Lab #0 Analog-to-Digital Converter

A. Sample

Bench #17

EECE.0000 Circuits I, II; Electronics I, II

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I. SUMMARY

This document reports assembly and operation of a basic ADC (analog-to-digital converter) accompanied with some observations made during the process. Some functional improvements to the circuit were suggested as well. ADCs change continuous analog signals into discrete digital signals for the ease of their processing by a computer or a microcontroller. In this laboratory work, 0-5V DC input signal was converted into hexadecimal value that was displayed using an LED (light emitting diode) graph bar. Additionally, a simple S/H (sample and hold) circuit was examined, as well as overall effect of clock and input signal frequency studied.

II. EQUIPMENT

Table I introduces the equipment used in this laboratory procedure accompanied by their make, model, and serial number. Table II lists the components used, their name codes, or characteristic values.

Table 1. Equipment Used

Equipment Type	Details	
• Oscilloscope	*Make:*	Agilent Technologies
	Model:	DSO-X 2004A
	Serial Number:	MY52161212
• Digital Multimeter	*Make:*	Keithley
	Model:	2110 5 ½ Digital Multimeter
	Serial Number:	8001860
• DC Power Supply	*Make:*	Gw INSTEK
	Model:	GPD-3303S
	Serial Number:	EM823353
• Breadboard • Bench "Shoebox" with the connector cables, adapters, clips, and other items	N/A	

Table 2. Components Used

Component Type	Quantity	Details
8 bit μP Compatible Converter	1	National Semiconductor ADC0804
S&H microchip	1	LF398
Capacitor	1	100 pF
Capacitor	1	150 pF
Capacitor (Tantalum)	1	10 μF
(Tantalum)	2	0.1 μF
Resistor	1	10 kΩ
Resistors	8	1.3 kΩ
LEDs (LED Bar Graph)	8	Red HDSP-4820

III. INTRODUCTION

There are two types of electronic signals in the time domain: continuous and discrete. Continuous (also called "analog") signals are very common in nature, however the computers and microcontrollers can only process information digitally, that is - in discrete chunks. Thus, in order to be able to record, process, and output a signal using microcontrollers, the analog signal from a sensor, microphone, or potentiometer has to be converted into digital. This is done using an Analog-to-Digital Converter (ADC), while the reverse is done by Digital-to-Analog Converter (DAC).

ADCs have two crucial parameters: resolution and frequency. Resolution parameter is easy to understand because it is similar to the understanding of the pixel-resolution of a digital screen – the more pixels one has the higher the definition of the picture. Similarly, the more bits the ADC has the higher precision of approximation is achieved; 3 bits give 8 steps (=2^3) and 8 bits give 256 steps (=2^8). Frequency of ADC is how often the converter samples the analog signal. If it is not often enough, then the digital approximation of the analog signal will not be accurate enough. This phenomenon is examined using a sample-and-hold circuit.

