Mechatronics

Topic #7

Sensors: Principle of operation & BS2 interfacing

Photoresistors—I

- Photoresisotrs exhibit a nonlinear characteristics for incident optical illumination versus the resulting resistance.
- A log-log relation between illumination v/s resistance is frequently used:

$$\log_{10} R = \alpha - \beta \log_{10} P$$

  – R is photoresistor's resistance when exposed to optical power P.

  – For two different illumination levels, the above formula yields:

$$\log_{10} R_a = \alpha - \beta \log_{10} P_a \quad (1)$$

$$\log_{10} R_b = \alpha - \beta \log_{10} P_b \quad (2)$$

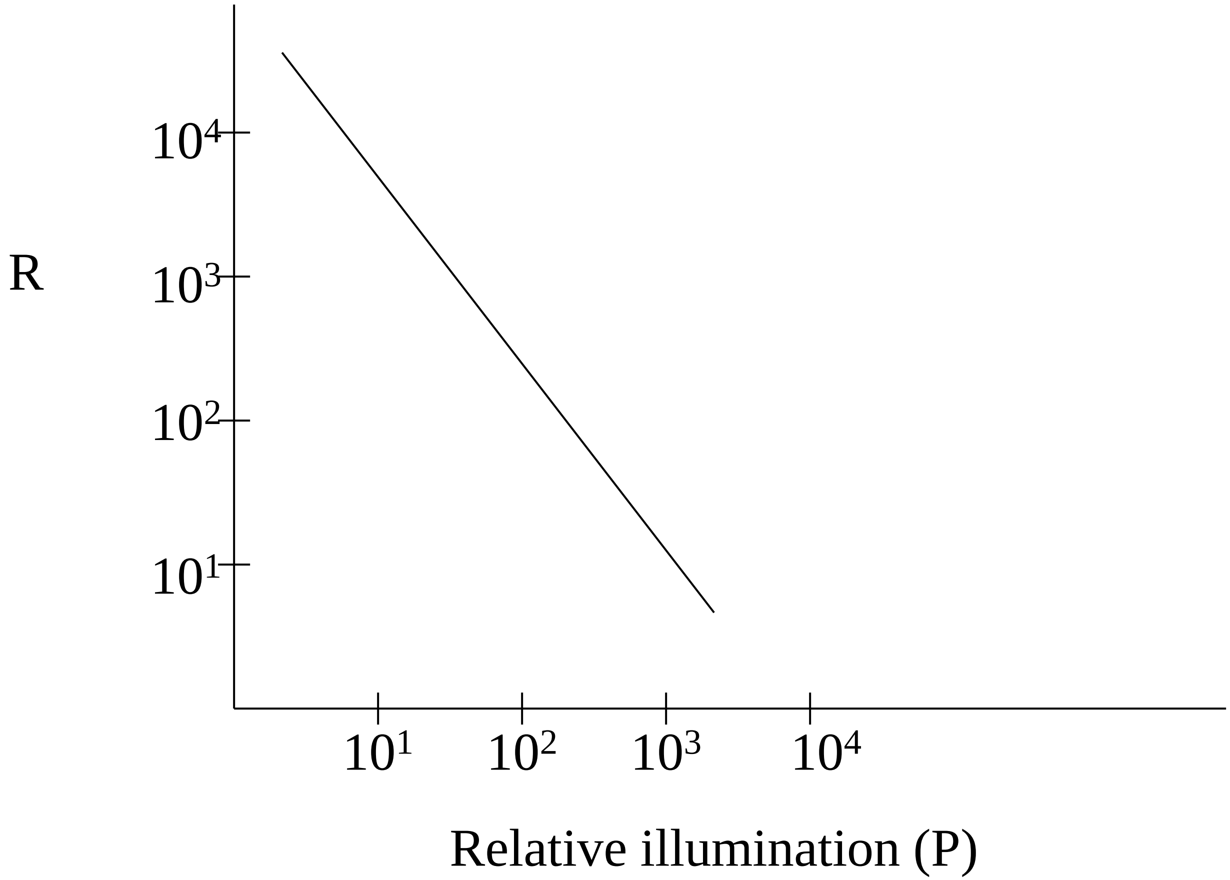
- Forming Eq1-Eq2, we obtain:

$$\log\left({R_a}/{R_b} \right) = \beta \log\left({P_b}/{P_a} \right)$$

$$\Rightarrow \beta = \frac{\log\left({R_a}/{R_b} \right)}{\log\left({P_b}/{P_a} \right)} = -\frac{\log\left({R_a}/{R_b} \right)}{\log\left({P_a}/{P_b} \right)}$$

where β is the slope of $\log_{10}P$ v/s $\log_{10}R$.

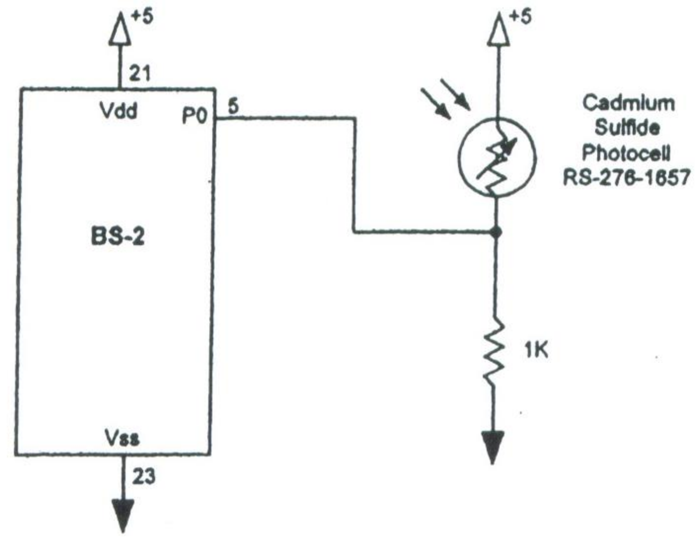
Photoresistors—II

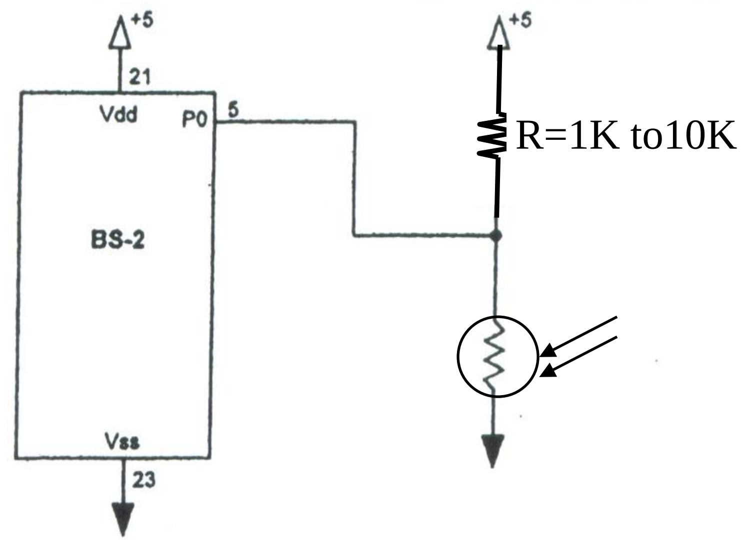


- Illustration of typical log-log dependence of photoresistance on illumination.
- Very large resistance in dark condition (in MΩ).
- Resistance falls down to several 100Ω when it is exposed to light.

Using Photoresistor with BS2: Circuit #1—I

- Photoresistor can be used as one of the resistor in a voltage divider circuit.
- When photocell is placed in dark: 1k resistor pulls P0 to ground.
- When photocell is exposed to light, its resistance falls and P0 is pulled high.
- This acts as an on-off sensor.
- Thus, this circuit simply detects if the light level has crossed a certain threshold. Once light level crosses this threshold, P0 sees a high input for all light higher than the threshold.
- If you want a high signal to be produced for light of a certain intensity (and above), you can size the lower resistor appropriately by trial and error.
- To have BS2 report dark as "High" and light as "Low" use the lower circuit.

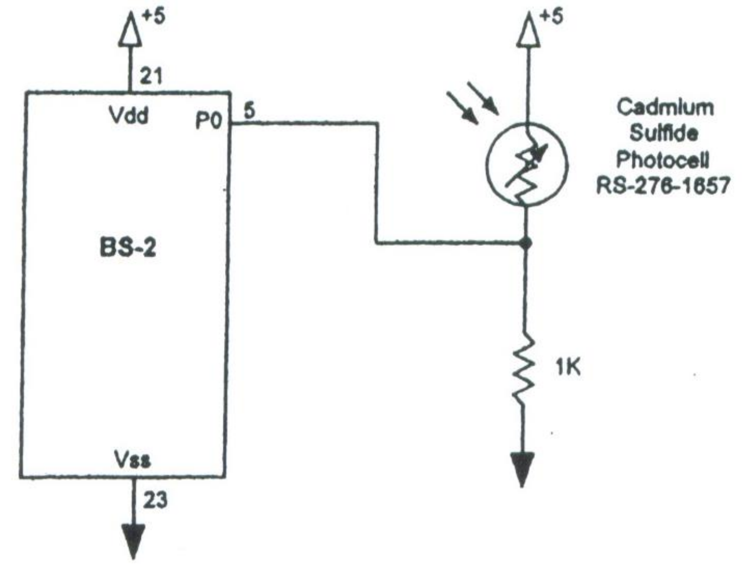




Using Photoresistor with BS2: Sample Code

- Sample code for Circuit #1

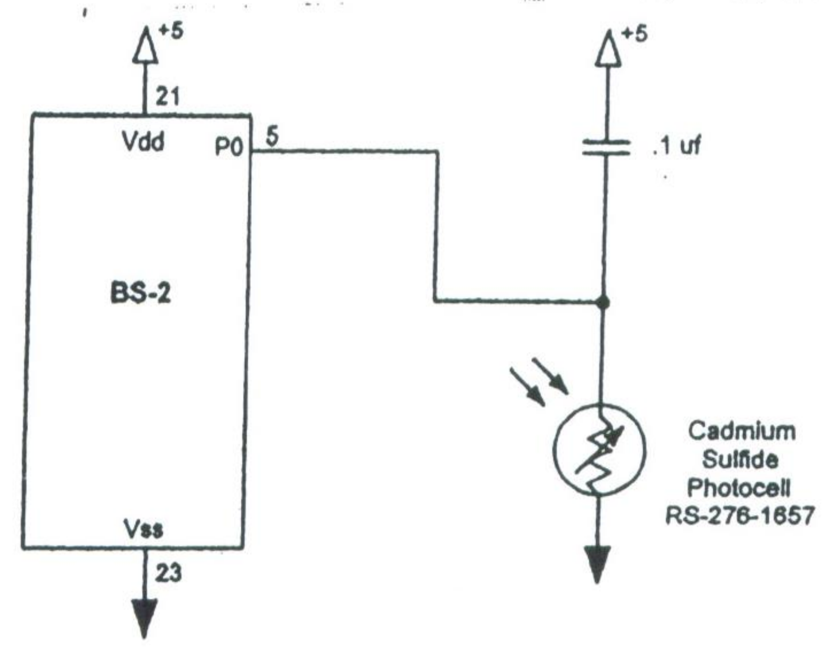
```
PhotoResPin con 0
Input PhotoResPin
PhotoResChk:
  if in0=0 then Dark
  debug "I see light.",cr
  goto PhotoResChk
Dark:
  debug "I do not see light.",cr
  goto PhotoResChk
end
```



If you use photoresistor from Basic A2D kit, use 10K resistor above instead of 1K

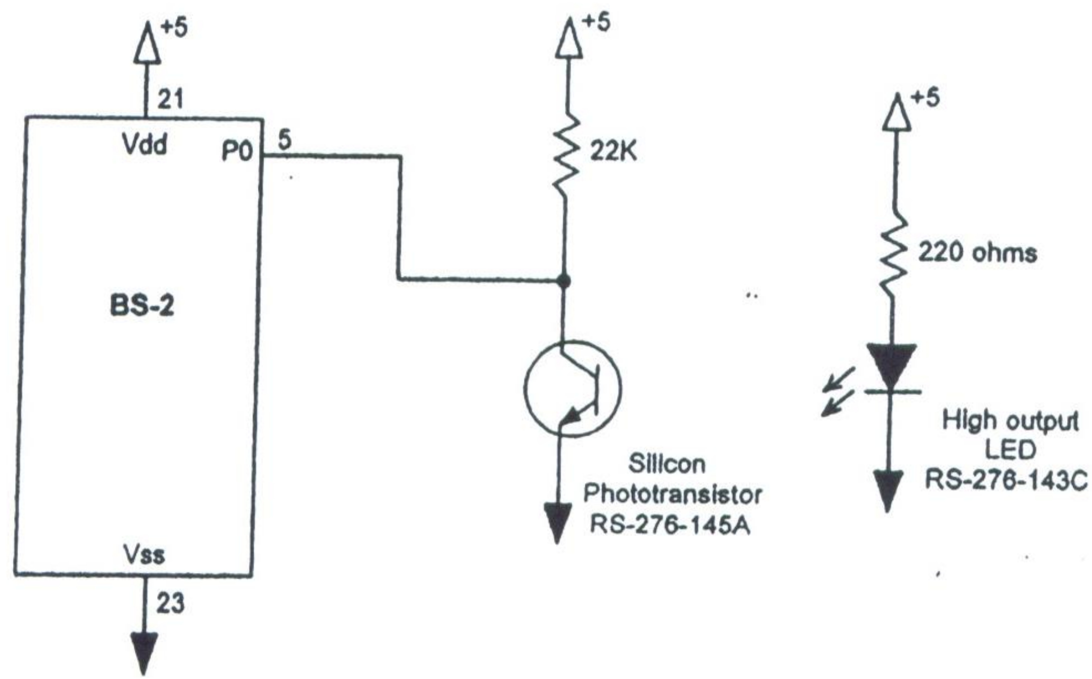
Using Photoresistor with BS2: Circuit #2

- Use of a photoresistor in a voltage divider circuit allows detection of whether a preset light level threshold has been crossed.
- Photoresistor in a voltage divider circuit does not allow measurement of different levels of light intensity.
- To measure the intensity of light incident upon a photoresistor, use a series RC network.
- In this RC network, the C value is given and the photoresistor forms the R component whose value changes with the level of light falling on it.
- Various levels of light falling on the photoresistor can be determined by measuring R using RCTIME command.
- Having determined R, the light level can be inferred by proper calibration.



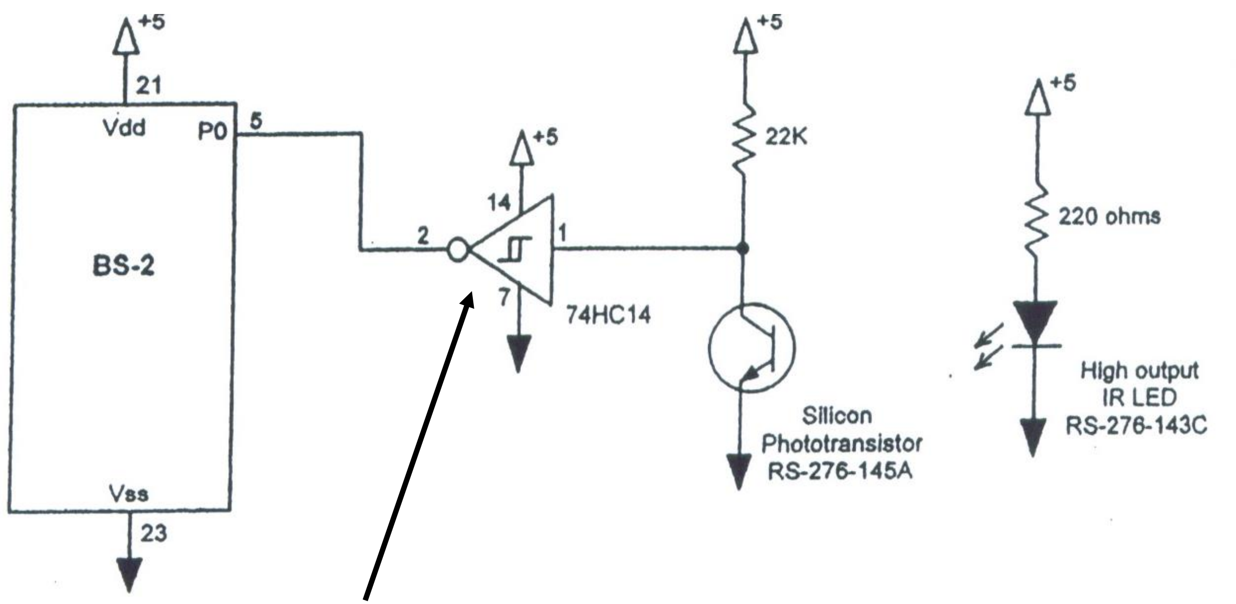
Using Phototransistor with BS2: Circuit #1—I

- When light from LED falls on the phototransistor's base, a current flows from the base to emitter, which enables collector-emitter pair to conduct.
- When no light falls on phototransistor's base: collector-emitter pair does not conduct and 22k resistor pulls P0 high.
  - P0 high → dark
- When light falls on phototransistor: collector-emitter pair conducts and voltage at P0 falls sufficiently low to be recognized as a logic low.
  - P0 low → light



Using Phototransistor with BS2: Circuit #2—I

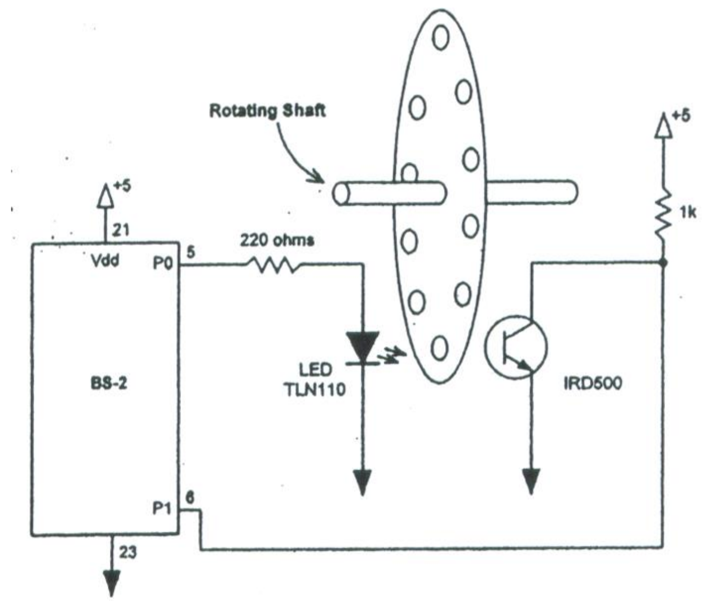
- When phototransistor is exposed to partial-light condition, it operates in a linear region. In this case, the voltage input at P0 may oscillate producing a false light-dark transition.
- To prevent the above problem, a "Schmitt Trigger" can be used.
- The phototransistor shown in the diagram is most sensitive to IR light, thus, the given circuit utilizes an IR LED.



Schmitt Trigger: Comparator with +ve feedback

Using Phototransistor with BS2: Applications—I

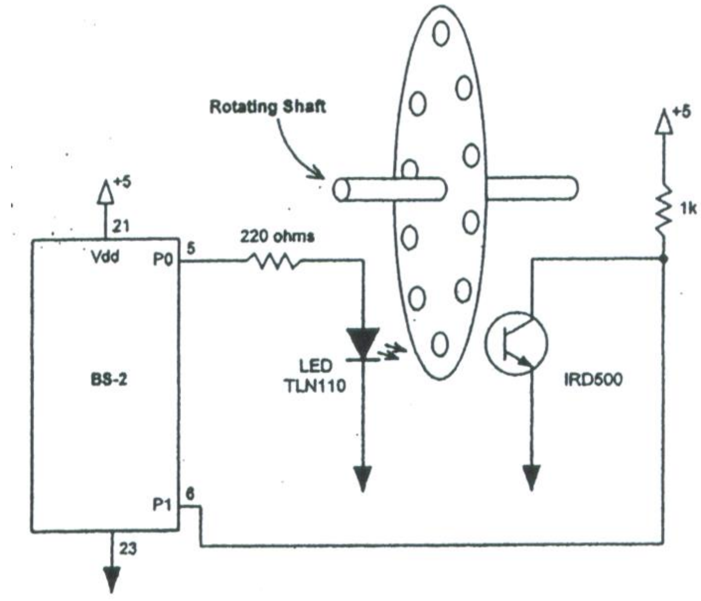
- Rotational motion measurement.
  - A disc with equally spaced holes punched through it is attached to a shaft whose rotational motion is to be measured.
  - The holes allow passage of light from one side of the disc to the other.
  - Using BS2, the LED is turned on and the phototransistor output is monitored by BS2.
  - Angular displacement of the shaft is measured by counting the number of high-low transitions of the phototransistor.
  - Alternatively, angular speed is obtained by measuring the time duration of high pulse.



Rotational Motion Measurement: Sample Code—I

•Sample code for shaft movement detector:

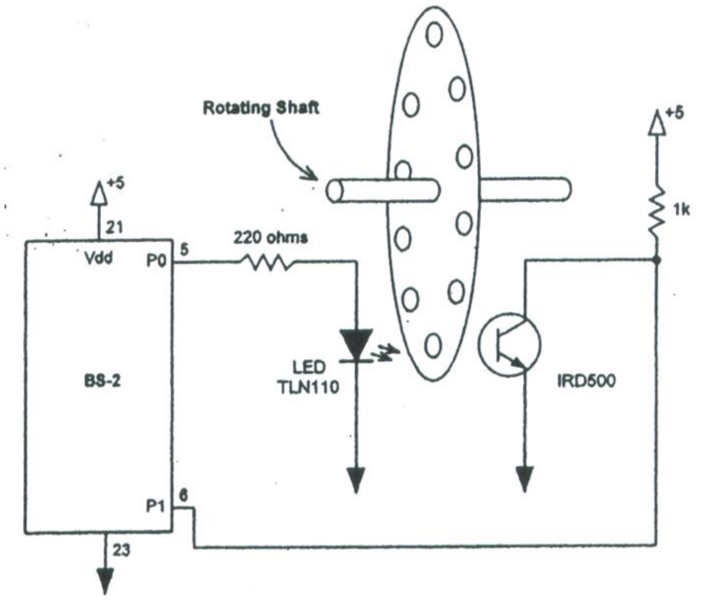
```
AngDisp var word
high 0                'Turn on LED
Monitor:
If in1=1 then AngDispIncr
Goto Monitor
AngDispIncr:
AngDisp=AngDisp +1
'increment AngDisp at each hole detection
debug ? AngDisp
Wait4Low:
if in1=1 then Wait4Low
goto Monitor
```



Rotational Motion Measurement: Sample Code—II

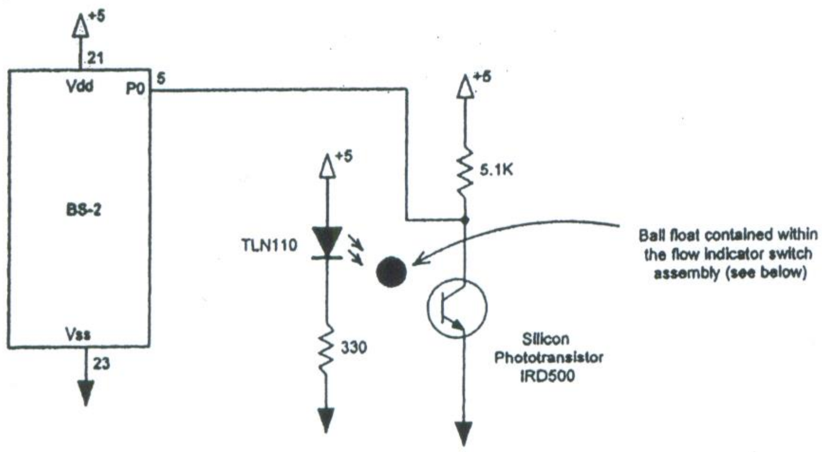
- Sample code for shaft rotation speed detector.

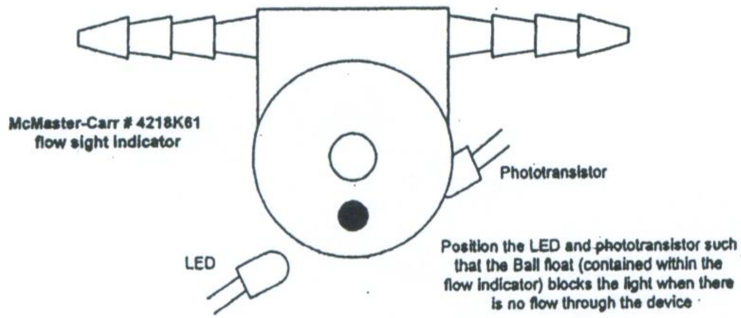
```
Speed var word
High 0            'Turn on LED
SpeedMeas:
Pulsin 1,1,Speed
          'measure the speed
Debug ? Speed
          'lower number = faster
Goto SpeedMeas
```



Using Phototransistor with BS2: Applications—II

- LED-phototransistor pair can be used to detect air/liquid flow.
- Flow sight indicator shown in the diagram contains a ball.
- The ball has a fixed neutral position in the device when in no flow condition.
- The LED-phototransistor pair can be properly oriented so that the ball blocks the LED light from reaching phototransistor in the neutral position.
- When the device is subject to flow, the ball moves back and forth in the device.
- In this case, LED light falls on the phototransistor and the phototransistor conducts. This can be used to indicate that air/liquid flow exists.

