Data Conversion and Lab (17.368)

Fall 2013

Lecture Outline

Class # 07

October 17, 2013

Dohn Bowden

Today's Lecture Outline

- Administrative
- Detailed Technical Discussions
  - Digital to Analog Conversion
- Lab
  - Lab #3
- Homework

Course Admin

Syllabus Review

Week	*Date*	*Topics*	*Lab*	*Lab Report Due*
~~1~~	~~09/05/13~~	~~Introduction/Basic Data Conversion, Course Overview, Op Amps in Data Conversion~~		
~~2~~	~~09/12/13~~	~~Op Amp Lab~~	~~1~~	
~~3~~	~~09/19/13~~	~~Sample and Hold Lecture and Lab~~	~~2~~	
~~4~~	~~09/26/13~~	~~A/D Conversion Fundamentals and Lab~~	~~3~~	~~1~~
5	10/03/13	A/D Conversion Lab Continuation	3 con't	
~~6~~	~~10/10/13~~	~~**Examination 1**~~		
7	10/17/13	D/A Conversion Fundamentals and Lab	3	
8	10/24/13	D/A Conversion Lab Continuation	4	2
9	10/31/13	Microcontroller and Sensors	4 con't	3
10	11/07/13	Microcontroller and Sensor Lab	5	
11	11/14/13	V/F and F/V Conversion Lecture	5 con't	4
12	11/21/13	**Examination 2**	Project	5
X	**11/28/13**	**No Class – Thanksgiving**		
13	12/05/13	Work on Course Project	Project	
14	12/12/13	Final Exam/Course Project Brief and Demonstration	Demo	

Exam #1

- Exams have been graded ...
  - I will pass them back when you start the lab portion of the class tonight

Detailed
Technical Discussion

References …

References

- Lecture material is covered in the text as follows ...
  - Data Conversion Handbook
    - On line version (PDF)
      - 3.1 – 3.35
    - Textbook (Hard Copy)
      - Pages 147 - 173

DAC Overview …

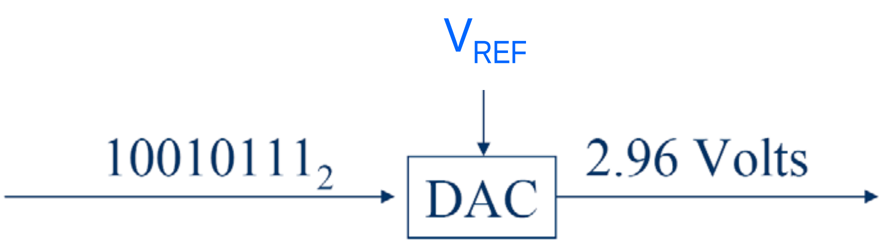
Digital to Analog Converters

- Devices with digital input and analog output

- Abbreviations ...

  – D/A converters ~~~ Digital-to-Analog (D/A) Converters
  – DAC ~~~ Digital-to-Analog Converters

- DACs are used to convert digital values in the form of a binary number into proportional analog voltages or currents



DAC Lecture Overview

- We shall consider the various architectures of DACs
- And we shall also consider the forms which the reference may take

DACs

- Although DACs are available in IC packages ...
  - We shall analyze them in a discrete form to better describe and understand how they function

DAC Example …

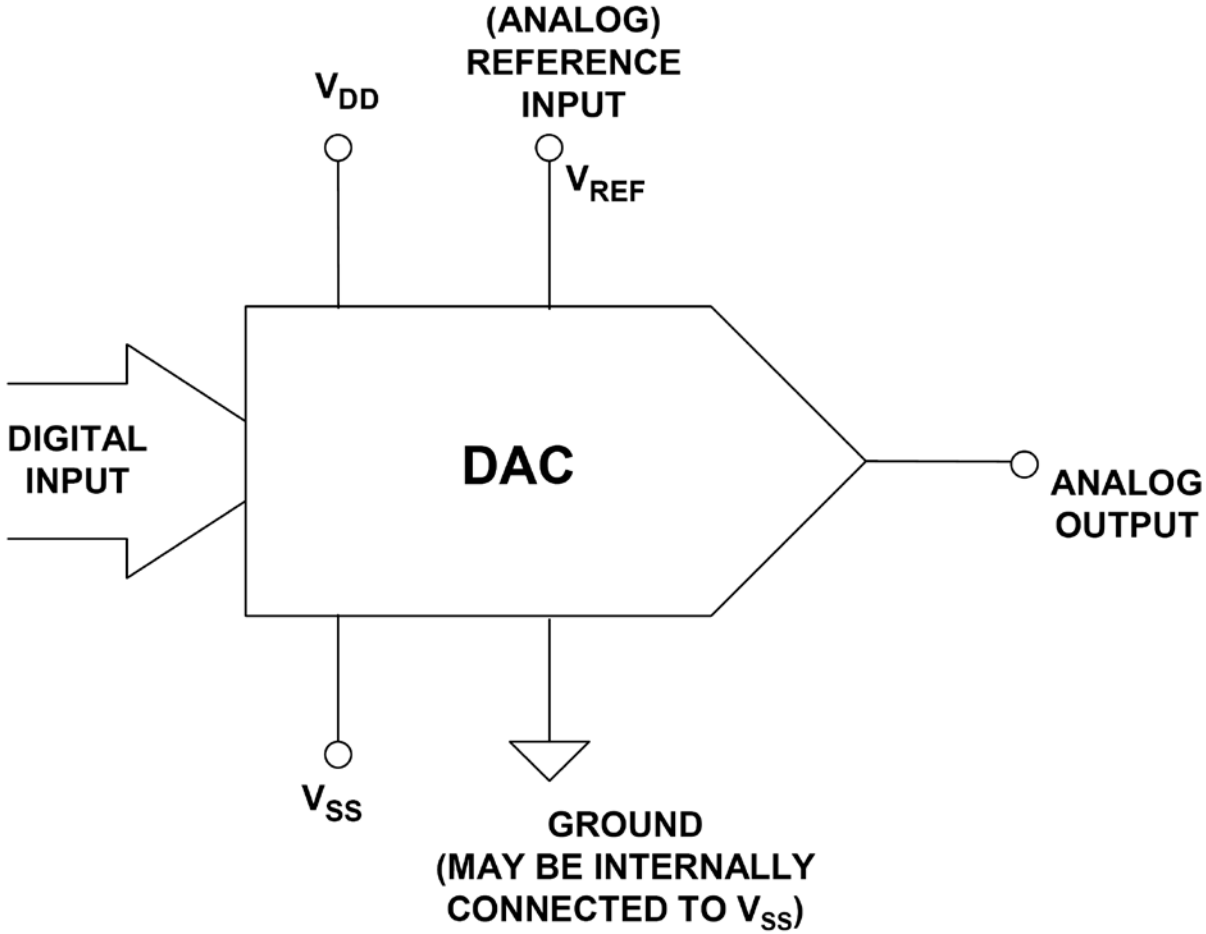
- A voice signal can be digitized for storage, processing, or transmission and then ...
  - Converted back to an analog (audio) signal to drive a speaker