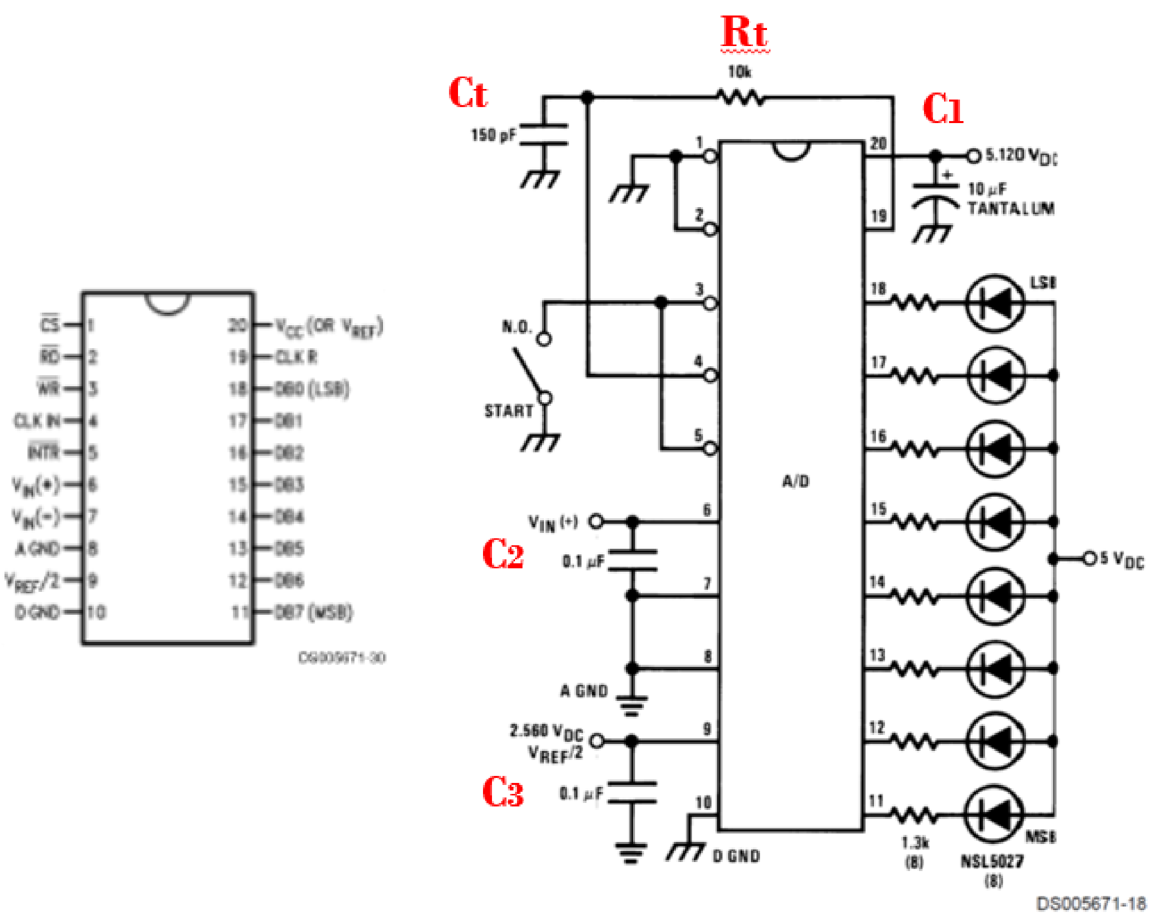
This document reports the examination of an ADC based on 8-bit National Semiconductor ADC0804 microchip. The corresponding voltage step is then calculated using the following formula:

$$V_{step} = \frac{V_{max-}V_{min}}{256} \tag{1}$$

This chip converted a DC signal into hexadecimal code that was outputted using an LED bar. The hex code was then decoded by the student to compare it with the input and verify the proper operation of the circuit. The effect of the capacitor value on a clock, as well as the effect of the frequency of the code on the operation of the ADC were examined.

IV. CIRCUIT DESCRIPTION

Figure 1 illustrates the ADC circuit used in this lab as well as the pin description of the chip. The internal structure of the clock circuit of the microchip is shown in Figure 2.



(a) (b)

Figure 1. a) Pin description of the ADC0804 microchip; b) ADC circuit [1].

Grounding pins 1 and 2 ensures the operation of the microchip in a free-run mode as opposed to chip select mode that is used in more complex electronic systems for optimization. Pins 5 and 3 are shorted for the internal interrupt control of the write function; they are also connected to a physical button for hardware interrupt by the operator. Pins 11-18 are connected to LED in order to display the hex-encoded digital signal of an analog input. There are resistors in series with LEDs in order to control the amount controllers through the diodes and not burn them out. Additionally, there are coupling capacitors, C1, C2, and C3, that are necessary to stabilize the input signal, output, and power source voltage fluctuations. Last but not the least are resistor, Rt, and capacitor, Ct – if one refers to Figure 2, one can conclude that the values of the resistor and capacitor define the frequency of the Schmitt trigger oscillator circuit. The frequency of this circuit is calculated using this formula:

$$f = \frac{1}{1.1RC} \tag{2}$$

Note that the digital output of "0" on any of the pins 11-18 will keep an LED on due to a voltage drop across the diode. It would be more intuitive if "0" on the pin output was associated with "0" state of a bit (LED). This can be achieved by using eight BJTs as switches since we do not expect operation at very high frequencies and want relatively high gain. Base contacts of the BJTs can be connected to the pin outputs, while emitter and collector contacts are connected in the 5V-resistor-LED-ground branch with the collector contact being grounded. This suggestion is discussed in more detail in the Discussion section.

