Electronic Instruments

Disadvantages of PMMC voltmeter

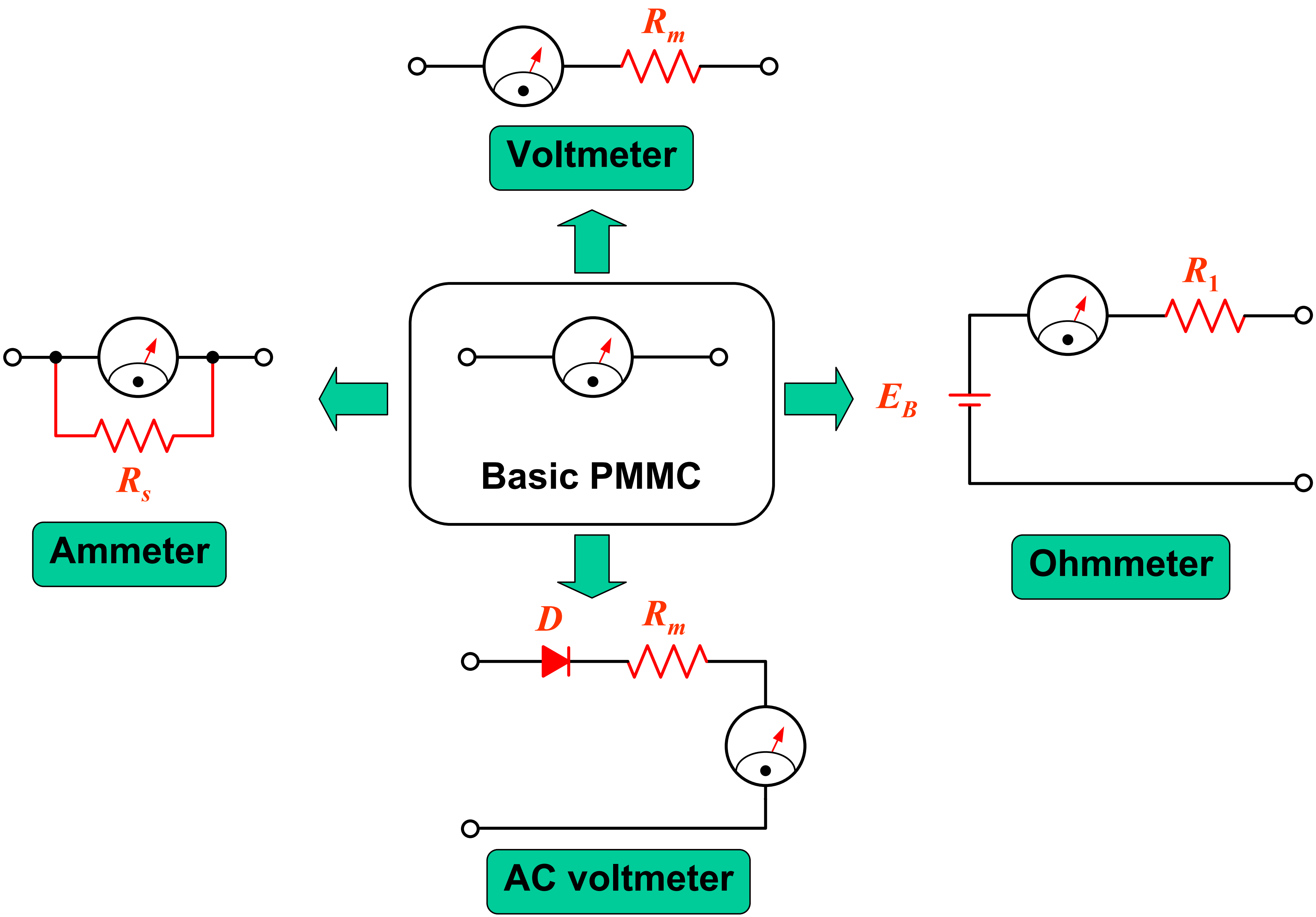
- Low input impedance: Loading effect
- Insufficient sensitivity to detect low level signal

Approach

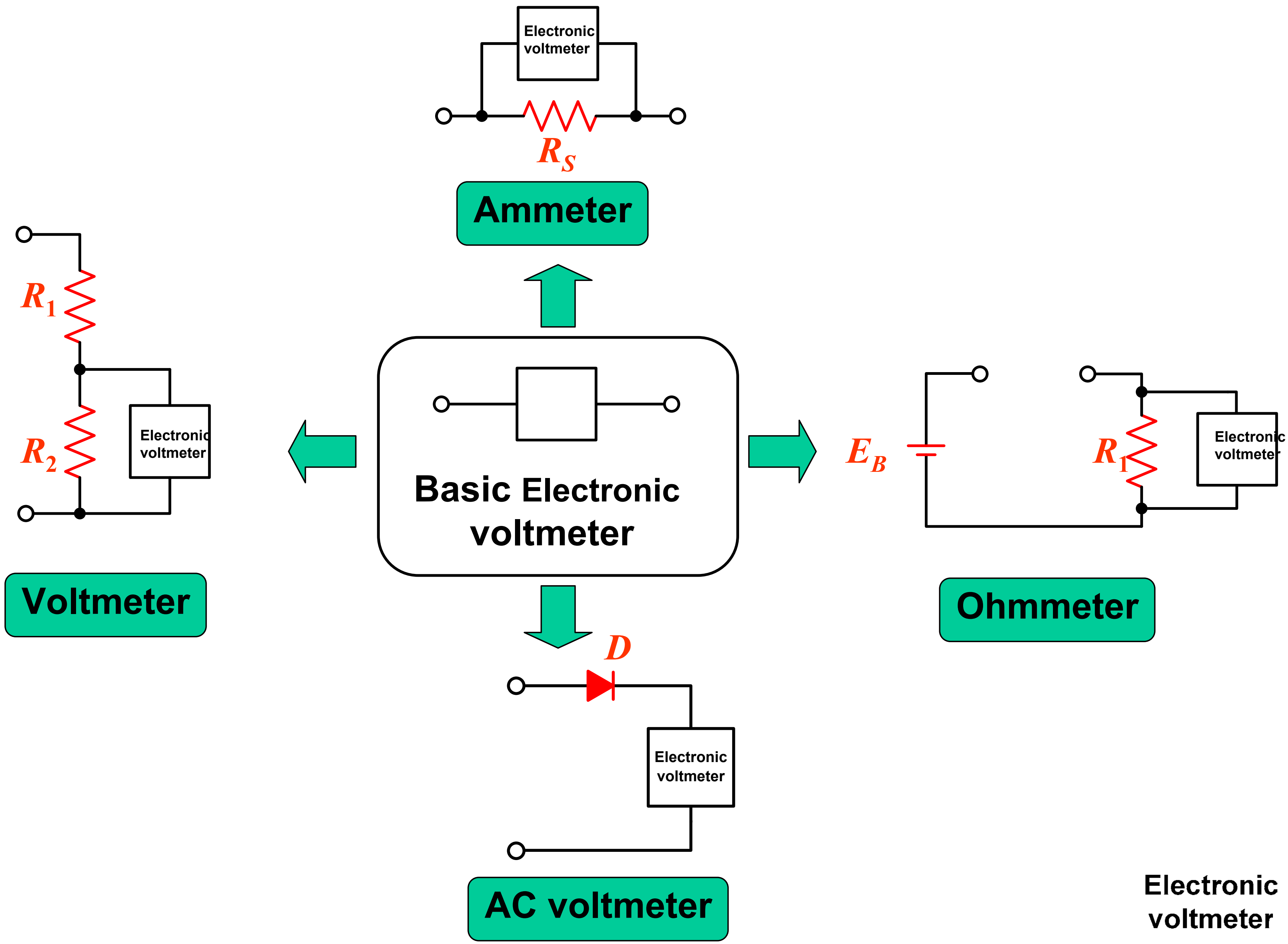
- Utilized electronic devices such as BJT, FET or op amp to solve the above problems

Electronic voltmeters

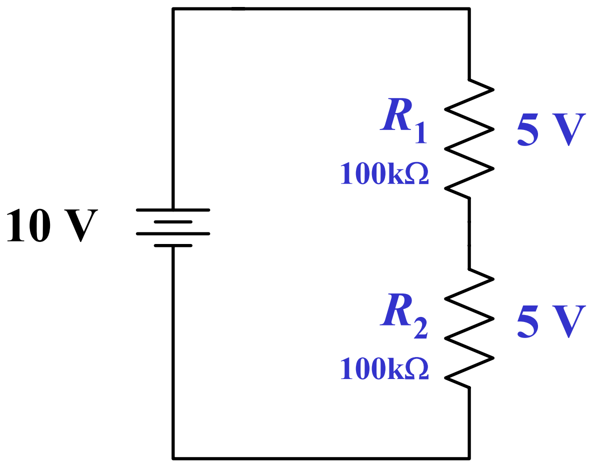
- Analog instrument
- Digital instrument



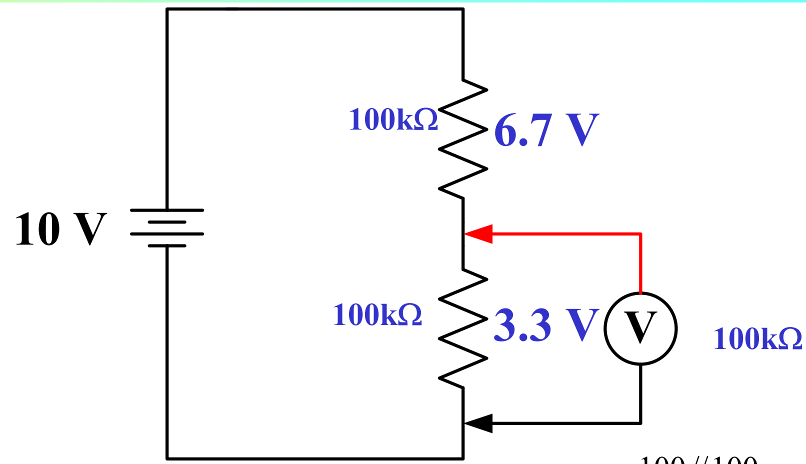
Rm
Voltmeter
R1
Rs
Basic PMMC
EB
Ammeter
Ohmmeter
D
Rm
AC voltmeter


