ECE/CS 5780/6780: Embedded System Design

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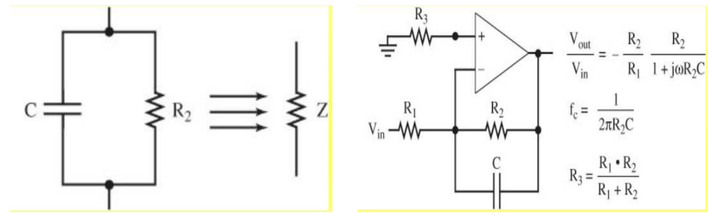
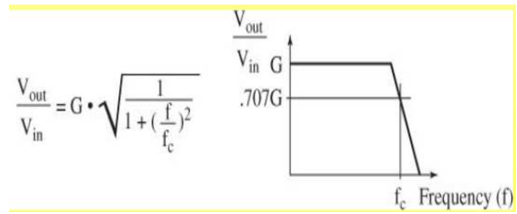
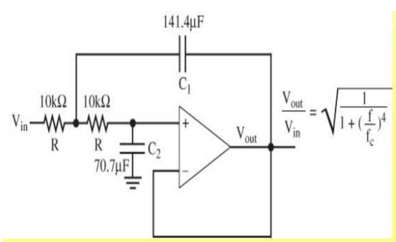
Lecture 18: Analog Filters and DACs

Simple Active Filter



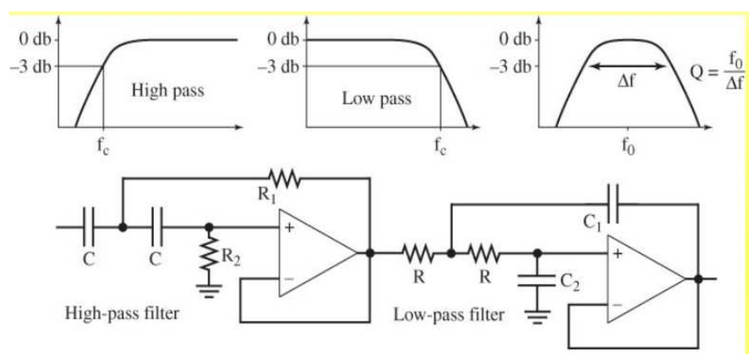


Two-Pole Butterworth Low-Pass Analog Filter

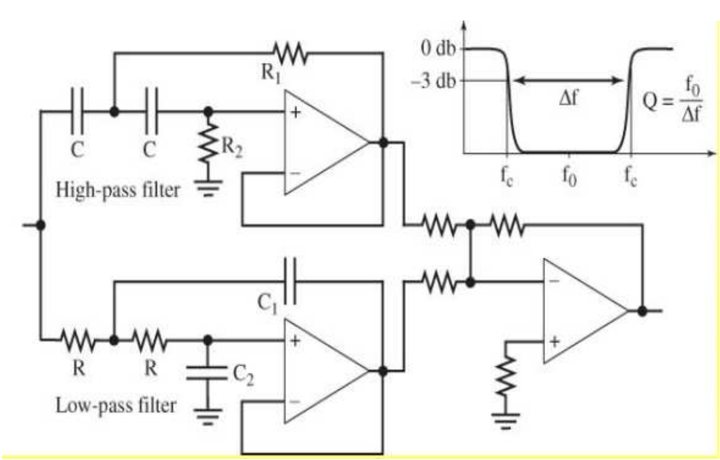


1. Select the cutoff frequency f_c.
2. Divide the two capacitors by $2\pi f_c$.
$$C_{1A} = \frac{141.4\mu F}{2\pi f_c} \quad C_{2A} = \frac{70.7\mu F}{2\pi f_c}$$
3. Select standard capacitors with same order of magnitude.
$$C_{1B} = \frac{C_{1A}}{x} \quad C_{2B} = \frac{C_{2A}}{x}$$
4. Adjust resistors to maintain f_c (i.e., $R = 10k\Omega \cdot x$).