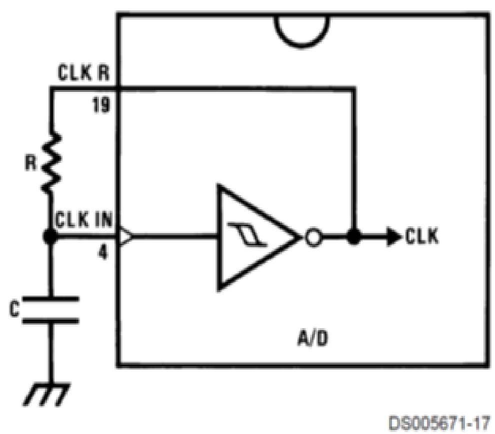


Figure 2. The structure of the microchip clock circuit [1].

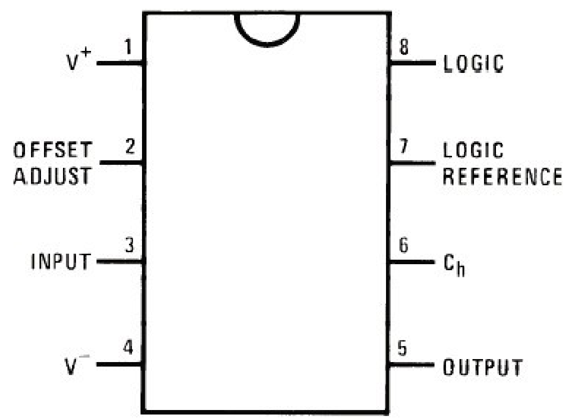


Figure 3. Pin description of the LF398 sample and hold circuit [2].

Figure 3 lays out the pin diagram of LF398 S&H circuit. Pins 1 and 4 are connected to +15V and -15V correspondingly, pin 2 was left floating, and pin 7 was grounded. Waveform generator was connected to the pin 3, pin 5 was connected to pin 6 of ADC, pin 6 of LF398 was grounded through a 100pF capacitor, and pin 8 was connected to pin 3 of the ADC microchip. Figure 4 shows the ADC circuit assembled on the breadboard.

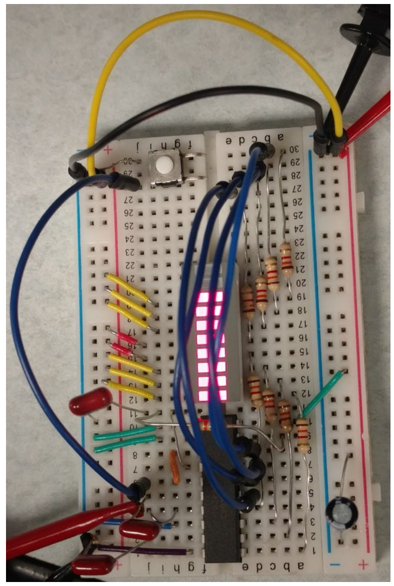


Figure 4. Breadboard layout of the ADC circuit.

V. MEASUREMENTS

After circuit from Figure 1 was assembled DC voltages from 0V to 5V were applied to the ADC input pin (pin 6) in a step of 0.5V. The LED-displayed code was recorded, deciphered using the datasheet, and tabulated in Table 3. Perfect match was observed.

