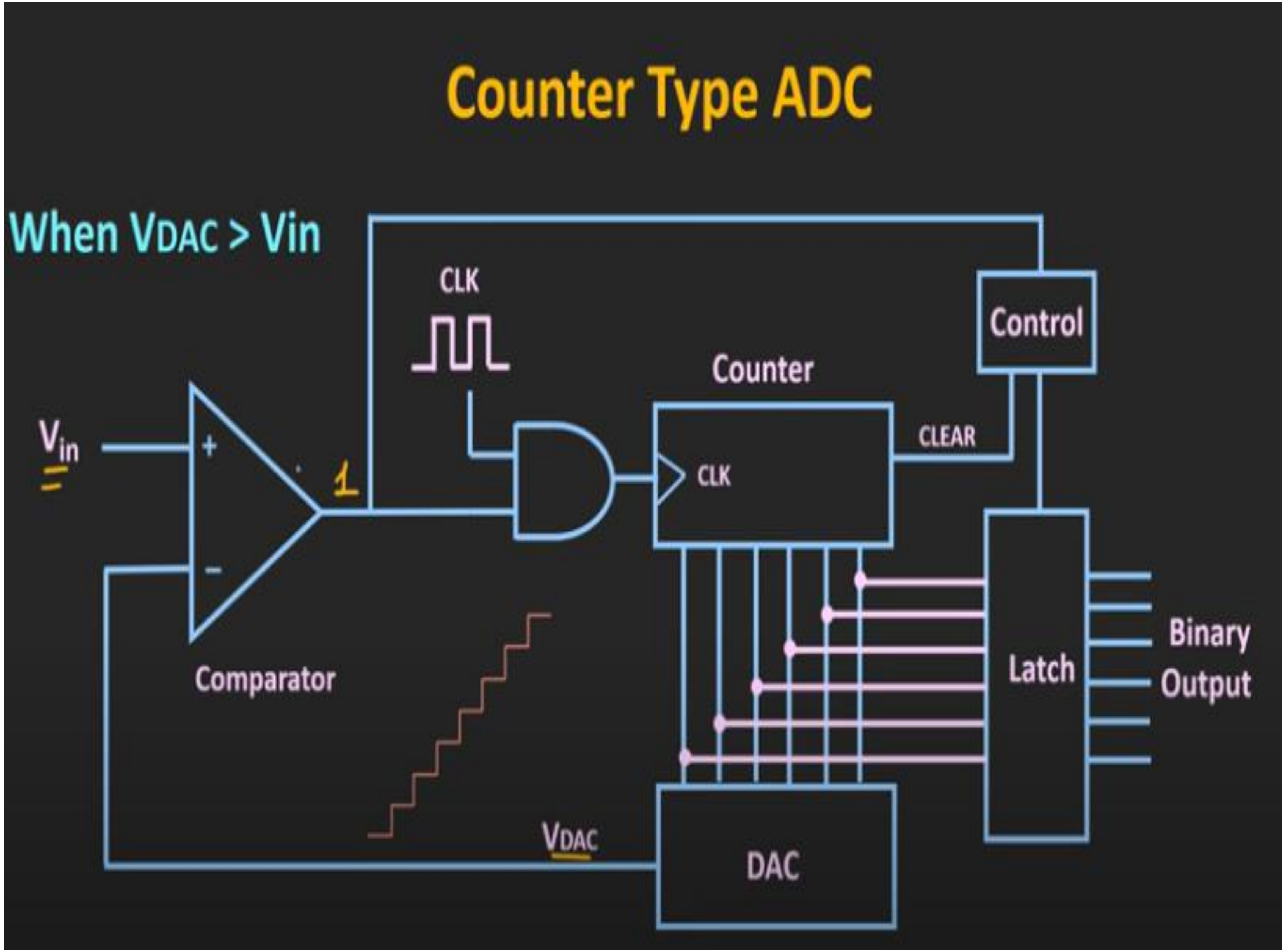
$$e_i = \frac{\overbrace{e_r f_2}^{K_2}}{t_1}$$

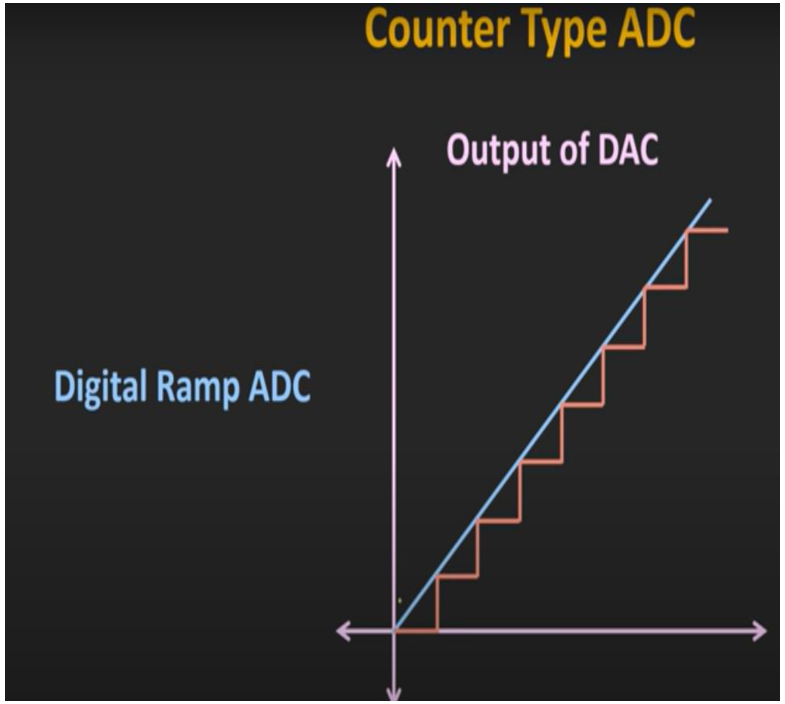
DFM

$$e_i = \frac{k_2}{t_1} = k_2 f_1$$

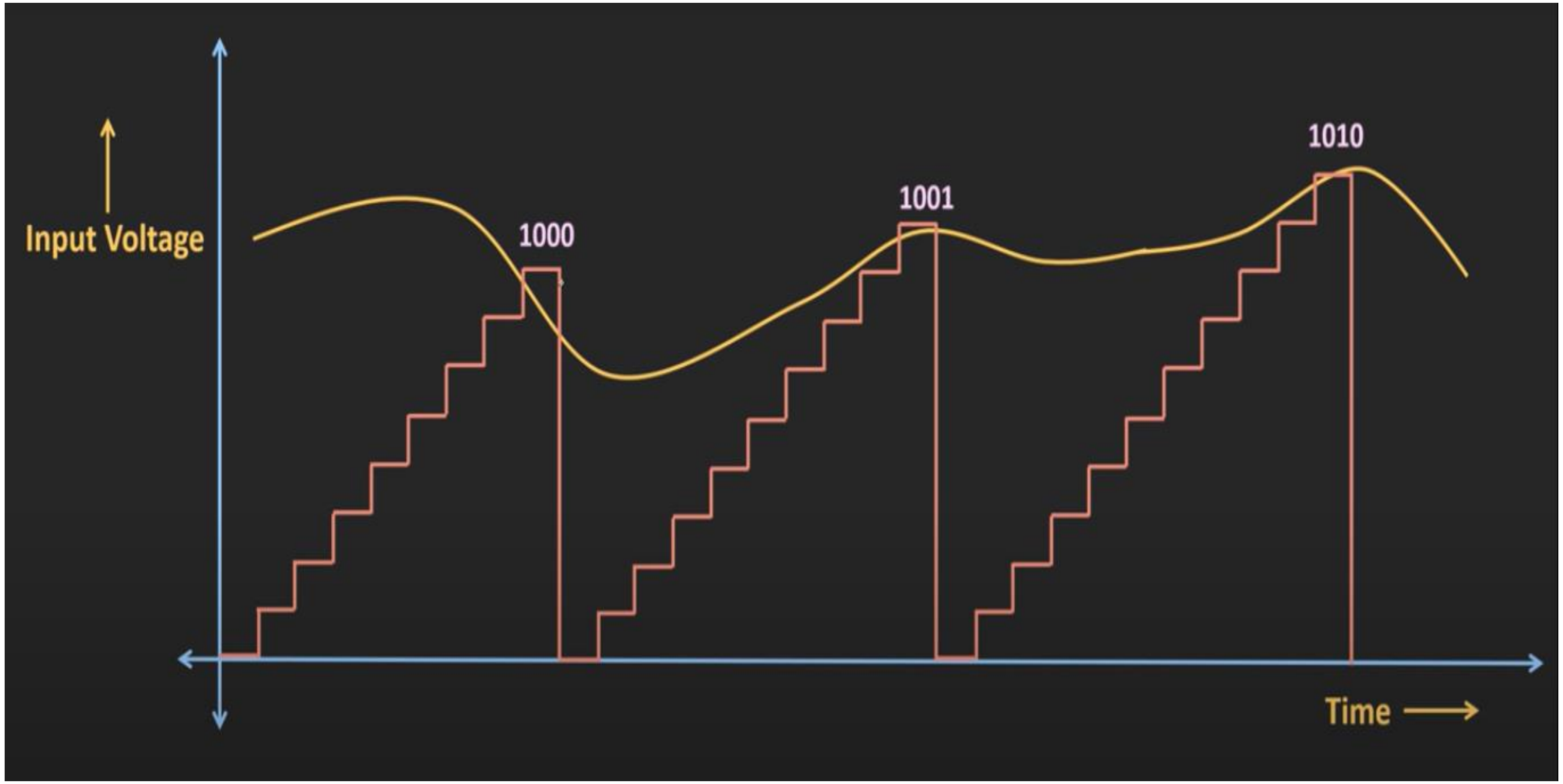
DVM.

