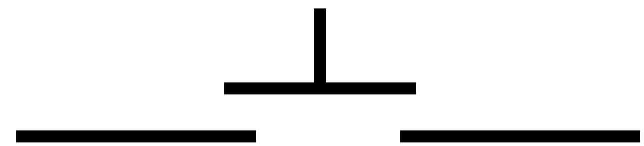
Mechatronics

Topic #4

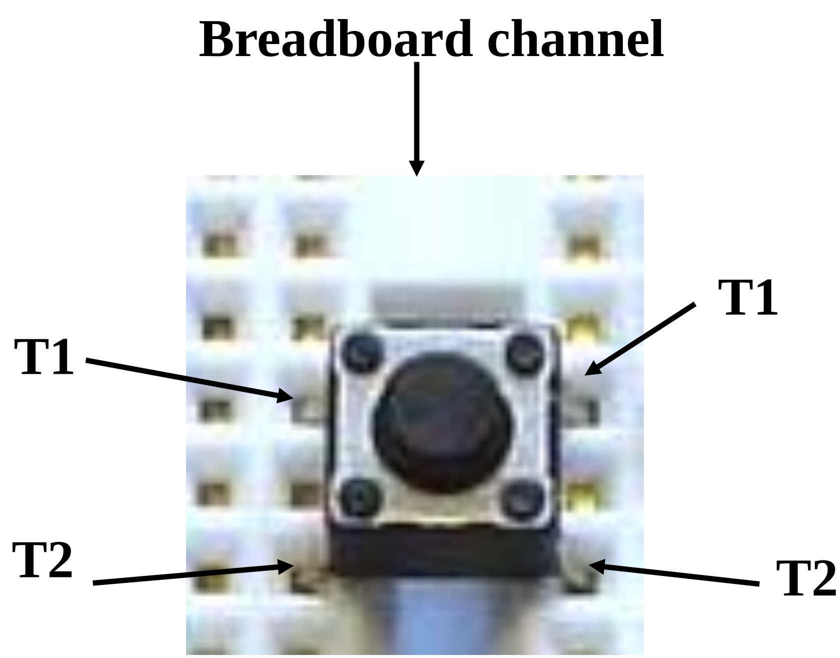
Interfacing Digital and Analog Inputs to BS2

Interfacing Digital Inputs with BS2

Buttons/Switches —I

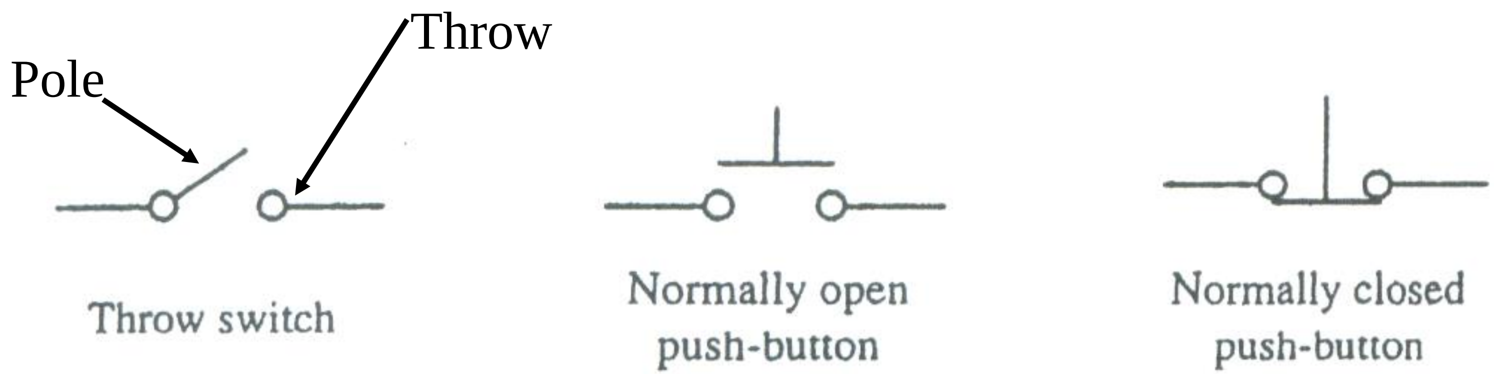


Symbol

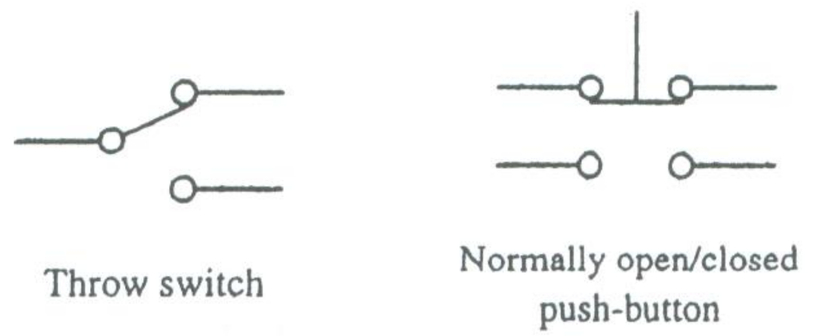


Buttons/Switches —II

- SPST switches

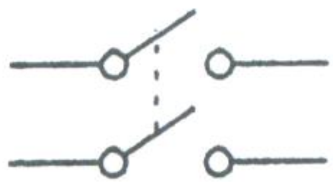


- SPDT switches



Buttons/Switches —III

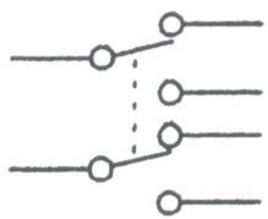
- DPST switches



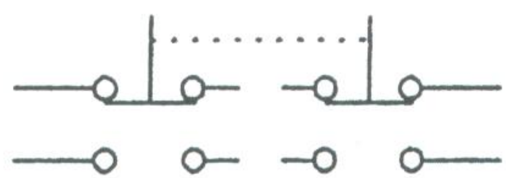
Throw switch

Normally open
push-button

- DPDT switches



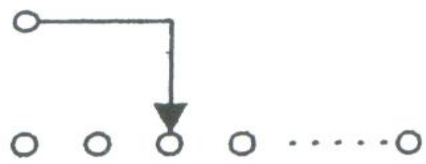
Throw switch



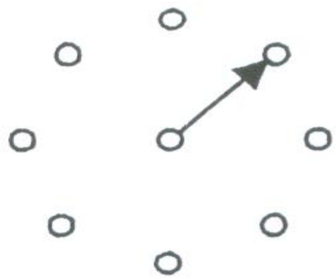
Normally open/closed
push-button

Buttons/Switches —IV

- SP(n)T switches

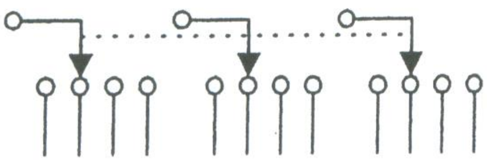


Multiple contact slider switch

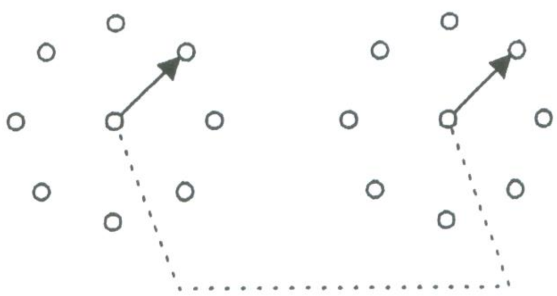


Multiple contact rotary switch (SP8T)

- (n)P(m)T switches



3P4T

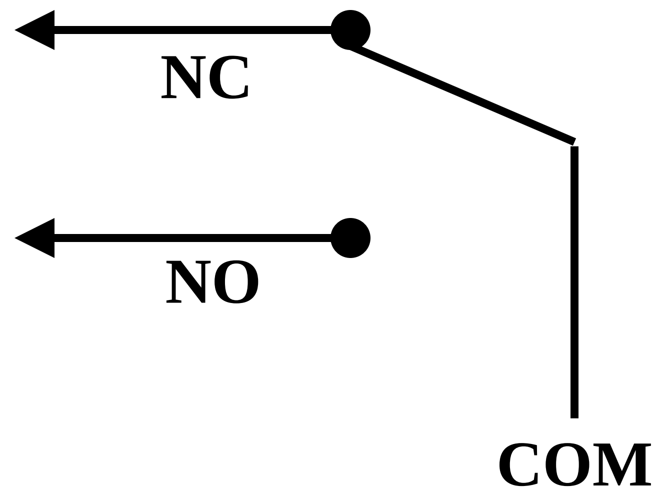


2-deck rotary (DP8T)

Buttons/Switches —V

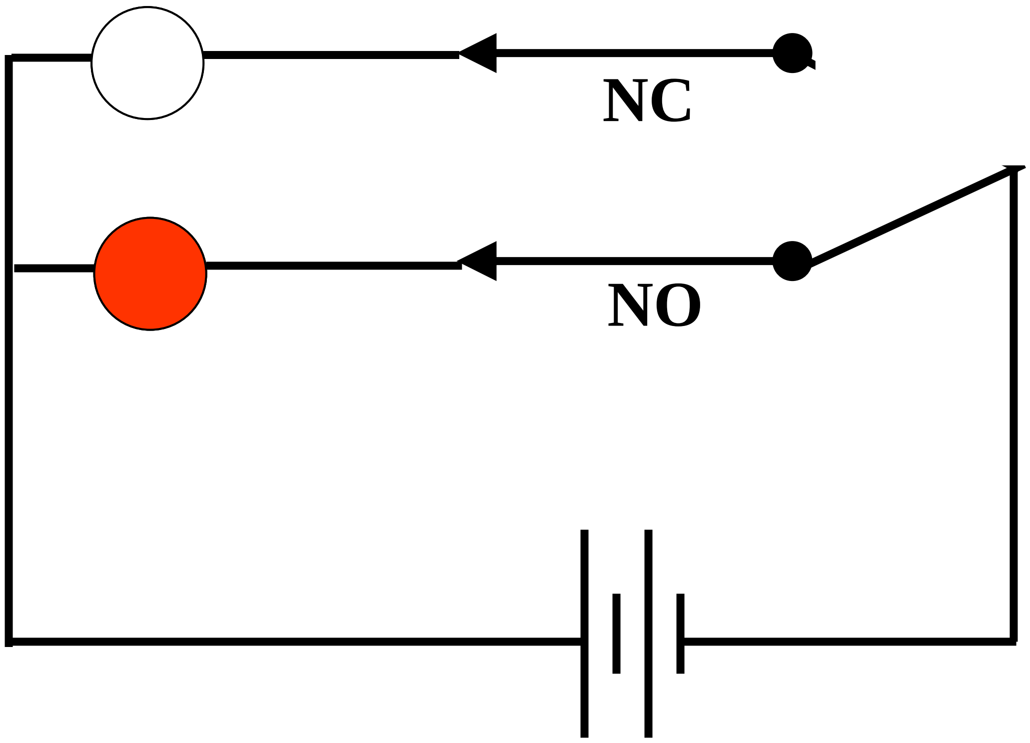
- Two major categories:
  - Momentary switch: its state is altered only during it actuation.
  - Permanent switch: its state is altered and maintained after it is actuated. Separate actions are required to open and close the switch.
- “Make-before-break” and “Break-before-make” (more common) switches:
  - Suppose you have a make-before-break switch with contacts A, B, and C.
  - Let B be the common terminal and let A be connected to +5V supply and C to the ground.
  - When the switch is moved from C to A, for a brief moment C and A are connected before connection to C is broken.
  - We get an unintended momentary short circuit!

Limit Switch

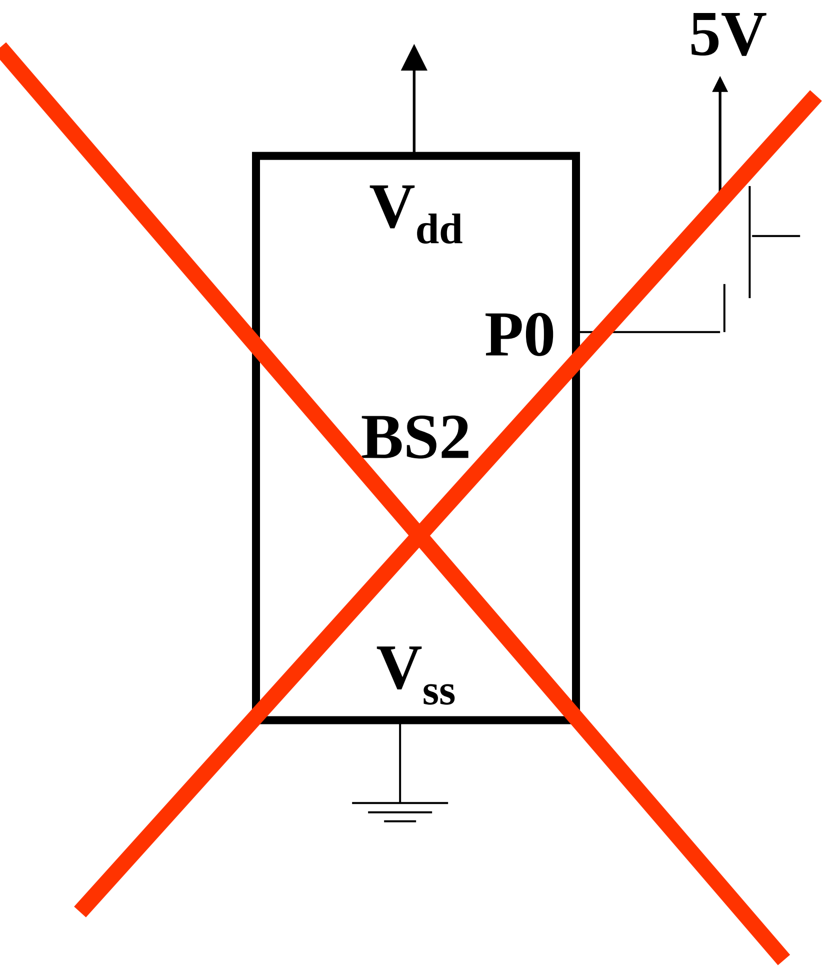


SPDT Limit Switch

Limit Switch



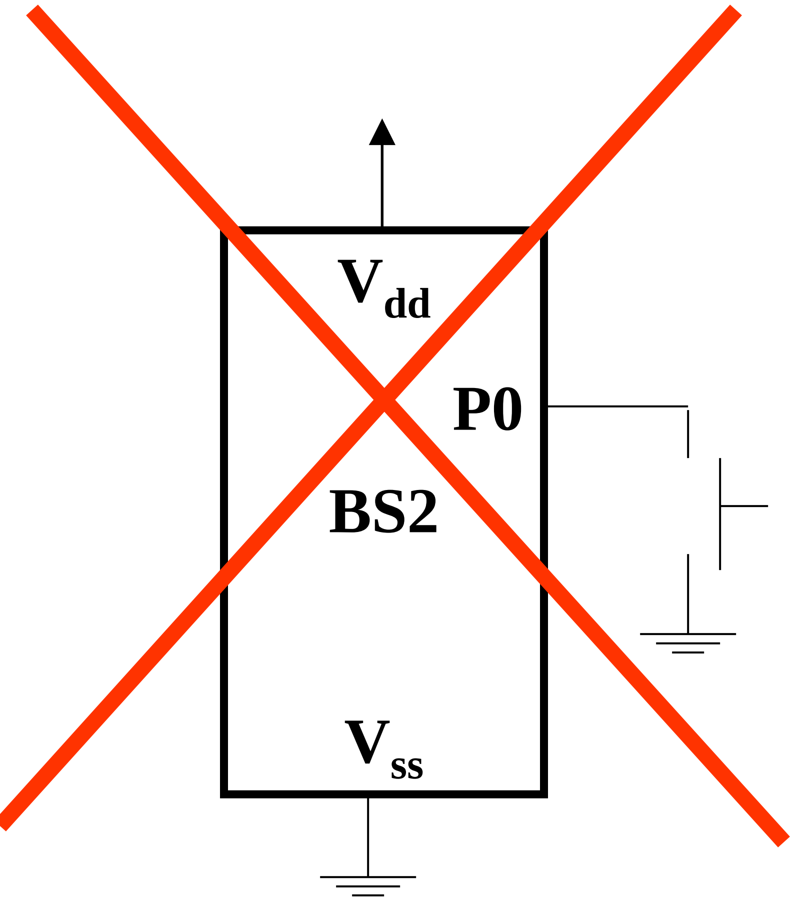
Wrong Button Connection—I



Wrong

- Floating input condition when button is not pressed!
- When button is pressed, P0 is driven high.
- When button is pressed and erroneously one makes P0 output a low, then 5V is in short with ground → BS2 may be damaged!

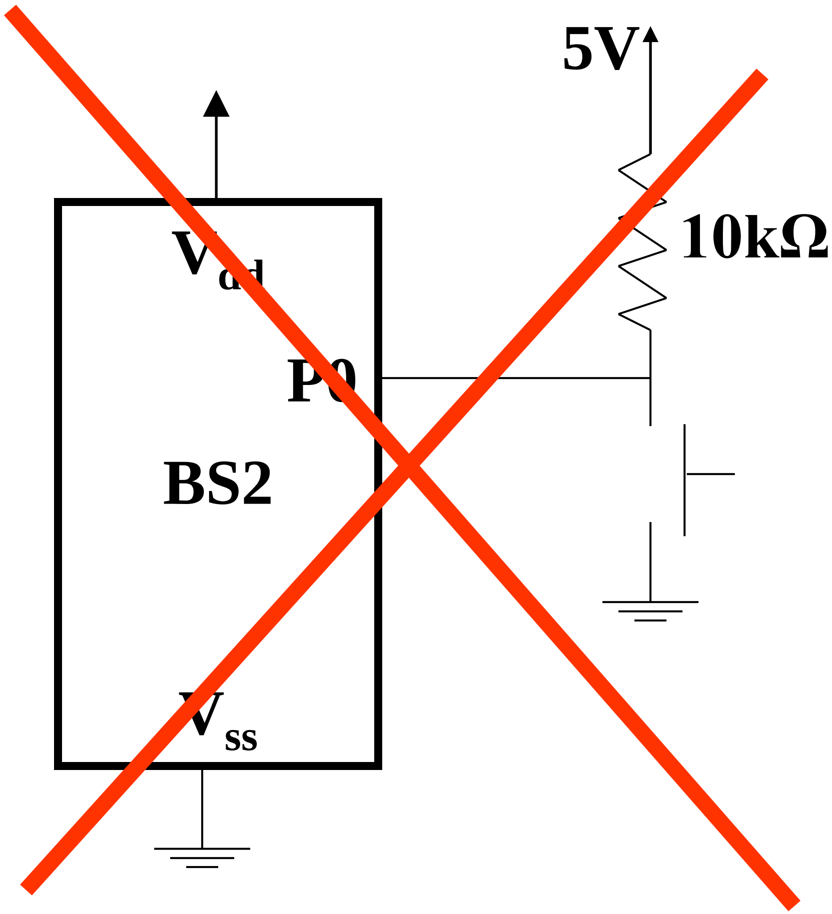
Wrong Button Connection—II



Wrong

- Floating input condition when button is not pressed!
- When button is pressed, P0 is driven low.
- When button is pressed and erroneously one makes P0 output a high, then 5V is in short with ground → BS2 may be damaged!

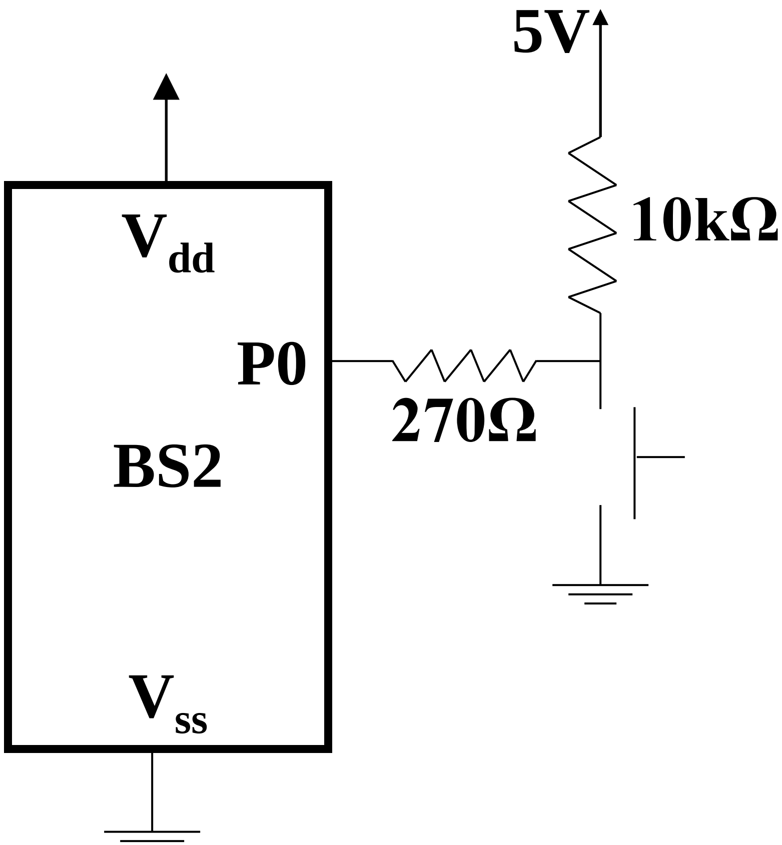
Wrong Button Connection—III



Wrong

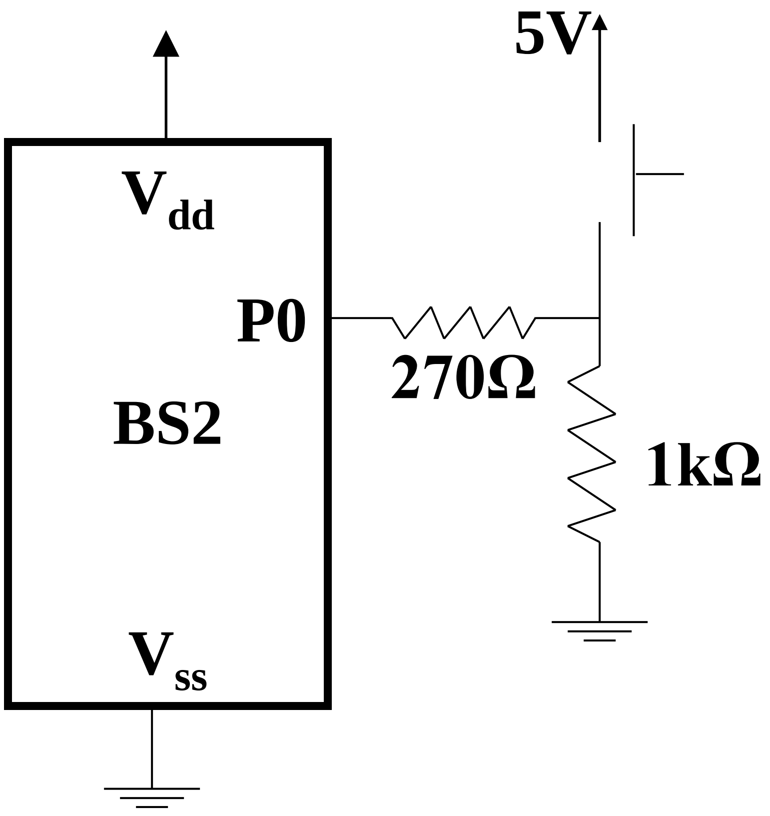
- Button is pressed, P0 is pulled down to ground.
- Button is not pressed, the 10kΩ resistor pulls P0 high.
- When button is pressed and erroneously one makes P0 output a high, then 5V is in short with ground → BS2 may be damaged!

NO Active Low Button Connection



- SPST normally open switch installed as an active low device:
  - P0 high → open switch (10K pull-up resistor).
  - P0 low → closed switch (switch is activated).
  - 270Ω is for protecting I/O pin

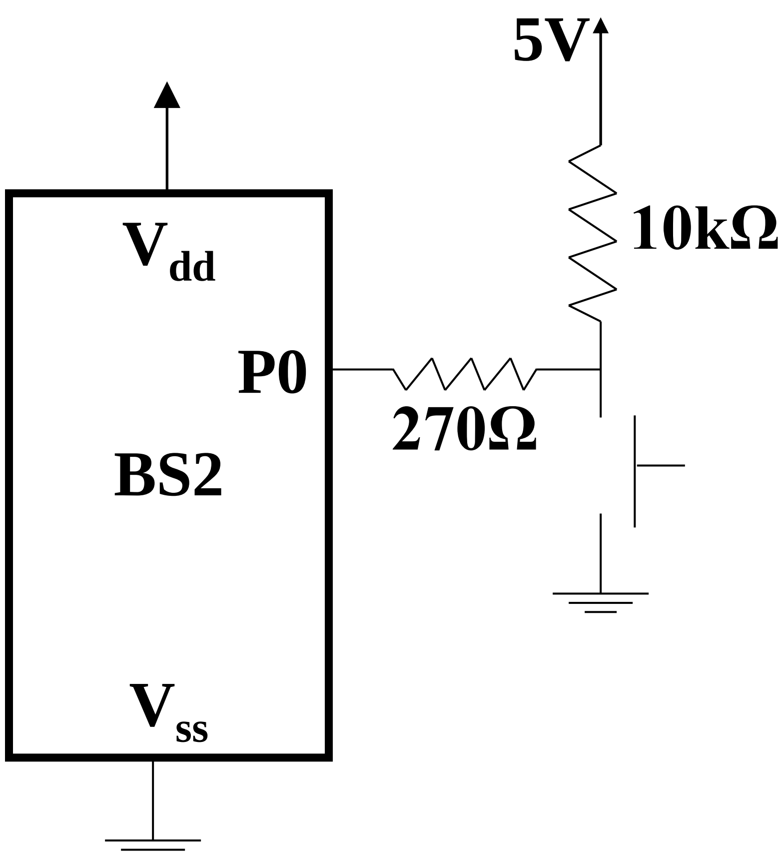
NO Active High Button Connection

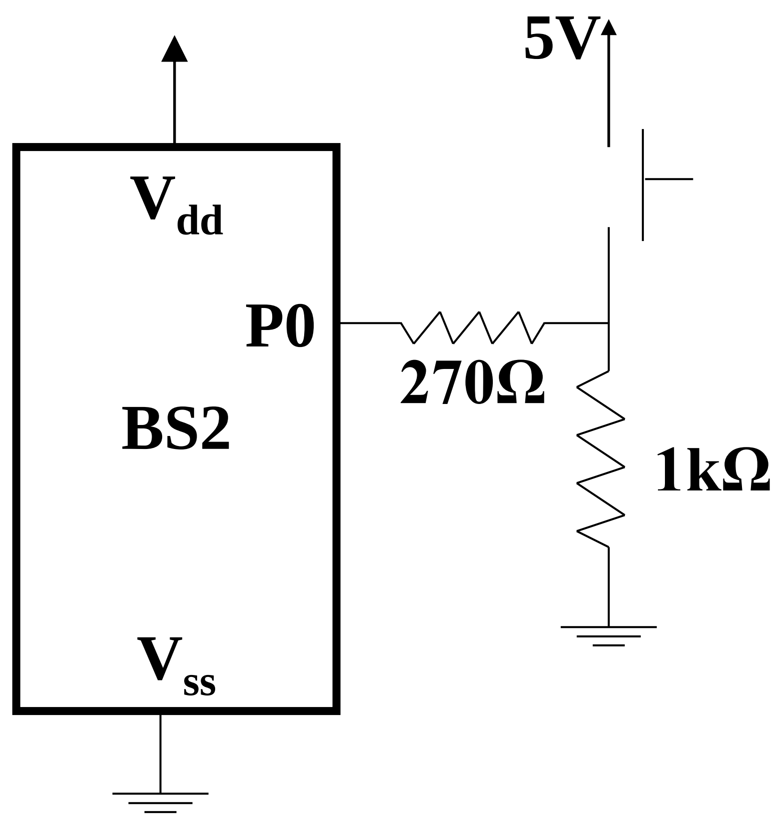


- SPST normally open switch installed as an active high device:
  - P0 high → closed switch (switch is activated).
  - P0 low → open switch (1K pull-down resistor).
  - 270Ω is for protecting I/O pin

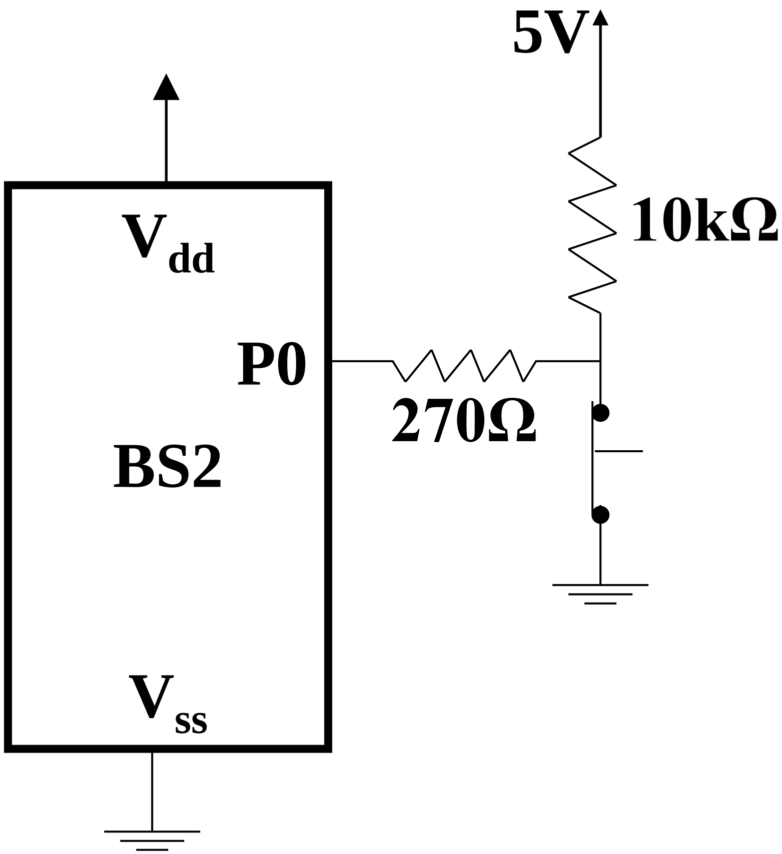
NO Button Connection Preference

- NO active low circuit is preferred as it yields better noise immunity.
  - Low state detection threshold is 1.4V. In order for this circuit to incorrectly report switch closure, a noise level of –3.6V is needed at the 5V supply.
- In a NO active high circuit, a noise level of 1.4V at the ground of the supply will incorrectly report an open switch as a closed switch.