Electronic voltmeter
R_S
Ammeter
R_1
R_2
Electronic voltmeter
Voltmeter
Basic Electronic voltmeter
E_B
R_1
Electronic voltmeter
Ohmmeter
D
Electronic voltmeter
AC voltmeter

Loading Effect

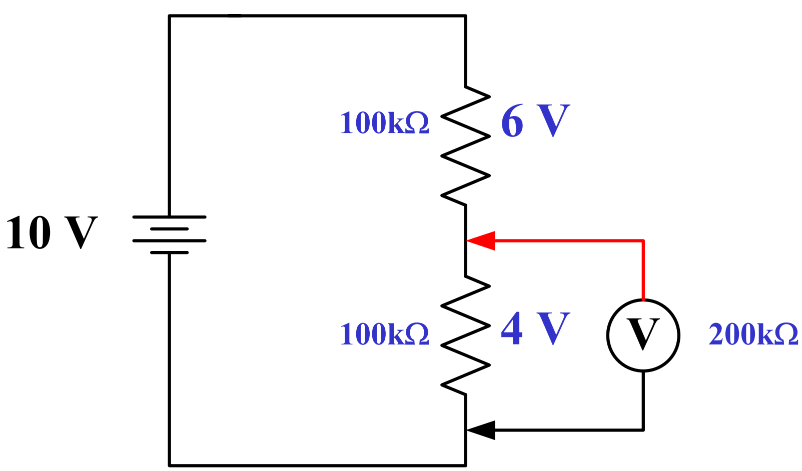


Circuit before measurement

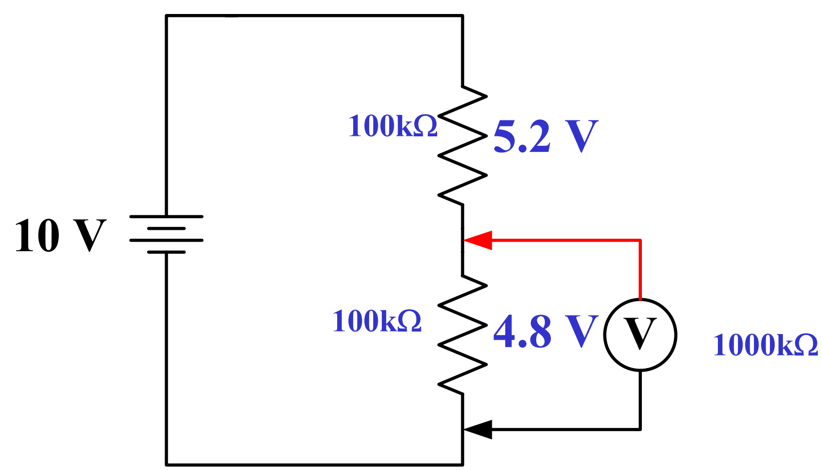


$$V_{meas} = \frac{100 // 100}{100 + 100 // 100} 10 \text{ V} = 3.3 \text{ V}$$

Circuit under measurement



$$V_{meas} = \frac{200 // 100}{100 + 200 // 100} 10 \text{ V} = 4.0 \text{ V}$$

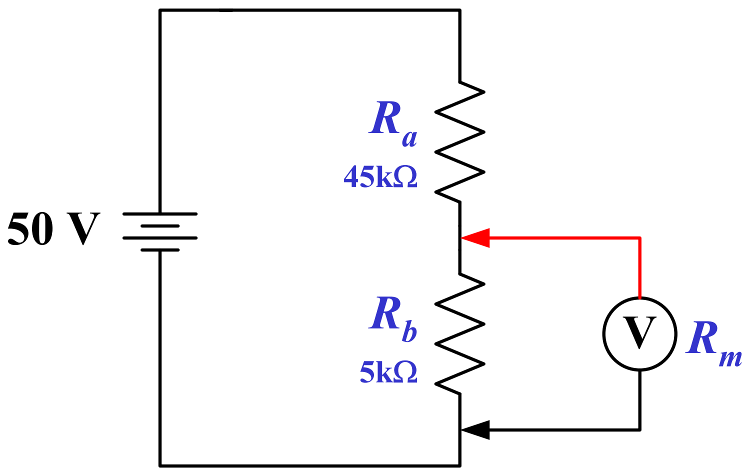


$$V_{meas} = \frac{1000 // 100}{100 + 1000 // 100} 10 \text{ V} = 4.8 \text{ V}$$

Loading Effect

Example Find the voltage reading and % error of each reading obtained with a voltmeter on (i) 5 V range, (ii) 10 V range and (iii) 30 V range, if the instrument has a 20 kΩ/V sensitivity, an accuracy 1% of full scale deflection and the meter is connected across R_b

SOLUTION The voltage drop across R_b with output to the voltmeter connection

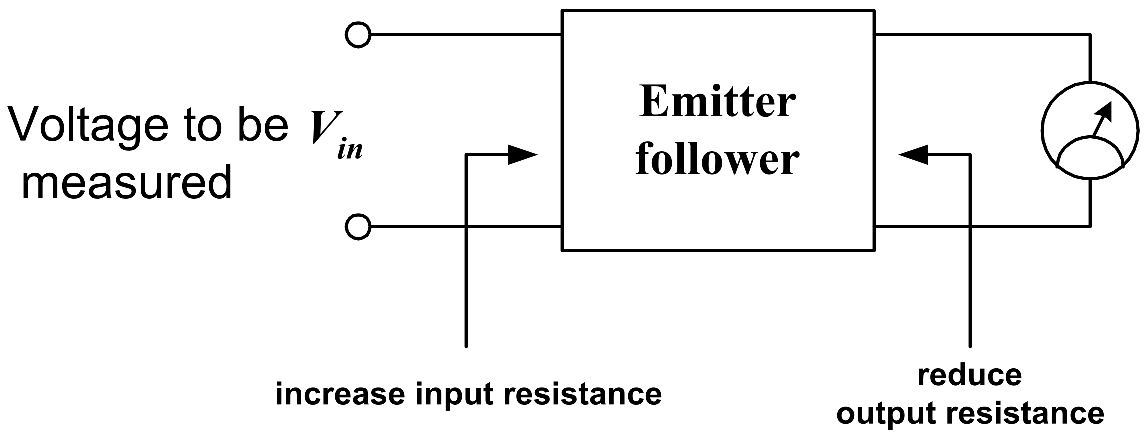


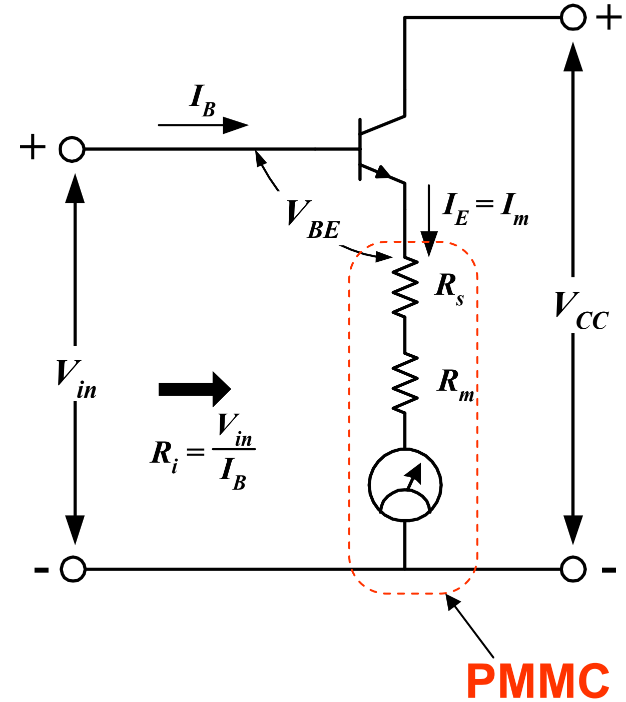
Loading Effect

Range (V)	V_b. (V)	Loading error (V)	Meter error (V)	Total error (V)	% error
5	4.78	-0.22	± 0.05	± 0.27	± 5.36
10	4.88	-0.12	± 0.1	± 0.22	± 4.40
30	4.95	-0.05	± 0.3	± 0.35	± 6.10

Transistor Voltmeter: Emitter Follower

Basic concept





Schematic diagram of emitter follower

Voltage drop across meter: $V_m = V_{in} - V_{BE}$

where V_{BE} is base-emitter voltage ~ 0.7 V for Si

Meter current: $$I_m = \frac{V_{in} - V_{BE}}{R_s + R_m}$$

Transistor base current: $$I_B \approx \frac{I_E}{h_{FE}}$$

h_{FE} = Transistor current gain (Typical values ~ 100-200

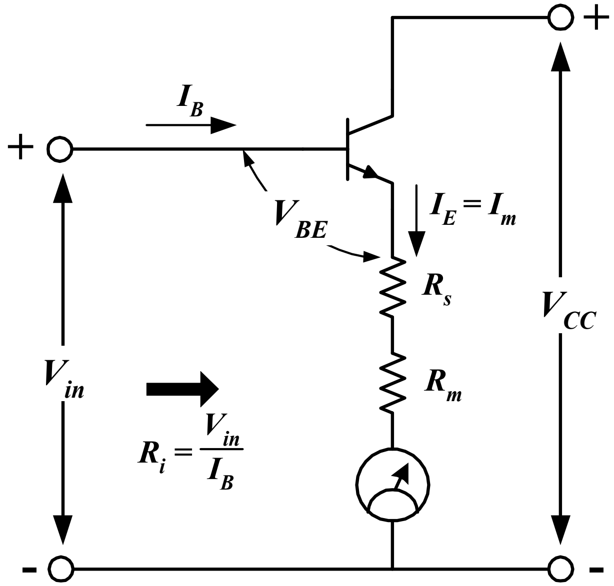
Transistor Voltmeter: Emitter Follower

Circuit input resistance: $$R_i = \frac{V_{in}}{I_B} \approx h_{FE}\frac{V_{in}}{I_E} \approx h_{FE}(R_s + R_m)$$

Example The simple emitter-follower circuit has V_{CC} = 20 V, R_s+R_m = 9.3 kΩ, I_m = 1mA at full scale, and transistor h_{FE} = 100

(a) Calculate the meter current when V_{in} = 10 V

(b) Determine the voltmeter input resistance with and without the transistor.