Counter type ADC – (Staircase Ramp)





Counter type ADC – (Staircase Ramp)



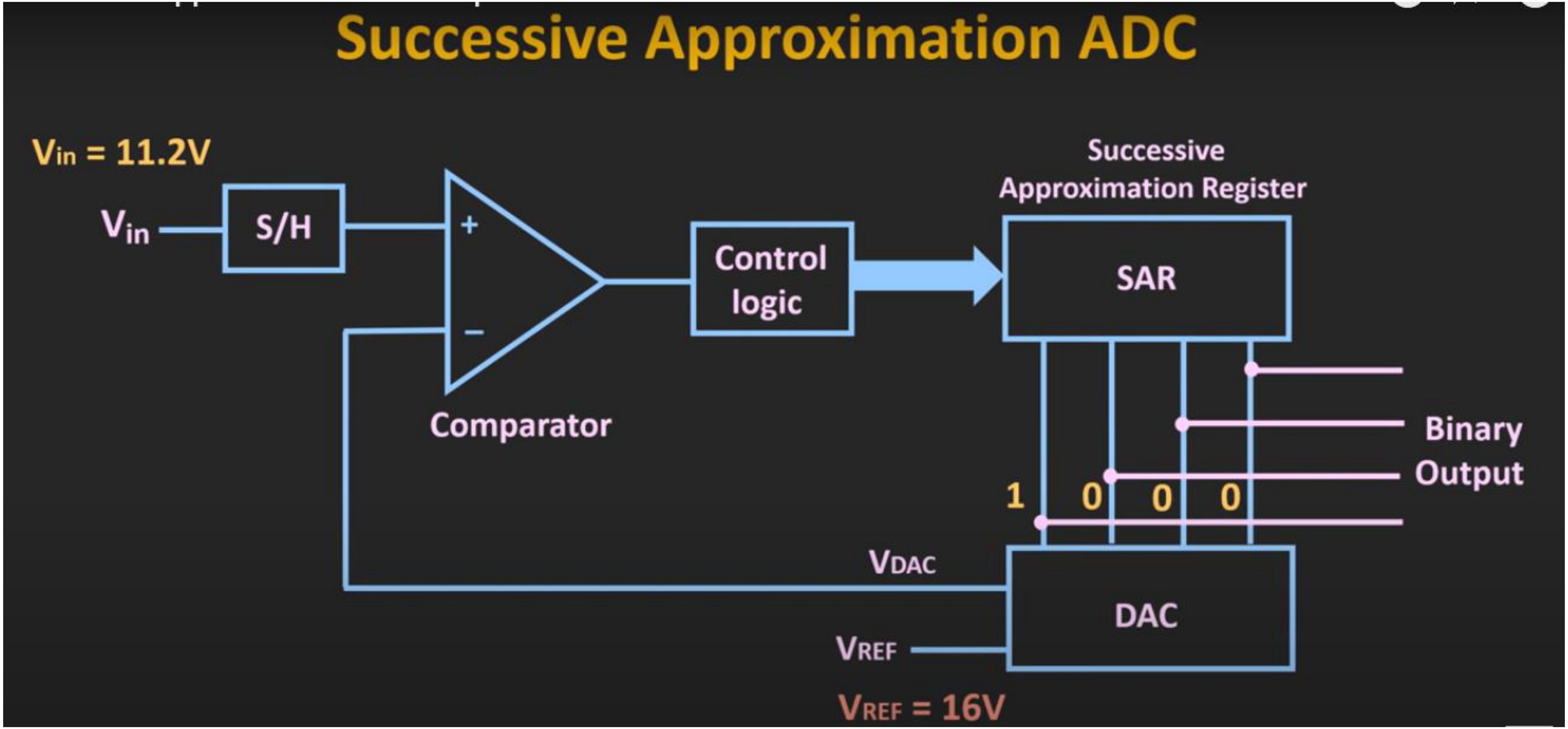
Maximum Conversion Time :