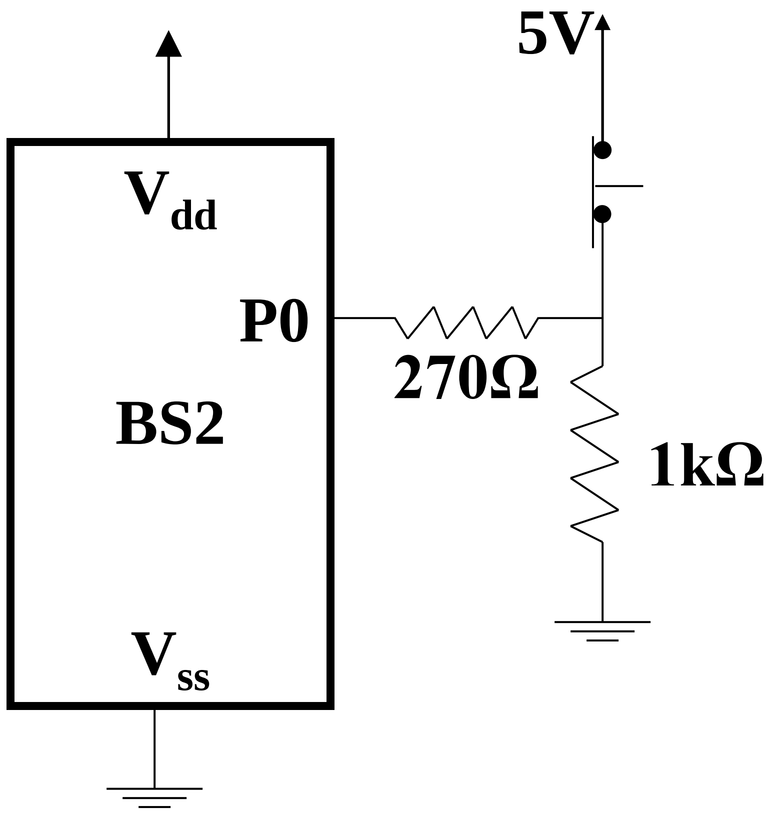


NC Active High Button Connection



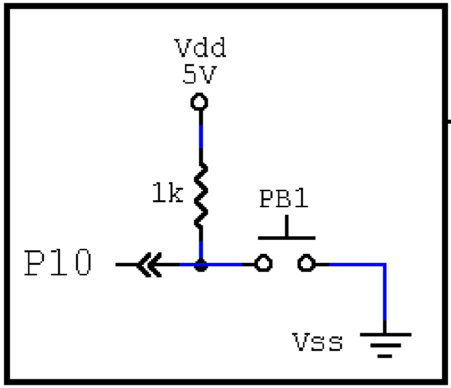
- SPST normally closed switch installed as an active high device:
  - P0 low → closed switch (switch is not activated).
  - P0 high → open switch, switch is activated (10K pull-up resistor).

NC Active Low Button Connection



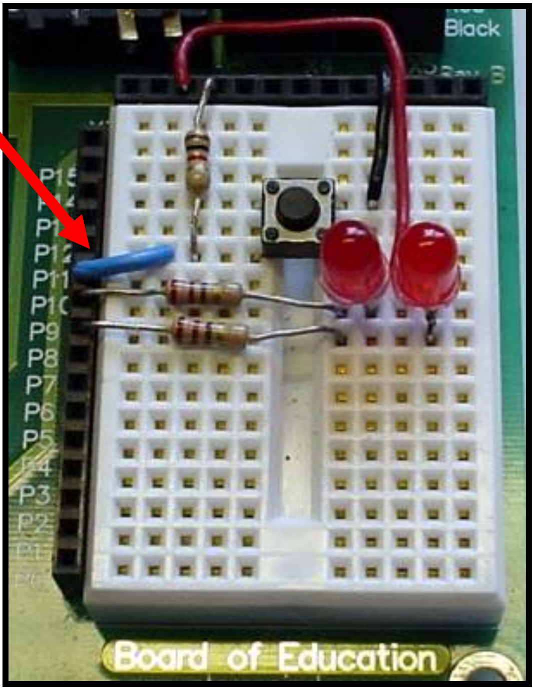
- SPST normally closed switch installed as an active high device:
  - P0 high → closed switch (switch is not activated).
  - P0 low → open switch, switch is activated (1K pull-down resistor).
  - 270Ω is for protecting I/O pin

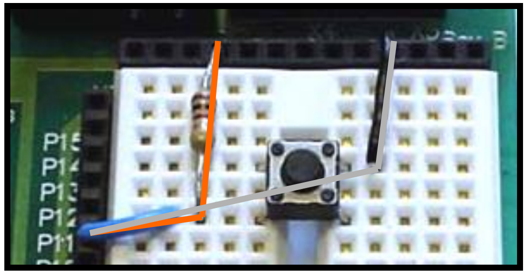
Illustrative Button Connections on a BS2



The push-buttons used here have 4 terminals. 2 are electrically connected on one side of the button, and the other 2 on the other side. By wiring to opposing corners we ensure the proper connection independent of button rotation.

Use a 270 Ω resistor



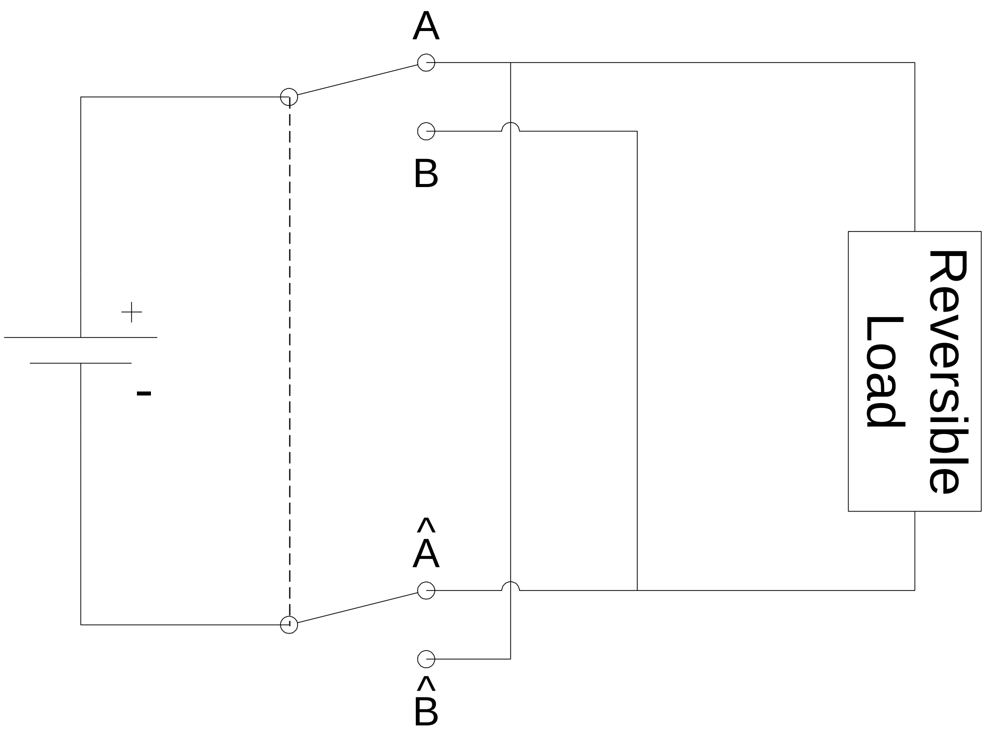


Button alone

- This push-button is a momentary normally-open (N.O.) switch. When the button IS NOT pressed (open), P10 will sense Vdd (5V, HIGH, 1) because it is *pulled-up* to Vdd.

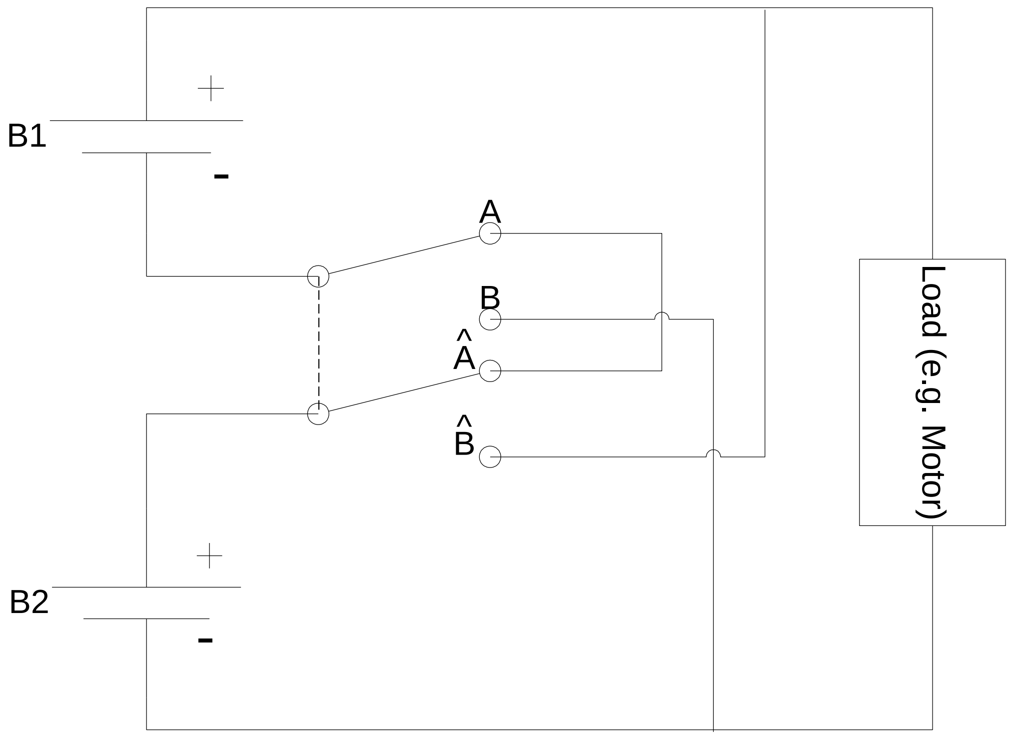
- When PB1 IS pressed (closed), P10 will sense Vss (0V, LOW, 0) making it *Active-Low*.

Button Applications: Load Reversal



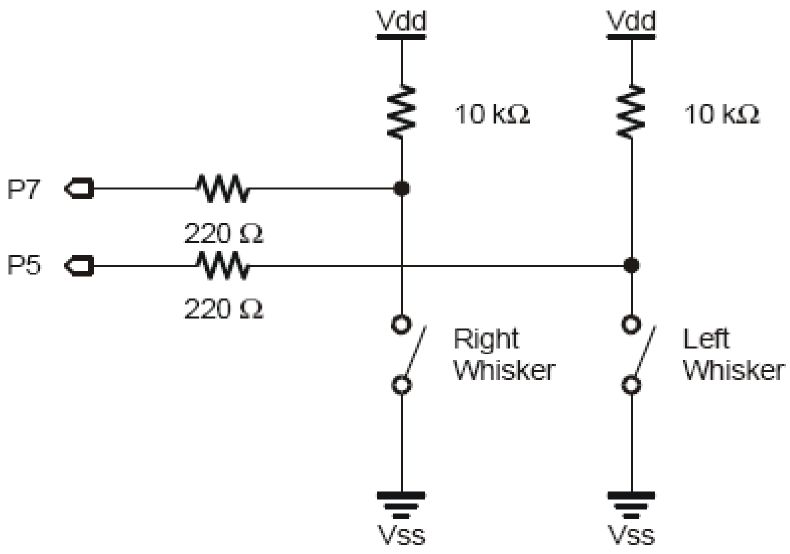
- DPDT switch used to reverse a load (e.g., a motor).
- When switch makes contacts with A and $\hat{A}$, load runs in forward direction.
- When switch makes contacts with B and $\hat{B}$, load runs in reverse direction.

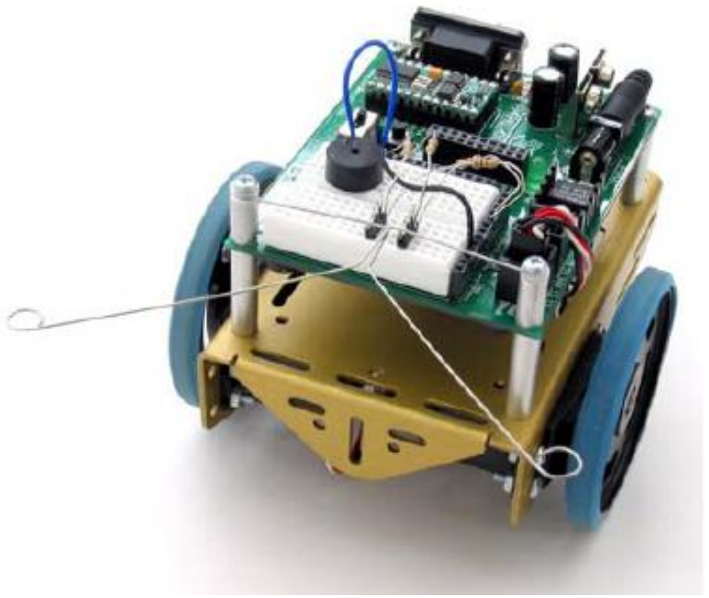
Button Applications: Series/Parallel Connection



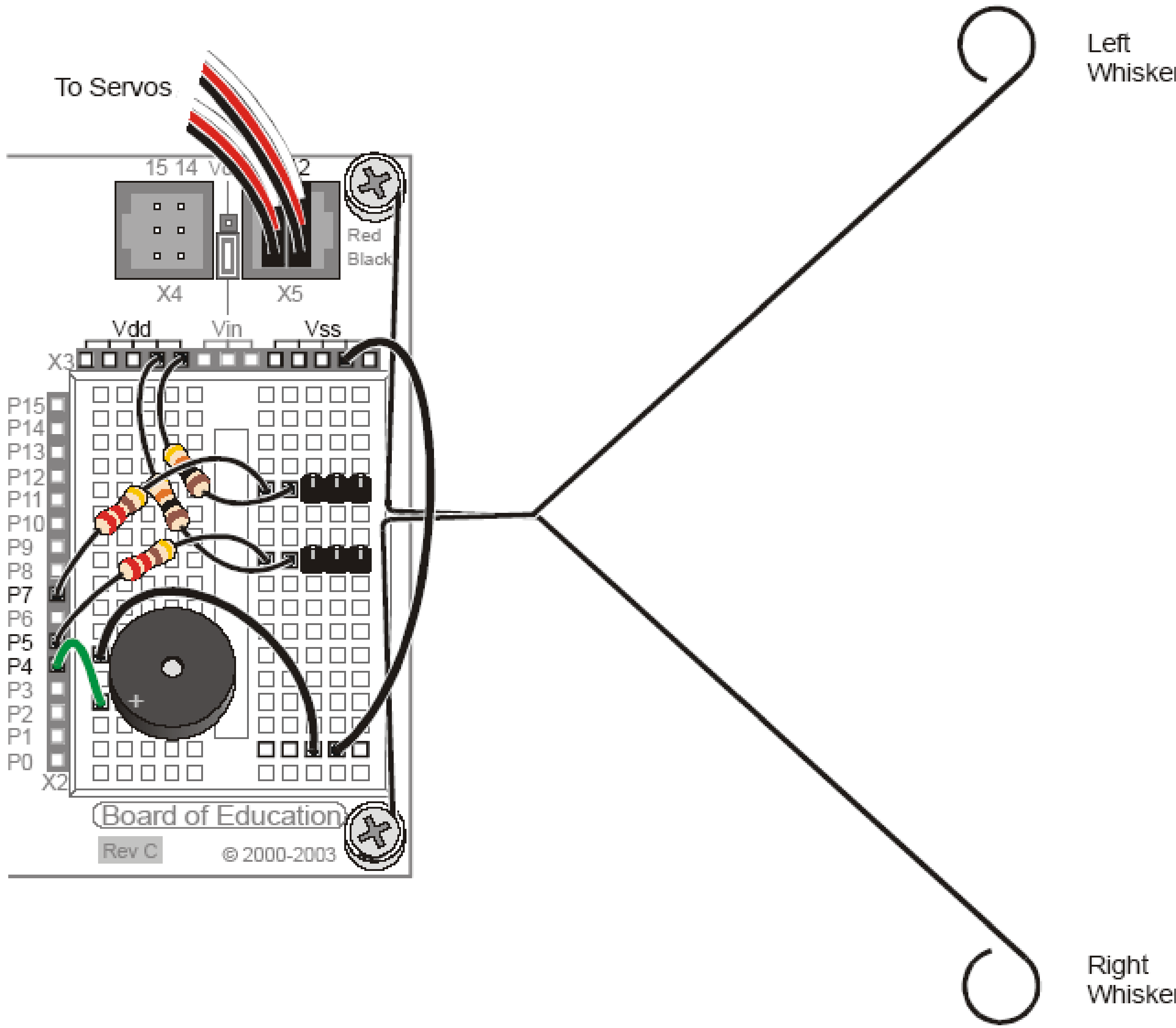
- Series-Parallel connection of power sources using DPDT switch.
- When switch makes contact with A and $\hat{A}$, B1 and B2 are in series and supply $2V_B$ volts (each battery provides V_B volts).
- When switch makes contact with B and $\hat{B}$, B1 and B2 are in parallel and can supply a larger current.

Button Applications: Tactile Sensing —I

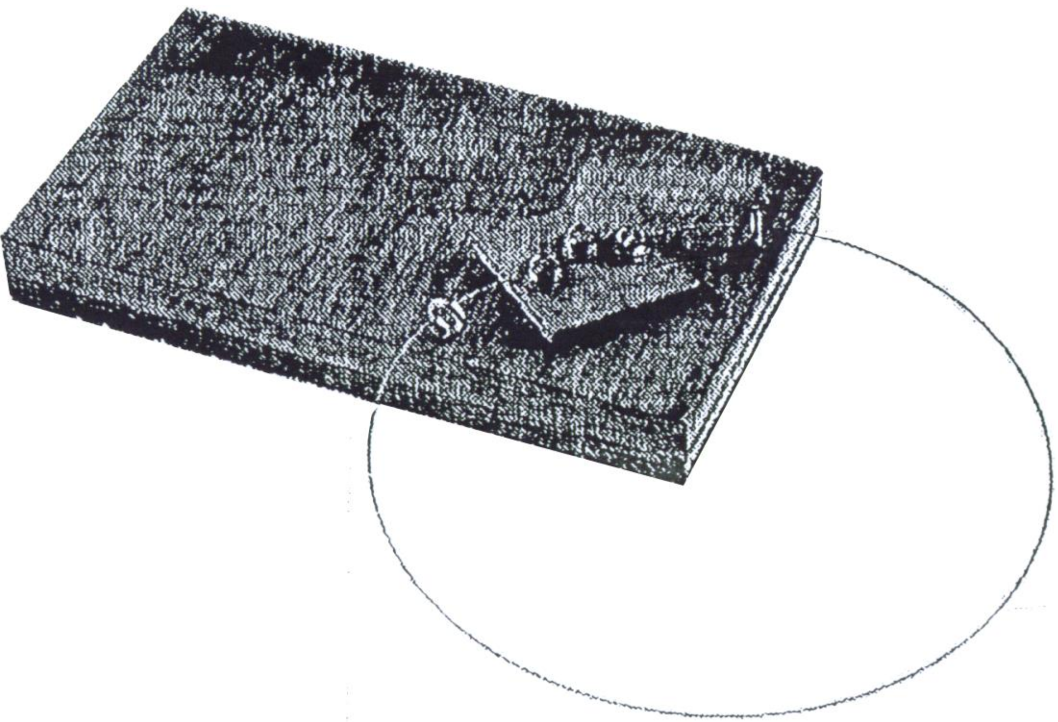




Button Applications: Tactile Sensing —II



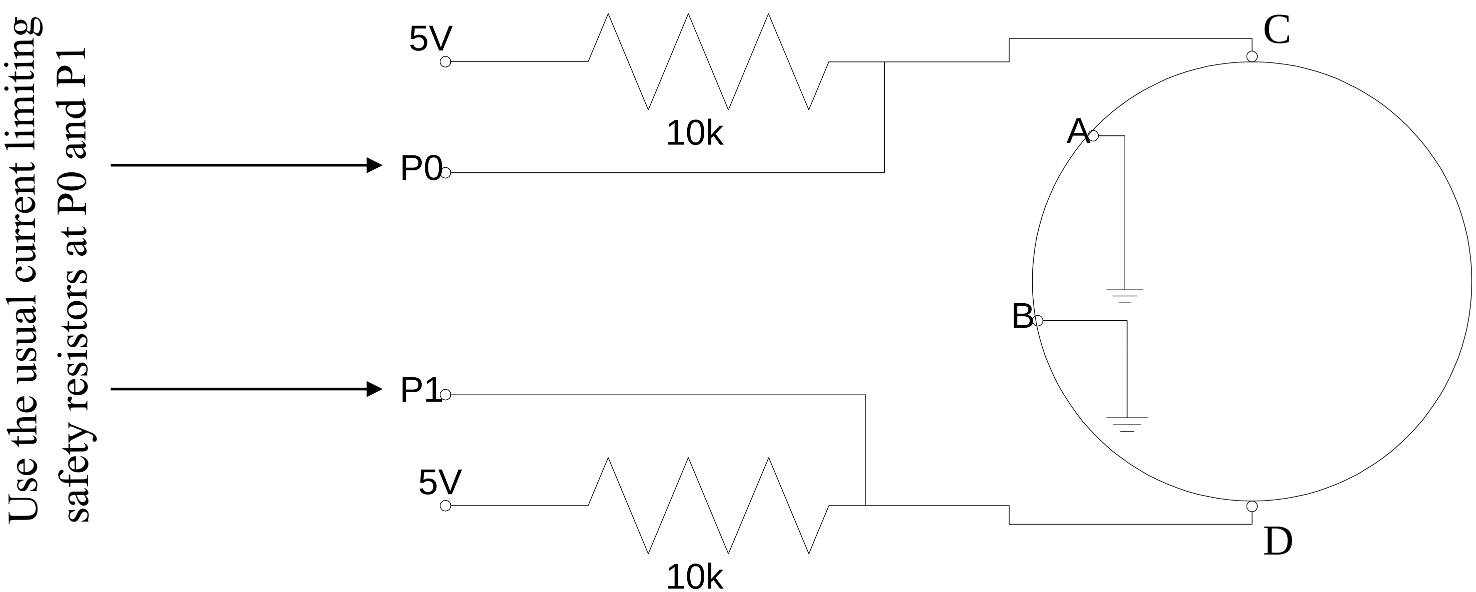
Button Applications: Tactile Sensing —III



- Tactile sensing using guitar string looped through the center of a pair of small screw-eyes.

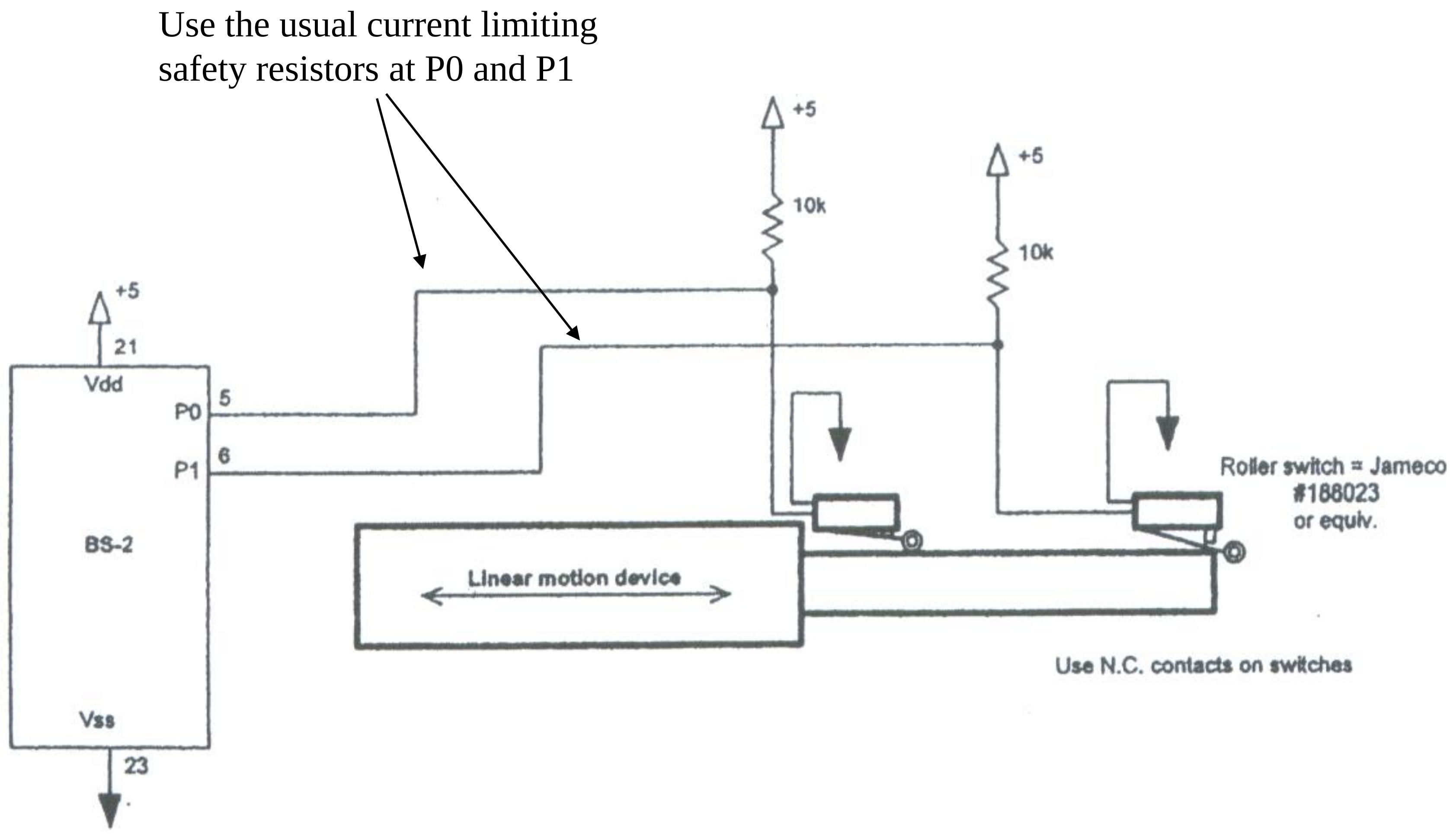
Button Applications: Tactile Sensing —IV

- A loop of guitar string is formed and connected to ground at A and B.
- Two screw eyes at C and D are used as switches. The guitar string loop is passed through C and D such that normally the string does not contact C and D. When the loop comes under pressure, the string will touch the screw eye either at C or D, thereby bringing C/D to ground.
- The two screw eyes are connected to BS2 pins P0 and P1 as shown and to 5V source via 10kΩ resistors.
- When the loop is under no pressure, P0 and P1 are pulled high by 10kΩ resistors.
- When the loop is deflected towards screw eye C/D, thereby bringing screw eye C/D to ground, switch C/D closes, bringing P0/P1 to low.