Table 3. DC Input – Hex LED Output Matching

DC Input (V)	*Binary LED Output*	*Inverse Logic LED Output*	*Hexadecimal Value*	*Decoded result (V)*
0.0	1111 1111	0000 0000	00	0
0.5	1110 0110	0001 1001	19	0.5
1.0	1100 1101	0011 0010	32	1.0
1.5	1011 0100	0100 1011	4B	1.5
2.0	1001 1011	0110 0100	64	2.0
2.5	1000 0010	0111 1101	7D	2.5
3.0	0110 1001	1001 0110	96	3.0
3.5	0101 0000	1010 1111	AF	3.5
4.0	0011 0111	1100 1000	C8	4.0
4.5	0001 1110	1110 0001	E1	4.5
5.0	0000 0101	1111 1010	FA	5.0

Using Formula 1, the step voltage was calculated to be 20mV. Some sample readings of the exact voltage values when the switching of the LEDs states occur were recorded to test if the step voltage value is consistent. This data was tabulated in Table 4. Note that there is some deviation, however, it is more or less the same with the exception of the very first step, which is 7mV instead of 20mV.

Table 4. State Transitioning Voltage Values

LEDs Binary State	*Voltage when Switching Occurred (V)*
1111 1111	0.000
1111 1110	0.007
1111 1101	0.027
1111 1100	0.047
1111 1011	0.067
... [skipped]	… [skipped]
0010 0010	4.405
0010 0001	4.426
0010 0000	4.446

Using Formula 2, the frequency of the A/D clock was calculated to be around 635 kHz – this is using R=9.54kΩ (meas.) and C=150pF (nominal). However, when the scope capture of the clock cycle was taken, it showed the frequency of around 396kHz. There was a puzzling 38% discrepancy; refer to Figure 5. This was solved, however, when using an RLC-meter student measured the capacitance of the capacitor and found that it is 254pF – not 150pF. When the updated value of capacitance was used in Formula 2, then the discrepancy was much less and more realistic. Similar situation occurred with a capacitor of 100pF nominal value. All these findings are presented in Table 5.