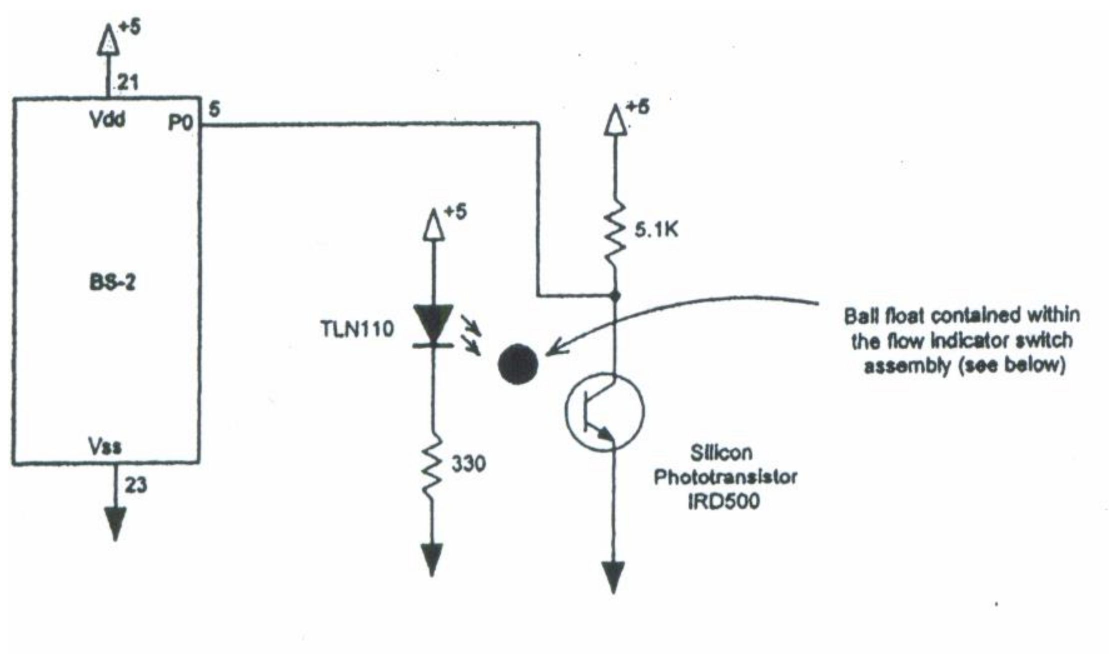




Flow Detector: Sample Code

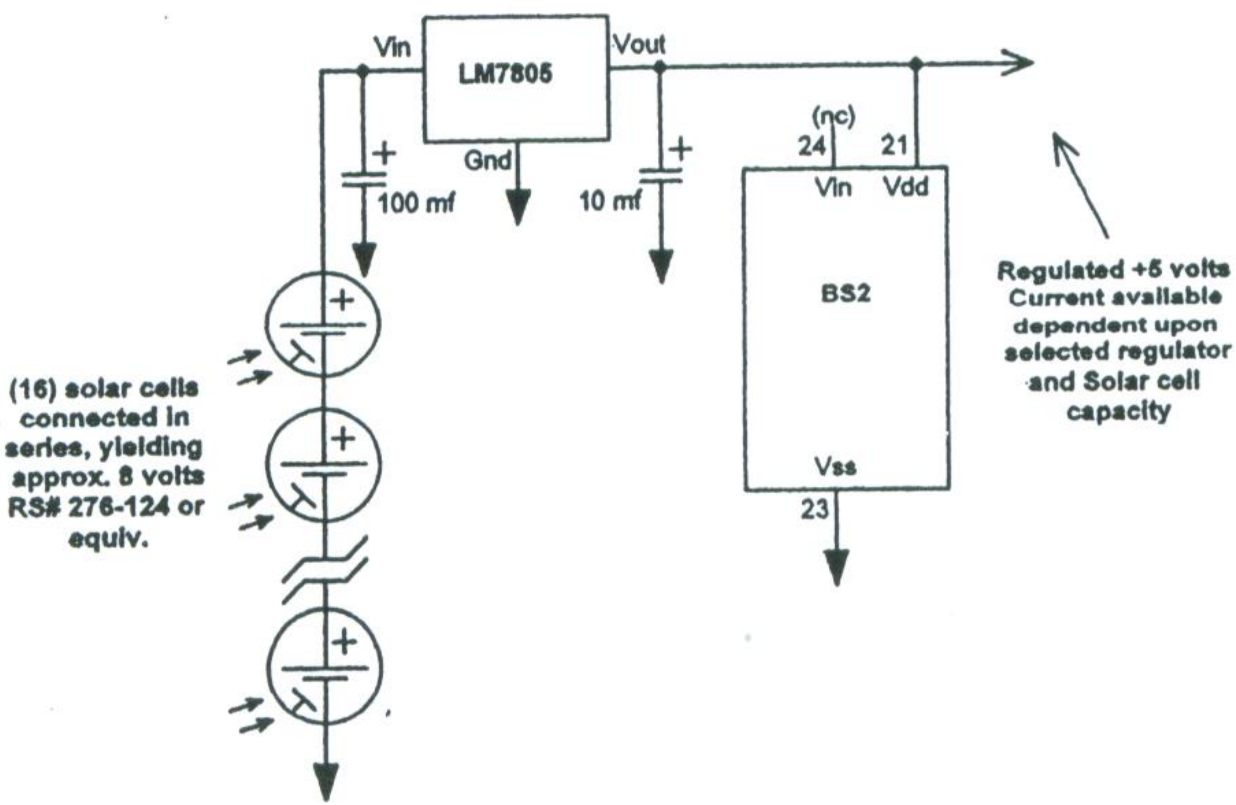
```
Monitor:
 If in0=0 then Airflow                  'ball not blocking light?
 debug "there is no flow"
 debug cr
 goto Monitor
 Airflow:
 debug "Air or liquid is flowing"       'ball has movement
 debug cr
 goto Monitor
```

"carriage return"



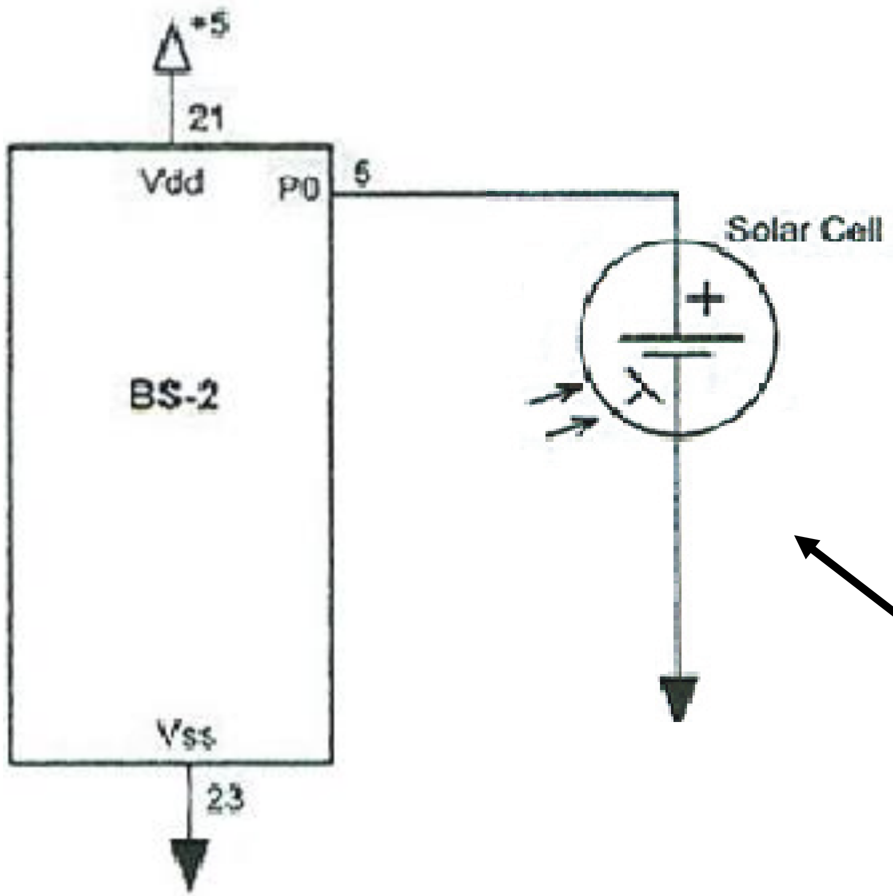
Using Solar Cells with BS2: Circuit #1

- In this circuit, we use 16 solar cells connected in series.
- Each solar cell produces approximately 0.5V. Thus, 16 solar cells connected in series provide a total of 8V, approximately.
- The o/p of this series connection of solar cells can be used to power a voltage regulator that provides regulated 5V input for BS2.



Using Solar Cells with BS2: Circuit #2 —I

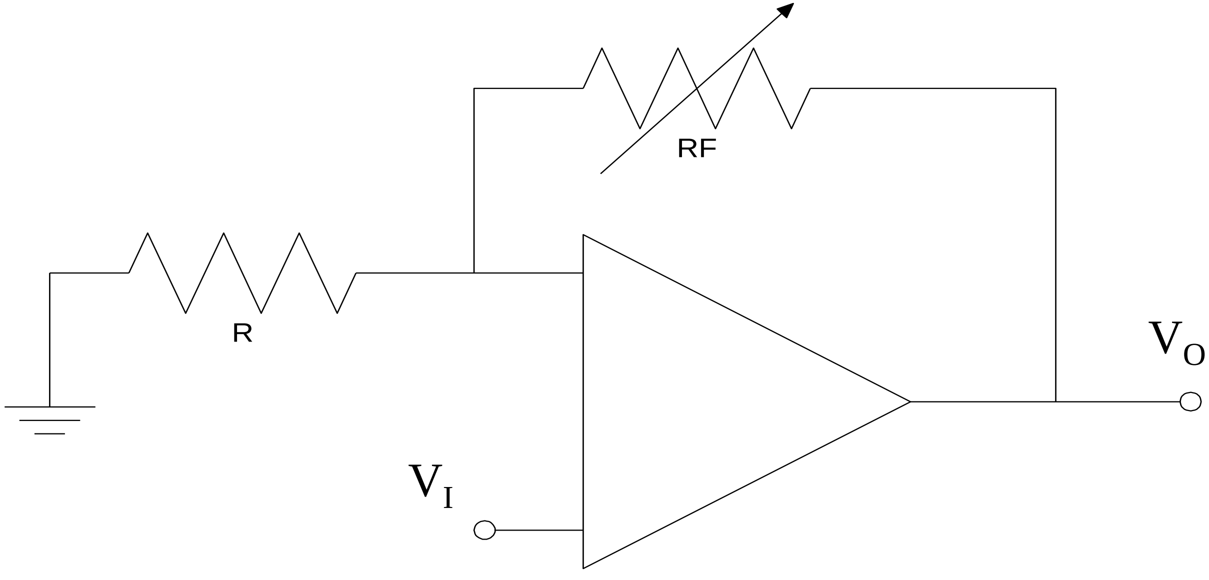
- In this circuit, we use a solar cell as a sensitive light detector.
- Recall a single solar cell outputs at most 0.5V! BS2 can’t identify this as high.



No Use!

Using Solar Cells with BS2: Circuit #2 —II

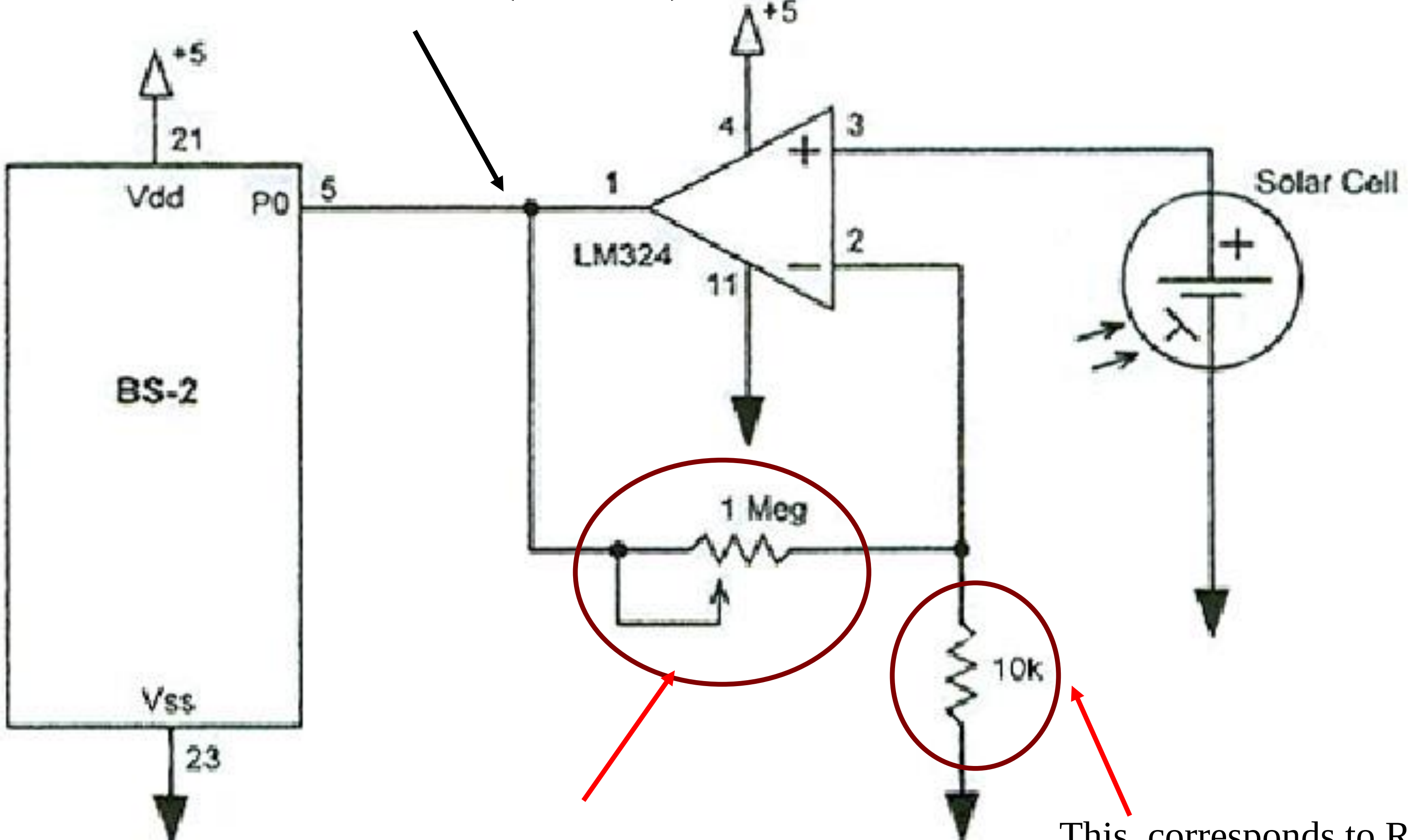
- Idea: process solar cell o/p through a non-inverting op-amp as shown.
- Denote the solar cell o/p as V_I. Note that V_I is i/p to the op-Amp.
- Denote the op-Amp o/p as V_O, which is interfaced to BS2 digital I/O pin P0.
  - By selecting an appropriate value for R_F, V_I can be scaled to be identified as high by P0.
  - When varying R_F, start with a value close to R and slowly increase (if you start with R_F >> R there is a possibility that V_O > 5V, which is not good for BS2).



$$V_0 = \left(1 + \frac{R_F}{R}\right) V_I$$

Using Solar Cells with BS2: Circuit #2—III

$$V_0 = \left(1 + \frac{R_F}{R}\right) V_I$$

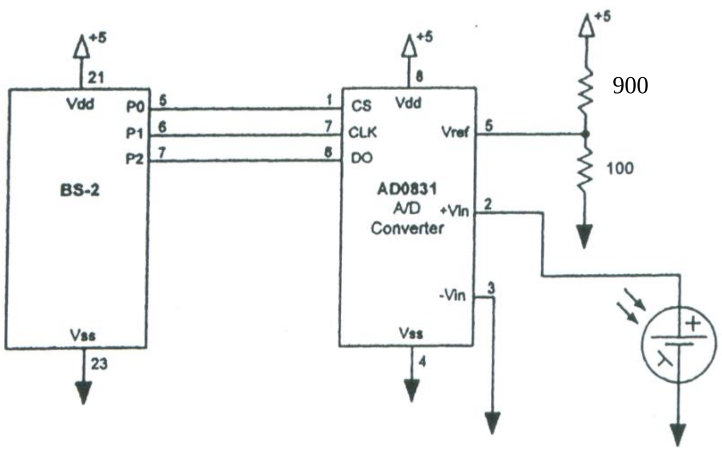


This corresponds to R.

Select R_F carefully. Begin with 10K and slowly increase. Do not violate $V_O \leq 5V$ (specially if the upper supply voltage of op-amp is larger than 5V).

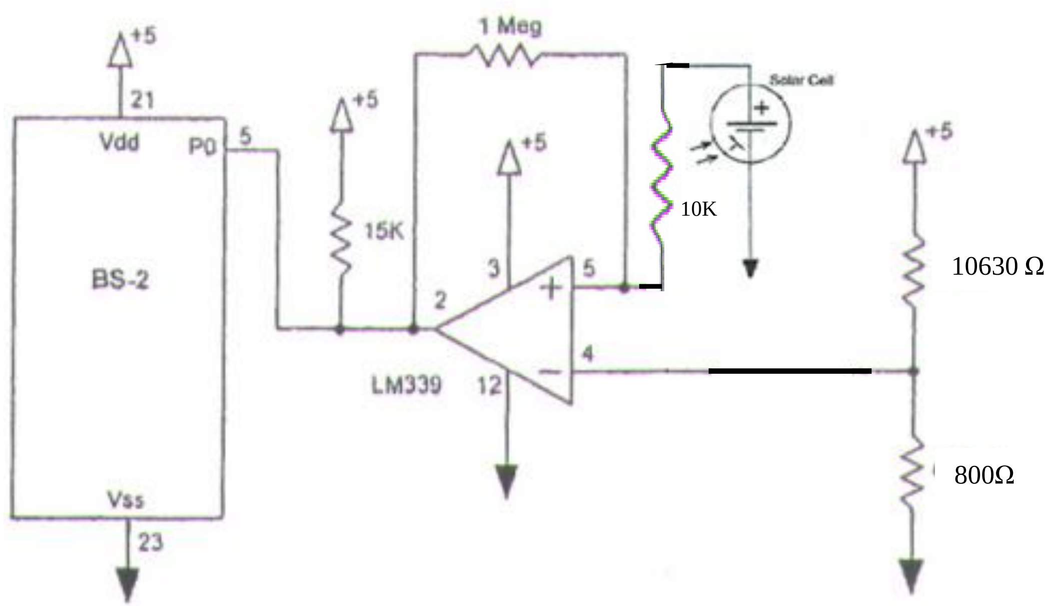
Using Solar Cells with BS2: Circuit #3

- Use of a solar cell and an A2D enables construction of a light level measuring device.
- Recall, a solar cell produces approximately 0.5V when placed in sunlight.
- Based on light intensity, the solar cell o/p varies (in low intensity sunlight, o/p decreases).
- For our light level sensor, we need to use a 0-0.5V span. That is BS2 and A2D circuitry is required to yield a measurement of voltage levels from 0V to 0.5V.
- Voltage o/p of solar cell can be correlated to light intensity incident upon it by appropriate calibration (i/p-o/p experiments or using manufacturer's data sheets).

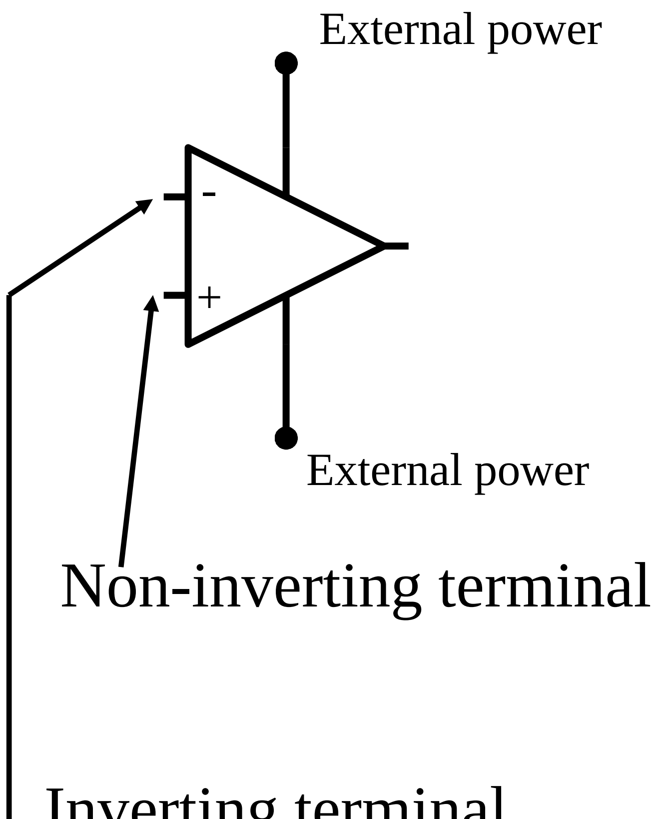


Using Solar Cells with BS2: Circuit #4

- Use comparator with positive feedback to detect if the solar cell is exposed to light.
- Solar cell produces 0.3 to 0.5V when exposed to light
- The inverting input of the comparator is biased to ≈ 0.35V.
- The positive feedback in the comparator produces a hysteresis effect such that
  - –When V_{SC}>0.354V, the comparator outputs high
  - –When V_{SC}<0.3V, the comparator outputs low



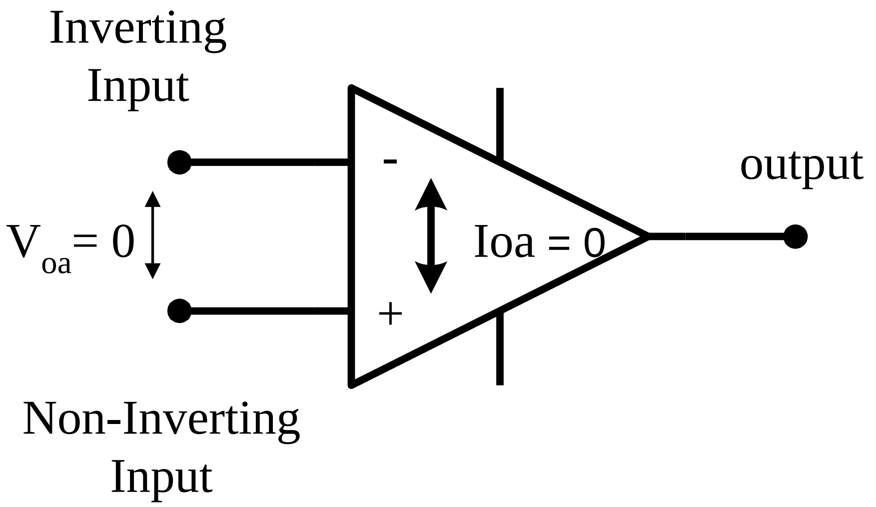
Op Amp 101 (Aside)



For LM358, external power is 5v

Two Rules for Op-Amps Circuits

- Op-amp input terminals (inverting and non-inverting terminals) have very high input impedance.
- No current flows through the op-amps input terminal ($I_{oa} = 0$).
- The voltage drop across the op-amp input terminals is zero ($V_{oa} = 0$).



Op Amp Applications

- Inverting Amplifier
- Non-Inverting Amplifier
- Summing Amplifier
- Difference Amplifier
- Integrator Amplifier
- Differentiator Amplifier
- Active Filters

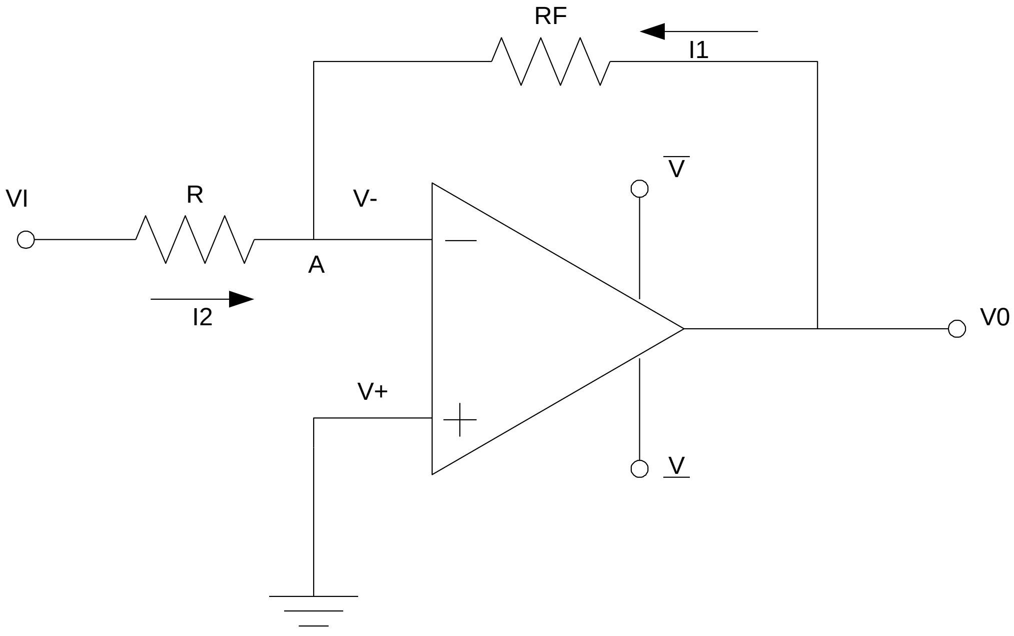
Inverting Op-Amp—I

- Condition:

$$I_- = I_+ = 0 \quad \text{and } V_- = V_+ \;\Rightarrow\; V_- = 0 \text{ since } V_+ = 0$$

$$I_1 = \frac{V_0 - V_-}{R_F} = \frac{V_0}{R_F}$$

$$I_2 = \frac{V_I - V_-}{R} = \frac{V_I}{R}$$



Inverting Op-Amp—II

- Since I_-=0, using KCL at A, we obtain:

$$I_1 + I_2 - I_- = 0 \quad \Rightarrow \quad I_1 + I_2 = 0$$

$$\Rightarrow I_2 = -I_1 \Rightarrow \frac{V_I}{R} = -\frac{V_0}{R_F}$$

- So

$$V_0 = -\left(\frac{R_F}{R}\right)V_I$$

- If R and R_F are replaced by impedances Z and Z_F, respectively and V_I and V_0 are replaced by their respective phasors, then

$$\frac{\overline{V_0}}{\overline{V_I}} = -\frac{Z_F}{Z}$$

$$\text{where } \overline{V_0} : P[V_0], \overline{V_I} = P[V_I]$$

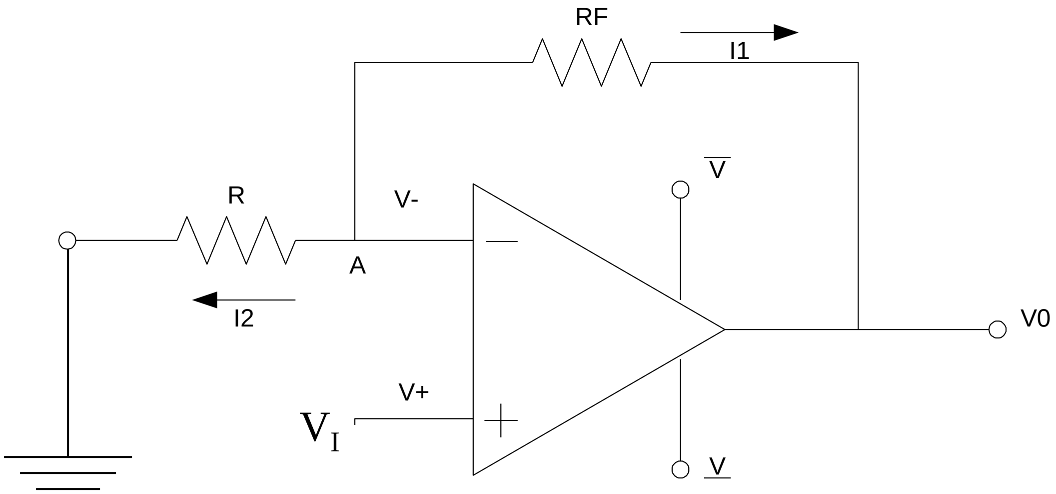
Non-Inverting Op-Amp—I

- Condition:

$$I_- = I_+ = 0 \quad \text{and } V_- = V_+ \;\Rightarrow\; V_- = V_I \text{ since } V_+ = V_I$$

$$I_1 = \frac{V_0 - V_I}{R_F}$$

$$I_2 = \frac{V_I}{R}$$



Non-Inverting Op-Amp—II

- Since I_{-}=0, by applying KCL at A we obtain:

$$I_1 - I_2 - I_- = 0 \quad \Rightarrow \quad I_1 - I_2 = 0 \quad \Rightarrow \quad I_1 = I_2$$

$$\Rightarrow \frac{V_I}{R} = \frac{V_0 - V_I}{R_F} \Rightarrow \frac{V_0}{R_F} = \frac{V_I}{R} + \frac{V_I}{R_F}$$

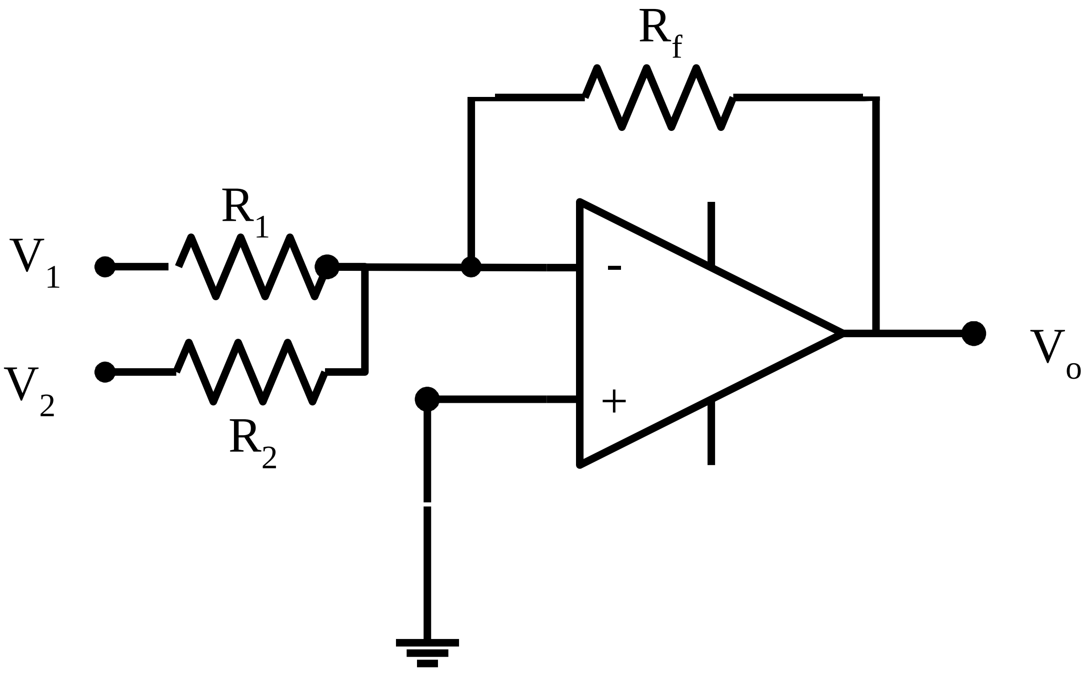
- So

$$V_0 = \left(1 + \frac{R_F}{R}\right) V_I$$

- Once again, if AC inputs and outputs are involved and if R and R_F are replaced by Z and Z_F, respectively, then

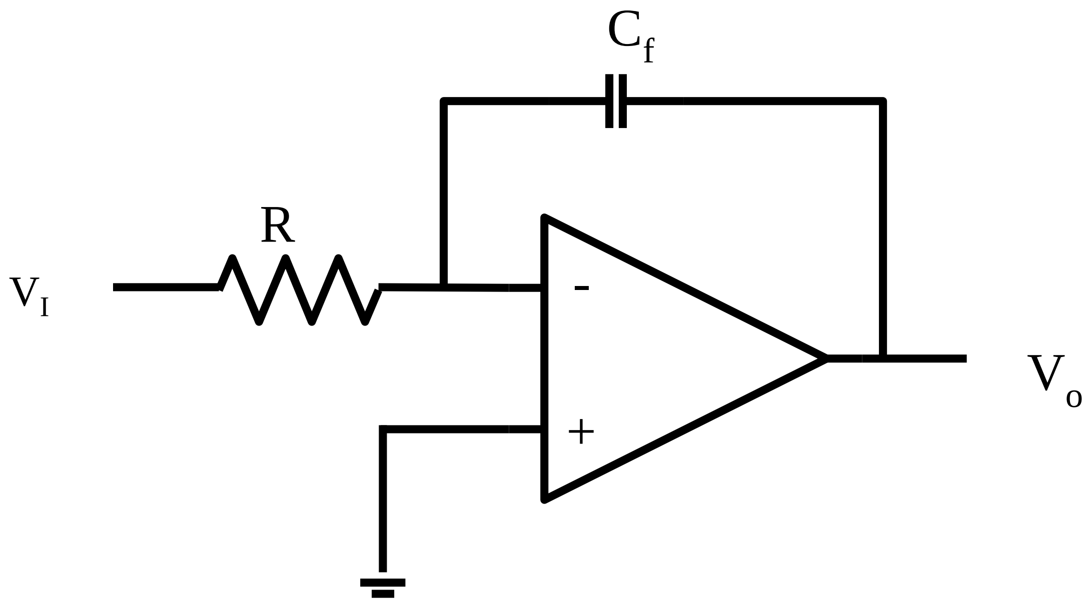
$$\frac{\overline{V_0}}{\overline{V_I}} = \left(1 + \frac{Z_F}{Z}\right)$$

Summing Amplifier



$$V_o = -\frac{R_f}{R_1}V_1 - \frac{R_f}{R_2}V_2$$

Integrator Amplifier

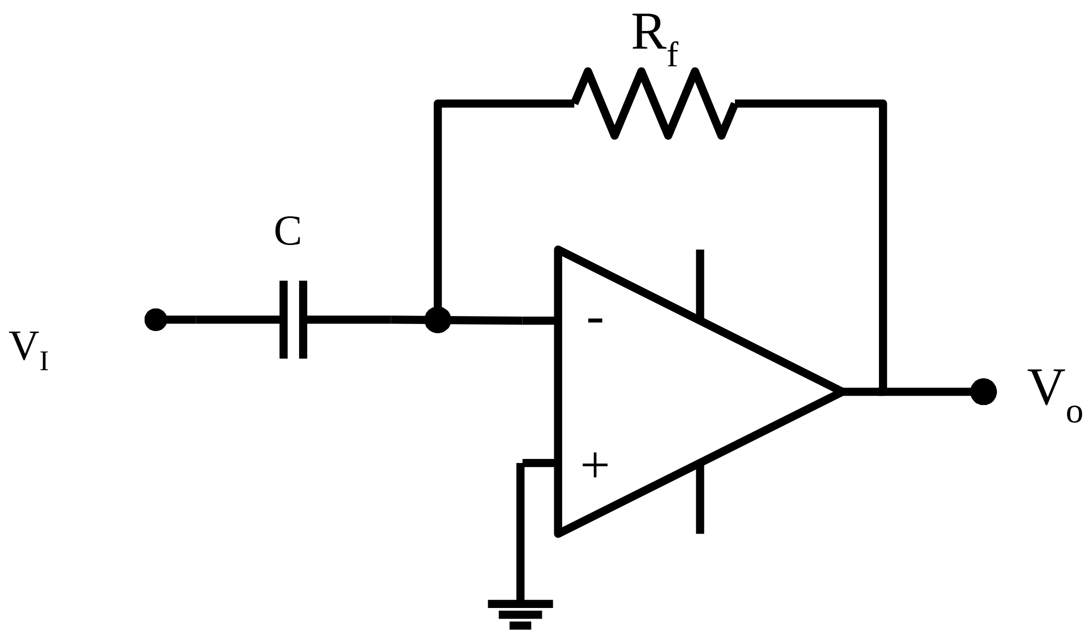


Recall $\dfrac{\overline{V_0}}{\overline{V_I}} = -\dfrac{Z_F}{Z}$. Also, recall $Z_F = \dfrac{1}{j\omega C_f}$ and $Z = R$.