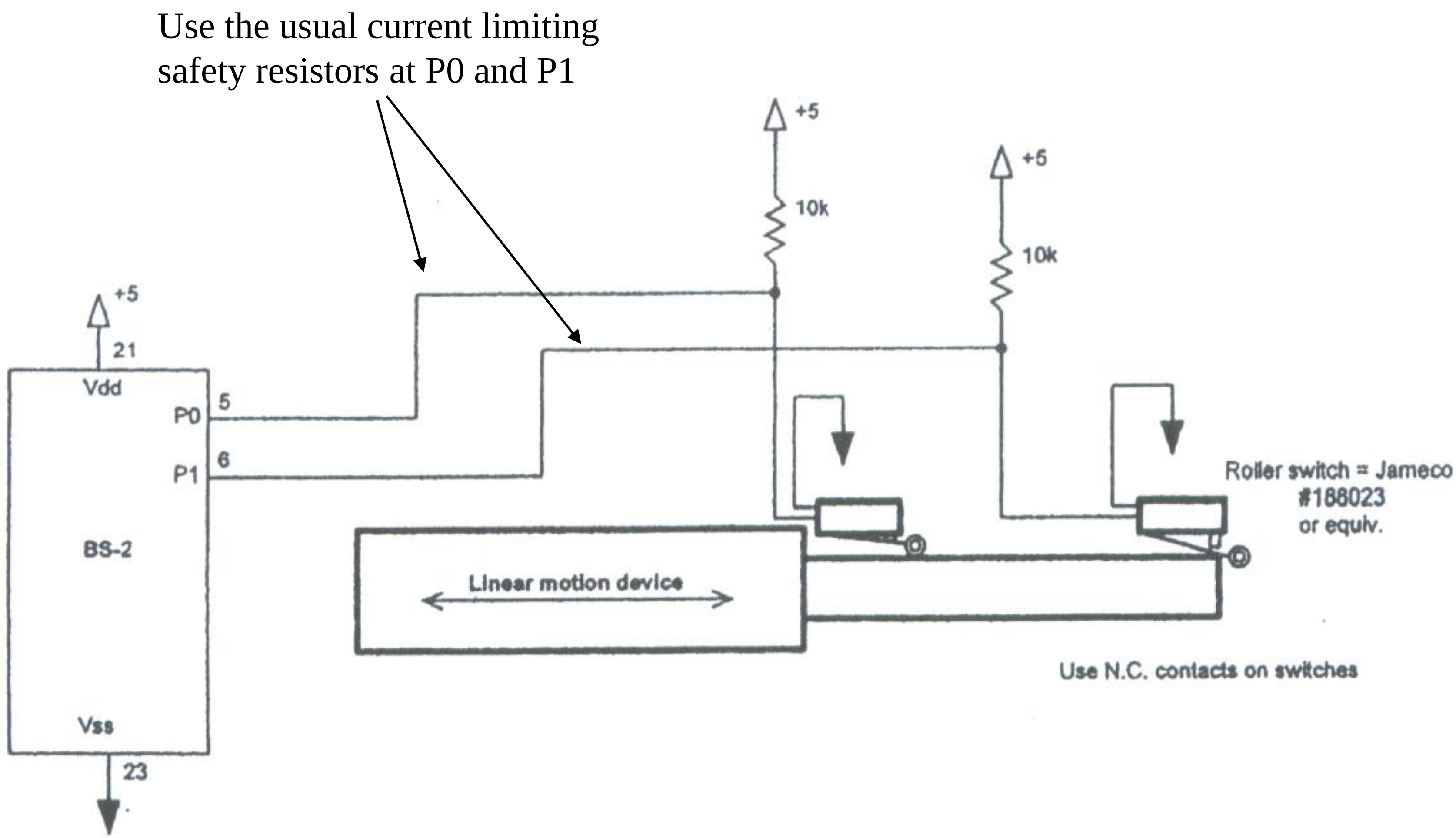
Button Applications: Travel Limit Detection —I

- Two limit switches are used to detect the minimum and maximum position of travel in a mechanical system.



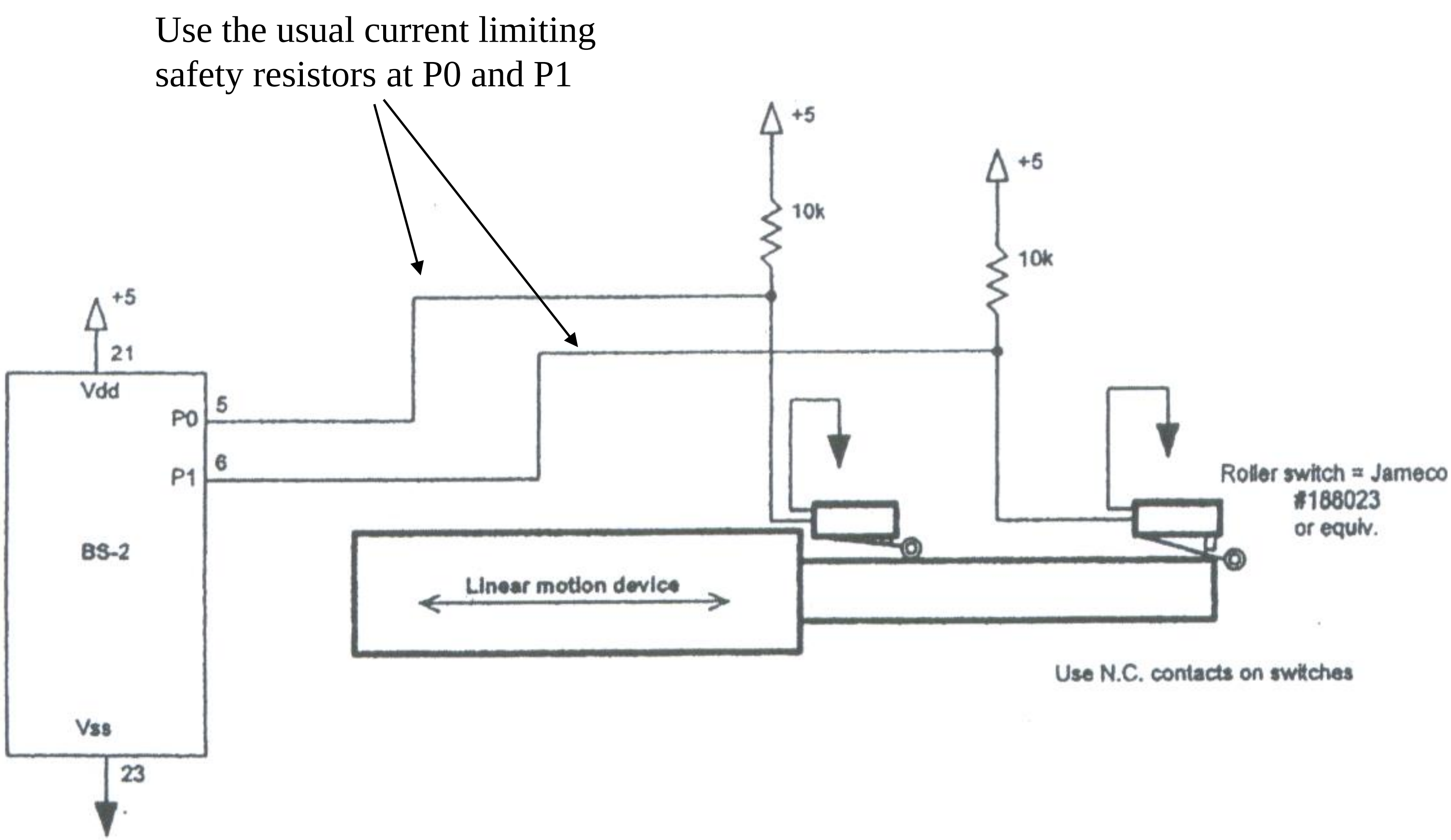
Button Applications: Travel Limit Detection—II

- The left switch detects minimum travel limit.
  - When the arm undergoing linear motion is at a position above its allowable minimum position, the roller on left switch is pressed which opens the switch. When the arm is fully retracted, the left switch becomes closed.
    - At the limit of minimum travel: left switch is closed→P0 is low (i.e., arm is fully retracted).



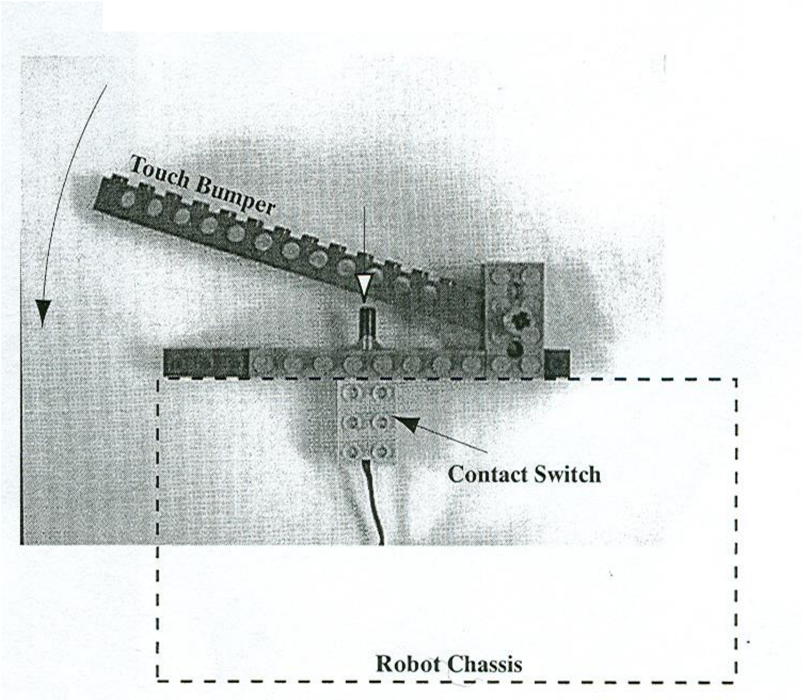
Button Applications: Travel Limit Detection—III

- The right switch detects maximum travel limit.
  - When the arm undergoing linear motion is at a position below its allowable maximum position, the roller on the right switch is not pressed and hence switch is closed, when the arm is fully extended, the right switch is open.
    - At the limit of maximum travel: right switch is open →P1 is high (i.e., arm is fully extended).



Button Applications: Push Button Switch for Tactile Sensing

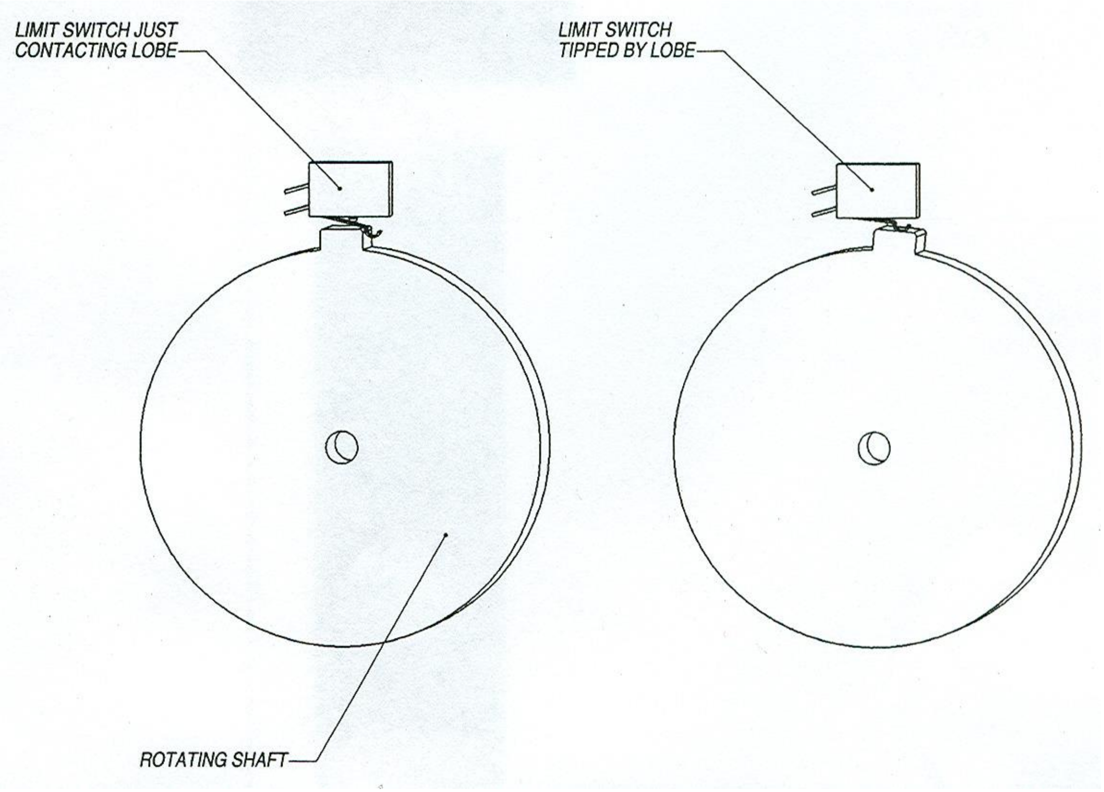
- The push button switch is actuated by a touch bumper whenever it runs into objects.



Pushbutton Switch Sensor

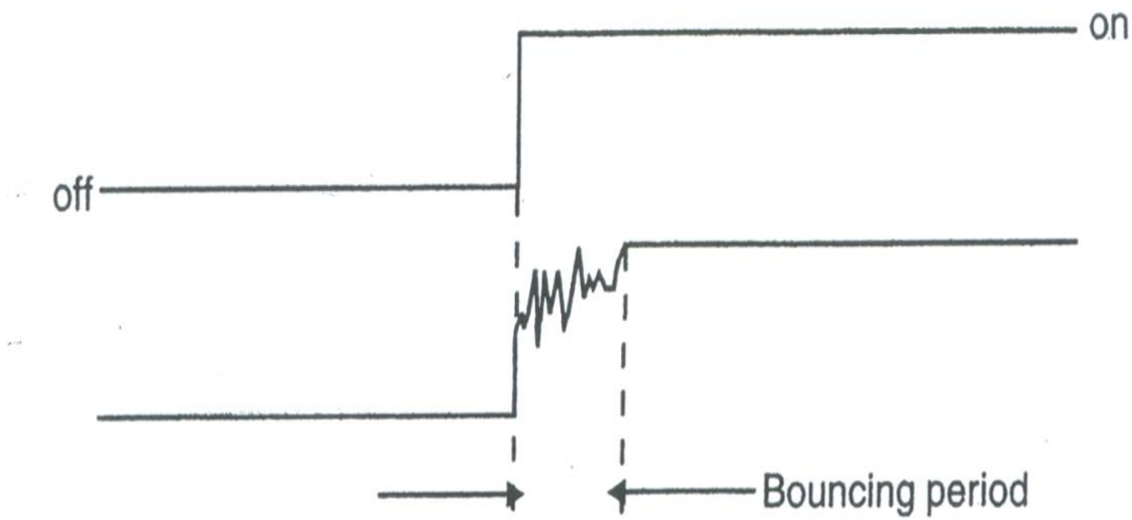
Button Applications: Limit Switch for Rotation Sensing

- The limit switch closes once every revolution of the wheel.

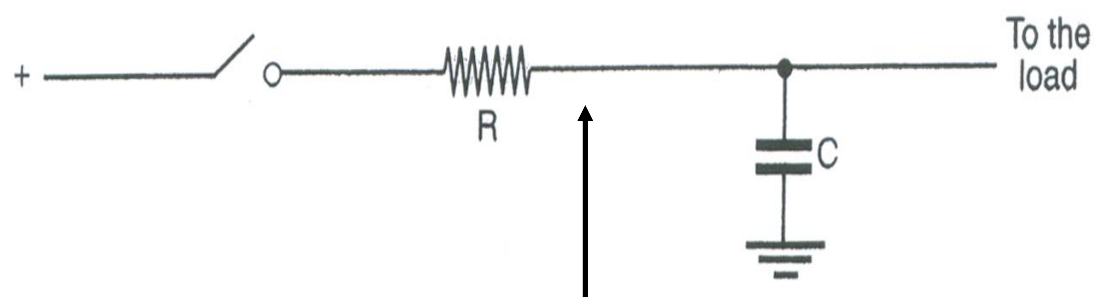


Switch Bounce

- Mechanical switches often suffer from switch bounce.
- When a switch contact is first closed, often an instantaneous permanent connection is not made, instead the switch chatters for a brief moment resulting in multiple low-high transitions.
- This makes it difficult to get a true indication of a switch’s current state.
- An RC circuit can be used for simple debouncing.
- BS2 command “Button” can be used to eliminate switch bounce in software.
- Button command needs 250µsec to execute.



Contact bounce when turning on a switch.



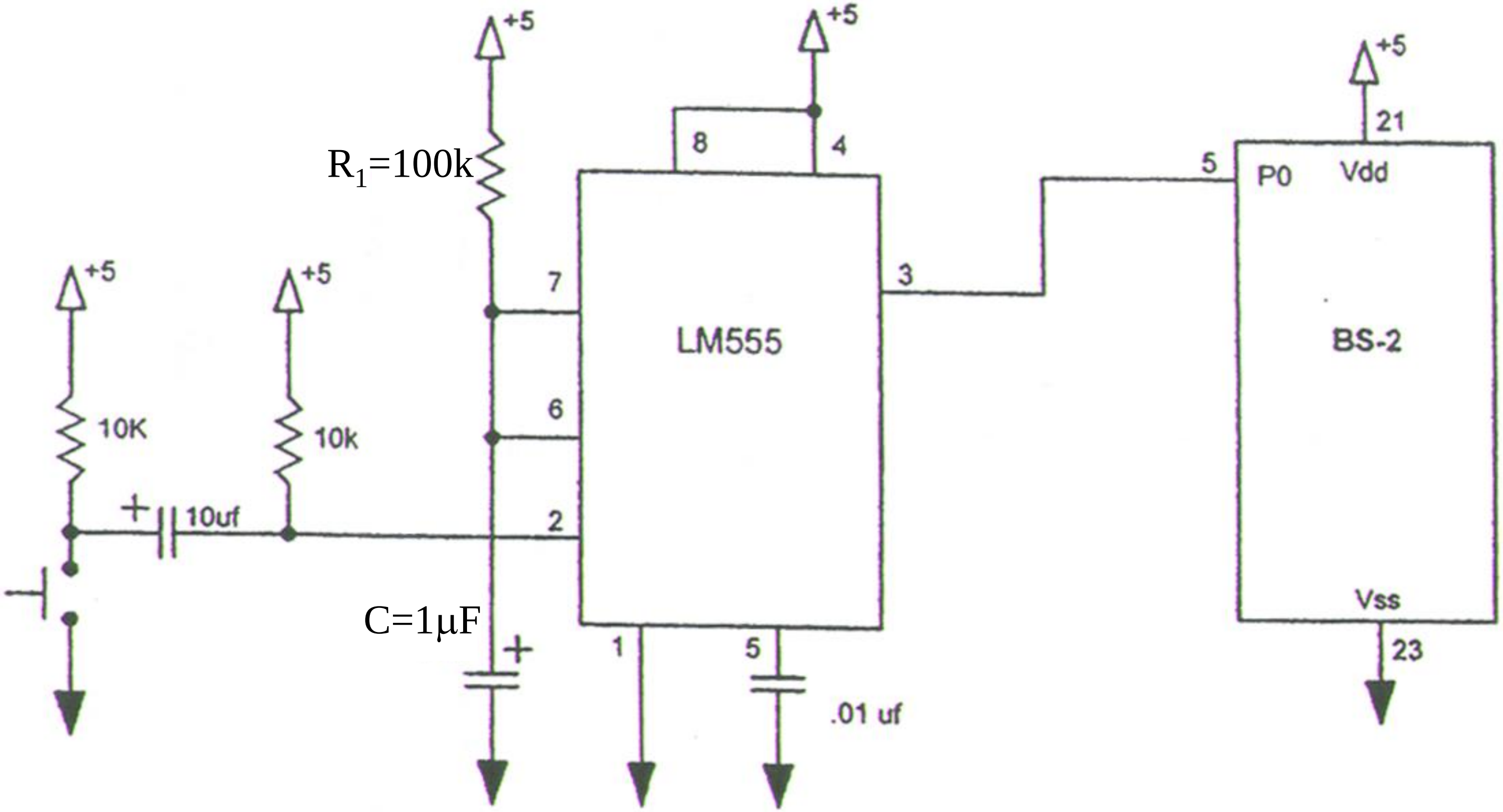
This circuit may cause time delay.

Simple debouncing.

Hardware Solution for Bounceless Switching Detection —I

- A 555 timer-based monostable circuit can be used to develop hardware debounce for a switch.
- The monostable circuit is also called a one-shot circuit.
  - It produces a single output pulse which goes from low to high and back to low once the switch is pressed.
  - The duration for high pulse output is controlled by appropriate selection of R and C.
  - The timer doesn’t output another pulse (with transition to high) until the switch is released and pushed again.
- If a switch closing happens too quickly for BS2 to register, then the monostable circuit can be quite useful.
  - The monostable circuit elongates the duration of high pulse o/p through proper sizing of R and C so that BS2 is able to detect the high o/p.
- The given monostable circuit is not very useful for monitoring the current state of a switch on a continuous basis.

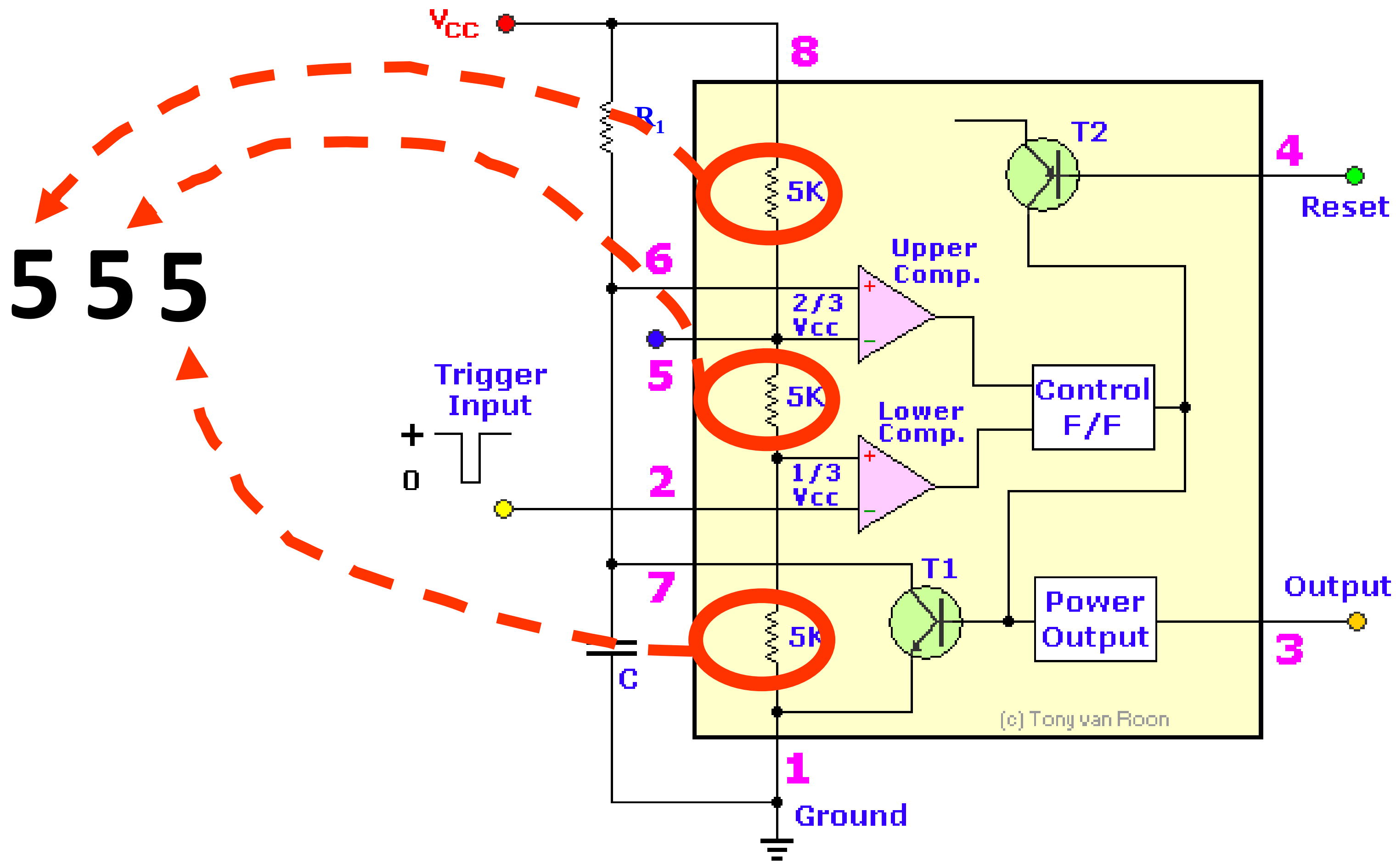
Hardware Solution for Bounceless Switching Detection —II



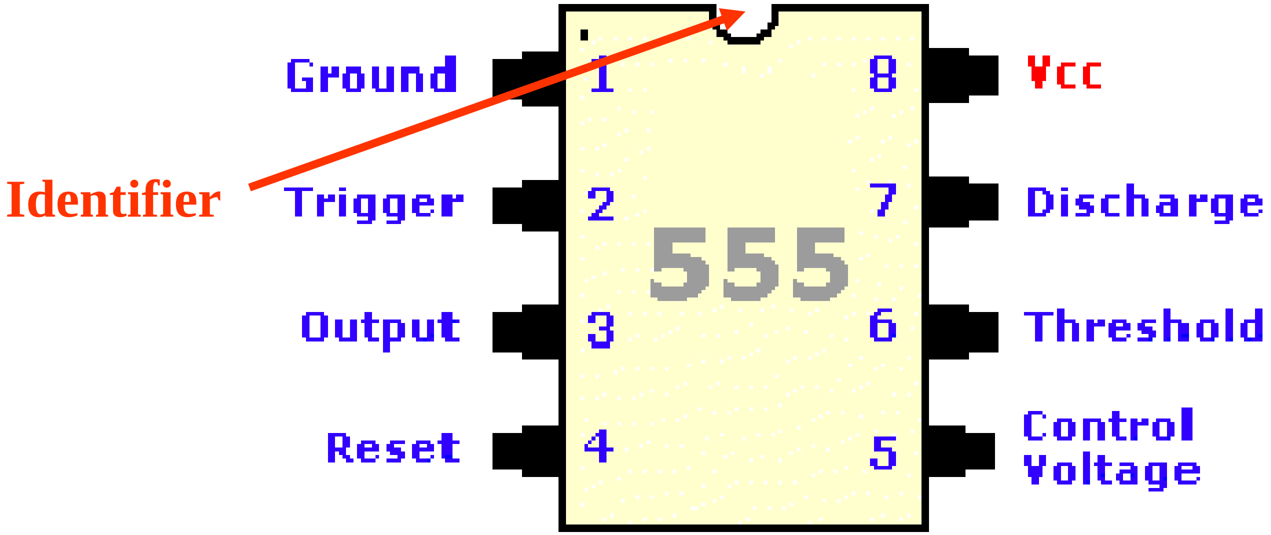
555 Timer

- Highly stable device for generating accurate time delay or oscillation.
- Not programmable.
- Controlled by resistors and capacitors.
- Applications
  - Pulse generation
  - PWM
  - Time delay generation

555 Timer: Block Diagram

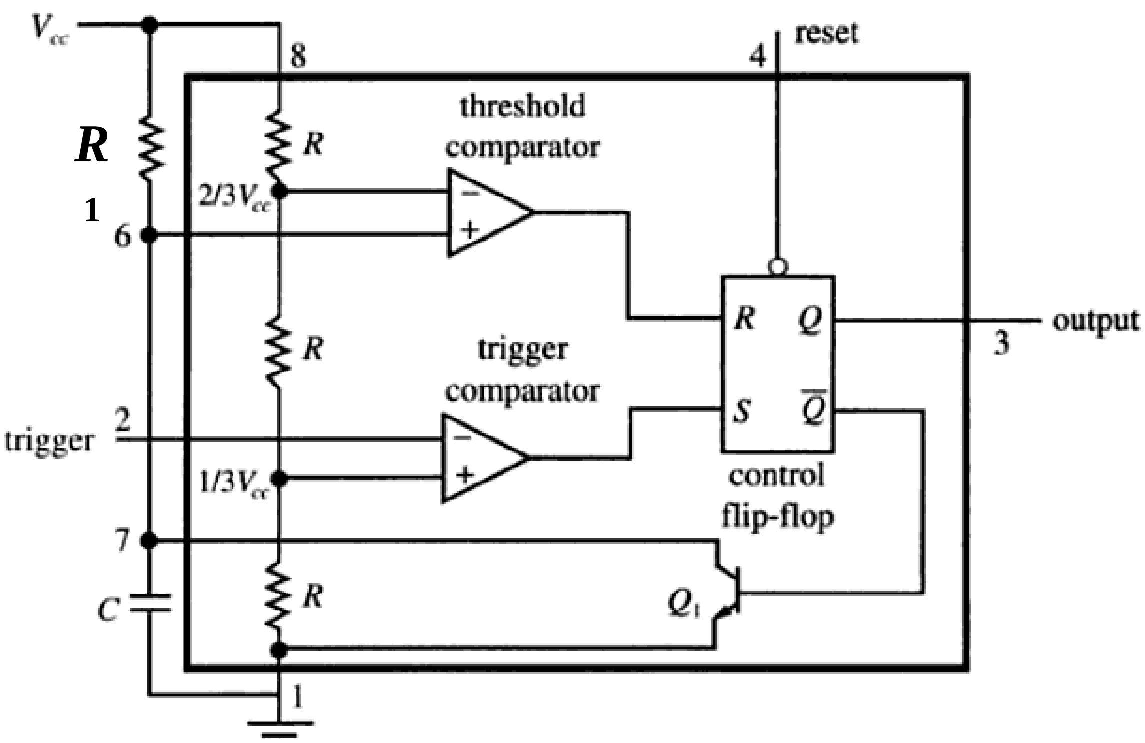


555 Timer: Pinout Diagram



555 Timer: Monostable Circuit Operation—I

- On power-up or after reset: Q=low → output low, $\overline{Q}$ =high → transistor Q_1 in saturation → capacitor C is shorted
  - o Threshold comparator: V_-=(2/3)V_{cc} and V_+=0 → comparator o/p low (R=0)
  - o Trigger comparator: V_-=High and V_+=(1/3)V_{cc}→ comparator o/p low (S=0)
  - o R=0, S=0 →Q and $\overline{Q}$ maintain their initial state