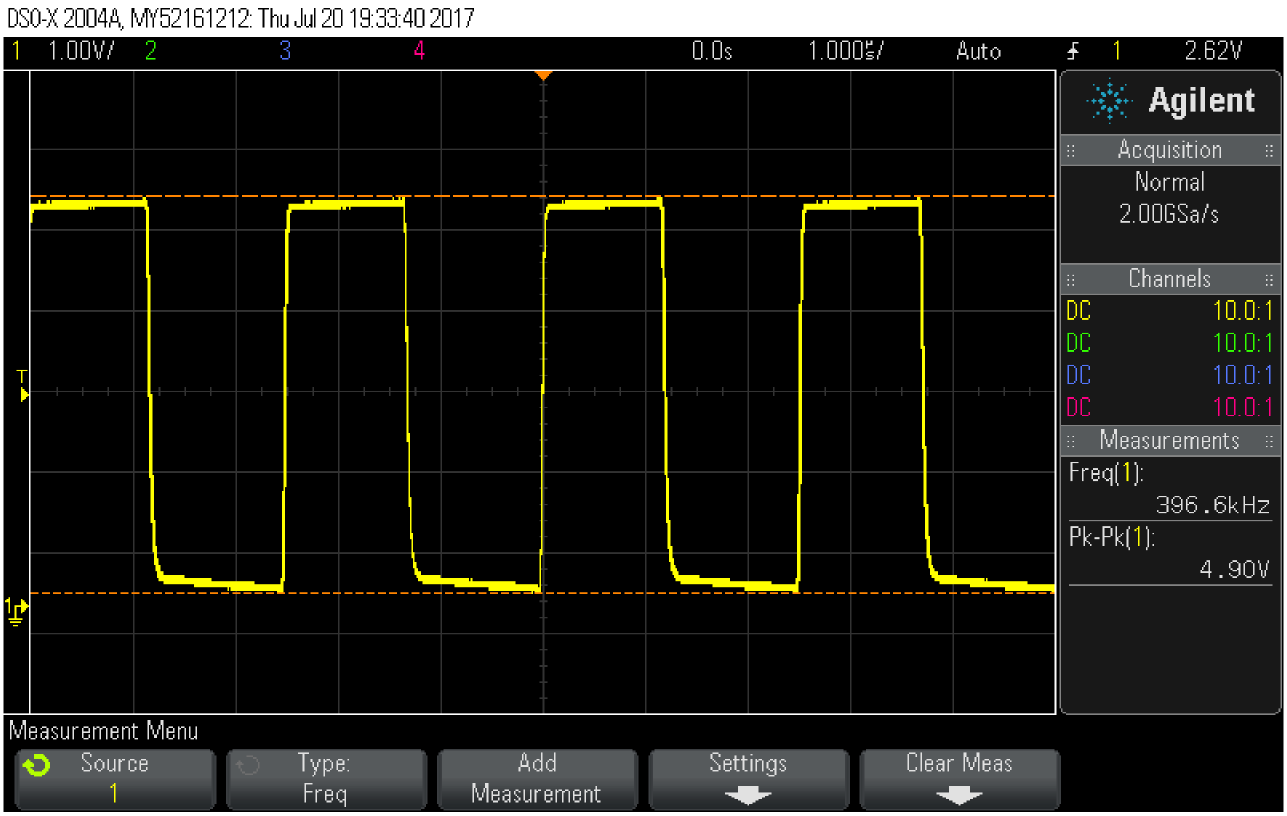


Figure 5. Clock cycle frequency measurement.

Table 5. Clock cycle frequency calculation

	i. Nominal Value	*ii. Measured Value*	*%-error i&ii*	*iii. Frequency calculated using nominal capacitance*	*iv. Frequency calculated using measured capacitance*	*v. Frequency measured*	*%-error iii&v*	*%-error iv&v*
C1	150pF	254pF	69%	635 kHz	381 kHz	396 kHz	38%	4%
C2	100pF	200pF	100%	967 kHz	476 kHz	490 kHz	49%	3%

Afterwards, a variable DC voltage was applied to the input of the A/D converter. As expected, constant-rate transitioning of LEDs was observed since the input voltage was periodically changing. During the laboratory procedure, it was mistakenly assumed that the frequency at which A/D will not be able to process the data is the frequency at which the LEDs will appear to stop changing their state. This occurred at 35Hz, however it shows the limitations of a human eye and perception and not the frequency when the converter will not be able to process the data. However, the original question is somewhat ambiguous since the converter will be able to process the input signal of any frequency, but the values are going to be useless after a certain point because they are not the accurate representation of the original signal.

The following information was requested in the lab handout and was found in the ADC0804 datasheet. Conversion time for the A/D converter at 640kHz is around 109us [1]. However, we know that the real frequency of the oscillator is 396kHz – thus, if the proportions are the same, the conversion time of the converter at 396kHz should be around 176us. Supply current of the microchip at 640kHz clock frequency is documented to be around 1.9mA, and the chip can have 1460kHz max operational frequency [1].

Figures 6 and 7 show the output waveforms of the sample-and-hold-circuit at 8kHz and 13kHz input variable DC-signal. Note the significant distortion on the latter figure.

