Recap
Synchronization: hardware/software, between threads
SCI interrupts
Fifo queue: what why how

Overview
Design a DAC
Experimental method
Output a sine wave

Digital to Analog Conversion
Signal generation (sound, image, touch…)
Output to affect external devices (power, flow, heat…)

The DAC precision is the number of distinguishable DAC outputs
(e.g., 16 alternatives, 4 bits).

The DAC range is the maximum and minimum DAC output
(0 to 5V).

The DAC resolution is the smallest distinguishable change in output.
\( (5V/16 = 0.31V) \)

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

The DAC accuracy is \( (\text{Actual} - \text{Ideal}) / \text{Ideal} \)

For example, if we were to build a 2-bit DAC. Assume \( V_{OH} \) of the 9S12 is 5, and its \( V_{OL} \) is 0

<table>
<thead>
<tr>
<th>N</th>
<th>Q1</th>
<th>Q0</th>
<th>( V_1(\text{V}) )</th>
<th>( V_2(\text{V}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>5</td>
<td>1.25</td>
<td>1.67</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>0</td>
<td>2.50</td>
<td>3.33</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>5</td>
<td>3.75</td>
<td>5.00</td>
</tr>
</tbody>
</table>

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

\[ \text{The DAC accuracy is } (\text{Actual} - \text{Ideal}) / \text{Ideal} \]

For example, if we were to build a 2-bit DAC. Assume \( V_{OH} \) of the 9S12 is 5, and its \( V_{OL} \) is 0

\[ N \quad Q_1 \quad Q_0 \quad V_1(\text{V}) \quad V_2(\text{V}) \]
\[ \begin{array}{cccc}
0 & 0 & 0 & 0.00 \\
1 & 0 & 5 & 1.25 \\
2 & 5 & 0 & 2.50 \\
3 & 5 & 5 & 3.75 \\
\end{array} \]

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

\[ \text{The DAC accuracy is } (\text{Actual} - \text{Ideal}) / \text{Ideal} \]

Figure 8.1. DAC allows the software to create music.
You can realistically build a 4-bit DAC using this method. $Q_3$ is 5V or 0V.

Two alternatives (four resistors)

$$V_{\text{out}} = \frac{(8Q_3 + 4Q_2 + 2Q_1 + Q_0)}{15}$$

Assume $V_{\text{OH}}$ of the 9S12 is 5V, and its $V_{\text{OL}}$ is 0

<table>
<thead>
<tr>
<th>N</th>
<th>Q3</th>
<th>Q2</th>
<th>Q1</th>
<th>Q0</th>
<th>theory</th>
<th>V_{out}(V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5*0/15</td>
<td>0.00</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>5*1/15</td>
<td>0.33</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>5*2/15</td>
<td>0.67</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5*8/15</td>
<td>2.67</td>
</tr>
<tr>
<td>15</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5*15/15</td>
<td>5.00</td>
</tr>
</tbody>
</table>

or (five resistors)

$$V_{\text{out}} = \frac{(8Q_3 + 4Q_2 + 2Q_1 + Q_0)}{16}$$

Assume $V_{\text{OH}}$ of the 9S12 is 5V, and its $V_{\text{OL}}$ is 0

<table>
<thead>
<tr>
<th>N</th>
<th>Q3</th>
<th>Q2</th>
<th>Q1</th>
<th>Q0</th>
<th>theory</th>
<th>V_{out}(V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5*0/16</td>
<td>0.00</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>5*1/16</td>
<td>0.31</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>5*2/16</td>
<td>0.63</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5*8/16</td>
<td>2.50</td>
</tr>
<tr>
<td>15</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5*15/16</td>
<td>4.69</td>
</tr>
</tbody>
</table>

4-bit sin table

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>

**SinTab**

| fcB | 8, 9, 11, 12, 13, 14, 14, 15, 15, 15, 14 |
| fcB | 14, 13, 12, 11, 9, 8, 7, 5, 4, 3, 2 |
| fcB | 2, 1, 1, 1, 2, 2, 3, 4, 5, 7 |

**How to create a sin wave with period T?**

- Periodic interrupt every $T/32$
- Output next entry in table

What happens to the voltage when your DAC is connected to the headphones?

**In EE445L we will**

- Interface a 12-bit DAC
- Use this amplifier (Rf=10k, Ri=20k) to drive the speaker
- Play songs
- Include melody and harmony
- Change instruments
- Add envelops

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Using Ohm's law and fact that the digital output voltages will be approximately 0 and 5 V, make a table of the theoretical DAC voltage and as a function of digital value (without the speaker attached). Calculate resolution, range, precision and accuracy.

**DAC parameters**
- Range, resolution, precision
- Speed
- Cost (is it easy to manufacture?)
- Monotonic (always increasing)
- Accuracy

**Try to use this method to build an 8-bit DAC**
- Becomes expensive to use very high tolerance resistors
- DAC becomes non-monotonic

**Show R-2R ladder, and implement an 8-bit DAC**

**The bottom line**
- DAC: precision, range, resolution, monotonic
- Use OC interrupts and a DAC to create waveforms
- Measurement of accuracy

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