Truth table for the RS flip-flop

Inputs		Outputs	
S	R	Q	$\overline{Q}$
0	0	Q_0	$\overline{Q}_0$
1	0	1	0
0	1	0	1
1	1	NA	

- S: set i/p
- R: reset i/p
- Q, $\overline{Q}$ complementary o/ps

555 Timer: Monostable Circuit Operation—II

- When trigger pulse goes low (below $(1/3)V_{cc}$), momentarily,
  - Trigger comparator: V_{-}=low and $V_{+}=(1/3)V_{cc} \rightarrow$ comparator o/p high (S=1)
  - Threshold comparator: $V_{-}=(2/3)V_{cc}$ and V_{+}=voltage across capacitor which charges from 0V initial state towards $(2/3)V_{cc} \rightarrow$ comparator o/p low (R=0)
  - R=0, S=1 $\rightarrow$Q =1 (output high) and $\overline{Q}=0$ transistor stops conducting
  - This state persists till Threshold comparator: $V_{+}=(2/3)V_{cc}$ then R=1 and S=0 (since trigger goes low only momentarily) $\rightarrow$Q=0 (output low) and $\overline{Q}=1$ so transistor conducts again and causes the capacitor to be shorted.
  - Note that the capacitor charges from 0V initial state towards $(2/3)V_{cc}$ with time constant R_1C

555 Timer: Monostable Circuit Operation—III

- This circuit has only one stable state.
- The o/p resets at 0V, until a negative-going trigger pulse is applied to the trigger lead: pin 2.
- After trigger pulse is applied, the o/p will go high (around V_{cc}-1.5V) for the duration set by R_1C network.
- The width of the high output pulse is:

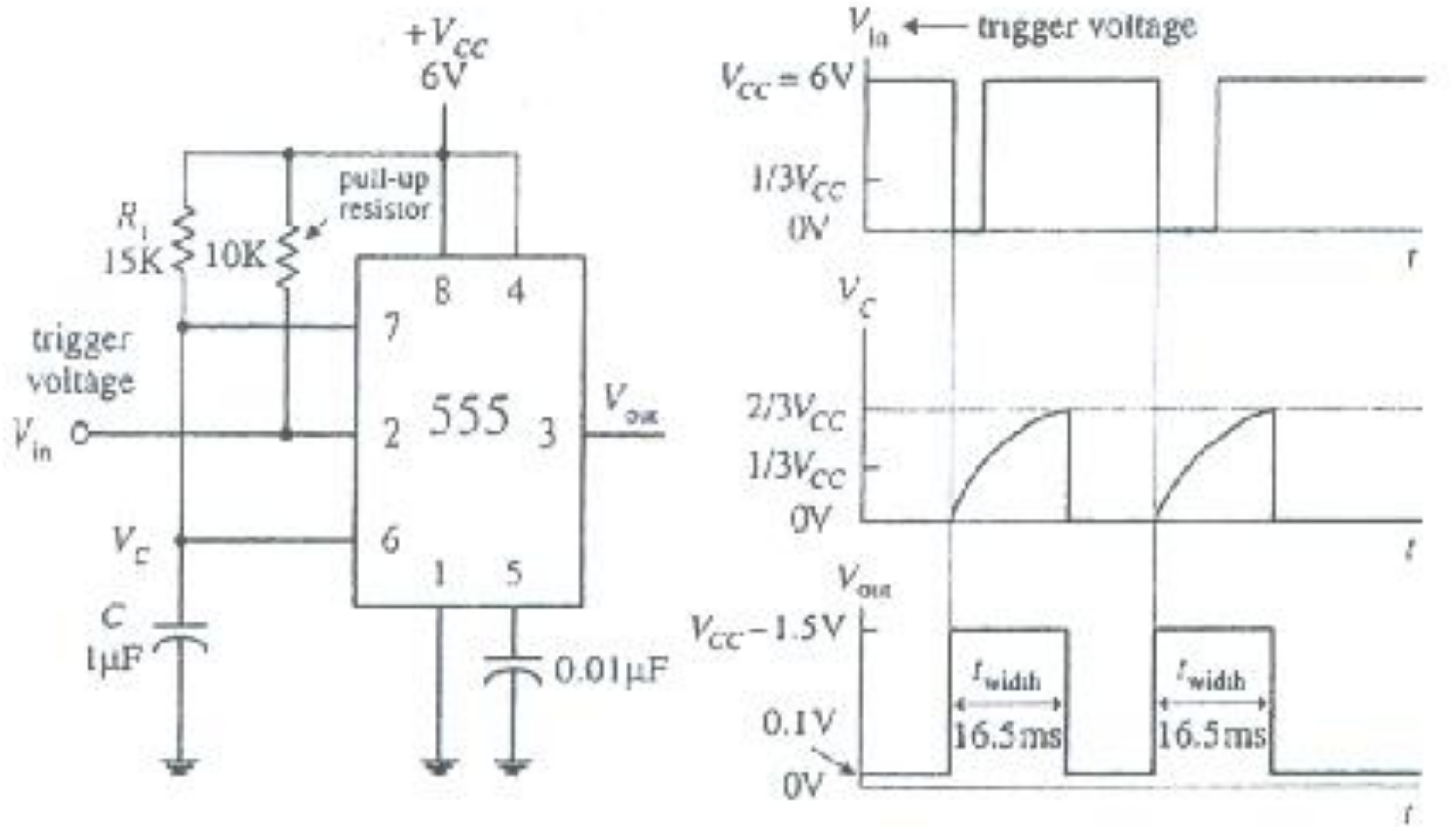
$$V_c(t) = V_{cc}(1 - e^{-t/\tau})\,\big|_{t=1.1\tau}$$

$$V_c(1.1\tau) = \frac{2}{3}V_{cc}$$

$$t_{width} = 1.10 R_1 C$$

- For reliable operation, R_1 should be between 10kΩ and 14MΩ and the capacitor should be from around 100pF to 1000μF.

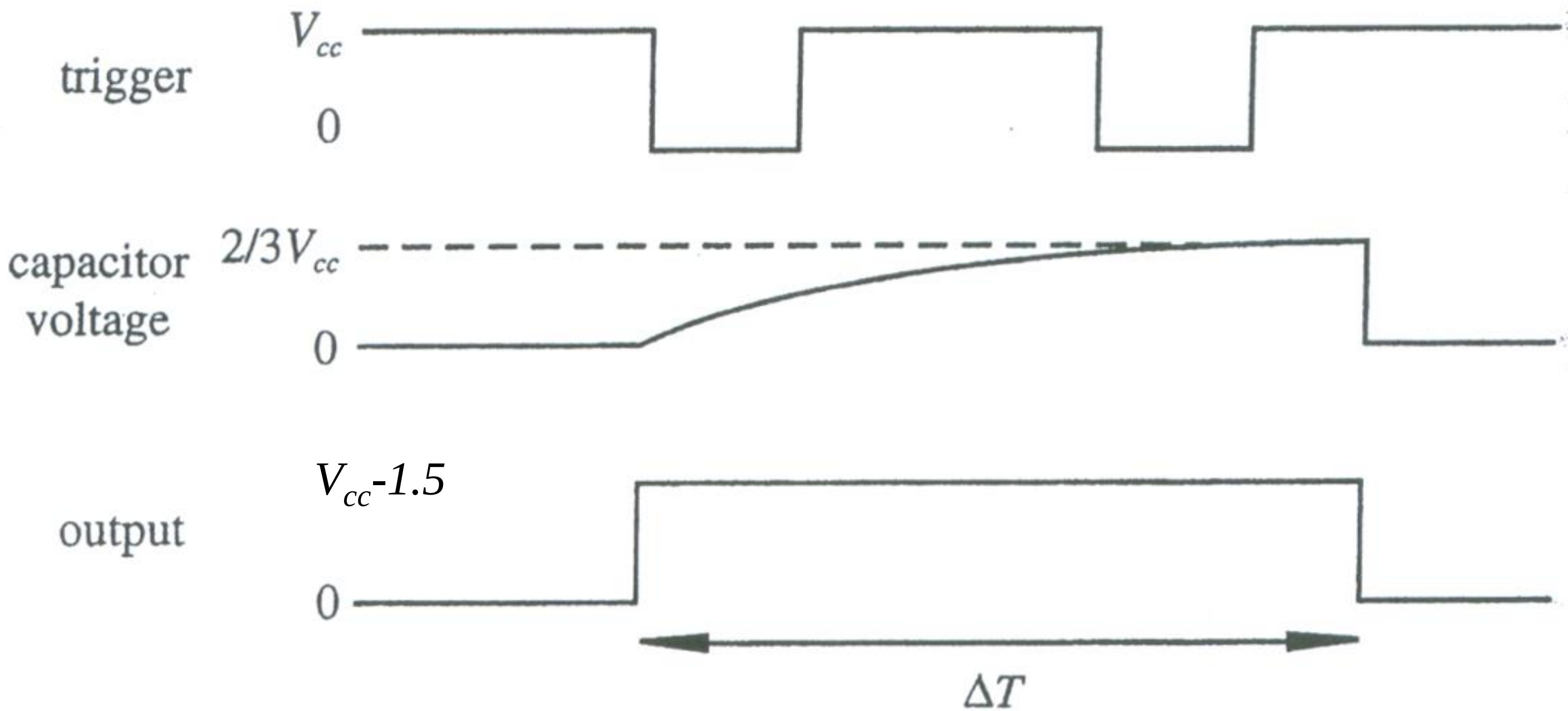
555 Timer: Monostable Circuit Operation—IV



$t_{width} = 1.10\ R_1 C$

$t_{width} = 1.10\ (15K)(1\mu F) = 16.5ms$

555 Timer: Monostable Circuit Operation—V



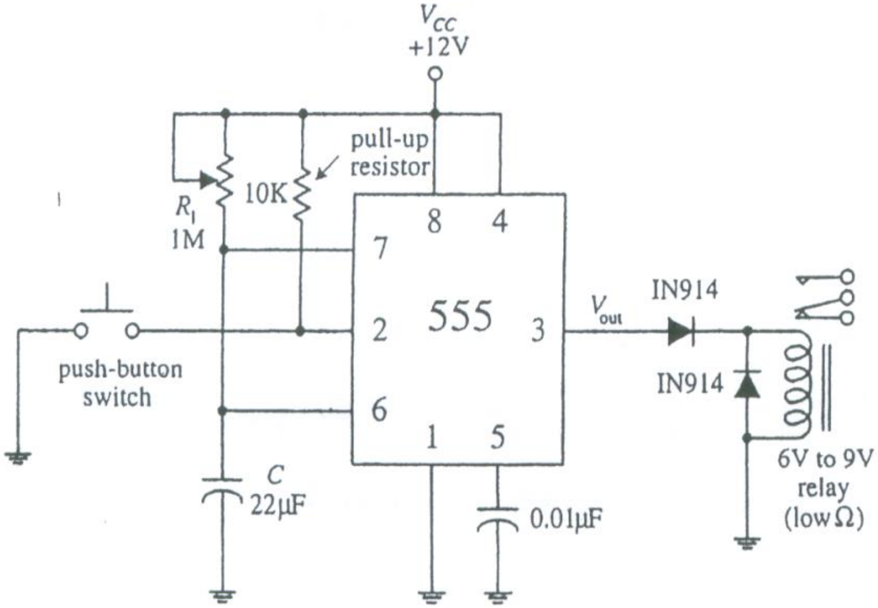
One-shot timing.

555 Timer: Monostable Circuit Application

- A delay timer to actuate a relay for a given duration.
- With push-button switch open, output is low and relay is off.
- When the push-button is momentarily closed, the 555 begins its timing cycle; the output goes high (in this case, ~10.5V) for a duration of

$$t_{width} = 1.10 R_1 C$$

- The relay is actuated for the same time duration.
- The diodes prevent inductive kickback from damaging the 555 IC and the switch contacts of relay.



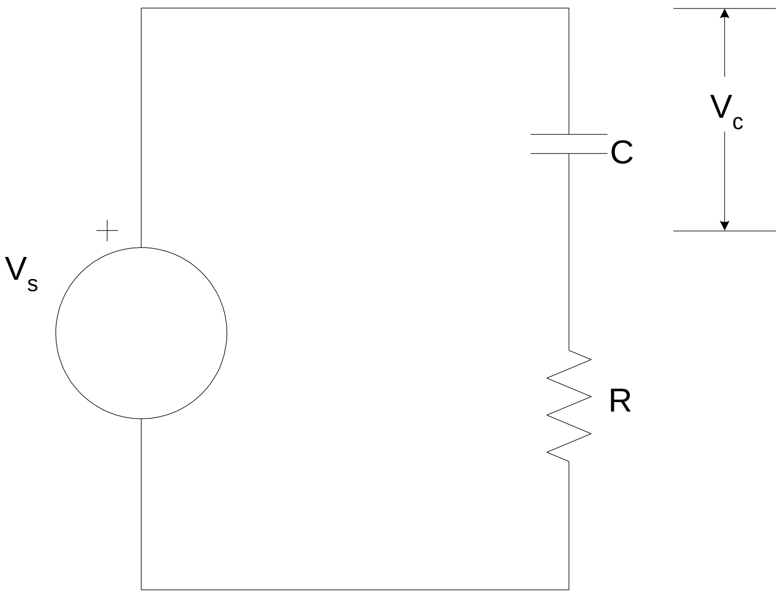
Interfacing Analog Inputs with BS2

Reading Analog Values with RCTime

- One method of bringing analog data into BASIC Stamp is to use “RCTime” instruction.
- Application of RCTime instruction requires construction of a series network consisting of a capacitor and a resistor, either of which may be variable. That is, analog variation is caused by change in the value of capacitor or resistor.
- Common variable resistance devices are:
  - Potentiometers
  - Photoresistors
  - Thermistors
- Use of RCTime instruction in conjunction with any of these devices can allow analog measurement of variation in their resistance value!

Measuring an Analog Value using RCTime

- Given an unknown resistor and a known capacitor.
  - Determine the value of the unknown resistance.
- To solve this problem, we use a series RC circuit and BS2's RCTime command.
- Our measurement technique consists of measuring time taken to charge/discharge the capacitor in the series RC circuit to/from a specified voltage level.
- The capacitor charging/discharging time is used to infer the value of unknown resistor.
- To explain the nuts and bolts of how this technique works, we begin by considering the series RC circuit shown.



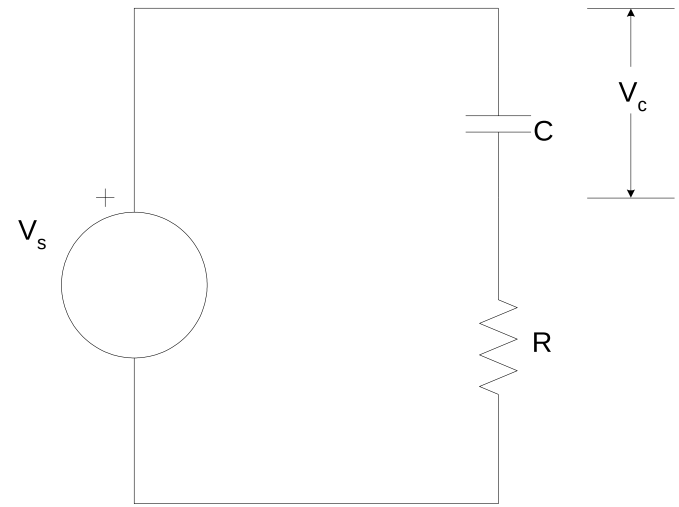
Series RC Circuit Fundamentals—I

- In phasor domain, the relationship between V_s and V_c is:

$$\frac{V_c}{V_s}(j\omega) = \frac{1}{j\omega RC + 1}$$

- In Laplace domain, the above can be expressed as:

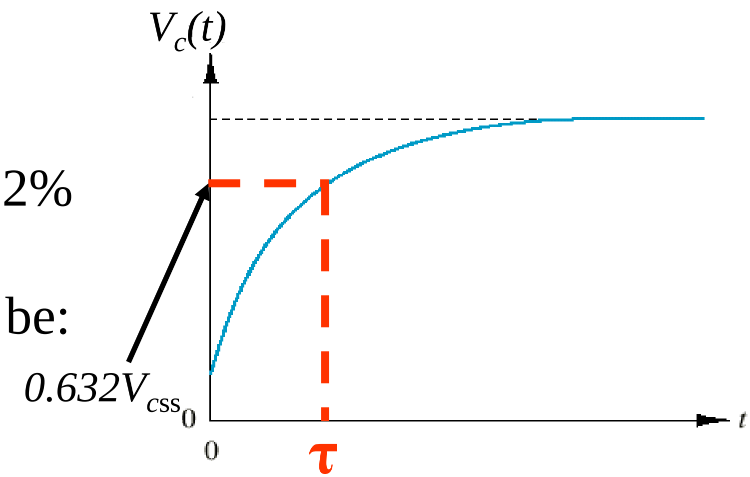
$$\frac{V_c(s)}{V_s(s)} = \frac{1}{\tau s + 1}$$



$$RC\dot{V}_c + V_c = V_s$$

- $\tau = RC$ is named time constant.
- τ is time taken by system response to reach 63.2% of its steady-state value.
- The initial condition response can be shown to be:

$$V_c(t) = V_c(0)e^{-t/\tau}$$



Series RC Circuit Fundamentals—II

- Let $V_s(t)=V_s$, $t \geq 0$, be a step input, then

$$\frac{V_c(s)}{V_s(s)} = \frac{1}{\tau s+1} \quad \Rightarrow \quad V_c(s) = \frac{1}{\tau s+1} V_s(s)$$

$$V_c(s) = \frac{1}{(\tau s+1)} \times \frac{V_s}{s}$$

- Computing the inverse Laplace transform of the above:

$$V_c(t) = V_s(1-e^{-t/\tau}) \quad \Rightarrow \quad \frac{V_c(t)}{V_s} = 1-e^{-t/\tau}$$

$$e^{-t/\tau} = 1 - \frac{V_c(t)}{V_s} = \frac{V_s - V_c(t)}{V_s}$$

- Now, taking natural log on both side, we produce:

$$-\frac{t}{\tau} = \ln\left[\frac{V_s - V_c(t)}{V_s}\right] \quad \Rightarrow \quad t = -\tau \quad \ln\left[\frac{V_s - V_c(t)}{V_s}\right]$$

Series RC Circuit Fundamentals—Alternative Sol^n

- Let $V_s(t)=V_s$, $t \ge 0$, be a step input, then

$$t\dot{V}_c + V_c = V_s \;\Rightarrow\; t\dot{V}_c = -(V_c - V_s) \;\Rightarrow\; -\frac{dV_c}{V_c - V_s} = \frac{dt}{t}$$

$$-\ln(V_c - V_s)\Big|_0^t = \frac{t}{t} \;\Rightarrow\; \ln\frac{V_c(0) - V_s}{V_c(t) - V_s} = \frac{t}{t}$$

$$\frac{V_c(0) - V_s}{V_c(t) - V_s} = e^{\frac{t}{t}} \;\Rightarrow\; V_c(t) - V_s = (V_c(0) - V_s)e^{-\frac{t}{t}}$$

$$V_c(t) = V_c(0)e^{-\frac{t}{t}} + V_s(1 - e^{-\frac{t}{t}})$$

- For zero initial condition:

$$V_c(t) = V_s(1 - e^{-\frac{t}{t}})$$

Series RC Circuit Fundamentals—III

- Now let

$$@ \quad t = t_f, \quad V_f \equiv V_c(t_f), \quad V_f \equiv V_s - V_f$$

- Then, using

$$t = -\tau \quad \ln\left[\frac{V_s - V_c(t)}{V_s}\right]$$

with t=t_f yields

$$t_f = -\tau \quad \ln\left[\frac{V_f}{V_s}\right]$$

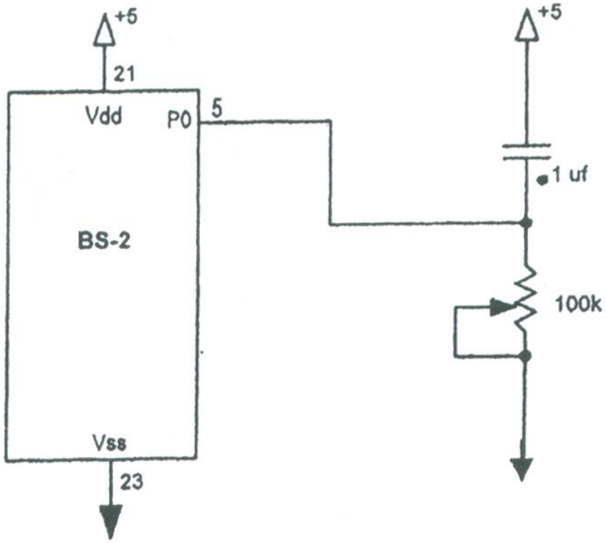
- which produces:

$$\tau = -\frac{t_f}{\ln\left[\dfrac{V_f}{V_s}\right]}$$

- Now, knowing V_s and having measured V_f at t_f, we can compute τ from above.
- Next, knowing C and τ, R can be computed (recall $\tau = RC$).

Series RC Circuit Fundamentals—IV

- Now, the idea behind RCTime method of measuring charging/discharging time for a capacitor is as follows.
  - First using a BS2 pin as an output pin, force the capacitor to be in discharge state (i.e., same potential at both plates of the capacitor).
  - Now, using the RCTime command, monitor the state of the capacitor until it changes from discharge (0V) to charge state (3.6V).
  - As an example, consider the figure shown. First turn P0 high for a sufficiently long time. This ensures both plates of the capacitor are at 5 volts. In this case, the capacitor is discharged.
  - Having discharged the capacitor, switch P0 to be an input pin. Now monitor the status of P0. As soon as P0 is turned form output to input pin, the RC series circuit sees a +5V input and starts producing its first-order response. When P0 crosses transition from high to low (i.e., 1.4V), capture that time and store it.



High 0

Pause 3

Rctime 0,1, tau

RCTime with BS2—I

- Note that when the lower plate of capacitor is @ 1.4V, the voltage across capacitor is 3.6 volts (since the upper plate is @ 5V).
- Thus, at $t = t_f$, $V_c(t_f) = V_f = 3.6$V. Also, note that $V_s = 5$V.

$$V_f \;\square\; V_s - V_f \quad \Rightarrow \quad V_f = 5 - 3.6 = 1.4V$$

- Then, using

$$t_f = -\tau \quad \ln\left[\frac{V_f}{V_s}\right]$$

we obtain

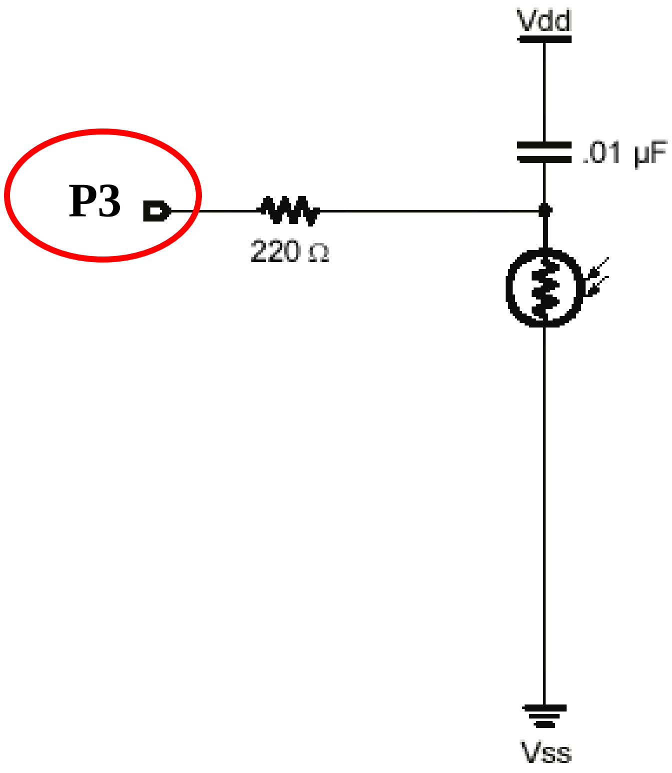
$$t_f = -\tau \quad \ln\left(\frac{1.4}{5}\right)$$

- Suppose we are using $R = 10$KΩ and $C = 0.1$μF.
- Then, $\tau = RC = (10 * 10^3)(0.1 * 10^{-6}) = 10^{-3}$sec.
- $t_f \approx 1.273 * 10^{-3}$sec.
- Note that BS2 returns the time when state transitions from set state (2nd argument of RCTime) in 2μs units. So for selected R and C values, BS2 will return:

$$t_f = 636 \text{ units}$$

RCTime with BS2—II

- RCTime *Pin*, *State*, *Variable*
- Measure time while Pin remains in state; usually to measure the charge/discharge time of resistor/capacitor (RC) circuit
  - **Pin** is a variable/constant/expression (0-15) that specifies the I/O pin to use. This pin will be placed into input mode
  - **State** is a variable/constant/expression (0-1) that specifies the desired state to measure. Once Pin is not in state, the command ends and stores the result in variable
  - **Variable** is a variable in which the time measurement will be stored. The unit of time for variable in BS2 is described in 2µs



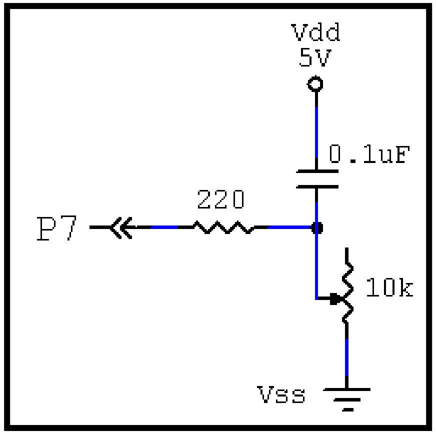
The pause time should be about 4 τ to allow the system response to reach 99% of its steady state value.

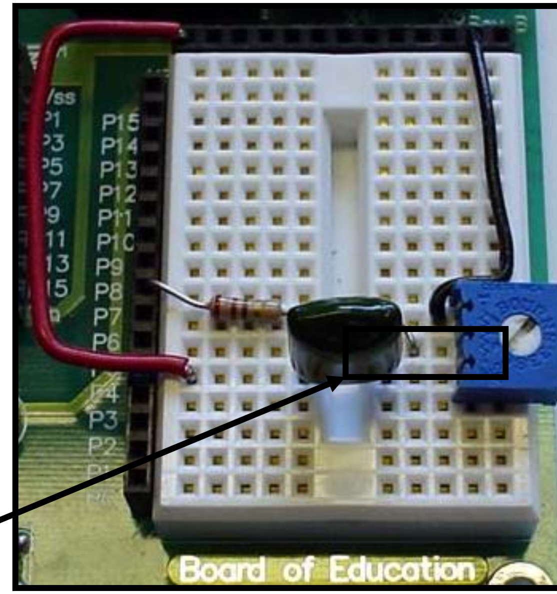
```
High 3
Pause 3
Rctime 3,1, tau
```

Connecting the RC Network to BS2

- Connect the Resistor-Capacitor (RC) network:

In some cases, potentiometer may be replaced by another variable resistor, e.g., photoresistor.





RC Network alone

Resistor, capacitor and center pin of potentiometer on same row.

RCTime measures the time to charge the capacitor through the resistor. The higher the resistance, the longer the time. For a full discussion on RCTime, please see your editor help files or BASIC Stamp Manual.

RCTime Code

- Enter and run the following code.