$$T_c\,(max) = (2^N - 1)\,T_{CLK}$$

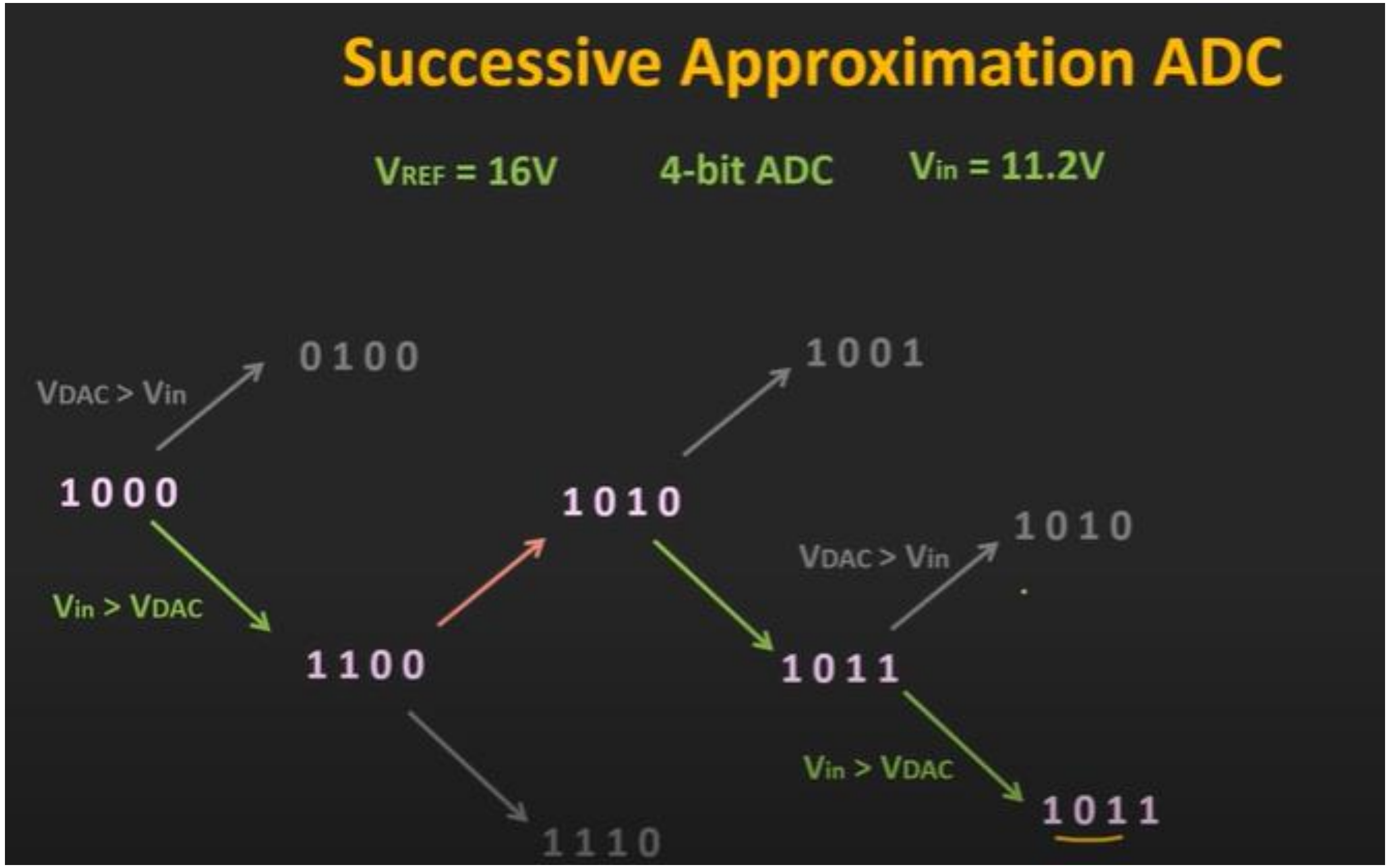
T_{CLK} : Duration of the clock pulse

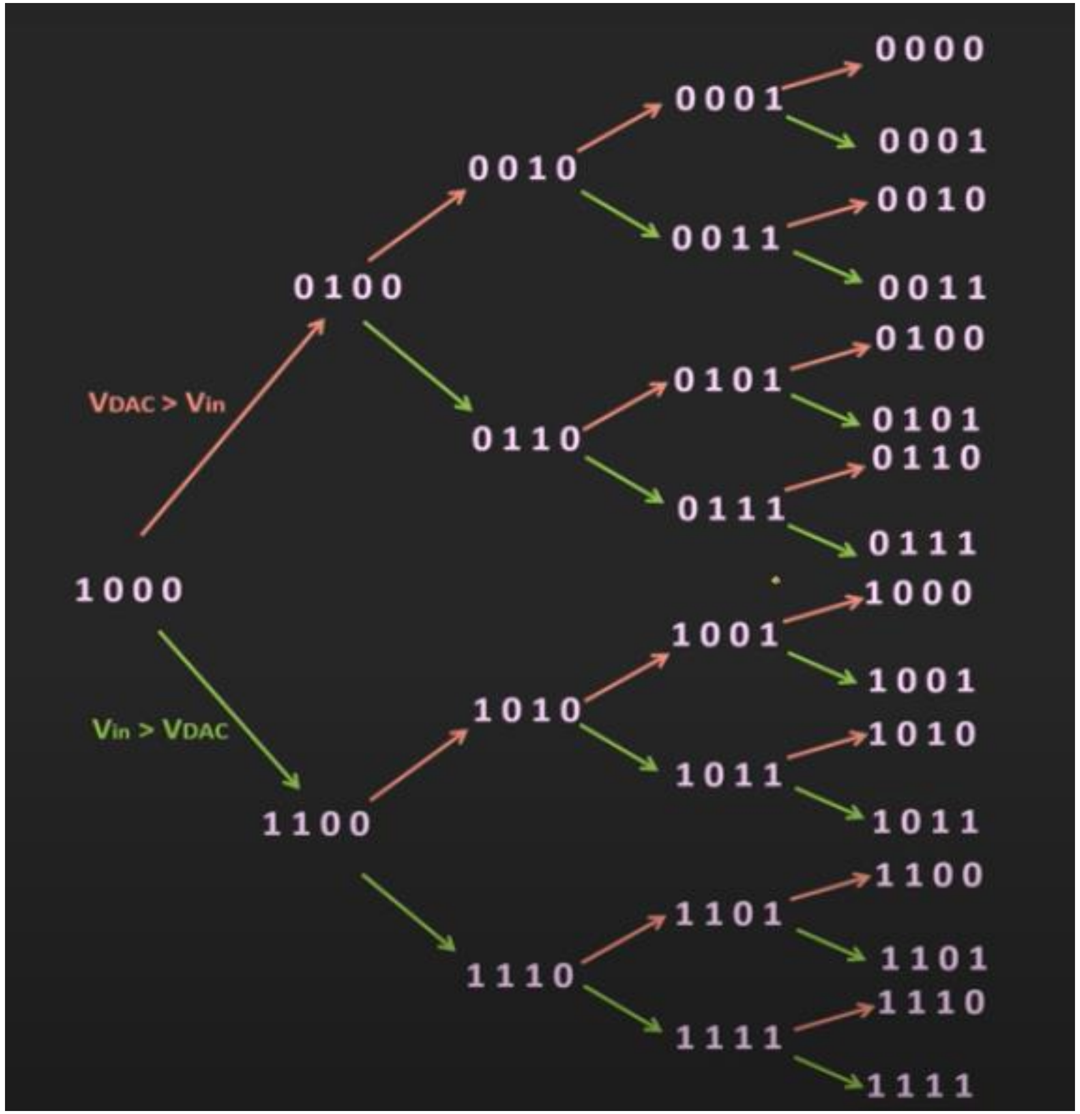
N : Number of bits of ADC

Successive Approximation ADC

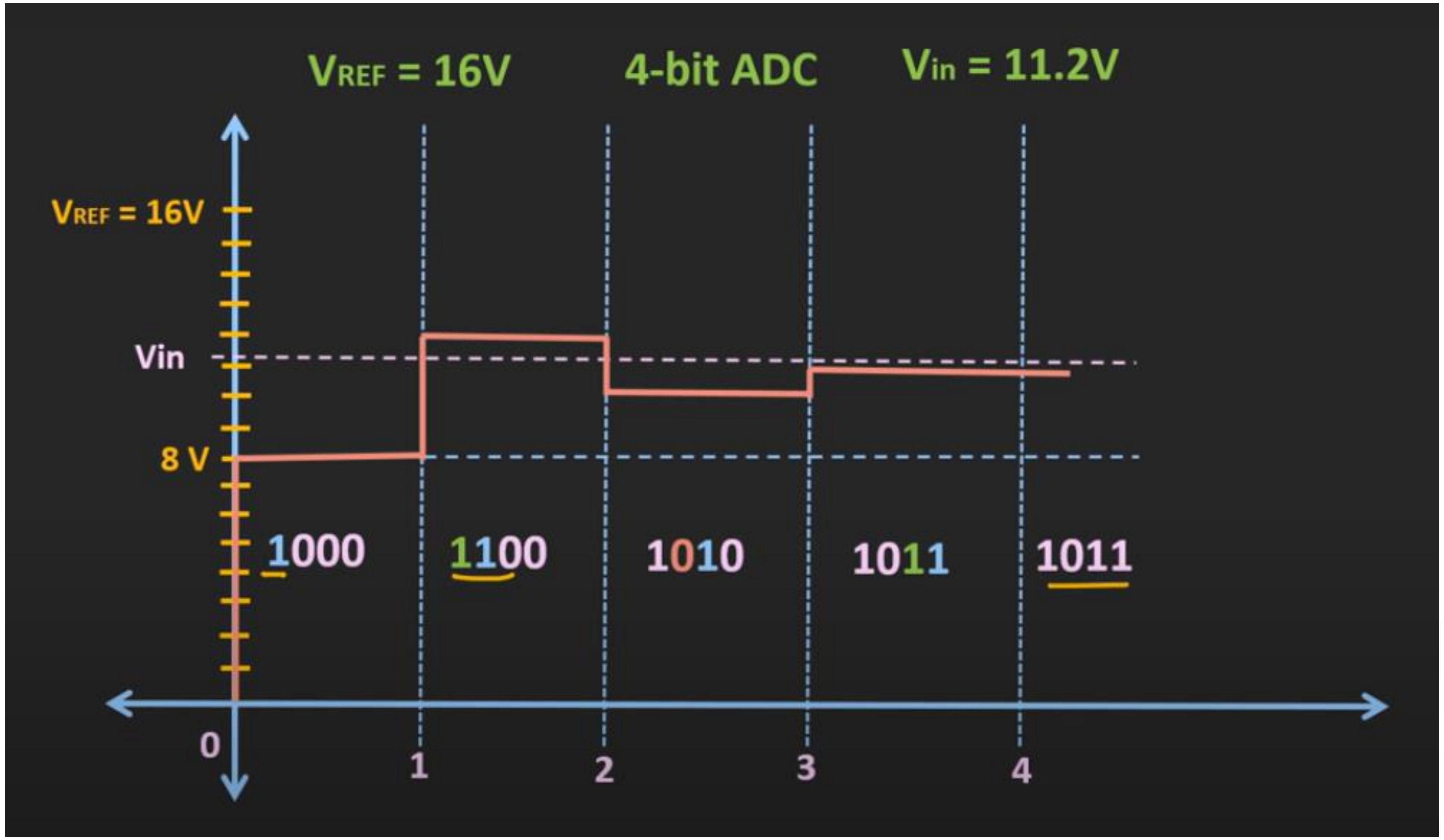


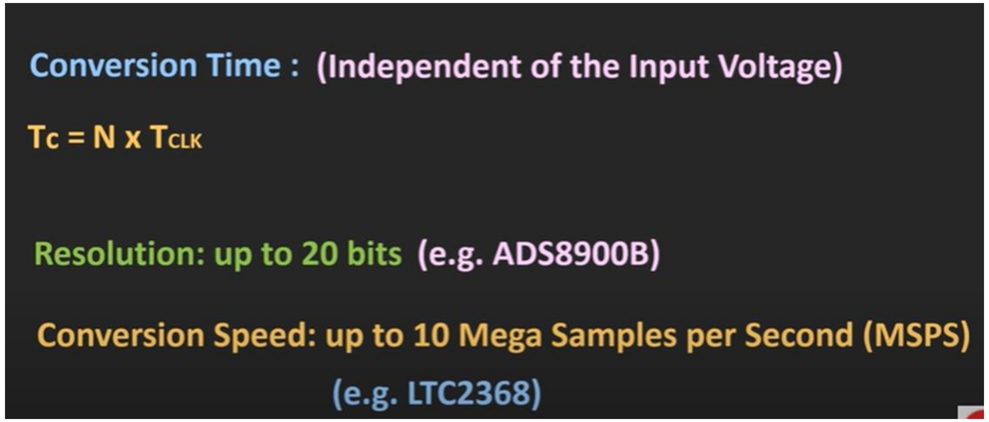
Successive Approximation ADC





Successive Approximation ADC





Continuous Servo balancing potentiometer type DVM

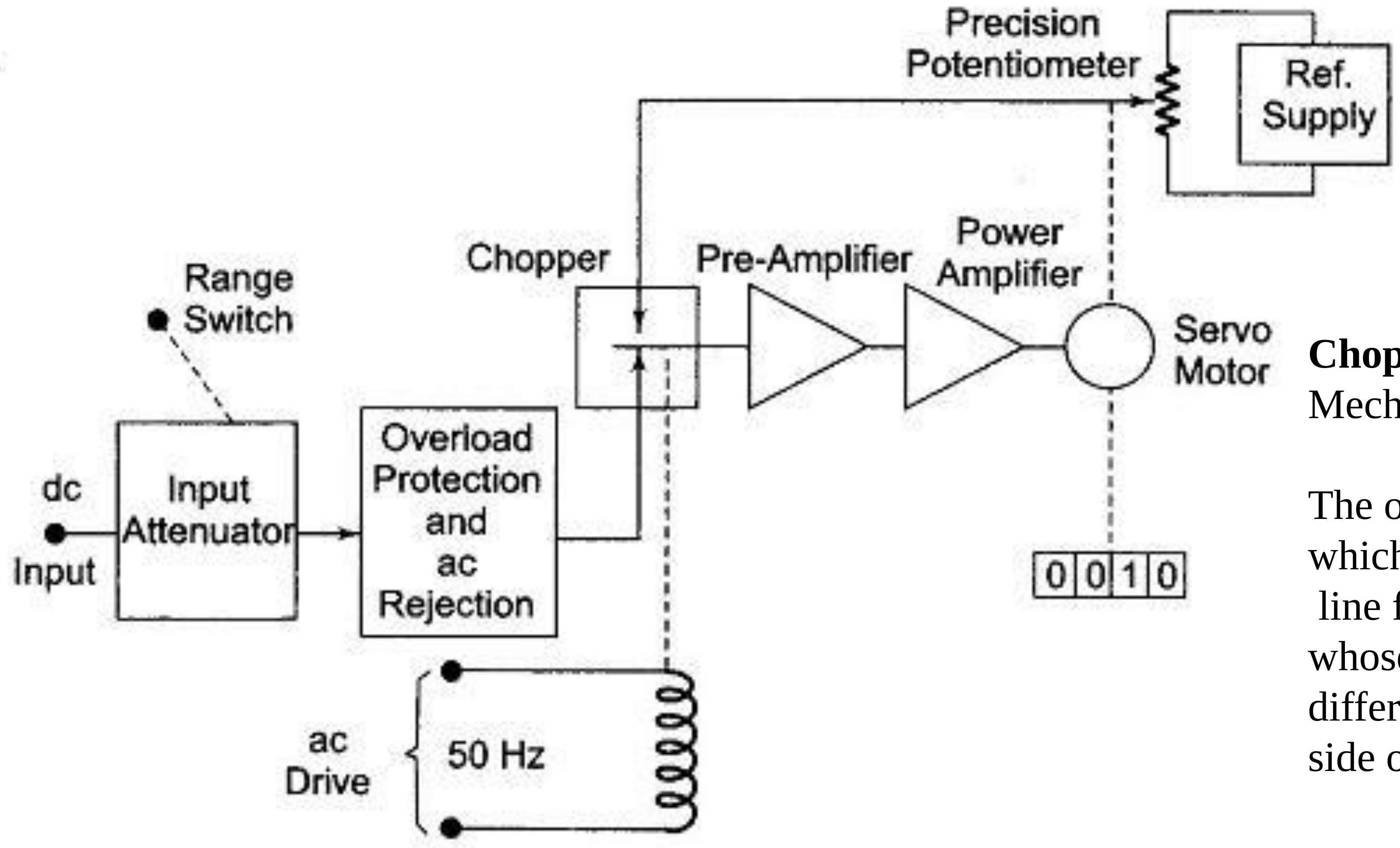
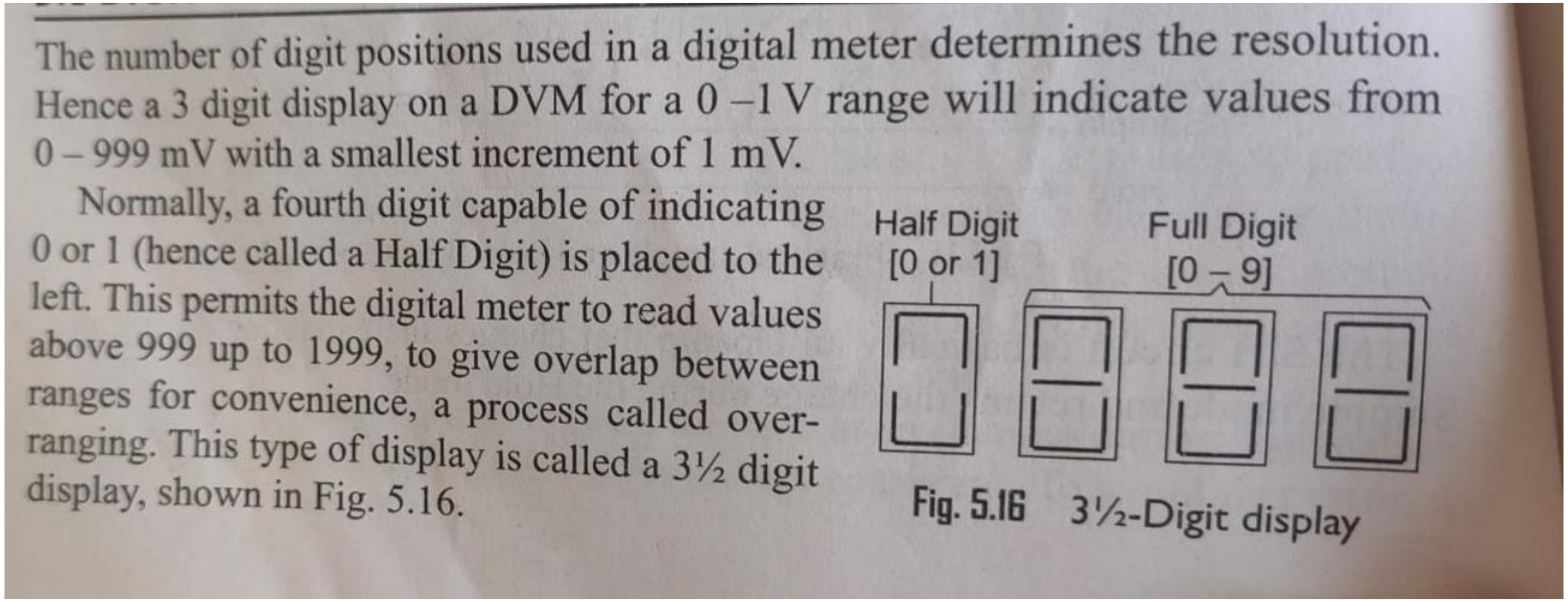