Then, $\dfrac{\overline{V_0}}{\overline{V_I}} = -\dfrac{1}{j\omega C_f R} \quad \Rightarrow \quad$ In Laplace domain: $\dfrac{V_0}{V_I}(s) = -\dfrac{1}{s} \times \dfrac{1}{C_f R}$

$V_0 = -\dfrac{1}{C_f R} \int_{t_0}^{t} V_I \, d\tau$ since in time domain $\dfrac{1}{s}$ corresponds to integration!

Differentiator Amplifier

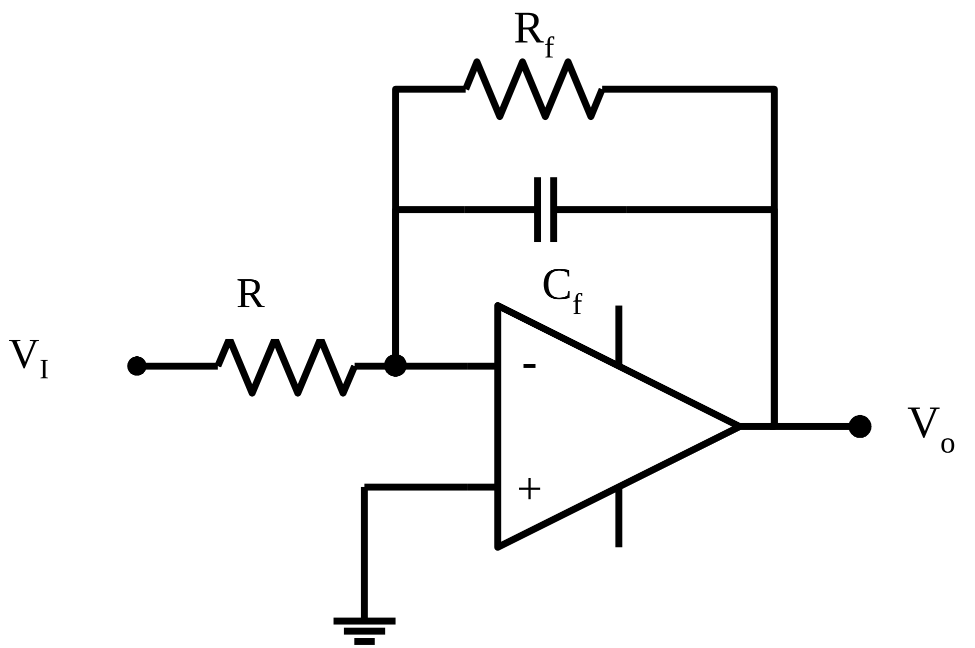


Recall $\dfrac{\overline{V_0}}{\overline{V_I}} = -\dfrac{Z_F}{Z}$. Also, recall $Z_F = R_\mathrm{f}$ and $Z = \dfrac{1}{j\omega C}$.

Then, $\dfrac{\overline{V_0}}{\overline{V_I}} = -j\omega R_\mathrm{f} C \quad \Rightarrow \quad$ In Laplace domain: $\dfrac{V_0}{V_I}(s) = -s \times R_\mathrm{f} C$

$V_0 = -R_\mathrm{f} C \dfrac{dV_I}{dt}$ since in time domain s corresponds to differentiation!

Active First-Order Low-Pass Filter



Recall $\dfrac{\overline{V_0}}{\overline{V_I}} = -\dfrac{Z_F}{Z},\ Z_F = \dfrac{R_f}{j\omega C_f R_f + 1}$ and $Z = R$.

Then, $\dfrac{\overline{V_0}}{\overline{V_I}} = -\dfrac{R_f / R}{j\omega C_f R_f + 1}$

$\Rightarrow$ In Laplace domain: $\dfrac{V_0}{V_I}(s) = -\dfrac{R_f / R}{sC_f R_f + 1}$, Low-Pass filter!

Thermistor—I

- Temperature dependent resistor.
- A small epoxy coated element with a pair of electrical leads.
  - The epoxy encapsulation protects the sensor element.
- The sensing element of a thermistor is made using
  - compressed mixture of sintered oxides of manganese, nickel, copper, and cobalt.
- The sensing element is essentially a semiconductor material with an effective energy gap E_g (≈1 electron-volt).
- The resistance of thermistor satisfies:

$$R \propto \exp\left(\frac{E_g}{2kT}\right)$$

$\underbrace{\text{Therm}}_{\text{Thermal}}\ \underbrace{\text{istor}}_{\text{Resistor}}$

- k: Boltzman constant (8.6×10^{-5} eV/K)
- T: temperature in degree Kelvin (°K)

Thermistor—II

- Let $\beta \approx E_g / 2k$ and let *A* be a constant of proportionality. Then:

$$R = A\exp\left(\frac{\beta}{T}\right)$$

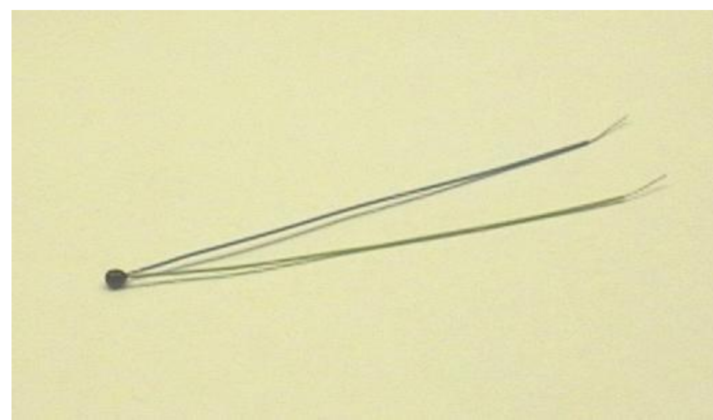
- Usually β=3000 to 6000 °K.
- Suppose at a temperature T_0, thermistor's resistance is R_0. Then:

$$R = Ae^{\frac{\beta}{T}} \Rightarrow R_0 = Ae^{\frac{\beta}{T_0}}$$

$$\Rightarrow A = R_0 e^{-\frac{\beta}{T_0}}$$

- Thus, we obtain:

$$R = R_0 \exp\left(\frac{\beta}{T} - \frac{\beta}{T_0}\right)$$



Thermistor—III

- Taking the natural log of

$$R = R_0 \exp\left(\frac{\beta}{T} - \frac{\beta}{T_0}\right)$$

and manipulating the resulting equation, we obtain the following.

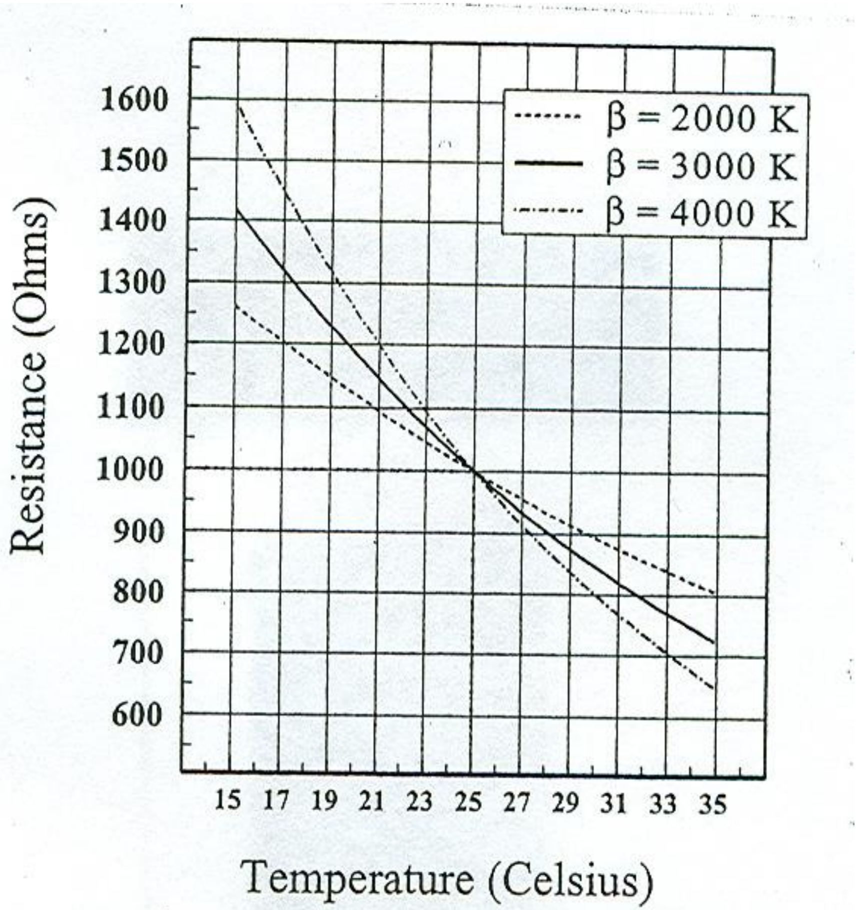
$$\ln R = \ln R_0 + \ln\left[\exp\left(\frac{\beta}{T} - \frac{\beta}{T_0}\right)\right]$$

$$\ln R = \ln R_0 + \frac{\beta}{T} - \frac{\beta}{T_0}$$

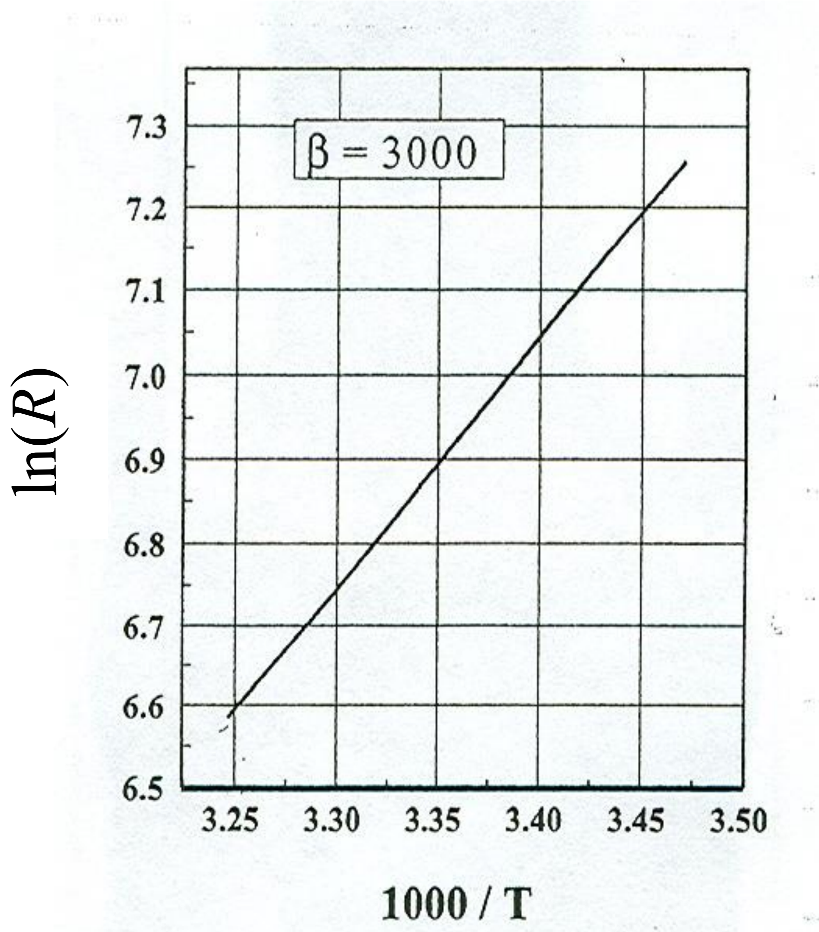
$$\ln R = \frac{\beta}{T} + \left(\ln R_0 - \frac{\beta}{T_0}\right)$$

- Thus, plot of reciprocal of T v/s ln(R) yields a linear curve.

Thermistor—IV



Temperature dependence of thermistors made from three slightly different semiconductor compounds. In this example, all the sensors have a resistance of 1000Ω at the nominal temperature of 25°C



Data for a thermistor made of a particular semiconductor illustrating the reciprocal temperature dependence of ln(R).

Linearization of Thermistor—I

- Although thermistor's temperature v/s resistance characteristic is quite nonlinear, in a small neighborhood of an operating point, a thermistor can be viewed as a linear device
- Specifically, let T_0 be the nominal operating temperature being monitored. Let a thermistor's resistance at temperature T_0 be R_0.
- When temperature changes from T_0 to T, the new resistance value for thermistor is:

$$R = R_0 \exp\left(\frac{\beta}{T} - \frac{\beta}{T_0}\right)$$

$$\Rightarrow \quad \frac{dR}{dT} = R_0 \exp\left(\frac{\beta}{T} - \frac{\beta}{T_0}\right) \times \left(-\frac{\beta}{T^2}\right)$$

- Evaluating dR/dT at the nominal operating point, we obtain:

$$\left.\frac{dR}{dT}\right|_{T=T_0} = -\frac{\beta R_0}{T_0^{\,2}}$$

- Thus, the slope of T v/s R curve at T=T_0 is $-\dfrac{\beta R_0}{T_0^{\,2}}$.

Linearization of Thermistor—II

- Recall, equation of a line is:

$$y = mx + c$$

- At temp T_0, we obtain:

$$R_0 = mT_0 + c$$

$$c = R_0 - mT_0$$

- Then, at temperature T, we obtain:

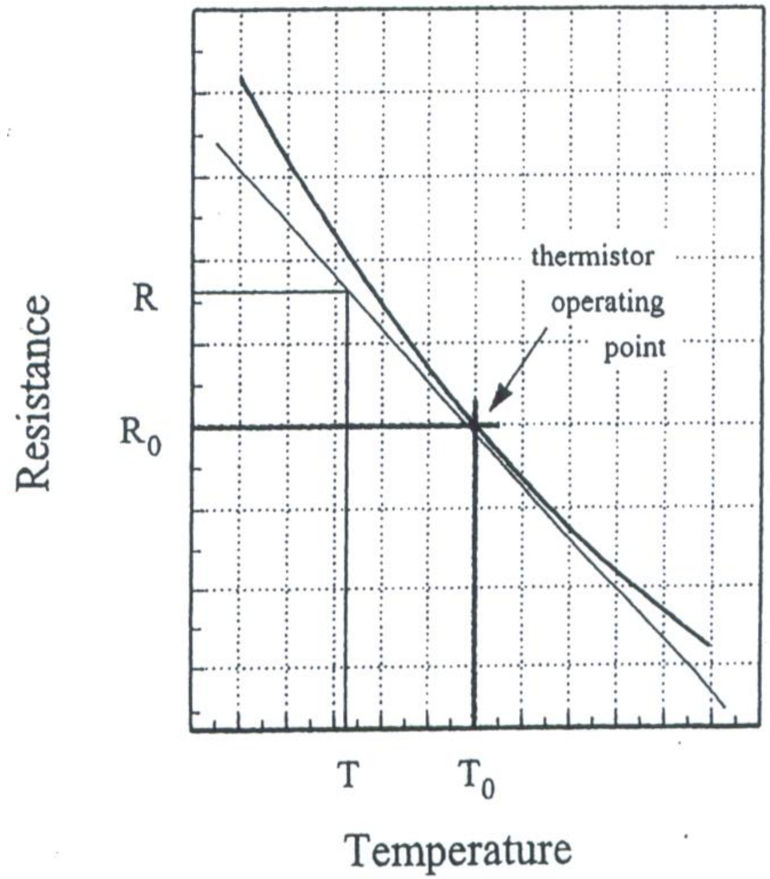
$$R = mT + c = mT + R_0 - mT_0$$

$$\Rightarrow R - R_0 = m\left(T - T_0\right) = -\frac{\beta R_0}{T_0^{\,2}}\left(T - T_0\right)$$

$$R - R_0 = \frac{\beta R_0}{T_0^{\,2}}\left(T_0 - T\right)$$

- Thus, using linear approximation, at a temperature T in the NBHD of T_0, resistance R of the thermistor is:

$$R = R_0 + \frac{\beta R_0}{T_0^{\,2}}\left(T_0 - T\right)$$



Thermistor operating about the point (R_0, T_0). A tangent line at this operating point provides the linear approximation to $R(T)$.

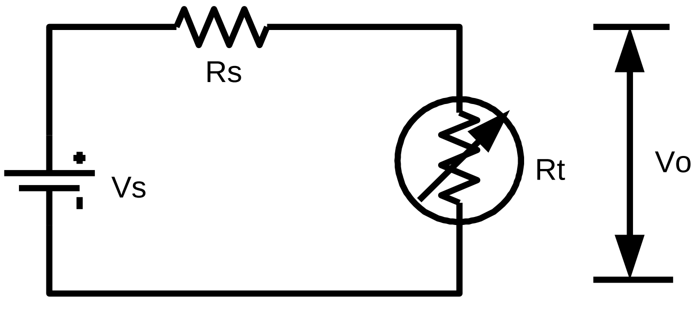
A Simple Thermometer

- Use a series connection of a known resistor R_s and a thermistor and apply a known voltage V_s across the series network
- V_0 can be measured and it can be correlated to R_T.

$$V_o = \frac{R_T}{R_T + R_s} V_s$$

$$\Rightarrow (V_s - V_o) R_T = V_o R_s$$

$$\Rightarrow R_T = \frac{V_o R_s}{(V_s - V_o)}$$



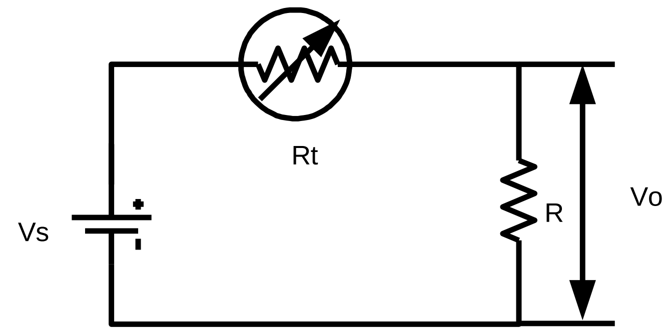
- Note V_0 vs. R_T is nonlinear relationship. In addition, R_T vs. temperature is nonlinear.
- We can possibly collect V_0 vs. T data for known values of T. Then when thermistor is subjected to unknown temperature, having measured V_0, we can get T using interpolation

Linearization with a Series Resistor —I

- Voltage division yields:

$$V_o = V_s\left(\frac{R}{R_T + R}\right) = \frac{V_s}{1+\dfrac{R_T}{R}}$$

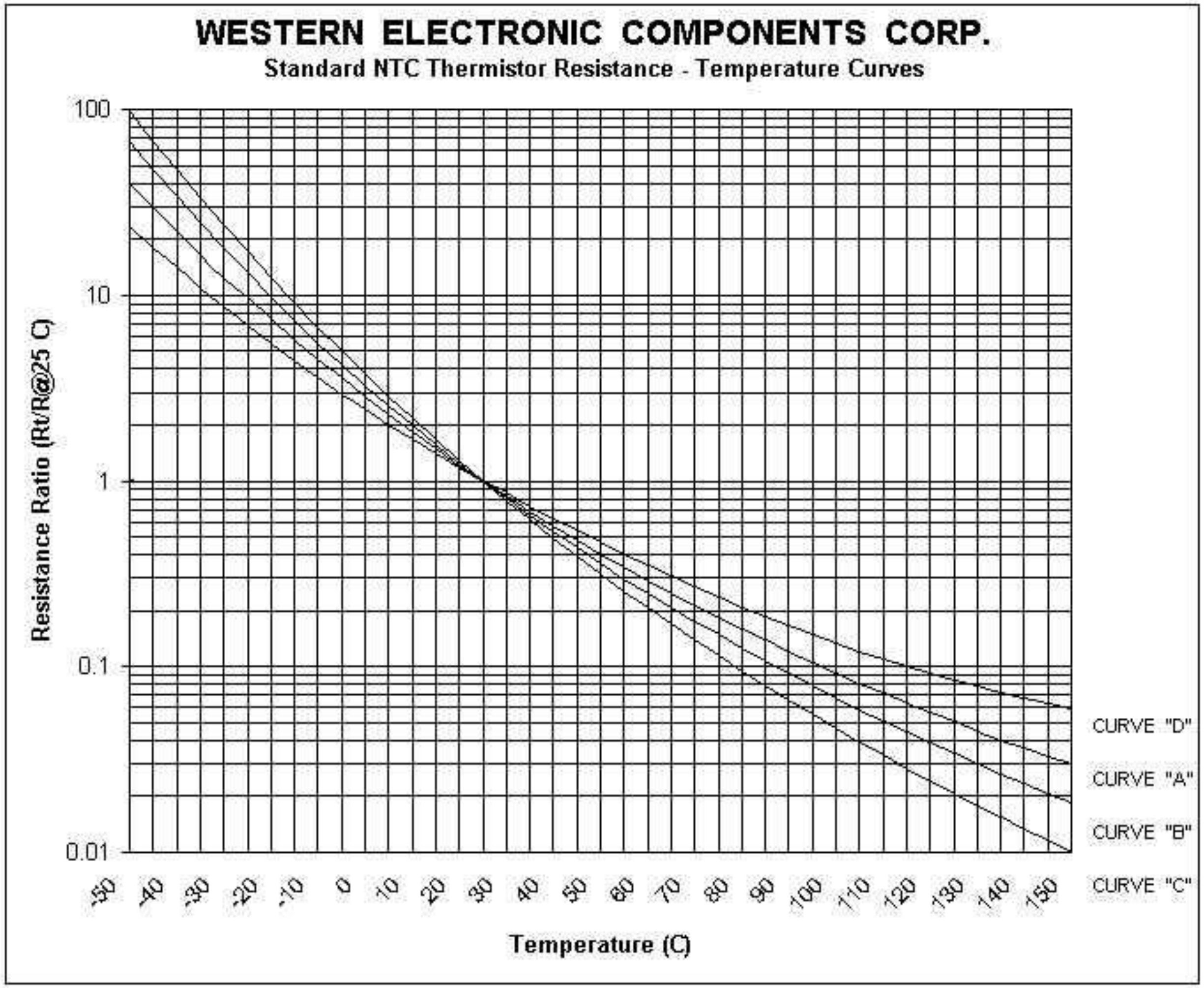
- R_T: temperature dependent resistor
- R_{25}: resistance of R_T at $T = 298K$
- R: known resistance

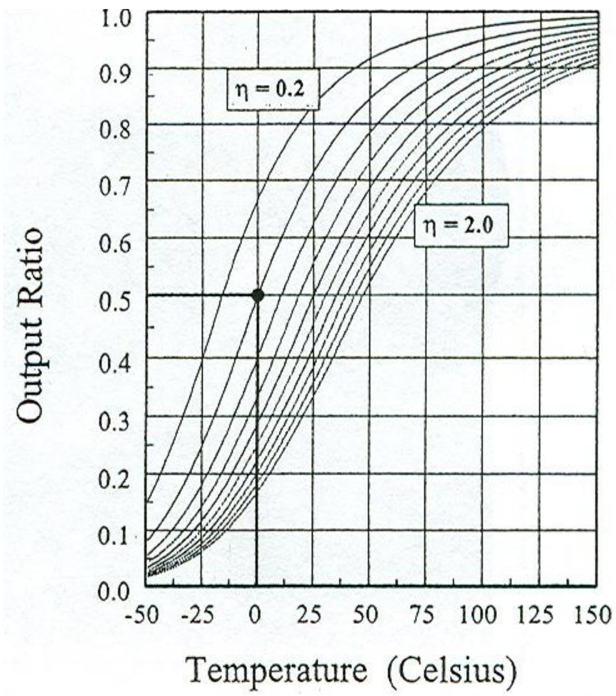


$$\frac{R_T}{R} = \frac{R_T}{R_{25}} \times \frac{R_{25}}{R} = \eta\frac{R_T}{R_{25}} \text{ with } \eta \triangleq \frac{R_{25}}{R}$$

$$\Rightarrow \frac{Vo}{Vs} = \frac{1}{1+\eta\dfrac{R_T}{R_{25}}}$$

Linearization with a Series Resistor —II





$$\frac{Vo}{Vs} = \frac{1}{1+\eta\frac{R_T}{R_{25}}},\quad \frac{Vo}{Vs}$$ is termed o/p ratio.

Linearization with a Parallel Resistor—I

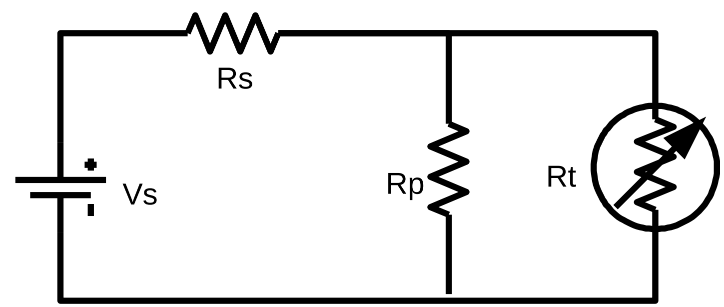
- Consider the given diagram with known R_s, R_p, and V_s. It follows that:

$$\mathrm{R}_{eq} = R_p \parallel R_T = \frac{R_p R_T}{R_p + R_T}$$

- Let, the nominal operating temperature be T_0 with nominal thermistor resistance $R_t|_{T=T_0}=R_0$. Let us select $R_p=R_0$. Then,

$$\mathrm{R}_{\mathrm{eq}} = \frac{R_0 R_T}{R_0 + R_T} = \frac{R_0}{\frac{R_0}{R_T}+1}, \quad \text{where we now use: } R_T = R_0 \exp\left(\frac{\beta}{T} - \frac{\beta}{T_0}\right)$$

$$\mathrm{R}_{\mathrm{eq}} = \frac{R_0}{1 + e\,\mathrm{xp}\left(-\frac{\beta}{T} + \frac{\beta}{T_0}\right)} = \frac{R_0}{1+e^{\varepsilon}}$$



where $\varepsilon \triangleq -\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)$

$$e^{\varepsilon} = 1 + \varepsilon + \frac{\varepsilon^2}{2!} + \cdots$$

when $T \approx T_0$, such that $T - T_0$ is small and $TT_0 >> \beta$,

then, $\varepsilon << 1$. Therefore, $R_{\mathrm{eq}} = \dfrac{R_0}{1+\left(1+\varepsilon+\frac{\varepsilon^2}{2!}+\cdots\right)} \approx \dfrac{R_0}{2+\varepsilon} \approx R_0\left(\dfrac{1}{2} - \dfrac{\varepsilon}{4}\right)$

Linearization with a Parallel Resistor—II

- Next, with $\varepsilon = \dfrac{T - T_0}{TT_0}\beta, \quad TT_0 \approx T_0^{\,2}, \quad \Delta T \approx T - T_0$

  we obtain $\varepsilon = \dfrac{\Delta T}{T_0^{\,2}}\beta$ which yields the following.

$$R_{\text{eq}} = R_0\left(\frac{1}{2} - \frac{\Delta T\beta}{4T_0^{\,2}}\right)$$

- Now, the equivalent resistance is a linear function of temperature change ΔT.
- Also, it follows from the above that

$$\frac{\mathrm{d}R_{\text{eq}}}{\mathrm{d}T} = \frac{-R_0\beta}{4T_0^{\,2}}\frac{\mathrm{d}}{\mathrm{d}T}(\Delta T) = \frac{-R_0\beta}{4T_0^{\,2}}$$

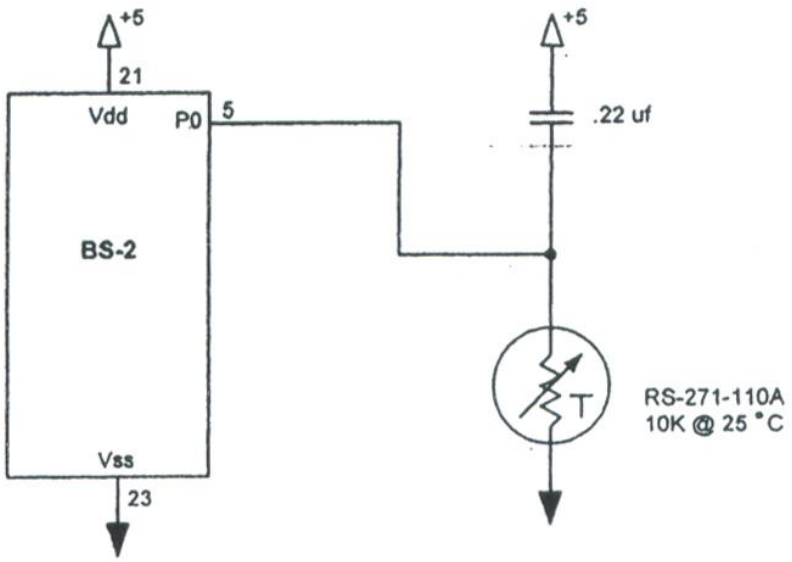
- Recall, earlier we had

$$\left.\frac{\mathrm{d}R}{\mathrm{d}T}\right|_{T=T_0} = \frac{-\beta R_0}{T_0^{\,2}}$$

- So, now the sensitivity has dropped to one-quarter of its original value.