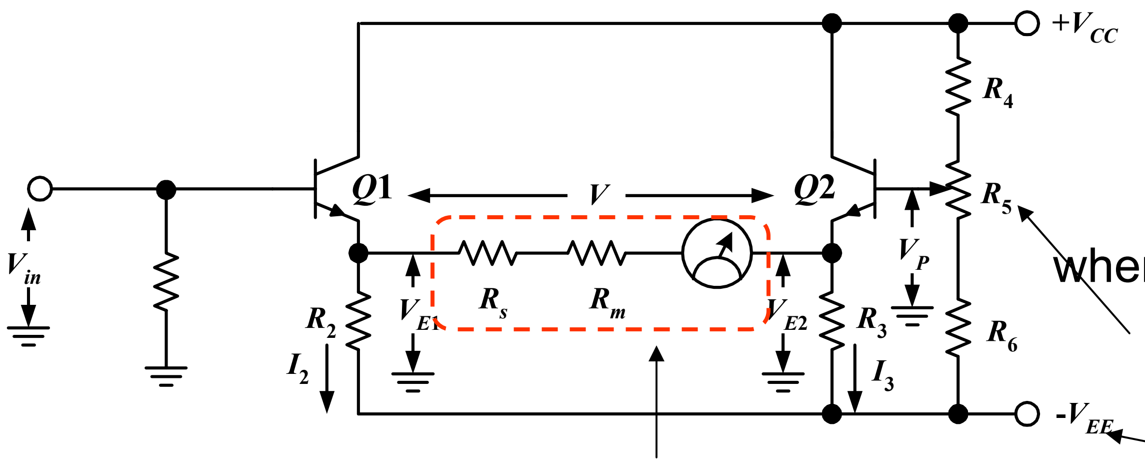
SOLUTION

Transistor Voltmeter: Emitter Follower

***The base-emitter voltage drop (V_{BE}) introduces some limitations in using emitter follower as a voltmeter:**

- **The circuit cannot measure the input voltage less than 0.6 V**
- **a non-proportional deflection: error**

From the above experiment, if we apply V_{in} with 5 V, the meter should read half of full scale I.e. I_m = 0.5 mA. But, the simple calculation shows that I_m = 0.46 mA



PMMC

Bridge configuration

$$V_m = V_{E1} - V_{E2}$$

where $V_{E1} = V_{in} - V_{BE1}$ $\quad V_{E2} = V_P - V_{BE2}$

Zero adjust

Use negative supply also to measure V_{in} < 0.6 V

Practical emitter-follower voltmeter using second transistor Q_2 and voltage divider R_4, R_5 and R_6 to eliminate V_{BE} error in Q_1

Transistor Voltmeter: Emitter Follower

At the condition of V_{in} = 0, V_p should be set to give zero meter reading, V_m = 0.
Therefore, the potentiometer R_5 is for the zero adjust.
If transistors Q_1 and Q_2 are identical, $V_{BE1} = V_{BE2}$

$$V_m = V_{E1} - V_{E2} = V_{in} - V_{BE1} - (V_p - V_{BE2}) = V_{in} - V_p$$

At V_{in} = 0 -> V_m = 0, give V_p = 0

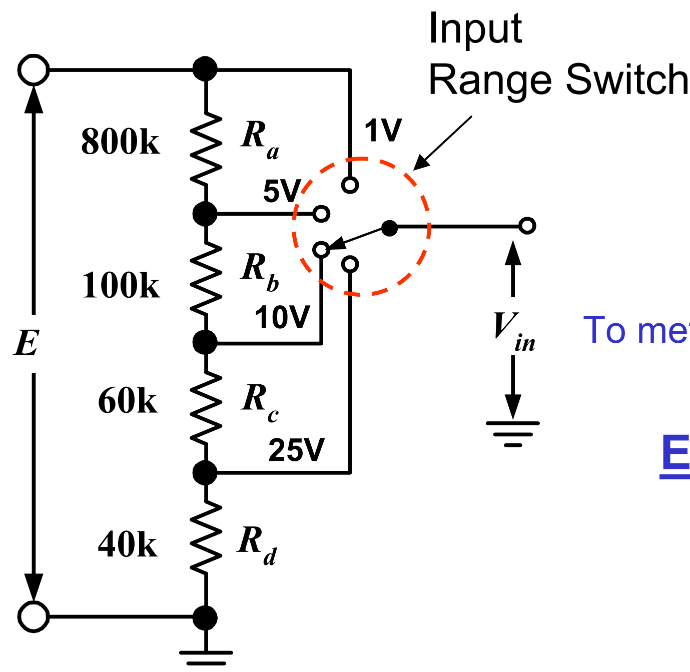
Consequently, if V_p is set properly, V_m will be the same as V_{in}

Example An emitter-follower voltmeter circuit as shown in the previous picture has $R_2 = R_3$ = 3.9 kΩ and supply with ±12 V. Calculate the meter circuit voltage when V_{in} = 1 V and when V_{in} = 0.5 V. Assume, both transistors have V_{BE} = 0.7 V

SOLUTION when V_{in} = 1 V

when V_{in} = 0.5 V

Voltage Range Changing: Input Attenuator



Voltage to be measured

To meter

The input attenuator accurately divides the voltage to be measured before it is applied to the input transistor. Calculation shows that the input voltage V_{in} is always 1 V when the maximum input is applied on any range

The measurement point always sees a constant input resistance of 1 MΩ

Example On the 5 V range:

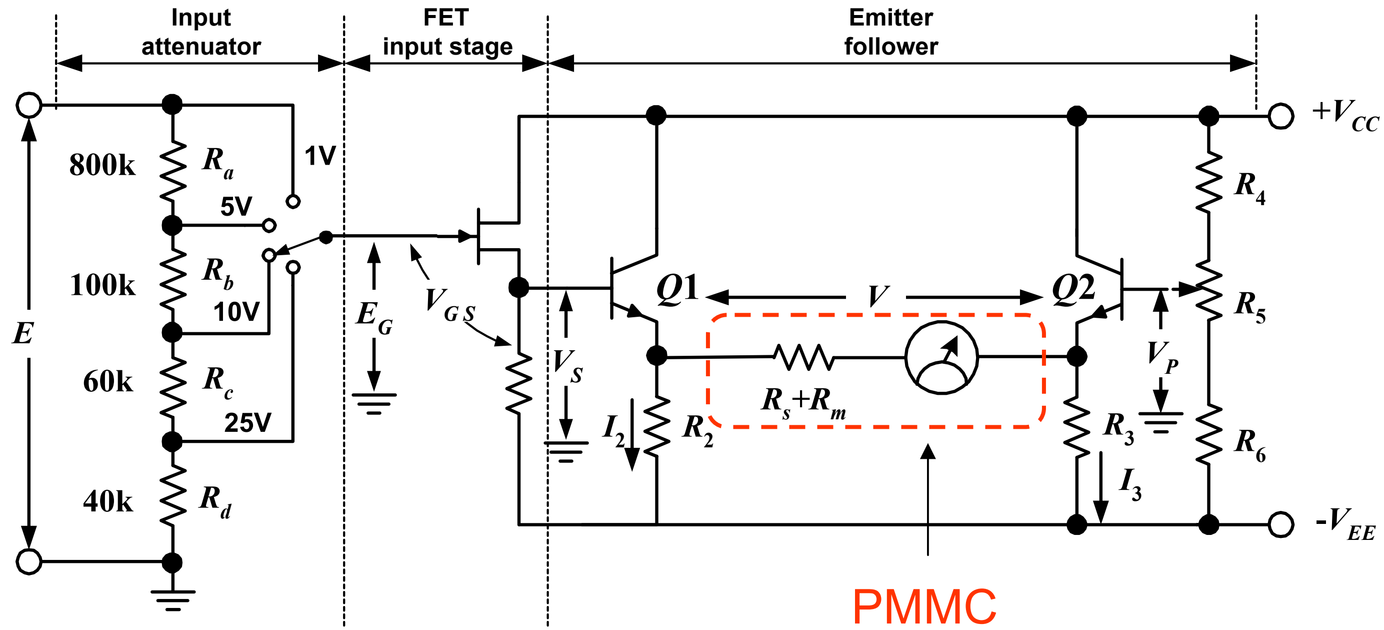
$$V_{in} = 5\text{ V} \times \frac{R_b + R_c + R_d}{R_a + R_b + R_c + R_d}$$

$$= 5\text{ V} \times \frac{100\text{ k}\Omega + 60\text{ k}\Omega + 40\text{ k}\Omega}{800\text{ k}\Omega + 100\text{ k}\Omega + 60\text{ k}\Omega + 40\text{ k}\Omega}$$

$$= 1\text{ V}$$

FET Input Voltmeter

The addition of FET at the input gives higher input resistance than can be achieved with a bipolar transistor



A FET Input Voltmeter

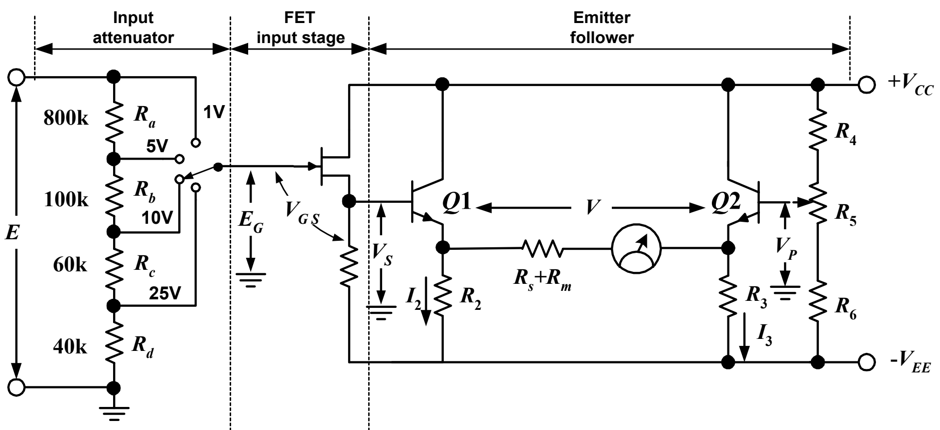
$V_m = V_{E1} - V_{E2}$ where $V_{E1} = E_G - V_{GS} - V_{BE1}$ $\quad V_{E2} = V_P - V_{BE2}$

In general, it is not simple to calculate V_{GS}, for simplicity, we assume that V_{GS} will be given.