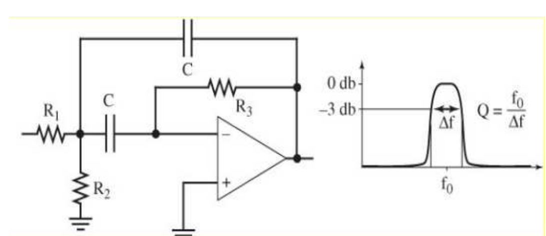
Bandpass Filters



Band-Reject Filters

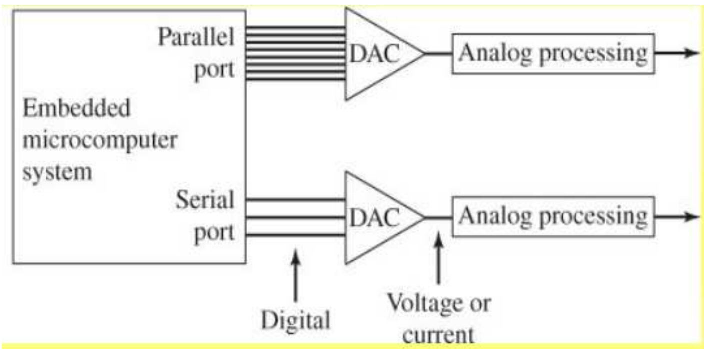


Multiple Feedback Bandpass Filter



1. Select a convenient capacitance value for the two capacitors.
2. Calculate the three resistor values for $x = 1/(2\pi f_0 C)$.
$$R_1 = Q \cdot x \quad R_2 = x/(2Q - 1/Q) \quad R_3 = 2 \cdot Q \cdot x$$
3. Resistors should be in the 5kΩ to 5MΩ range. If not, repeat with different capacitance value.

Digital-to-Analog Converters



DAC Parameters

- *Precision* is number of distinguishable DAC outputs.
- *Range* is maximum and minimum DAC output.
- *Resolution* is smallest distinguishable change in output.

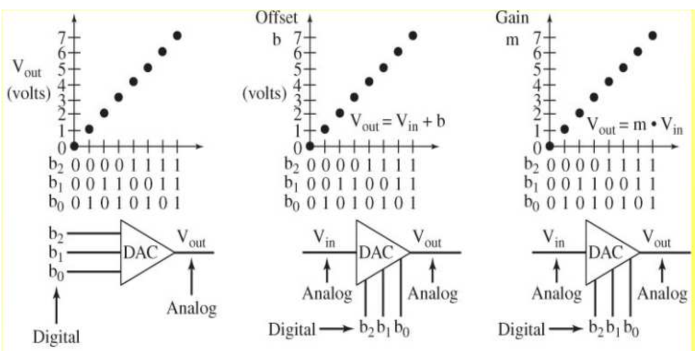
$$\text{Range (volts)} = \text{Precision (alternatives)} \cdot \text{Resolution (volts)}$$

- *Accuracy* is (actual-ideal)/ideal.
- Two common encoding schemes:

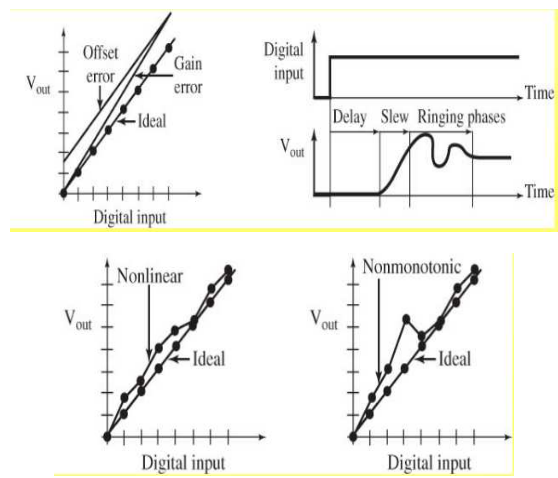
$$V_{out} = V_{fs}\left(\frac{b_7}{2}+\frac{b_6}{4}+\frac{b_5}{8}+\frac{b_4}{16}+\frac{b_3}{32}+\frac{b_2}{64}+\frac{b_1}{128}+\frac{b_0}{256}\right)+V_{os}$$

$$V_{out} = V_{fs}\left(-\frac{b_7}{2}+\frac{b_6}{4}+\frac{b_5}{8}+\frac{b_4}{16}+\frac{b_3}{32}+\frac{b_2}{64}+\frac{b_1}{128}+\frac{b_0}{256}\right)+V_{os}$$