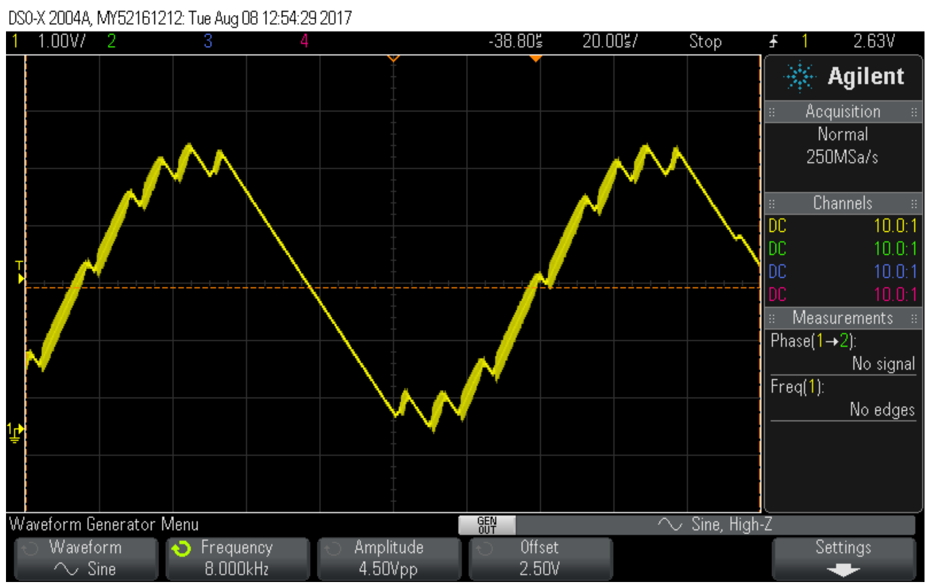


Figure 6. Sample-and-Hold circuit output of the 8kHz sine wave.

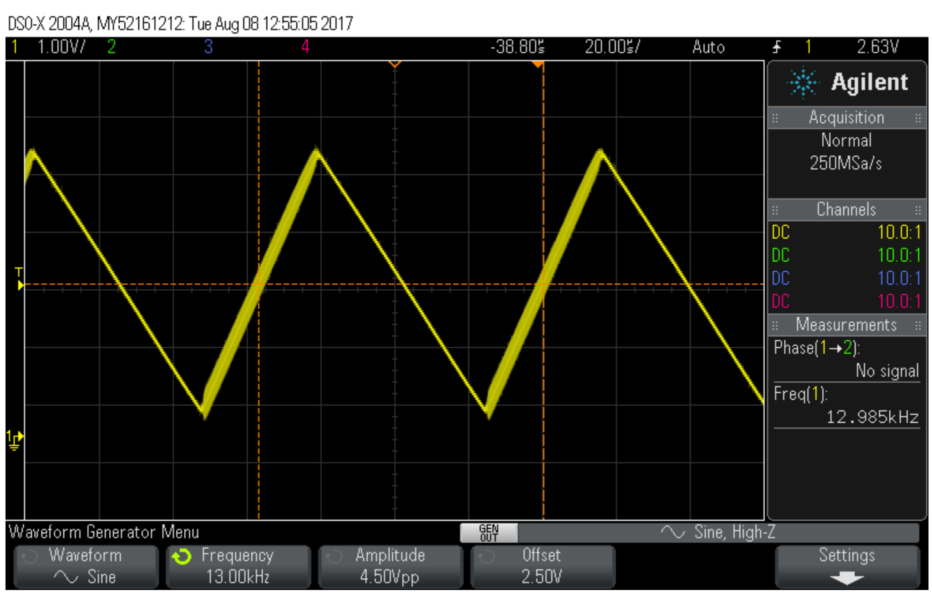


Figure 7. Sample-and-Hold circuit output of the 13kHz sine wave.

VI. DISCUSSION

Data gathered in Table 5 shows how important it is to use measured values whenever possible. The real capacitance values were 70 to 100% off from the nominal values, even though the “J” tolerance marking on the ceramic capacitor means there should only be 5% deviation. The clock waveform measurements are only 3-4% different from the measured values and 40-50% different from theoretical. This perplexing tendency of small ceramic capacitance values being so off from nominal should be further examined and considered with great care in further experiments.

Table 3 demonstrated that the converter showed the correct input voltage value at the chosen voltages throughout the permissible range. The step voltage value of 20mV might be considered not small enough, but should be acceptable for many applications that do not require high precision (e.g. battery charge level display). The student would also not recommend using this particular chip for somewhat precise applications because according to the datasheet it has an allowable error of $\pm 1LSB$ (19.53mV) [1], which might be considered pretty high.

It was already stated that the converter shows the values in inverse logic, which might be counterintuitive for most of the applications. This can be fixed by adding a BJT as a switch in every output branch as shown in Figure 8. Given that the BJT that will be used is 2N3903 with DC gain of around 150 [3], and 10 segment LED bar graph is Red HDSC-4820 which according to its datasheet has the forward bias voltage drop of 1.6V [4], the given resistor values should be chosen. Calculations that derived these values are provided in the Appendix A. The drawback of this circuit is that the number of components is significantly increased. This might have been a problem for a mass-produced product, but if the intuitive use of the device is the priority then this improvement is worth it.

