

## Unit 3

### Binary Representation

## ANALOG VS. DIGITAL

## Analog vs. Digital

- The analog world is based on continuous events. Observations can take on (\_\_\_\_) any value.
- The digital world is based on discrete events. Observations can only take on a \_\_\_\_\_ number of discrete values



## Analog vs. Digital

- Q. Which is better?
- A. Depends on what you are trying to do.
- Some tasks are better handled with analog data, others with digital data.
  - Analog means continuous/real valued signals with an infinite number of possible values
  - Digital signals are discrete [i.e. 1 of n values]

## Analog vs. Digital

- How much money is in my checking account?
  - Analog: Oh, some, but not too much.
  - Digital: \$243.67

## Analog vs. Digital

- How much do you love me?
  - Analog: I love you with all my heart!!!!
  - Digital:  $3.2 \times 10^3$  MegaHearts

## The Real (Analog) World

- The real world is inherently analog.
- To interface with it, our digital systems need to:
  - Convert analog signals to digital values (numbers) at the input.
  - Convert digital values to analog signals at the output.
- Analog signals can come in many forms
  - Voltage, current, light, color, magnetic fields, pressure, temperature, acceleration, orientation

## Digital is About Numbers

- In a digital world, numbers are used to represent all the possible discrete events (i.e. 1-of-n possibilities)
  - Numerical values (5.7, 1923.8, ...)
  - Computer instructions (ADD, SUB, BLE, ...)
  - Characters ('a', 'b', 'c', ...)
  - Conditions (on, off, ready, paper jam, ...)
- Numbers allow for easy manipulation
  - Add, multiply, compare, store, ...
- Results are repeatable
  - Each time we add the same two number we get the same result

## DIGITAL REPRESENTATION

## Interpreting Binary Strings

- Given a string of 1's and 0's, you need to know the *representation system* being used, before you can understand the value of those 1's and 0's.
- Information (value) = \_\_\_\_\_

01000001 = ?

<p>Unsigned Binary system</p>  <p>65<sub>10</sub></p>	<p>BCD System</p>  <p>41<sub>BCD</sub></p>	<p>ASCII system</p>  <p>'A'<sub>ASCII</sub></p>
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## Binary Representation Systems

- Integer Systems
  - Unsigned
    - Unsigned (Normal) binary
  - Signed
    - Signed Magnitude
    - 2's complement
    - Excess-N\*
    - 1's complement\*
- Floating Point\*
  - For very large and small (fractional) numbers
- Codes
  - Text
    - ASCII / Unicode
  - Decimal Codes
    - BCD (Binary Coded Decimal) / (8421 Code)

\* = Not fully covered in this class

## OVERVIEW

## 4 Skills

- We will teach you 4 skills that you should know and be able to apply with confidence
  - Convert a number in any base (base r) to decimal (base 10)
  - Convert a decimal number (base 10) to binary
  - Use the shortcut for conversion between binary (base 2) and hexadecimal (base 16)
  - Understand the finite number of combinations that can be made with n bits (binary digits) and its implication for codes including ASCII and Unicode

## Number Systems

- Number systems consist of
  1. A base (radix) r
  2. \_\_\_ coefficients \_\_\_\_\_
- Human System: Decimal (Base 10): 0,1,2,3,4,5,6,7,8,9
- Computer System: Binary (Base 2): 0,1
- Human systems for working with computer systems (shorthand for human to read/write binary)
  - Octal (Base 8): 0,1,2,3,4,5,6,7
  - Hexadecimal (Base 16): 0-9,A,B,C,D,E,F (A thru F = 10 thru 15)

## Skill 1: Converting to Decimal

- Number systems use implied place values (weights) that are powers of the base

$$\left( \underline{\quad} \underline{\quad} \underline{\quad} . \underline{\quad} \right)_{10} \quad \left( \underline{\quad} \underline{\quad} \underline{\quad} . \underline{\quad} \underline{\quad} \right)_2$$

$10^2=100 \quad 10^1=10 \quad 10^0=1 \quad 10^{-1}=0.1$ 
 $2^3=8 \quad 2^2=4 \quad 2^1=2 \quad 2^0=1 \quad 2^{-1}=0.5 \quad 2^{-2}=0.25$

- Converting from **another base** to **decimal** requires summing the product of each digit with its implied place value

$$\left( \begin{array}{ccccccc} 1 & 1 & 1 & 0 & . & 0 & 1 \\ \hline & & & & & & \end{array} \right)_2 = \left( \underline{\quad} \right)_{10}$$