BS2 with Thermistor—I

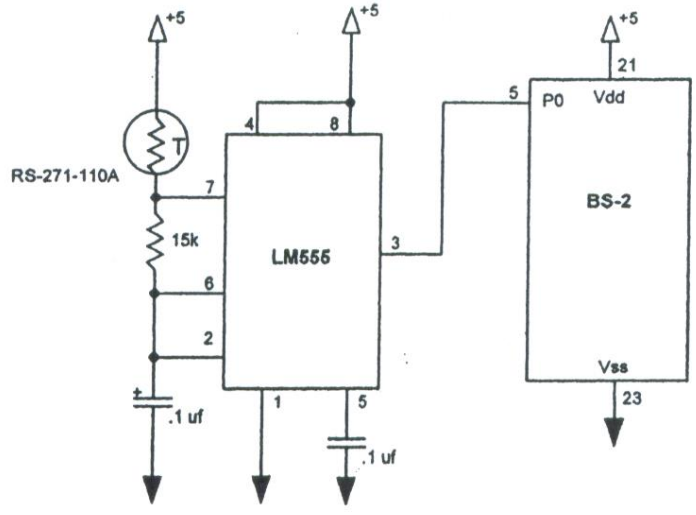
- Use thermistor as the unknown resistive element of a series RC network.
- Using the RCTIME command of BS2, determine the value of thermistor resistance under different temperature conditions.
- Increasing temperature lowers thermistor resistance → lower RCTIME value.



A thermistor used in a simple R/C time circuit

BS2 with Thermistor—II

- Use thermistor as one of the resistors connected to LM555 timer.
- The thermistor resistance varies in response to varying temperature condition thus altering the duration of high pulse output in the astable operating mode.
- → o/p frequency of 555 timer varies in response to the varying temperature!
- Use the pulsin command of BS2, to measure the time period between pulses and correlate this period to thermistor resistance and temperature that the thermistor is exposed to.

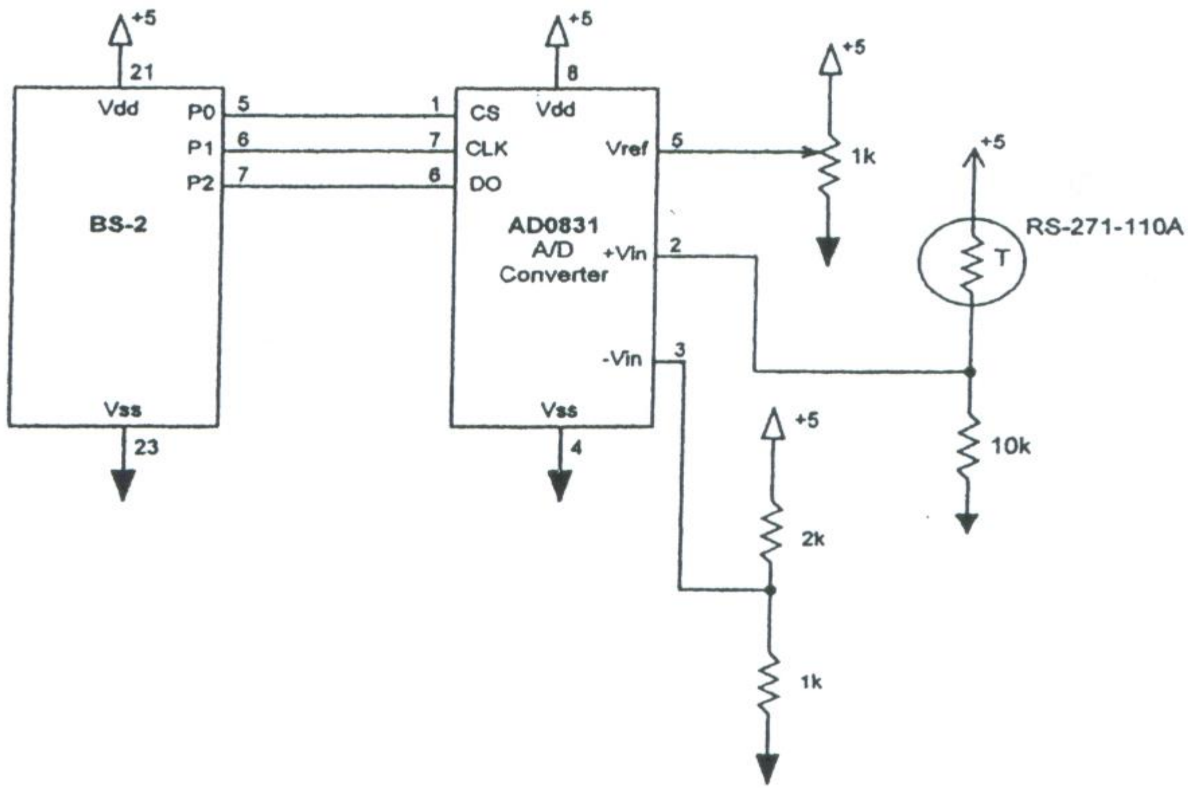


Changing resistance in the thermistor alters the pulse width of the 555 timer

```
HighDura var word
monitor:
pulsin 0,1,HighDura
debug ? HighDura
goto monitor
```

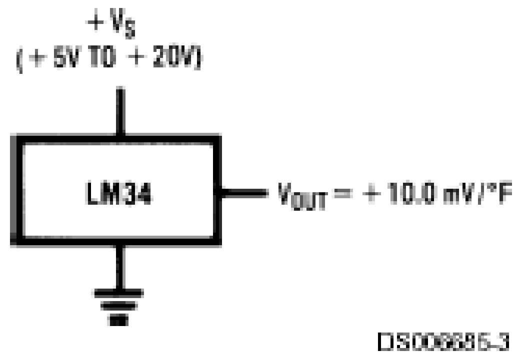
BS2 with Thermistor—III

- Thermistor is used as an unknown resistor in a voltage divider circuit.
- Voltage divider o/p varies with variation in thermistor resistance (in response to varying temperature condition).
  - Higher temperature → lower thermistor resistance → higher voltage divider o/p.
- The voltage divider o/p is digitized using an ADC and data is transferred to BS2.



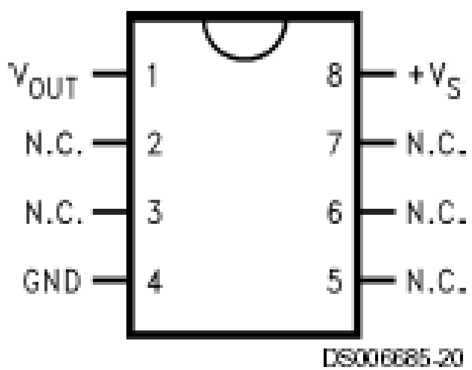
BS2 with Linear Temperature Sensor—I

- The National Semiconductor LM34 is a precision temperature sensor that outputs 10 mV/°F. The measurement of temperature in °C can be done using LM35



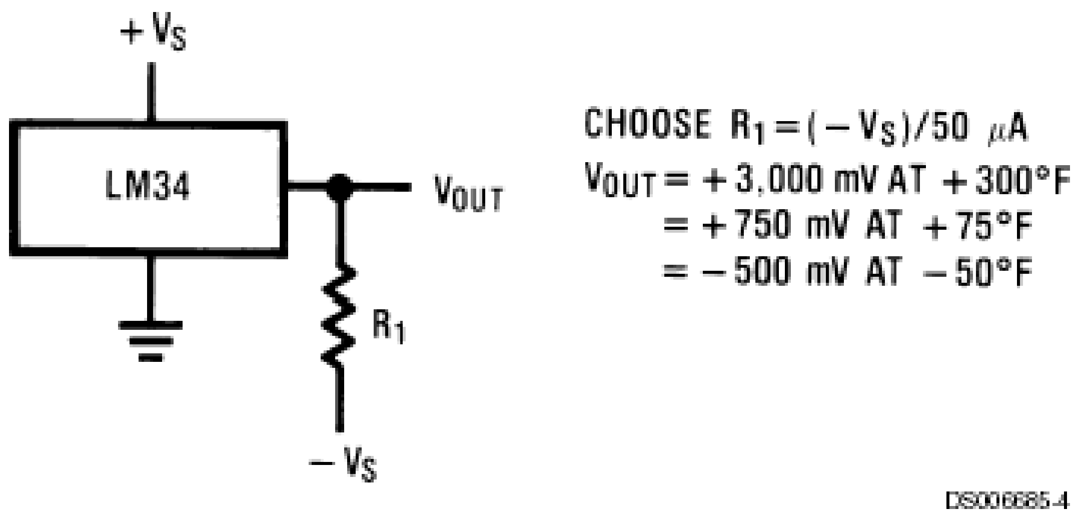
Basic Fahrenheit Temperature Sensor
(+5° to +300°F)

SO-8
Small Outline
Molded Package



N.C. = No Connection

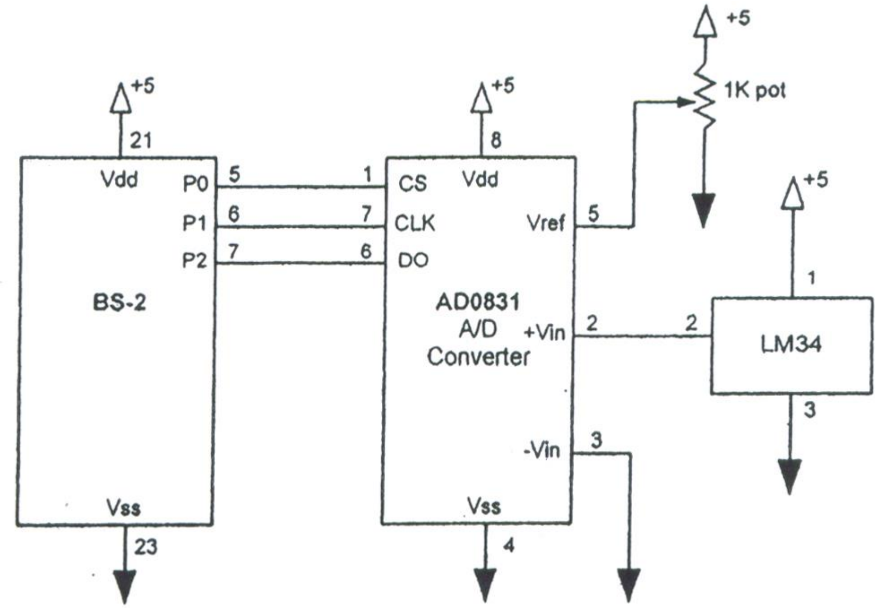
Top View



Full-Range Fahrenheit Temperature Sensor

BS2 with Linear Temperature Sensor—II

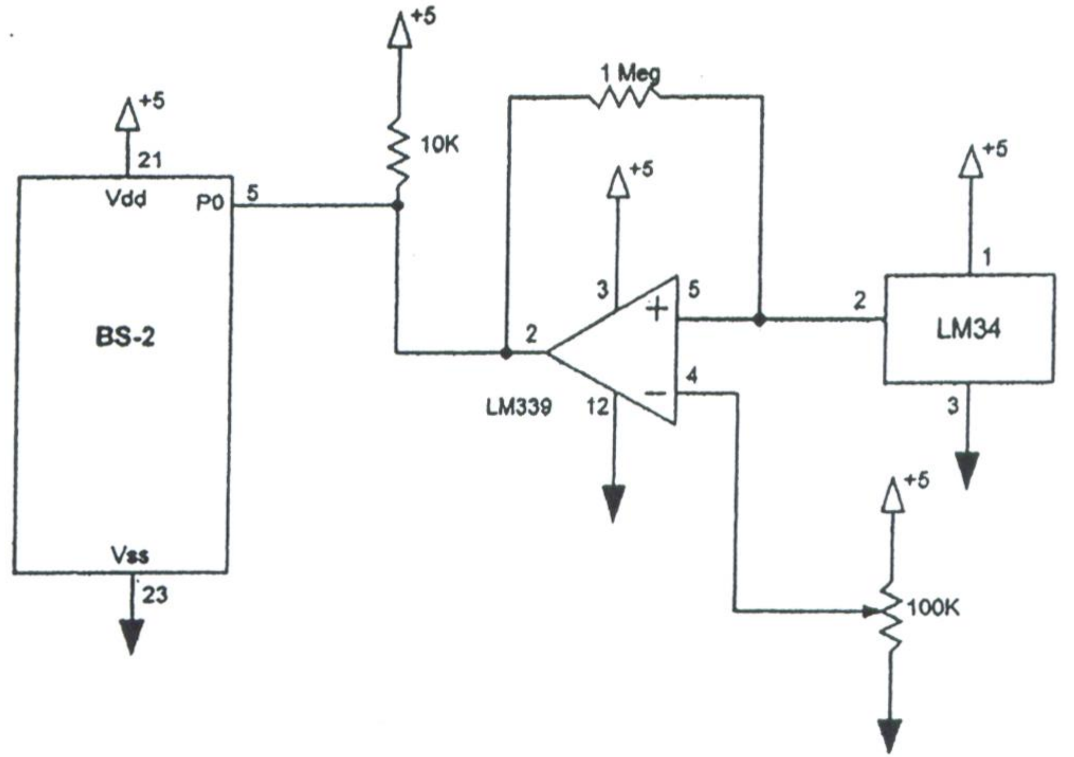
- LM34 outputs analog voltage proportional to temperature input.
- LM34 o/p is interfaced to BS2 using an A2D.
- The A2D digitizes the LM34 voltage o/p.
- Based on the range of temperature measurement needed in a given application, the span and zero offset of the A2D can be adjusted to utilize full scale of A2D.



Reading the digital value of the temperature sensor

Linear Temperature Sensor—III

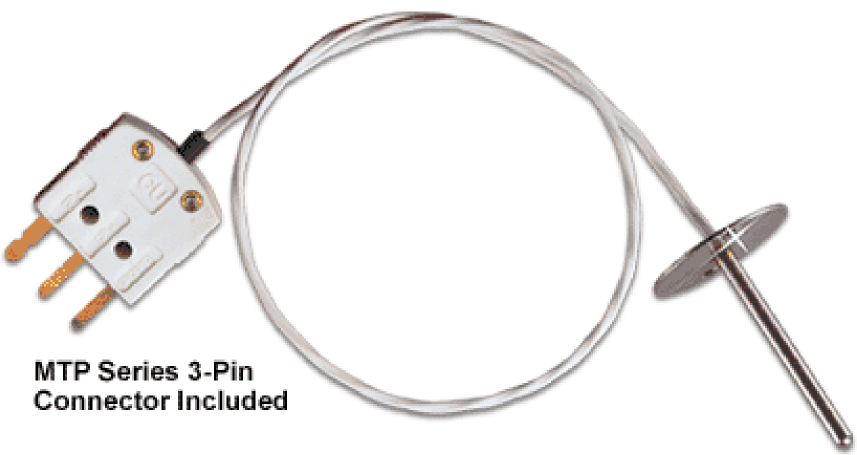
- A particular application requires determination of threshold temperature crossover.
- The potentiometer can be adjusted to set the bias voltage at PIN4 of the comparator.
  - The bias voltage corresponds to the threshold temperature.
- When LM34 voltage o/p falls below the voltage applied at PIN4 of comparator, the comparator o/p is low.



A simple temperature "alarm" circuit

Other Temperature Sensors

- Resistance Temperature Detector (RTD)



- Thermocouple: Seeback effect to transform a temperature difference to a voltage difference

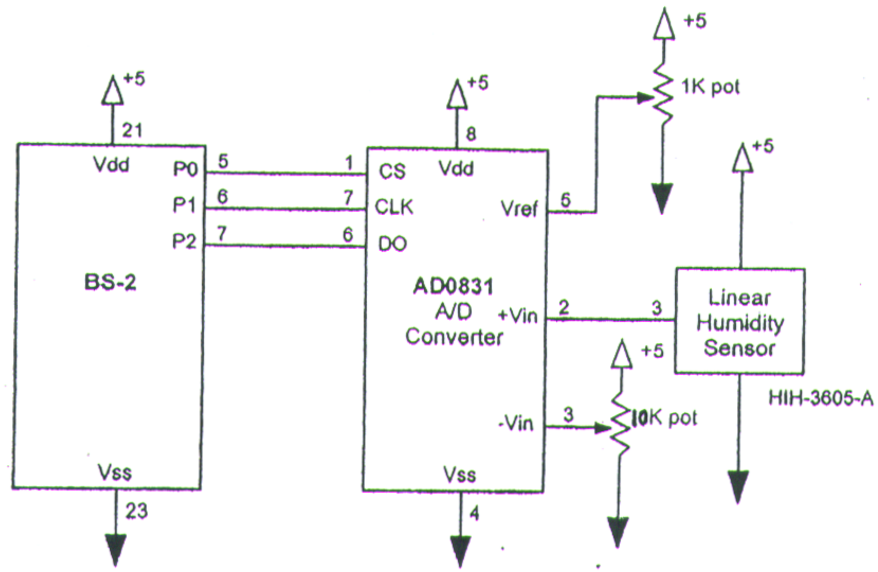
Humidity/Moisture Sensors

Humidity Sensor

Direct moisture sensor to factory computer

BS2 with Humidity/Moisture Sensors—I

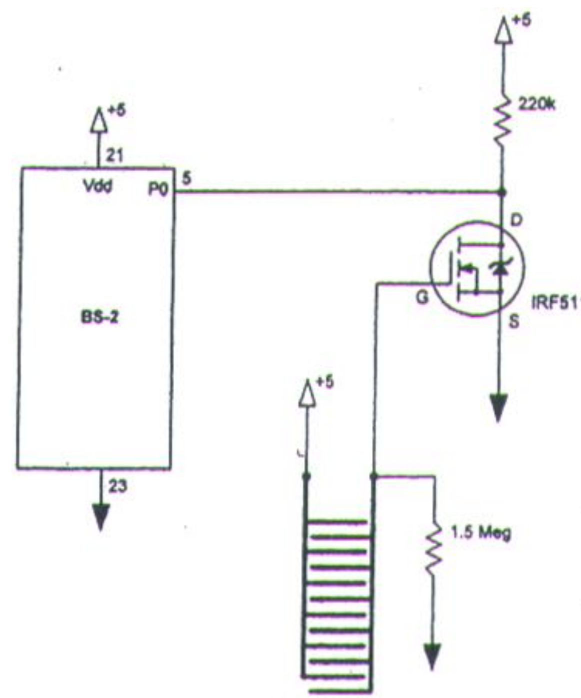
- A linear relative humidity sensor is used to measure the amount of moisture in surrounding air.
- The sensor outputs 0.8 – 3.9 volts over a span of 0 – 100% RH.
- The given voltage span is valid for 25°C temperature.
- A decrease in the ambient temperature increases the upper span of sensor.
- To account for temperature dependence of sensor, temperature compensation may be included.
- Since the sensor outputs analog voltage an A2D circuit with proper bias voltage for span and zero offset should be used to utilize full scale of A2D.



The analog voltage produced by the humidity sensor is converted to a binary value by the A/D converter

BS2 with Humidity/Moisture Sensors——II

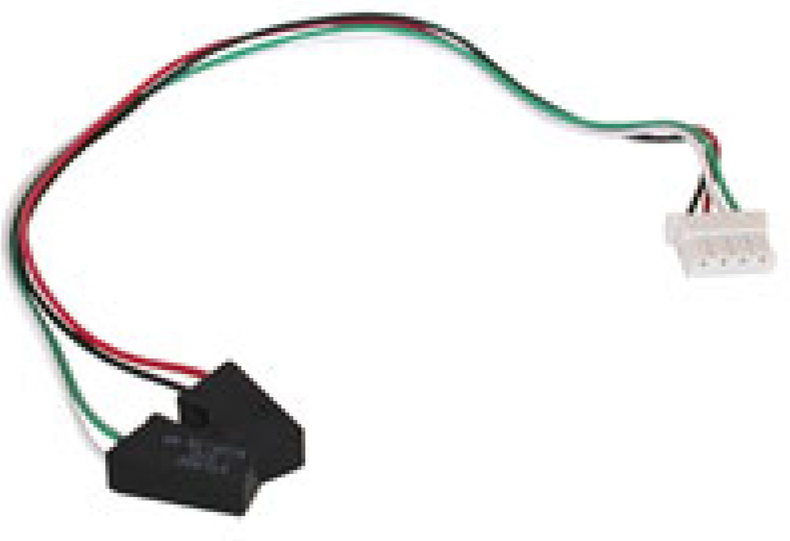
- Two interlocking, non-touching wires form a moisture sensor.
- Just two non-touching bare wires as shown can form the sensor or one can etch the given pattern on a PCB.
- Existence of water/dampness causes the gap between non-touching fingers to be bridged causing conduction to occur between +5V and ground via 1.5 MΩ resistor.
- When the two wires of the sensor are in conduction, the gate of the enhancement-type, N-channel MOSFET is driven high. This allows the source-drain pair to conduct.
- No water, no moisture:
  - $\rightarrow$ Two wires of sensor not conducting.
  - $\rightarrow$ Gate voltage =source voltage.
  - $\rightarrow$ Drain-source pair not conducting.
  - $\rightarrow$ P0 pulled high.
- When water is present on sensor, P0 goes low.



Simple moisture sensor

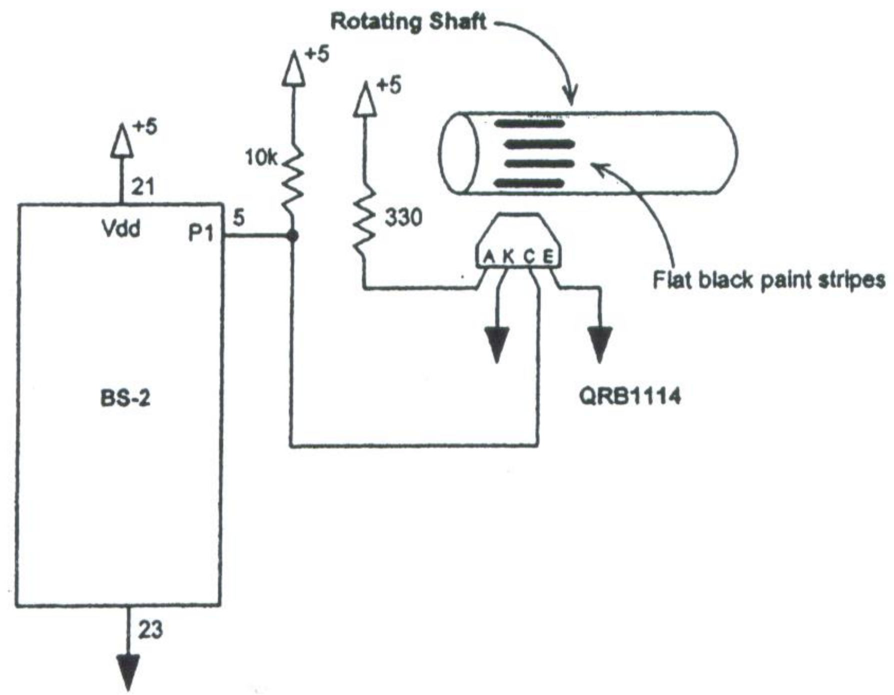
Reflective Optical Sensors

- Detect reflected light
- Emitter-detector pair in one unit



BS2 with Reflective Optical Sensors—I

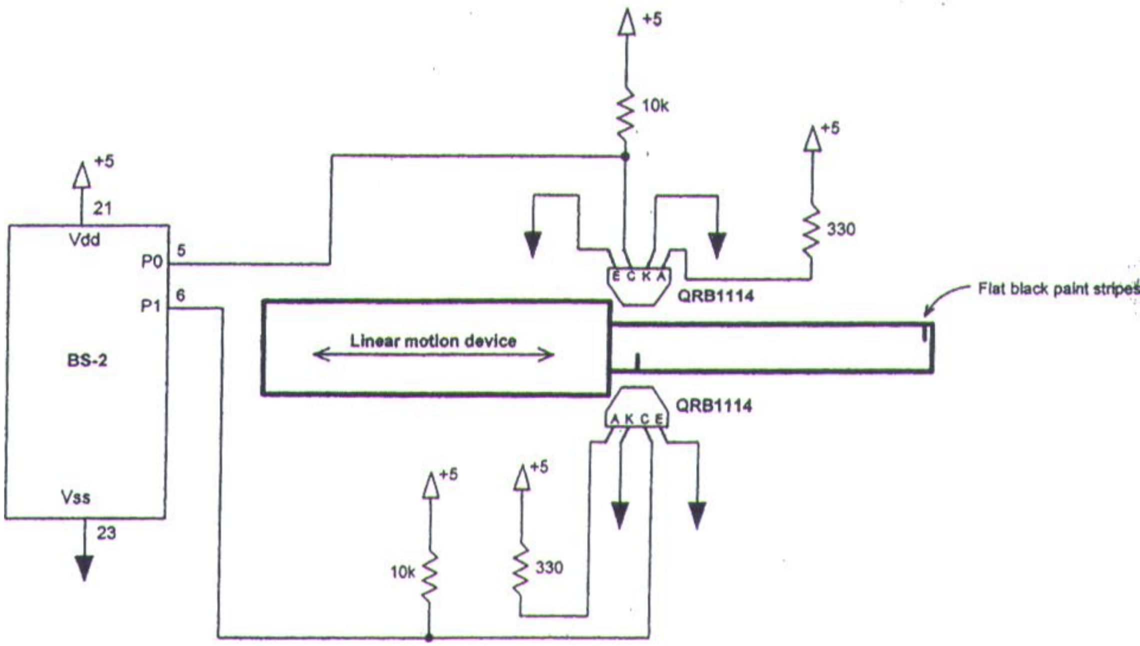
- A reflective optical sensor can be used measure angular motion of a shaft.
- If in a rotating shaft application, a disk (encoder disk) can not be attached to the shaft, then a reflective optical sensor can be used.
- Suppose the rotating shaft is made of light reflecting material.
- Draw equally spaced dark colored lines on the rotating shaft.
- The dark lines will not reflect light.
- Alternatively, if the shaft is made of a material that does not reflect light then, instead of drawing dark lines, adhere strips made of reflective material on the shaft.
- In either case, when shaft rotates, the detector in reflective optical sensor detects when light is reflected vs. not reflected.



A reflective optical feedback sensor

BS2 with Reflective Optical Sensors—II

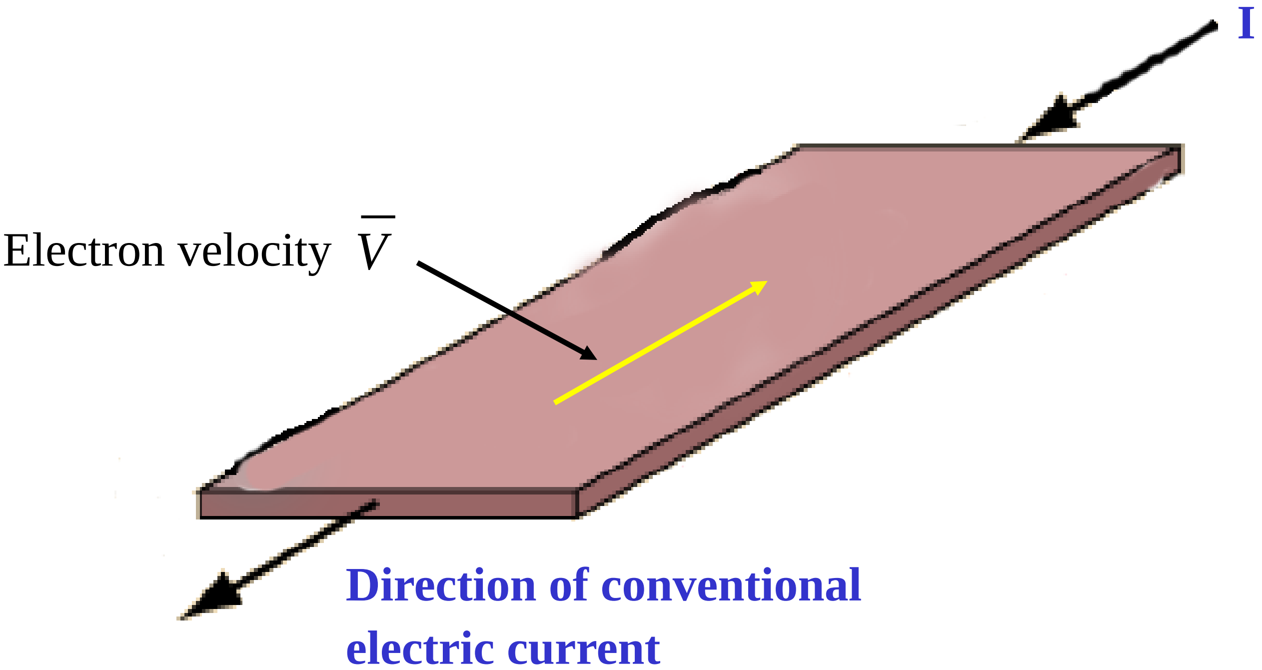
- Detect when the machine tool slide is fully retracted v/s fully extended.
- Use two reflective optical sensors placed at either side of the machine tool slide as shown.
- Adhere strips made of reflective material on the shaft at its two extreme ends.