Sample and Hold circuit showed the expected result, however there are some uncertainties. First, from the datasheet, it seems that the acquisition frequency with 100pF capacitor should be less more than 250kHz [2]. In contrast, simple examination of Figure 6 (8-9 acquisitions per 7kHz cycle) tells that the real acquisition frequency is around 60kHz. Second, the signal is already significantly distorted at 13kHz, which corresponds to 77us period. However, again from the datasheet, the acquisition time of the S&H circuit should be at least 4us [2], and thus it should make around 20 acquisitions per cycle, which is obviously not the case. This can be partially explained by the early findings about the discrepancies of nominal and measured capacitance values, but that alone cannot be the reason; there might be an additional chip nominal and actual performance data discrepancy factor that is affecting the results.

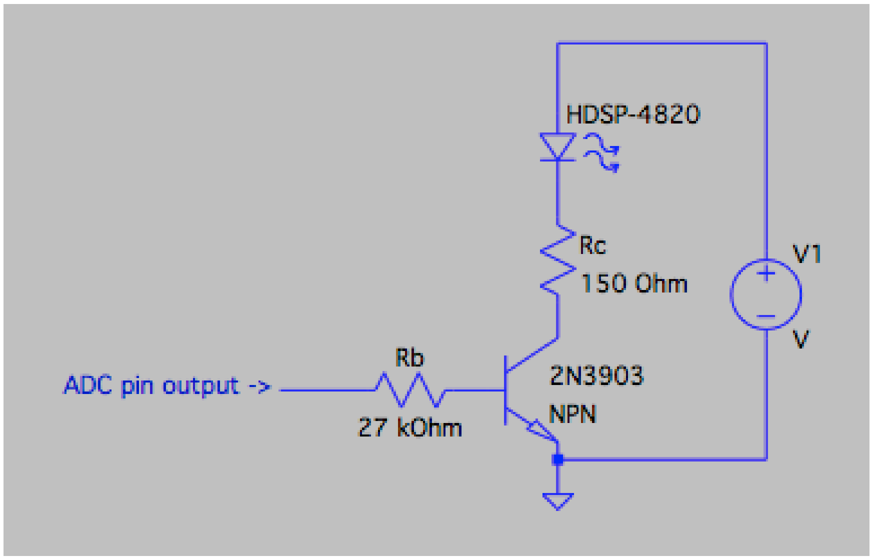


Figure 8. Suggested improvement of the LED output segment of the circuit (only one output pin shown).

VII. CONCLUSION

The operation of an A/D converter and a simple Sample-and-Hold (S&H) circuit were examined. Their outputs were evaluated with regard to theoretical expectations and it was concluded that the A/D converter circuit worked in the expected way, whereas the S&H circuit deviated from the theoretical prognosis. Additionally, A way to improve the A/D converter circuit in order to achieve easier LED output signal interpretation at a cost of increasing the number of components was suggested.

VIII. QUESTIONS

This section answers the questions encountered throughout the lab handout. Some of them were answered in the body of the document, but were copied along with their original page numbers.

c) What signal from the A/D converter will turn on the LEDs? If you want the LEDs to turn on with the opposite output of the A/D converter, how would you change the circuit? Would this be a good idea in this case? Why?

Answer (page 5): "Note that the digital output of "0" on any of the pins 11-18 will keep an LED on due to a voltage drop across the diode. It would be more intuitive if "0" on the pin output was associated with "0" state of a bit (LED). This can be achieved by using eight BJTs as switches since we do not expect operation at very high frequencies and want relatively high gain. Base contacts of the BJTs can be connected to the pin outputs, while emitter and collector contacts are connected in the 5V-resistor-LED-ground branch with the collector contact being grounded." Refer to Figure 8.

(page 9): The drawback of this circuit is that the number of components is significantly increased. This might have been a problem for a mass-produced product, but if the intuitive use of the device is the priority then this improvement is worth it.

j) At what frequency will the A/D not be able to process the data?