Three-Bit DAC Examples



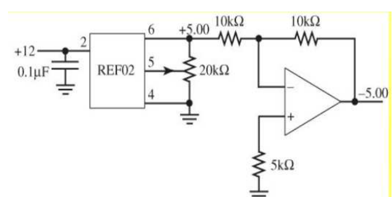
DAC Performance Measures

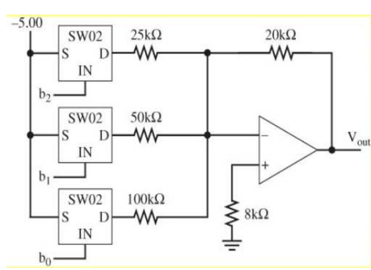


DAC Errors: Sources and Solutions

Errors can be due to	Solutions
Incorrect resistor values	Precision resistors w/low tolerances
Drift in resistor values	Precision resistors w/good temperature coefficients
White noise	Reduce BW w/low pass filter, reduce temperature
Op amp errors	Use more expensive devices w/low noise and low drift
Interference from external fields	Shielding, ground planes

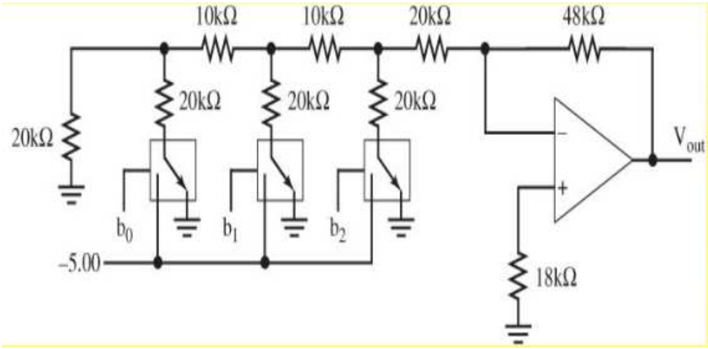
DAC Using a Summing Amplifier



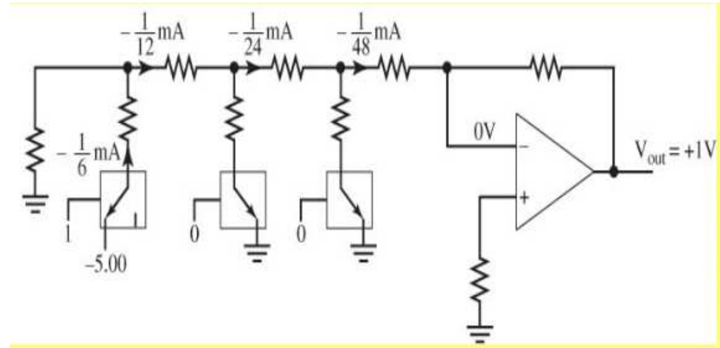


b_2	b_1	b_0	V_{out}
0	0	1	+1
0	1	0	+2
1	0	0	+4

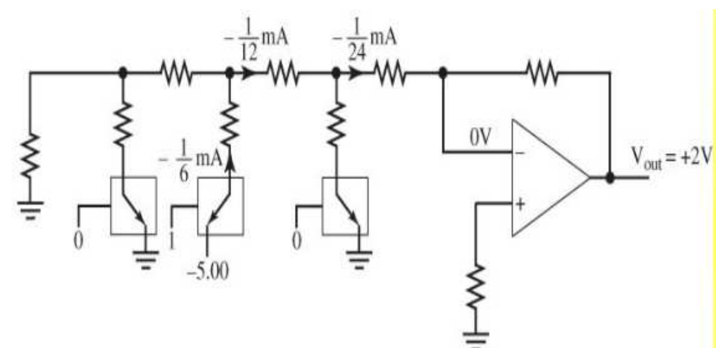
Three-Bit DAC with an R-2R Ladder



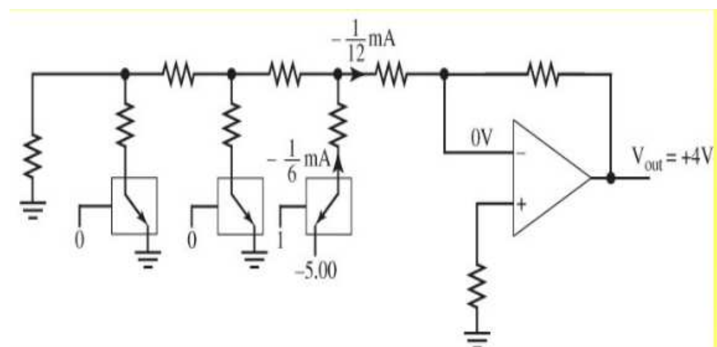
Three-Bit DAC with an R-2R Ladder



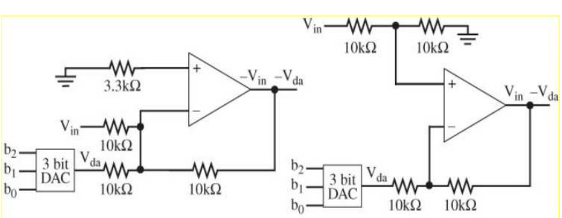
Three-Bit DAC with an R-2R Ladder