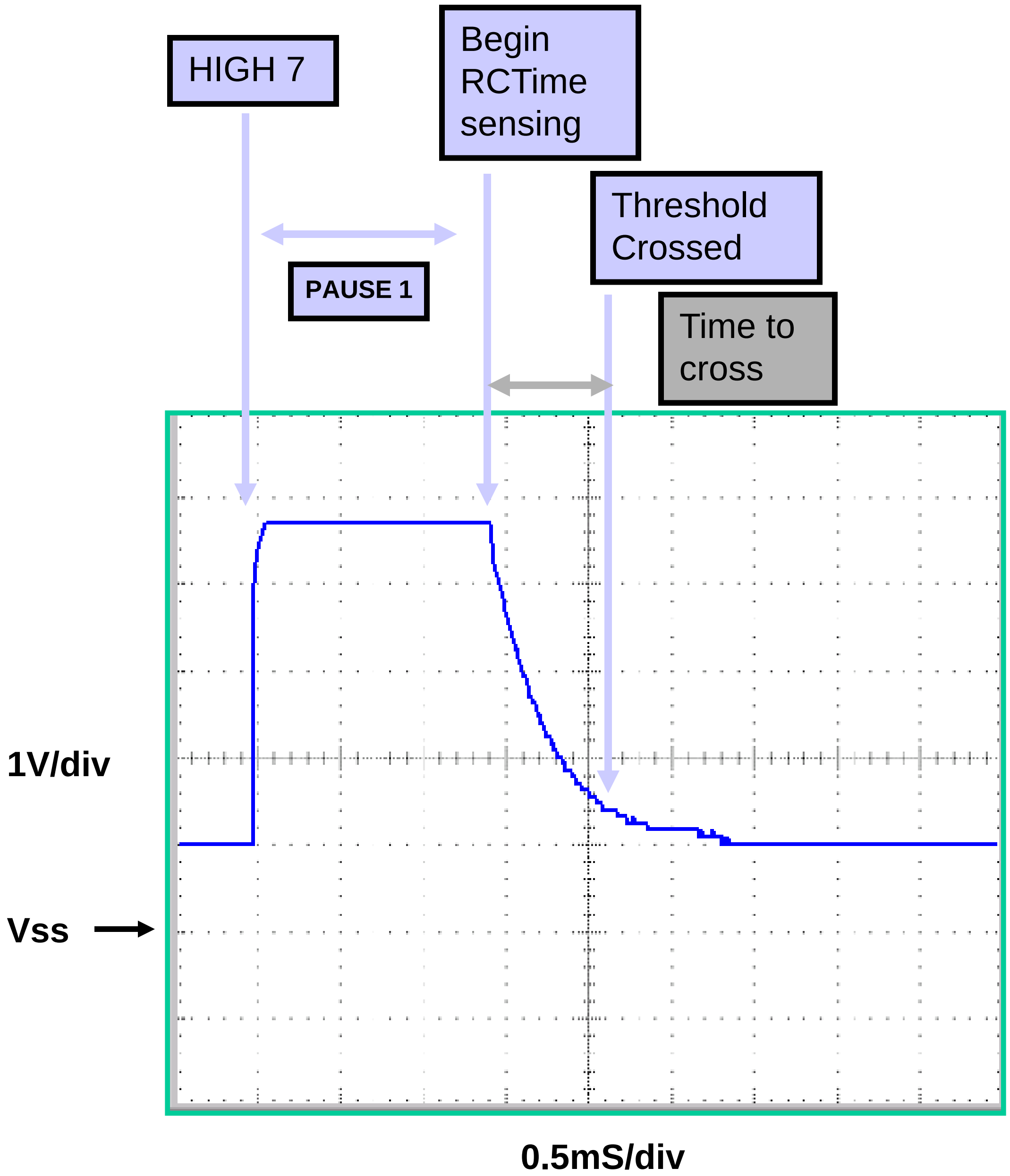
```
'Program: Monitoring RCTime

Pot VAR WORD   'Variable to hold results

Main:
   HIGH 7                  'Discharge network
   PAUSE 1                 'Time to fully discharge
   RCTIME 7,1,Pot          'Read charge time and store in Pot
   DEBUG ? Pot             'Display value of Pot
   PAUSE 500               'Short pause
GOTO Main                  'Jump back to beginning
```

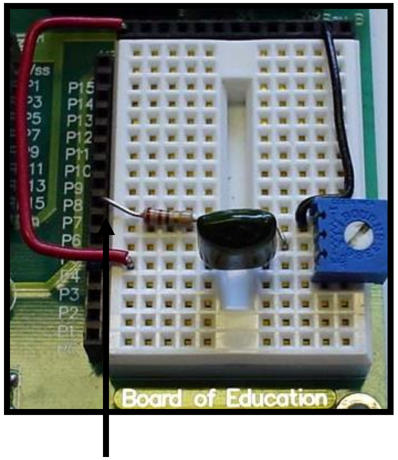
- Adjust the potentiometer resistance in each direction and monitor the RCTime value. The full range should be approximately 0-640.

RCTime Code Discussion

- **Pot VAR WORD** defines a variable named Pot.
- **HIGH 7** places +5V on pin 7, discharging the capacitor.
- **PAUSE 1** provides time to allow the capacitor to fully discharge.
- **RCTIME 7,1,Pot** instructs the BS2 to find how long it takes pin 7 to leave from given state (1=high). This time is stored in the variable Pot.
  - **RCTIME pin, state, variable**

RCTime Graph



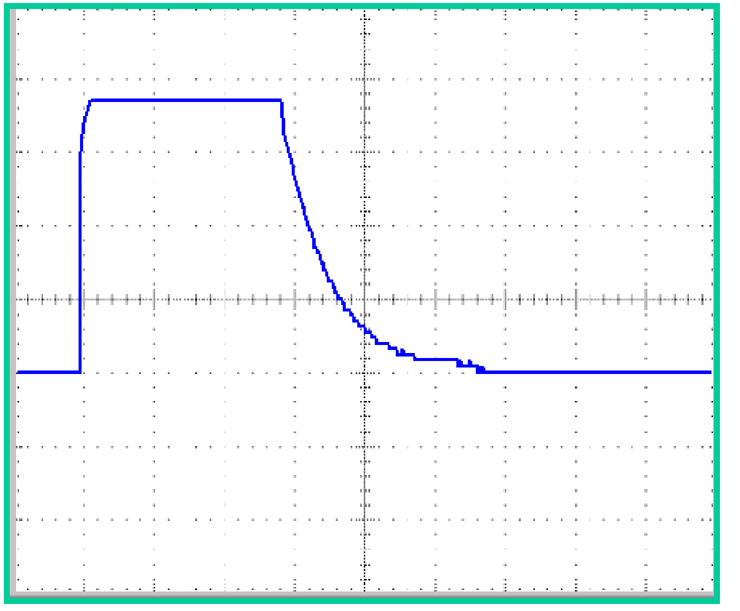


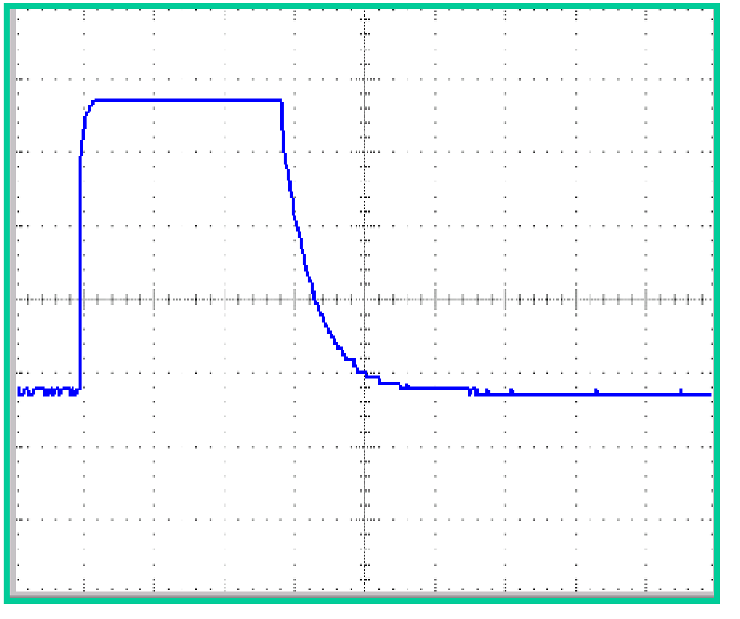
Measured at P7

- In digital, a HIGH (1) or LOW (0) is commonly denoted by Vdd or Vss (5V and 0V), but there exists a **threshold voltage**, above which the controller senses a HIGH, and below which the controller senses a low.
- The threshold voltage for the BASIC Stamp is around 1.7V.

RCTime Graph Comparison

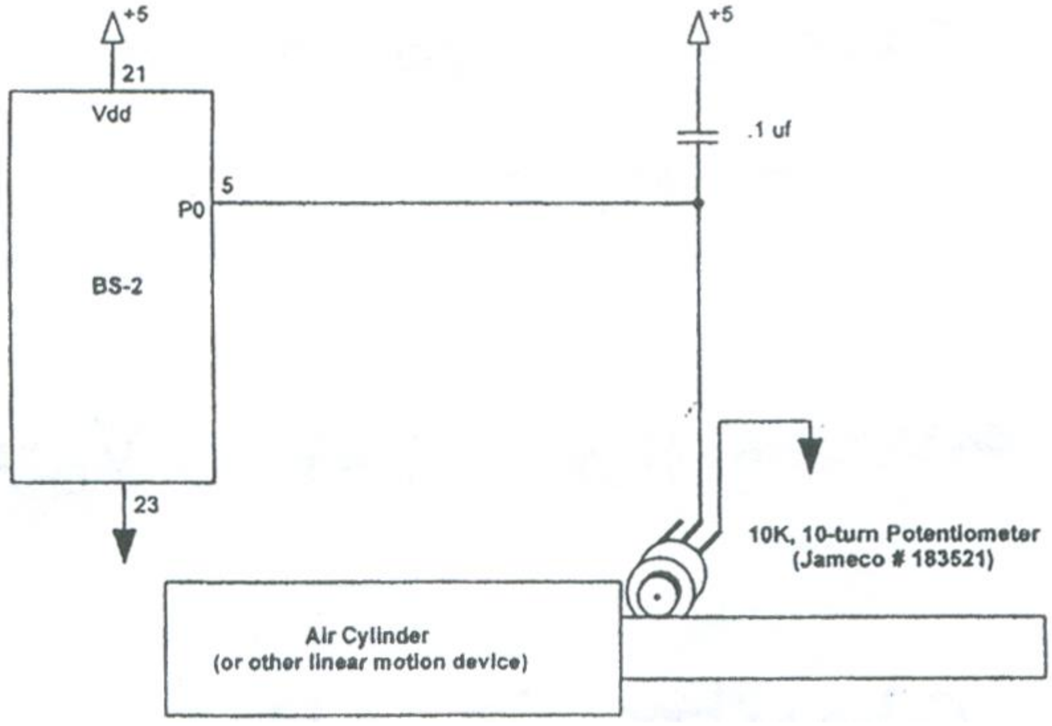
- With a high resistance, the current is low and the capacitor takes a relatively long time to charge.
- As resistance decreases the current increases allowing the capacitor to charge more quickly.
- A value proportional to the time to reach the new state is stored.





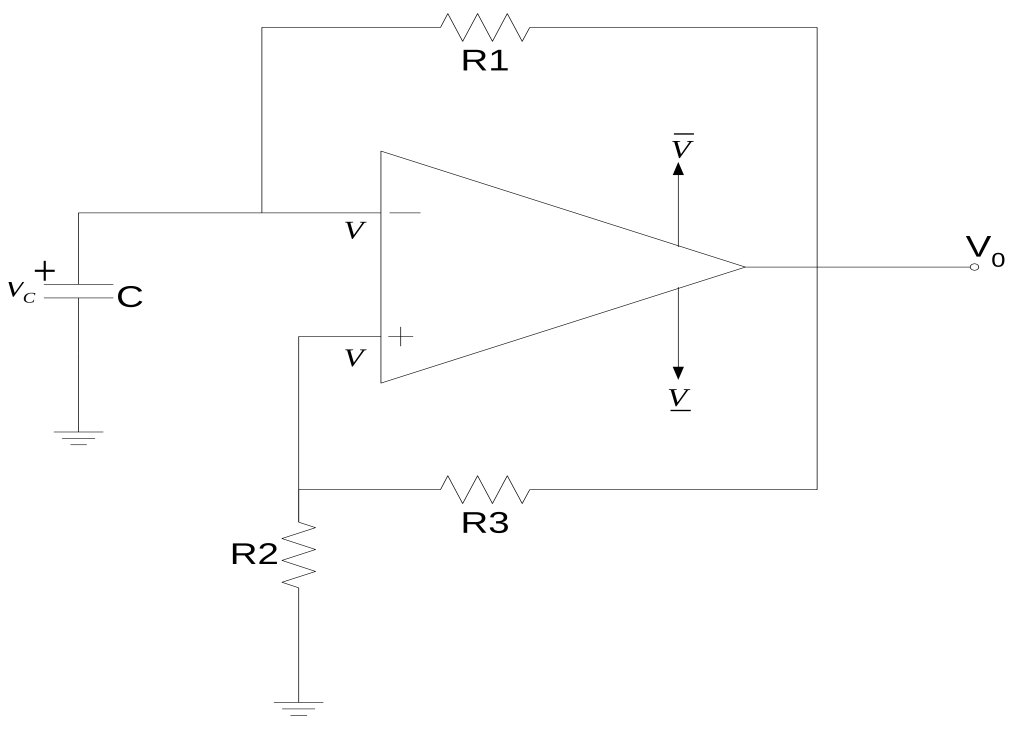
Application of RC Circuit

- The RC circuit and RCTime can be used to measure linear travel of an air cylinder position or a machine tool slide.
- A pot is coupled to the shaft moving linearly using mechanical coupling.
  - A rubber wheel can be fixed to the output shaft of pot.
  - Friction causes the rubber wheel and in turn pot to rotate as the slide undergoes translation.
- RCTime $\propto$ Pot resistance $\propto$ Linear travel of slide.
- If a single turn pot is being used, then a suitable diameter wheel can be selected to measure the full range of linear travel within a single turn of pot.
- If an excessively large rubber wheel is necessitated by a single turn pot, then use a multi-turn pot.



Astable Multivibrator 101— I

- Consider a comparator with the given schematic.
- This is not the usual comparator circuit with positive feedback!
  - This circuit has negative feedback too.
  - In addition, there is an RC circuit that generates the inverting input V-.



- In a comparator:
  - Let

$$\varepsilon \triangleq V_+ - V_-$$

  - When ε > 0

$$V_0 = \overline{V}$$

  - When ε < 0

$$V_0 = \underline{V}$$

Astable Multivibrator—II

- First, using voltage division we obtain

$$\boxed{V_+ = \frac{R_2}{R_2 + R_3} V_0}$$

- Note that, V_- is voltage V_c at the capacitor.
- The capacitor charges and discharges at a rate dictated by resistor R_1 and capacitance C according to time constant.

$$\tau = R_1 C$$

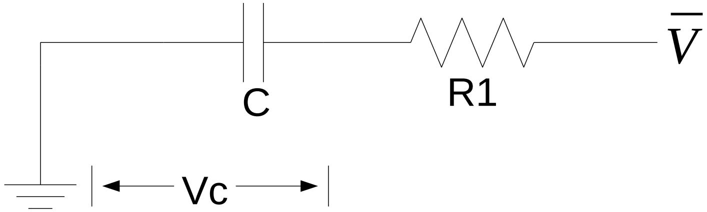
- Let us begin with the assumption that @ $t=0$

$$V_0 = \overline{V}$$

- Assume initially (i.e., @ $t=0$) the capacitor is discharged.
- Since the lower plate is at ground potential, in discharge state, the upper plate is also at ground potential. Thus, $V_c = 0$ at $t = 0$.

Astable Multivibrator—III

- Note that with $V_0 = \bar{V}$ we obtain $V_+ = \dfrac{R_2}{R_2 + R_3}\bar{V}.$
- At $t = 0$ we have $V_c = 0 \Rightarrow V_- = V_c = 0$ so $V_+ > V_- \Rightarrow \varepsilon > 0$
- Thus, $V_0 = \bar{V}$ continues to hold true as long as $\varepsilon > 0$ holds true.
- $V_c(t)$ can be determined using the following circuit.



$\dfrac{V_c}{\bar{V}}(s) = \dfrac{1}{R_1 C s + 1}.$ For step I/P $\bar{V}(t) = \bar{V}$ we have $\bar{V}(s) = \dfrac{\bar{V}}{s}.$

$\Rightarrow V_c(s) = \dfrac{\bar{V}}{s(R_1 C s + 1)}$ which upon taking inverse Laplace transform yields

$V_c(t) = \bar{V}(1 - e^{-t/\tau}).$

Astable Multivibrator—IV

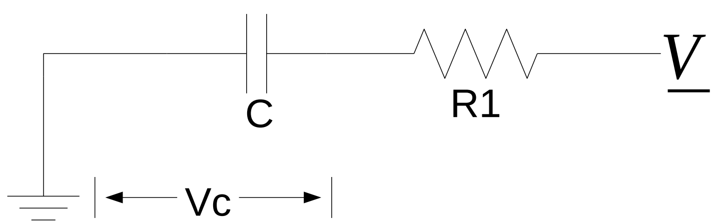
- Note that $\lim_{t \to \infty} V_c(t) \to \overline{V}$. Actually by t=4$\tau$, $V_c(t) \cong 0.98\overline{V}$.
- Also, note that:

$$V_+ < \overline{V} \quad \text{since} \quad V_+ = \frac{R_2}{R_2 + R_3}\overline{V} \quad \text{and} \quad \frac{R_2}{R_2 + R_3} < 1.$$

- Hence, at some time t = t_0, $V_- = \frac{R_2}{R_2 + R_3}\overline{V}$
- And after this time, $\varepsilon < 0$, so V_0 switches to $\underline{V}$.

Astable Multivibrator—V

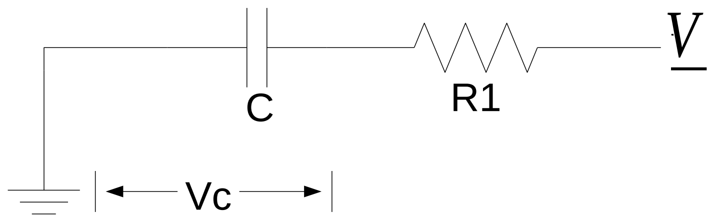
- Starting @ $t = t_0$, $V_+ = \dfrac{R_2}{R_2 + R_3}\underline{V}$
- Recall that the capacitor was earlier charging towards $\overline{V}$ and @ $t = t_0$, V_0 switched from $\overline{V}$ to $\underline{V}$.
- At $t = t_0, \quad V_c(t_0) = \dfrac{R_2}{R_2 + R_3}\overline{V}$.
- So, now, analyze the following circuit with I.C. $\dfrac{R_2}{R_2 + R_3}\overline{V}$.



Astable Multivibrator — VI

- The DEQ for the series RC circuit is:

$R_1 C \frac{dV_c}{dt} + V_c = \underline{V}$ whose Laplace Transform yields



$$R_1 C\,[sV_c(s) - V_c(0)] + V_c(s) = \frac{\underline{V}}{s}$$

$$(R_1 Cs + 1)\,V_c(s) = \frac{\underline{V}}{s} + R_1 C V_c(0)$$

$$V_c(s) = \frac{\underline{V}}{s(R_1 Cs + 1)} + \frac{R_1 C V_c(0)}{(R_1 Cs + 1)}$$

$$= \frac{\underline{V}}{s(R_1 Cs + 1)} + \frac{V_c(0)}{(s + 1/\tau)},$$ where we use the usual $\tau = R_1 C$

$$V_c(t) = \underline{V}(1 - e^{-t/\tau}) + V_c(0)e^{-t/\tau}$$

- Note however that the initial time began at t_0 instead of at 0. Thus,

$$V_c(t) = \underline{V}(1 - e^{-(t-t_o)/\tau}) + V_c(t_0)e^{-(t-t_o)/\tau}$$

$$V_c(t) = \left(V_c(t_0) - \underline{V}\right)e^{-(t-t_o)/\tau} + \underline{V}$$

Astable Multivibrator — VII

- So now, $V_0 = \underline{V}$ condition will be maintained as long as $\varepsilon<0$.
- However, once

$$V_-(t) = V_c(t) < \frac{R_2}{R_2+R_3}\underline{V} \quad \Rightarrow \quad \varepsilon > 0$$

V_0 will switch from $\underline{V}$ to $\overline{V}$.

- Now, with

$$\overline{V} = V_{sat} \quad \text{and} \quad \underline{V} = -V_{sat}$$

$$\text{For} \quad V_0 = \overline{V}:$$

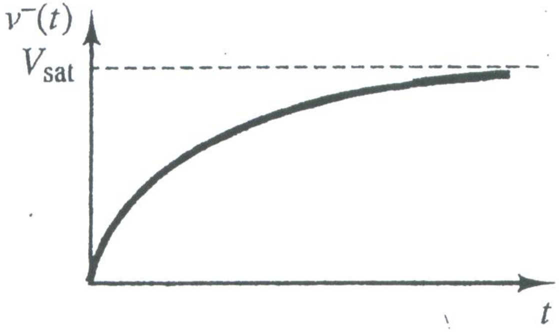
$$V_c(t) = (1-e^{-t/\tau})V_{sat}$$

$$\text{For} \quad V_0 = \underline{V}:$$

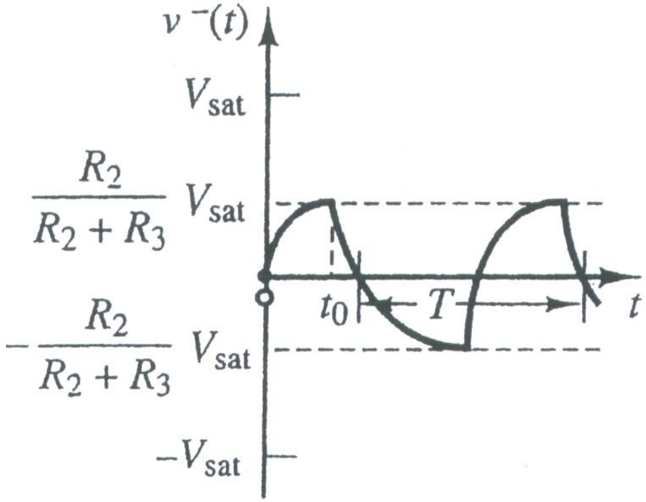
$$V_c(t) = [V_c(t_0) + V_{sat}]e^{-(t-t_0)/\tau} - V_{sat}$$

- Under these conditions, the following waveforms are obtained.

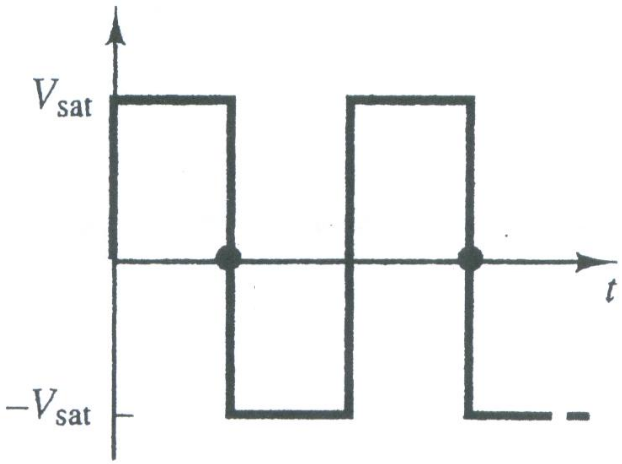
Astable Multivibrator—VIII



Capacitor charging



Multivibrator inverting terminal voltage



Multivibrator output waveform

Astable Multivibrator — IX

- To determine the period of oscillation follow the procedure given below:

$$\text{Period} = \text{Time for "C" to go from } \overline{V}\frac{R_2}{R_2+R_3} \text{ to } \underline{V}\frac{R_2}{R_2+R_3}$$

$$+\text{ Time for "C" to go from } \underline{V}\frac{R_2}{R_2+R_3} \text{ to } \overline{V}\frac{R_2}{R_2+R_3}$$

$$= 2\cdot[\text{Time C to discharge from } \overline{V}\frac{R_2}{R_2+R_3} \text{ to } \underline{V}\frac{R_2}{R_2+R_3}]$$

- Let $\overline{V} = -\underline{V} = V_s$
- Recall, when C starts discharging:

$$V_c(t) = \left(V_s\frac{R_2}{R_2+R_3} + V_s\right)e^{-t/\tau} - V_s$$

Astable Multivibrator—X

$$\text{At} \quad t = T/2 \quad V_c(t) = -\frac{V_s \cdot R_2}{R_2 + R_3}$$

$$\text{Thus,} \quad -\frac{V_s \cdot R_2}{R_2 + R_3} = \left(V_s \frac{R_2}{R_2 + R_3} + V_s \right) e^{-\frac{T/2}{\tau}} - V_s$$

$$\Rightarrow V_s \left(1 - \frac{R_2}{R_2 + R_3} \right) = V_s \left(\frac{R_2 + R_2 + R_3}{R_2 + R_3} \right) e^{-\frac{T/2}{\tau}}$$

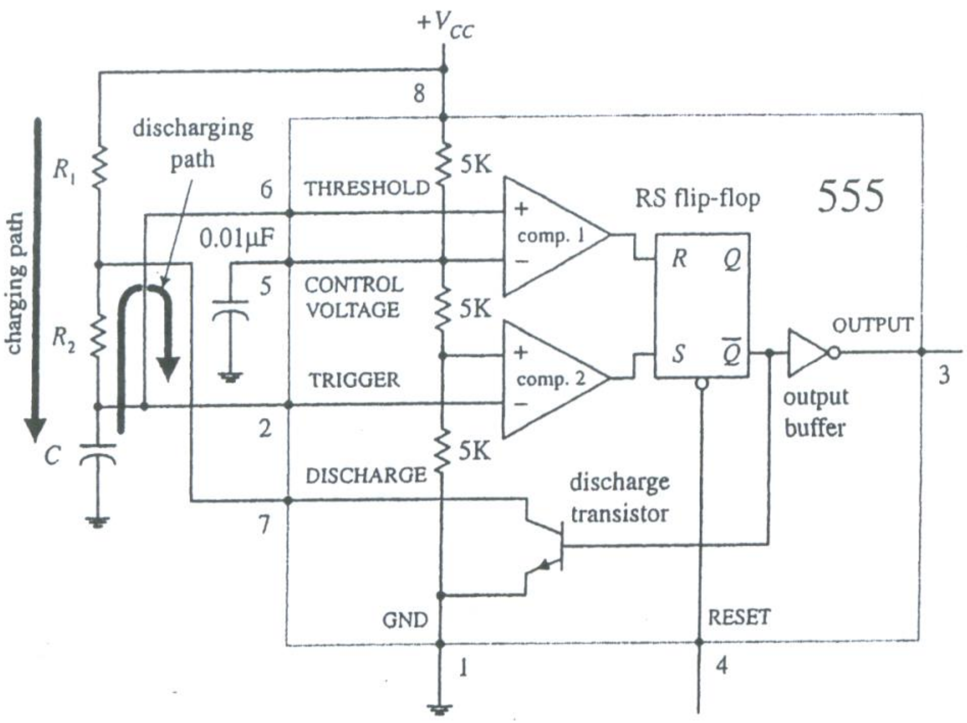
$$\Rightarrow \frac{R_3}{R_2 + R_3} = \frac{2R_2 + R_3}{R_2 + R_3} e^{-\frac{T/2}{\tau}} \Rightarrow e^{-\frac{T/2}{\tau}} = \frac{R_3}{2R_2 + R_3}$$

Taking natural log on both sides, we obtain:

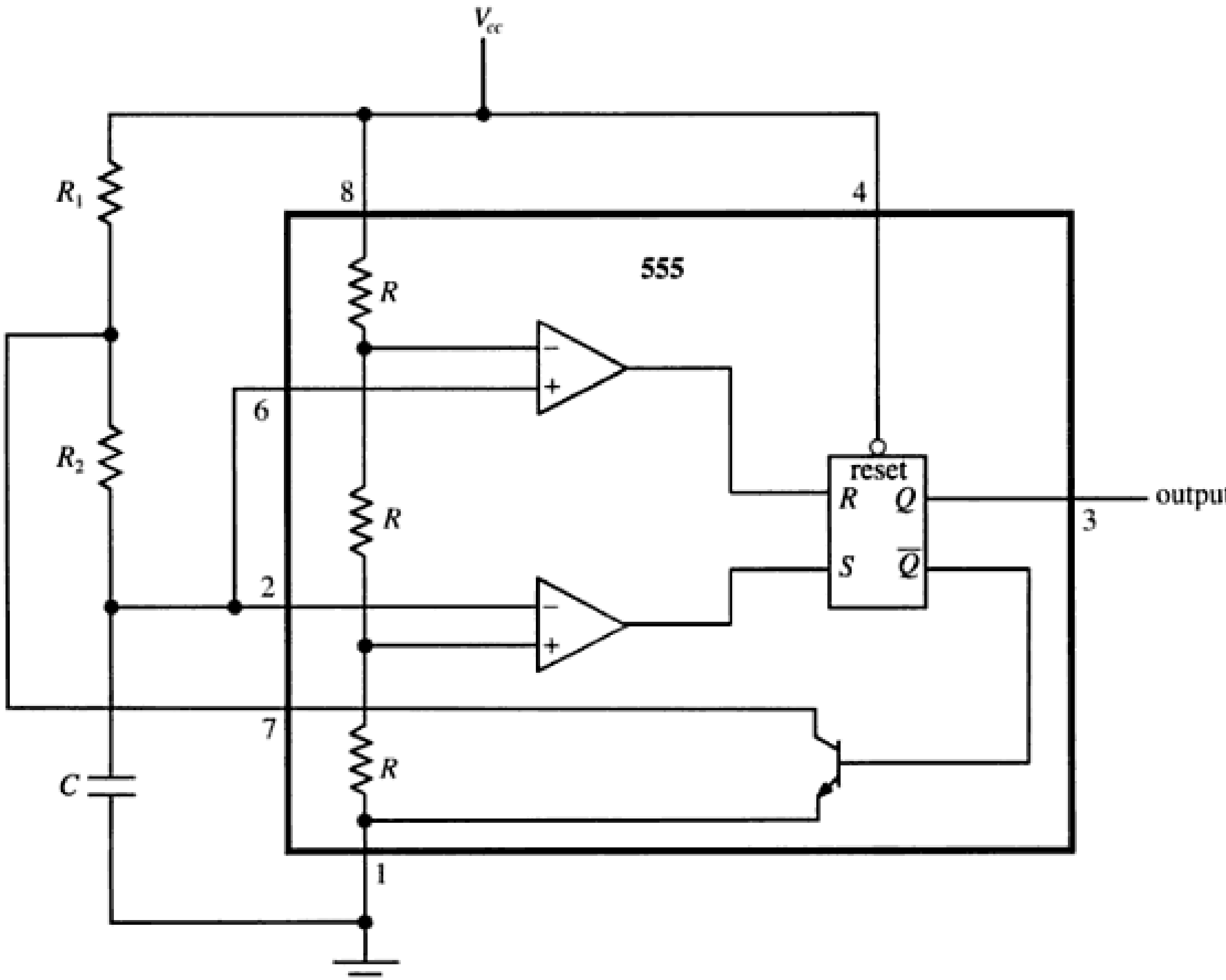
$$\frac{-\frac{T}{2}}{\tau} = \ln\left(\frac{1}{2R_2 / R_3 + 1} \right) \Rightarrow T = 2R_1 C \ln\left(\frac{2R_2}{R_3} + 1 \right)$$

555 Timer: How it works (Astable Operation)?

- Gets its name from the 3 5-kΩ resistors shown in the block diagram.
- These three resistors act as a three-step voltage divider between the supply voltage (V_{cc}) and ground.
- Top of the lower resistor = 1/3 V_{cc}.
- Top of the middle resistor = 2/3 V_{cc} .
- Two comparators output either a high or low voltage based on the analog voltages being compared at their inputs.
- If one of the comparator's positive input is more positive than its negative input, its output logic level goes high; if the positive input voltage is less than the negative input voltage, the output logic level goes low.

