EE 230
Lecture 37

Data Converters
Review from Last Time:

Data Converters

Analog variables: Voltage, Current, time, charge, occasionally other physical variables

Digital variables: Usually represented in binary form but other forms occasionally used (e.g. gray, Thermometer code)
Data Converters

An ideal DAC

(Some specific shifted versions of this DAC would also be termed an ideal DAC)
(Some specific shifted versions of this ADC would also be termed an ideal ADC)
Review from Last Time:

**Data Converters**

Terminology:

\[ B: [b_1 b_2 \ldots b_n] \]

- **b_1**: Most Significant Bit (MSB)
- **b_n**: Least Significant Bit (LSB)

**Resolution**: Defines number of distinct levels for DAC or Boolean outputs for ADC. If there are \( N \) distinct levels, resolution generally defined as \( n = \log_2 N \) thus, \( N = 2^n \)

**\( X_{\text{REF}} \)**: specifies the full-scale range of the data converter. Input range for ADC or output range for DAC is usually

\[
X_{\text{REF}} \left( \frac{2^n - 1}{2^n} \right)^{n \text{ large}} \approx X_{\text{REF}}
\]
Data Converters

Terminology:

**LSB (or** $X_{\text{LSB}}$ **):** Analog change (in input to ADC or output of DAC) corresponding to one LSB digital change

$$X_{\text{LSB}} = \frac{X_{\text{REF}}}{2^n}$$

**Transition Points (for ADC):** values of $X_{\text{IN}}$ where output changes by 1 LSB
(an $n$-bit ADC has $N-1$ transition points partitioning input into $N$ distinct intervals)

**Decimal Equivalent:** Decimal equivalent of $B$: $[b_1\ b_2\ldots\ b_n]$

$$D(B) = \left(\frac{b_1}{2} + \frac{b_2}{4} + \ldots + \frac{b_n}{2^n}\right) \quad \rightarrow \quad D(B) = \sum_{k=1}^{n} \frac{b_k}{2^k}$$

Review from Last Time:
Review from Last Time:

**Number of levels for different resolution**

<table>
<thead>
<tr>
<th>n</th>
<th>N</th>
<th>n</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$2^1$</td>
<td>10</td>
<td>$2^{10}$</td>
</tr>
<tr>
<td>2</td>
<td>$2^2$</td>
<td>11</td>
<td>$2^{11}$</td>
</tr>
<tr>
<td>3</td>
<td>$2^3$</td>
<td>12</td>
<td>$2^{12}$</td>
</tr>
<tr>
<td>4</td>
<td>$2^4$</td>
<td>13</td>
<td>$2^{13}$</td>
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<tr>
<td>5</td>
<td>$2^5$</td>
<td>14</td>
<td>$2^{14}$</td>
</tr>
<tr>
<td>6</td>
<td>$2^6$</td>
<td>15</td>
<td>$2^{15}$</td>
</tr>
<tr>
<td>7</td>
<td>$2^7$</td>
<td>16</td>
<td>$2^{16}$</td>
</tr>
<tr>
<td>8</td>
<td>$2^8$</td>
<td>20</td>
<td>$2^{20}$</td>
</tr>
<tr>
<td>9</td>
<td>$2^9$</td>
<td>24</td>
<td>$2^{24}$</td>
</tr>
</tbody>
</table>

The entries represent the number of levels for different resolutions, with $N$ being a power of 2, and the corresponding values ranging from 2 to 16,772,216.
Data Converters

An ideal DAC

\[ X_{\text{OUT}} = X_{\text{REF}} D(X_{\text{IN}}) = X_{\text{REF}} \sum_{k=1}^{n} \frac{b_k}{2^k} \]

B: \([b_1, b_2, ..., b_n]\)
Data Converters

An ideal ADC

\[ X_{\text{OUT}} = B \]

\[ X_{\text{REF}} D(B) < X_{\text{IN}} < X_{\text{REF}} D(B) + X_{\text{LSB}} \]
Example

Determine $V_{\text{LSB}}$ for a 16-bit ADC if $X_{\text{REF}}$ is a voltage of 1V.

$$X_{\text{LSB}} = \frac{1V}{2^{16}} = 15.25\mu\text{V}$$

Observe $X_{\text{LSB}}$ is very small and for a 16-bit ADC, must resolve an input signal to $\pm X_{\text{LSB}}/2 = \pm 7.5\mu\text{V}$
Example

Determine the number of bits of resolution, \( n \), required in an ADC if it is to be used in a DMM that has accuracy corresponding to \( m \) decimal digits.