Fig. 5.15 Block Diagram of a Servo Balancing Potentiometer Type DVM

Chopper
Mechanical Comparator

The output of the chopper comparator, which is driven by the line voltage at the line frequency rate , is a square wave signal whose amplitude is a function of the difference in voltages connected to the opposite side of the chopper

3 ½ digit



The number of digit positions used in a digital meter determines the resolution. Hence a 3 digit display on a DVM for a 0 –1 V range will indicate values from 0 – 999 mV with a smallest increment of 1 mV.

Normally, a fourth digit capable of indicating 0 or 1 (hence called a Half Digit) is placed to the left. This permits the digital meter to read values above 999 up to 1999, to give overlap between ranges for convenience, a process called over-ranging. This type of display is called a 3½ digit display, shown in Fig. 5.16.

Fig. 5.16 3½-Digit display

3 ½ digit Resolution and sensitivity of digital meters

RESOLUTION AND SENSITIVITY OF DIGITAL METERS 5.9

Resolution If n = number of full digits, then resolution (R) is $1/10^n$.

The resolution of a DVM is determined by the number of full or active digits used,

If $n = 3$,
$$R = \frac{1}{10^n} = \frac{1}{10^3} = 0.001 \text{ or } 0.1\,\%$$

Sensitivity of Digital Meters Sensitivity is the smallest change in input which a digital meter is able to detect. Hence, it is the full scale value of the lowest voltage range multiplied by the meter's resolution.

$$\text{Sensitivity } S = (fs)_{min} \times R$$

where $(fs)_{min}$ = lowest full scale of the meter
R = resolution expressed as decimal

Example 5.5 *What is the resolution of a 3½ digit display on 1 V and 10 V ranges?*

Solution Number of full digits is 3. Therefore, resolution is $1/10^n$ where $n = 3$.
Resolution $R = 1/10^3 = 1/1000 = 0.001$

Hence the meter cannot distinguish between values that differ from each other by less than 0.001 of full scale.

For full scale range reading of 1 V, the resolution is $1 \times 0.001 = 0.001$ V.

For full scale reading of 10 V range, the resolution is $10 \text{ V} \times 0.001 = 0.01$ V.

Hence on 10 V scale, the meter cannot distinguish between readings that differ by less than 0.01 V.

Example 5.6 *A 4½ digit voltmeter is used for voltage measurements.*

(i) Find its resolution
(ii) How would 12.98 V be displayed on a 10 V range?
(iii) How would 0.6973 be displayed on 1 V and 10 V ranges.

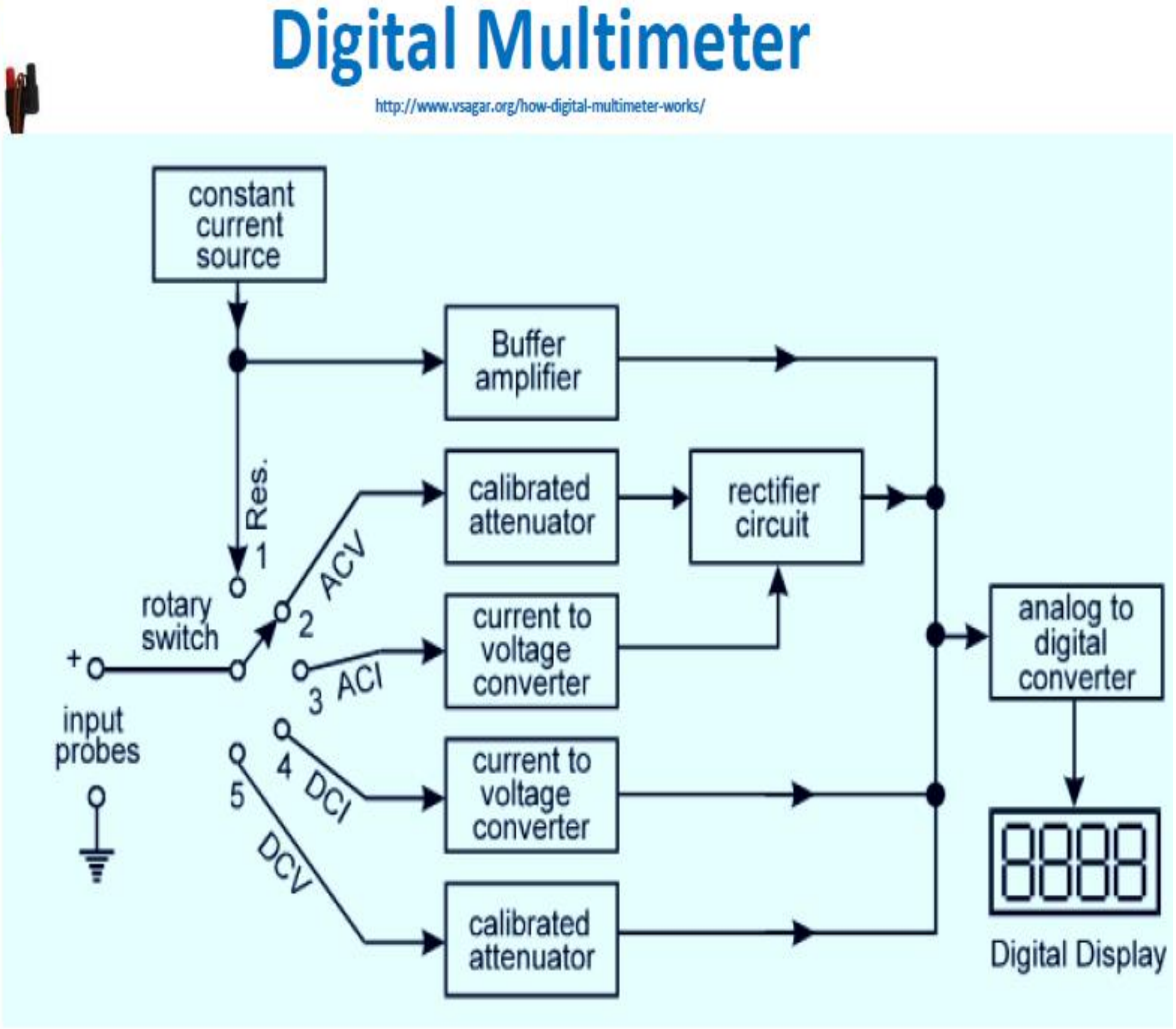
Solution

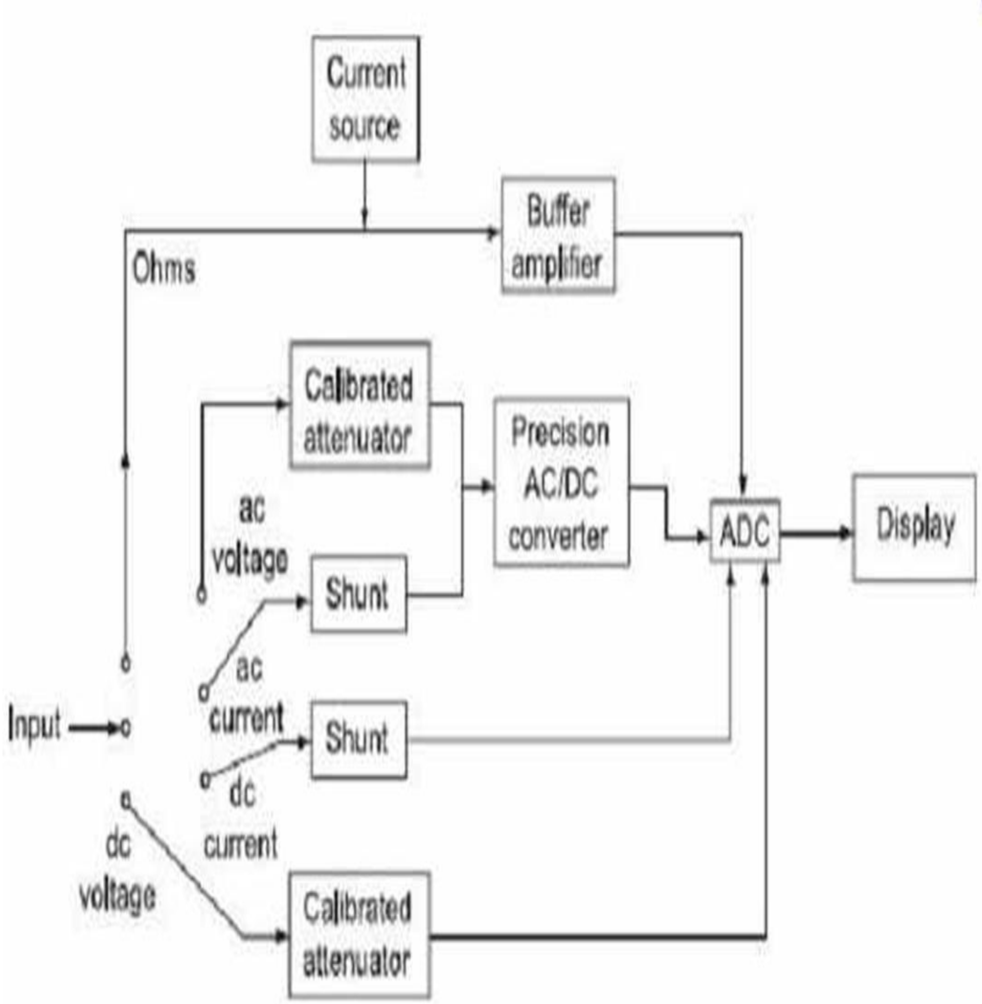
(i) Resolution $= 1/10^n = 1/10^4 = 0.0001$
where the number of full digits is $n = 4$

(ii) There are 5 digit places in 4½ digits, therefore 12.98 would be displayed as 12.980.
Resolution on 1 V range is $1 \text{ V} \times 0.0001 = 0.0001$
Any reading up to the 4th decimal can be displayed.
Hence 0.6973 will be displayed as 0.6973.

