Fall 2023

School of Mechanical Engineering
College of Engineering
University of Tehran

Mechatronics Lab Manual

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SESSION #2

Digital I/O - Transistors - ADC

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Session Objectives

- Introduction to Analog to Digital Converter (ADC)
- Introduction to Transistors and simple experiments on how they actually work

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Introduction to TA

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1. Digital I/O

1.1. Digital Output

A digital output allows the microcontroller's program to control a pin's voltage. If the program instructs the pin to be HIGH, the output pin will have a HIGH voltage level (higher than 2.7V in 5V TTL). If the program instructs the pin to be LOW, the output pin will have a LOW voltage level (lower than 0.4V in 5V TTL).

1.2. Digital Input

A digital input detects a voltage level based on the logic used. In 5V TTL, if the voltage is higher than 2V, the microcontroller will detect the digital input as HIGH. If the voltage is lower than 0.8V, the microcontroller will detect the digital input as LOW.

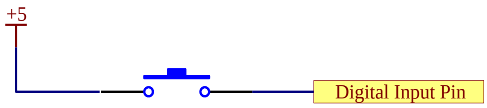

Figure 1: Pushbutton circuit diagram

A very simple application of digital input is to know when a pushbutton is pushed and do something in that event. The simplest circuit to use here is to connect one side of the pushbutton to either GND or 5V and the other side of the pushbutton to a digital input pin. Fig. 1 shows the corresponding circuit diagram.

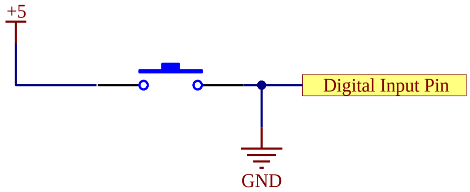

Figure 2: Shorted pushbutton circuit diagram

In this circuit, when the button is pushed, the digital input pin will be shorted to 5V hence having a HIGH logical state. The problem arises when the button is not pushed. In that case, the digital input pin is neither connected to 5V nor connected to GND resulting in a floating state. The microcontroller will read arbitrary logic levels. In order to fix the issue, one can connect the digital input pin directly to GND (Fig. 2) so when the button is not pushed, the digital input pin will have a LOW state but when the button is pushed, the circuit is shorted and 5V will be connected to GND resulting in drawing a huge current and probably damaging the microcontroller.

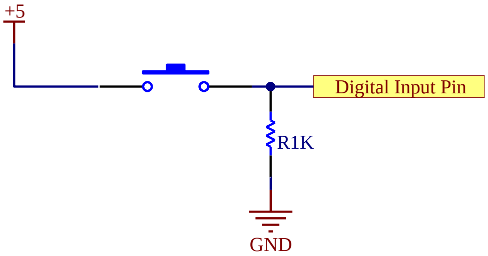

Figure 3:Pull-down resistor circuit diagram

To limit the drawn current when the button is pushed, a resistor can be used. Fig. 3 shows the corresponding circuit diagram.

The resistor used in Fig. 3 is called a pull-down resistor. It pulls down the digital input pin's level when the button is not pushed and won't let it float. The same concept can be implemented when connecting the pushbutton to a GND. Fig. 19 shows the corresponding circuit diagram.

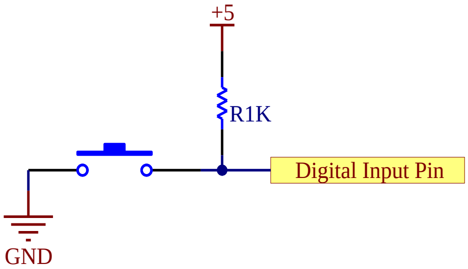

Figure 4: Pull-up resistor circuit diagram

The resistor used in Fig. 4 is called a pull-up resistor. It pulls up the digital input pin's level when the button is not pushed and won't let it float.

2. Analog to Digital Converter

An analog-to-digital converter (ADC, A/D, or A-to-D) is a system that converts a continuous-time and continuous-amplitude analog signal to a discrete-time and discrete-amplitude digital signal. The conversion involves quantization of the input, so it necessarily introduces a small amount of error. Furthermore, instead of continuously performing the conversion, an ADC does the conversion periodically, sampling the input, and limiting the allowable bandwidth of the input signal. The ADC range is the maximum and minimum allowable input voltage.

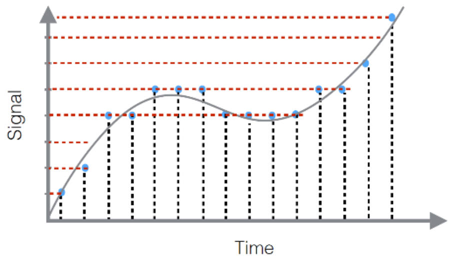

Figure 5: Analog vs Digital signal

2.1. Resolution

The resolution of the converter indicates the number of different, discrete, values it can produce over the allowed range of analog input values. In other words, The ADC resolution is defined as the smallest incremental voltage that can be recognized. The input samples are usually stored electronically in binary form within the ADC, so the resolution is generally expressed as the audio bit depth. In consequence, the number of discrete values available is usually a power of two. For example, an ADC with a range of 0-5V and a resolution of 8 bits can encode an analog input to one in 256 different levels ($2^8 = 256$), each representing a voltage level with 0 representing 0V and 255 representing 5V.