DAC Reference Signal

- The analog output depends on the presence of an analog input known as the reference (V_{REF})

- The accuracy of the reference input (V_{REF}) is almost always the limiting factor on the absolute accuracy of a DAC

Basic DAC with External Reference



Digital to Analog Conversion – Output

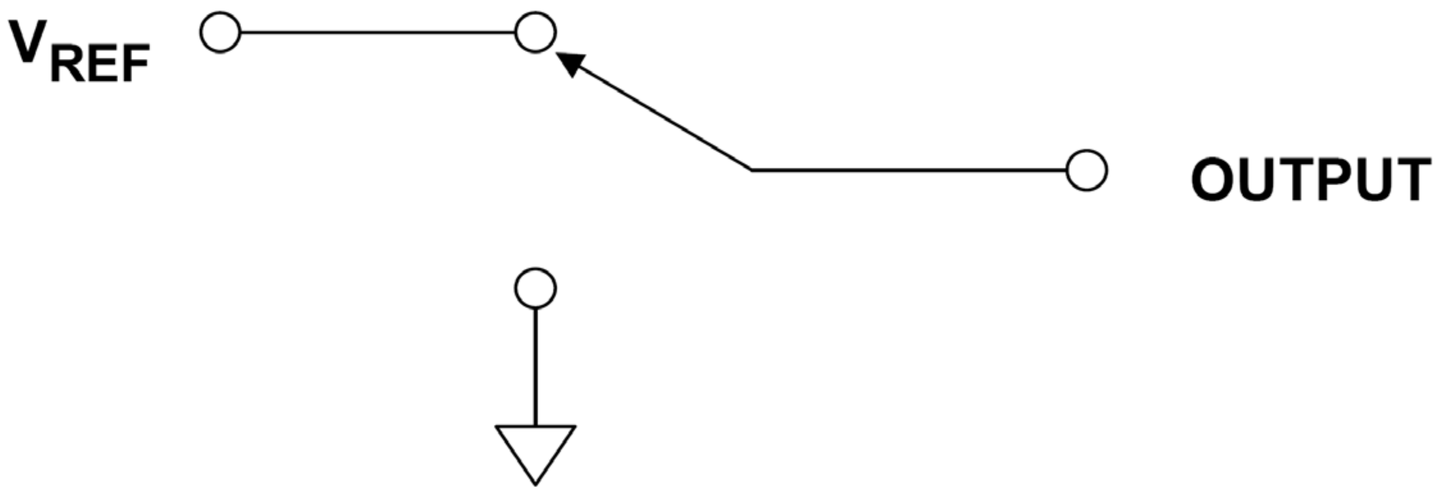
- The output of a DAC may be a voltage or a current

Basic – DAC Structures

- In the ADC lecture ... we saw that a comparator was a ...
  - ... Simple 1-Bit Analog to Digital Converter
- The equivalent DAC (a ... 1-Bit DAC) is a ***changeover switch***
  - Switching an output between ...
    - » A reference ... and ... Ground

