Embedded systems intro, Number systems

http://xkcd.com/74/
Overview

• What exactly is an *embedded system*?
• Why study embedded systems?
• Number systems
  – Base 2, 8, 10, 16
  – Converting between them all
**General-purpose computer**

- Device with a microprocessor
- Jack of all trades
- People willing to pay big $$$
- Rich input/output
- Crashing is irritating
- Complex operating system
- Lots of memory
- Powerful processor
- Program in high level languages ignoring hardware details

**Embedded system**

- Device with a microprocessor
- Specialize in 1 or a few things
- Must be very cheap
- Little to no input/output
- Crashing could kill somebody
- Often no operating system
- Little memory
- Simple processor
- Program “to the metal” often in low level languages (e.g. assembly)
General-purpose computer

1%

Embedded system

99%
Blurred lines?

LG VX5600

iPhone 4

Nokia 810

Android microwave

Android washing machine
Why study embedded?

• Opens up the other 99% of microprocessors
• **Learn how computers work** from ground up
• Prepare you for more advanced computer architecture courses
  – Binary, octal, hexadecimal **number systems**
  – How computers **store numbers**
  – **Bitwise operations**
  – **Boolean algebra**
  – Combinational and sequential **circuits**
  – How computers **fetch and execute** instructions
Why study embedded?

• Gain assembly language experience
  – Makes you appreciate high-level languages
  – Understand underlying hardware realities
  – Programming simple processors with no memory/cycles to waste
  – Extreme optimization of certain portions of a program (e.g. frequent calculations)
    – Modern optimizing compilers make gains questionable
  – Interacting directly with hardware (e.g. device drivers)
  – Real-time programs needing precise timing
Where have all the simple processors gone?

Microprocessor Transistor Counts 1971-2011 & Moore’s Law

curve shows transistor count doubling every two years

Date of introduction

Transistor count

2,600,000,000
1,000,000,000
400,000
2,300
100,000
10,000

Real-time

• Soft real-time - respond to a click in 100 ms
• Hard real-time - respond to rudder correction in 100 ms
• Timing unpredictable in high-level languages & operating systems
  – Java garbage collection
  – Thread scheduling by OS
  – Windows update

• Real-time versions of languages & operating systems
  – Real-time Java, real-time Linux, Windows CE
Embedded development challenges

• Reliability
  – Cannot crash, devices often run 24 x 7 x 365
  – Thorough testing, must handle errors and unexpected events

• Performance
  – Real time systems, rapid response
    • Antilock brakes → detect slippage and react within ms
  – Must not be bottleneck, good throughput
  – Multitasking, handle interrupts when data arrives
Embedded development challenges

• Resource constraints
  – Cost of device
  – Amount of memory
  – Power consumption (huge for mobile devices)

• Debugging
  – Is this a software or hardware problem?
  – Easier than hardware circuits, harder than desktop

• User interface
  – One-off device with perhaps limit I/O capabilities
  – Users won’t read manual
Number systems
Our friend: base 10

• “one thousand two hundred fifty two”
• Let’s convert this to 6-digit base 10:

**Most significant**

**Least significant**
Our friend: base 10

- “one thousand two hundred fifty two”
- Let’s convert this to 6-digit base 10:

$$10^5=100000 \quad 10^4=10000 \quad 10^3=1000 \quad 10^2=100 \quad 10^1=10 \quad 10^0=1$$

Most significant

Least significant
Our friend: base 10

• “one thousand two hundred fifty two”
• Let’s convert this to 6-digit base 10:

<table>
<thead>
<tr>
<th>$10^5 = 100000$</th>
<th>$10^4 = 10000$</th>
<th>$10^3 = 1000$</th>
<th>$10^2 = 100$</th>
<th>$10^1 = 10$</th>
<th>$10^0 = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

$1252 - 0 \cdot 100000 = 1252$

Most significant

Least significant
Our friend: base 10

• “one thousand two hundred fifty two”

• Let’s convert this to 6-digit base 10:

<table>
<thead>
<tr>
<th>$10^5$=100000</th>
<th>$10^4$=10000</th>
<th>$10^3$=1000</th>
<th>$10^2$=100</th>
<th>$10^1$=10</th>
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</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Most significant

Least significant

$1252 - 0 \cdot 100000 = 1252$

$1252 - 0 \cdot 10000 = 1252$
Our friend: base 10

- “one thousand two hundred fifty two”
- Let’s convert this to 6-digit base 10:

<table>
<thead>
<tr>
<th>10^5 = 100000</th>
<th>10^4 = 10000</th>
<th>10^3 = 1000</th>
<th>10^2 = 100</th>
<th>10^1 = 10</th>
<th>10^0 = 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Most significant: $1252 \times 0 \times 100000 = 1252$
$1252 \times 0 \times 10000 = 1252$
$1252 \times 1 \times 1000 = 252$

Least significant: $10$
Our friend: base 10

- “one thousand two hundred fifty two”
- Let’s convert this to 6-digit base 10:

<table>
<thead>
<tr>
<th>$10^5$=100000</th>
<th>$10^4$=10000</th>
<th>$10^3$=1000</th>
<th>$10^2$=100</th>
<th>$10^1$=10</th>
<th>$10^0$=1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Most significant

$1252 - 0 \times 100000 = 1252$
$1252 - 0 \times 10000 = 1252$
$1252 - 1 \times 1000 = 252$
$252 - 2 \times 100 = 52$

Least significant
Our friend: base 10

• “one thousand two hundred fifty two”
• Let’s convert this to 6-digit base 10:

<table>
<thead>
<tr>
<th>Power</th>
<th>Value</th>
<th>Digit</th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>10⁵</td>
<td>100000</td>
<td>0</td>
<td>$1252 - 0 \cdot 100000 = 1252$</td>
</tr>
<tr>
<td>10⁴</td>
<td>10000</td>
<td>0</td>
<td>$1252 - 0 \cdot 10000 = 1252$</td>
</tr>
<tr>
<td>10³</td>
<td>1000</td>
<td>1</td>
<td>$1252 - 1 \cdot 1000 = 252$</td>
</tr>
<tr>
<td>10²</td>
<td>100</td>
<td>2</td>
<td>$252 - 2 \cdot 100 = 52$</td>
</tr>
<tr>
<td>10¹</td>
<td>10</td>
<td>5</td>
<td>$52 - 5 \cdot 10 = 2$</td>
</tr>
<tr>
<td>10⁰</td>
<td>1</td>
<td></td>
<td>$2$</td>
</tr>
</tbody>
</table>

Most significant: $1252 - 1 \cdot 1000 = 252$
Least significant: $52 - 5 \cdot 10 = 2$
Our friend: base 10

• "one thousand two hundred fifty two"
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<table>
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<th>10^5</th>
<th>10^4</th>
<th>10^3</th>
<th>10^2</th>
<th>10^1</th>
<th>10^0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>2</td>
</tr>
</tbody>
</table>

Most significant

1252 – 0 \cdot 100000 = 1252
1252 – 0 \cdot 10000 = 1252
1252 – 1 \cdot 1000 = 252
252 – 2 \cdot 100 = 52
52 – 5 \cdot 10 = 2
2 – 2 \cdot 1 = 0

Least significant
Our geeky friend: base 2

- Binary = base 2
- 0s and 1s
- low voltage (0-1V) vs. high voltage (3-5V)

01100111 0101
Our geeky friend: base 2

- Binary = base 2
- 0s and 1s
- low voltage (0-1V) vs. high voltage (3-5V)

01100111 0101

8 bits = byte 4 bits = nibble
Our geeky friend: base 2

- “forty two”
- Let’s convert this to 6-digit base 2:

Most significant

Least significant
Our geeky friend: base 2

- “forty two”
- Let’s convert this to 6-digit base 2:

<table>
<thead>
<tr>
<th>2^5=32</th>
<th>2^4=16</th>
<th>2^3=8</th>
<th>2^2=4</th>
<th>2^1=2</th>
<th>2^0=1</th>
</tr>
</thead>
</table>

Most significant

Least significant
Our geeky friend: base 2

- “forty two”
- Let’s convert this to 6-digit base 2:

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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$$42 - 1 \cdot 32 = 10$$

Most significant

Least significant
Our geeky friend: base 2

- “forty two”
- Let’s convert this to 6-digit base 2:

<table>
<thead>
<tr>
<th>$2^5=32$</th>
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<tr>
<td>1</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Most significant

42 – 1 · 32 = 10
10 – 0 · 16 = 10

Least significant
Our geeky friend: base 2

- “forty two”
- Let’s convert this to 6-digit base 2:

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<th>$2^5=32$</th>
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<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
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</table>

Most significant: $42 - 1 \cdot 32 = 10$

Least significant: $10 - 0 \cdot 16 = 10$

$10 - 1 \cdot 8 = 2$
Our geeky friend: base 2

- “forty two”
- Let’s convert this to 6-digit base 2:

<table>
<thead>
<tr>
<th>$2^5$=32</th>
<th>$2^4$=16</th>
<th>$2^3$=8</th>
<th>$2^2$=4</th>
<th>$2^1$=2</th>
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<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Most significant:
- $42 - 1 \cdot 32 = 10$
- $10 - 0 \cdot 16 = 10$
- $10 - 1 \cdot 8 = 2$
- $2 - 0 \cdot 4 = 2$

Least significant:
Our geeky friend: base 2

• “forty two”
• Let’s convert this to 6-digit base 2:

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</tr>
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<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Least significant

$42 - 1 \cdot 32 = 10$
$10 - 0 \cdot 16 = 10$
$10 - 1 \cdot 8 = 2$
$2 - 0 \cdot 4 = 2$
$2 - 1 \cdot 2 = 0$

Most significant
Our geeky friend: base 2

- “forty two”
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<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Most significant

42 – 1 · 32 = 10
10 – 0 · 16 = 10
10 – 1 · 8 = 2
2 – 0 · 4 = 2
2 – 1 · 2 = 0
0 – 0 · 1 = 0

Least significant
Our geeky friend: base 2

• Given a binary number: 011100
• What is this number in base 10?

0 1 1 1 0 0

Most significant

Least significant
Our geeky friend: base 2

- Given a binary number: 011100
- What is this number in base 10?

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</tr>
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<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

16 + 8 + 4 = 28

Most significant

Least significant
1110 0101 1010 0111
Our super geeky friend: base 16

1110 0101 1010 0111
E 5 A 7

- Hexadecimal (or hex)
- 16 digits: 0 1 2 3 4 5 6 7 8 9 A B C D E F
- Often written: 0xE5A7
Our super geeky friend: base 16

Binary : 1110 0101 1010 0111
Decimal : 58791
Hex : ?

\[16^3=4096\quad 16^2=256\quad 16^1=16\quad 16^0=1\]
Our super geeky friend: base 16

**Binary**: 1110 0101 1010 0111

**Decimal**: 58791

**Hex**: E

\[16^3 = 4096 \quad 16^2 = 256 \quad 16^1 = 16 \quad 16^0 = 1\]

\[
\begin{array}{c|c|c|c}
E & & & \\
\hline
\end{array}
\]

\[58791 - 14 \cdot 4096 = 1447\]
Our super geeky friend: base 16

Binary : 1110 0101 1010 0111

Decimal : 58791

Hex : E5

\[
\begin{array}{cccc}
16^3 = 4096 & 16^2 = 256 & 16^1 = 16 & 16^0 = 1 \\
E & 5 & & \\
\end{array}
\]

58791 – 14 \cdot 4096 = 1447

1447 – 5 \cdot 256 = 167
Our super geeky friend: base 16

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary</td>
<td>Decimal</td>
<td>Hex</td>
<td></td>
</tr>
<tr>
<td>1110 0101 1010 0111</td>
<td>58791</td>
<td>E5A</td>
<td></td>
</tr>
</tbody>
</table>

16<sup>3</sup> = 4096  
16<sup>2</sup> = 256  
16<sup>1</sup> = 16  
16<sup>0</sup> = 1

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>5</td>
<td>A</td>
<td></td>
</tr>
</tbody>
</table>

58791 − 14 · 4096 = 1447
1447 − 5 · 256 = 167
167 − 10 · 16 = 7
Our super geeky friend: base 16

Binary : 1110 0101 1010 0111
Decimal : 58791
Hex : E5A7

<table>
<thead>
<tr>
<th>16³=4096</th>
<th>16²=256</th>
<th>16¹=16</th>
<th>16⁰=1</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>5</td>
<td>A</td>
<td>7</td>
</tr>
</tbody>
</table>