Resolution of an \( m \)-digit DMM is \( V_{REF}/10^m \).

Thus equating the resolution of an ADC represented in binary form to that of the DMM, we obtain the expression:

\[
\frac{V_{REF}}{2^n} = \frac{V_{REF}}{10^m}
\]

It thus follows that

\[
m = n \log_{10} 2
\]

Solving for \( n \), we obtain

\[
n = \frac{m}{\log_{10} 2}
\]

If \( m=6 \), \( n=20 \)  
If \( m=7 \), \( n=23+ \)

If \( V_{REF}=1V, V_{LSB}=0.95\mu V \)  
If \( V_{REF}=1V, V_{LSB}=112nV \)

Very high resolution is required in applications such as this!
Data Converter Implementations

Discrete implementations of data converters are seldom used
– Not cost effective
– Too large
– Vary difficult to maintain acceptable accuracies of components

Integrated data converters usually have voltage or current as input or output variables
– If conversion of other physical units is required, a transducer precedes or follows a voltage or current data converter
Types of Data Converters

(Angle Devices is one of several companies that is a big player in the Data Converter marketplace. Others include TI, National, Maxim and Cyrus)
Data Converter Selection

### Digital-to-Analog Converters Resolution/Update Rate Selection Matrix

<table>
<thead>
<tr>
<th>Resolution, Bits</th>
<th>10-100 MSPS</th>
<th>≥100 MSPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>14</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>12</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>10</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>8</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>

### Digital-to-Analog Converters DAC Resolution vs Settling Time Selection Matrix

<table>
<thead>
<tr>
<th>Resolution, Bits</th>
<th>≥10 μs</th>
<th>10 μs-1 μs</th>
<th>1 μs-100 ns</th>
<th>100 ns-10 ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>13-18</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>12</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>10</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>8</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>
Data Converter Selection

### Analog-to-Digital Converters

<table>
<thead>
<tr>
<th>Resolution, Bits</th>
<th>&lt;16 kps</th>
<th>10 kps to 190 kps</th>
<th>100 kps to 1 MSPS</th>
<th>1 MSPS to 10 MSPS</th>
<th>10 MSPS to 100 MSPS</th>
<th>100 MSPS +</th>
</tr>
</thead>
<tbody>
<tr>
<td>174</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14-16</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>12-13</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>10-11</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>8-2</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>&lt;8</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td></td>
</tr>
</tbody>
</table>
Engineering Issues for Using Data Converters

1. Inherent with Data Conversion Process
   - Amplitude Quantization
   - Time Quantization
   (Present even with Ideal Data Converters)

2. Nonideal Components
   - Uneven steps
   - Offsets
   - Gain errors
   - Response Time
   - Noise
   (Present to some degree in all physical Data Converters)

How do these issues ultimately impact performance?
Engineering Issues for Using Data Converters

Inherent with Data Conversion Process

- Amplitude Quantization
- Time Quantization
- Present even with Ideal Data Converters
  - Somewhat challenging to characterize
  - Avoid over-specification
    Power
    Cost
  - Key questions to ask
    How much resolution is needed?
    What range is needed?
    How fast must the converter operate?
    What are the implications of noise?
Engineering Issues for Using Data Converters

Nonideal Components

- Uneven steps
- Offsets
- Response Time
- Noise
- Present to some degree in all physical Data Converters

- Somewhat challenging to characterize
  - Many parameters (specifications) have been given
  - Mathematical analysis often complicated
  - Often statistical in nature
  - Computer simulations help but still leave some questions unanswered

- Somewhat challenging to predict affects on system performance
  - Depends upon application
  - Computer simulations help but still leave some questions unanswered