2.2. Sampling Rate

An analog signal is continuous in time, and it is necessary to convert this to a flow of digital values. It is therefore required to define the rate at which new digital values are sampled from the analog signal. The rate of new values is called the sampling rate or sampling frequency of the converter. A continuously varying bandlimited signal can be sampled, and then the original signal can be reproduced from the discrete-time values by a reconstruction filter. The Nyquist–Shannon sampling theorem implies that a faithful reproduction of the original signal is only possible if the sampling rate is higher than twice the signal's highest frequency.

2.3. Sample and hold

Since a practical ADC cannot make an instantaneous conversion, the input value must be held constant during the time the converter performs a conversion (called the conversion time). An input circuit called a sample and hold performs this task—in most cases, by using a capacitor to store the analog voltage at the input and using an electronic switch or gate to disconnect the capacitor from the input. Many ADC integrated circuits include the sample and hold subsystem internally. Fig. 6 shows a simple sample and hold circuit diagram.

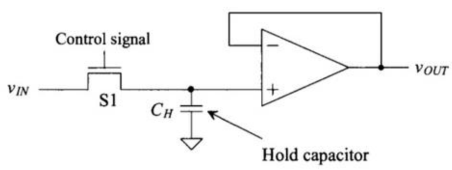

Figure 6: sample and hold circuit

2.4. ADC Channels

The number of ADC channels is the number of inputs it can select from. It means there are several pins connected to a MUX (multiplexer) that feed into the ADC, and when the ADC is called, the channel to be read from must be specified. Fig. 7 shows a block diagram of a 4-channel ADC.

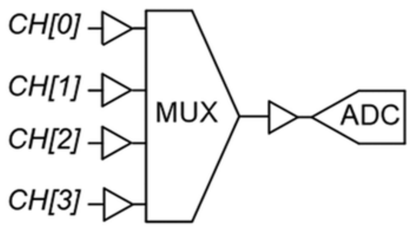

Figure 7: Block diagram of a 4-channel ADC

3. Transistors

Transistors are one of the basic elements that play a key role in today's electronics and are responsible for many of the advances in technology during the 3rd industrial revolution. This Semiconductor element is used in order to switch a part of the circuit and can amplify and regulate the current flow. One of the most common types of transistors are BJTs or Bipolar Junction Transistors. Although these transistors might have different packaging, the structure is the same.

A BJT has 3 Terminals, Base, Collector, and Emitter, as depicted in Fig. 8. These types of transistors include NPN & PNP types, which both consist of two P-N junctions in their structure.

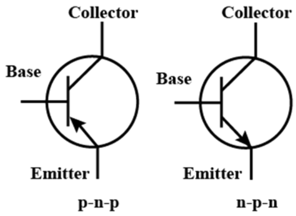

Figure 8: transistors

As shown in Fig. 9, each transistor has two junctions, the base-collector junction and the base-emitter junction. In the NPN type with a current flow to the base, a current flows from the collector to the emitter. The PNP type is just the opposite. Current flows from the emitter to the collector, and in order for that to happen, a current should be drawn from the base.

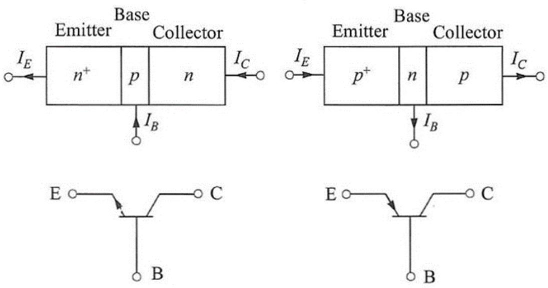

Figure 9: structure of transistors

In order to understand different regions while a transistor operates under different conditions the $I_C - V_{CE}$ diagram is shown in Fig. 10. This diagram illustrates the relation between the collector current (I_c) and the collector emitter voltage (V_{CE}) for different base currents (I_b). There are four main regions in this diagram.

- The breakdown region is further than the maximum ratings of the transistor so it shouldn't be reached.
- The cutoff region is when no current flows (ideally) and the transistor is closed.
- The active region is where the transistor should operate. Here, the relation between I_b and I_c is ideally linear and $\frac{I_c}{I_b} = \beta$, which is the transistor gain.
- If the saturation region is reached, then I_c will not increase further with the increase of I_b. This region is optimal if the transistor is going to be only used as a switch.

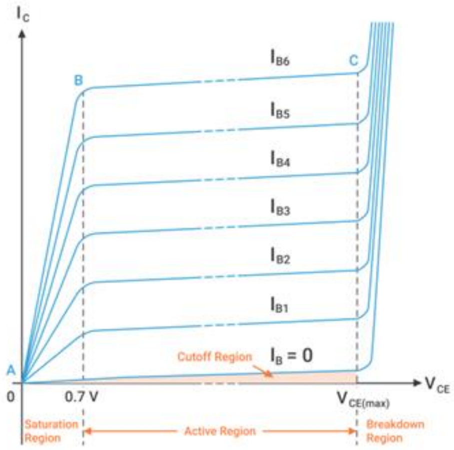

Figure 10: I_C vs V_{CE} for transistors

A Transistor has different characteristics which can be found in the datasheet of the part.