Reflective optical linear movement feedback

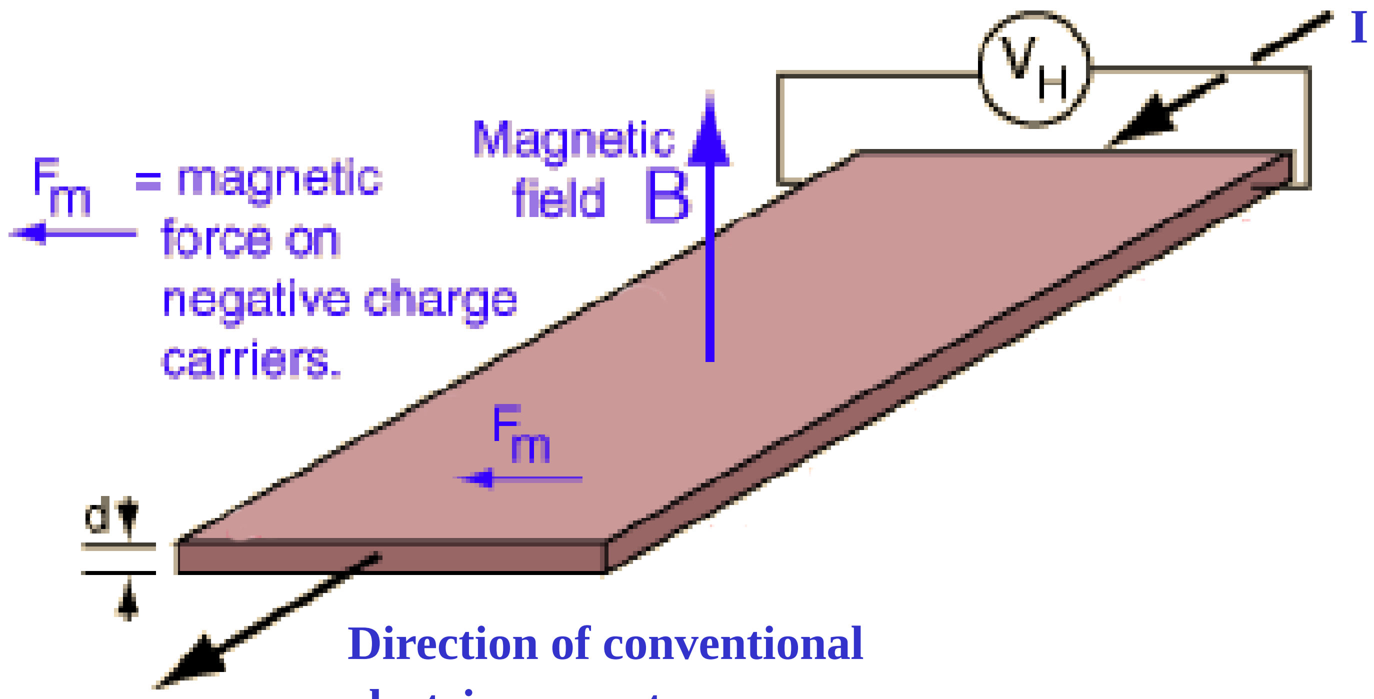
Hall Effect—I

- Consider that a metallic conductor forms a flat conductive strip with two contacts @ front end and back end of the strip.
  - These two contacts are connected to a current source.
- Since the conducting strip is made of a metallic conductor, free charge careers are electrons.
- When an electric field is applied on this conductive strip (by turning on the current source), the electrons move from the front end to the back end of the strip causing the current flow in the direction shown.



Hall Effect—II

- The conductive strip has two additional contacts @ its left and right as shown.
  - These two contacts are connected to a voltmeter.
- While the electrons are moving in the strip due to electric field, a magnetic field *B* normal to the *x*-*y* plane (flat plane) of the conductive strip is applied to the strip.
- The moving charge carriers (electrons) and the applied magnetic field interact and cause a force to be applied on the charge carriers. This force is called Lorenz force.



Hall Effect—III

- The Lorenz force acting on the charge carriers is given by the following.

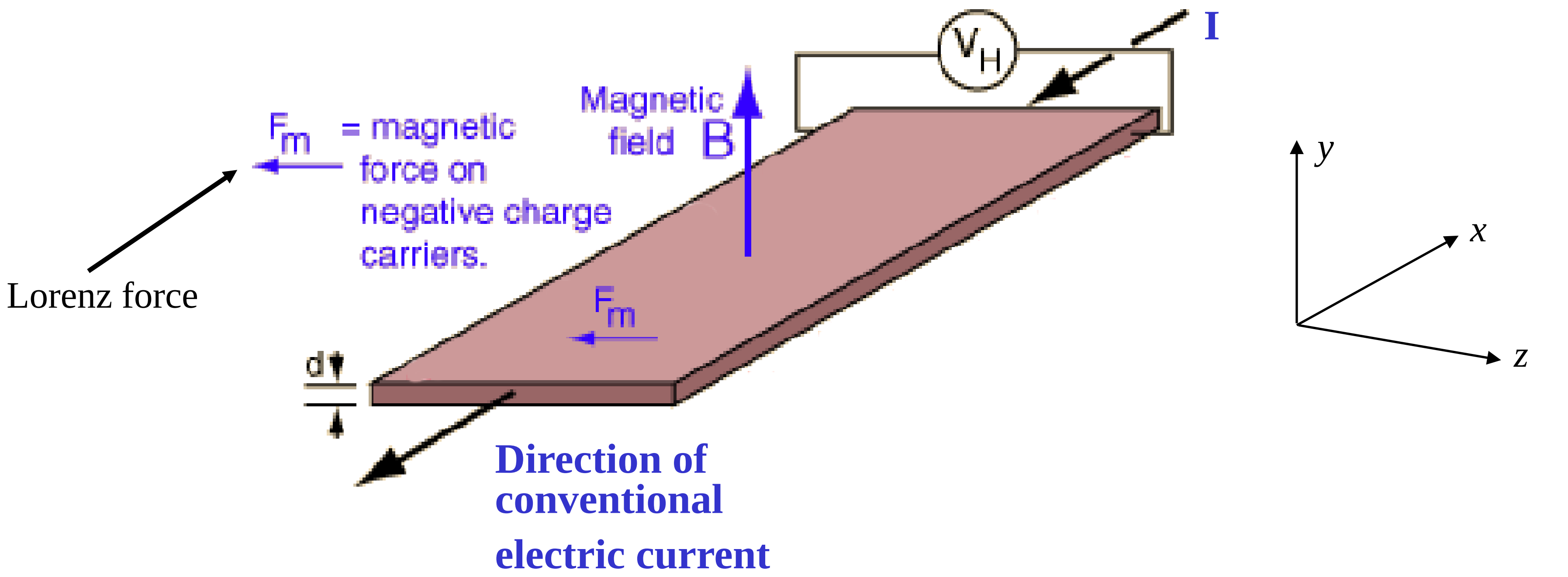
$$\overline{F}_L = q(\overline{V} \times \overline{B})$$

q: charge of an electron

$\overline{V}$: velocity of electron

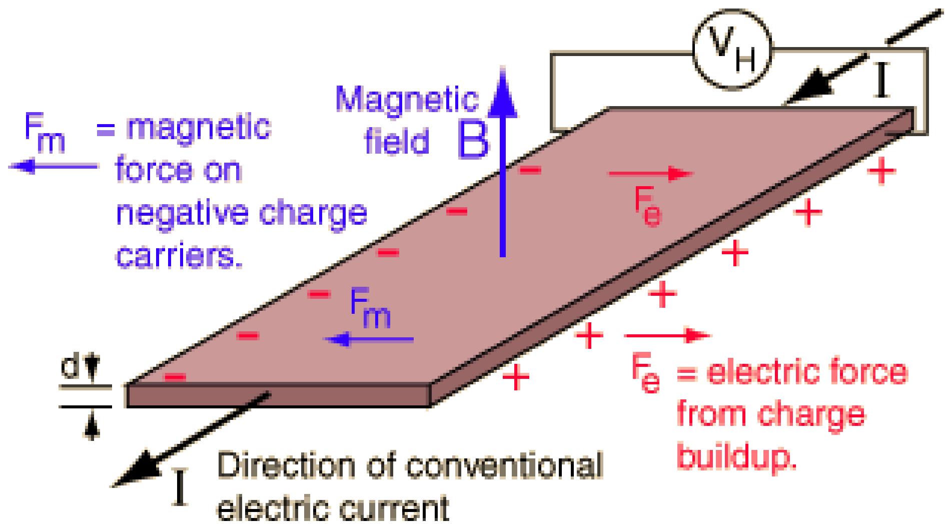
$\overline{B}$: magnetic field vector

- Since $\overline{V}$ and $\overline{B}$ are normal to one-another, resultant $\overline{F}_L$ is mutually $\perp$ to $\overline{V}$ and $\overline{B}$.



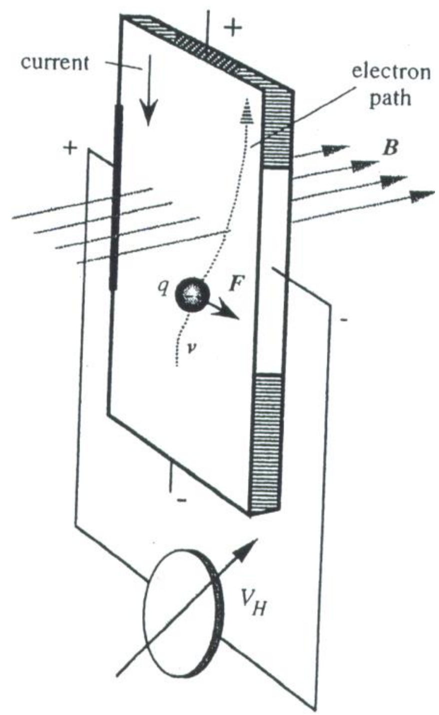
Hall Effect—IV

- The Lorenz force $\overline{F}_L$ causes the moving electrons to shift toward the left side of the strip.
  - This shifting of electrons causes the left side of the strip to become more negative than the right side.
- The interaction of magnetic field and electric field thus produces a transverse potential difference in the strip.
  - This potential difference is called Hall potential and this effect is called the "Hall Effect."



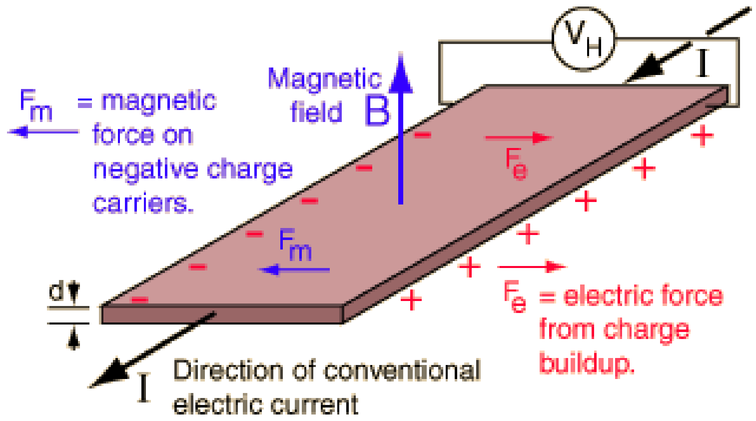
Hall Effect—V

- Here the direction of magnetic field is opposite that of the previous diagram. Thus, the Lorenz force $\overline{F}_L$ causes the moving electrons to shift toward the right side of the strip.
  - This shifting of electrons causes the right side of the strip to become more negative than the left side.



Hall Effect—VI

- Hall Effect: It is the small voltage generated in the transverse direction across a current carrying conductor exposed to external magnetic field.
- The magnitude and sign of the Hall voltage depends on
  - magnitude and direction of magnetic field
  - magnitude of current



$$V_H = hIB\sin\alpha$$

V_H : Hall voltage

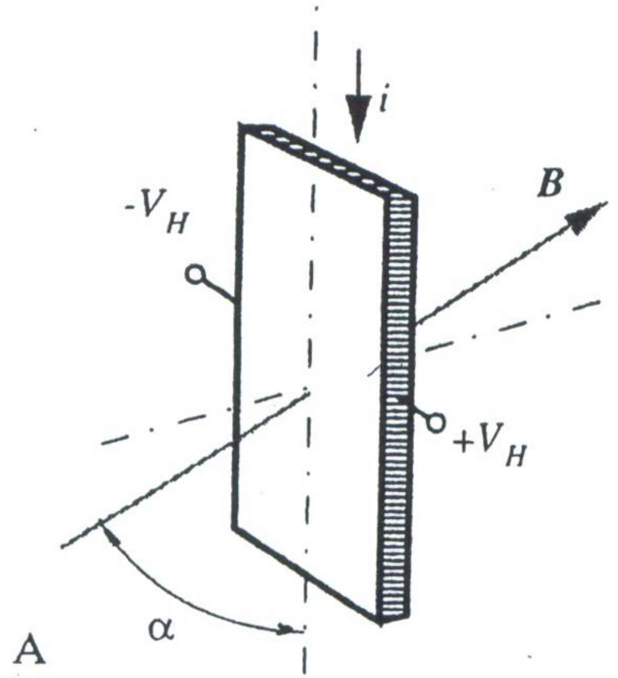
h : Hall coefficient

I : Current due to electric field

B : Magnetic field magnitude

α : Angle btween magnetic field vector and the Hall plate

Hall Effect—VII



Output signal of a Hall sensor depends on the angle between the magnetic field vector and the plate

$$V_H = hIB\sin\alpha$$

α : Angle between magnetic field vector and the Hall plate

Hall Effect—VIII

- The flat conductive “Hall plate” can be made of
  - metallic conductor
  - semiconductor material
- Thus, in general, charge carriers in the Hall plate may be either electrons (negative) or holes (positive).
  - As a result, the Hall effect may be either positive or negative!
- Hall effect is quite small when one uses metallic conductor for the Hall plate.
- Semiconductor based Hall plate yields orders of magnitude increase in Hall effect.

Hall Effect Sensors—Types

- Linear Hall Sensor
  - This type of Hall sensors operate by exploiting the linear relationship between the Hall voltage o/p (V_H) and the magnetic filed density (B). It may incorporate an amplifier for easier interface with peripheral electronics/devices.
- Threshold Hall Sensor (Digital)
  - This type of Hall sensors contain a Schmitt trigger detector with a built-in hysteresis. When the applied magnetic field exceeds a certain threshold, then the sensor switches from its off to on state.
  - The built-in hysteresis eliminates spurious oscillations (similar to how we used positive feedback in comparator circuitry).
- Indium Arsenide (InAs) is a common semiconductor used in Hall effect sensors
  - Low temperature sensitivity, good sensitivity "h", etc.
  - Control current 100mA to as low as 1mA.
  - Sensitivity: 10mV/Telsa to 1.4V/Telsa

Linear Output Hall Effect IC-TLE4990

ZH10 Hall Effect Zero Speed Sensor

Angular Displacement Measurement using Hall Sensor—I

- In order to measure angular displacement using Hall sensor, we exploit the following.

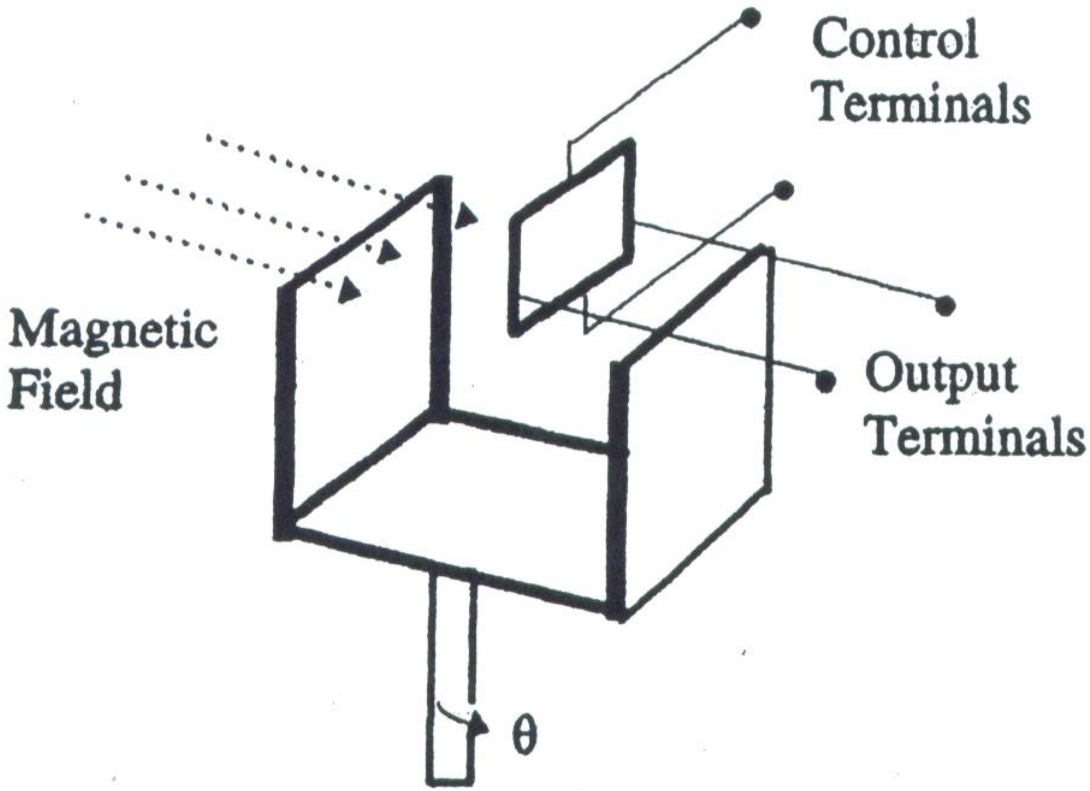
$$V_H = hIB\sin\alpha$$

- Essentially, we begin by suspending the Hall sensor between the poles of a permanent magnet connected to a shaft.
- The Hall plane is stationary while the permanent magnet rotates with the shaft whose angular displacement is to be measured.
- Use of permanent magnet $\rightarrow$ magnitude of B is constant.
- A constant control current is applied to the control leads of the Hall probe.
- Thus, now

$$V_H \propto \sin\alpha$$

- This technique can be used to measure small angular displacement of up to 6°.
- This is a non-contact based measurement (so the rotating shaft is not adversely affected by loading).
- Small sensor size and good resolution.

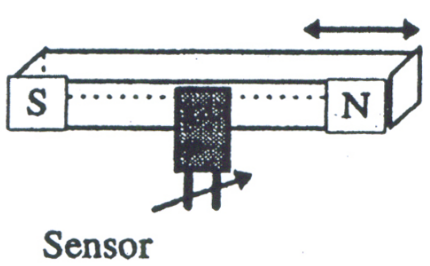
Angular Displacement Measurement using Hall Sensor—II



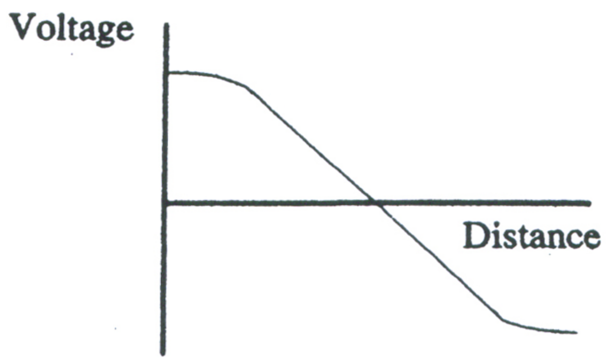
Rotational Transducer

Position Sensing using Hall Sensor

- Goal: Measure position in sliding motion.
- A permanent magnet is attached to the object undergoing sliding motion.
- Hall probe is stationary.
- A tightly controlled spacing is maintained between the magnet and the sensor probe.
  - It is important to control the gap between the magnet and sensor probe to prevent orthogonal movement of the magnet.
- When the north pole of the magnet approaches the sensing element, a negative magnetic field is induced in it.
- When the south pole of the magnet approaches the sensing element, a positive magnetic field is induced in it.
- Using a large magnet, this translation motion measurement sensor can measure position over a large travel of magnet.
- The sensor o/p is fairly linear.



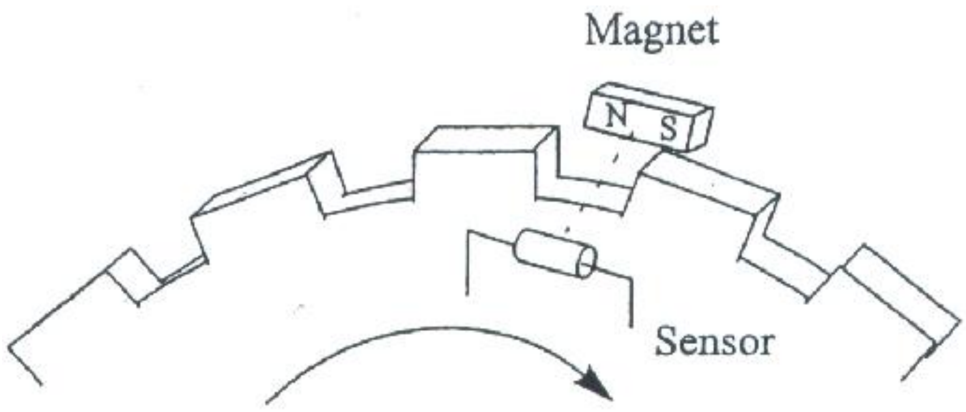
Sliding sensor



I/p-o/p characteristic

Rotational Speed Sensing using Hall Sensor—I

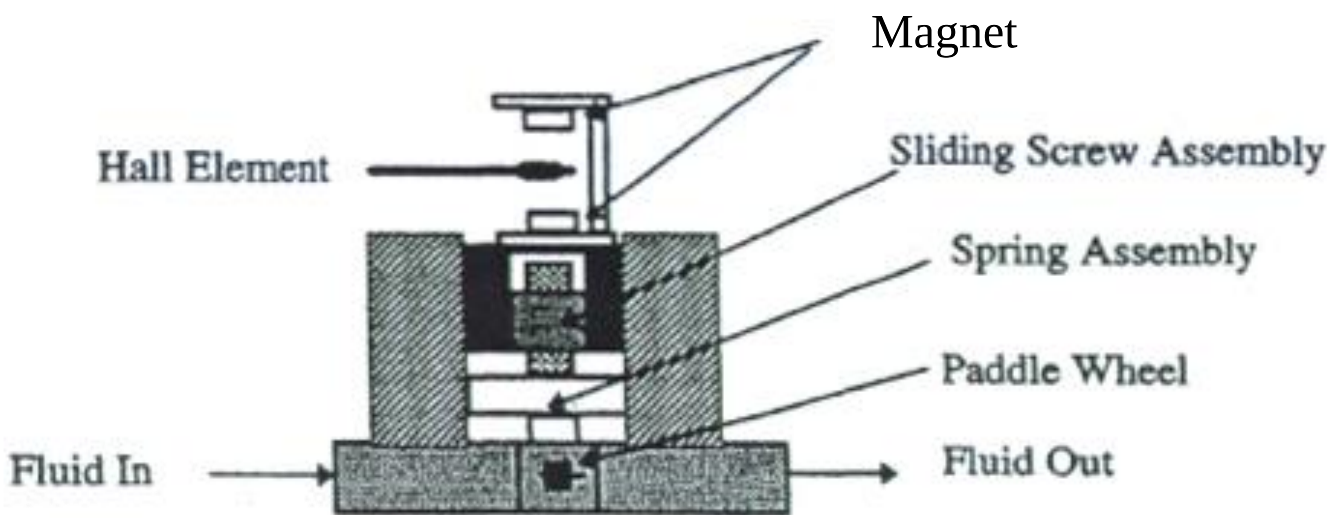
- Goal: Measure rotational speed.
- A threshold type Hall sensor and a permanent magnet is used for rotational speed sensing.
- A gear tooth presence between the senor-magnet pair interrupts the interaction between the electric and magnetic fields.
- Absence of gear tooth causes the sensor-magnet pair to interact, turning on the senor o/p.
- By counting the high-low pulses at the sensor o/p, rotational speed can be determined.



Rotational speed sensor.

Flow Measurement using Hall Effect

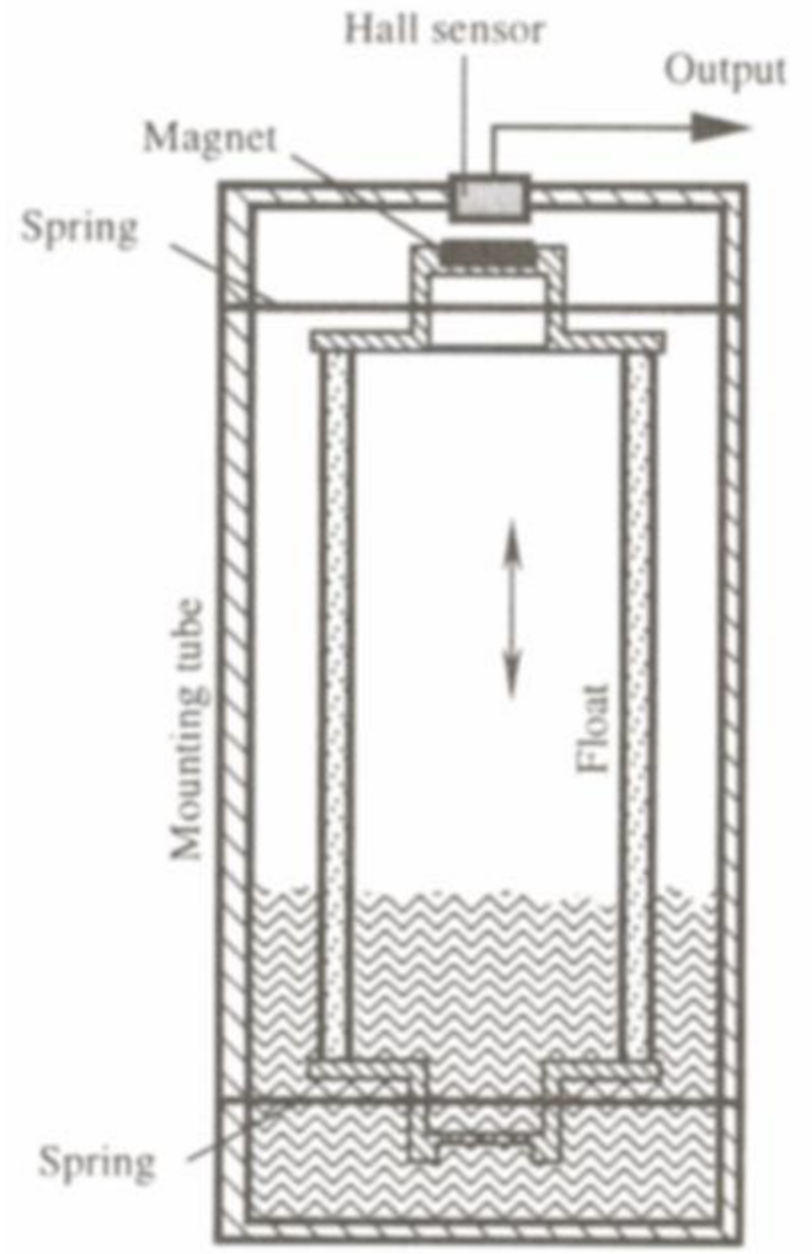
- The chamber has a fluid inlet and outlet.
- Increasing flow through the chamber causes a spring-loaded paddle to turn a threaded shaft.
- As the shaft turns, it raises a magnetic assembly that energizes a linear Hall element increasing its o/p.
- When the flow rate decreases, the coil spring causes the assembly to lower, which reduces the o/p of Hall element.
- The magnetic assembly and the sliding screw-nut assembly are calibrated to yield a linear response for flow rate v/s Hall element voltage o/p.



Fluid flow measurement

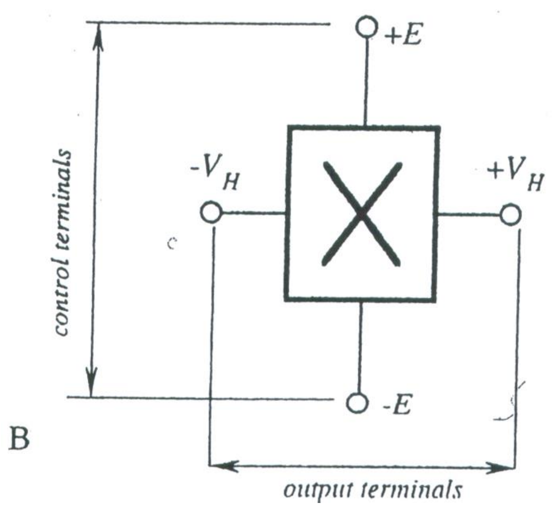
Liquid Level Measurement using Hall Effect

- The float is made of a chemical inert, tough, and low-cost plastic.
  - Its buoyancy in the liquid (say fuel) is such that as the liquid level moves from minimum to maximum level, the float moves by approx. 2mm.
- The float is supported by a pair of springs, which are rigid radially but flexible longitudinally.
- Fluid enters the bottom of float through holes and air leaves from the top of float through slots.
- An air bubble is maintained near the magnet at the top of the float to prevent magnetic particles in the liquid from contaminating the magnetic field.