FET Input Voltmeter

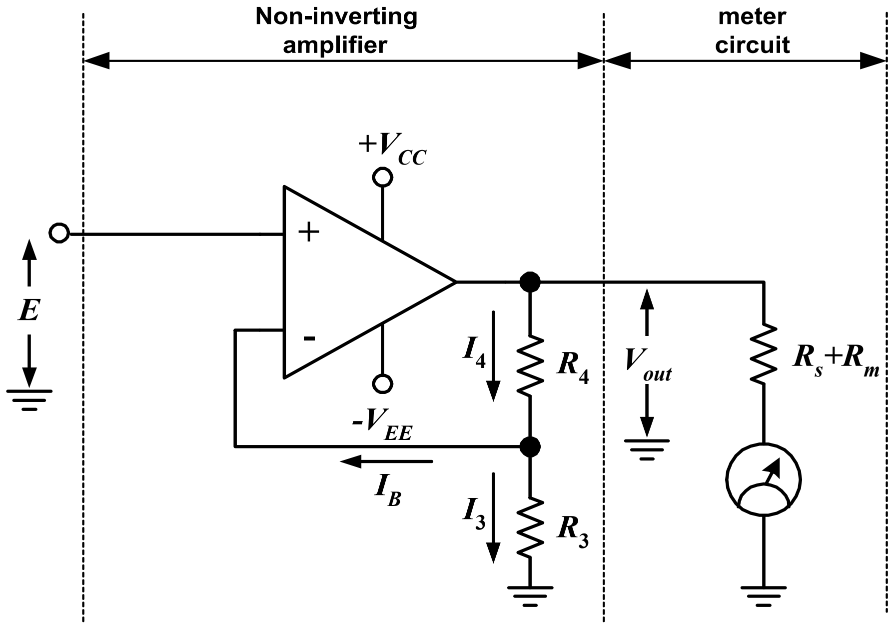
Example Determine the meter reading for the FET input voltmeter in the previous figure, when E = 7.5 V and the meter is set to its 10 V range. The FET gate-source voltage is –5 V, V_P = 5 V, R_s+R_m = 1 kΩ and I_m = 1 mA at full scale

SOLUTION On the 10 V range:



Operational Amplifier Voltmeter

Op-Amp Amplifier Voltmeter



$$V_{out} = (1 + \frac{R_4}{R_3})E$$

The voltage gain

$$A_v = (1 + \frac{R_4}{R_3})$$

Selection of R_3 and R_4

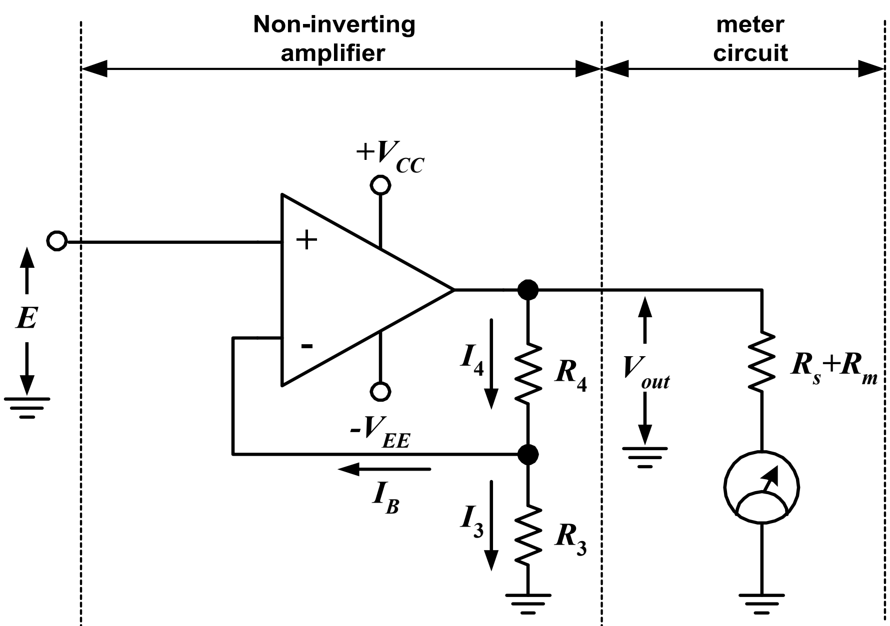
$$R_3 = \frac{E}{I_3}$$ and $$R_4 = \frac{V_{out} - E}{I_3}$$

The non-inverting amplifier gives a very high input impedance and very low output impedance. Therefore, the loading effect can be neglected. Furthermore, it can provide gain with enabling to measure low level input voltage.

Operational Amplifier Voltmeter

Example Design an op-amp Voltmeter circuit which can measure a maximum input of 20 mV. The op-amp input current is 0.2 μA, and the meter circuit has I_m = 100 μA FSD and R_m = 10 kΩ. Determine suitable resistance values for R_3 and R_4

SOLUTION To neglect the effect of I_B, the condition of $I_4 >> I_B$ must be satisfied. The rule of thumb suggested I_4 should be at least 100 times greater than I_B

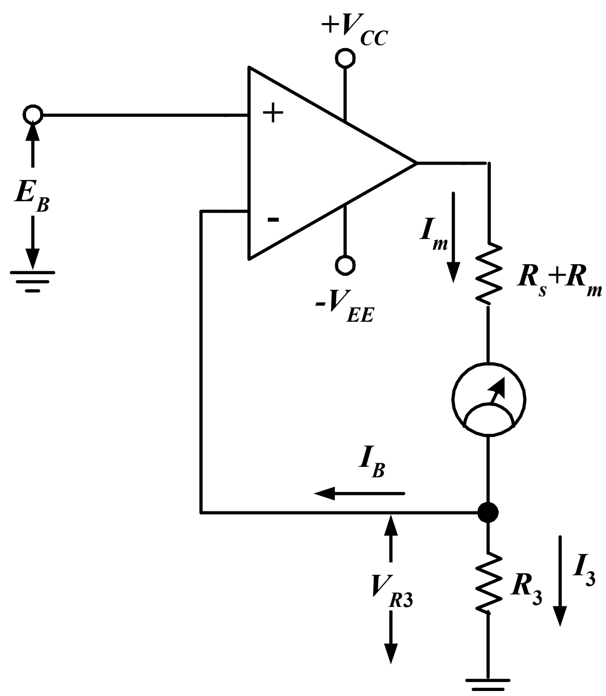


Select I_4 = 1000 x I_B = 1000 x 0.2 μA = 0.2 mA

At full scale: I_m = 100 μA

Operational Amplifier Voltmeter

Op-Amp Amplifier Voltmeter: voltage to current converter



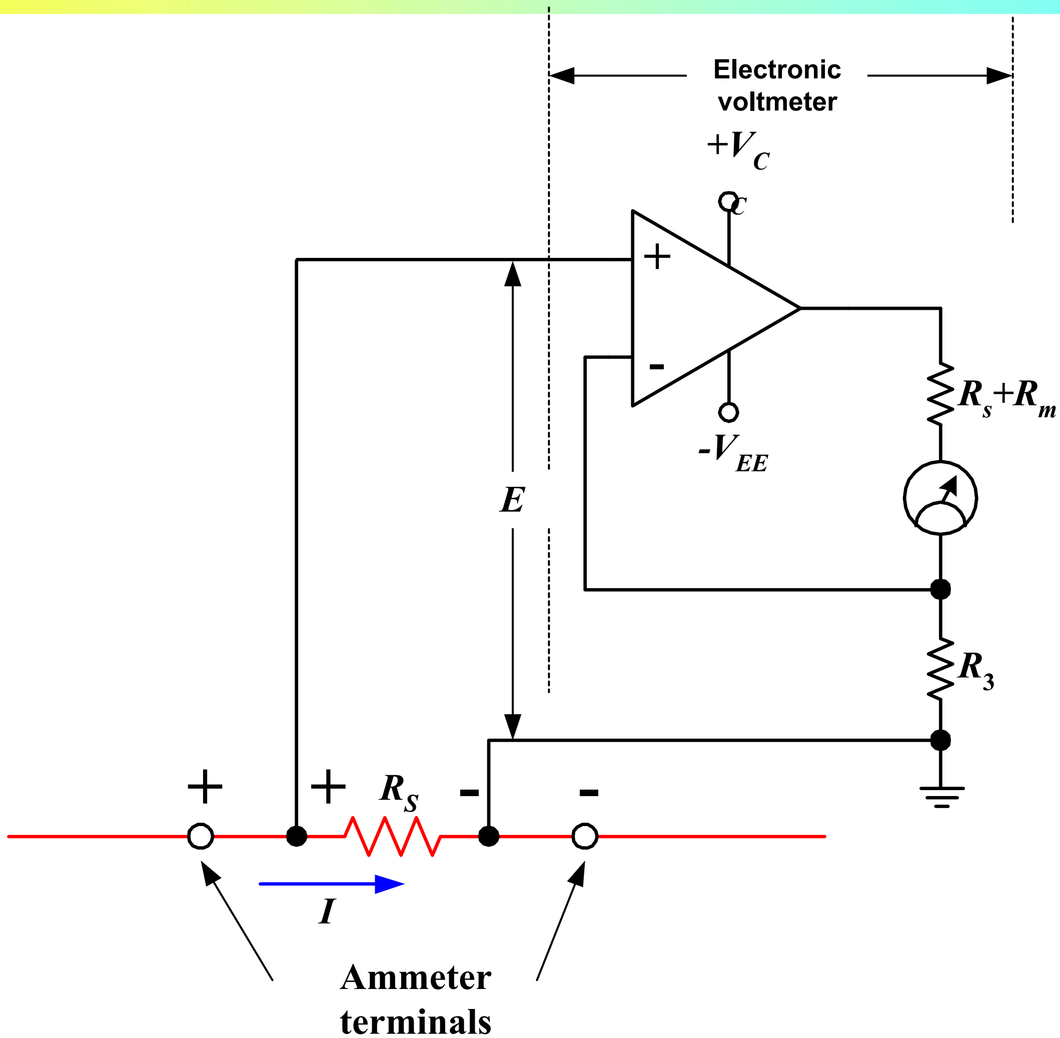
Since $I_3 >> I_B$, therefore $I_m = I_3$

