CprE 281: Digital Logic

Instructor: Alexander Stoytchev

http://www.ece.iastate.edu/~alexs/classes/
Binary Numbers
Administrative Stuff

This is the official class web page:

http://www.ece.iastate.edu/~alexs/classes/2015_Fall_281/

If you missed the first lecture, the syllabus and other class materials are posted there.
Administrative Stuff

• HW1 is out

• It is due on Monday Aug 31 @ 4pm.

• Submit it on paper before the start of the lecture
The labs and recitations start next week:

- Section N: Monday 9:00 AM - 11:50 AM (Coover Hall, room 2050)
- Section P: Monday 12:10 PM - 3:00 PM (Coover Hall, room 2050)
- Section R: Monday 5:10 PM - 8:00 PM (Coover Hall, room 2050)
- Section U: Tuesday 11:00 AM - 1:50 PM (Coover Hall, room 2050)
- Section M: Tuesday 2:10 PM - 5:00 PM (Coover Hall, room 2050)
- Section J: Wednesday 8:00 AM - 10:50 AM (Coover Hall, room 2050)
- Section Y: Wednesday 6:10 PM - 9:00 PM (Coover Hall, room 2050)
- Section Q: Thursday 11:00 AM - 1:50 PM (Coover Hall, room 2050)
- Section L: Thursday 2:10 PM - 5:00 PM (Coover Hall, room 2050)
- Section K: Thursday 5:10 PM - 8:00 PM (Coover Hall, room 2050)
- Section G: Friday 11:00 AM - 1:50 PM (Coover Hall, room 2050)

- The lab schedule is also posted on the class web page
Labs Next Week

Figure 1.5 in the textbook: An FPGA board.
Labs Next Week

• Please download and read the lab assignment for next week before you go to your lab section.

• You must print the answer sheet and do the prelab before you go to the lab.

• The TAs will check your answers at the beginning of the lab.
Did you get the textbook?
The Decimal System
What number system is this one?
The Binary System

Number Systems

\[ N = d_n B^n + d_{n-1} B^{n-1} + \cdots + d_1 B^1 + d_0 B^0 \]
Number Systems

\[ N = d_n B^n + d_{n-1} B^{n-1} + \cdots + d_1 B^1 + d_0 B^0 \]

n-th digit (most significant)

0-th digit (least significant)
Number Systems

\[ N = d_n B^n + d_{n-1} B^{n-1} + \cdots + d_1 B^1 + d_0 B^0 \]
The Decimal System

$$524_{10} = 5 \times 10^2 + 2 \times 10^1 + 4 \times 10^0$$
The Decimal System

\[524_{10} = 5 \times 10^2 + 2 \times 10^1 + 4 \times 10^0\]

\[= 5 \times 100 + 2 \times 10 + 4 \times 1\]

\[= 500 + 20 + 4\]

\[= 524_{10}\]
Another Way to Look at This

5 2 4
Another Way to Look at This

\[
\begin{array}{ccc}
10^2 & 10^1 & 10^0 \\
5 & 2 & 4 \\
\end{array}
\]
Another Way to Look at This

Each box can contain only one digit and has only one label. From right to left, the labels are increasing powers of the base, starting from 0.
Base 7

\[ 524_7 = 5 \times 7^2 + 2 \times 7^1 + 4 \times 7^0 \]
Base 7

\[ 524_7 = 5 \times 7^2 + 2 \times 7^1 + 4 \times 7^0 \]
Base 7

\[ 524_{7} = 5 \times 7^2 + 2 \times 7^1 + 4 \times 7^0 \]
Base 7

\[524_7 = 5 \times 7^2 + 2 \times 7^1 + 4 \times 7^0\]

\[= 5 \times 49 + 2 \times 7 + 4 \times 1\]

\[= 245 + 14 + 4\]

\[= 263_{10}\]
Another Way to Look at This

\[
\begin{array}{ccc}
7^2 & 7^1 & 7^0 \\
5 & 2 & 4 \\
\end{array}
\quad = \quad \begin{array}{ccc}
10^2 & 10^1 & 10^0 \\
2 & 6 & 3 \\
\end{array}
\]
Binary Numbers (Base 2)