## Conversion Examples 1

$$\begin{aligned} (746)_8 &= 7 * \underline{\quad} + 4 * \underline{\quad} + 6 * \underline{\quad} \\ &= 448 + 32 + 6 = 486_{10} \end{aligned}$$

$$\begin{aligned} (1A5)_{16} &= 1 * \underline{\quad} + \underline{\quad} * \underline{\quad} + 5 * \underline{\quad} \\ &= 256 + 160 + 5 = 421_{10} \end{aligned}$$

## Skill 2: Converting from Decimal

- Number systems use implied place values (weights) that are powers of the base

$$\left( \underline{\quad} \underline{\quad} \underline{\quad} \cdot \underline{\quad} \right)_{10} \quad \left( \underline{\quad} \underline{\quad} \underline{\quad} \underline{\quad} \cdot \underline{\quad} \underline{\quad} \right)_2$$

$$10^2=100 \quad 10^1=10 \quad 10^0=1 \quad 10^{-1}=0.1 \quad 2^3=8 \quad 2^2=4 \quad 2^1=2 \quad 2^0=1 \quad 2^{-1}=0.5 \quad 2^{-2}=0.25$$

- Converting from **decimal** to **another base** requires finding the digits that, when multiplied times each place value, will sum to the desired value (i.e. making change).

$$(29.75)_{10} = \left( \underline{\quad} \underline{\quad} \underline{\quad} \underline{\quad} \underline{\quad} \cdot \underline{\quad} \underline{\quad} \right)_2$$

$$16 \quad 8 \quad 4 \quad 2 \quad 1 \quad 0.5 \quad 0.25$$

## Conversion Examples 2

$$(87)_{10} = \quad = \left( \quad \right)_2$$

$$\frac{2^7}{128} \frac{2^6}{64} \frac{2^5}{32} \frac{2^4}{16} \frac{2^3}{8} \frac{2^2}{4} \frac{2^1}{2} \frac{2^0}{1}$$

$$(77)_{10} = \quad = \left( \quad \right)_{16}$$

$$\frac{16^1}{16} \frac{16^0}{1}$$

$$(4.375)_{10} = \quad = \left( \quad \right)_2$$

$$\frac{2^2}{4} \frac{2^1}{2} \frac{2^0}{1} \frac{2^{-1}}{1/2} \frac{2^{-2}}{1/4} \frac{2^{-3}}{1/8}$$

Shortcuts for Converting Binary (r=2), Hexadecimal (r=16) and Octal (r=8)

## SHORTHAND FOR BINARY

## Binary, Octal, and Hexadecimal

- |  |  |
|--|--|
| • Octal (base 8 = 2 <sup>3</sup> )                                       | • Hex (base 16=2 <sup>4</sup> )  |
| • 1 Octal digit ( ? ) <sub>8</sub> can represent: _____                  | • 1 Hex digit ( ? ) <sub>16</sub> can represent: _____                     |
| • 3 bits of binary ( ? ? ? ) <sub>2</sub> can represent: 000-111 = _____ | • 4 bits of binary ( ? ? ? ? ) <sub>2</sub> can represent: 0000-1111= 0-15 |
| • Conclusion...<br>1 Octal digit = _____                                 | • Conclusion...<br>1 Hex digit = _____                                     |

## Skill 3: Binary to Octal or Hex

- Make groups of 3 bits starting from radix point and working outward
- Add 0's where necessary
- Convert each group of 3 to an octal digit
- Make groups of 4 bits starting from radix point and working outward
- Add 0's where necessary
- Convert each group of 4 to a hex digit

$$\begin{array}{cccc} 1 & 0 & 1 & 0 \\ \hline \underbrace{101}_{421} & \underbrace{011}_{011} & \underbrace{1110}_{0110} & \underbrace{110}_{011} \\ 5 & 1 & 6 & 6 \end{array}$$

516.6<sub>8</sub>

$$\begin{array}{cccc} 0 & 0 & 0 & 1 \\ \hline \underbrace{000}_{000} & \underbrace{1010}_{1010} & \underbrace{01110}_{01110} & \underbrace{1100}_{1100} \\ & & & 0 \end{array}$$