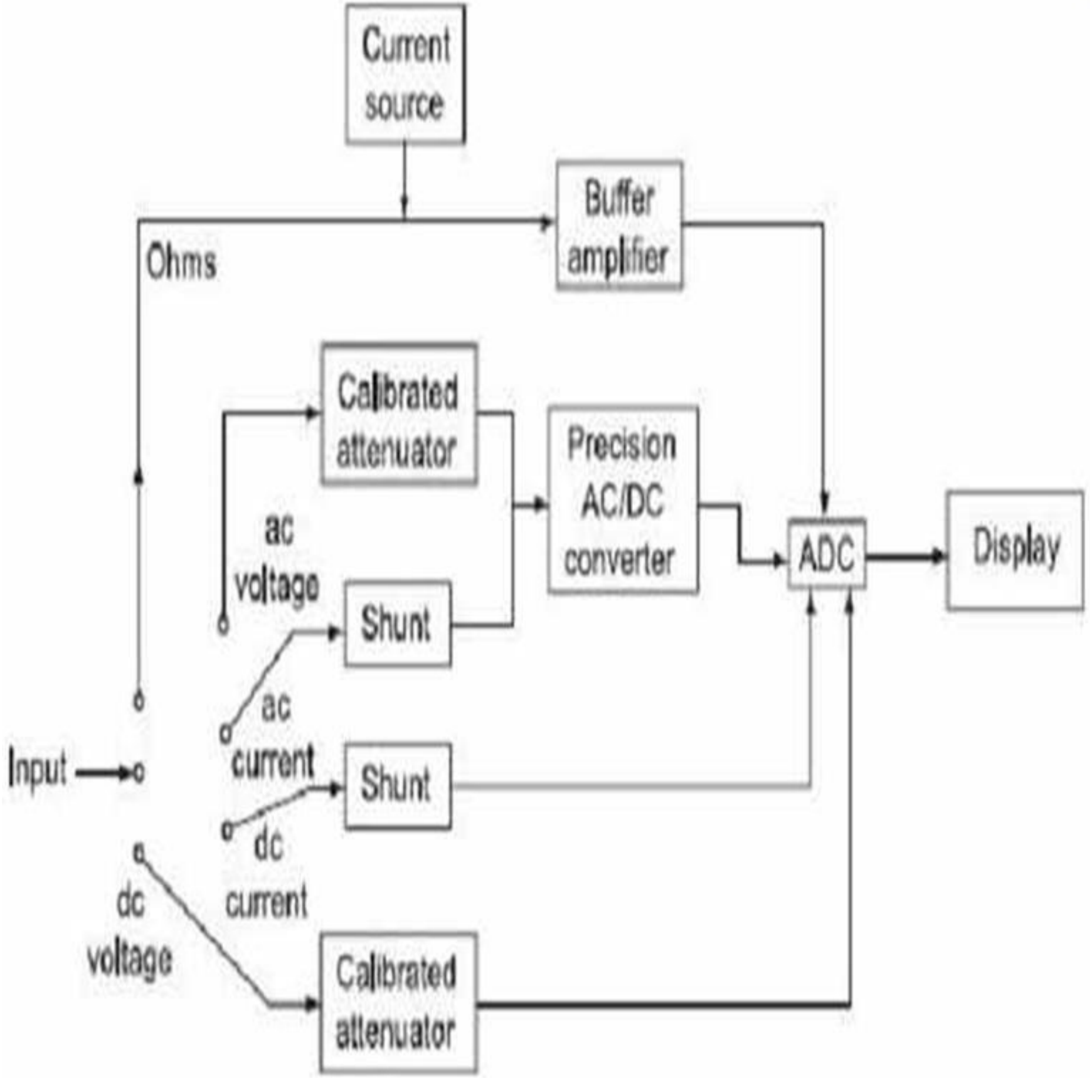
(iii) Resolution on 10 V range $= 10 \text{ V} \times 0.0001 = 0.001$ V
Hence decimals up to the 3rd decimal place can be displayed.

Digital Multimeter





Digital Multimeter function



Digital meters

Panel meters-fixed or at one location
Bench meter and System meters are often multimeter they can read AC, DC voltage, current and resistance over several range

Panel meters

They have a readout range from the basic 3 digit (999 counts, accuracy of ± 0.1% of reading, ± 1 count) to high precision 4 3/4 digit ones (± 39,999 counts, accuracy ± 0.005% of reading ± 1 count).

Units are available to accept inputs such as dc voltage (from microvolts range to ± 20 volts) ac voltage (for true rms measurement), line voltage, strain gauge bridges (meter provides bridge excitation), RTDs (meter provides sensor excitation), thermocouples of many types (meter provides cold junction compensation and linearisation) and frequency inputs, such as pulse tachometers.

Panel meters block diagram

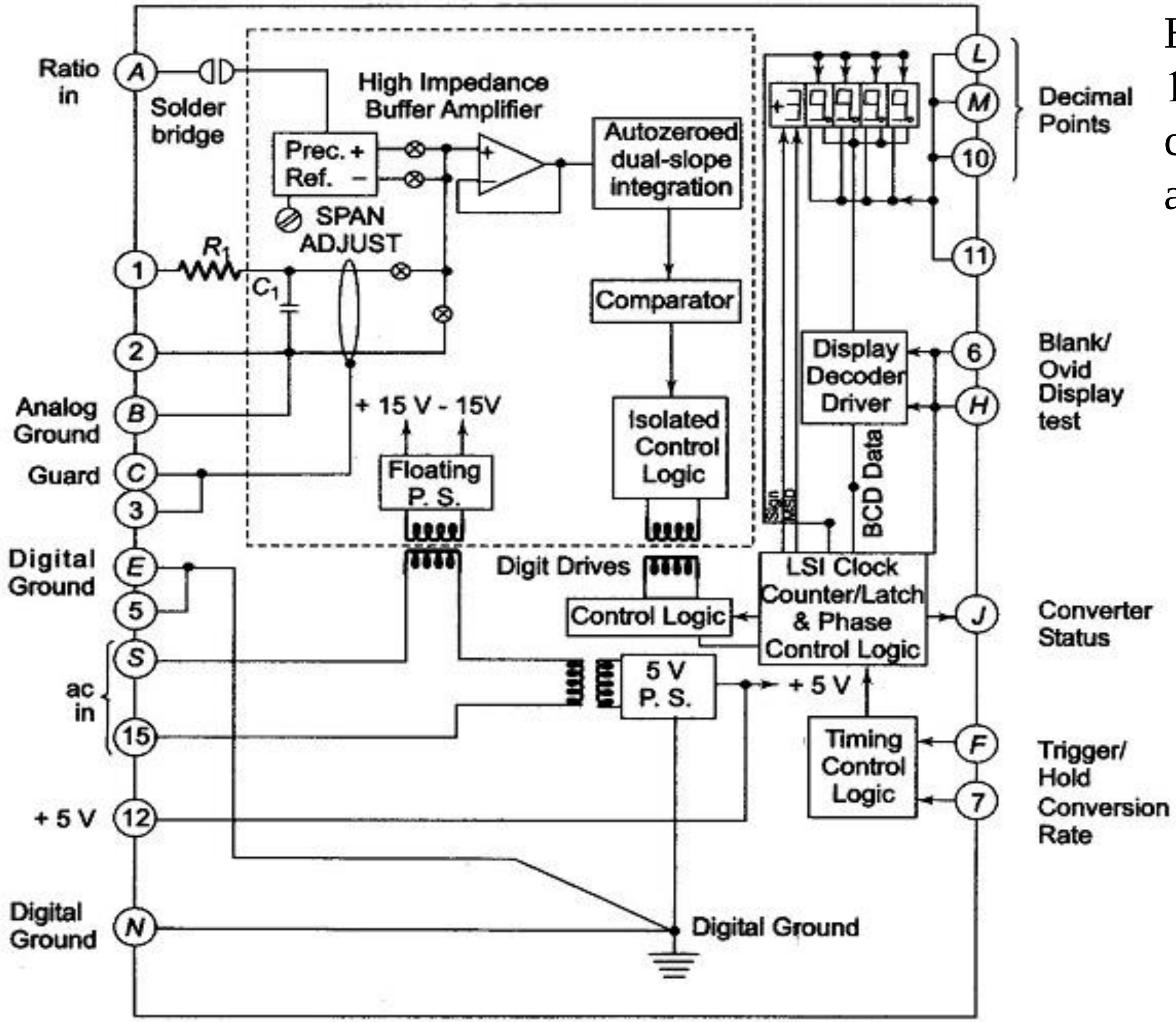


Fig. 6.3 High Precision Digital Panel Meter

High precision Digital Panel Meter unit with an input resistance of 109 Ω, ± 0.00250% resolution (10 and ± 0.005% of reading ± 1 count accuracy, which uses a dual slope A/D conversion with automatic zero.

The sampling rate is 2.5 per second when it is free running and a maximum of 10 per second when it is externally triggered.