Interfacing BS2 with Hall Effect Sensor—I

- HESs are semiconductor devices that change their o/p in relation to the influence of a magnetic field.
- Usually HES has an active area closer to one face of the package.
- For proper sensor operation, a magnetic field of sufficient flux density and correct polarity must be introduced.
- The magnetic flux lines must be perpendicular to the active face of the HES.



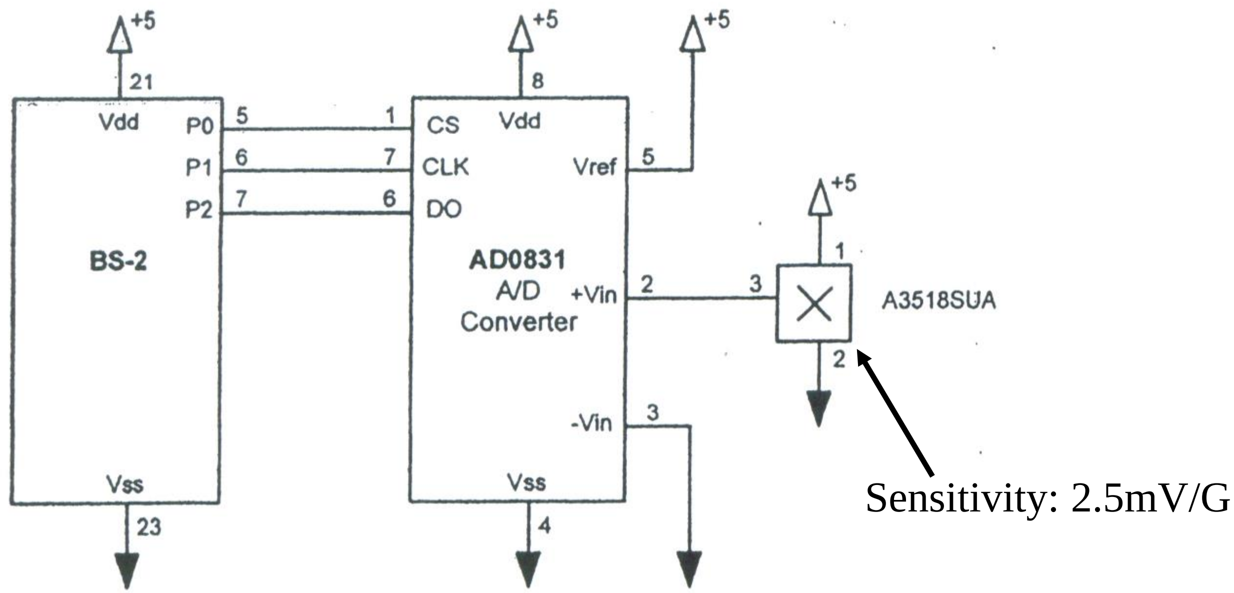
Four terminals of a Hall Sensor

Interfacing BS2 with Hall Effect Sensor—II

- Linear HES: The sensor outputs an analog voltage in proportion to the strength of the applied magnetic field. The sensor o/p is ratio-metric.
  - Consider the sensor has an operating range of 0-V volts.
  - In the absence of a magnetic field, the senor outputs V/2 volts.
  - When a magnet’s south pole approaches the sensor, its output increases.
  - When a magnet’s north pole approaches the sensor, its output decreases.

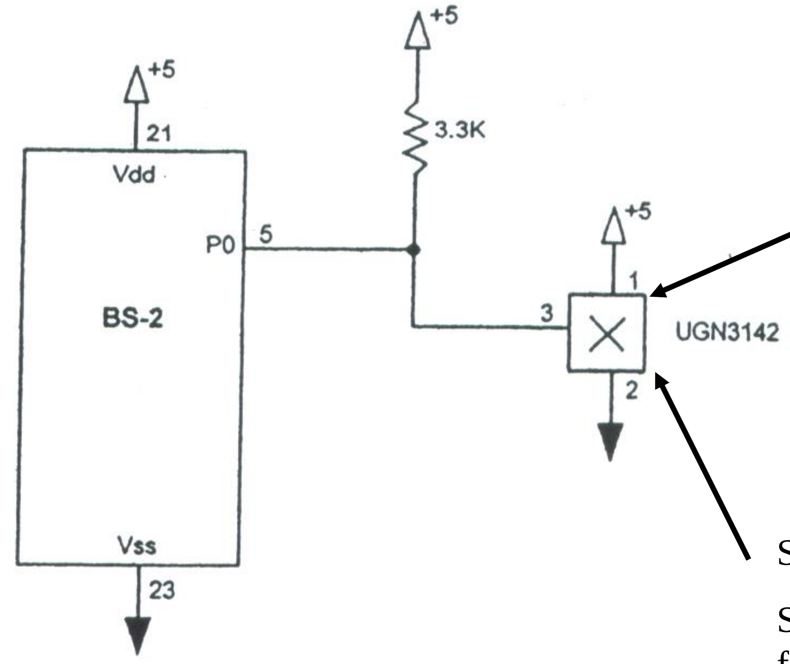
- Digital HES: This sensor is used to produce switching action in the presence/absence of magnetic fields.
- A digital HES is essentially a linear HES with an integrated Schmitt trigger.
- An approaching south pole of a magnet turns the digital HES switch on.
- Two types of digital HES:
  - Unipolar HES: An approaching south pole of a magnet turns the digital HES switch on. In the absence of the south pole, the sensor o/p remains off.
  - Bipolar HES: An approaching south pole of a magnet turns the digital HES switch on. When the south pole is removed, the sensor o/p remain on. In order to turn the sensor o/p off, the digital HES must be exposed to the north pole of a magnet.

Interfacing BS2 with Hall Effect Sensor—III



A linear Hall-effect sensor, through an A/D converter

Interfacing BS2 with Hall Effect Sensor—IV



Unipolar HES

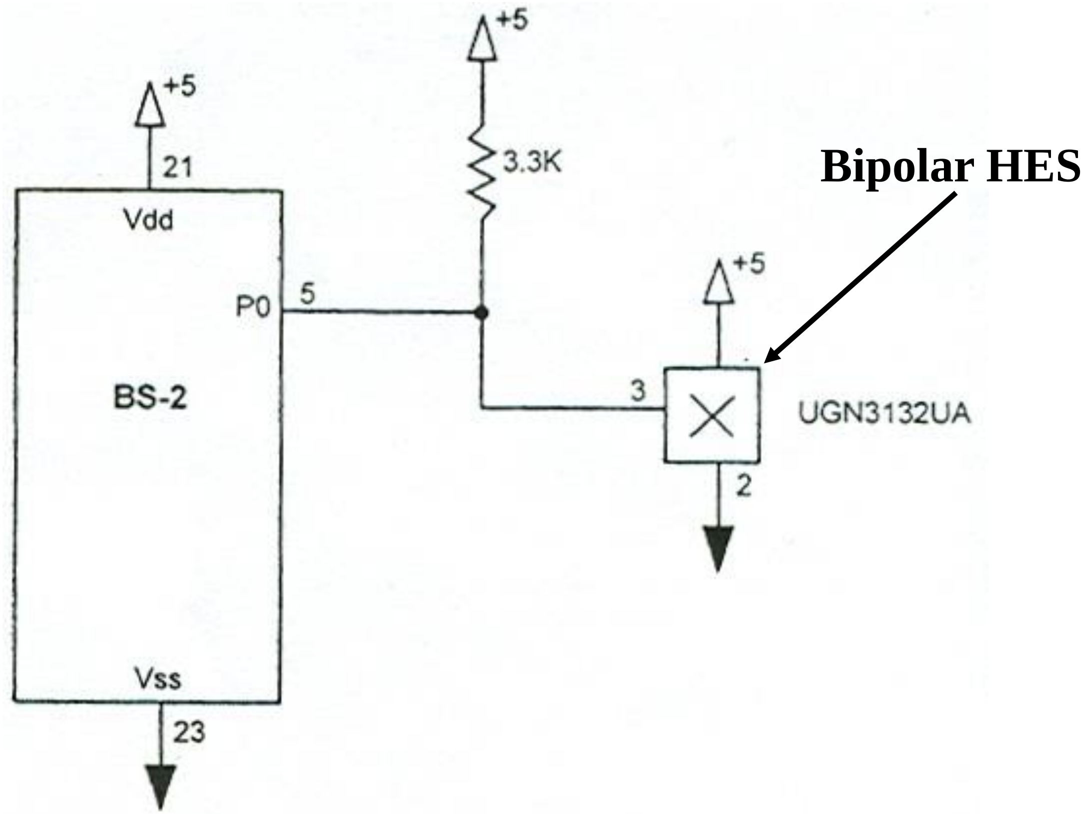
Sensor has an open collector output

Sensor output is high when magnetic field is below detection threshold

Senor output is low when magnetic field exceeds detection threshold

A very sensitive digital Hall-effect sensor

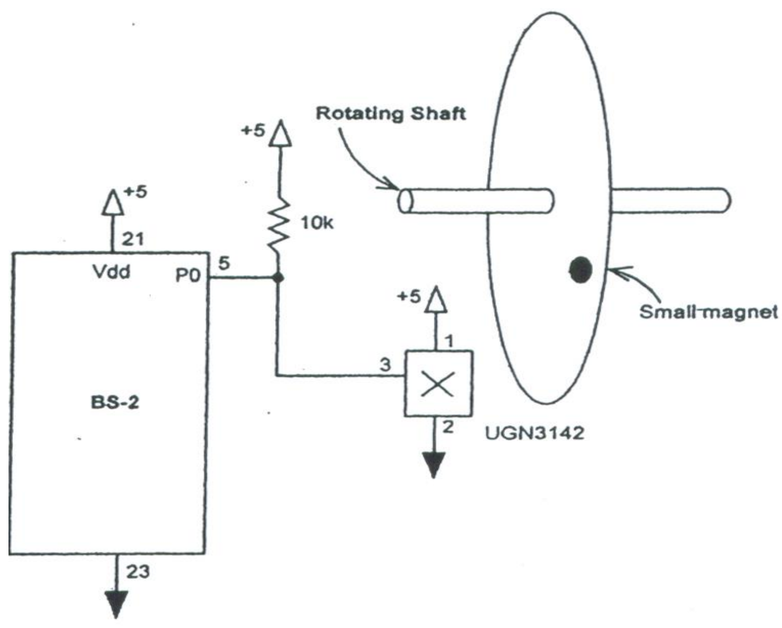
Interfacing BS2 with Hall Effect Sensor—V



A bipolar Hall-effect switch

Interfacing BS2 with Hall Effect Sensor—VI

- Illustration of the use of a unipolar HES to detect rotation of a disc.
- A small magnet is mounted on the rotating disc.
- Every time the disc moves past the HES, a switching action is generated.
- This switching action can be recorded using BS2 to count number of revolutions of the disc.
- When used in high speed rotating machinery applications, this setup can be used to determine operating speed of the machine.



A hall-effect rotary sensor

Capacitance Transducers—I

- Recall, capacitance of a parallel plate capacitor is:

$$C = \frac{\varepsilon_0 A}{d}$$

  – A: overlapping area of plates (m^2)
  – d: distance between the two plates of the capacitor (m)
  – ε_0: permittivity of air or free space 8.85pF/m

Capacitance Transducers—II

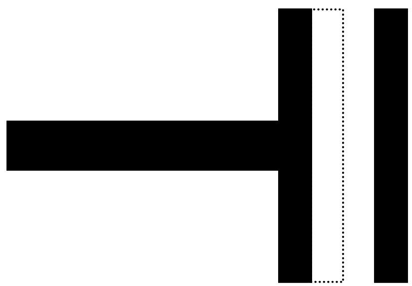
- When a dielectric material with dielectric constant ε_r is introduced between the capacitor plates the following is obtained.

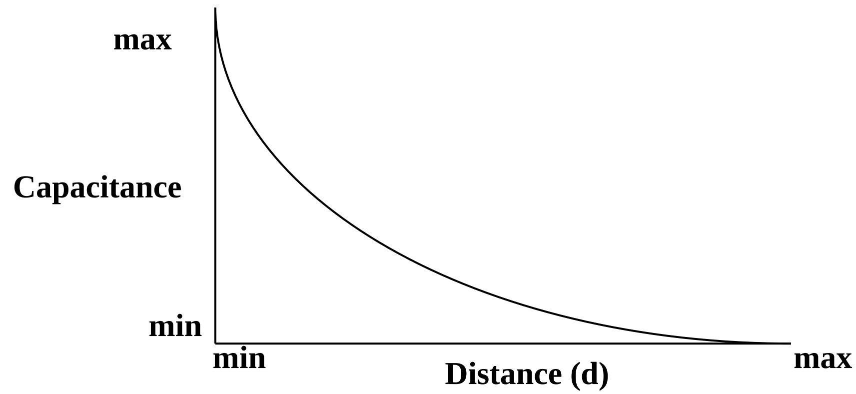
$$C = \frac{\varepsilon_r \varepsilon_0 A}{d}$$

- The following variations can be utilized to make capacitance-based sensors.
  - Change distance between the parallel electrodes.
  - Change the overlapping area of the parallel electrodes.
  - Change the dielectric constant.

Displacement Measurement using Capacitive Sensor—I

Capacitance change due to plate separation





- Capacitance transducer using change in distance between plates:
  - The right plate of capacitor is fixed while the left place undergoes displacement that is to be measured.
  - Let air be the dielectric (so $\varepsilon_r = 1$)

$$C = \frac{\varepsilon_0 A}{d}$$

  - C is inversely proportional to d. Thus, the relationship d v/s C is nonlinear.

Displacement Measurement using Capacitive Sensor—II

- The sensitivity of the sensor: $S = \frac{\partial C}{\partial d} = -\frac{\varepsilon_0 A}{d^2}$
- For small displacement, a linear relationship is obtained as follows.
  - Let d be the nominal separation, and $d + \Delta$ separation when a Δ displacement is introduced.
  - Then, capacitance value is obtained using Taylor's series expansion as follows.
    - o Taylor expansion of a function *f(x)* in the NBHD of x_0 is obtained as:

$$f(x) = f(x_0) + f'(x)\Big|_{x_0}(x - x_0) + f''(x)\Big|_{x_0}\frac{(x - x_0)^2}{2!} + \dots$$

- So: $C = \frac{\varepsilon_0 A}{d} - \frac{\varepsilon_0 A}{d^2}(\Delta + d - d) + \dots$

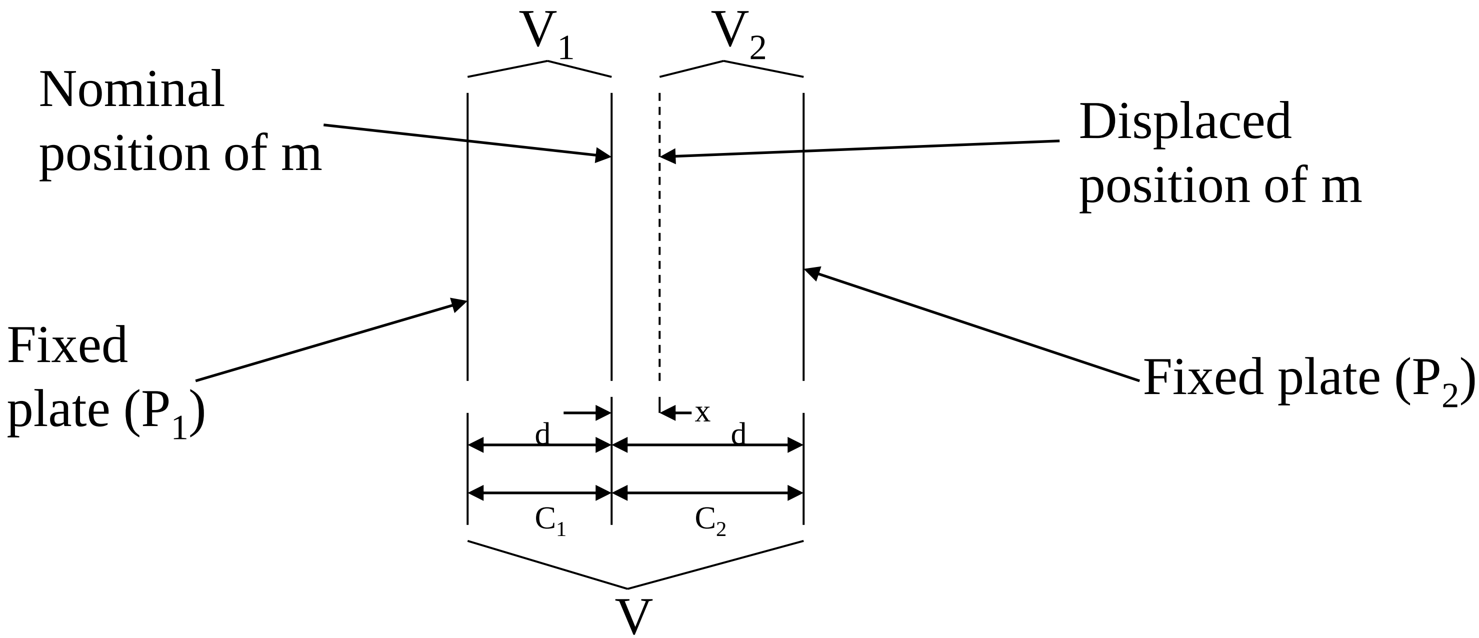
$$C \cong \frac{\varepsilon_0 A}{d}\left[1 - \frac{\Delta}{d}\right]$$

Now *C* has linear relationship w.r.t Δ. This is valid as long as $\Delta \ll$ d.

Displacement Measurement using Differential Capacitor—I

- This transducer consists of three parallel plates.
- The center plate undergoes position displacement that is to be measured. (Label center plate: m)
- The plates on the left and right of the center plate are stationary. (Label these as P_1 and P_2).
- Let C_1 be the capacitance of P_1-m (i.e. between left and center plate)
- Let C_2 be the capacitance of P_2-m (i.e. between center and right plate)
- When m is equidistant from P_1 and P_2, $C_1 = C_2$
- Apply a voltage V across P_1 and P_2.

Displacement Measurement using Differential Capacitor—II



Differential arrangement of capacitor plates

Displacement Measurement using Differential Capacitor—III

- Voltage across P1-m is:

$$V_1 = \frac{C_2}{C_1 + C_2} V$$

- Voltage across P2-m is:

$$V_2 = \frac{C_1}{C_1 + C_2} V$$

- If the plate m is equidistant from P_1 and P_2, $C_1 = C_2$ and:

$$V_1 = V_2 = \frac{V}{2}$$

- In this case, $V_1 - V_2 = 0$
- If m is moved by amount "*x*" towards P_2, then:

$$C_1 = \frac{\varepsilon A}{d + x}, \quad C_2 = \frac{\varepsilon A}{d - x}$$

Displacement Measurement using Differential Capacitor—IV

- In this case we obtain the following.

$$\Delta V = V_1 - V_2 = \frac{\dfrac{\varepsilon A}{d-x}}{\dfrac{\varepsilon A}{d+x} + \dfrac{\varepsilon A}{d-x}} V - \frac{\dfrac{\varepsilon A}{d+x}}{\dfrac{\varepsilon A}{d+x} + \dfrac{\varepsilon A}{d-x}} V$$

$$= \left[\frac{d+x}{2d} - \frac{d-x}{2d} \right] V$$

$$= \frac{x}{d} V$$

- Thus, the differential arrangement of capacitors yields an output voltage ΔV that is linearly varying w.r.t displacement x.

Displacement Measurement using Differential Capacitor—V

- Typical range of measurement for *x*: 0.001mm to 10mm.
- Typical accuracy: 0.05%
- Sensitivity (*S*): $\dfrac{\partial(\Delta V)}{\partial x} = \dfrac{V}{d}$

Capacitive Displacement Sensor in a Bridge Ckt.—I

- Consider once again the parallel plate type capacitor where one plate of the capacitor is fixed and the other is movable. In this case:

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d}$$

  - ε_0: Permittivity of air: $\approx 8.854 \times 10^{-12}\,\mathrm{F/m} = 8.854\,\mathrm{pF/m}$
  - A: Surface area of plates overlapping one another
  - d: Separation distance between plates (varies as the movable plate undergoes displacement)
  - ε_r: Dielectric constant of insulating medium (ε_r=1 for air).

- So, with air as dielectric medium, for a parallel plate capacitor:

$$C = \frac{8.854A}{d}\,\mathrm{pF}$$

  - d: nominal separation of moving plate from fixed plate.

Capacitive Displacement Sensor in a Bridge Ckt.—II

- Recall, in the Phasor notation, impedance of a capacitor:

$$Z_c = \frac{1}{j\omega C} = \frac{1}{\omega C} < -90^\circ >$$

$$= \frac{d}{j(8.854A\omega)}\Omega$$

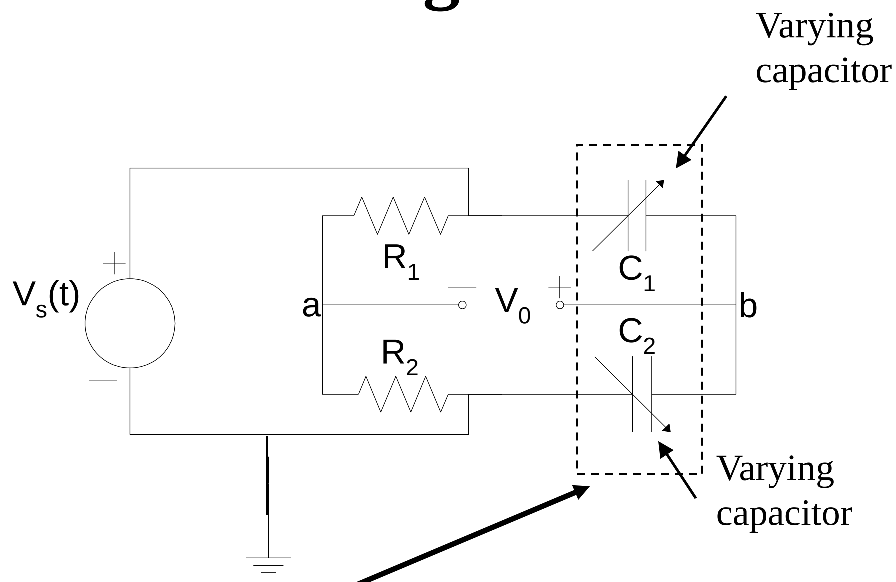
- Now, let us use two parallel plate capacitors in a wheatstone bridge circuit (in one arm) as shown. The capacitors are arranged such that
  - Under *0* displacement condition, the nominal separation of movable plate of each capacitor is *d*.
  - Under displacement condition *x*, the upper capacitor has plate separation *d*-*x* and the lower capacitor has plate separation *d*+*x*.

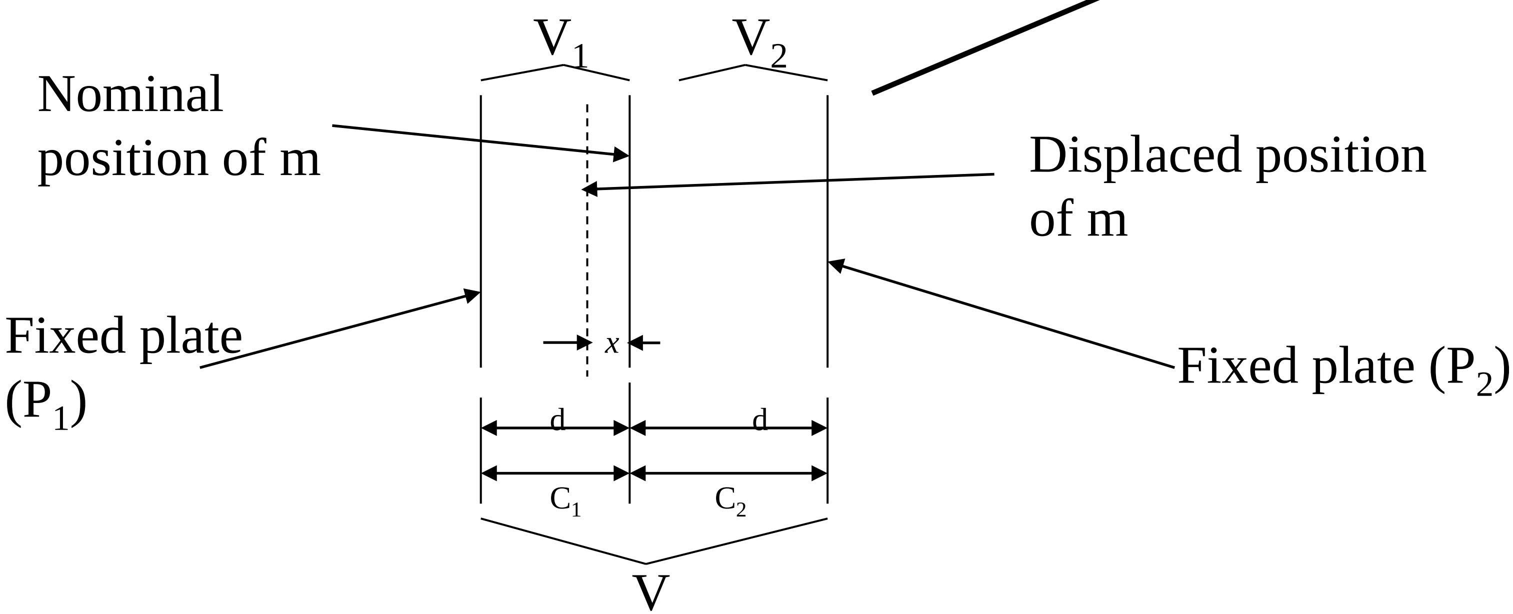
Capacitive Displacement Sensor in a Bridge Ckt.—III

- Under displacement condition *x*:

$$C_1 = \frac{8.854A}{d-x}\,pF, \quad C_2 = \frac{8.854A}{d+x}\,pF$$

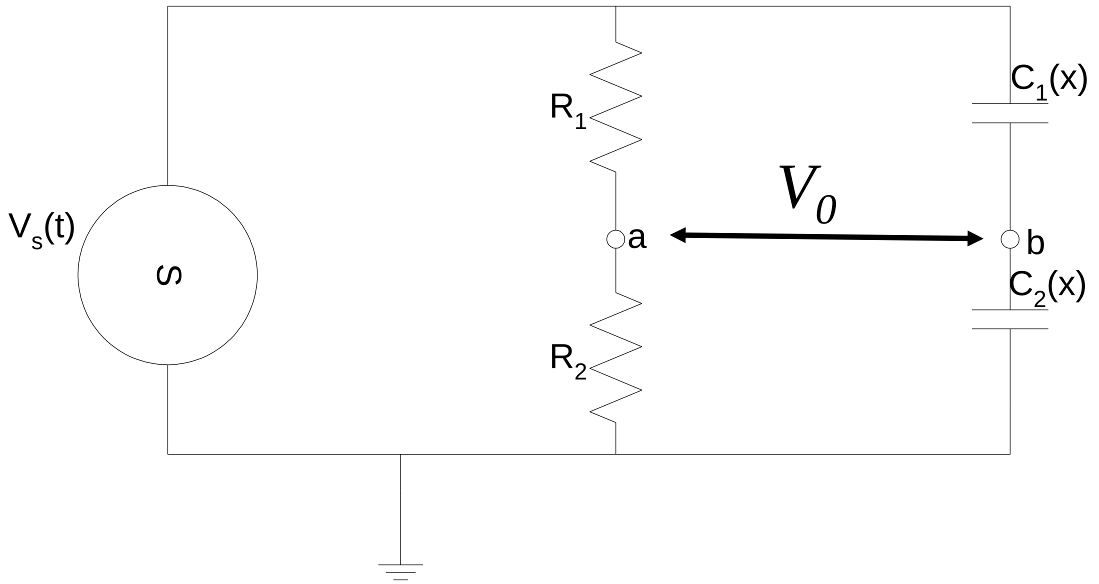
$$Z_{C_1} = \frac{d-x}{j\omega(8.854A)}, \quad Z_{C_2} = \frac{d+x}{j\omega(8.854A)}$$





Differential arrangement of capacitor plates

Capacitive Displacement Sensor in a Bridge Ckt.—IV



- The bridge circuit is equivalent to the above circuit.
- Now:

$$V_0 = V_b - V_a$$

Capacitive Displacement Sensor in a Bridge Ckt.—V

- Using voltage division (note: $\overline{V} = \text{phasor of } V$)

$$V_a = \frac{R_2}{R_1 + R_2} V_s$$

$$\overline{V_b}(j\omega) = \frac{Z_{C_2}}{Z_{C_1} + Z_{C_2}} \overline{V_s}(j\omega)$$

- So:

$$\overline{V_0}(j\omega) = \overline{V_b}(j\omega) - \overline{V_a}(j\omega)$$

$$= \left[\frac{Z_{C_2}}{Z_{C_1} + Z_{C_2}} - \frac{R_2}{R_1 + R_2} \right] \overline{V_s}(j\omega)$$

Capacitive Displacement Sensor in a Bridge Ckt.—VI

$$\frac{\overline{V_0}}{\overline{V_s}}(j\omega) = \frac{Z_{C_2}}{Z_{C_1} + Z_{C_2}} - \frac{R_2}{R_1 + R_2}$$

$$= \frac{\dfrac{d+x}{j\omega(8.854A)}}{\dfrac{d-x}{j\omega(8.854A)} + \dfrac{d+x}{j\omega(8.854A)}} - \frac{R_2}{R_1 + R_2}$$

$$= \frac{d+x}{2d} - \frac{R_2}{R_1 + R_2}$$

$$= \frac{1}{2} + \frac{x}{2d} - \frac{R_2}{R_1 + R_2}$$

Capacitive Displacement Sensor in a Bridge Ckt.—VII

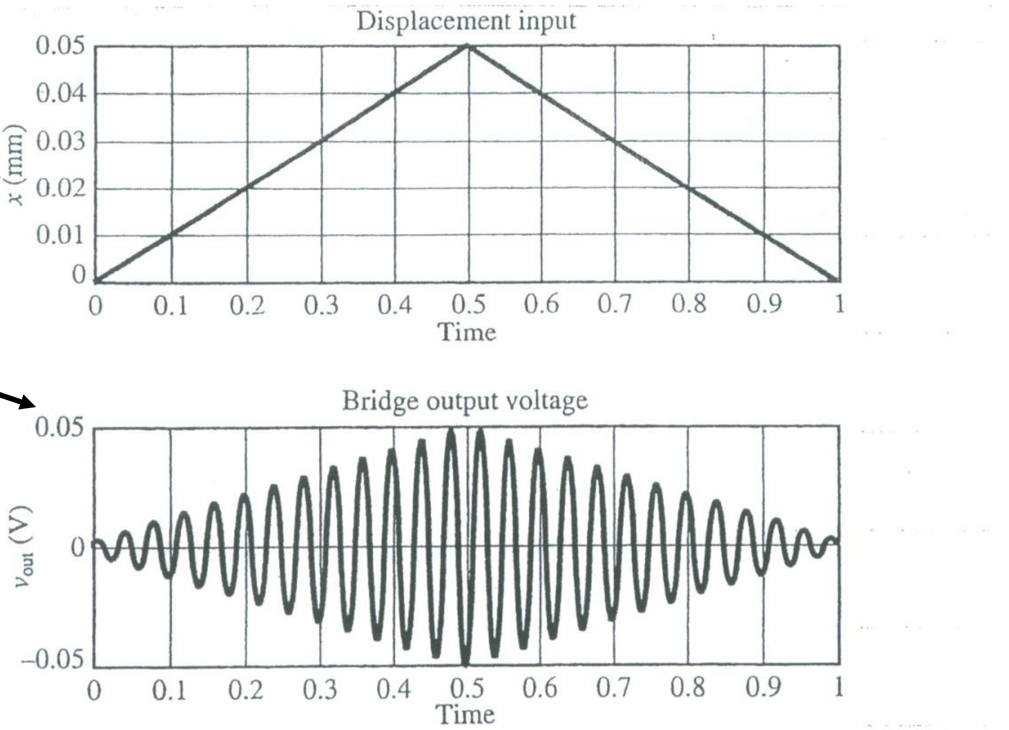
- Selecting: $R_1 = R_2 \Rightarrow \dfrac{R_2}{R_1 + R_2} = \dfrac{1}{2} \Rightarrow \dfrac{\overline{V_0}}{\overline{V_s}}(j\omega) = \dfrac{x}{2d}$

- So, the output voltage varies as a scaled version of the input voltage (no phase shift, only amplitude scaling).