\[1001_2 = 1 \times 2^3 + 0 \times 2^2 + 0 \times 2^1 + 1 \times 2^0\]
Binary Numbers (Base 2)

$$1001_2 = 1 \times 2^3 + 0 \times 2^2 + 0 \times 2^1 + 1 \times 2^0$$
Binary Numbers (Base 2)

\[ 1001_2 = 1 \times 2^3 + 0 \times 2^2 + 0 \times 2^1 + 1 \times 2^0 = \]
\[ = 1 \times 8 + 0 \times 4 + 0 \times 2 + 1 \times 1 = \]
\[ = 8 + 0 + 0 + 1 = 9_{10} \]
Another Example

\[ \begin{align*}
11101_2 &= 1 \times 2^4 + 1 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0 = \\
&= 1 \times 16 + 1 \times 8 + 1 \times 4 + 0 \times 2 + 1 \times 1 = \\
&= 16 + 8 + 4 + 0 + 1 = 29_{10}
\end{align*} \]
<table>
<thead>
<tr>
<th>$2^n$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$2^{10}$</td>
<td>1024</td>
</tr>
<tr>
<td>$2^9$</td>
<td>512</td>
</tr>
<tr>
<td>$2^8$</td>
<td>256</td>
</tr>
<tr>
<td>$2^7$</td>
<td>128</td>
</tr>
<tr>
<td>$2^6$</td>
<td>64</td>
</tr>
<tr>
<td>$2^5$</td>
<td>32</td>
</tr>
<tr>
<td>$2^4$</td>
<td>16</td>
</tr>
<tr>
<td>$2^3$</td>
<td>8</td>
</tr>
<tr>
<td>$2^2$</td>
<td>4</td>
</tr>
<tr>
<td>$2^1$</td>
<td>2</td>
</tr>
<tr>
<td>$2^0$</td>
<td>1</td>
</tr>
</tbody>
</table>
What is the value of this binary number?

- 0 0 1 0 1 1 0 0

- 0 0 1 0 1 1 0 0

- \(0 \times 2^7 + 0 \times 2^6 + 1 \times 2^5 + 0 \times 2^4 + 1 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 0 \times 2^0\)

- \(0 \times 128 + 0 \times 64 + 1 \times 32 + 0 \times 16 + 1 \times 8 + 1 \times 4 + 0 \times 2 + 0 \times 1\)

- \(0 \times 128 + 0 \times 64 + 1 \times 32 + 0 \times 16 + 1 \times 8 + 1 \times 4 + 0 \times 2 + 0 \times 1\)

- \(32 + 8 + 4 = 44\) (in decimal)
Another Way to Look at This

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

- A binary digit is called a *bit*

- A group of eight bits is called a *byte*

- One bit can represent only two possible states, which are denoted with 1 and 0
Relationship Between a Byte and a Bit

1 0 1 0 1 1 1 0
Relationship Between a Byte and a Bit

1 0 1 0 1 1 1 0

1 bit
Relationship Between a Byte and a Bit

8 bits = 1 byte
### Bit Permutations

<table>
<thead>
<tr>
<th>1 bit</th>
<th>2 bits</th>
<th>3 bits</th>
<th>4 bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>00</td>
<td>000</td>
<td>0000</td>
</tr>
<tr>
<td>1</td>
<td>01</td>
<td>001</td>
<td>0001</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>010</td>
<td>0010</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>011</td>
<td>0011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>0100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>101</td>
<td>0101</td>
</tr>
<tr>
<td></td>
<td></td>
<td>110</td>
<td>0110</td>
</tr>
<tr>
<td></td>
<td></td>
<td>111</td>
<td>0111</td>
</tr>
</tbody>
</table>

Each additional bit doubles the number of possible permutations
Bit Permutations

- Each permutation can represent a particular item
- There are $2^N$ permutations of N bits
- Therefore, N bits are needed to represent $2^N$ unique items