Meter current $$I_m = I_3 = \frac{E}{R_3}$$

Meter voltage $$V_m = \frac{R_m}{R_3} E$$

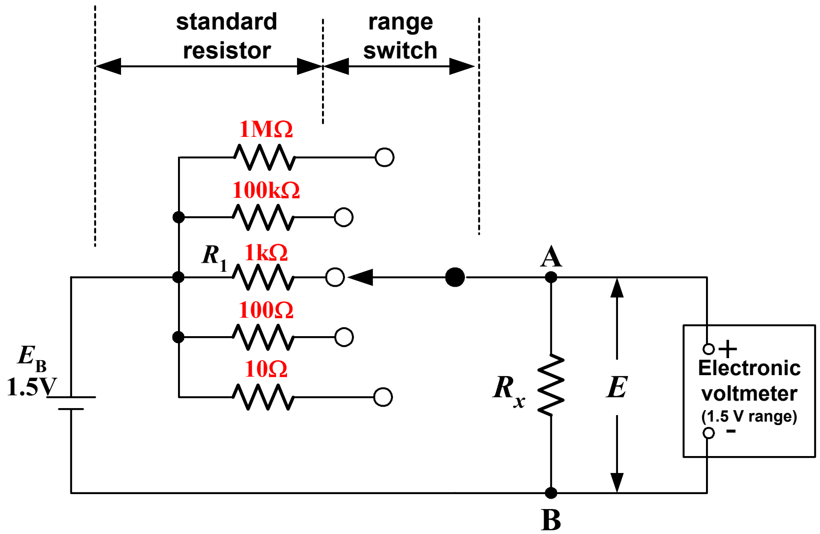
if $R_m > R_3$, voltage E is amplified by the ratio of R_m/R_3

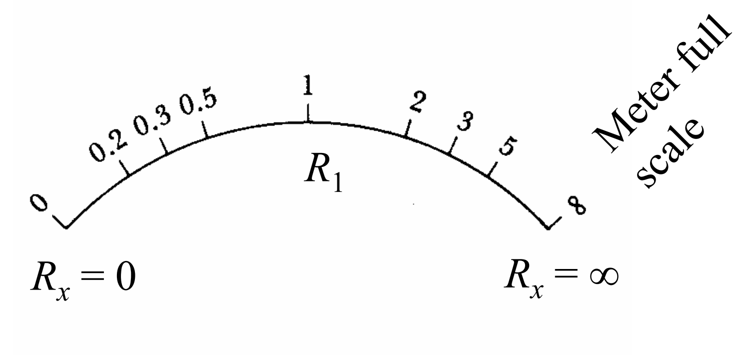
Current Measurement with Electronic Voltmeter



An electronic voltmeter can be used for current measurement by measuring the voltage drop across a shunt (R_s). The instrument scale is calibrated to indicate current.

Electronic Ohmmeter: Series Connection





Ohmmeter scale for electronic instrument

Series Ohmmeter for electronic instrument

At $R_x = \infty$ or open circuit, the voltmeter indicate full scale defection (E = 1.5 V) and R_x = 0 or shorted circuit, since E = 0, no defection is observed. At other values of resistance, the battery voltage E_B is potentially divided across R_1 and R_x, given by

$$E = E_B \frac{R_x}{R_1 + R_x}$$

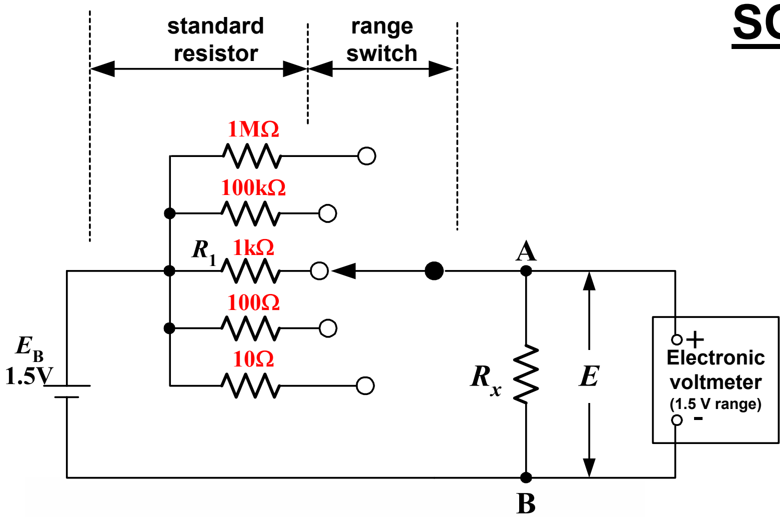
Suppose that R_1 is set to $1\ \text{k}\Omega$

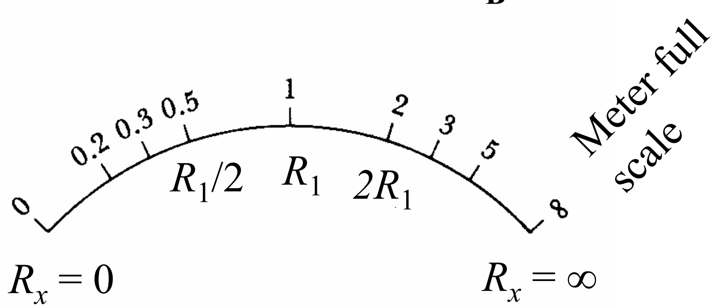
$$E = 1.5\ \text{V} \times \frac{1\ \text{k}\Omega}{1\ \text{k}\Omega + 1\ \text{k}\Omega} = 0.75\ \text{V}$$ (50% defection)

Thus if $R_x = R_1$, half scale will be indicated

Electronic Ohmmeter: Series Connection

Example For the electronic ohmmeter in the Figure, determine the resistance scale marking at 1/3 and 2/3 of full scale





SOLUTION From

$$E = E_B \frac{R_x}{R_1 + R_x}$$

Rearrange, give us

$$R_x = \frac{R_1}{E_B/E - 1}$$

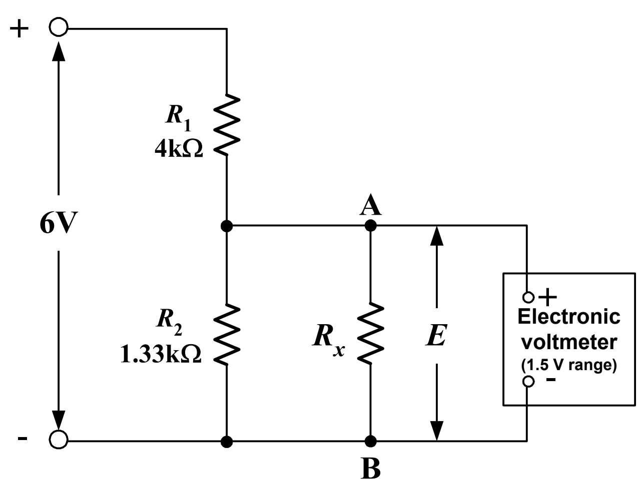
At 1/3 FSD; $E = E_B/3$

$$R_x = \frac{R_1}{\frac{E_B \times 3}{E_B} - 1} = \frac{R_1}{2}$$

At 2/3 FSD; $E = 2E_B/3$

$$R_x = \frac{R_1}{\frac{E_B \times 3}{2E_B} - 1} = 2R_1$$

Electronic Ohmmeter: Parallel Connection



Shunt Ohmmeter for electronic instrument

At $R_x = \infty$ or open circuit,

$$E = E_B \frac{R_2}{R_1 + R_2}$$

$$= 6\ \text{V} \times \frac{1.33\ \text{k}\Omega}{4\ \text{k}\Omega + 1.33\ \text{k}\Omega} = 1.5\ \text{V}$$

Therefore, this circuit give FSD, when $R_x = \infty$

When, $R_x = 0\ \Omega$, E = 0 V, therefore, the meter gives no defection.

At any value of R_x

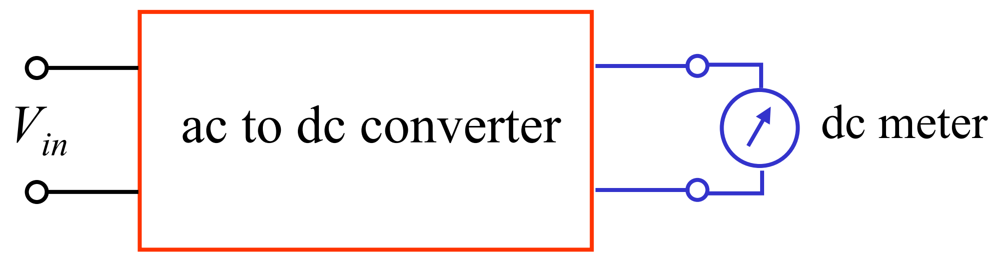
$$E = E_B \frac{R_2 \parallel R_x}{R_1 + R_2 \parallel R_x}$$

So, the meter indicates half-scale when $R_x = R_1 \parallel R_2$

AC Electronic Voltmeter

Principle

Most ac measurements are made with ac-to-dc converter, which produce a dc current/voltage proportional to the ac input being measured



Classification:

- **Average responding**
- **Peak responding**
- **RMS responding (True rms meter)**

} periodic signal only (Average responding, Peak responding)

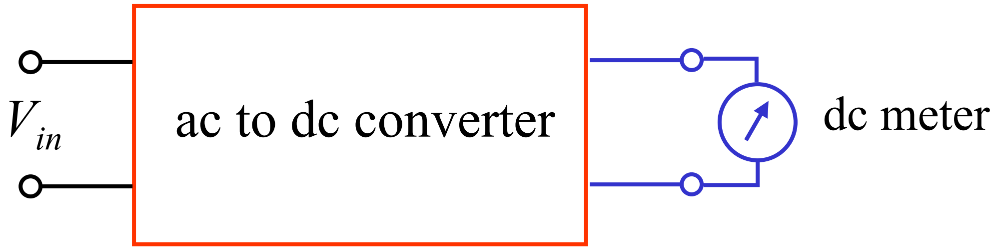
any signal (RMS responding)

AC Electronic Voltmeter

The scale on ac voltmeters are ordinarily calibrated in rms volts

Average responding meter

Form factor is the ratio of the rms value to the average value of the wave form



$$\text{Form Factor} = \frac{V_{rms}}{V_{average}}$$

It should be noted that the rms value is calculated from V_{in}, while the average value is calculated from the output of ac-dc converter.