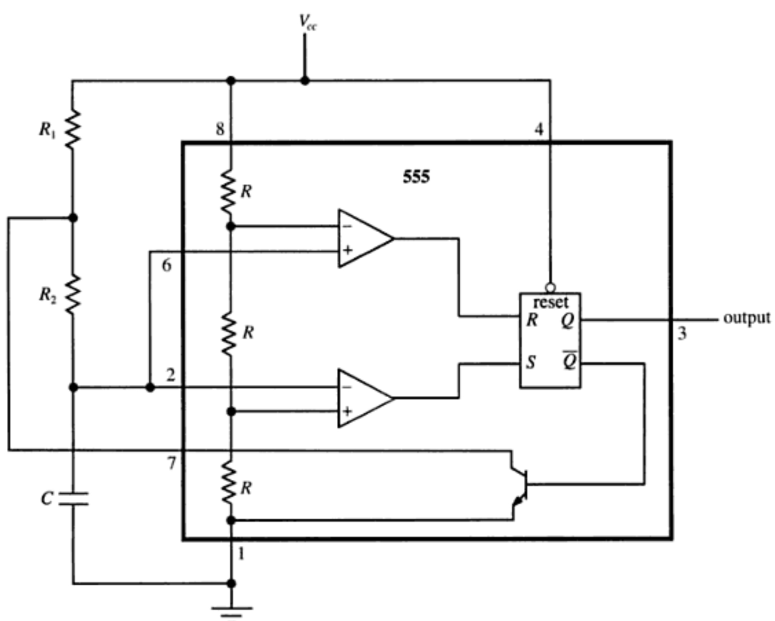


555 Timer: How it works (Astable Operation)?



555 Timer: Astable Circuit Operation—I

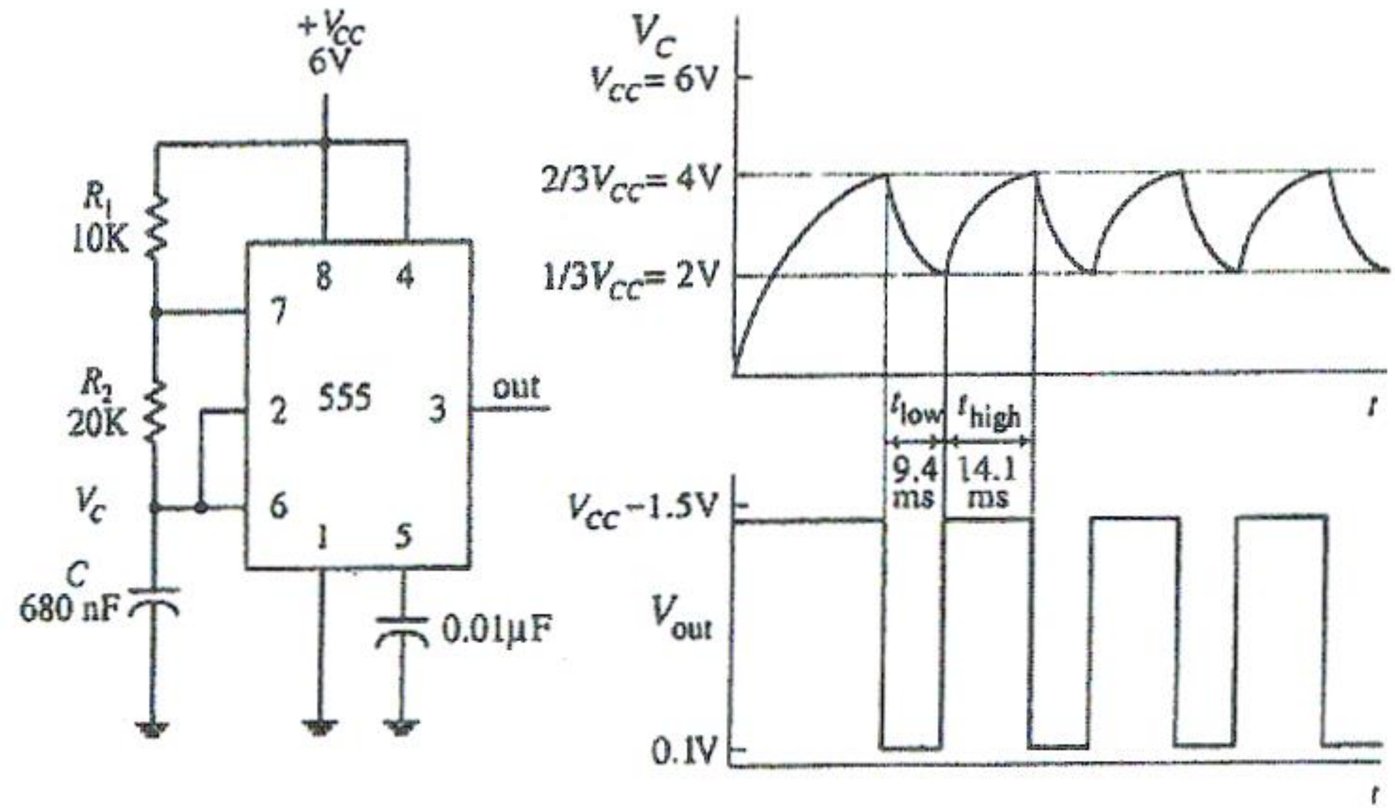
- On power-up: C is discharged, so pin 2 is low (0V), Comp2: $V_-=0$, $V_+=(1/3)Vcc \rightarrow S=1$, Comp1: $V_+=0$, $V_-=(2/3)Vcc \rightarrow R=0$, So $\rightarrow Q=1$ and $\overline{Q}=0 \rightarrow$ output is high, transistor not conducting, capacitor C charges via R_1+R_2
  - o Capacitor gets to $(1/3)V_{cc}$, Comp2: $V_-= (1/3)V_{cc}$, $V_+=(1/3)Vcc \rightarrow S=0$, Comp1: $V_+= (1/3)V_{cc}$, $V_-=(2/3)Vcc \rightarrow R=0$, So $\rightarrow Q$ and $\overline{Q}$ do not change, output is high, transistor not conducting, capacitor C charges via R_1+R_2
  - o Capacitor gets to $(2/3)V_{cc}$, Comp2: $V_-= (2/3)V_{cc}$, $V_+=(1/3)Vcc \rightarrow S=0$, Comp1: $V_+= (2/3)V_{cc}$, $V_-=(2/3)Vcc \rightarrow R=1$, So $\rightarrow Q=0$ and $\overline{Q}=1 \rightarrow$ output is low, transistor conducts, capacitor C discharges via R_2



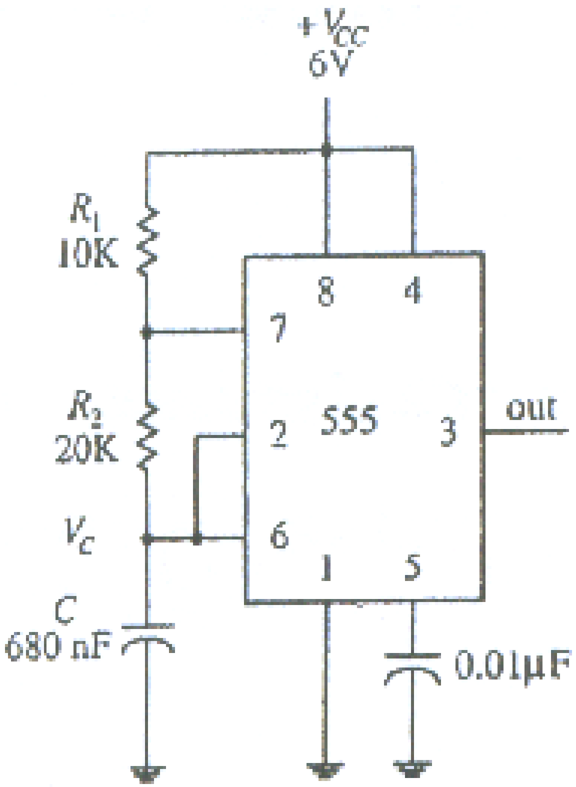
Truth table for the RS flip-flop

Inputs		Outputs	
S	R	Q	$\overline{Q}$
0	0	Q_0	$\overline{Q_0}$
1	0	1	0
0	1	0	1
1	1	NA	

555 Timer: Astable Operation



555 Timer: Astable Mode Duty Cycle—I

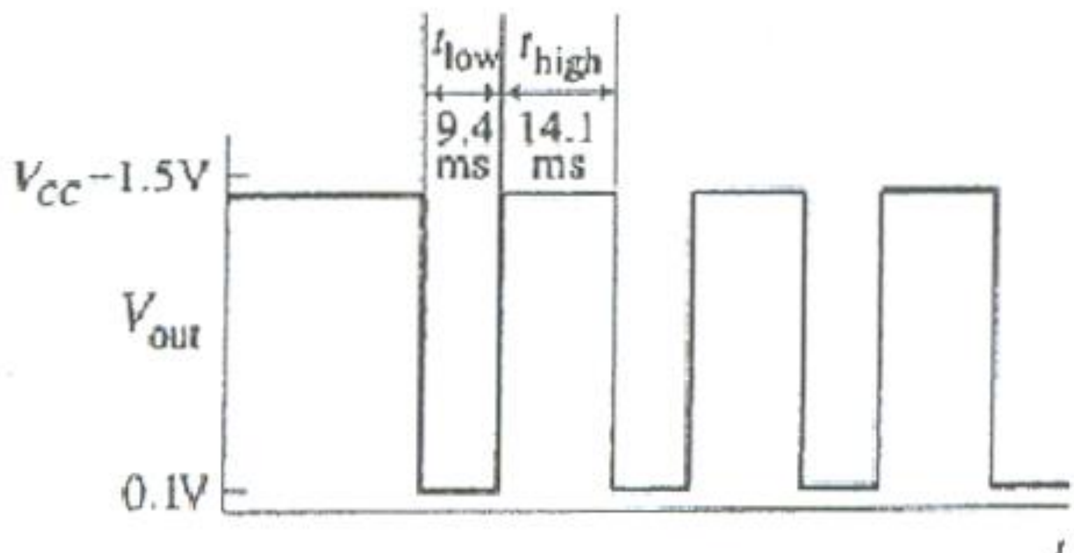


$$t_{low} = 0.693 R_2 C$$

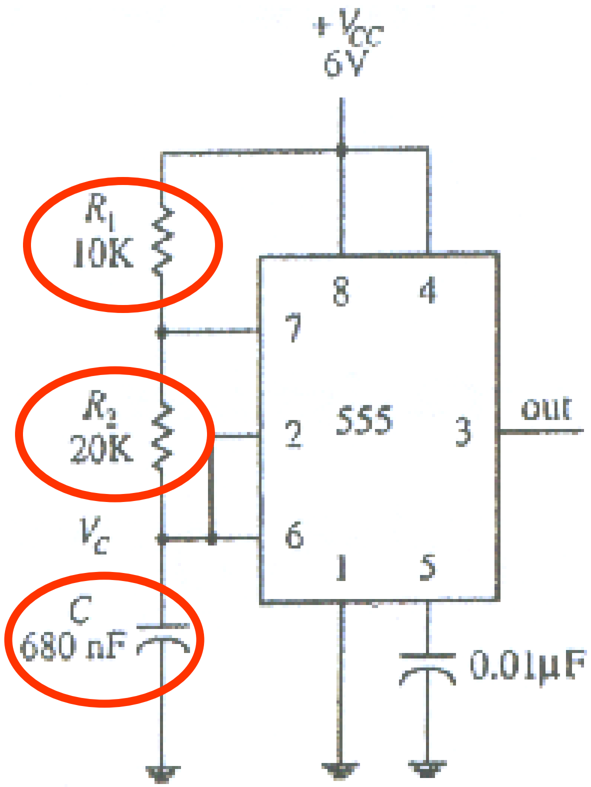
$$t_{high} = 0.693(R_1 + R_2)C$$

$$Duty\ cycle = \frac{t_{high}}{t_{high} + t_{low}}$$

$$f = \frac{1}{t_{high} + t_{low}}$$



555 Timer: Astable Mode Duty Cycle—II



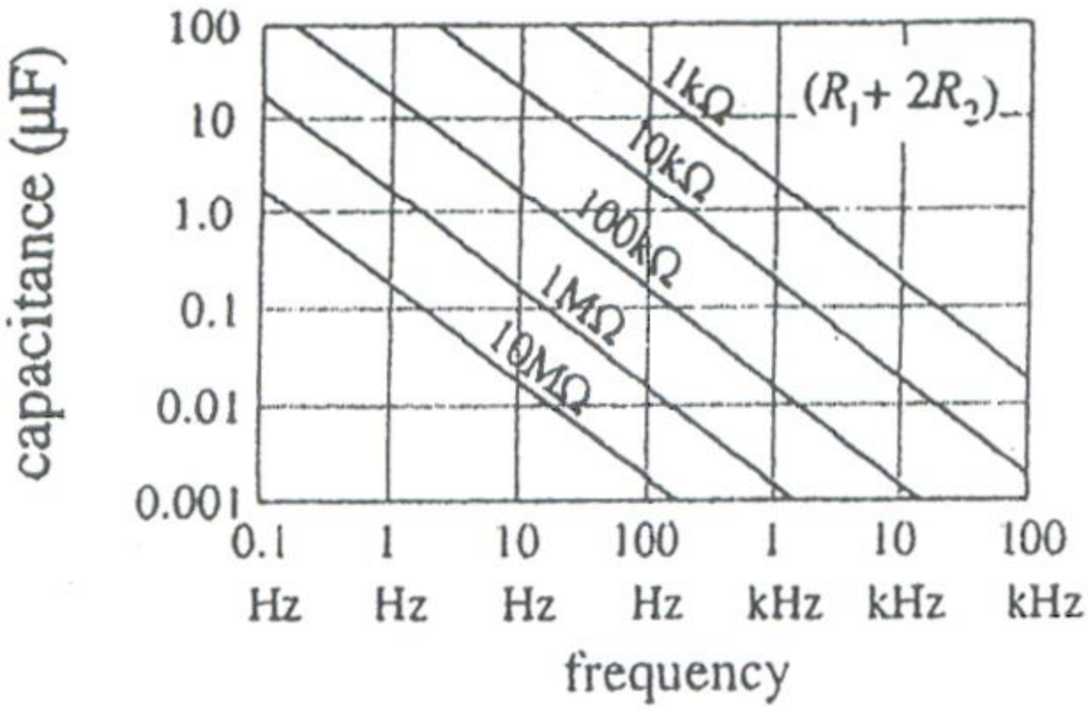
$$t_{low} = 0.693\,(20K)\,(680nF) = 9.6ms$$

$$t_{high} = 0.693\,(10K + 20K)\,(680nF) = 14.1ms$$

$$Duty\ cycle = \frac{14.1ms}{14.1ms + 9.6ms} = 0.6$$

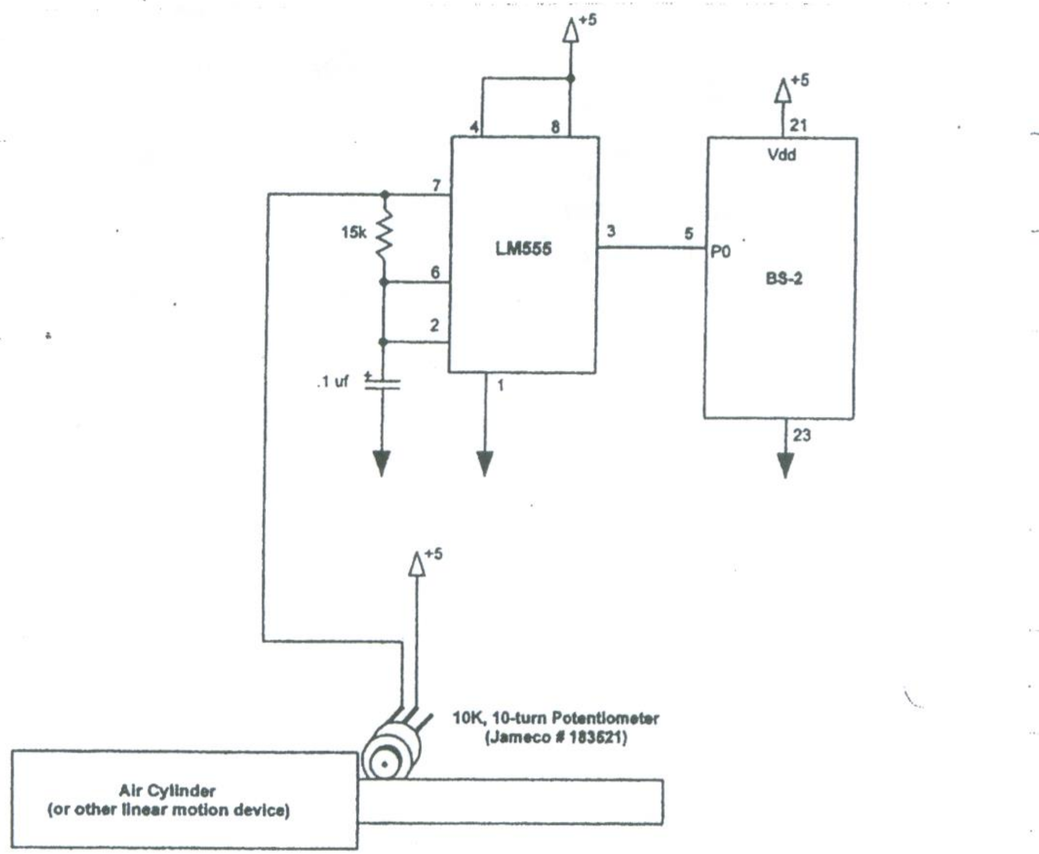
$$f = \frac{1}{14.1ms + 9.6ms} = 42Hz$$

555 Timer: Astable Mode Frequency v/s C, R_1, and R_2



Measuring an Analog Value using Astable LM555 Timer

- The astable LM555 timer and the pulsin command of BS2 can be employed to measure the linear travel of a machine tool slide
- A pot is mechanically coupled to the arm undergoing linear motion via a rubber wheel.
- The translation motion of the arm changes the pot resistance.
- The pot resistance forms the "R1" resistor of the astable LM555 timer.
- Time duration of high pulse by 555 timer ∝ Pot resistance ∝ Linear travel of slide.



Figure

Using pulse-width modulation for linear movement detection

Pulsin 0, 1, Highdura

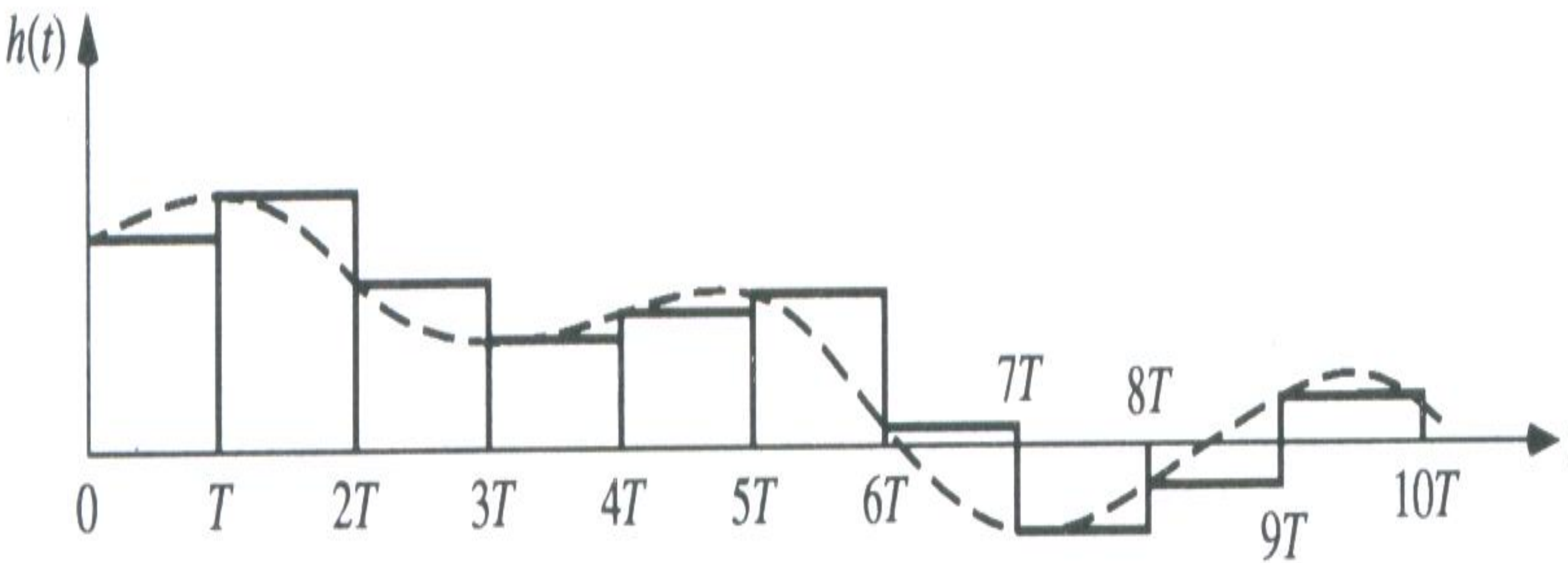
Will give time over which 555 outputs "high" pulse.

Analog to Digital (A2D) Conversion

- Process of representing an analog signal digitally.
- Three step procedure:
  - Sampling (sample and hold)
  - Quantization
  - Coding

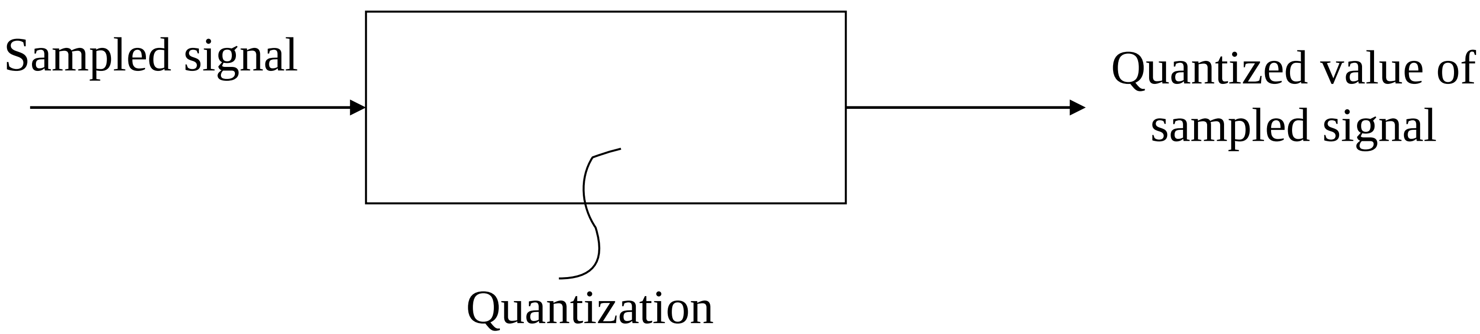
A2D: Sampling

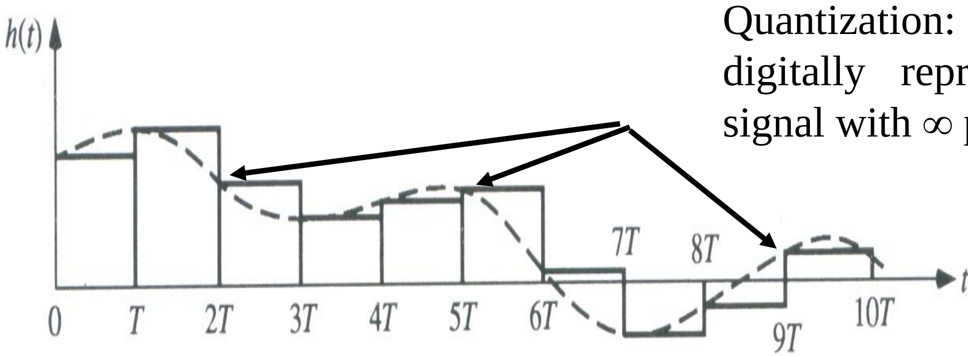
- The process of sampling refers to obtaining the analog signal measurement at discrete instants (sampling instants).
- The sampled value of signal is held constant until the next sampling instant.



A2D: Quantization—I

- Represent sampled signal magnitude at allowable discrete levels.
- Use of a finite number of bits to store data allows only a finite resolution A2D.
- This is because a digital number can assume only a finite number of levels with finite bit representation. Thus, the analog number is rounded/truncated in the quantization process.
- This approximation is termed as quantization.





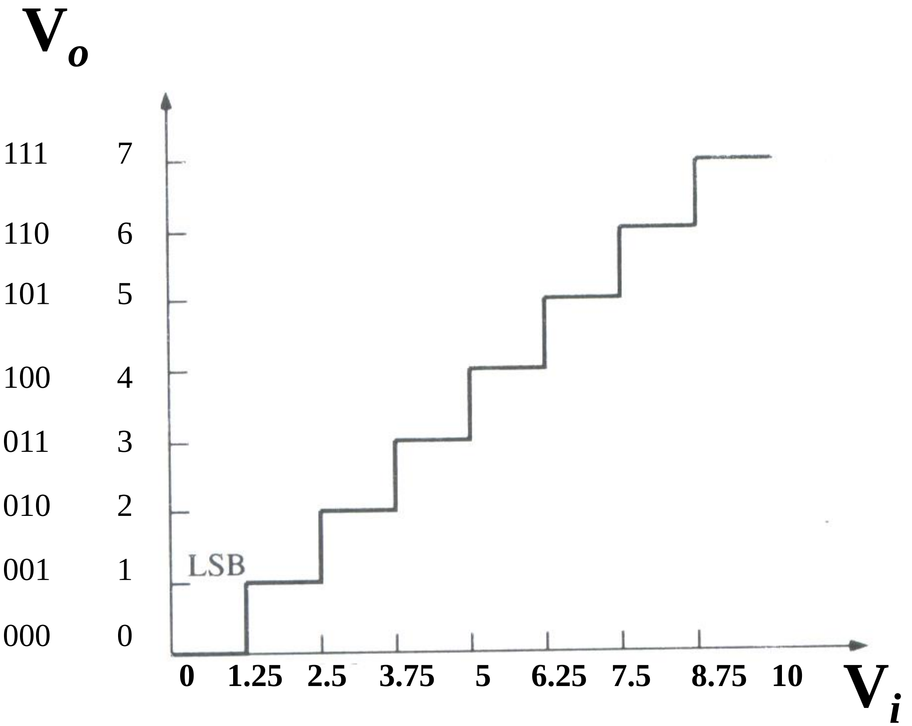
Quantization: It is not possible to digitally represent sampled value of signal with ∞ precision!