Capacitive Displacement Sensor in a Bridge Ckt.—VIII

- Let V_s be of 1-V amplitude, 25Hz sinusoidal signal.
- Let Displacement x be a 0.05mm amplitude triangular signal.
  - Then the output V_0 is as shown.
    - o V_0 is a function of displacement x.
    - o V_0 is a sinusoidal signal so it is not in a convenient form to measure x directly

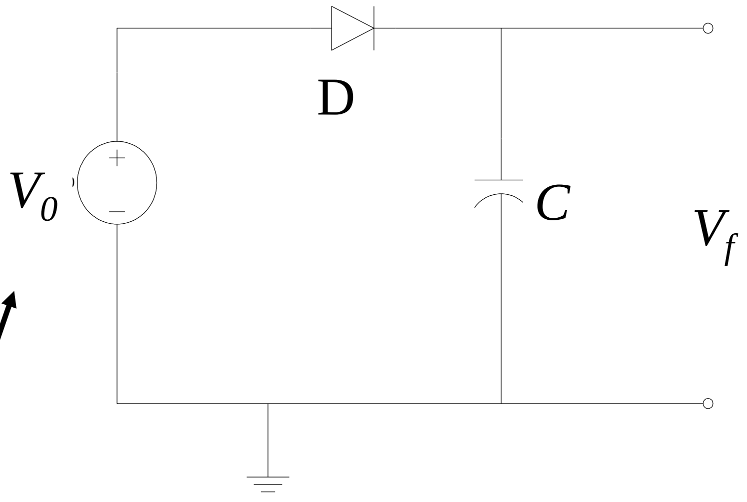
$$\overline{V_0}(j\omega) = \frac{x}{2d}\overline{V_s}(j\omega)$$



•Displacement input and bridge output voltage for capacitive displacement transducer.

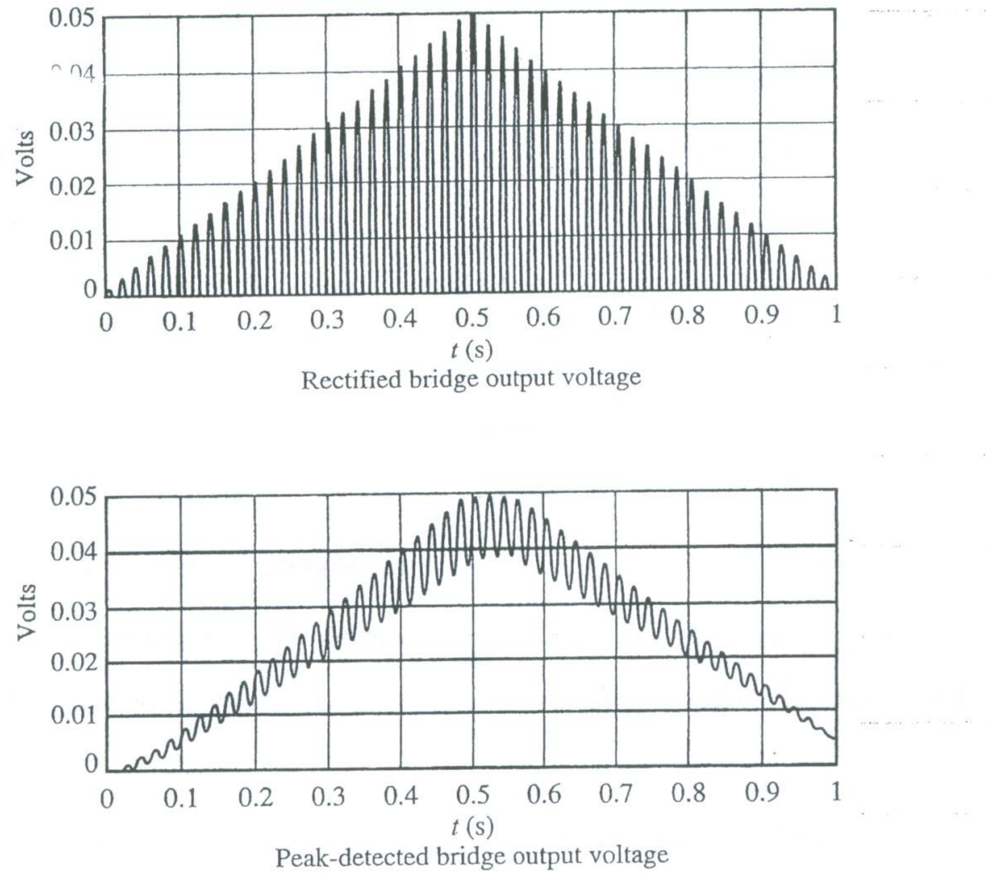
Capacitive Displacement Sensor in a Bridge Ckt.—IX

- Consider a peak detecting circuit which conditions the bridge circuit output and presents it in a form that is useful for displacement measurement.
- This circuit uses the rectification property of diode and the filtering effect of shunt capacitor (which acts as a low pass filter).



$$\overline{V_0}(j\omega) = \frac{x}{2d}\overline{V_s}(j\omega)$$

Capacitive Displacement Sensor in a Bridge Ckt.—X



Rectified and peak-detected bridge output voltage waveforms

Capacitive Sensor using Change in Area —I

- In a parallel plate capacitor:

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d} = \frac{\varepsilon_r \varepsilon_0 (wL)}{d}$$

  – w = width of the two parallel plates (overlapping part), keep this fixed.

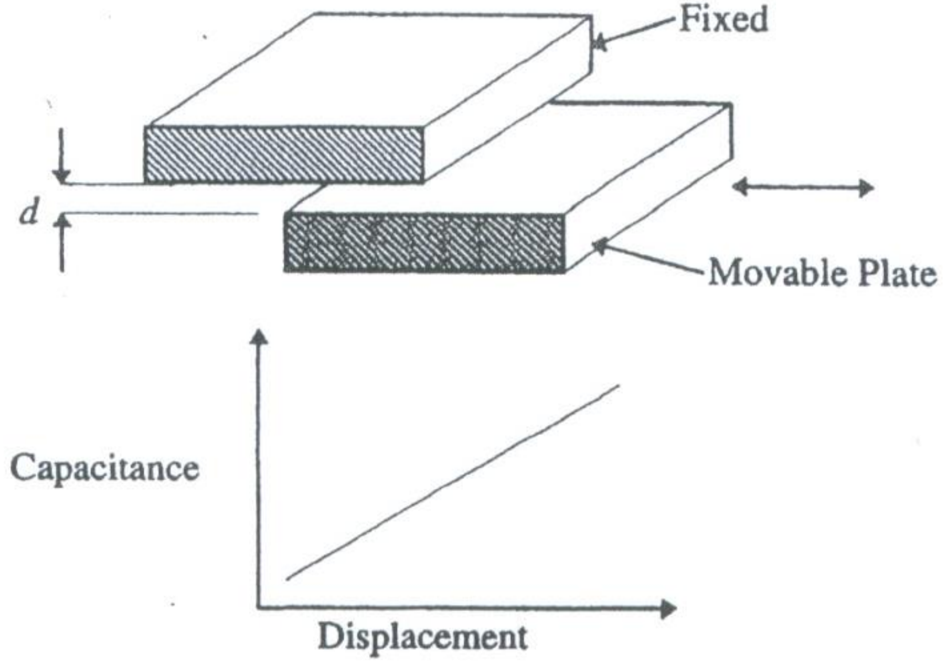
  – L = overlapping length of the parallel plates. This changes as one of the plates undergoes displacement that needs to be measured.

- Clearly, capacitance is linearly proportional to overlapping length (L) and hence displacement.

- Sensitivity:

$$S = \frac{\partial C}{\partial L} = \frac{\varepsilon_r \varepsilon_0 w}{d}$$

Capacitive Sensor using Change in Area —II



Capacitance variation by change in area

Capacitive Transducer: Illustrative Example—I

- Problem:
  - Consider a capacitor consisting of two conductive plates in parallel. Each conductive plate has a width *w* of 0.1m and length *l* of 0.5m. The distance *d* between the two plates is 0.1m. The relative permeability of the dielectric ε_r is 1. Given that the permittivity of free space ε_0 is 8.854x10^{-12}F.m^{-1}, determine the capacitance of this device. If the overlap of the plates is reduced by moving one plate horizontally a distance *x* of 50mm, determine the new value of the capacitance.
- Solution
  - From the problem statement,
    - $w=0.1$m
    - $l=0.5$m,
    - $d=0.1$m,
    - $\varepsilon_r=1$
    - $\varepsilon_0= 8.854\times 10^{-12}$F.m^{-1}
  - The area *A* of each plate is

$$A = wl = 0.1m \times 0.5m = 0.05m^2$$

- To find the capacitance, use:

$$C = \frac{A\varepsilon_0\varepsilon_r}{d}$$

$$= \frac{0.05 \times 8.854 \times 10^{-12} \times 1}{0.1}$$

$$= 4.427 \times 10^{-12}\,\mathrm{F}$$

$$= 4.427\mathrm{pF}$$

Capacitive Transducer: Illustrative Example—II

- If the length of the overlap area is reduced by moving one plate horizontally a distance $x=50$mm
  - New area of overlap:

$$= (A - wx)$$

$$= 0.05 - (0.1 \times 0.05)$$

$$= 0.045 m^2$$

- Thus, the new value of capacitance C_x will be;

$$C = \frac{A\varepsilon_0\varepsilon_r}{d}$$

$$= \frac{0.045 \times 8.854 \times 10^{-12} \times 1}{0.1}$$

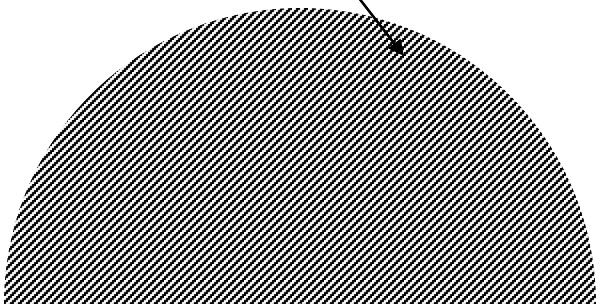
$$= 3.984 \times 10^{-12}\,\mathrm{F}$$

$$= 3.984\mathrm{pF}$$

Capacitive Sensor for Angular Rotation: Area Change—I

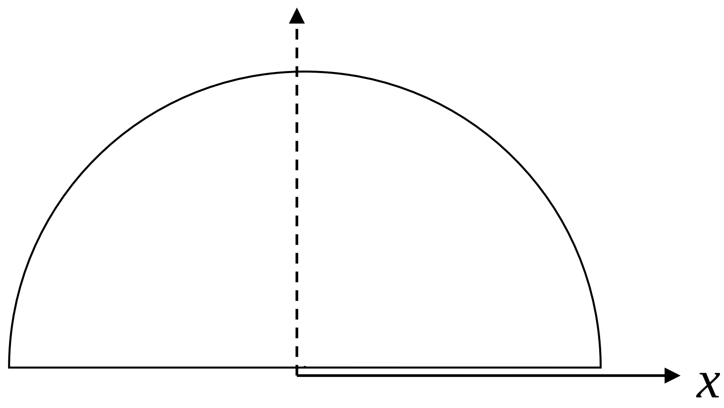
- Two semi-circular parallel plates are used as the two plates of a capacitor. One plate is fixed while the other plate undergoes angular rotation that needs to be measured.
- As the movable plate undergoes rotation, the overlapping area of the capacitor plates changes. This then is used to relate angular displacement to capacitance change.
- When the 2 semicircular plates are completely overlapping:

$$A = \frac{\pi r^2}{2} \, (For\ a\ semicircle)$$



$$C = \frac{\varepsilon_0 \varepsilon_r A}{d}$$

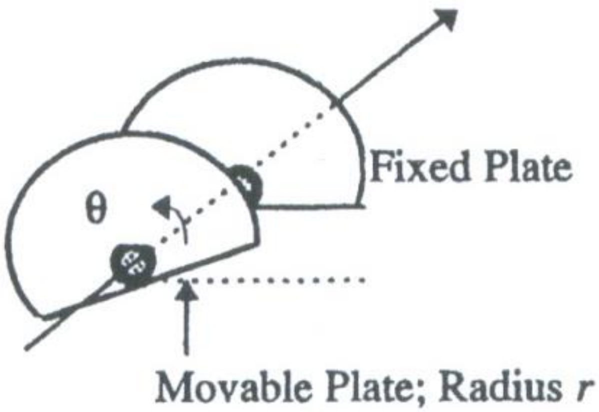
Capacitive Sensor for Angular Rotation: Area Change—II



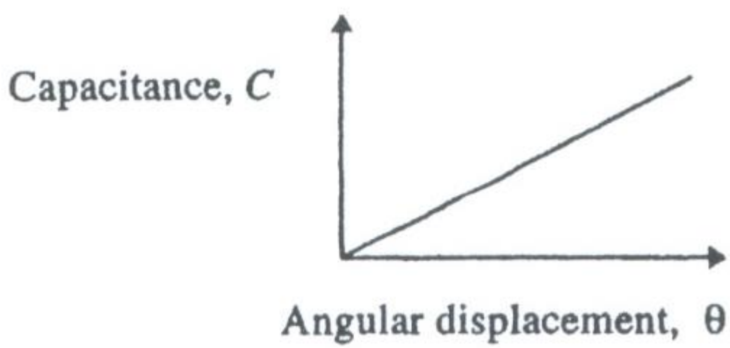
- The lower edge of fixed plate coincides with x axis.
- When the lower edge of rotating plate coincides with x axis, then the overlapping area of two plates is maximum.

- θ is measured from x axis. So, when $\theta = 0$, the two plates do not overlap at all. In this case, $A=0$ and $C=0$.
- When $\theta = \pi$, the two plates fully overlap
$$A = \frac{\pi r^2}{2}$$
- At $\theta \in (0, \pi)$, the overlapping area is:
$$A = \frac{\theta}{\pi}\left(\frac{\pi r^2}{2}\right) = \frac{\theta r^2}{2}$$
- Thus, now
$$C = \frac{\varepsilon_0 \varepsilon_r}{d}\left(\frac{\theta r^2}{2}\right)$$
- Clearly C is directly proportional to angular displacement θ.
- Sensitivity: $\dfrac{\partial C}{\partial \theta} = \dfrac{\varepsilon_r \varepsilon_0 r^2}{2d}$

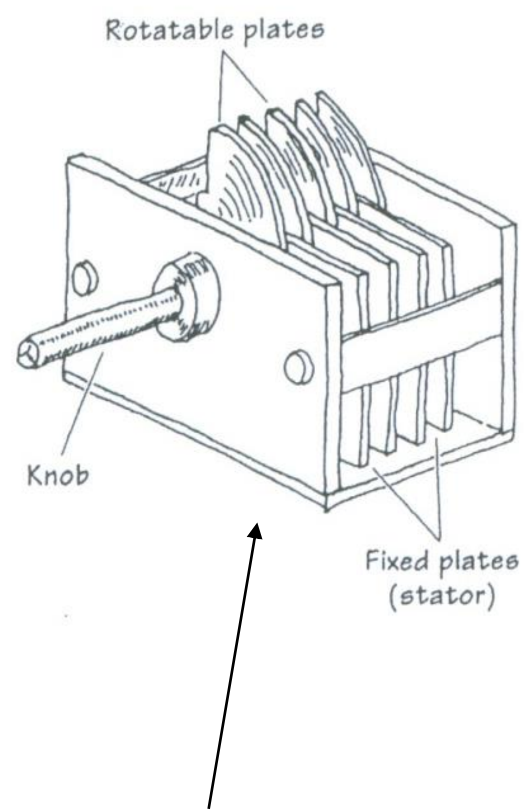
Capacitive Sensor for Angular Rotation: Area Change—II



Angular Rotation of Plates



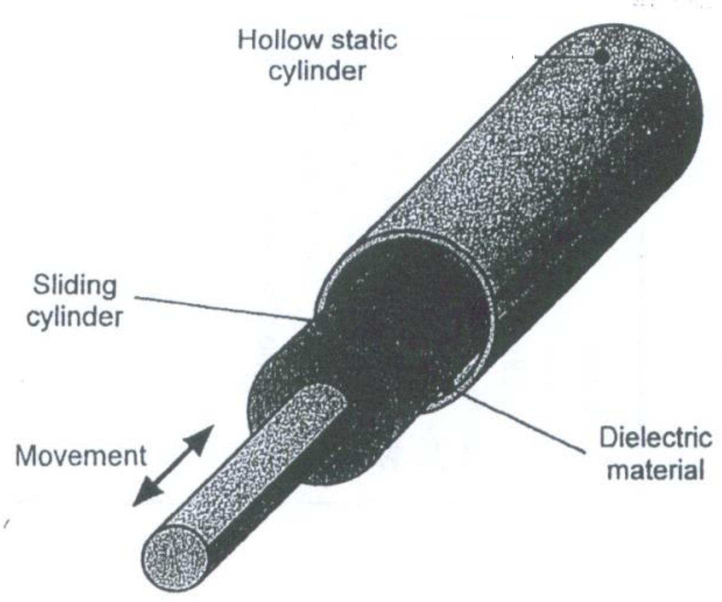
Capacitance v/s angular displacement



Variable capacitor

Capacitive Sensor for Displacement Measurement: Area Change in a Cylindrical Capacitor —I

- A cylindrical capacitor has two coaxial cylinders.
  - The outer cylinder is hollow and has radius is *R*.
  - The inner cylinder is solid with radius *r*.
- The overlapping length of two cylinders is *L*. A dielectric material with dielectric constant ε_r is filled between two cylinders.



Here the dielectric does not move

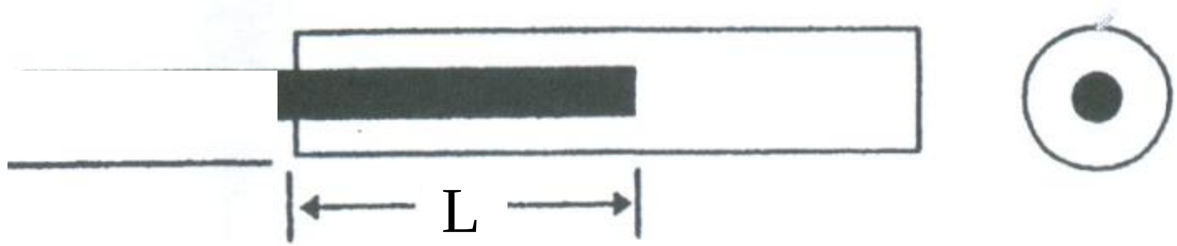
Variable area capacitance displacement transducer

Capacitive Sensor for Displacement Measurement: Area Change in a Cylindrical Capacitor —II

- It can be shown that the capacitance of the cylindrical capacitor is:

$$C = \frac{\varepsilon_0 \varepsilon_r (2\pi L)}{\ln(R/r)}$$

- Now, as the inner cylinder moves in and out of the outer cylinder, "*L*" the overlapping length of 2 cylinders changes.
- "*L*" influences *C* linearly.
- This is the principle of displacement measurement using cylindrical capacitors.



Change in area based on cylindrical shapes

Capacitance Sensor: Change in Dielectric Constant—I

- Consider an arrangement of two parallel plates with:
  - surface area $A = wL$, w: width, L: length and
  - separation distance d.
- Consider a plate made of a dielectric material moves in and out of the empty space that separates the two parallel plates of the capacitor.
- The dielectric plate has:
  - width w and thickness d and
  - dielectric constant $\boldsymbol{\varepsilon_r}$.
- When the dielectric plate moves in and out of the region separating the two fixed plates of the capacitor, the capacitance value is changed. This is the principle of capacitance transducer that exploits change in dielectric constant.

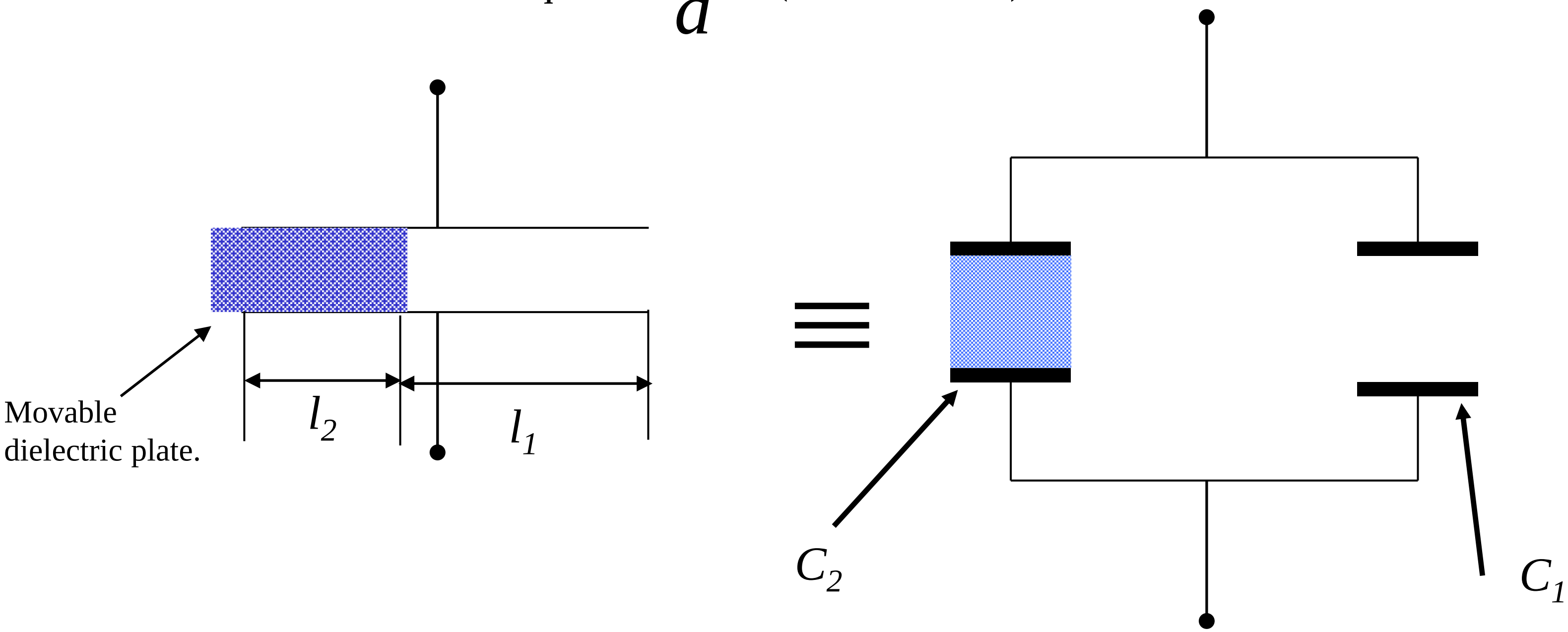
Capacitance Sensor: Change in Dielectric Constant—II

- Consider the nominal case, when dielectric plate is inserted up to length l_2.
- C_1 and C_2 are connected in parallel, so: $C_{\mathrm{eq}} = C_1 + C_2$, where

$$C_1 = \frac{\varepsilon_0 [w l_1]}{d}, \quad C_2 = \frac{\varepsilon_0 \varepsilon_r [w l_2]}{d}$$

- Thus we obtain the following.

$$C_{\mathrm{eq}} = \frac{\varepsilon_0 w}{d}\left(l_1 + \varepsilon_r l_2\right)$$



Capacitance Sensor: Change in Dielectric Constant—III

- Let us call $C_{eq}=C_1+C_2$ obtained on the previous slide, simply C.
- Now, if the dielectric plate is moved a distance "x" to right, C changes to $C+\Delta C$ as follows:

$$C+\Delta C=\frac{\varepsilon_r\varepsilon_0[w(l_2+x)]}{d}+\frac{\varepsilon_0[w(l_1-x)]}{d}$$

$$=\underbrace{\frac{w\varepsilon_0}{d}[l_1+\varepsilon_r l_2]}_{C\text{ as before}}+\frac{\varepsilon_0 w}{d}[-x+\varepsilon_r x]$$

$$\Rightarrow \Delta C=\frac{\varepsilon_0 wx}{d}(\varepsilon_r-1)$$

$$\Delta C=\left[\frac{\varepsilon_0 w(\varepsilon_r-1)}{d}\right]x$$

Capacitance Sensor: Change in Dielectric Constant—IV

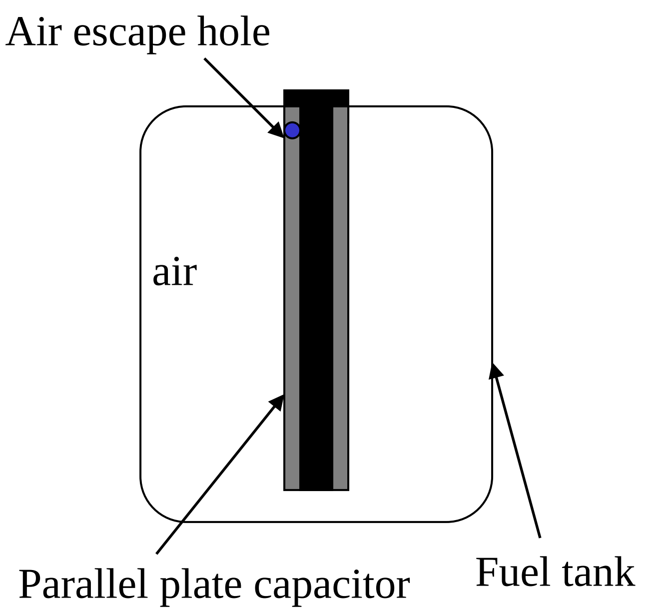
$$\Delta C = \left[\frac{\varepsilon_0 w(\varepsilon_r - 1)}{d} \right] x$$

- The above expression for ΔC illustrates that the change in capacitance is directly proportional to displacement
- Sensitivity:

$$S = \frac{\partial}{\partial x}[\Delta C] = \frac{\varepsilon_0 w(\varepsilon_r - 1)}{d}$$

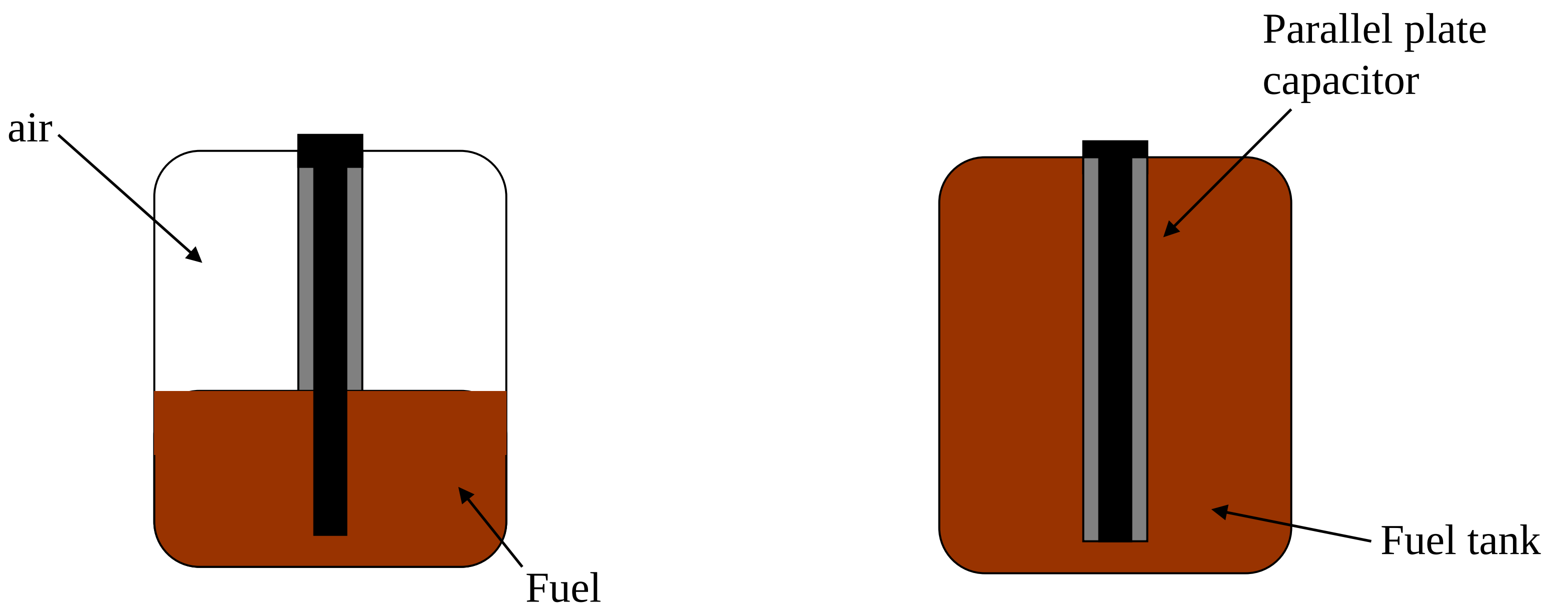
- The principle of capacitance based transducer using change in dielectric constant can be used to design sensors for measuring liquid level in non-conducting liquids.
- The rising and falling level of liquid causes changes in the dielectric constant, which provides a basis for level measurement.