4. Experiment 1

Using transistors, signals can be amplified to switch a load such as LEDs. The general circuit is shown below.

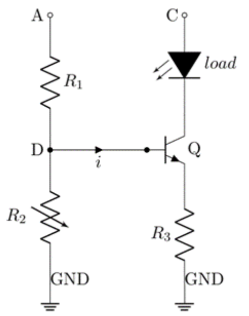

Figure 11: circuit for LED light control

Using KVL and KCL equations and the transistor values from the datasheet, this values for this circuit can be determined. The equations are written below.

$$V_1 - i_p R_p - V_{BE} - i_E R_E = 0 \qquad i_p = i_B + i_v$$
$$V_2 - V_{Load} n - V_{CE} - i_E R_E = 0 \qquad i_B + i_C = i_E$$
$$V_1 - R_p i_p - i_v R_v = 0$$

Transistor Characteristics for a BD137 NPN BJT are:

$$V_{CE\ (saturation)} = 500mV$$
$$V_{BE} = 1V$$
$$\beta = 80$$

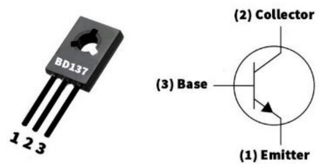

Figure 12: BD137 pinout

Finally, the values can be chosen as the circuit below. R_2 is a variable resistor (such as a potentiometer). Changing its resistance will change the base current therefore changing how the transistor behaves. Increasing its value will result in more current flowing to the base, which ultimately leads to transistor saturation. In the saturation region, the voltage drop across the collector and emitter becomes minimum. After saturation point, increasing the base current will no longer increase the collector current as the maximum gain (beta) has been reached.

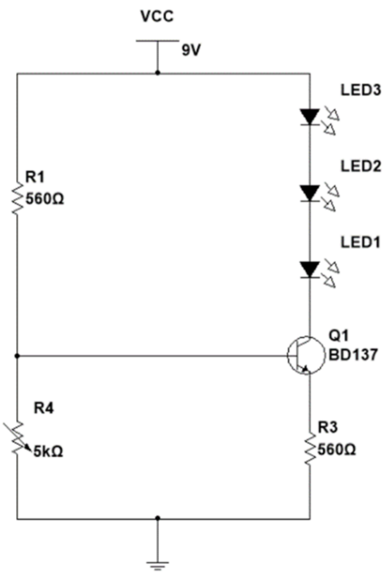

Figure 13: experiment circuit

4.1. Task

Using the screw on the potentiometer, increase the resistance and report what happens. Report the saturation and cutoff values for R_2 and V_{CE} in the table below.

Table 1-cutoff and saturation values for R_2 and V_{CE}

Region / Values	R_2 (Ohms)	V_{CE} (Volts)
Cutoff		
Saturation		

5. Experiment 2

A photoresistor can be used instead of the potentiometer of the previous circuit to control the transistor base current. Besides, using a microcontroller that receives the voltage signal from the divider part of the circuit, we can output an appropriate voltage signal to the base of the transistor in order to switch the transistor.

The circuit is shown below.

Figure 14: Two separate circuits for LED light control using Arduino

Using a photoresistor (Light Dependent Resistor or LDR), an automatic light switch can be designed to turn on the LEDs in dark places and turn them off if there is enough light available.

The photoresistor's resistance (R_v) will decrease with brightness and increase with darkness, so:

- In a bright environment R_v is low so V_D will decrease. the transistor **closes**.
- In a dark environment R_v is high so so V_D will increase. the transistor **opens**.

✓ Please note that since a transistor can be switched on and off in high speeds, a PWM signal can also be given to the base terminal.

5.1. Task

Write a code that receives the input signal from the photoresistor, processes it and then outputs a corresponding signal to the transistor turning on or off the LEDs. The detailed circuit is as shown.

Then, change the code so the brightness of the LED changes with respect to the input signal from the photoresistor. Map the ADC's full range to a PWM signal from 0 to 5 Volts. Is the transistor in saturation when 5 Volts is applied to the base?

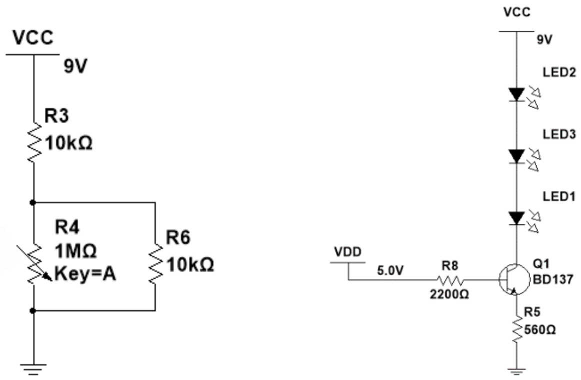

Figure 15: experiment circuit