<table>
<thead>
<tr>
<th>How many items can be represented by</th>
<th>1 bit ?</th>
<th>$2^1 = 2$ items</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 bits ?</td>
<td>$2^2 = 4$ items</td>
</tr>
<tr>
<td></td>
<td>3 bits ?</td>
<td>$2^3 = 8$ items</td>
</tr>
<tr>
<td></td>
<td>4 bits ?</td>
<td>$2^4 = 16$ items</td>
</tr>
<tr>
<td></td>
<td>5 bits ?</td>
<td>$2^5 = 32$ items</td>
</tr>
</tbody>
</table>
What is the maximum number that can be stored in one byte (8 bits)?
What is the maximum number that can be stored in one byte (8 bits)?

- 1 1 1 1 1 1 1 1
- 1 1 1 1 1 1 1 1
- \(1 \times 2^7 + 1 \times 2^6 + 1 \times 2^5 + 1 \times 2^4 + 1 \times 2^3 + 1 \times 2^2 + 1 \times 2^1 + 1 \times 2^0\)
- \(1 \times 128 + 1 \times 64 + 1 \times 32 + 1 \times 16 + 1 \times 8 + 1 \times 4 + 1 \times 2 + 1 \times 1\)
- \(128 + 64 + 32 + 16 + 8 + 4 + 2 + 1 = 255\) (in decimal)
- Another way is: \(1 \times 2^8 - 1 = 256 - 1 = 255\)
What would happen if we try to add 1 to the largest number that can be stored in one byte (8 bits)?

```
1 1 1 1 1 1 1 1
+ 1
---------------
1 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0
```
Analogy with car odometers
Analogy with car odometers
Decimal to Binary Conversion
(Using Guessing)

$$17 = 16 + 1 \rightarrow 10001_2$$

\[
\begin{align*}
2^7 &= 128 \\
2^6 &= 64 \\
2^5 &= 32 \\
2^4 &= 16 & \checkmark \\
2^3 &= 8 \\
2^2 &= 4 \\
2^1 &= 2 \\
2^0 &= 1 & \checkmark 
\end{align*}
\]
Decimal to Binary Conversion
(Using Guessing)

\[ 212 = 128 + 64 + 16 + 4 \rightarrow 11010100_2 \]

\[
\begin{array}{ccc}
2^7 & = & 128 & \checkmark \\
2^6 & = & 64 & \checkmark \\
2^5 & = & 32 \\
2^4 & = & 16 & \checkmark \\
2^3 & = & 8 \\
2^2 & = & 4 & \checkmark \\
2^1 & = & 2 \\
2^0 & = & 1 \\
\end{array}
\]
### Converting from Decimal to Binary

<table>
<thead>
<tr>
<th>result</th>
<th>remainder</th>
</tr>
</thead>
<tbody>
<tr>
<td>235 / 2 = 117</td>
<td>1</td>
</tr>
<tr>
<td>117 / 2 = 58</td>
<td>1</td>
</tr>
<tr>
<td>58 / 2 = 29</td>
<td>0</td>
</tr>
<tr>
<td>29 / 2 = 14</td>
<td>1</td>
</tr>
<tr>
<td>14 / 2 = 7</td>
<td>0</td>
</tr>
<tr>
<td>7 / 2 = 3</td>
<td>1</td>
</tr>
<tr>
<td>3 / 2 = 1</td>
<td>1</td>
</tr>
<tr>
<td>1 / 2 = 0</td>
<td>1</td>
</tr>
</tbody>
</table>
# Converting from Decimal to Binary

<table>
<thead>
<tr>
<th>Result</th>
<th>Remainder</th>
</tr>
</thead>
<tbody>
<tr>
<td>235</td>
<td>1</td>
</tr>
<tr>
<td>117</td>
<td>1</td>
</tr>
<tr>
<td>58</td>
<td>0</td>
</tr>
<tr>
<td>29</td>
<td>1</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