A2D: Quantization—II

- Let us assume $0V \le V_i \le 10V$
- Let us assume 3 bits are used to store V_i. Note that using 3 bits we can get at most 8 different states (2^3). Then, V_i can be subdivided into 8 levels.

$$\frac{10}{8} = 1.25V$$

Quantization level resolution



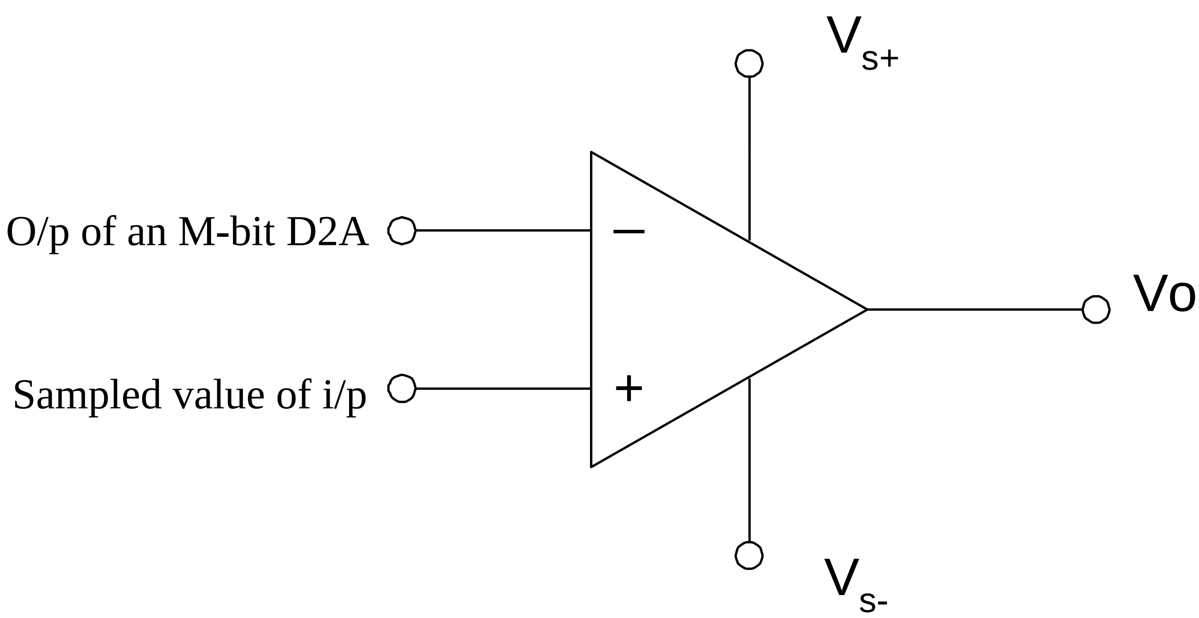
0V ~ 10V

- In general, let us say $V_{\min} \le V_i \le V_{\max}$
- Let us say n bits are used, then, the quantization level (size) is:

$$Q = \frac{V_{\max} - V_{\min}}{2^n}$$

Successive Approximation A2D Converter—I

- Input voltage sampled at a time instant t_0.
- A D2A converter:
  - Provides an equivalent analog voltage signal to represent contents of an M-bit register.
- A comparator:
  - Compares input voltage to the output of D2A converter and successively turns the bits of an M-bit register on/off to approximate input voltage.



Successive Approximation A2D Converter—II

- 0-15V range, 4-bit successive approximation A2D converter, input voltage 10.1V.

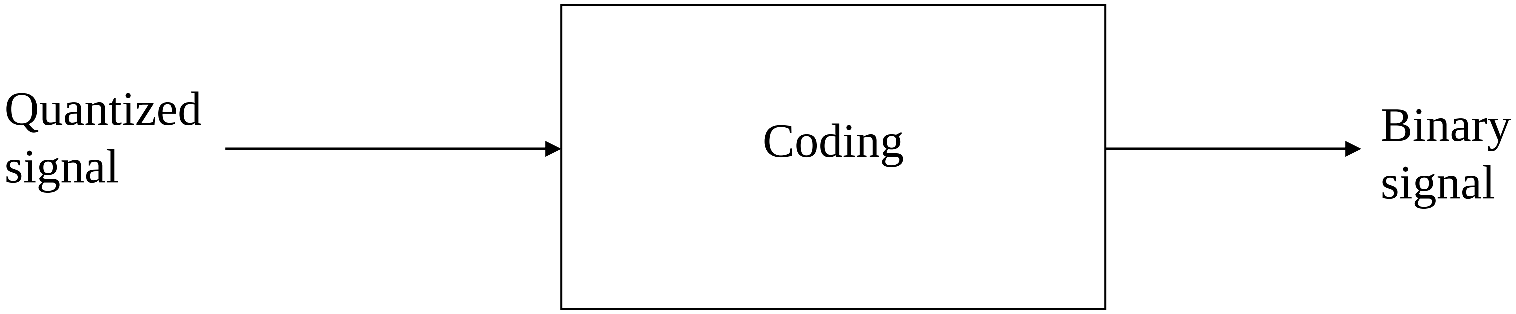
$$\text{Step size: } \frac{15}{2^4} = 0.9375$$

Initial status	Register (Level)	Equivalent Voltage	Input Voltage	Comparator
All bits off	0000 (0)	0	10.1	High
Turn MSB to 1	1000 (8)	7.5	10.1	High
Leave MSB at 1, turn next bit to 1	1100 (12)	11.25	10.1	Low
Leave MSB at 1, turn next to MSB to 0, and the one following that to 1	1010 (10)	9.375	10.1	High
Keep previous ones and turn LSB to 1	1011 (11)	10.3125	10.1	Low
Turn the LSB to 0	1010 (10)	9.375	10.1	High

- Answer: $\boxed{9.375}$ Quantized Value

A2D: Coding

- Converts the quantized signal (which is in the decimal format; i.e. base 10) to binary format (base 2).



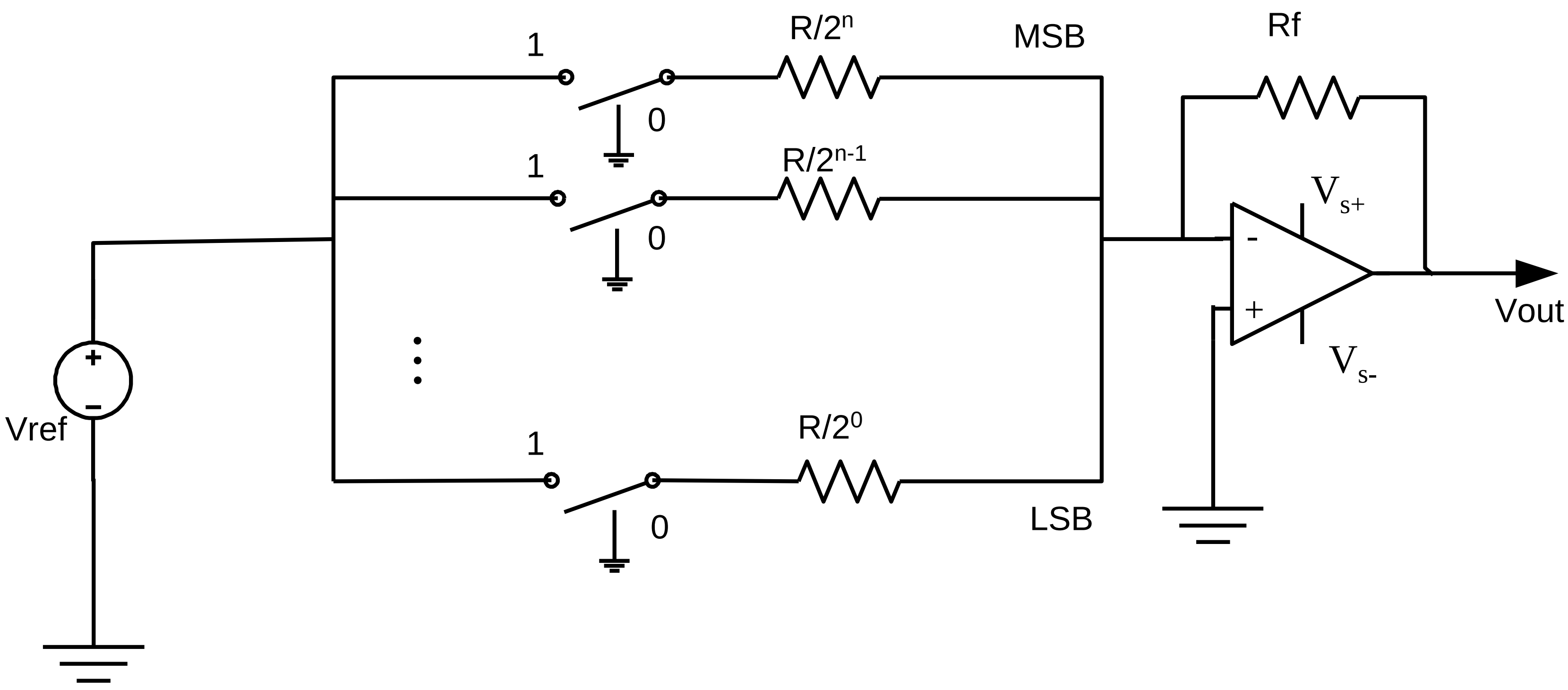
- Aside:
  - Commercial A2D converters have 8,10,12, or 16 bit resolution which give quantization levels of 256,1024,4096, 65536, respectively.
  - Maximum sampling rate and resolution (# of bits) of A2D will dictate its accuracy and reliability.

D2A Conversion

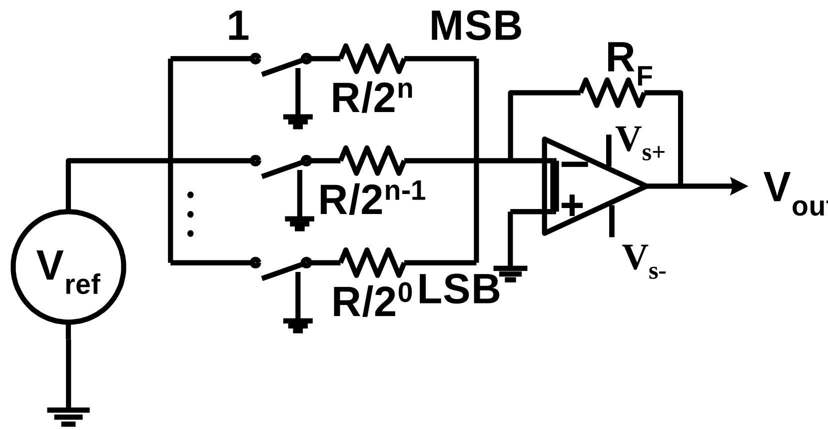
- Often a computer needs to provide a signal that actuates a motor/pump/electromagnet/…etc.
- Note that here the computer is a digital device whereas the object being actuated is usually an analog device.
- In this case, one needs to perform digital-to-analog (D2A) conversion, which is “to reverse the process of A2D conversion.”
- D2A converter takes a data input in binary representation and provides its decimal representation. This is accomplished by implementing the following conversion equation.

$$(b_n b_{n-1} \cdots b_1 b_0)_2 = b_n 2^n + b_{n-1} 2^{n-1} + \cdots + b_1 2^1 + b_0 2^0$$

Op-Amp Circuit for D2A—I



Op-Amp Circuit for D2A—II



- Each switch can be in either of two positions:
  - On → 1 (Connected to V_{ref})
  - Off → 0 (Connected to Ground)
- Using the result from summing amplifier:

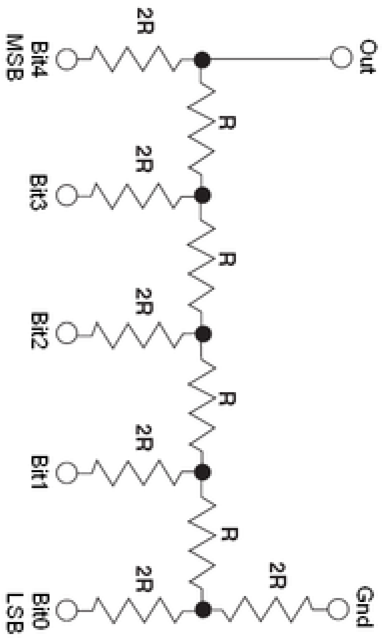
$$V_{out} = -\frac{R_F}{R/2^n} V_n - \frac{R_F}{R/2^{n-1}} V_{n-1} - \cdots - \frac{R_F}{R/2^0} V_0$$

- $V_0, V_1, V_2, \ldots, V_{n-1}, V_n$ are voltages across $R/2^0$, $R/2^1$, $R/2^2, \ldots, R/2^{n-1}, R/2^n$, resistors, respectively.
- Note: $V_i = V_{ref} b_i$ where $b_i = 1$ or 0, $i = 0,1,\ldots,n$.
- Then,

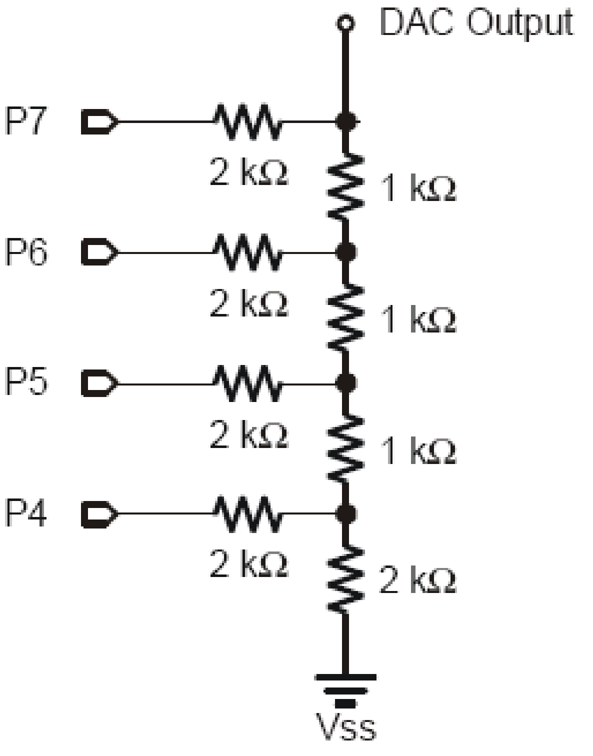
$$V_{out} = -\frac{R_F}{R} V_{ref} \left[b_n 2^n + b_{n-1} 2^{n-1} + \cdots + b_0 2^0 \right]$$

  - Output voltage is directly proportional to decimal equivalent of binary numbers.
- Note: getting resistors with exact values $R/2^i, i = 0,\ldots,n$ is not easy!

R-2R Resistive-Ladder D2A



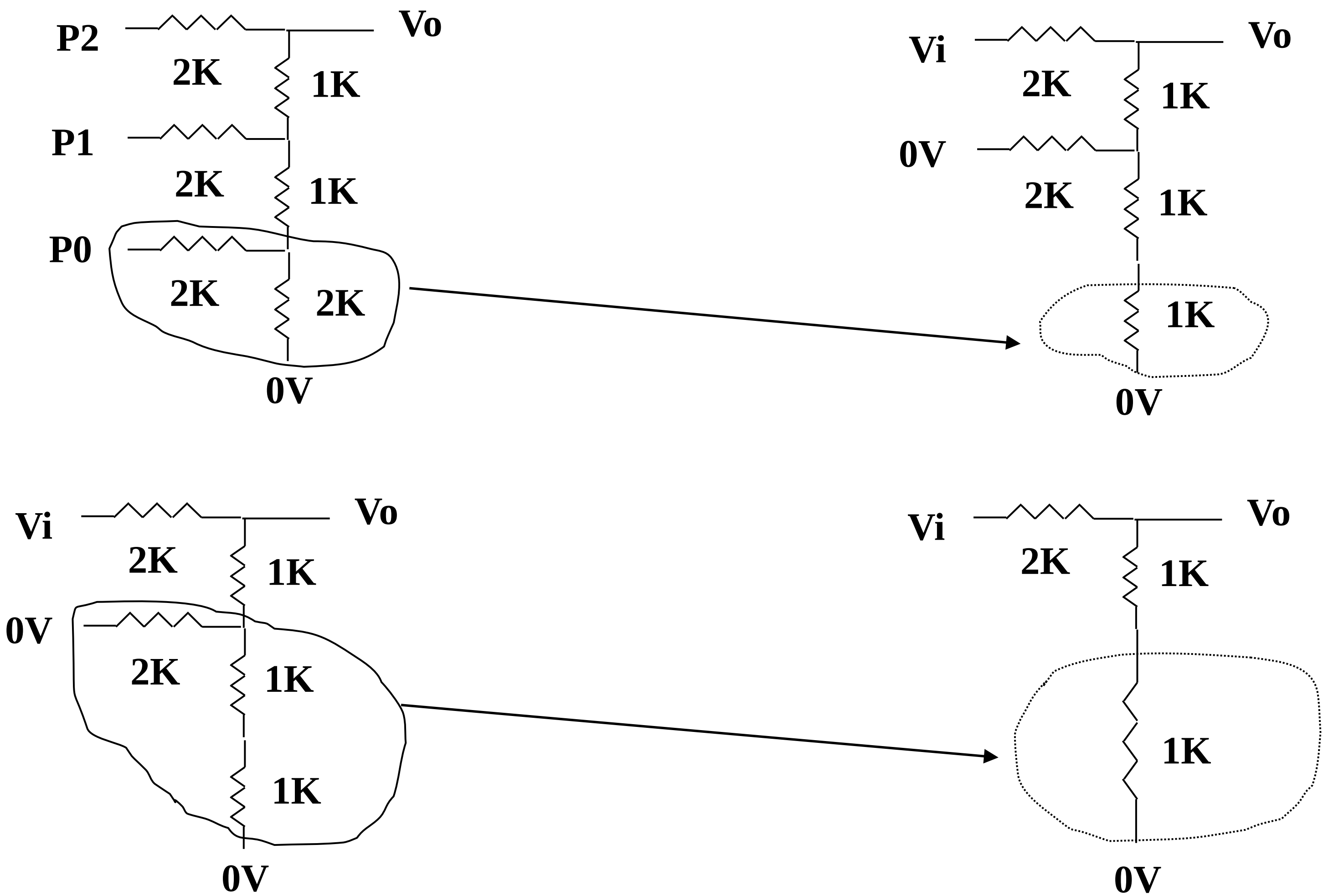
5-bit D2A



4-bit D2A

R-2R Resistive-Ladder D2A: 3Bit Example—I

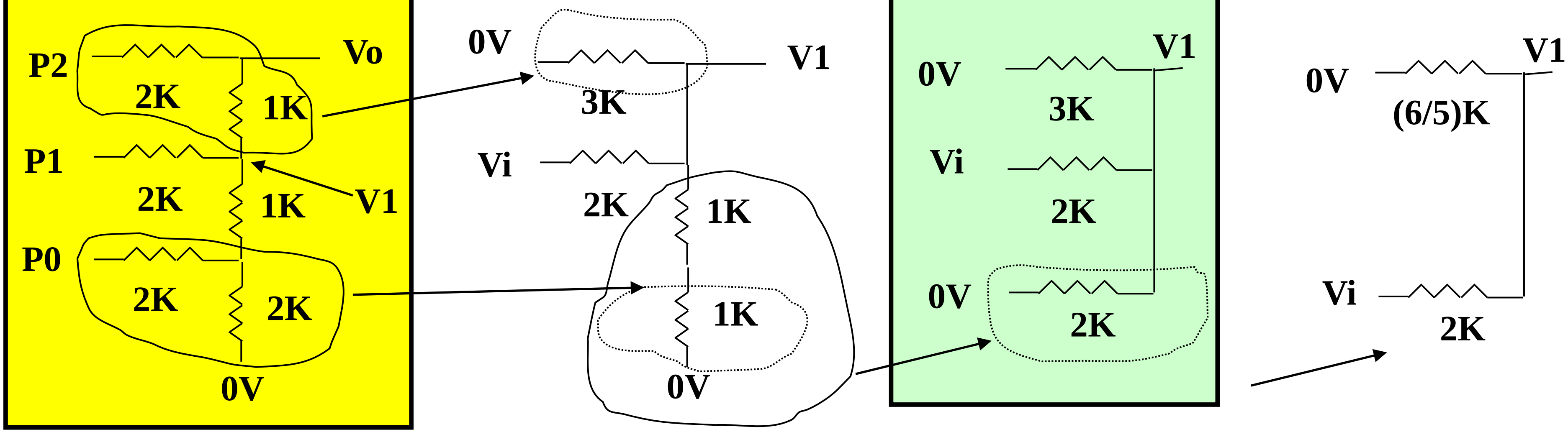
- Consider P0=P1=0 and P2=Vi=5V



- So Vo=(1/2)Vi=2.5V

R-2R Resistive-Ladder D2A: 3Bit Example—II

- Consider P0=P2=0 and P1=Vi=5V

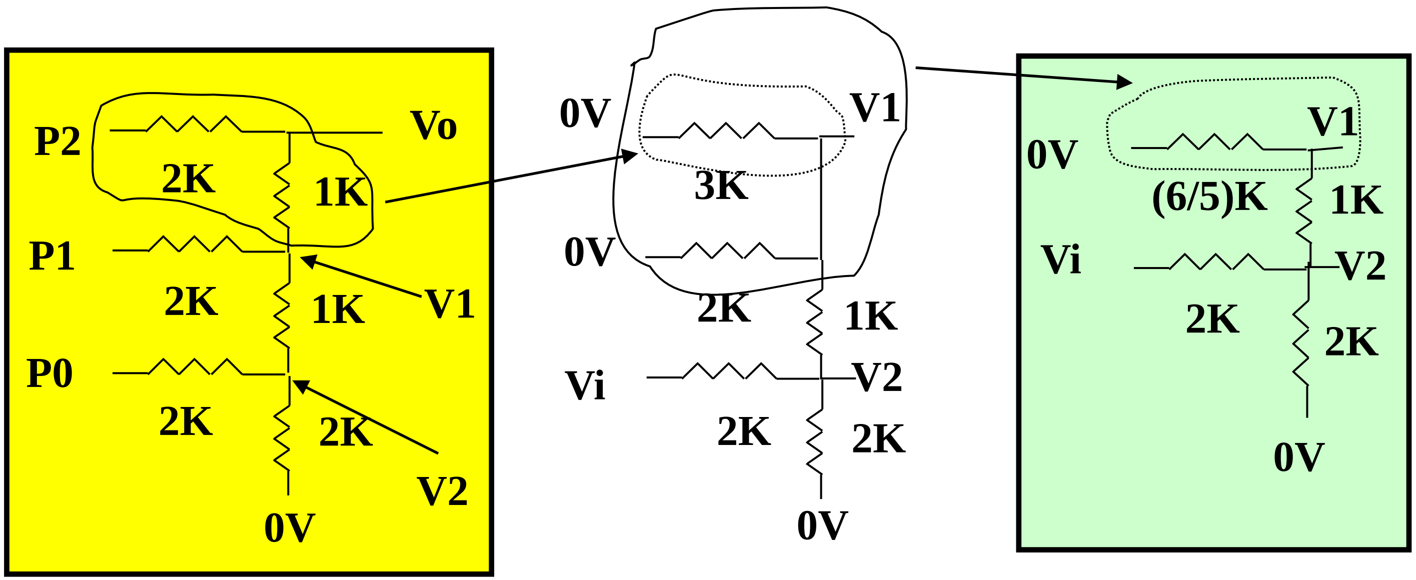


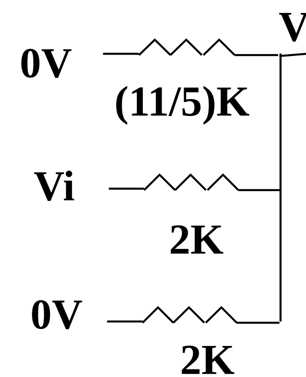
$$V1 = \frac{\frac{6}{5}}{\frac{6}{5} + 2} Vi = \frac{6}{16} Vi$$

$$Vo = \frac{2}{3} V1 = \frac{2}{3} \times \frac{6}{16} Vi = \frac{1}{4} Vi = \frac{1}{4} \times (5V)$$

R-2R Resistive-Ladder D2A: 3Bit Example—III

- Consider P1=P2=0 and P0=Vi=5V



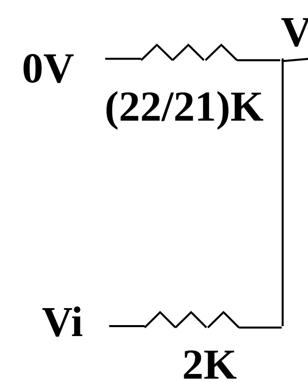


$$V2 = \frac{\frac{22}{21}}{\frac{22}{21} + 2} Vi = \frac{22}{64} Vi$$

$$V1 = \frac{\frac{6}{5}}{\frac{6}{5} + 1} Vi = \frac{6}{11} V2$$

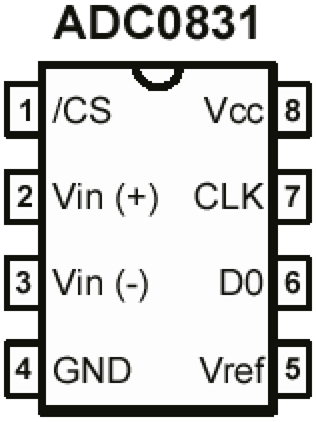
$$Vo = \frac{2}{3} V1 = \frac{2}{3} \cdot \frac{6}{11} V2 = \frac{4}{11} V2$$

$$Vo = \frac{4}{11} \cdot \frac{22}{64} Vi = \frac{1}{8} Vi = \frac{1}{8}(5V)$$



AD0831—I

- AD0831 is an 8-bit converter
  - PIN1: is chip select pin. When it is driven low, A2D is ready to do conversion.
  - PIN2: is connected to 0 to 5 Volt analog input that needs to be digitized.
  - PIN3: is used for zero offset adjustment. The zero point of converter is equal to voltage present at PIN3. If 0 to 5 Volts at PIN2 need to be digitized, PIN3 ought to be at 0 volts. If 2 to 5 Volts at PIN2 need to be digitized, PIN3 ought to be at 2 Volts. (Then input of 0-2V at PIN2 will be reported as 0V).
  - PIN4: is connected to the ground.



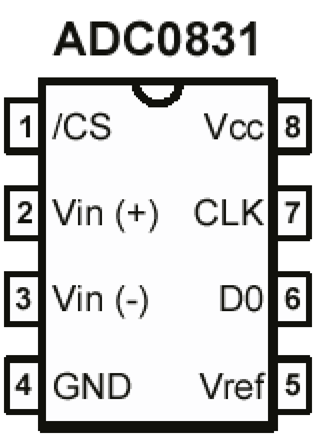
AD0831—II

- PIN5: is used for span adjustment of A2D. If 0 to 5V at PIN2 needs to be digitized, then PIN5 ought to be at 5V. If however, 0 to 2V at PIN2 need to be digitized, then providing 2V input at PIN5 will give a span of 2V for digitization. If 0-2V at PIN2 is being digitized and PIN5 is at 5V, then span is 5V and 0-2V will be digitized without using all of the 256 steps of A2D (8-bit of A2D has 256 steps). Instead, only 102 steps of A2D will be used!

- PIN6: gives the digitized output (8 bits of A2D output).

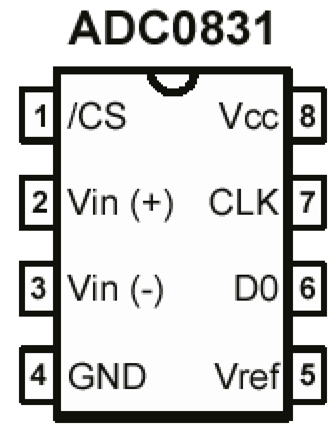
- PIN7: the clock signal from BS2 is applied to this pin. When PIN1 (chip select) has been driven low and clock pulse is sent to PIN7, after receiving each pulse, the A2D pushes bits of A2D output from left to right at DO (PIN6).

- PIN8: is connected to regulated 5V supply.



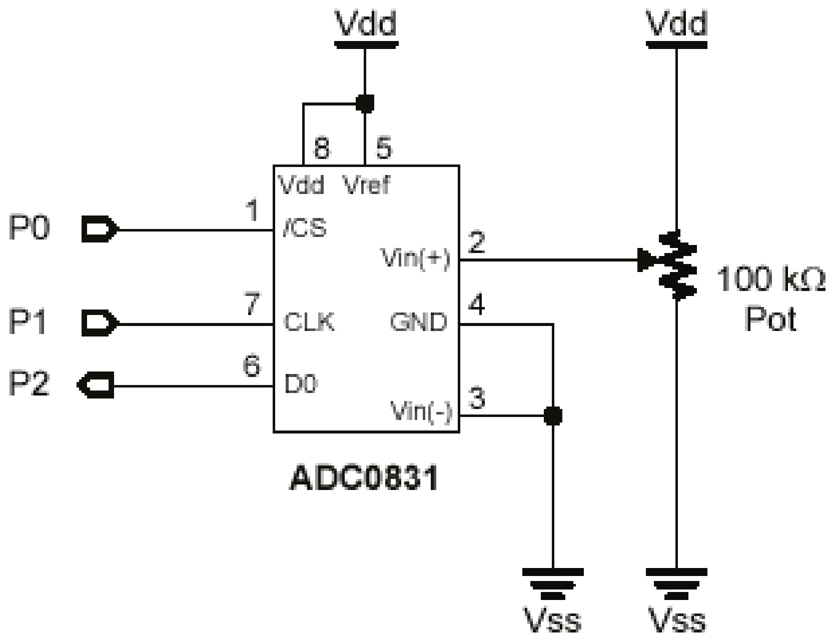
AD0831—III

Pins	Description
PIN1	A2D is ready to do conversion when PIN1 is driven low
PIN2	0 to 5V analog input that needs to be digitized
PIN3	Zero offset adjustment
PIN4	Ground
PIN5	Span adjustment
PIN6	8 bit A2D output
PIN7	Clock signal from BS2
PIN8	Regulated 5V (Power supply)



A2D Circuit

- In the A2D circuit shown here, we wish to measure a 0-5V analog signal.
  - The signal is generated using a potentiometer connected to a 5V source.
  - The zero offset is fixed at 0V by connecting PIN3 to 0V.
  - The span is set at 5V by connecting PIN5 to 5V.
  - This A2D has 8-bit resolution, thus the O/P is a number from 0 to 255.