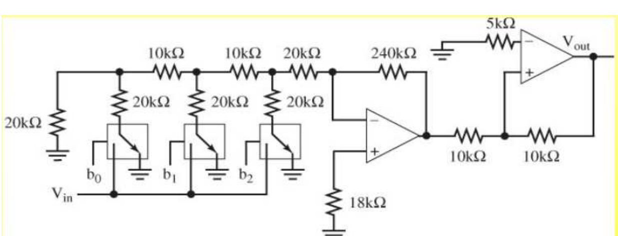


Three-Bit DAC with an R-2R Ladder

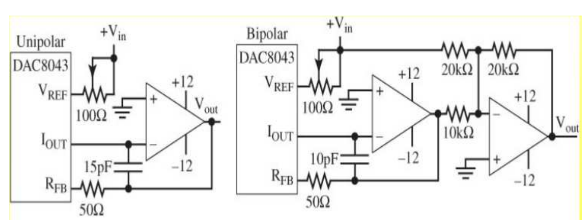


Variable-Offset and Gain Using 3-bit DACs





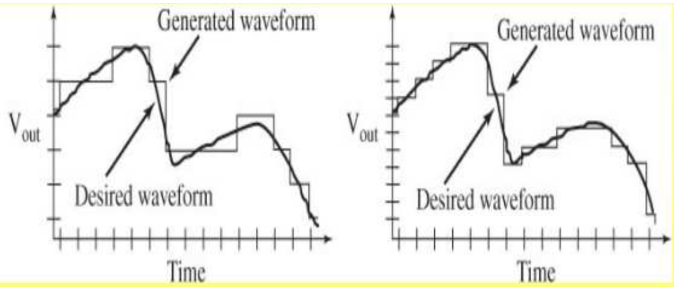
Twelve-Bit DAC with a DAC8043



Digital Input	Unipolar V_{out}	Bipolar V_{out}	Unipolar gain	Bipolar gain
1111,1111,1111	-4.999	4.998	$-\frac{4095}{4096}$	$+\frac{2047}{2048}$
1000,0000,0001	-2.501	0.002	$-\frac{2049}{4096}$	$+\frac{1}{2048}$
1000,0000,0000	-2.500	0.000	$-\frac{2048}{4096}$	$+\frac{0}{2048}$
0111,1111,1111	-2.499	-0.002	$-\frac{2047}{4096}$	$-\frac{1}{2048}$
0000,0000,0001	-0.001	-4.998	$-\frac{1}{4096}$	$-\frac{2047}{2048}$
0000,0000,0000	0.000	-5.000	$-\frac{0}{4096}$	$-\frac{2048}{2048}$

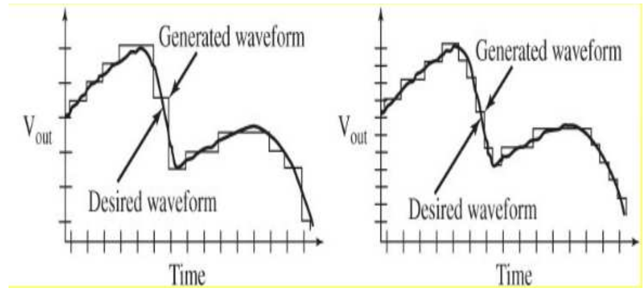
DAC Selection: Precision, Range, and Resolution

- Affect quality of signal that can be generated.
- More bits means finer control over the waveform.
- Can be hard to specify a priori.