      ... or ...
    - » Between equal positive and negative reference voltages

1-Bit DAC – Changeover Switch

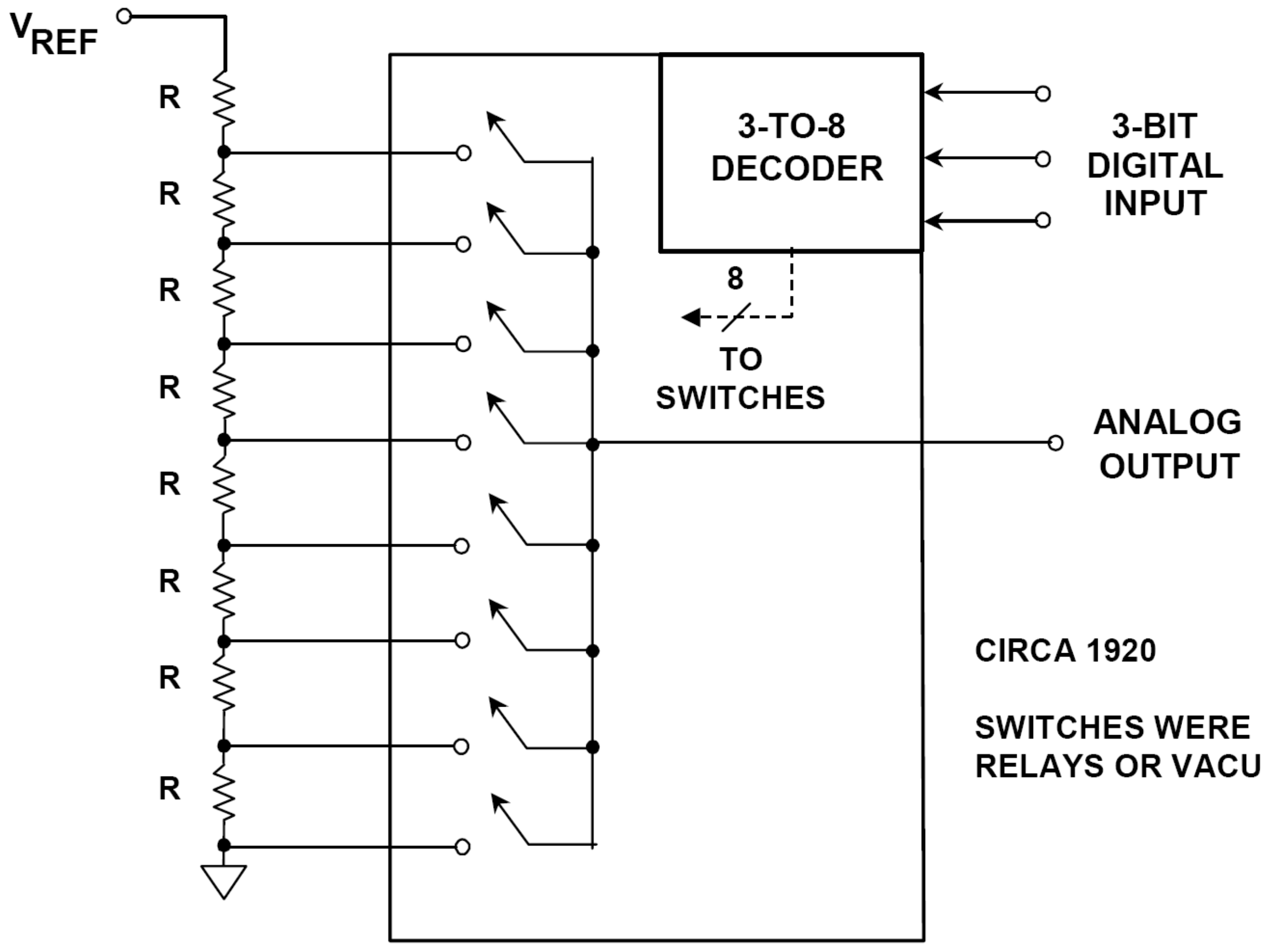


Single-Pole, Double Throw, SPDT

1-Bit Digital to Analog Converter

- Such a simple device is a component of many more complex DAC structures
- We shall go into more detail when we discuss more complex structures

The – Kelvin Divider (String DAC)



CIRCA 1920

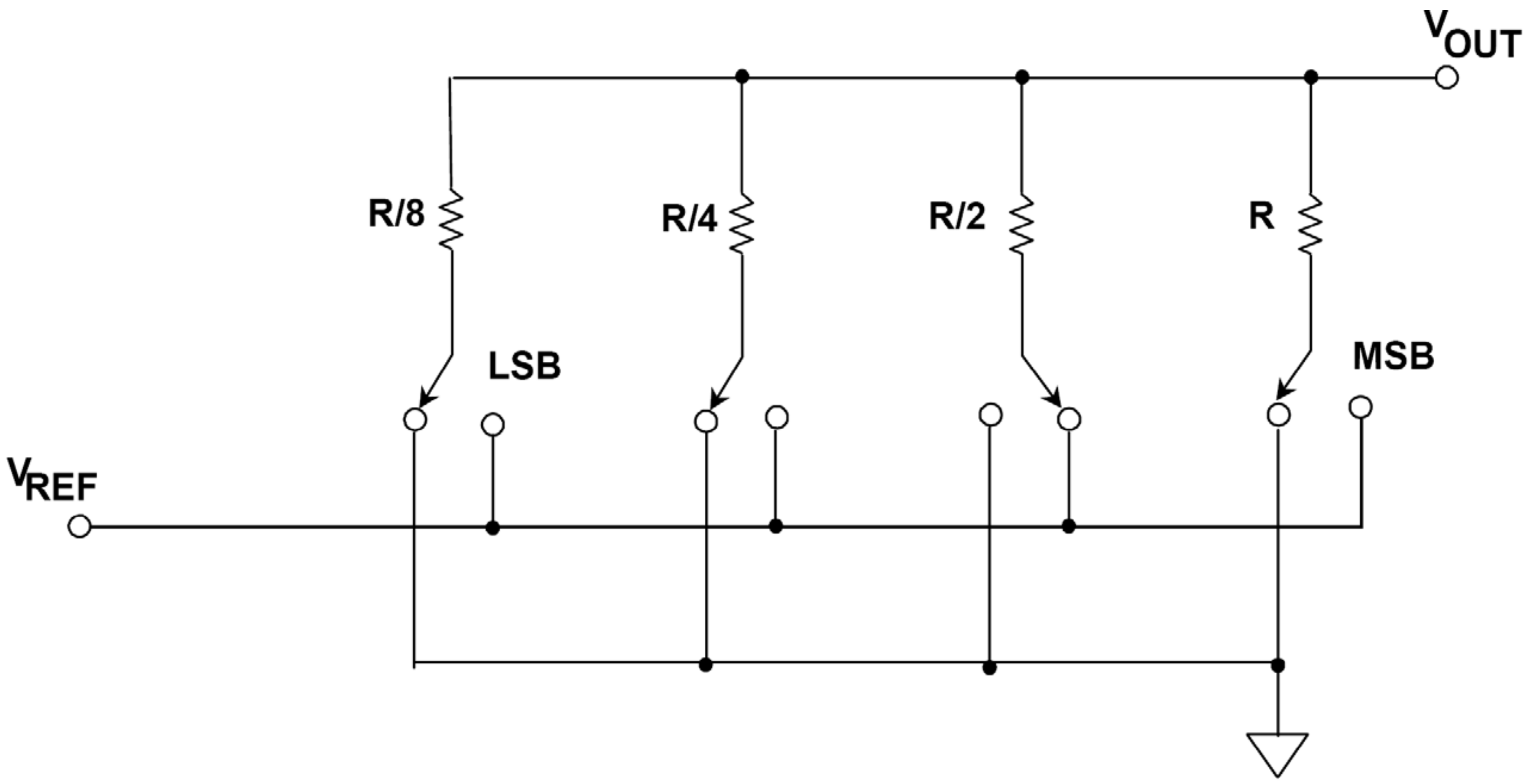
SWITCHES WERE
RELAYS OR VACUUM TUBES

The – Kelvin Divider ... or String DAC

- The simplest DAC structure of all, after the changeover switch
- An N-bit version of this DAC ... consists of
  - 2^N equal resistors in series ... and ...
  - 2^N switches
- The output is taken by closing just one of the switches
- The origins of this DAC date back to Lord Kelvin in the mid-1800s, and it was first implemented using resistors and relays, and later with vacuum tubes in the 1920s
- The major drawback of the String DAC is the large number of resistors and switches required for high resolution