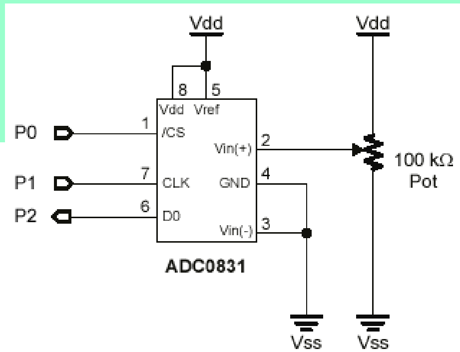


A2D Circuit and Sample PBasic Code—I

- In the given code:
  - –Low 0: enables chip select.
  - –Pulsout 1,1: sends clock pulse to BS2 PIN1 which is connected to CLK PIN (7) of A2D.
  - –In the for-next loop, the 8 bits of A2D output byte corresponding to digitized version of analog input are given to BS2.
- Note that the
  - –A2DOut = A2DOut * 2 and
  - –A2DOut = A2DOut + in2

  operations enable recording of bits from left to right.

```
A2DOut var byte
Loopvar var byte
Digitize:
low 0              'select the A2D
pulsout 1,1        'send the first "setup clock pulse"
A2DOut = 0         'set A2DOut to zero
for Loopvar = 1 to 8
                   'loop 8 times to get the 8 data bits
pulsout 1,1        'send a clock pulse
A2DOut = A2DOut * 2
                   'shift bits once to the left
A2DOut = A2DOut + in2
                   'add A2DOut to the incoming bit
next               'do the loop 8 times
high 0             'de-select the ad0831
debug? A2DOut      'print the result
goto Digitize
```



A2D Circuit—Bit Recording Example

•Example: suppose digitized signal is 0110 0101, which is 101 in decimal system.

$$\#1: x = 0, \quad in = 0$$
$$\text{Then} \quad x = 2x, \quad x = x + in \quad \Longrightarrow \quad x = 0$$
$$\#2: x = 0, \quad in = 1$$
$$\text{Then} \quad x = 2x, \quad x = x + in \quad \Longrightarrow \quad x = 1$$
$$\#3: x = 1, \quad in = 1$$
$$\text{Then} \quad x = 2x, \quad x = x + in \quad \Longrightarrow \quad x = 3$$
$$\#4: x = 3, \quad in = 0$$
$$\text{Then} \quad x = 2x, \quad x = x + in \quad \Longrightarrow \quad x = 6$$
$$\#5: x = 6, \quad in = 0$$
$$\text{Then} \quad x = 2x, \quad x = x + in \quad \Longrightarrow \quad x = 12$$
$$\#6: x = 12, \quad in = 1$$
$$\text{Then} \quad x = 2x, \quad x = x + in \quad \Longrightarrow \quad x = 25$$
$$\#7: x = 25, \quad in = 0$$
$$\text{Then} \quad x = 2x, \quad x = x + in \quad \Longrightarrow \quad x = 50$$
$$\#8: x = 50, \quad in = 1$$
$$\text{Then} \quad x = 2x, \quad x = x + in \quad \Longrightarrow \quad x = \boxed{101}$$

A2D Circuit and Sample PBasic Code—II

Setup ADC for serial com and get 8-bit data

Shiftin: Synchronous serial com

MSBPOST: MSB is read first, sample data after clock pulse

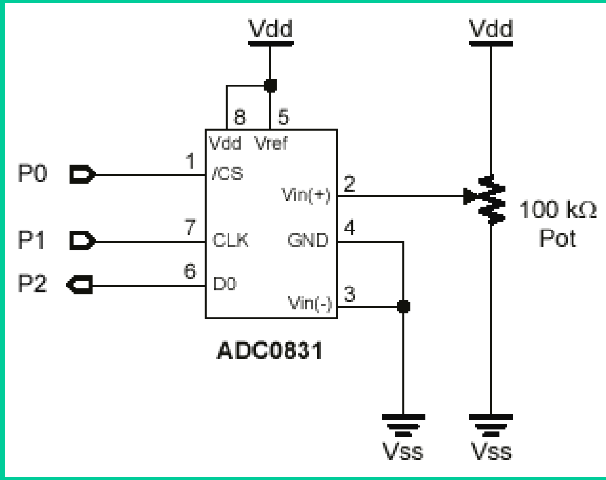
For $V_{in} \in \{0, 5V\}$, ADC returns $V_{bits} \in \{0, 255\}$

$Int(V_{in})=5^* V_{bits} /255$

$V_{Res}=5^* V_{bits}//255$ yields residue of $5^* V_{bits}/255$

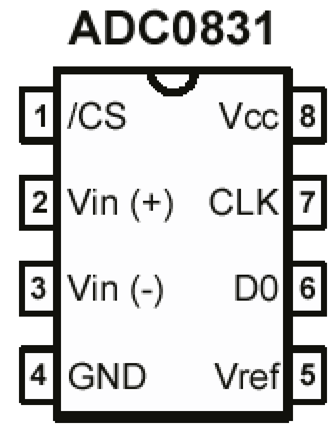
$Fract(V_{in})=V_{Res}*100/255$ (two digits)

```
' {$STAMP BS2}
' {$PBASIC 2.5}
adcBits VAR Byte
voltin VAR Byte
voltinr VAR Byte
CS PIN 0
CLK PIN 1
Datain PIN 2

DO
GOSUB Digitize
GOSUB Calc_Volts
GOSUB Display
LOOP

Digitize:
HIGH CS
LOW CS
LOW CLK
PULSOUT CLK, 210
SHIFTIN Datain,CLK,MSBPOST,[adcBits\8]
RETURN

Calc_Volts:
voltin = 5*adcBits/255
voltinr = 5*adcBits//255
voltinr=voltinr*100/255
RETURN

Display:
DEBUG HOME
DEBUG "8-bit binary value: ", BIN8 adcBits, ",  ", DEC3 adcBits, CR
DEBUG "Voltage Input: ", DEC voltin, ".", DEC2 voltinr, " Volts", "     "
RETURN
```

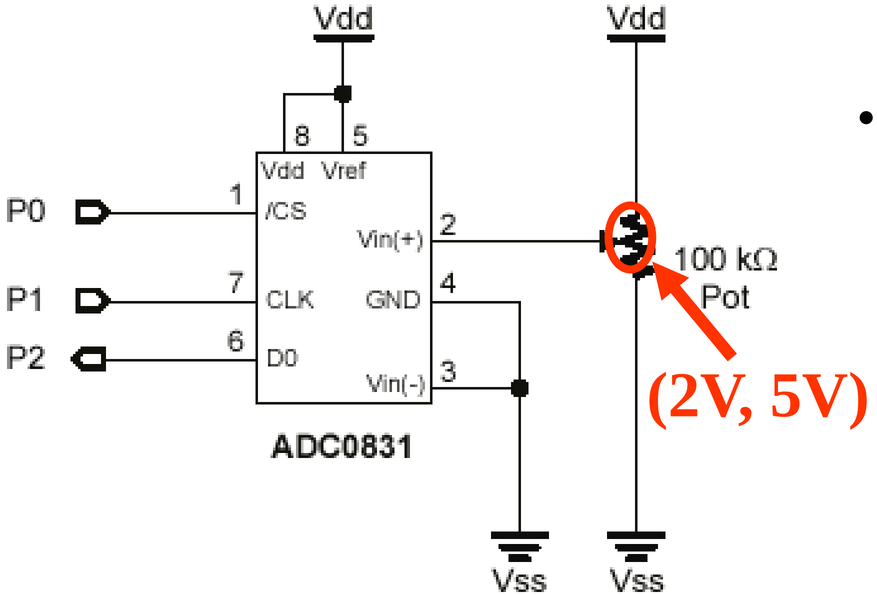


AD0831—Pin Functions

Pins	Description
PIN1	A2D is ready to do conversion when PIN1 is driven low
PIN2	0 to 5V analog input that needs to be digitized
PIN3	Zero offset adjustment
PIN4	Ground
PIN5	Span adjustment
PIN6	8 bit A2D output
PIN7	Clock signal from BS2
PIN8	Regulated 5V (Power supply)



A2D Circuit: Offset Adjustment—I



- Consider that a sensor outputs an analog signal in (2V, 5V) interval.
- For illustration, we produce the (2V, 5V) analog signal using a pot.
- If the A2D circuit shown here is used, the the A2D O/P will be from 102 to 255.
  - 8 bits resolution

$$\frac{2V}{5V} \times 255 = 102$$

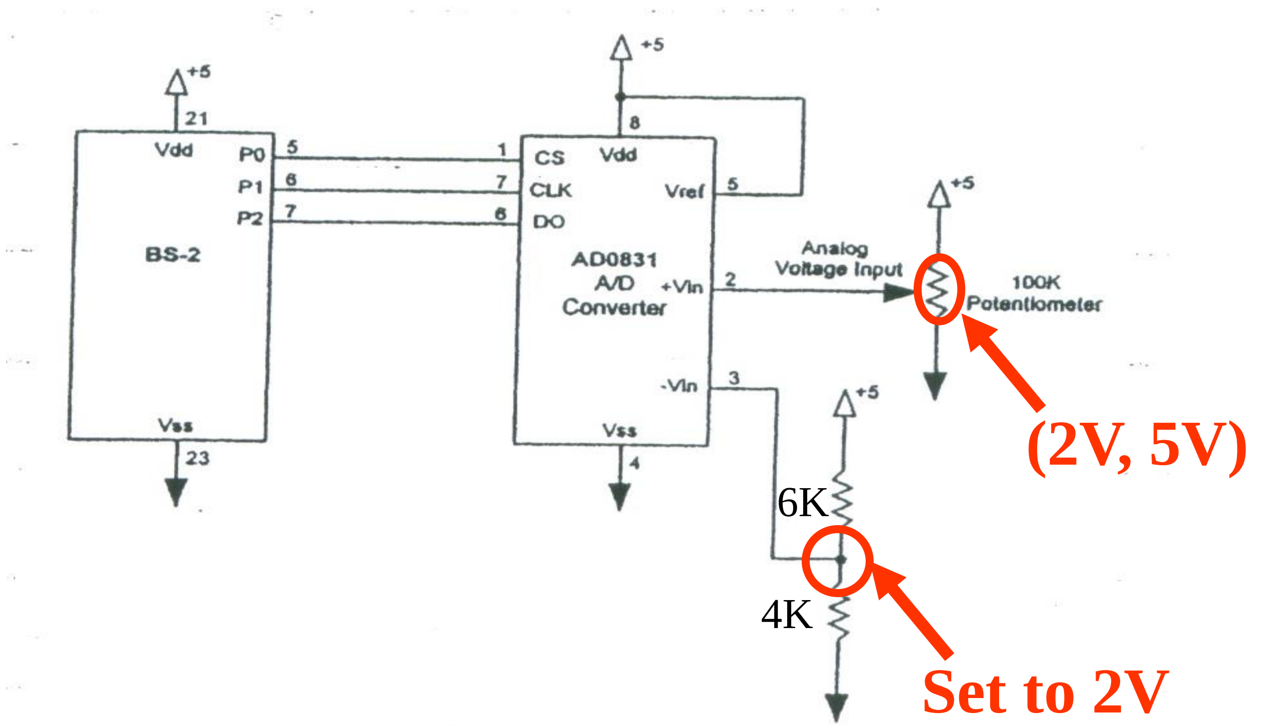
$$\frac{5V}{5V} \times 255 = 255$$

A2D Circuit: Offset Adjustment—II

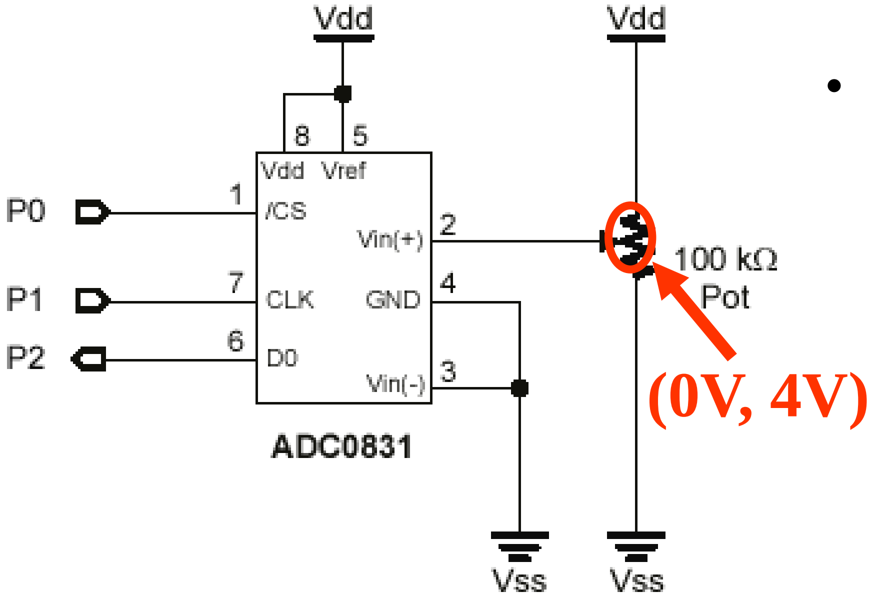
- Using a 2V bias input on Pin3 of A2D, the analog signal from (2V, 5V) is still digitized with 153 steps but now o/p ranges from 0 to 153!

$$\frac{(2-2)V}{5V} \times 255 = 0$$

$$\frac{(5-2)V}{5V} \times 255 = 153$$



A2D Circuit: Span Adjustment—I



- Consider that a sensor outputs an analog signal in (0V, 4V) interval.
- For illustration, we produce the (0V, 4V) analog signal using a pot.
- If the A2D circuit shown here is used, the the A2D O/P will be from 0 to 204.
  - 8 bits resolution

$$\frac{0V}{5V} \times 255 = 0$$

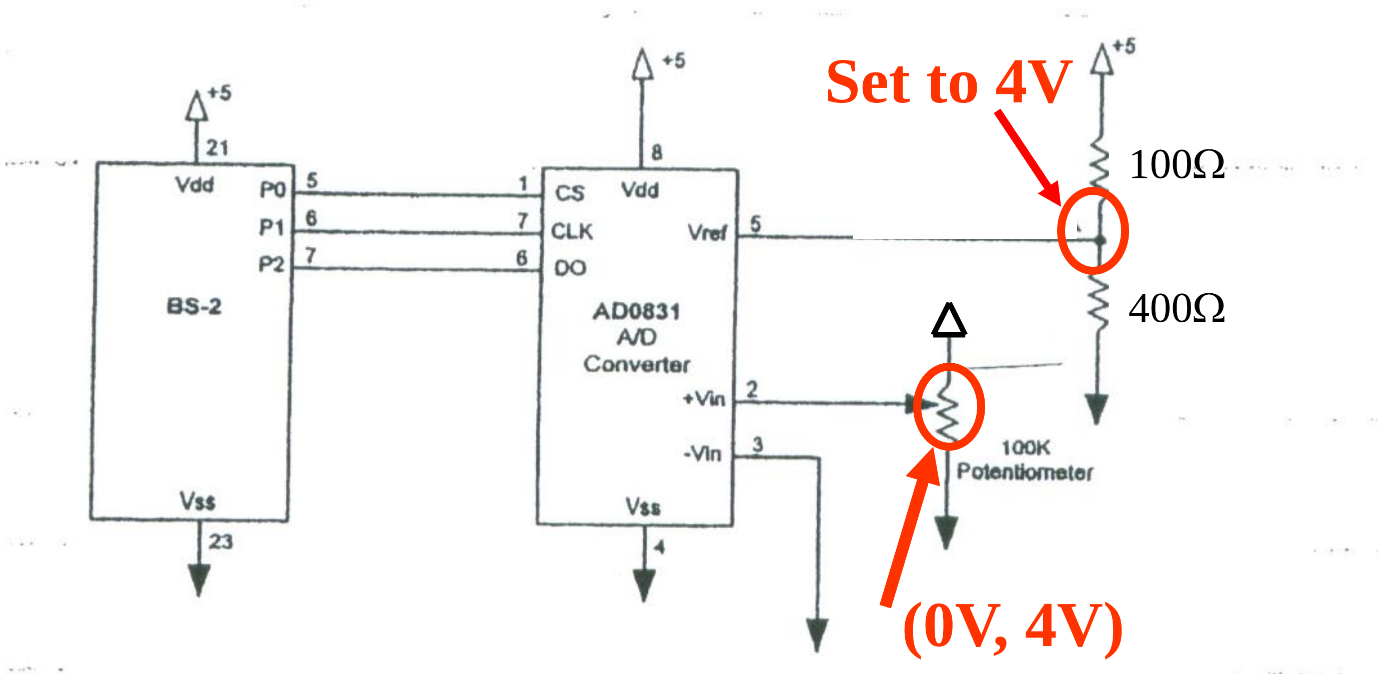
$$\frac{4V}{5V} \times 255 = 204$$

A2D Circuit: Span Adjustment—II

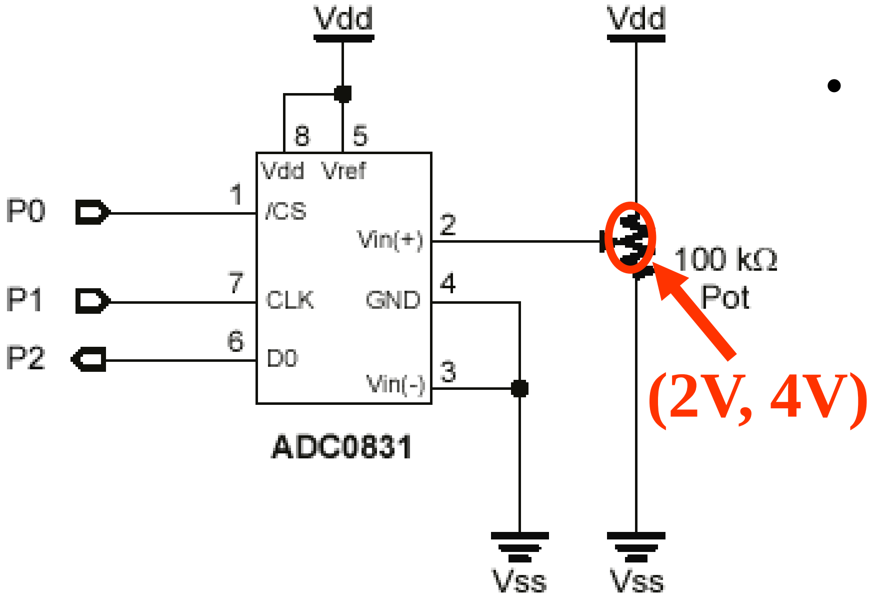
- By biasing PIN5 of A2D with 4V, now we use the entire range of A2D (256 steps) to digitize 0 to 4V.

$$\frac{0V}{4V} \times 255 = 0$$

$$\frac{4V}{4V} \times 255 = 255$$



A2D Circuit: Offset and Span Adjustment—I



- Consider that a sensor outputs an analog signal in (2V, 4V) interval.
- For illustration, we produce the (2V, 4V) analog signal using a pot.
- If the A2D circuit shown here is used, the the A2D O/P will be from 102 to 204.
  - 8 bits resolution

$$\frac{2V}{5V} \times 255 = 102$$

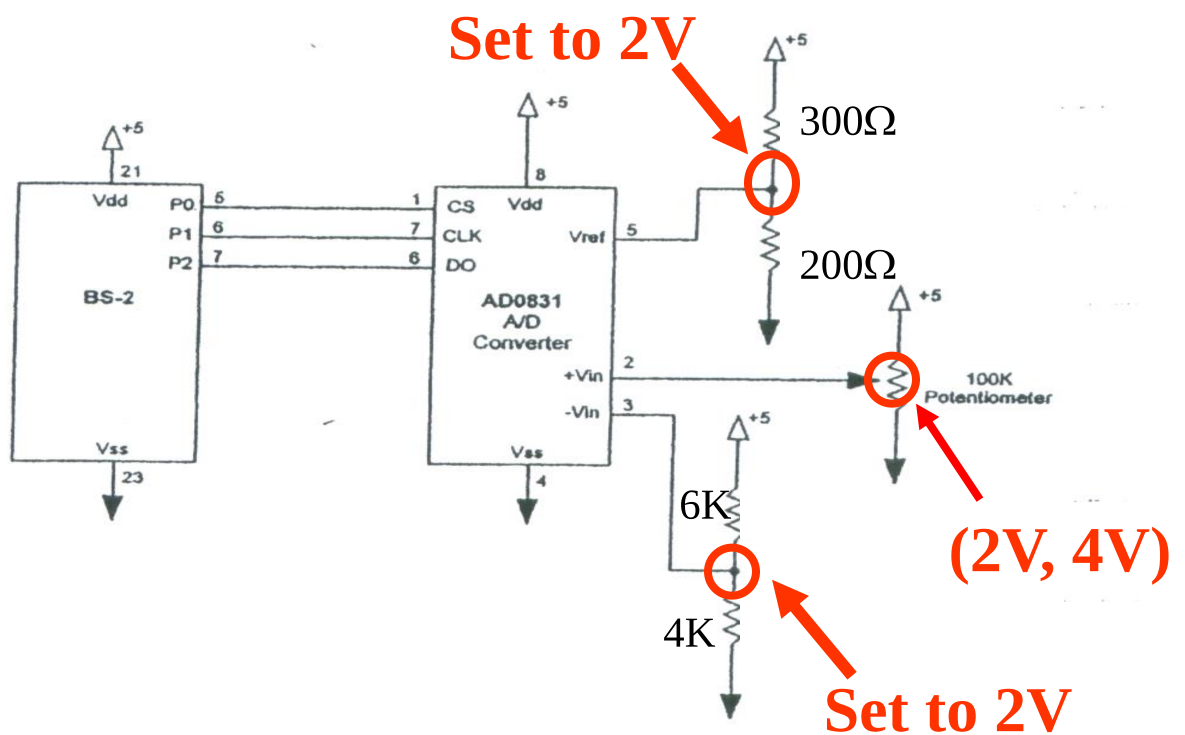
$$\frac{4V}{5V} \times 255 = 204$$

A2D Circuit: Offset and Span Adjustment—II

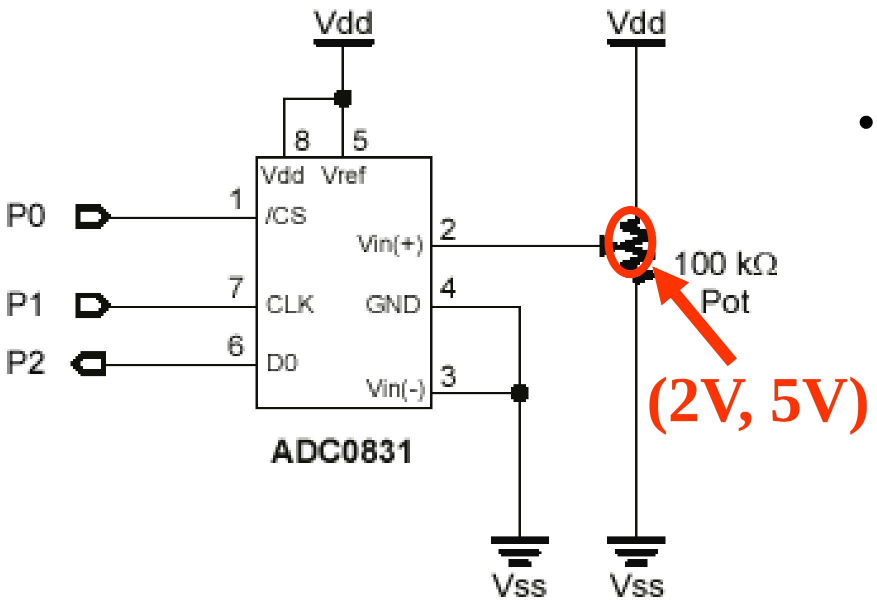
- Bias the $-V_{in}$ input of A2D with 2V.
- Bias the V_{ref} input of A2D with 4V.
- Now, an analog input signal ranging from 2 to 4V at $+V_{in}$ of A2D is digitized using 256 steps of A2D
- Analog voltage inputs from 0 to 2V are treated as 0V and A2D outputs a byte corresponding to "0".

$$\frac{(2-2)V}{(4-2)V} \times 255 = 0$$

$$\frac{(4-2)V}{(4-2)V} \times 255 = 255$$



A2D Circuit: Offset and Span Adjustment—III



- Consider that a sensor outputs an analog signal in (2V, 5V) interval.
- For illustration, we produce the (2V, 5V) analog signal using a pot.
- If the A2D circuit shown here is used, the the A2D O/P will be from 102 to 255.
  - 8 bits resolution

$$\frac{2V}{5V} \times 255 = 102$$

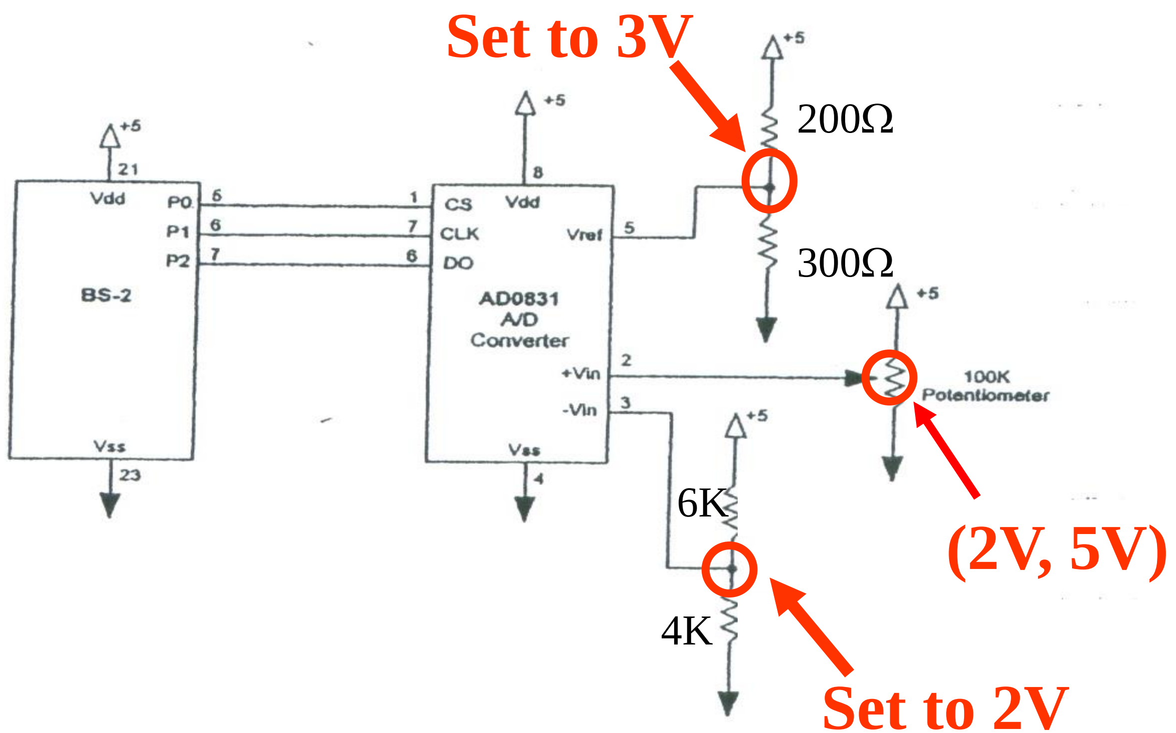
$$\frac{5V}{5V} \times 255 = 255$$

A2D Circuit: Offset Adjustment—IV

- Using a 2V bias input on Pin3 of A2D, and 3V on Pin5, the analog signal from (2V, 5V) is digitized with full 8-bit resolution.

$$\frac{(2-2)V}{(5-2)V} \times 255 = 0$$

$$\frac{(5-2)V}{(5-2)V} \times 255 = 255$$



Hands-on Exercises—I

Digital vs. analog	Basic Analog and Digital (Chapter 1)
RCTIME	BASIC Stamp Syntax and Reference Manual 2.2 (p363—p368)
Potentiometer	What's a Microcontroller? (Chapter 5 except activity#4)
Bit Crunching	Basic Analog and Digital (Chapter 2)
555 Timer	Basic Analog and Digital (Chapter 6)
Photoresistor	What's a Microcontroller? (Chapter 7 except activity#4)
ADC	Basic Analog and Digital (Chapter 3) StampWorks Manual (Experiment #28)
Resistive Ladder D2A	Basic Analog and Digital (Chapter 4)