235\textsubscript{10} = 11101011\textsubscript{2}
Convert \((857)_{10}\)

<table>
<thead>
<tr>
<th>Division</th>
<th>Result</th>
<th>Remainder</th>
<th>LSB</th>
<th>MSB</th>
</tr>
</thead>
<tbody>
<tr>
<td>857 ÷ 2</td>
<td>428</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>428 ÷ 2</td>
<td>214</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>214 ÷ 2</td>
<td>107</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>107 ÷ 2</td>
<td>53</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>53 ÷ 2</td>
<td>26</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26 ÷ 2</td>
<td>13</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 ÷ 2</td>
<td>6</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 ÷ 2</td>
<td>3</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 ÷ 2</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 ÷ 2</td>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Result is \((1101011001)_{2}\)
Octal System (Base 8)

<p>| | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
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<tbody>
<tr>
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<td>71</td>
<td>72</td>
<td>73</td>
<td>74</td>
<td>75</td>
<td>76</td>
<td>77</td>
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<td></td>
</tr>
</tbody>
</table>
## Binary to Octal Conversion

<table>
<thead>
<tr>
<th>Binary</th>
<th>Octal</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>0</td>
</tr>
<tr>
<td>001</td>
<td>1</td>
</tr>
<tr>
<td>010</td>
<td>2</td>
</tr>
<tr>
<td>011</td>
<td>3</td>
</tr>
<tr>
<td>100</td>
<td>4</td>
</tr>
<tr>
<td>101</td>
<td>5</td>
</tr>
<tr>
<td>110</td>
<td>6</td>
</tr>
<tr>
<td>111</td>
<td>7</td>
</tr>
</tbody>
</table>
Binary to Octal Conversion

101110010111_2 = ?_8
Binary to Octal Conversion

$101110010111_2 = ?_8$

101 110 010 111
Binary to Octal Conversion

\[ 101110010111_2 = ?_8 \]

\[ 101 \quad 110 \quad 010 \quad 111 \]

\[ 5 \quad 6 \quad 2 \quad 7 \]
Binary to Octal Conversion

101110010111_2 = ?_8

101 110 010 111
5  6  2  7

Thus, 101110010111_2 = 5627_8
Hexadecimal System (Base 16)

\[ 52_{16} = 5 \times 16^1 + 2 \times 16^0 = \]

\[ 5 \times 16 + 2 \times 1 = \]

\[ 80 + 2 = 82_{10} \]
The 16 Hexadecimal Digits

0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, F
The 16 Hexadecimal Digits

0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, F

10, 11, 12, 13, 14, 15
Hexadecimal to Decimal Conversion

\[ C3_{16} = C \times 16^1 + 3 \times 16^0 \]

\[ = 12 \times 16 + 3 \times 1 \]

\[ = 192 + 3 \]

\[ = 195_{10} \]
Hexadecimal to Decimal Conversion

\[ BEEF_{16} = ?_{10} \]
Hexadecimal to Decimal Conversion

\[ BEEF_{16} = B_{16} \times 16^3 + E_{16} \times 16^2 + E_{16} \times 16^1 + F_{16} \times 16^0 \]
\[ = 11 \times 16^3 + 14 \times 16^2 + 14 \times 16^1 + 15 \times 16^0 \]
\[ = 11 \times 4096 + 14 \times 256 + 14 \times 16 + 15 \times 1 \]
\[ = 45056 + 3584 + 224 + 15 \]
\[ = 48879_{10} \]
Binary to Hexadecimal Conversion