These meters can be obtained with a tri-state binary coded decimal output. Tri-state outputs provide a high impedance (disconnected) state, in addition to the usual digital high and low

This facilitates interconnection with the microcomputer data buses, since any number of devices can be serviced by a single bus, one at a time, disconnecting all except the two that are communicating with each other.

Panel meters

Bench Type Meters

Bench type meters range from inexpensive hand held units with a 31/2 digit readout and 0.5% accuracy, to 51/2 digit (200,000 count) devices with 1 μV resolution.

Digital nanovoltmeters are designed to measure extremely low voltages and they provide resolution down to about 10 nV (comparable analog meters go to about 1 nV).

Digital picoammeters measure very small currents and can resolve about 1 pA (analog instruments go to 3 femto (10-15) amperes). When extremely high input impedance is required for current, voltage, resistance or charge measurements, an electrometer type of instrument is employed.

Bench Type Meters

System Type Meters

System type DVMs or DMMs are designed to provide the basic A/D conversion function in data systems assembled by interfacing various peripheral devices with DVM capabilities and their cost vary widely.

A microprocessor is used to provide several mathematical functions in addition to managing the meter operations. A modified dual slope A/D converter is used with selectable integration times, ranging from 0.01 to 100 power lines cycle.

At maximum speed (330 readings per second) accuracy is ± 0.1%, while 0.57 readings per second gives a 61/2 digit resolution and 0.001% accuracy. Ac and dc voltages and resistance modes are available. The mathematical functions include the following.

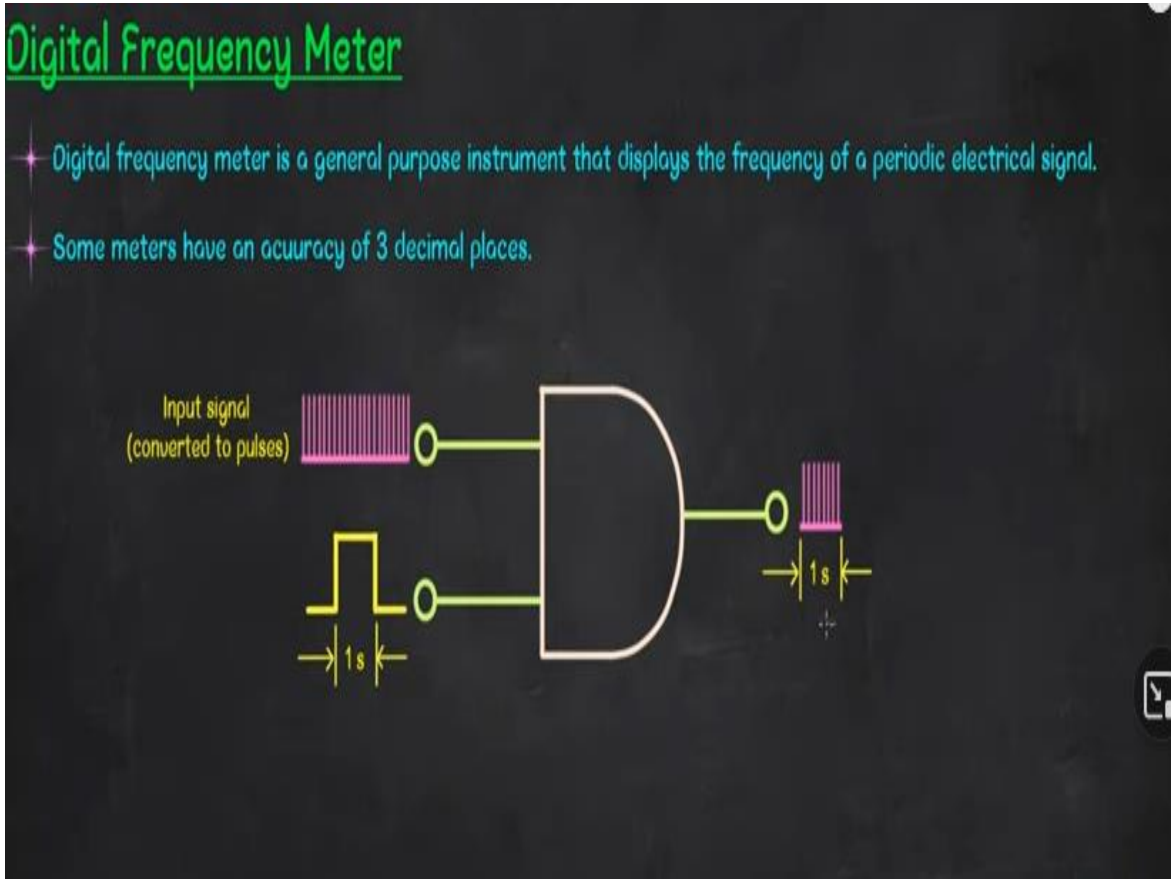
System Type Meters

1.Null
2.First reading is subtracted from each successive reading and the difference is displayed. (The first reading can be manually entered from the key-board.)
3.The function STAT accumulates reading and calculates mean and variance, (STAT-Statistics).
4.With dBm (R), the user enters the resistance and then all readings are displayed as power dissipated in R in decibel units (referred to 1 mV).
5.With THMS°F (voltmeter in ohms range), the temperature of a thermistor probe is displayed in degrees Fahrenheit or Centigrade (THMS -Temperature of Thermistor)
6.The function (X – Z)/Y provides offsetting and scaling with user entered Z and Y constants (where X is the reading).

The function 100 x (X – Y)/Y determines the percentage deviation, and 20 log X/Y displays X in decibels relative to the value of Y. An internal memory (RAM) can be used to store the results of measurements and programs for taking the measurements.

System Type Meters

Digital Frequency Meter



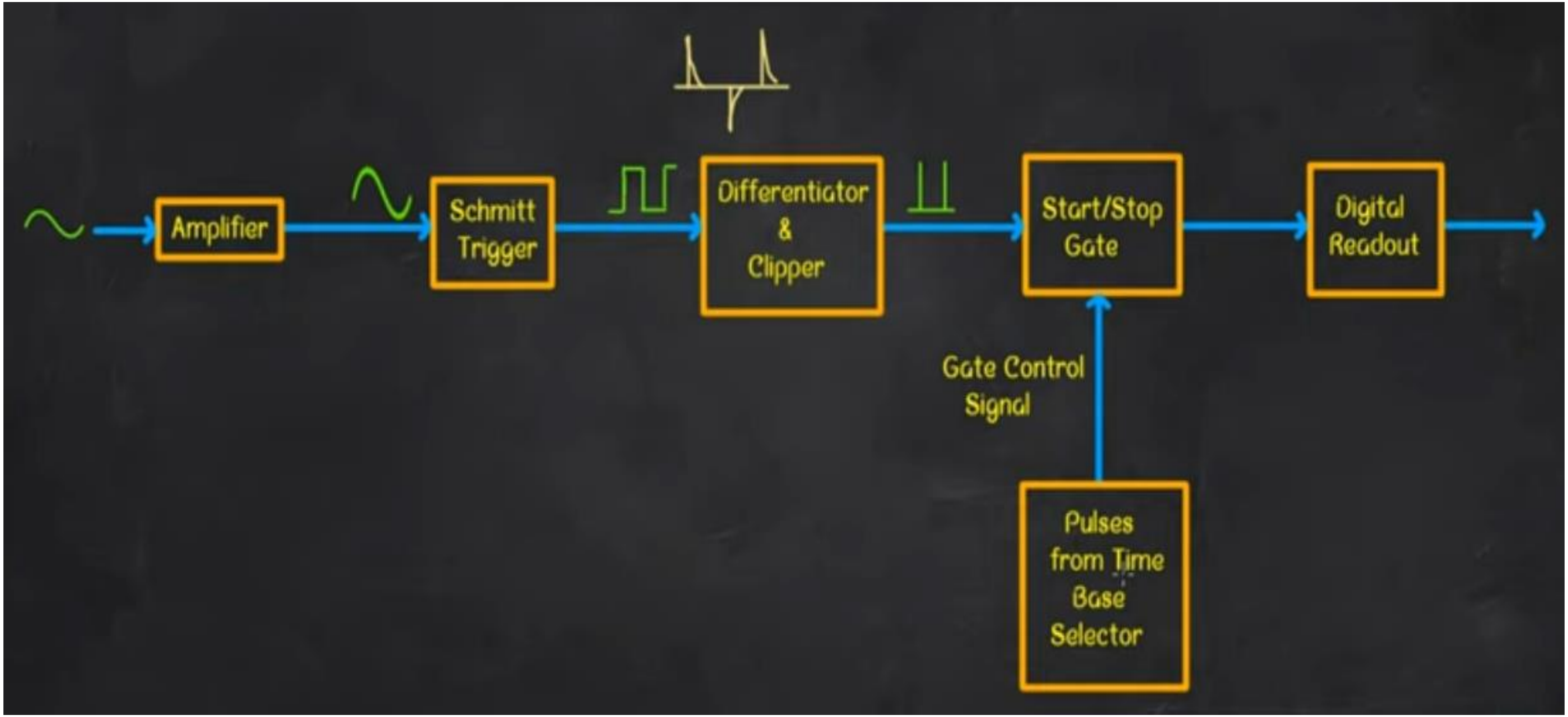
AND gate

- The signal whose frequency is to be measured is converted into train of pulse , one pulse for each cycle of the signal