Binary-Weighted DACs …

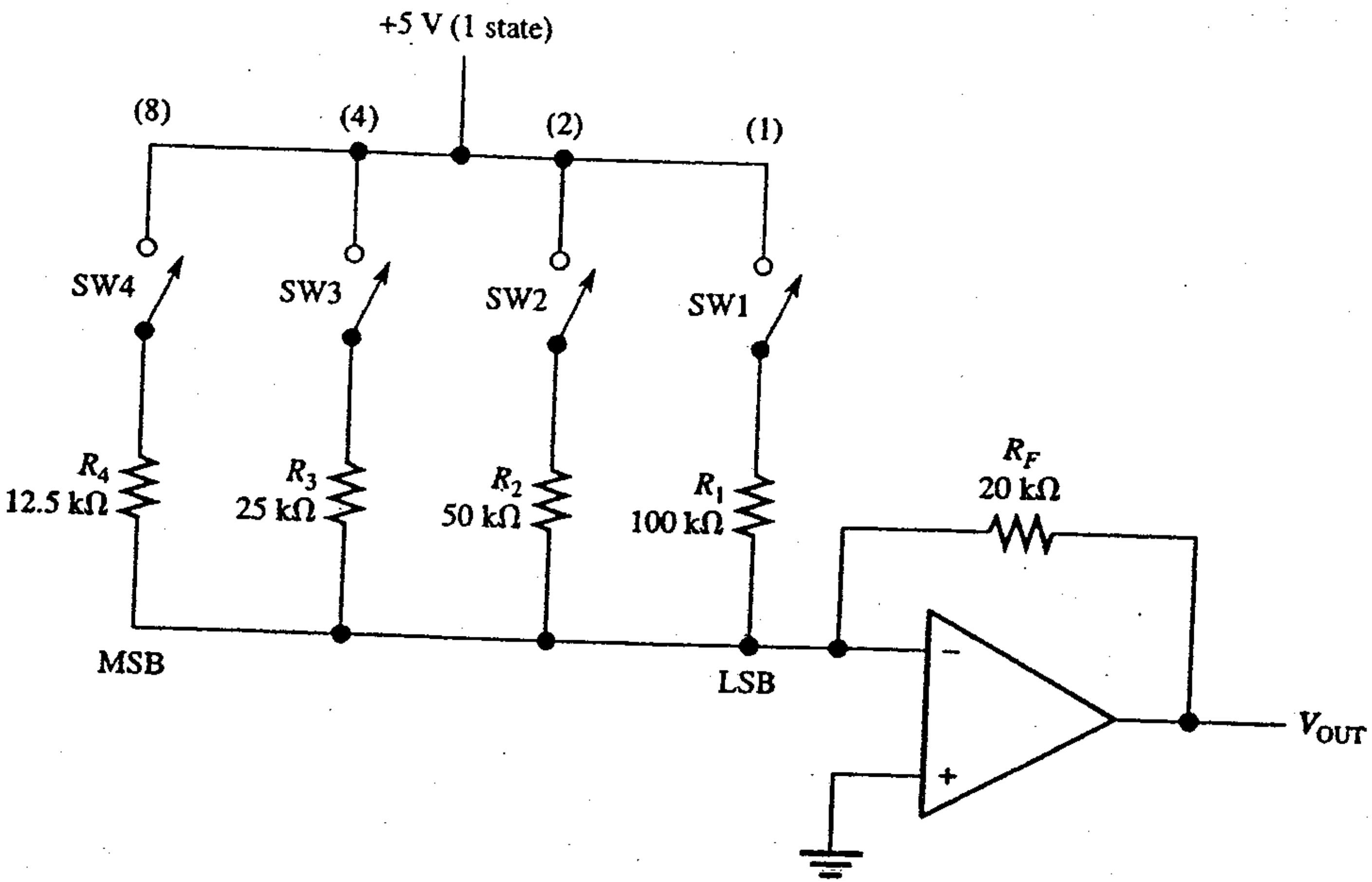
Voltage-Mode-Binary-Weighted Resistor DAC



Voltage-Mode-Binary-Weighted Resistor DAC

- Simplest textbook example of a DAC
- It's not inherently monotonic
  - A Monotonic DAC has an output that changes in the same direction (or remains constant) for each increase of the input code
- Hard to manufacture successfully at high resolutions
- The output impedance changes with the input code

4-Bit Binary-Weighted DAC



Binary-Weighted DACs

- A 4-Bit Binary-Weighted DAC is shown on the previous slide
- It consists of ...
  - A summing amplifier
  - Feedback resistor R_F
  - Four summing resistors (one for each input bit)
  - Four switches that are used to provide a 4-bit binary input
    - An open switch represents a ‘0’ state
    - A closed switch represents a ‘1’ state

Binary-Weighted DACs

- The switches correspond to the same ...
  - 8-4-2-1 weighted values of a 4-bit binary number
    - » 2^3 2^2 2^1 2^0

Binary-Weighted DACs

- The resistors are also selected with the same proportionality rule
- Since R4 is connected at the MSB input line ...
  - It will have the smallest value ...
    - So as to allow the most current going through it
      - » Hence contributing to the biggest output swing

Binary-Weighted DACs

- The next most significant bit contributes half that of the MSB, therefore ...
  - The resistor value R_3 is selected to be double of R_4
- With the same reasoning R_2 is to be double of R_3 ... and ...
- R_1 is selected to be double of R_2

Binary-Weighted DACs

- Therefore ...