Capacitive Sensor in a Fuel Tank —I



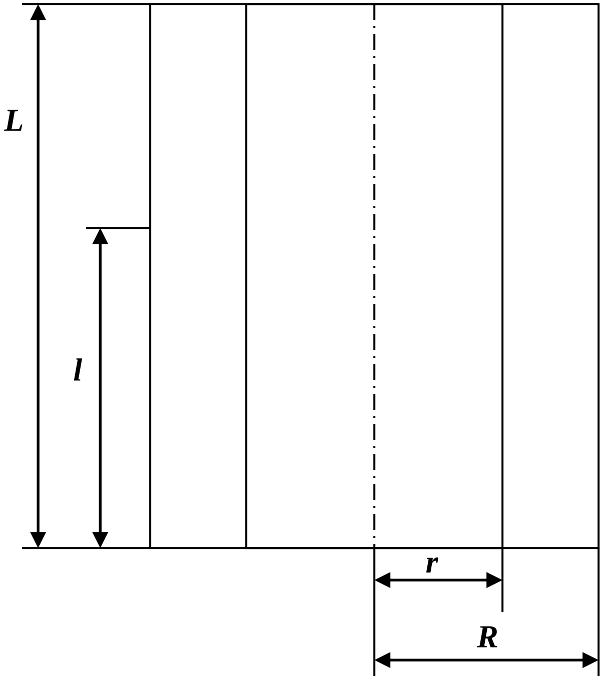
- The sensor comprises of two cylindrical tubes, one inside the other, which form a capacitor in the fuel tank as shown in the first figure.
- The gap between the inner and outer plates is normally air, and this is replaced by fuel as the level increases.

Capacitive Sensor in a Fuel Tank —II



- As the tank is filled with fuel, the capacitance value changes since fuel has a higher dielectric value than air.
  - If the tank is partially filled, the capacitance will change proportionally with the level of fuel in the tank.
- Thus, now as the fuel rises and falls, the added value of capacitance due to fuel also rises and falls.
- At the lower end of outer cylinder, there are holes that allow fuel to escape when fuel level in the tank begins to fall down.

Capacitive Sensor in a Fuel Tank—III



R:	Radius of outer cylinder
r:	Radius of inner cylinder
L:	Height of the two cylinders
l:	Liquid level

- Recall, for a cylindrical capacitor with overlapping length *x*, the capacitance is given by:

$$C = \frac{\varepsilon_0 \varepsilon_r (2\pi x)}{\ln(R/r)}$$

- We have two capacitors, C_1 and C_2 in parallel.
- Begin, with computing C for the case when $l=0$ (empty tank)

$$C = \frac{\varepsilon_0 2\pi L}{\ln(R/r)}$$

Capacitive Sensor in a Fuel Tank—IV

- C changes to $C+\Delta C$ when liquid level is $l \neq 0$

$$C+\Delta C = C_1 + C_2 = \frac{\varepsilon_0 \varepsilon_r 2\pi (l)}{\ln(R/r)} + \frac{\varepsilon_0 2\pi (L-l)}{\ln(R/r)}$$

$$= \frac{\varepsilon_0 \varepsilon_r 2\pi l}{\ln(R/r)} + \underbrace{\frac{\varepsilon_0 2\pi L}{\ln(R/r)}}_{\text{Same as } C} - \frac{\varepsilon_0 2\pi l}{\ln(R/r)}$$

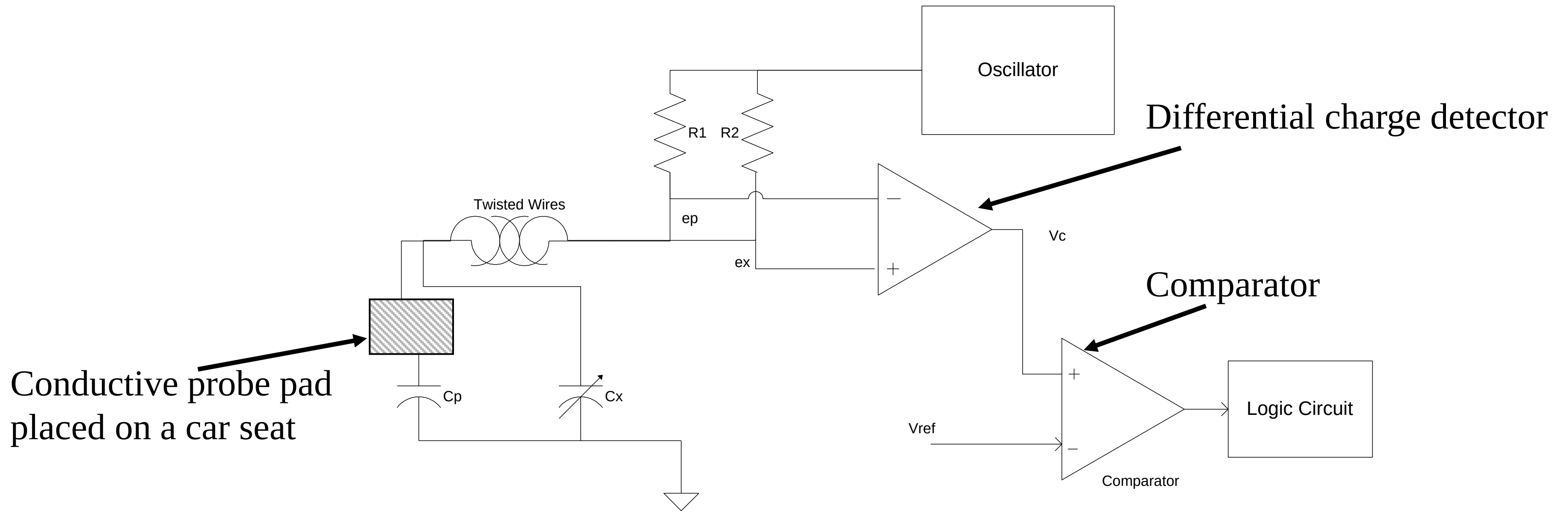
$$\Rightarrow \Delta C = \frac{\varepsilon_0 2\pi l}{\ln(R/r)}[\varepsilon_r - 1]$$

$$\Rightarrow \Delta C = \left[\frac{2\pi\varepsilon_0(\varepsilon_r - 1)}{\ln(R/r)}\right] l \longrightarrow \Delta C \text{ is linearly varying with } l$$

- Sensitivity:

$$S = \frac{\partial}{\partial l}(\Delta C) = \frac{2\pi\varepsilon_0(\varepsilon_r - 1)}{\ln(R/r)}$$

Capacitive Occupancy Detector for Cars—I



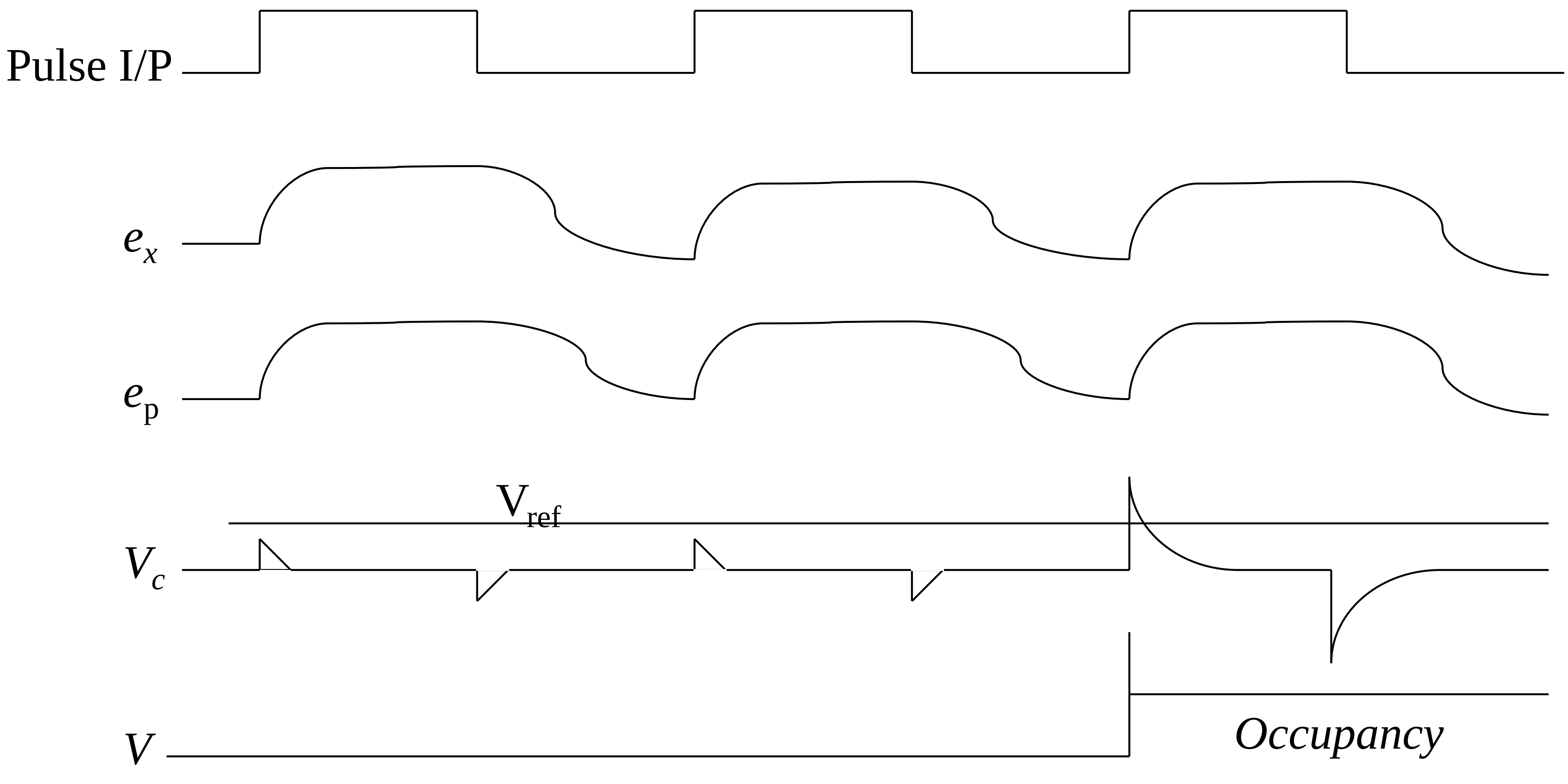
An automotive capacitive intrusion detector

- The figure above illustrates a capacitive security system for an automobile.
- A sensing probe is imbedded into a car seat.
  - It can be fabricated as a metal plate, metal net, a conductive fabric, etc.
- The probe forms one plate of a capacitor C_p. The other plate of the capacitor C_p is formed either by the automobile body or a separate plate positioned under a floor mat.
- A reference capacitor, C_x, is composed of a simple fixed or trimming capacitor which should be placed close to the seat probe.

Capacitive Occupancy Detector for Cars—II

- The probe plate and the reference capacitor are respectively, connected to two inputs of a charge detector (resistors R1 and R2).
- The conductors preferably should be twisted (e.g., use strips of a twinflex cabling) to reduce the introduction of spurious signals as much as possible.
- The differential charge detector is controlled by an oscillator.
  - Oscillator produces square pulse train.
- When the seat is not occupied, the reference capacitor is adjusted to be approximately equal to C_p.
- Resistors and the corresponding capacitors define time constants of the networks.
- Both RC circuits have equal time constants τ_1 .
- Voltages across the resistors are fed into the inputs of the differential amplifier, whose output voltage V_c is near zero under no occupancy condition.
- Small spike at the output is the result of some imbalance.
- When a person sits on the seat, his (her) body forms an additional capacitance in parallel with C_p, thus increasing the time constant of the R_1C_p-network from τ_1 to τ_2 .
- This is indicated by the increased spike amplitudes exceeding the threshold V_{ref}, which causes the comparator to send an indication signal to the logic circuit that generates signal V indicating that the car is occupied.
- Note that a capacitive detector is an active sensor, because it requires an oscillating test signal to measure the capacitance value.

Capacitive Occupancy Detector for Cars—III

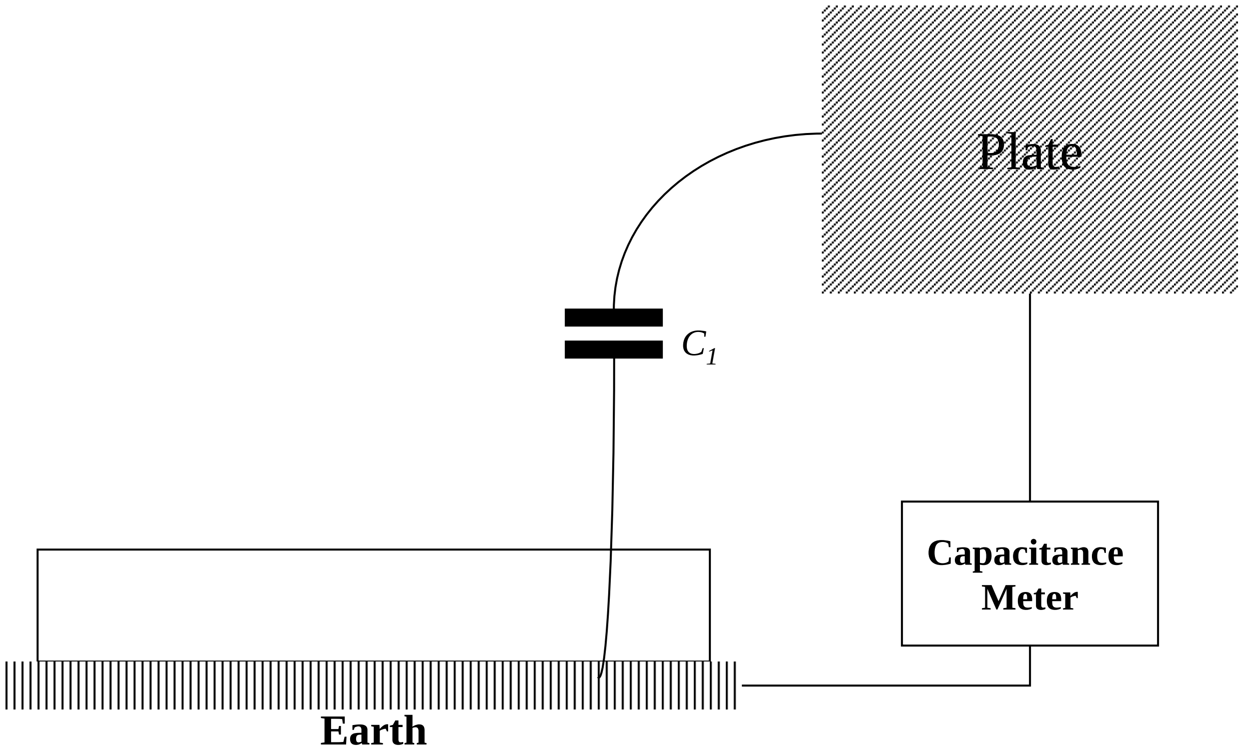


Timing diagrams for a capacitive intrusion detector

Capacitive Occupancy Detector: Intrusion Detection—I

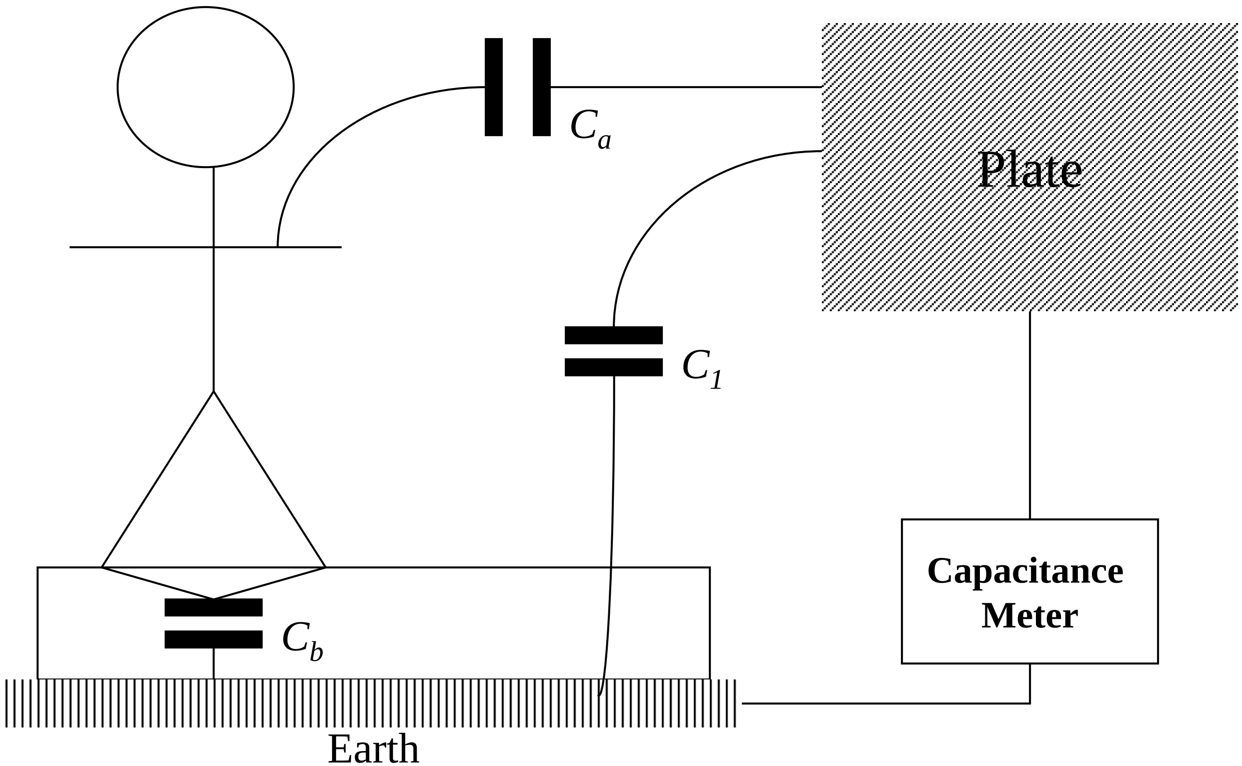
- Human body is a a conductive medium with a high dielectric constant.
- Human body develops a coupling capacitance to its surroundings, i.e., objects in its proximity.
- The coupling capacitance formed between a human body and its surroundings greatly depends on such factors as the body size, clothing, materials, type of the surrounding objects, weather, etc.
- However wide the coupling range (i.e., distance between a human body and surrounding objects), the coupling capacitance may vary from a few picofarads to several nanofarads.
- When a person moves, the coupling capacitance changes, thus making it possible to discriminate static objects from moving ones.

Capacitive Occupancy Detector: Intrusion Detection—II



- Actually all objects form some degree of capacitive coupling with one another.
- If a human (or for that purpose, anything) moves into the vicinity of the objects whose coupling capacitance with each other has been previously established, a new capacitive value arises between the objects due to the presence of an intruding body.
- In the figure C_1 is the capacitance between a test plate and earth.

Capacitive Occupancy Detector: Intrusion Detection—III

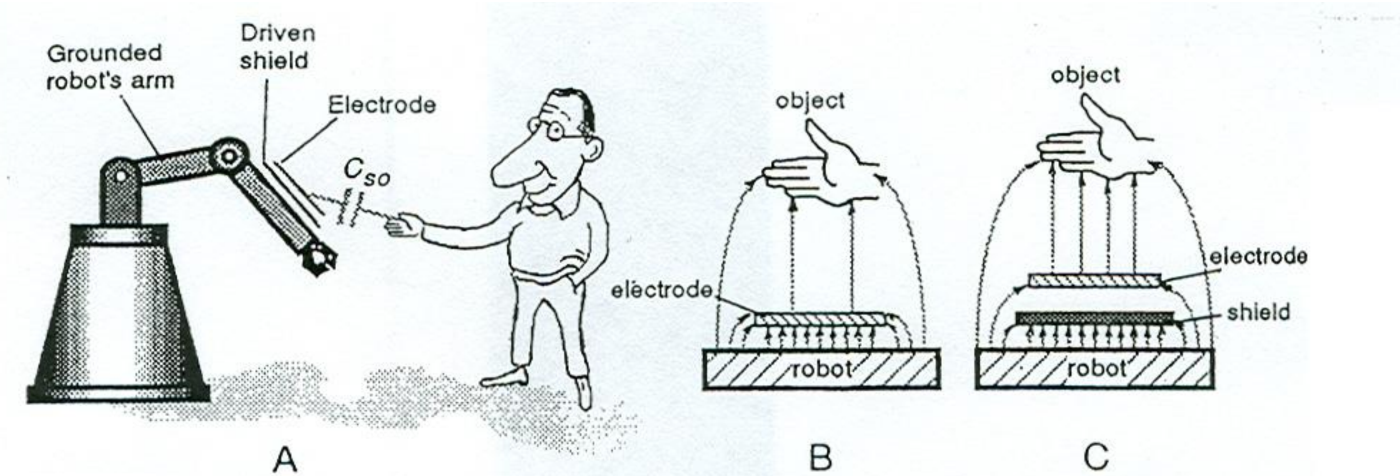


- When a person moves into the vicinity of the plate, two additional capacitors are formed: one between the plate and person's own body C_a, and the other between the person's body and the earth C_b. The resulting capacitance C between the plate and the earth becomes larger by ΔC

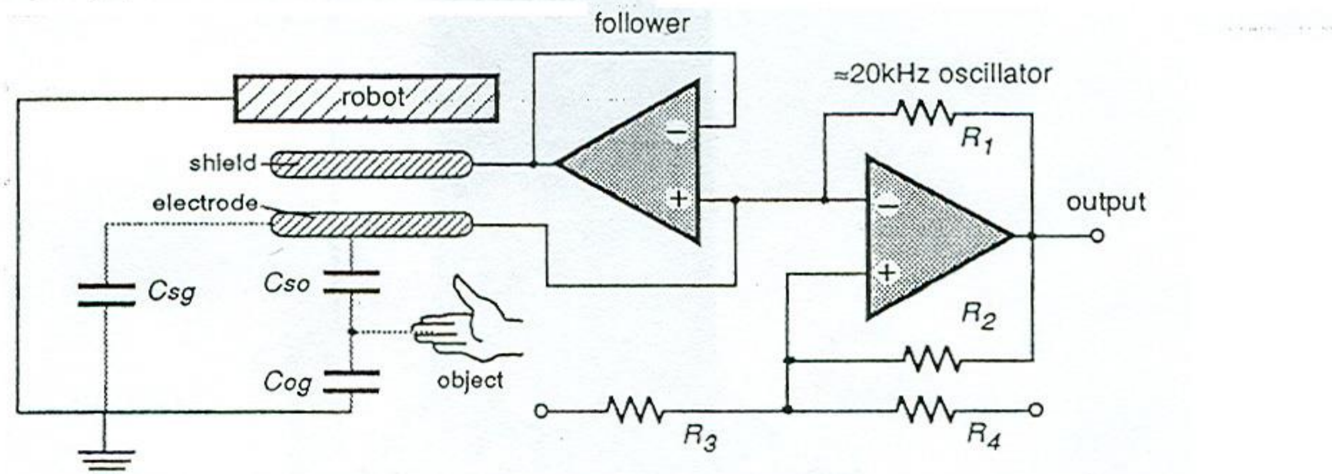
$$C = C_1 + \Delta C = C_1 + \frac{C_a C_b}{C_a + C_b}$$

- With appropriate apparatus, ΔC can be measured and used for occupancy detection.

Capacitive Occupancy Detector for a Robotic Manipulator

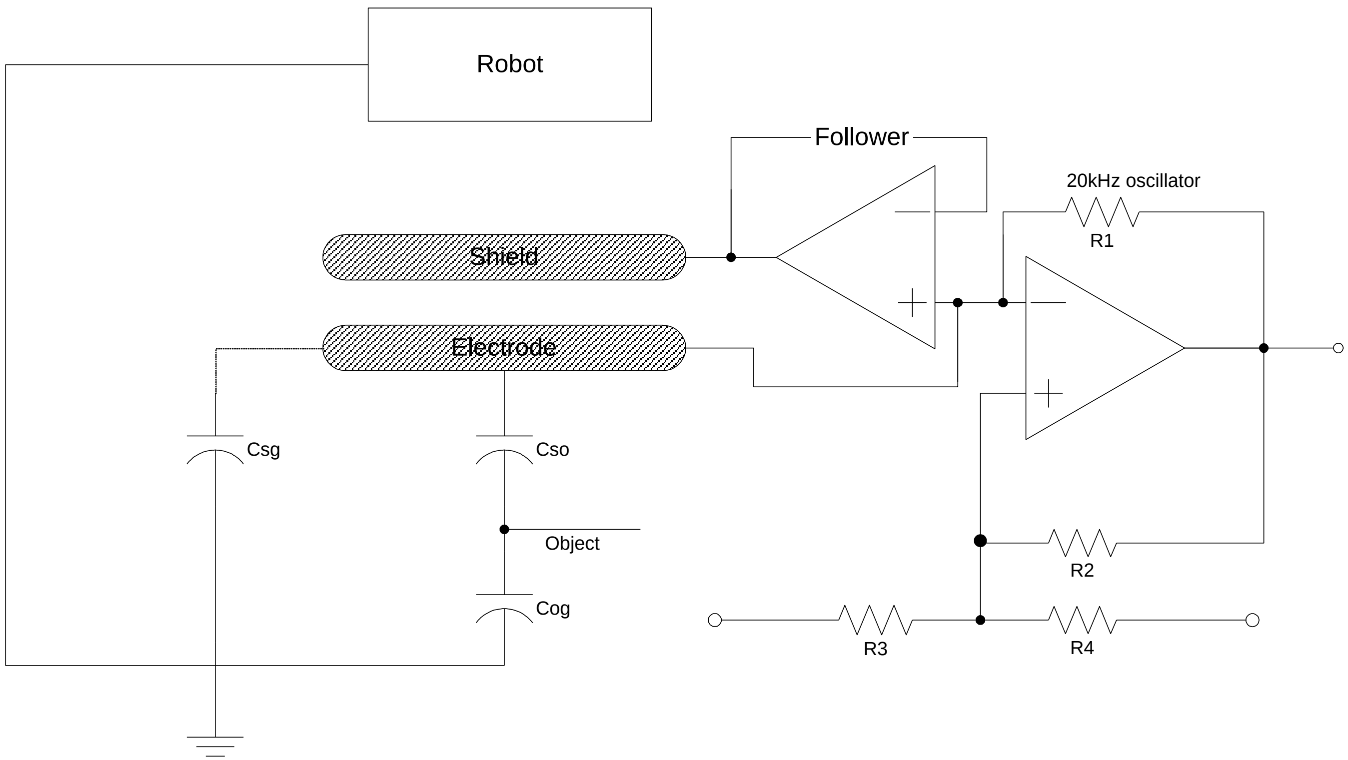


Capacitive proximity sensor. A driven shield is positioned on the metal arm of a grounded robot (A). Without the shield, the electric field is mostly distributed between the electrode and the robot (B), while a driven shield directs electric field from the electrode toward the object (C).



Simplified circuit diagram of a frequency modulator controlled by the input capacitances.

Capacitive Occupancy Detector—VII



- It is possible to adapt a robot's arm to sense things using capacitive occupancy detector. By directing the electrode towards object, it is possible for the robot to detect the conductive objects within range.
- The figure above shows a simplified circuit diagram of a frequency modulator controlled by the input capacitance.