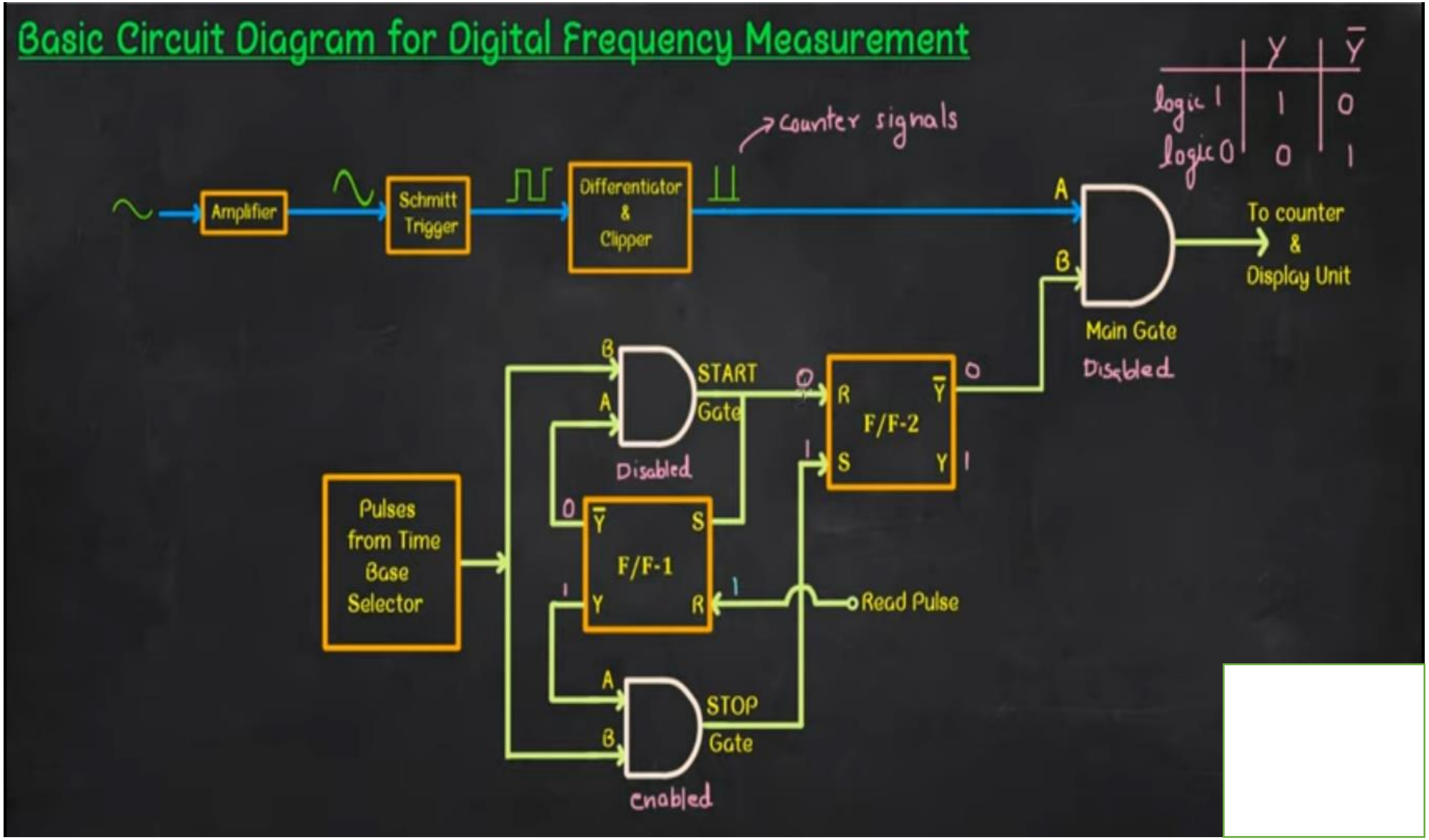
- The number of pulses occurring in a definite interval of time is then counted by an electronics counter.

- Since each pulse represents the cycle represents the cycle of the unknown signal, the number of counts is a direct indication of the frequency of the signal.

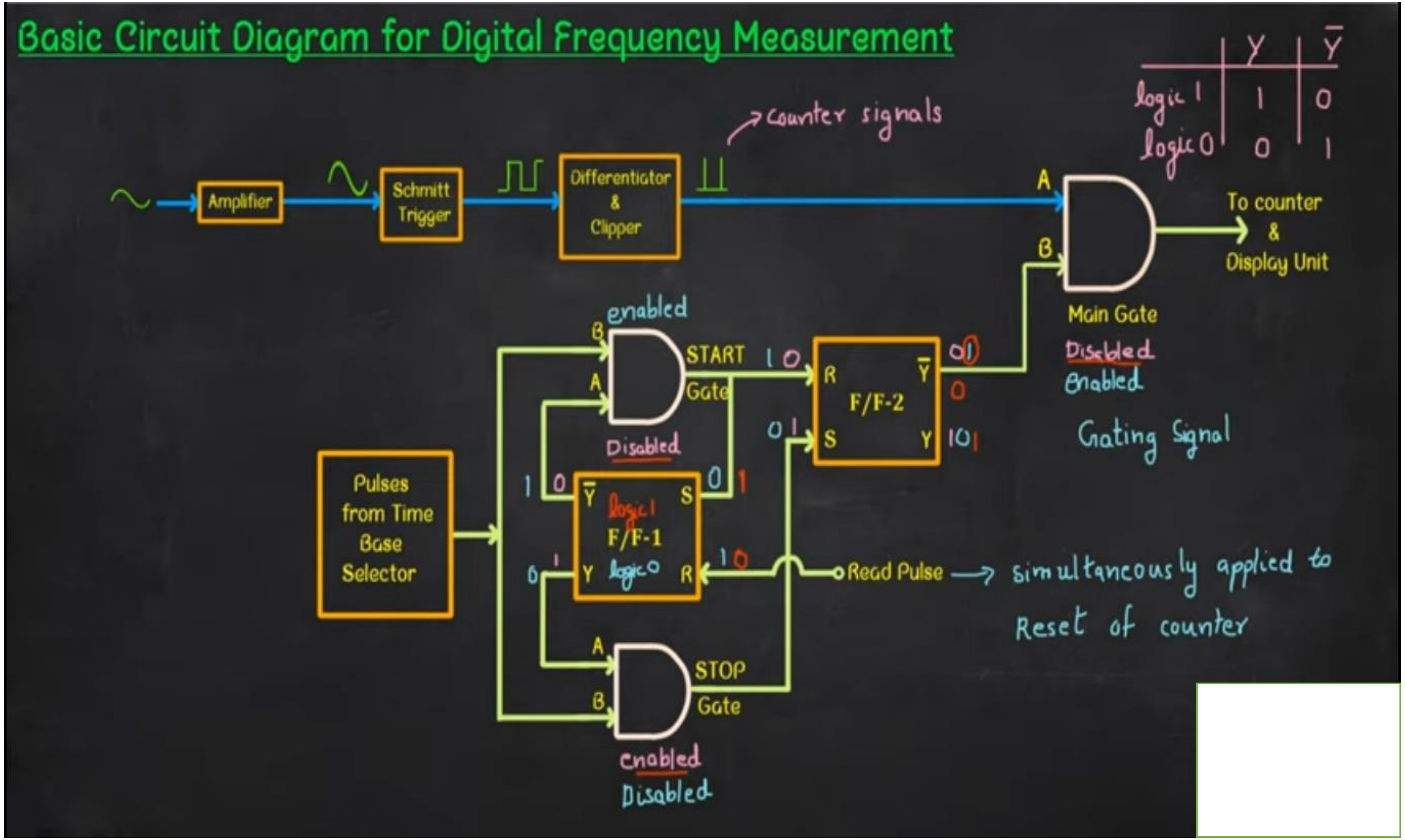
Digital Frequency Meter (Block Diagram)



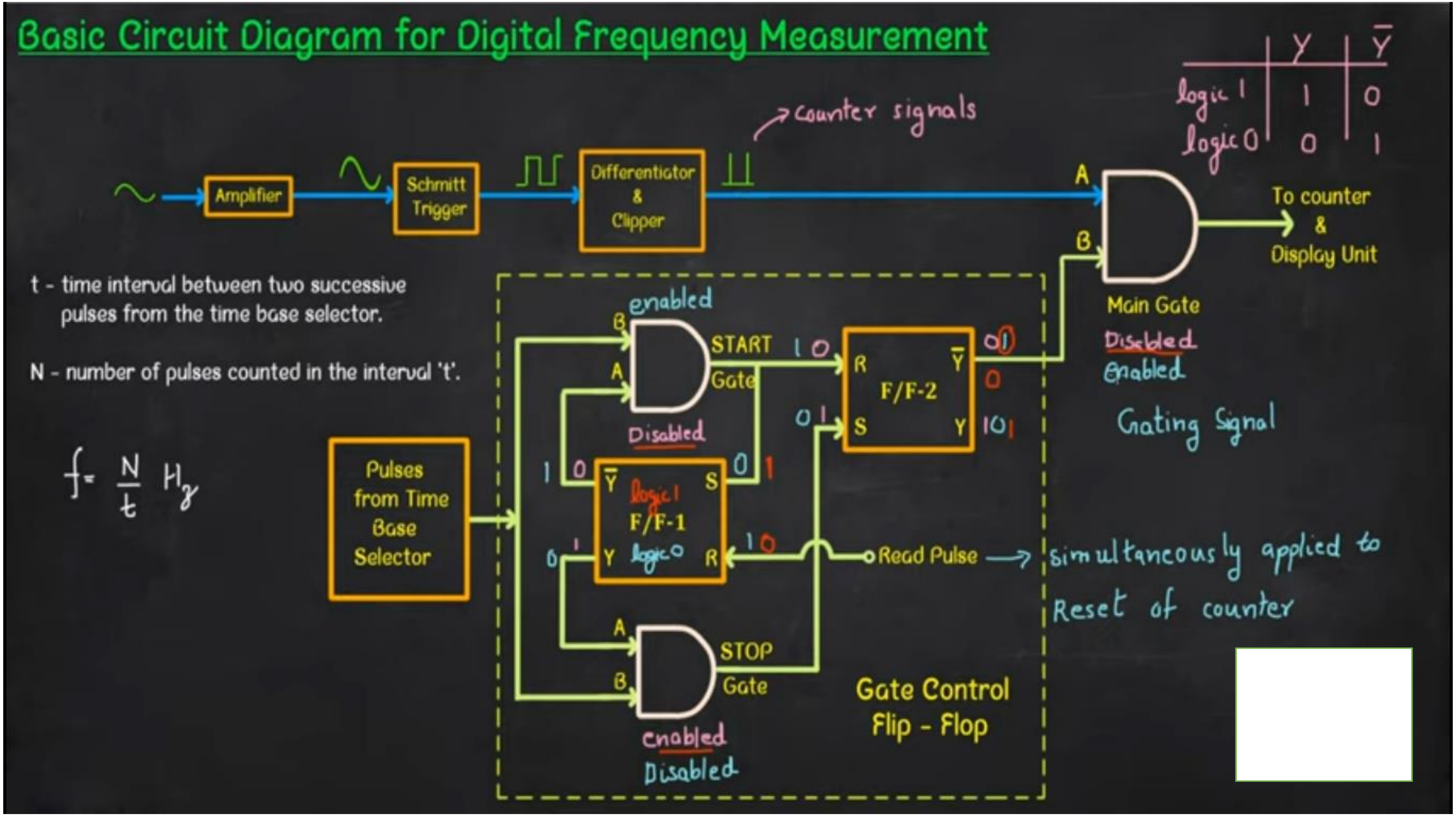
Digital Frequency Meter (Block Diagram)



Digital Frequency Meter (Block Diagram)



Digital Frequency Meter (Block Diagram)