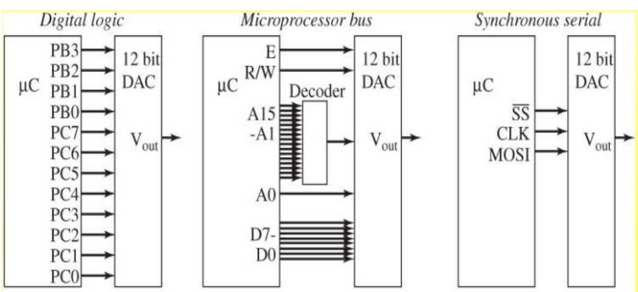
DAC Selection: Channels, Configuration, and Speed

- Usually more efficient to implement multiple *channels* using a signal DAC.
- *Configuration*: can have voltage or current outputs, internal or external references, etc.
- *Speed* specified in many ways: *settling time*, *maximum output rate*, *gain/BW product*, etc.



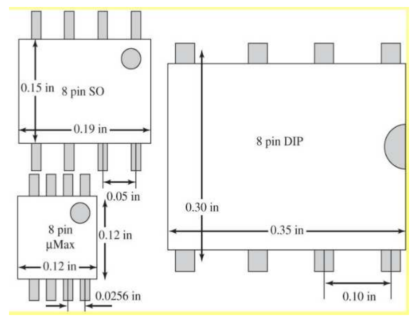
DAC Selection: Power and Interface

- Three power issues: type of power required, amount of power required, and need for low-power sleep mode.
- Three approaches for interfacing exist:



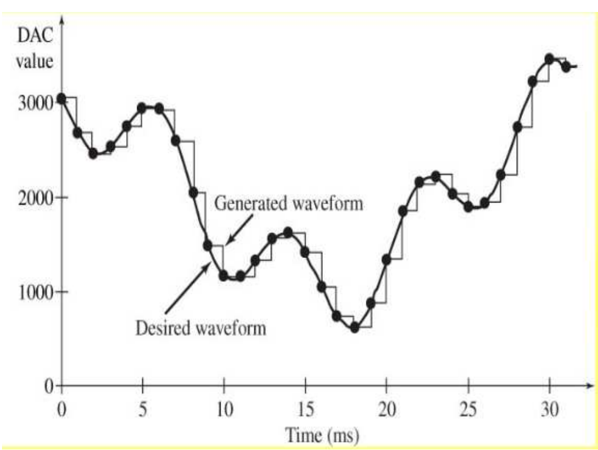
DAC Selection: Package and Cost

- Variety of packages exist:



- *Cost* includes direct cost of components, power supply requirements, manufacturing costs, labor in calibration, and software development costs.

DAC Waveform Generation



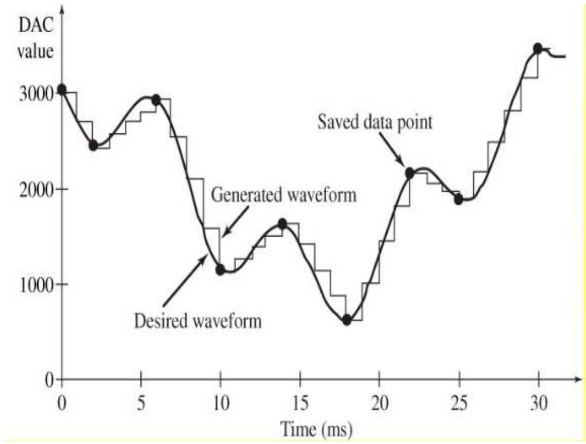
Periodic Interrupt Used to Generate Waveform

```
unsigned short wave(unsigned short t){
float result,time;
  time = 2*pi*((float)t)/1000.0;
// integer t in msec into floating point time in seconds
  result =2048.0+1000.0*cos(31.25*time)-500.0*sin(125.0*time);
  return (unsigned short) result;
}
#define RATE 2000
#define OC5  0x20
unsigned short Time;  // Inc every 1ms
void interrrupt 13 TOC5handler(void){
  TFLG1 = OC5;       // ack C5F
  TC5 = TC5+RATE;    // Executed every 1 ms
  Time++;
  DACout(wave(Time));
}
```