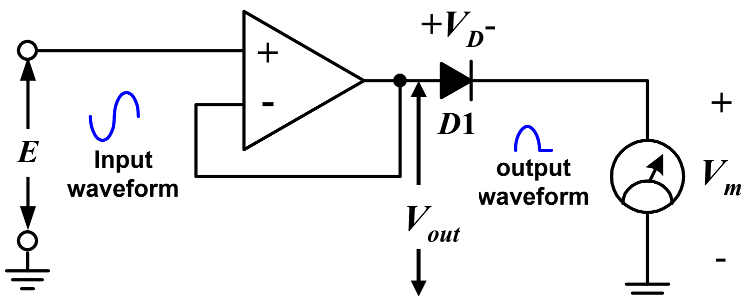
Peak responding meter

Form factor is the ratio of the peak value to the rms value of the wave form

$$\text{Crest Factor} = \frac{V_{peak}}{V_{rms}}$$

Average-Responding Meter

In this type of instrument, the ac signal is rectified and then fed to a dc millimeter.
In the meter instrument, the rectified current is averaged either by a filter or by the ballistic characteristics of the meter to produce a steady deflection of the meter pointer.



Conventional half-wave rectifier

$$\text{For the positive cycle,} \quad V_{out} = E$$

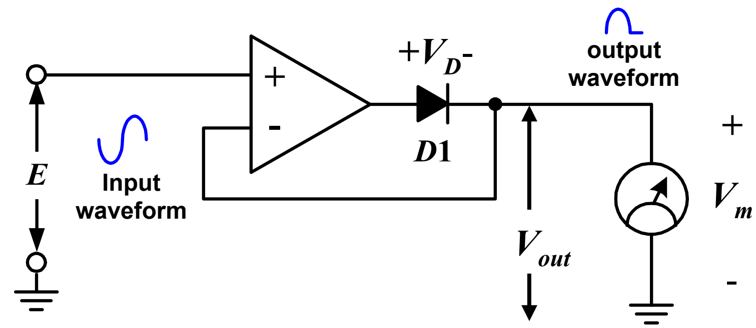
$$V_m = E - V_D$$

where V_D = cut-in voltage ~0.6-0.7 for Si

$$\text{For the negative cycle,} \quad V_{out} = E$$

$$V_m = 0$$

Since Diode D_1 is revered bias, no current flow through meter



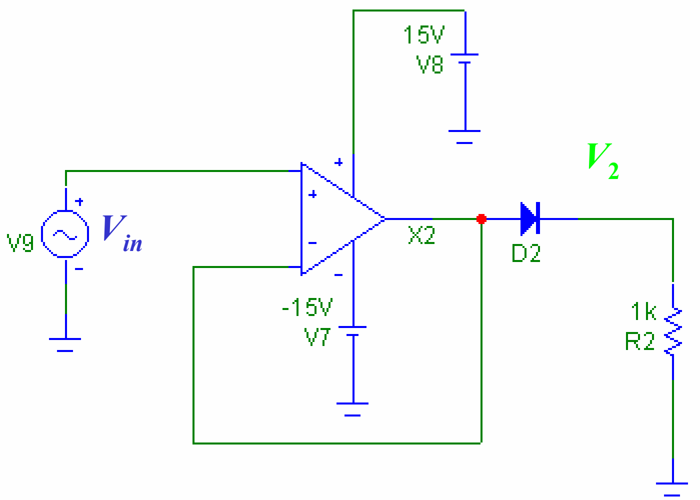
precision rectifier

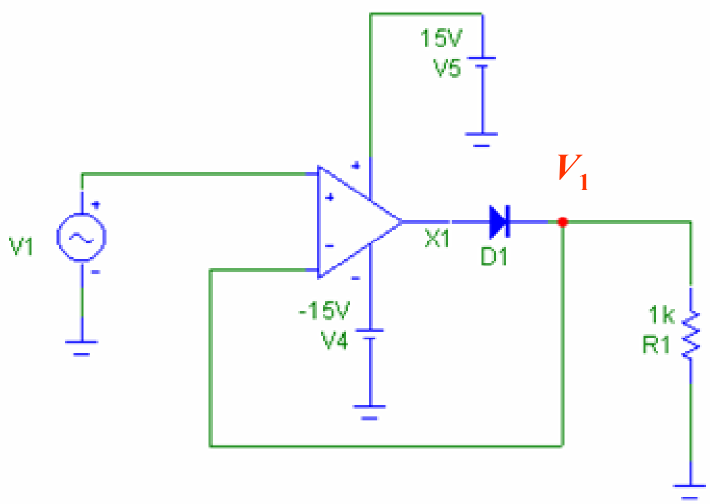
$$\text{For the positive cycle,} \quad V_{out} = V_m = E$$

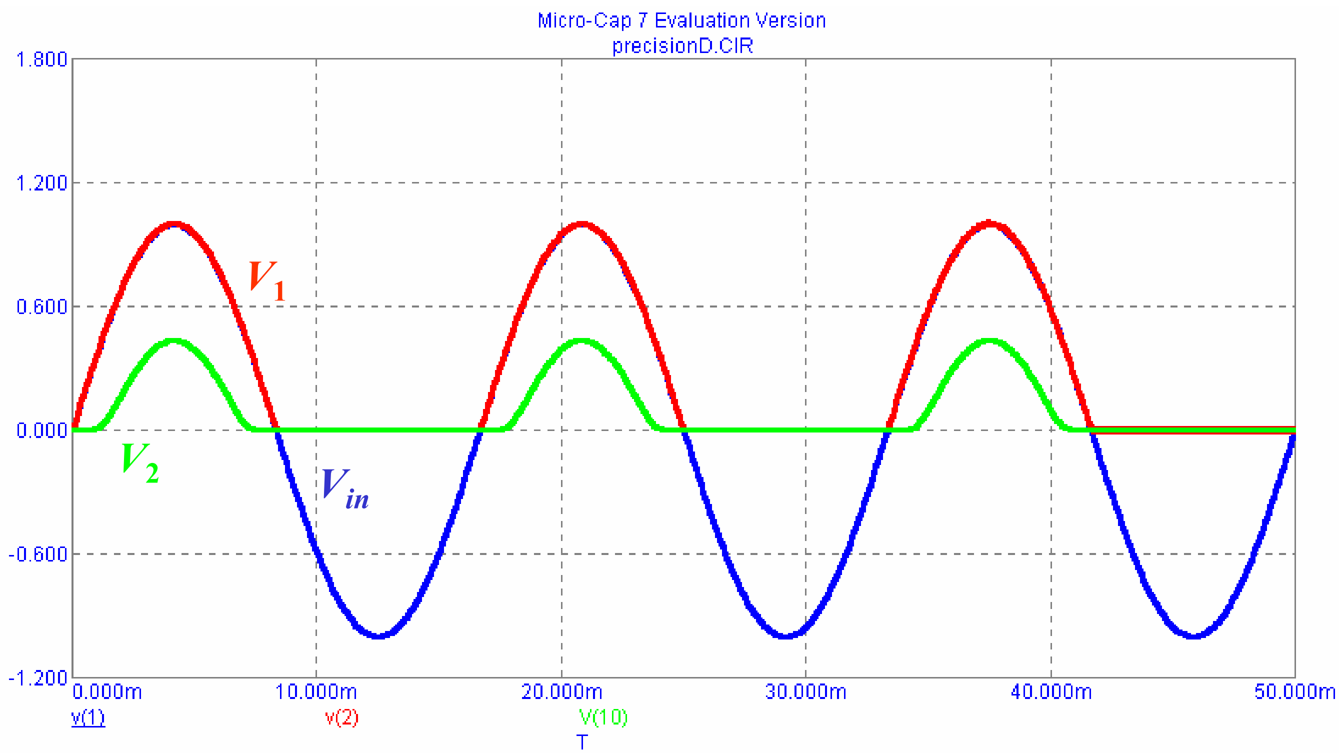
$$\text{For the negative cycle,} \quad V_{out} = 0$$

Therefore, the voltage drop in the forward bias can be compensated by this configuration