(page 8): During the laboratory procedure, it was mistakenly assumed that the frequency at which A/D will not be able to process the data is the frequency at which the LEDs will appear to stop changing their state. This occurred at 35Hz, however it shows the limitations of a human eye and perception and not the frequency when the converter will not be able to process the data. However, the original question is somewhat ambiguous since the converter will be able to process the input signal of any frequency, but the values are going to be useless after a certain point because they are not the accurate representation of the original signal.

k) From the data sheet find the following information:

i. What is the conversion time with the test circuit Clock frequency?

ii. Determine the supply current used in the test circuit.

iii. What is the max clock frequency that can be used?

iv. Are the resistors selected for the LEDs in the test circuit the correct value? What would be an ideal value for these resistors? Now defend the value you selected.

v. What device would you add to the test circuit to make a better A/D converter (list at least two)?

The following information was requested in the lab handout and was found in the ADC0804 datasheet [1]. Conversion time for the A/D converter at 640kHz is around 109us. However, we know that the real frequency of the oscillator is 396kHz – thus, if the proportions are the same, the conversion time of the converter at 396kHz should be around 176us. Supply current of the microchip at 640kHz clock frequency is documented to be around 1.9mA, and the chip can have 1460kHz max operational frequency [1].

The chosen resistor value only allows 2.23mA of current through the LED (assuming 4.5V output and Vf=1.6V), whereas the LED can take up to 30mA. However, there are limitations on how much current the A/D converter chip can output, thus this resistor value is acceptable as is.

I would add BJTs to output the results in more intuitive way, and I would also replace the clock resistor with a potentiometer to be able to change the frequency of converter operation.

REFERENCES

Hewlett Packard. (1997). *10-Element Bar Graph Array.* Datasheet.

National Semiconductor. (1999). *ADC0801/ADC0802/ADC0803/ADC0804/ADC0805 8-Bit μP Compatible A/D Converters.* Datasheet.

ON Semiconductor. (2012). *General Purpose Transistor.* Datasheet.

Texas Instruments. (2015). *LF198-N, LF298, LF398-N LF198A-N, LF398A-N.* Datasheet.

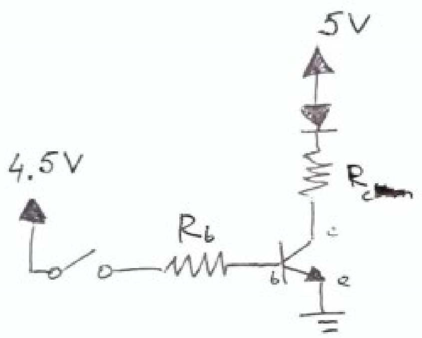
APPENDIX A. Improved Circuit Value Derivations

Figure A1 shows the derivation reasoning and process for the suggested improvements.

From datasheets:

HDSP-4820 LED
- max current per LED $I_{max} = 30\,mA$
- forward voltage per LED $V_f = 1.6\,V$

2N3903 NPN
- $V_{CEmax} = 40\,Vdc$
- $\beta \approx 150$
- $V_{CE} \approx 0.3\,V$
- $V_{BE} \approx 0.9\,V$



1) I_c should be around $20\,mA$ to power the LED

2) $I_b = \frac{I_c}{\beta} = \frac{20\,mA}{150} = 0.133\,mA$

3) $V_{be} \approx 0.9\,V$ thus the voltage drop across R_b is $3.6\,V$ with $0.133\,mA$ through it.

$$\boxed{R_b = \frac{3.6\,V}{0.133\,mA} = 27\,k\Omega}$$

(standard value)

4) V_{CE} is $0.3\,V$ and V_f is $1.6\,V$ this means that there should be a resistor across which the rest of the $3.1\,V$ drop.

$$\boxed{R_c = \frac{3.1\,V}{20\,mA} = 155\,\Omega}$$

(or $150\,\Omega$ standard)

Figure A1. Value Derivation for the Suggested Circuit.