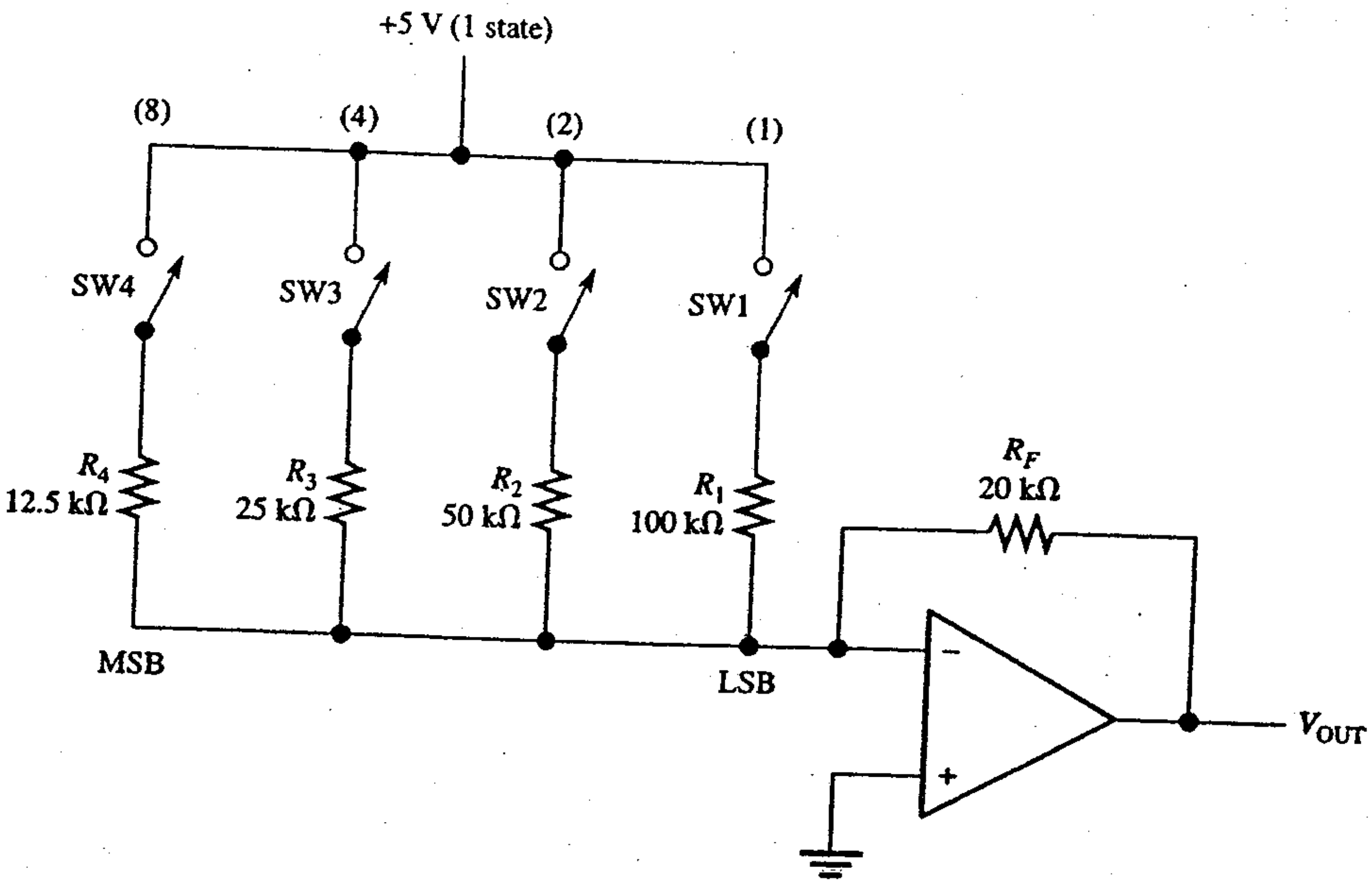
$$R_1 = 2R_2 = 4R_3 = 8R_4$$

- Selecting $R_4 = 12.5$ k

- We obtain ...

$R_3 = 25$ k	which is	$2 * R_4$
$R_2 = 50$ k	which is	$2 * R_3$
$R_1 = 100$ k	which is	$2 * R_2$

4-Bit Binary-Weighted DAC



Circuit Repeated for some additional analysis …

Binary-Weighted DACs

In this summing amplifier circuit we have ...

$$V_{OUT} = -\left(I_{R_F} * R_F\right)$$

Where

$$I_{R_F} = I_{R1} + I_{R2} + I_{R3} + I_{R4}$$

And

$$I_{R1} = \frac{V_1}{R_1} \qquad I_{R2} = \frac{V_2}{R_2} \qquad I_{R3} = \frac{V_3}{R_3} \qquad I_{R4} = \frac{V_4}{R_4}$$

Therefore ...

$$V_{OUT} = -\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \frac{V_4}{R_4}\right) * R_F$$

Binary-Weighted DACs

- Obviously, if one switch is open, the corresponding voltage is 0v

- And ... if one switch is closed, the corresponding voltage is 5v

Binary-Weighted DACs

- Assuming all switches are open ...

$$V_1 = V_2 = V_3 = V_4 = 0 \ldots volts$$

- therefore V_{OUT} = 0 volts

- Assuming all switches are closed ...

$$V_1 = V_2 = V_3 = V_4 = 5 \ldots volts$$

Binary-Weighted DACs

- What feedback resistor do we need if we want the maximum output voltage to be (-15 volts)?