Time base selector

Principle of operation

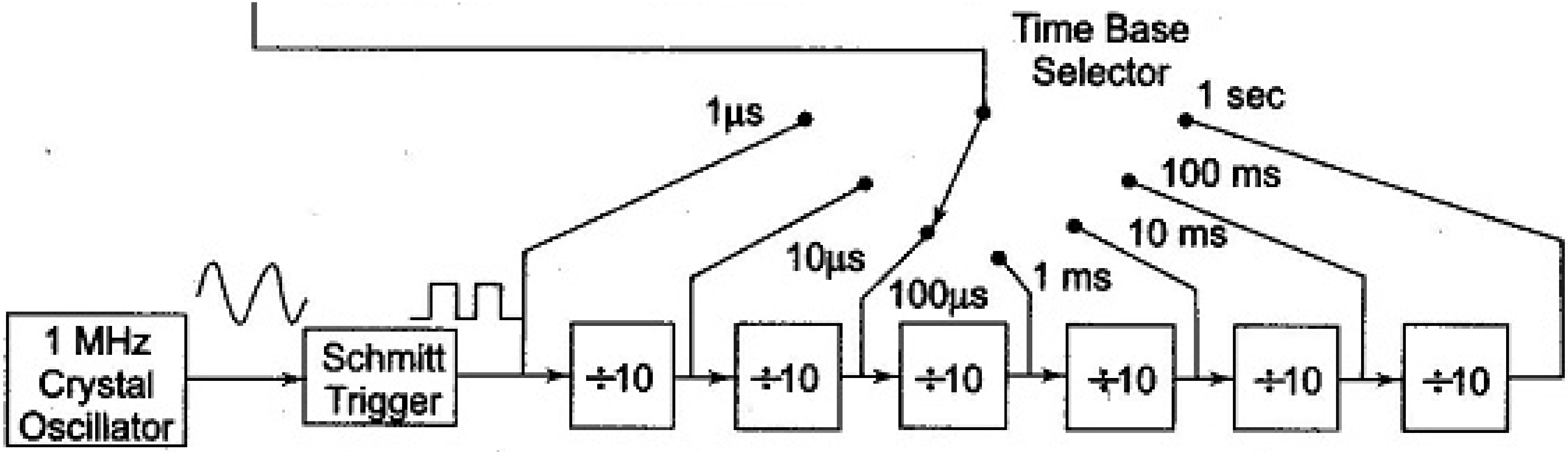
The beginning of the time period is the start pulse originating from input 1, and
the end of the time period is the stop pulse coming from input 2.

The oscillator runs continuously, but the oscillator pulses reach the output only during the period When the control F/F is in the 1 state .

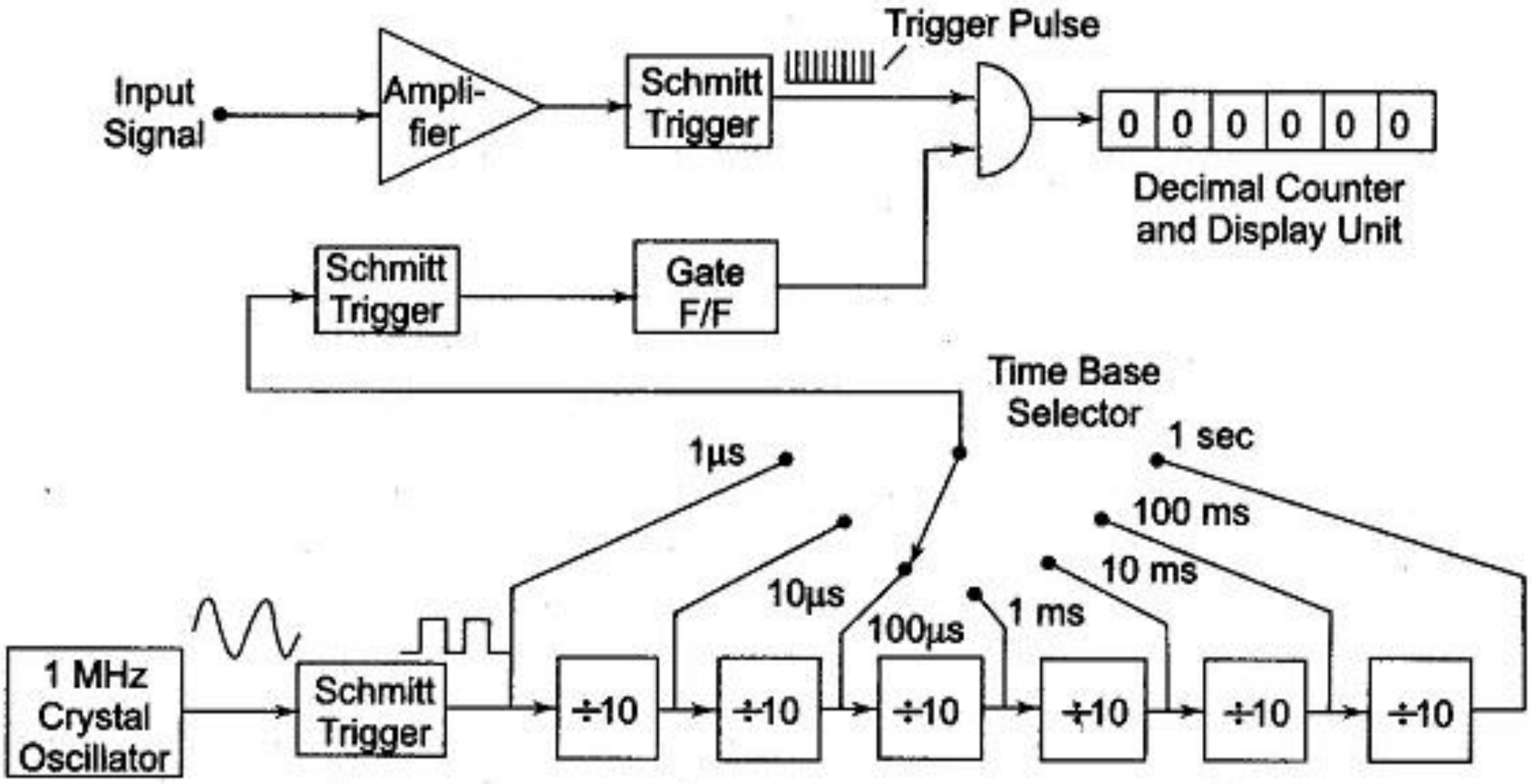
The time interval between the start and stop of the gate must be accurately known. This is called time base.

The time base consist of a fixed frequency crystal oscillator, called a clock oscillator.

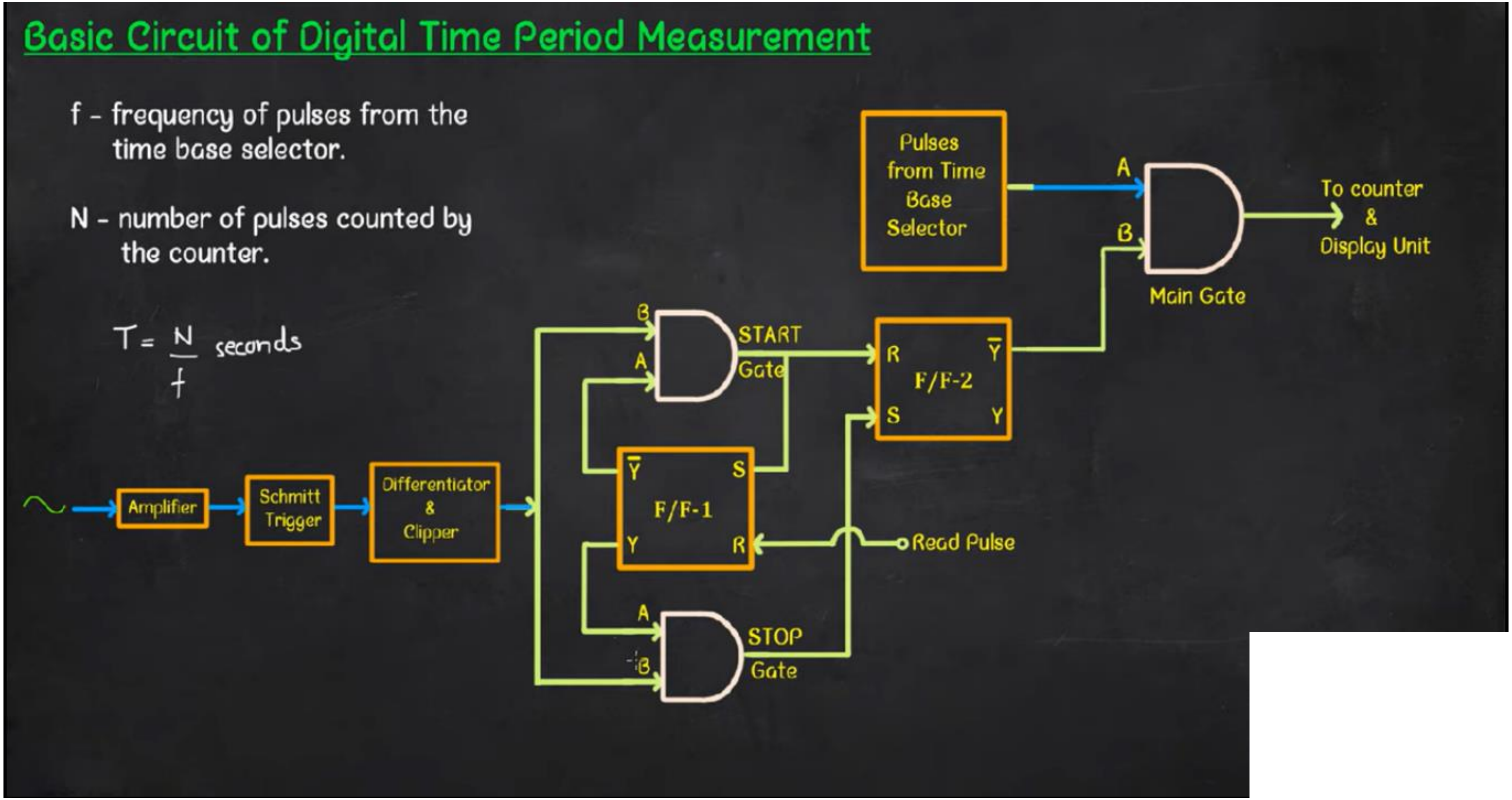
Block diagram for Time base selector



Digital Frequency Meter (Block Diagram)



Digital Time Meter (Block Diagram)



Universal counter