## Octal or Hex to Binary

- Expand each octal digit to a group of 3 bits
- Expand each hex digit to a group of 4 bits

$$\begin{array}{cccc} & 3 & 1 & 7 & . & 2 \\ & \hline \underbrace{011}_{421} & \underbrace{100}_{421} & \underbrace{1111}_{421} & \underbrace{010}_{421} & . & 010 \end{array}$$

$$\begin{array}{cccc} & D & 9 & 3 & . & 8 \\ & \hline \underbrace{1101}_{8421} & \underbrace{1001}_{8421} & \underbrace{1111}_{8421} & \underbrace{1000}_{8421} & . & 1000 \end{array}$$

$$11001111.01_2$$

## Hexadecimal Representation

- Since values in modern computers are many bits, we use hexadecimal as a shorthand notation (4 bits = 1 hex digit)
  - 11010010 = D2 hex or **0xD2** if you write it in C/C++
  - 0111011011001011 = 76CB hex or **0x76CB** if you write it in C/C++

ASCII & Unicode

## BINARY CODES

# Binary Representation Systems

- Integer Systems
  - Unsigned
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    - 2's complement
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    - Excess-N\*
- Codes
  - Text
    - ASCII / Unicode
  - Decimal Codes
    - BCD (Binary Coded Decimal) / (8421 Code)
- Floating Point\*
  - For very large and small (fractional) numbers

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# Skill 4: Unique Combinations

- Given  $n$  digits of base  $r$ , how many unique numbers can be formed?      What is the range? [            ]
- Use the examples below to generalize the relationship

2-digit, decimal numbers ( $r=10, n=2$ )	<u>    </u> <u>    </u>	100 combinations: 00-99
	0-9    0-9	
3-digit, decimal numbers ( $r=10, n=3$ )	<u>    </u> <u>    </u> <u>    </u>	1000 combinations: 000-999
4-bit, binary numbers ( $r=2, n=4$ )	<u>    </u> <u>    </u> <u>    </u> <u>    </u>	16 combinations: 0000-1111
	0-1    0-1    0-1    0-1	
6-bit, binary numbers ( $r=2, n=6$ )	<u>    </u> <u>    </u> <u>    </u> <u>    </u> <u>    </u> <u>    </u>	64 combinations: 000000-111111

Main Point: Given  $n$  digits of base  $r$ ,      unique numbers can be made with the range [            ]

# Approximating Large Powers of 2

- Often need to find decimal approximation of a large powers of 2 like  $2^{16}$ ,  $2^{32}$ , etc.  $2^{16} =$
- Use following approximations:  $2^{24} =$ 
  - $2^{10} \approx$
  - $2^{20} \approx$
  - $2^{30} \approx$
  - $2^{40} \approx$   $2^{28} =$
- For other powers of 2, decompose into product of  $2^{10}$  or  $2^{20}$  or  $2^{30}$  and a power of 2 that is less than  $2^{10}$   $2^{32} =$ 
  - 16-bit half word:      numbers
  - 32-bit word:      numbers
  - 64-bit dword: 16 million trillion numbers

# Binary Codes

- Using binary we can represent any kind of information by coming up with a code
- Using  $n$  bits we can represent  $2^n$  distinct items

Colors of the rainbow:	Letters:
•Red = 000	•'A' = 00000
•Orange = 001	•'B' = 00001
•Yellow = 010	•'C' = 00010
•Green = 100	•
•Blue = 101	•
•Purple = 111	•'Z' = 11001

## ASCII Code

- Used for representing text characters
- Originally 7-bits but usually stored as \_\_\_\_\_ in modern computer systems
- Example:
  - "Hello\n"
  - Each character is converted to ASCII equivalent
    - 'H' = 0x48, 'e' = 0x65, ...
    - \n = newline character is represented by either one or two ASCII character
      - LF (0x0A) = line feed (moves cursor down a line)
      - CR (0x0D) = carriage return character (moves cursor to start of current line)
      - Newline for Unix / Mac = LF only
      - Newline for Windows = CR + LF

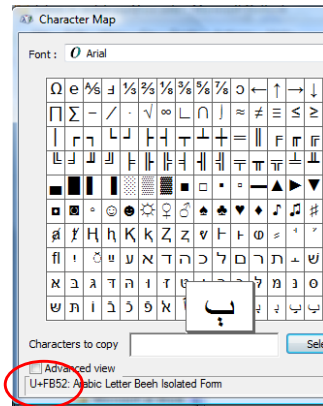
## ASCII Table

'M' = 0x4D = 0100 1101

LSD/MSD	0	1	2	3	4	5	6	7
0	NULL	DLW	SPACE	0	@	P	`	p
1	SOH	DC1	!	1	A	Q	a	q
2	STX	DC2	"	2	B	R	b	r
3	ETX	DC3	#	3	C	S	c	s
4	EOT	DC4	\$	4	D	T	d	t
5	ENQ	NAK	%	5	E	U	e	u
6	ACK	SYN	&	6	F	V	f	v
7	BEL	ETB	'	7	G	W	g	w
8	BS	CAN	(	8	H	X	h	x
9	TAB	EM	)	9	I	Y	i	y
A	LF	SUB	*	:	J	Z	j	z
B	VT	ESC	+	;	K	[	k	{
C	FF	FS	,	<	L	\	l	
D	CR	GS	-	=	M	]	m	}
E	SO	RS	.	>	N	^	n	~
F	SI	US	/	?	O	_	o	DEL