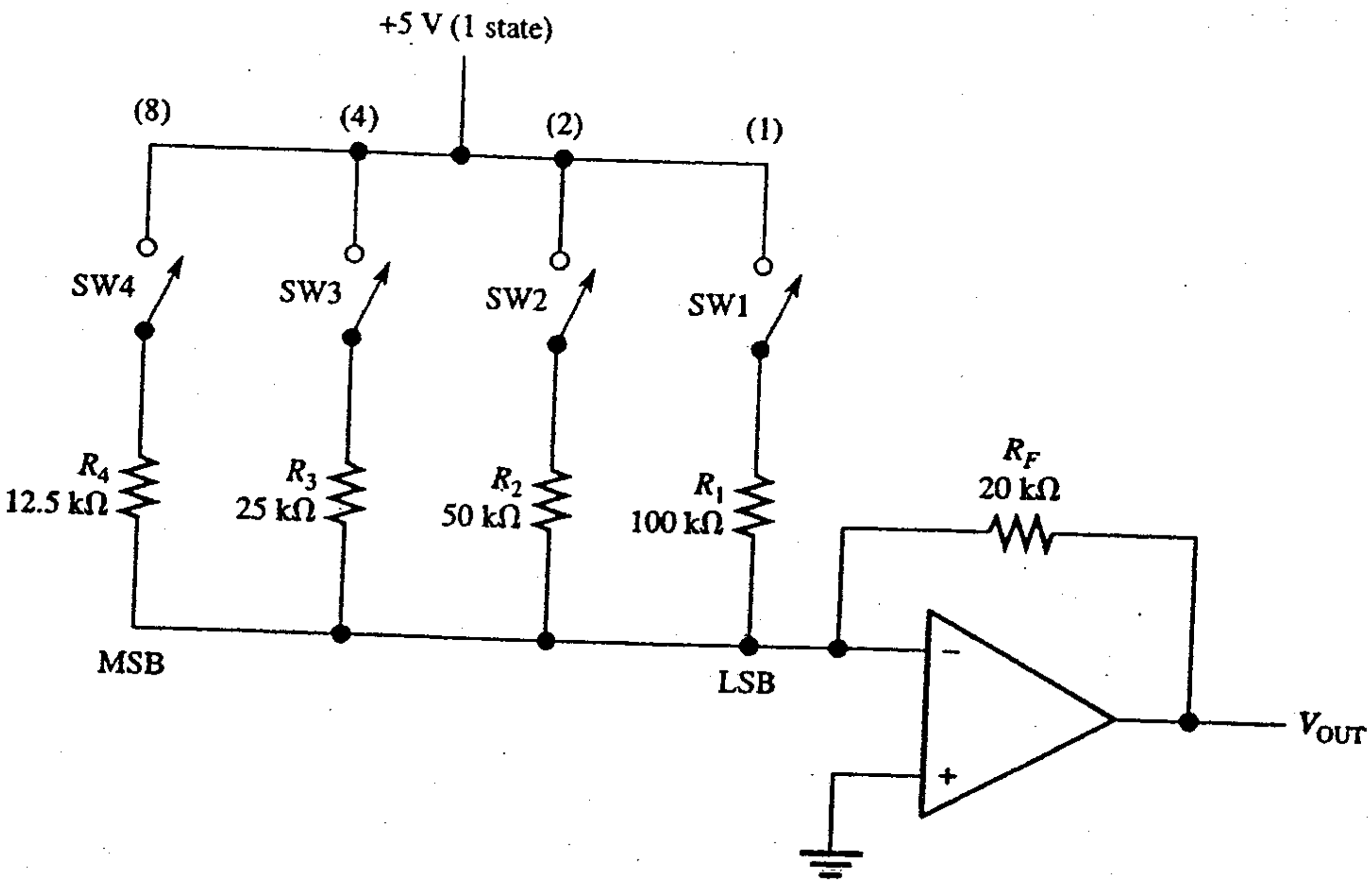
- From the prior equation ... the value of the feedback resistor is

$$-15 = -\left(\frac{5}{100} + \frac{5}{50} + \frac{5}{25} + \frac{5}{12.5}\right) * 10^{-3} * R_F \qquad 15 = \left(\frac{5 + 10 + 20 + 40}{100}\right) * 10^{-3} * R_F$$

$$15 = \left(\frac{75}{100}\right) * 10^{-3} * R_F \qquad \boxed{R_F = 20k}$$

- Having all the resistor values of the circuit, we now can look at an example ...

Example … **What will be the output voltage for a 1001 input, using the circuit below?**



See next slide …

Example … What will be the output voltage for a 1001 input, using the circuit on the prior slide?

- We would have …

$$I_{R4} = \frac{V_4}{R_4} = \frac{5}{12.5k} = 0.4mA \qquad I_{R3} = I_{R2} = 0 \qquad I_{R1} = \frac{V_1}{R_1} = \frac{5}{100K} = 0.05mA$$

Hence …

$$I_{R_F} = I_{R1} + I_{R2} + I_{R3} + I_{R4} = 0.05 + 0 + 0 + 0.4 = 0.45mA$$

Therefore …

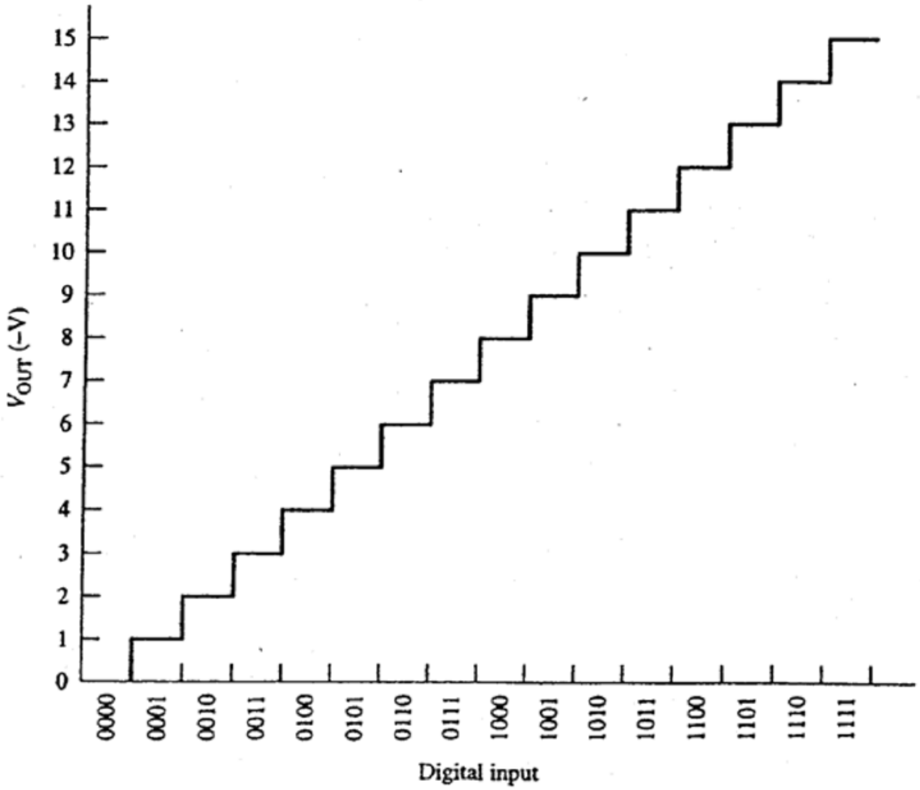
$$V_{OUT} = -\left(I_{R_F} * R_F\right) = -\left(0.45 * 10^{-3}\right) * \left(20 * 10^{-3}\right) = -9volts$$