Periodic Interrupt Used to Generate Waveform

```
unsigned short I;  // incremented every 1ms
const unsigned short wave[32]= {
  3048,2675,2472,2526,2755,2957,2931,2597,
  2048,1499,1165,1139,1341,1570,1624,1421,
  1048,714,624,863,1341,1846,2165,2206,2048,
  1890,1931,2250,2755,3233,3472,3382};
#define RATE 2000
#define OC5  0x20
void interrupt 13 TOC5handler(void){
  TFLG1 = OC5;       // ack C5F
  TC5 = TC5+RATE;    // Executed every 1 ms
  if((++I)==32) I = 0;
  DACout(wave[I]);
}
```


Generated Waveform Using Linear Interpolation



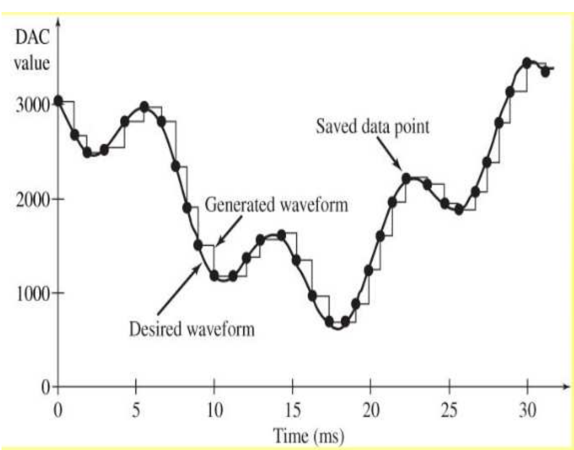
Periodic Interrupt Used to Generate Waveform

```
short I;  // incremented every 1ms
short J;  // index into these two tables
const short t[10]= {0,2,6,10,14,18,22,25,30,32};
const short wave[10]={3048,2472,2931,1165,1624,
                      624,2165,1890,3472,3048};
```


Periodic Interrupt Used to Generate Waveform

```
#define RATE 2000
#define OC5  0x20
void interrupt 13 TOC5handler(void){
  TFLG1 = OC5;       // ack C5F
  TC5 = TC5+RATE;    // Executed every 1 ms
  if((++I)==32) {I=0; J=0;}
  if(I==t[J])
    DACout(wave[J]);
  else if (I==t[J+1]){
    J++;
    DACout(wave[J]);
  } else
    DACout(wave[J]+((wave[J+1]-wave[J])
      *(I-t[J]))/(t[J+1]-t[J]));
}
```


Generated Waveform Using Uneven-Time



Periodic Interrupt Used to Generate an Analog Waveform

```
unsigned short I;  // incremented every sample
const unsigned short wave[32]= {
  3048,2675,2472,2526,2817,2981,2800,2337,1901,1499,1165,
  1341,1570,1597,1337, 952, 662, 654, 863,1210,1605,1950,
  2202,2141,1955,1876,2057,2366,2755,3129,3442,3382};
const unsigned short dt[32]= { // 500 ns cycles
  2000,2000,2000,2500,2500,2000,2000,1500,1500,2000,4000,
  2000,2500,2000,2000,2000,2000,1500,1500,1500,1500,2000,
  2500,2000,2000,2000,1500,1500,1500,2000,2500,2000};
#define OC5  0x20
void interrupt 13 TOC5handler(void){
  TFLG1 = OC5;       // ack C5F
  if((++I)==32) I=0;
  TC5 = TC5+dt[I];   // variable rate
  DACout(wave[I]);}
```