58791 – 14 · 4096 = 1447
1447 – 5 · 256 = 167
167 – 10 · 16 = 7
7 – 7 · 1 = 0
<table>
<thead>
<tr>
<th>Binary</th>
<th>Hex</th>
<th>Decimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000</td>
<td>0x0</td>
<td>0</td>
</tr>
<tr>
<td>0001</td>
<td>0x1</td>
<td>1</td>
</tr>
<tr>
<td>0010</td>
<td>0x2</td>
<td>2</td>
</tr>
<tr>
<td>0011</td>
<td>0x3</td>
<td>3</td>
</tr>
<tr>
<td>0100</td>
<td>0x4</td>
<td>4</td>
</tr>
<tr>
<td>0101</td>
<td>0x5</td>
<td>5</td>
</tr>
<tr>
<td>0110</td>
<td>0x6</td>
<td>6</td>
</tr>
<tr>
<td>0111</td>
<td>0x7</td>
<td>7</td>
</tr>
<tr>
<td>1000</td>
<td>0x8</td>
<td>8</td>
</tr>
<tr>
<td>1001</td>
<td>0x9</td>
<td>9</td>
</tr>
<tr>
<td>1010</td>
<td>0xA</td>
<td>10</td>
</tr>
<tr>
<td>1011</td>
<td>0xB</td>
<td>11</td>
</tr>
<tr>
<td>1100</td>
<td>0xC</td>
<td>12</td>
</tr>
<tr>
<td>1101</td>
<td>0xD</td>
<td>13</td>
</tr>
<tr>
<td>1110</td>
<td>0xE</td>
<td>14</td>
</tr>
<tr>
<td>1111</td>
<td>0xF</td>
<td>15</td>
</tr>
</tbody>
</table>

0100111101100101

“nibblize”

0100 1111 0110 0101

Lookup in table

4 F 6 5

(also works the other way: hex to binary)
Our fringe friend: base 8

Binary : 110100111
Decimal : 423
Octal : ???

• Octal has 8 digits:
  0 1 2 3 4 5 6 7

<table>
<thead>
<tr>
<th>Binary</th>
<th>Octal</th>
<th>Hex</th>
<th>Decimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>0</td>
<td>0x0</td>
<td>0</td>
</tr>
<tr>
<td>001</td>
<td>1</td>
<td>0x1</td>
<td>1</td>
</tr>
<tr>
<td>010</td>
<td>2</td>
<td>0x2</td>
<td>2</td>
</tr>
<tr>
<td>011</td>
<td>3</td>
<td>0x3</td>
<td>3</td>
</tr>
<tr>
<td>100</td>
<td>4</td>
<td>0x4</td>
<td>4</td>
</tr>
<tr>
<td>101</td>
<td>5</td>
<td>0x5</td>
<td>5</td>
</tr>
<tr>
<td>110</td>
<td>6</td>
<td>0x6</td>
<td>6</td>
</tr>
<tr>
<td>111</td>
<td>7</td>
<td>0x7</td>
<td>7</td>
</tr>
</tbody>
</table>
Our fringe friend: base 8

Binary : 110 100 111
Decimal : 423
Octal : 647

• Octal has 8 digits:
  0 1 2 3 4 5 6 7

<table>
<thead>
<tr>
<th>Binary</th>
<th>Octal</th>
<th>Hex</th>
<th>Decimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>0</td>
<td>0x0</td>
<td>0</td>
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<tr>
<td>001</td>
<td>1</td>
<td>0x1</td>
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<tr>
<td>010</td>
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<td>0x2</td>
<td>2</td>
</tr>
<tr>
<td>011</td>
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</tr>
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<td>0x5</td>
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</tr>
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<td>0x6</td>
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<tr>
<td>111</td>
<td>7</td>
<td>0x7</td>
<td>7</td>
</tr>
</tbody>
</table>
Our fringe friend: base 8

• Ancient 18-bit computers
• Some natural languages count using spaces between fingers
• Used in `chmod` unix command

<table>
<thead>
<tr>
<th>User</th>
<th>Group</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>w</td>
<td>x</td>
</tr>
<tr>
<td>0·2² + 1·2¹ + 1·2⁰</td>
<td>1·2² + 0·2¹ + 1·2⁰</td>
<td>0·2² + 0·2¹ + 1·2⁰</td>
</tr>
<tr>
<td>0</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

`chmod 0351  ⇔  chmod u=wx,g=rx,o=x`
Different bases in C

```c
void main(void)
{
    int a = 10;
    int b = 010;
    int c = 0x10;

    printf("a = %d\n", a);
    printf("b = %d\n", b);
    printf("c = %d\n", c);
}
```
Different bases in C

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void main(void)
{
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    printf("a = %d\n", a);
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    printf("c = %d\n", c);
}
```

```
a = 10 
b = 8  
c = 16  
```
Summary

• Embedded systems
  – Specialized computing devices
  – Limited: I/O, memory, power, cost
  – May be mission critical, real-time systems

• Number systems
  – Base 2 (binary), 8 (octal), 10 (decimal), 16 (hex)
  – Conversion using simple math
    • Add, subtract, division with remainder, powers
  – Conversion using a lookup table