$\boxed{V_{OUT} = -9 \text{ volts}}$

4-Bit Input Binary-Weighted D/A Converter Results

All 16 possible input combinations with the corresponding output voltage together with a plot of the analog output vs. the digital input

SW4 (8)	SW3 (4)	SW2 (2)	SW1 (1)	V_{OUT} (−V)
0	0	0	0	0
0	0	0	1	1
0	0	1	0	2
0	0	1	1	3
0	1	0	0	4
0	1	0	1	5
0	1	1	0	6
0	1	1	1	7
1	0	0	0	8
1	0	0	1	9
1	0	1	0	10
1	0	1	1	11
1	1	0	0	12
1	1	0	1	13
1	1	1	0	14
1	1	1	1	15



The actual output voltages are **negative**. The graph above actually has the magnitude (absolute value) of the output voltage

R-2R DACs …

R-2R DACs

- The next DAC architecture that we shall discuss is the R-2R
- A problem with the Binary-Weighted DAC is that it requires a large number of different value resistors ...
    - Some of which become very large

Problem with the Binary-Weighted DAC ...

- Consider the case of a 12-bit Binary-Weighted DAC ...
- You would need 12 different resistor values
- If you were to select a 12.5K for the resistor the MSB branch
- The resistor for the LSB branch would be 25.6M!

2^1=12.5K	2^2=25K	2^3=50K	2^4=100K
2^5=200K	2^6=400K	2^7=800K	2^8=1.6M
2^9=3.2M	2^{10}=6.4M	2^{11}=12.8M	2^{12}=25.6M

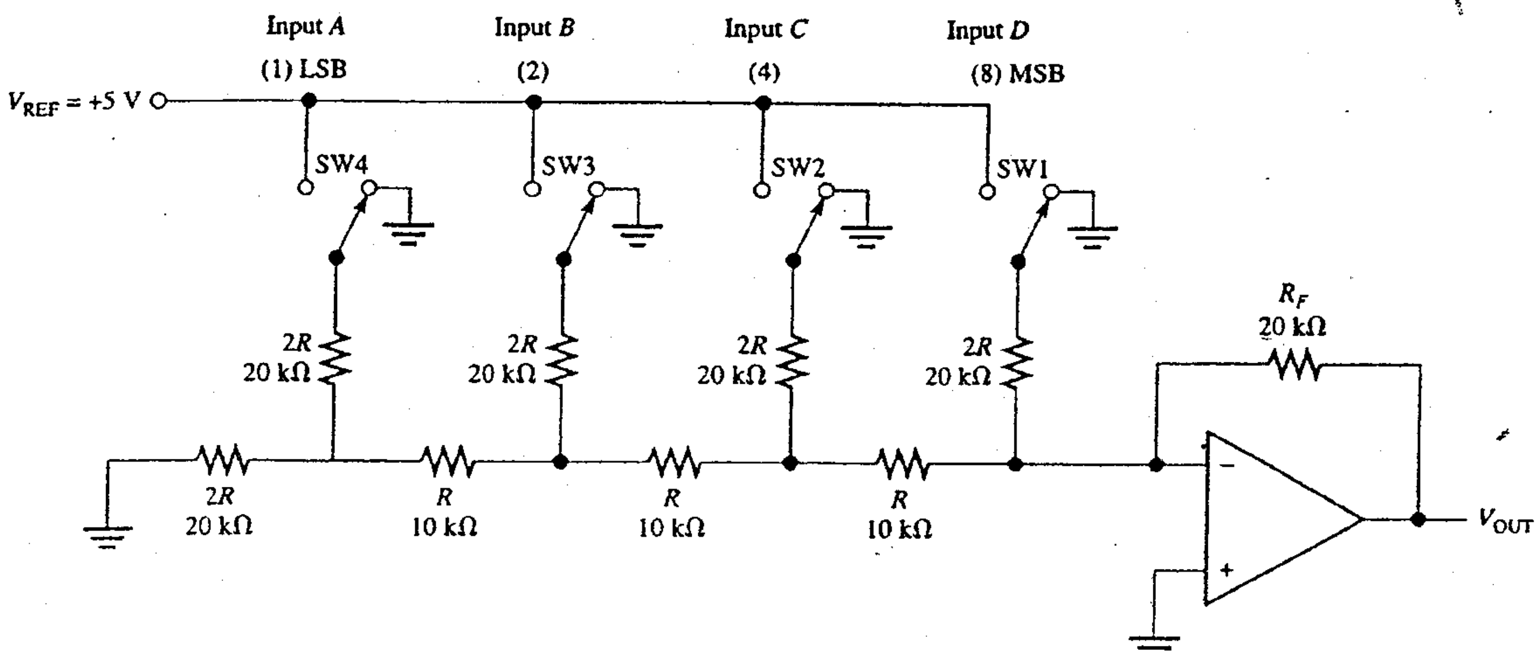
Problem with the Binary-Weighted DAC ...

- To avoid the problem of needing a large number of different value of resistors when using the Binary-Weighted DAC (some of which become very large) ...

  – Which is mainly a manufacturing cost-prohibitive issue ...

- We can use the R-2R Ladder D/A converter ...

R-2R Ladder D / A Converter



R-2R DACs

- The circuit gets its name from the fact that it uses two resistor values ...

- One being double (2R) ... of the other (R)

- The R-2R ladder resistor network is the same as the Binary-Weighted circuit ...

  – It weighs the input so that each input has twice the value of the previous one

R-2R DACs

- For example ...
  - The current supplied to the feedback resistor from the resistive network when Input B (SW3) is activated ...
    - Should be double that supplied when Input A (SW4) is activated

R-2R DACs

- Since the R-2R ladder is a linear circuit ...
  - We can apply the principle of superposition to calculate V_{OUT}
    - ***Superposition Theorem ...***
      - The total current in any part of a linear circuit equals the algebraic sum of the currents produced by each source separately
- The expected output voltage is calculated by summing the effect of all bits connected to V_{REF}.