Average-Responding Meter

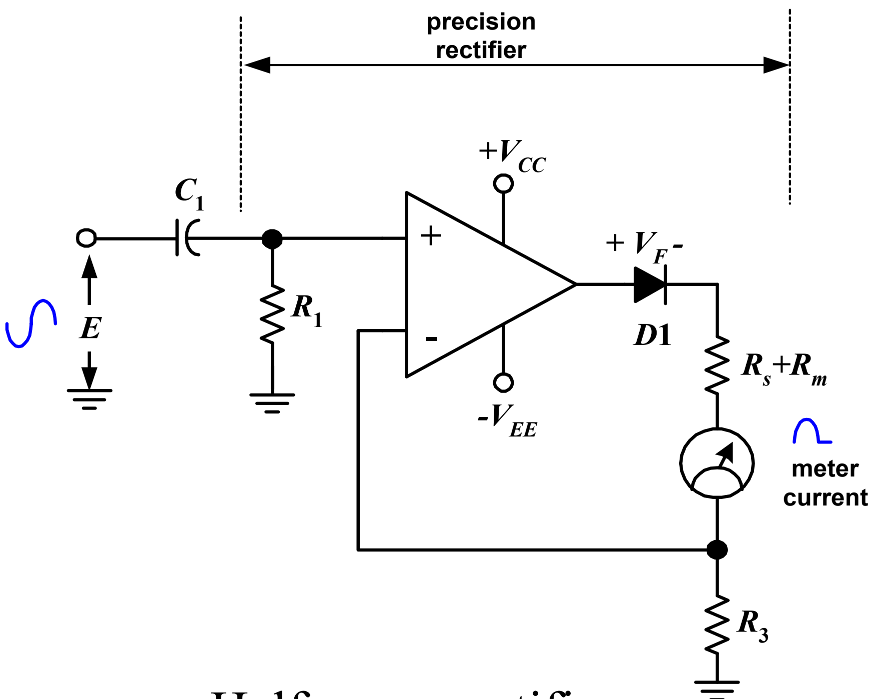




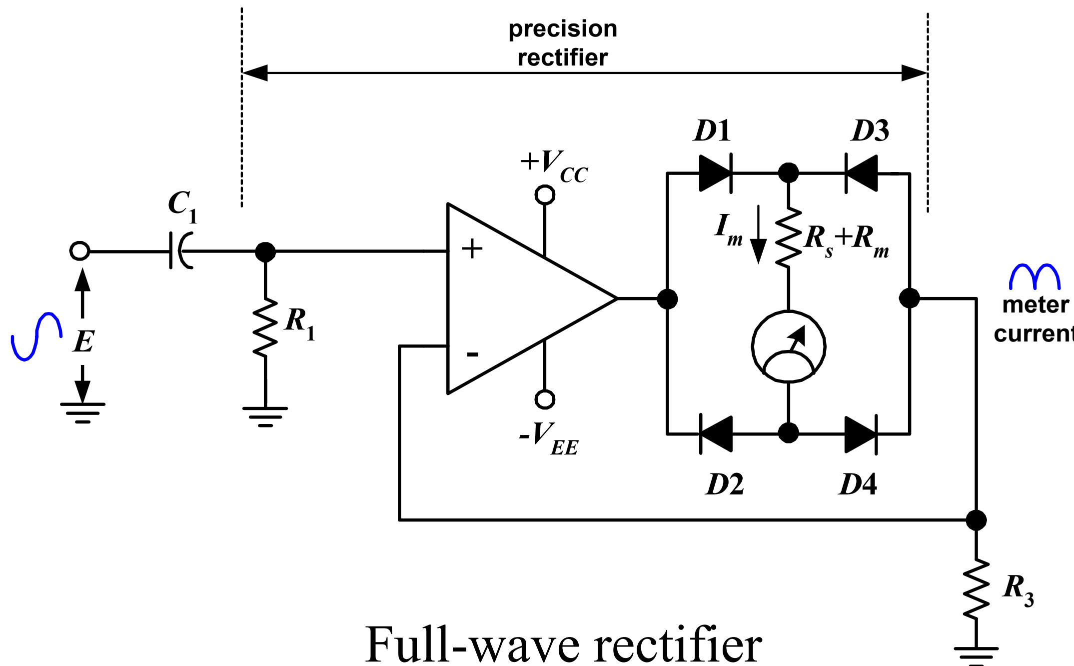


Average-Responding Voltmeter

Voltage to current converter



Half-wave rectifier



Full-wave rectifier

Half-wave rectifier:

Meter peak current $I_p = \frac{E_p}{R_3}$

Average meter current $I_{av} = \frac{1}{\pi} I_p = 0.318 I_p$

Full-wave rectifier:

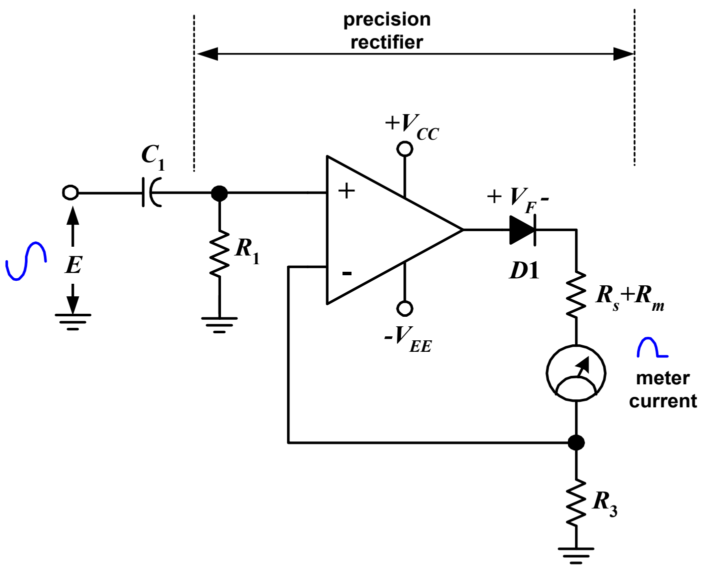
Meter peak current $I_p = \frac{E_p}{R_3}$

Average meter current $I_{av} = \frac{2}{\pi} I_p = 0.637 I_p$

Average-Responding Voltmeter

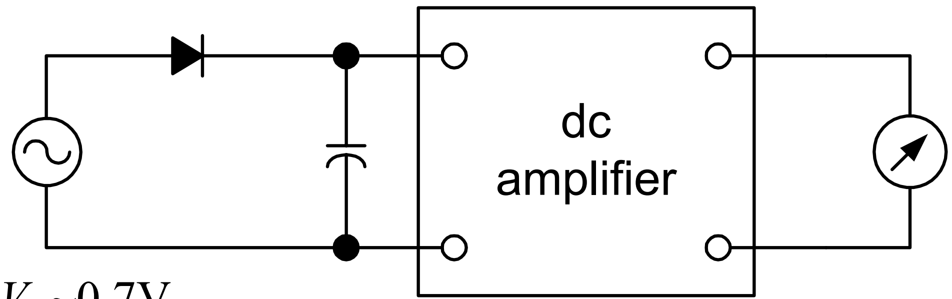
Example The half-wave rectifier electronic voltmeter circuit uses a meter with a FSD current of 1 mA. The meter a coil resistance is 1.2 kΩ. Calculate the value of R_3 that will give meter full-scale pointer deflection when the ac input voltage is 100 mV (rms). Also determine the meter deflection when the input is 50 mV.

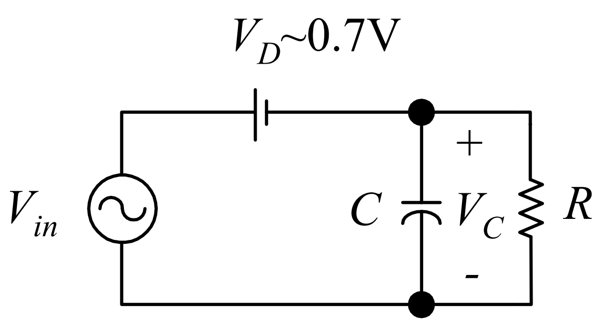
SOLUTION at FSD, the average meter current is 1 mA



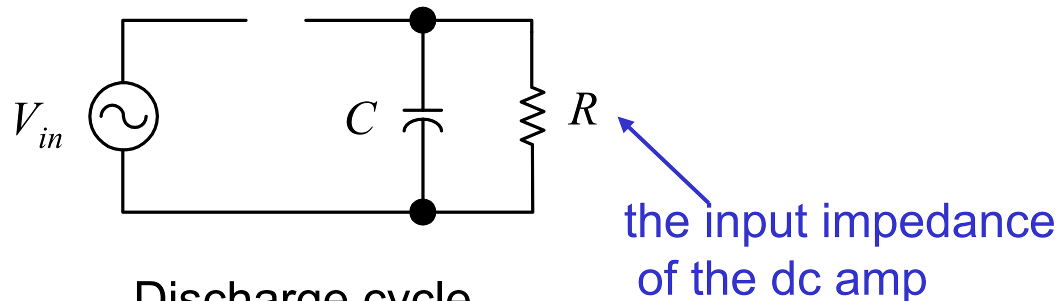
Peak-Responding Voltmeter

The primary difference between the peak-responding voltmeter and the average-responding voltmeter is the use of a storage capacitor with the rectifying diode.





Charge cycle

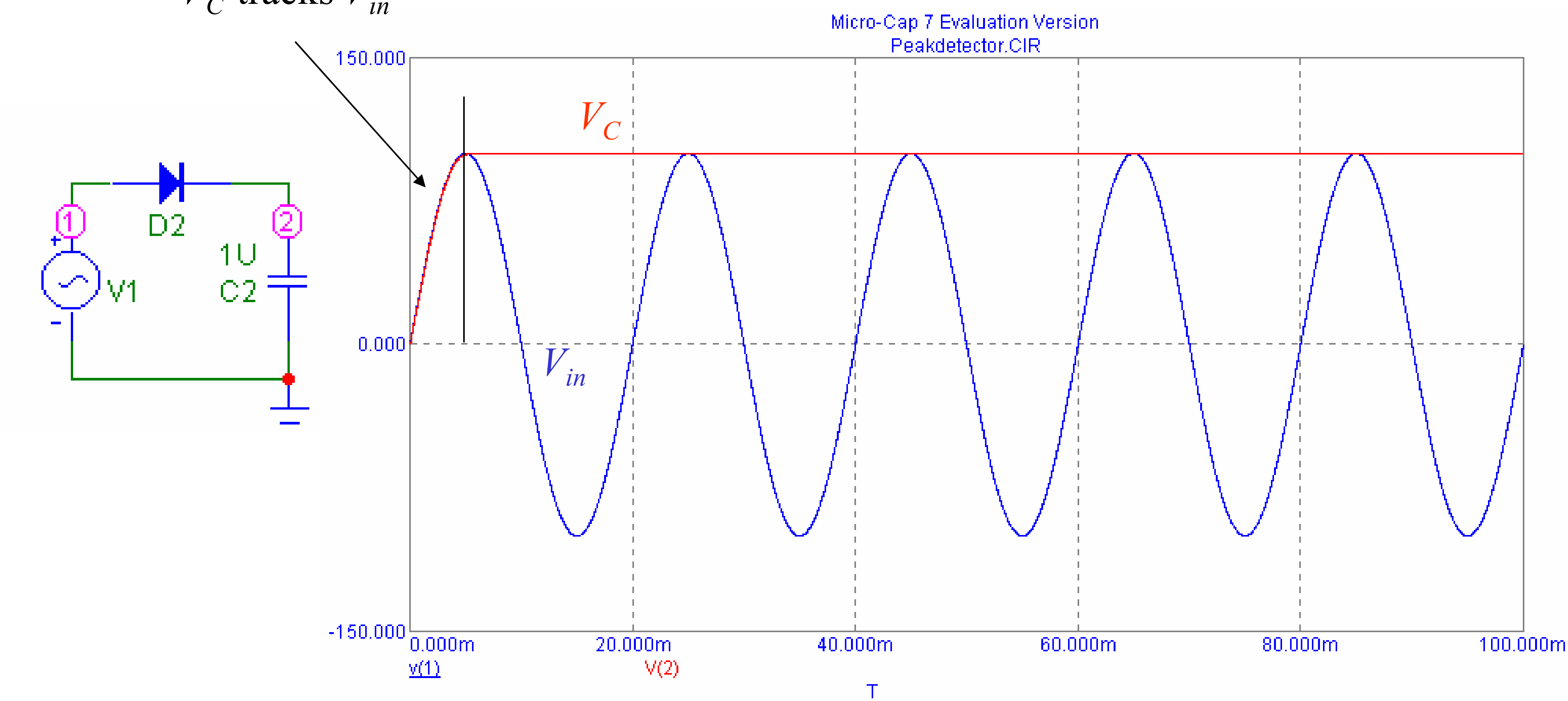


Discharge cycle

In the first positive cycle: V_C tracks V_{in} with the difference of V_D, until V_{in} reaches its peak value. After this point, diode is reversed bias and the circuit keeps V_C at $V_p - V_D$. The effect of discharging through R will be minimized if its value is large enough to yield that $RC >> T$.