## Unicode

- ASCII can represent only the English alphabet, decimal digits, and punctuation
  - 7-bit code =>  $2^7 = 128$  characters
  - It would be nice to have one code that represented more alphabets/characters for common languages used around the world
- Unicode
  - Up to 32-bit Code => up to 4 billion combinations
  - 137,000 character defined for many languages
  - Used by Java as standard character code



Unicode hex value  
(i.e. FB52 => 1111101101010010)

## Review: Chars and Ints

- The C/C++ language supports types char and int. Let's see what you know about these:

True/False	Question
_____	In C/C++: '1' and 1 are the same. - '1' is replaced with its equiv. _____ - Thus, storing '1' or _____ to a char variable are all equivalent (the hardware does not _____ how the bits will be interpreted...that is up to the code)
_____	chars and ints have different ranges of the values they can represent. - Range of char: _____ - _____
_____	chars are only for ASCII characters (e.g. char c = '1'; and not char c = 1;) -



## Application: Chars and Ints

- Lesson 1: A char is just an 8-bit storage location (it can hold integer values or ASCII values)
  - If a function uses a char for an argument or return value, you can still pass integer values (see example to the right)
- Lesson 2: For output (display), we must use ASCII
  - Code will take/expect a certain "interpretation" of a char (either as an ASCII digit for input/output related code or as a small integer (for processing related code))
- Lesson 3: We can use arithmetic to manipulate chars.

```
char invert(char x)
{
    if(x == '1') return '0';
    else return '1';
}
int main(){
    char y = invert('1'); // passes 0x31=49
}
```

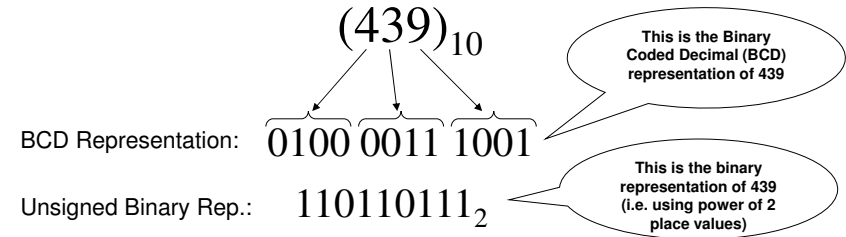
```
char invert(char x)
{
    if(x == 1) return 0;
    else return 1;
}
int main(){
    char y = invert(1); // passes 0x1 = 1
}
```

```
int main(){
    char c = 1;
    putchar(c); // prints nothing/garbage
}
```

```
int main(){
    char c = '1';
    putchar(c); // prints 1
    c = '0' + 7;
    putchar(c); // prints 7
}
```

## BCD (If Time Permits)

- Rather than convert a decimal number to binary which may lose some precision (i.e.  $0.1_{10} = \text{infinite binary fraction}$ ), BCD represents each decimal digit as a separate group of bits (exact decimal precision)
  - Each digit is represented as a separate 4-bit number (using place values 8,4,2,1 for each dec. digit)
  - Often used in financial and other applications where decimal precision is needed



**Important: Some processors have specific instructions to operate on #'s represented in BCD**

## Summary

- Convert Base r to Base 10
  - Apply place values (powers of r)
  - $N_r \Rightarrow \sum_i (a_i * r^i) \Rightarrow D_{10}$
- Convert Base 10 to Base r
  - "Make change" using powers of r as the weights/denominations
- Base 2 (Bin)  $\leftrightarrow$  Base 16 (Hex)
  - Group or expand 1 hex digit to/from 4 bits
  - Start at binary point and work outward

## BACKUP – MORE DETAILS

Using positional weights/place values

## BASE R TO BASE 10

## Skill 1: Converting Base r to Decimal

- $$934.7_{10} = \frac{9}{10^2=100} \frac{3}{10^1=10} \frac{4}{10^0=1} . \frac{7}{10^{-1}=0.1} = 934.7_{10}$$
- $$1101.1_2 = \frac{1}{2^3=8} \frac{1}{2^2=4} \frac{0}{2^1=2} \frac{1}{2^0=1} . \frac{1}{2^{-1}=0.5} = 8+4+1+0.5=13.5_{10}$$
- $$3B.4_{16} = \frac{3}{16^1=16} \frac{B}{16^0=1} . \frac{4}{16^{-1}=0.0625} = 48 + 11 + 0.25=59.25_{10}$$

**Main Point:** To convert any base to decimal (base 10), apply the implicit place values (weights) which are just the powers of the base and sum each digit times its place value.