R-2R DACs

- The output voltage is given by the following equation:

$$V_{OUT} = -\frac{R_f}{R}\left(\frac{D}{2} + \frac{C}{4} + \frac{B}{8} + \frac{A}{16}\right) * V_{REF}$$

- Where D, C, B, A corresponds to the inputs D, C, B, A
  - The values of D, C, B, A being either ...
    - » ‘1’ (switch to 5v)

      or

    - » ‘0’ (switch to ground)

R-2R DACs

- Assume R_f = R = 10K ... eliminates amplifying by 2 if R_f = 20K
- The minimum output voltage is 0 volts when Inputs A, B, C, D are all ‘0’ (switch grounded)
- And the maximum output voltage, when the inputs A, B, C, D are at ‘1’ is

$$V_{OUT_{(MAX)}} = -\left(\frac{1}{2}+\frac{1}{4}+\frac{1}{8}+\frac{1}{16}\right)*V_{REF} = -\frac{15}{16}V_{REF} = -\frac{15}{16}*5 = -4.6875Volts$$

- You would expect V_{OUT} to be able to reach V_{REF}, but it doesn't
  - Reason: 0v counts as a "digital step", otherwise we would have an extra step above the maximum number of steps allowed by the number of bits

DAC0808 an 8-Bit DAC

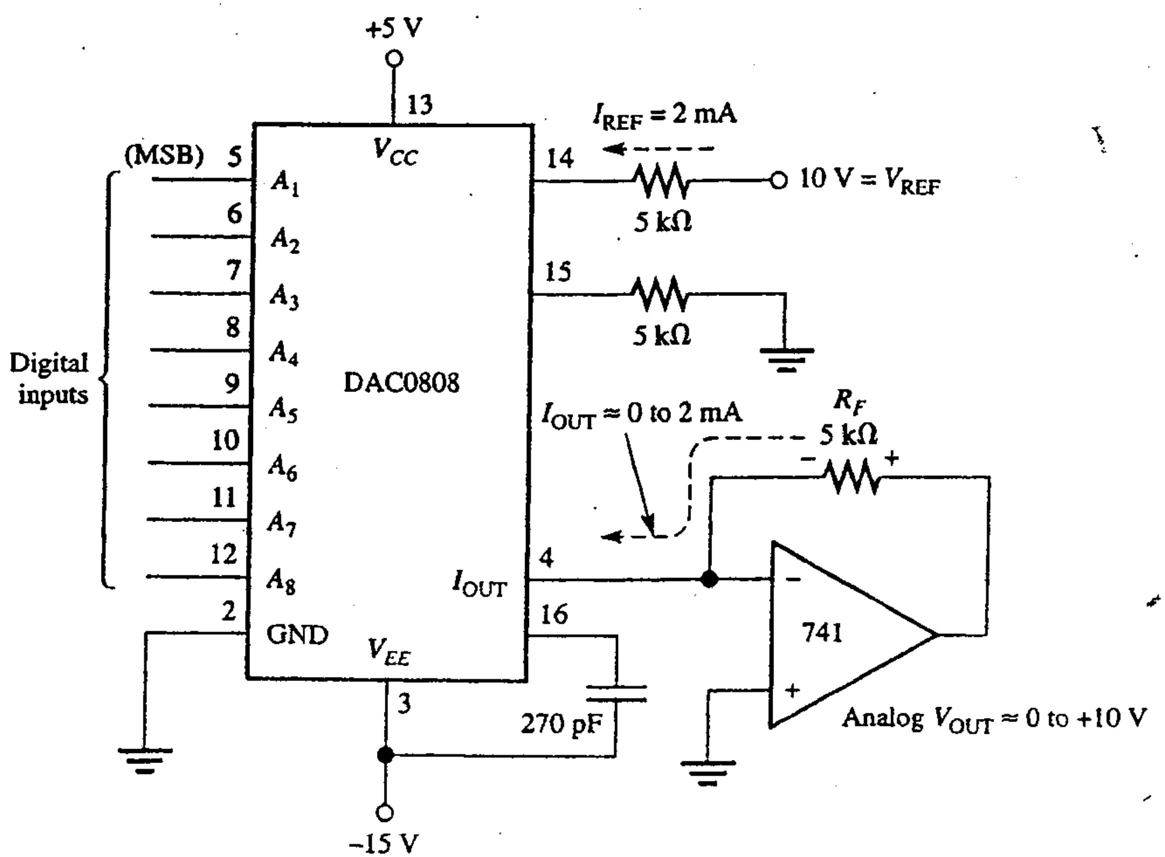


FIGURE 11.16

The DAC0808 and the 741 op-amp connected to form a DAC.

DAC0808 an 8-Bit DAC

- Some DACs contain an internal op-amp but the DAC0808 doesn’t
- The internal components supply proportional currents to its output lead (pin #4)
- We connect the DAC0808 to a 741 op-amp
- The max output current flow allowed out of pin #4 is 2 mA

AN EXAMPLE …

- We want …
  - An analog output ranging from 0V to 10V
  - Limit the output current to 2 mA max
  - What feedback resistor do we need?
- An input of 00000000 … we would have 0 volts and 0 mA at the input
- And for an input of 11111111 we want 10 volts and 2 mA output

$$V_{OUT} = -I_F * R_F$$

- Therefore …

$$R_F = \frac{V_{OUT}}{-I_F} = \frac{10}{.002} = 5K$$

- If we needed a different output voltage range we would adjust R_F accordingly to limit the output to 2 mA

Other DAC Architectures

- You now have the basic idea as to how DACs function
- The text contains a number of other architectures ...
  - We are not going to go into them ...
- The principles are similar to what we have just went over ...
- You may want to take some time and explore these architectures
  - At least know what they are if you need to use them

DAC Specifications …

Performance Specifications

- Resolution
- Accuracy
- Linearity
- Monotonicity
- Settling Time

» We will not discuss these at this time ...

Lab

Lab #3 and #4 …

Lab #3– Overview

- To construct and operate an A/D Converter using the ADC804

Lab #4 – Overview

- Will construct and operate a binary-weighted DAC
- Will construct and operate a Digital to Analog Converters
- Test the ADC and DAC With DC Input
- Test the ADC and DAC With A Sinusoidal Input
- **~~ OPTIONAL ~~** Integrated Digital to Analog Converter Signal Generator

Next Class

Next Class Topics

- Lab only

Homework

Homework

1. Lab Reports – Lab report #2 is due 10/24/13

    – Enough time so you can review your graded Lab Report #1 and make any changes for Lab #2

Time to start the lab …

Lab

- Lab #3

Questions?