Peak-Responding Voltmeter

V_C tracks V_{in}

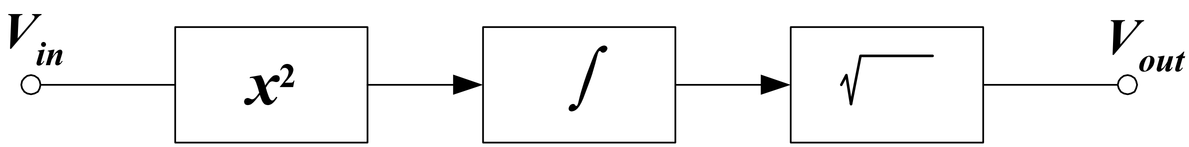


RMS-Responding Voltmeter

Suitable for: low duty-cycle pulse trains
voltages of undetermined waveform

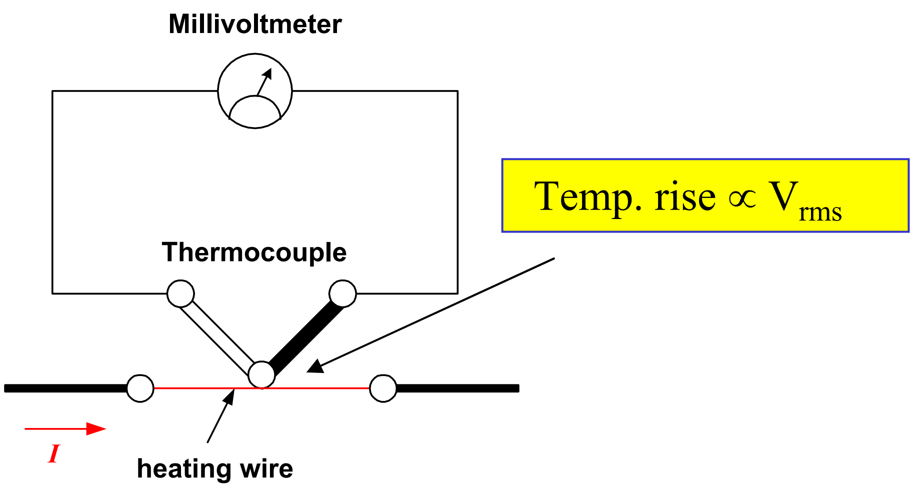
RMS value definition: Mathematic

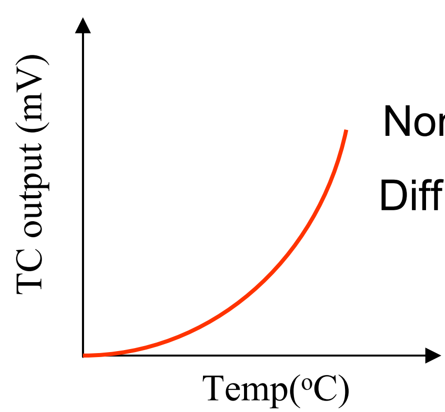
$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T v^2(t)\,dt}$$



RMS value definition: Physical

rms voltage is equivalent to a dc voltage which generates the same amount of heat power in a resistive load that the ac voltage does.





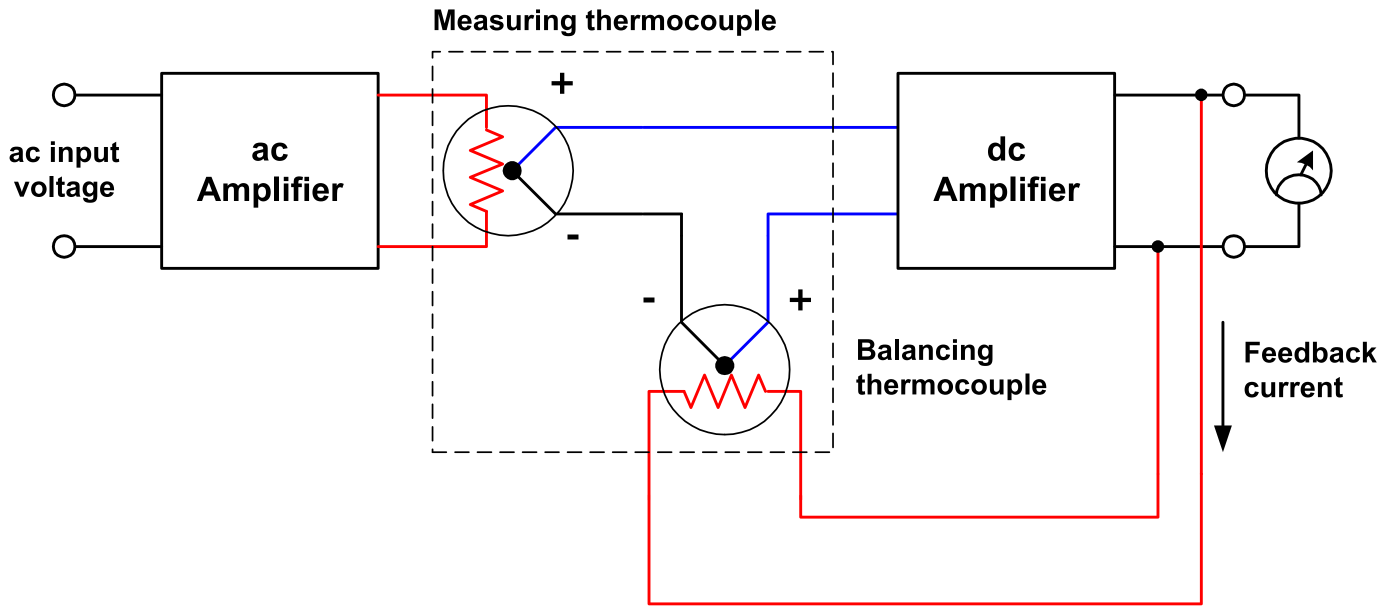
Non-linear

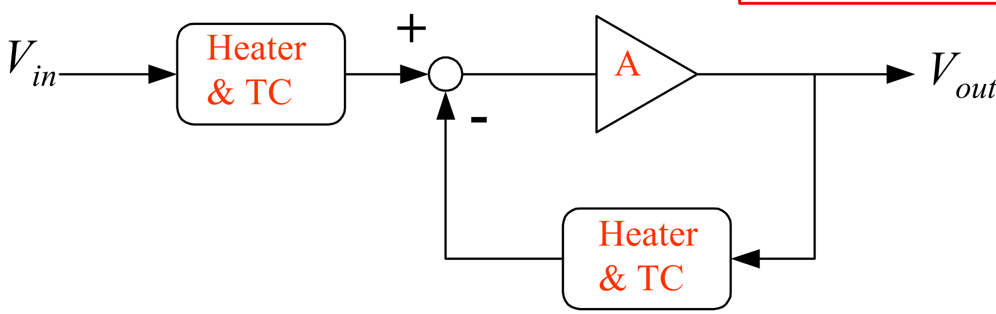
Difficult to calibrate scale

RMS-Responding Voltmeter

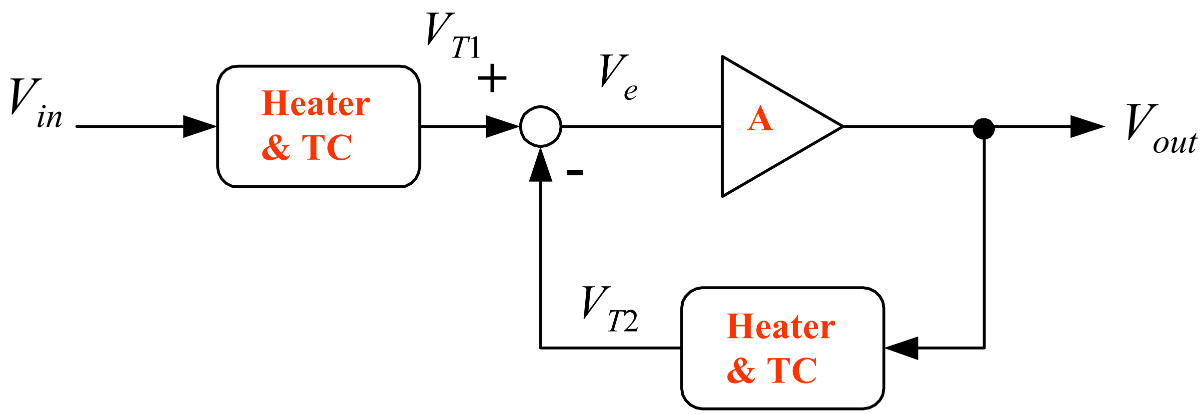
***Null-balance technique*: non-linear cancellation**

Compare the heating power generated by input voltage to the heating power generated the dc amplifier





Negative Feedback



$$V_{out} = V_e = A\left(V_{T1} - V_{T2}\right)$$

Let, $V_{T1} = k\ V_{in}$ and $V_{T2} = k\ V_{out}$ where k is proportional constant of the heater and TC in the system. Note that k may depend on the level of the input signal

$$V_{out} = A\left(kV_{in} - kV_{out}\right)$$

$$\frac{V_{out}}{V_{in}} = \frac{Ak}{1 + Ak}$$

If A is large → $V_{out} \approx V_{in}$

If the amplifier gain is very large, V_{out} is equal to V_{in}, this means that the dc voltage output is therefore equal to the effective, or rms value of the input voltage