<table>
<thead>
<tr>
<th>Binary</th>
<th>Hexadecimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000</td>
<td>0</td>
</tr>
<tr>
<td>0001</td>
<td>1</td>
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<tr>
<td>0010</td>
<td>2</td>
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<td>0011</td>
<td>3</td>
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<tr>
<td>0100</td>
<td>4</td>
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<tr>
<td>0101</td>
<td>5</td>
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<tr>
<td>0110</td>
<td>6</td>
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<tr>
<td>0111</td>
<td>7</td>
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<tr>
<td>1000</td>
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<tr>
<td>1001</td>
<td>9</td>
</tr>
<tr>
<td>1010</td>
<td>A</td>
</tr>
<tr>
<td>1011</td>
<td>B</td>
</tr>
<tr>
<td>1100</td>
<td>C</td>
</tr>
<tr>
<td>1101</td>
<td>D</td>
</tr>
<tr>
<td>1110</td>
<td>E</td>
</tr>
<tr>
<td>1111</td>
<td>F</td>
</tr>
</tbody>
</table>
Binary to Hexadecimal Conversion

<table>
<thead>
<tr>
<th>Binary</th>
<th>Decimal</th>
<th>Hexadecimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0001</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0010</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
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<tr>
<td>0110</td>
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<td>0111</td>
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<tr>
<td>1000</td>
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<td>1001</td>
<td>9</td>
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<tr>
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<td>10</td>
<td>A</td>
</tr>
<tr>
<td>1011</td>
<td>11</td>
<td>B</td>
</tr>
<tr>
<td>1100</td>
<td>12</td>
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<td>D</td>
</tr>
<tr>
<td>1110</td>
<td>14</td>
<td>E</td>
</tr>
<tr>
<td>1111</td>
<td>15</td>
<td>F</td>
</tr>
</tbody>
</table>
Binary to Hexadecimal Conversion

$101110010111_2 = ?_{16}$
Binary to Hexadecimal Conversion

$101110010111_2 = ?_{16}$

1011 1001 0111
Binary to Hexadecimal Conversion

\[ 101110010111_2 = ?_{16} \]

1011 1001 0111
\[ \underline{B} \quad \underline{9} \quad \underline{7} \]
Binary to Hexadecimal Conversion

\[ 101110010111_2 = ?_{16} \]

\[ 1011 \hspace{0.5cm} 1001 \hspace{0.5cm} 0111 \]

\[  \underline{B} \hspace{0.5cm} 9 \hspace{0.5cm} 7 \]

Thus, \[ 101110010111_2 = B97_{16} \]
Decimal to Hexadecimal Conversion

\[ 1396_{10} = 574_{16} \]

<table>
<thead>
<tr>
<th>result</th>
<th>remainder</th>
</tr>
</thead>
<tbody>
<tr>
<td>1396  / 16 = 87</td>
<td>4</td>
</tr>
<tr>
<td>87 / 16 = 5</td>
<td>7</td>
</tr>
<tr>
<td>5 / 16 = 0</td>
<td>5</td>
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## Decimal to Hexadecimal Conversion

\[
502_{10} = 1F6_{16}
\]

<table>
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<td>31</td>
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<tr>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Signed integers are more complicated

We will talk more about them when we start with Chapter 3 in a couple of weeks.
The story with floats is even more complicated
IEEE 754-1985 Standard

In the example shown above, the sign is zero so s is +1, the exponent is 124 so e is −3, and the significand m is 1.01 (in binary, which is 1.25 in decimal). The represented number is therefore $+1.25 \times 2^{-3}$, which is +0.15625.

On-line IEEE 754 Converter

- http://www.h-schmidt.net/FloatApplet/IEEE754.html

- More about floating point numbers in Chapter 3.
Storing Characters

• This requires some convention that maps binary numbers to characters.

• ASCII table

• Unicode
# ASCII Table

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<thead>
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<th>Hx</th>
<th>Oct</th>
<th>Char</th>
<th>Dec</th>
<th>Hx</th>
<th>Oct</th>
<th>Html</th>
<th>Chr</th>
<th>Dec</th>
<th>Hx</th>
<th>Oct</th>
<th>Html</th>
<th>Chr</th>
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Source: www.LookupTables.com
### Extended ASCII Codes

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The Unicode Character Code

- http://www.unicode.org/charts/
Egyptian Hieroglyphs

http://www.unicode.org/charts/
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| ![Image](http://www.unicode.org/charts/)

Close up

http://www.unicode.org/charts/
Questions?
THE END