## General Conversion From Base r to Decimal

- A number in base r has place values/weights that are the powers of the base
- Denote the coefficients as:  $a_i$

### Generalized approach:

$$(a_3 a_2 a_1 a_0 . a_{-1} a_{-2})_r = a_3 * r^3 + a_2 * r^2 + a_1 * r^1 + a_0 * r^0 + a_{-1} * r^{-1} + a_{-2} * r^{-2}$$

Left-most digit = Most Significant Digit (MSD)      Right-most digit = Least Significant Digit (LSD)

### Example:

$$(1001.01)_r = 1 * 2^3 + 0 * 2^2 + 0 * 2^1 + 1 * 2^0 + 0 * 2^{-1} + 1 * 2^{-2}$$

$$N_r \Rightarrow \sum_i (a_i * r^i) \Rightarrow D_{10}$$

Number in base r

Decimal Equivalent

## Examples

$$(746)_8 = 7 * 8^2 + 4 * 8^1 + 6 * 8^0 = 448 + 32 + 6 = 486_{10}$$

$$(1A5)_{16} = 1 * 16^2 + 10 * 16^1 + 5 * 16^0 = 256 + 160 + 5 = 421_{10}$$

$$(AD2)_{16} = 10 * 16^2 + 13 * 16^1 + 2 * 16^0 = 2560 + 208 + 2 = (2770)_{10}$$

## Binary Examples

$$\begin{array}{ccccccc} \underline{1} & \underline{0} & \underline{0} & \underline{1} & \underline{.} & \underline{1} & \\ 8 & 4 & 2 & 1 & .5 & & \\ (1001.1)_2 & = & 8 & + & 1 & + & 0.5 = 9.5_{10} \end{array}$$

$$\begin{array}{ccccccc} \underline{1} & \underline{0} & \underline{1} & \underline{1} & \underline{0} & \underline{0} & \underline{0} & \underline{1} & \\ 128 & 32 & 16 & & & & & 1 & \\ (10110001)_2 & = & 128 & + & 32 & + & 16 & + & 1 = 177_{10} \end{array}$$

## Powers of 2

- It helps to memorize the first 11 powers of 2

$$\begin{aligned} 2^0 &= 1 \\ 2^1 &= 2 \\ 2^2 &= 4 \\ 2^3 &= 8 \\ 2^4 &= 16 \\ 2^5 &= 32 \\ 2^6 &= 64 \\ 2^7 &= 128 \\ 2^8 &= 256 \\ 2^9 &= 512 \\ 2^{10} &= 1024 \end{aligned}$$

$$\begin{array}{cccccccccccc} \overline{1024} & \overline{512} & \overline{256} & \overline{128} & \overline{64} & \overline{32} & \overline{16} & \overline{8} & \overline{4} & \overline{2} & \overline{1} & \\ & & & & & & & & & & & \end{array}$$

"Making change"

## BASE 10 TO BASE 2 OR BASE 16

## Skill: Decimal to Base r

- To convert a decimal number,  $x$ , to binary:
  - Only coefficients of 1 or 0. So simply find place values that add up to the desired values, starting with larger place values and proceeding to smaller values and place a 1 in those place values and 0 in all others
  - Similar to how one would **make change**

$$25_{10} = \frac{0}{32} \frac{1}{16} \frac{1}{8} \frac{0}{4} \frac{0}{2} \frac{1}{1}$$

For  $25_{10}$ , the place value 32 is too large to include so we include 16. Including 16 means we have to make 9 left over. Include 8 and 1.

## Decimal to Unsigned Binary

$$73_{10} = \frac{0}{128} \frac{1}{64} \frac{0}{32} \frac{0}{16} \frac{1}{8} \frac{0}{4} \frac{0}{2} \frac{1}{1}$$

$$87_{10} = \frac{0}{128} \frac{1}{64} \frac{0}{32} \frac{1}{16} \frac{0}{8} \frac{1}{4} \frac{1}{2} \frac{1}{1}$$

$$145_{10} = \frac{1}{128} \frac{0}{64} \frac{0}{32} \frac{1}{16} \frac{0}{8} \frac{0}{4} \frac{0}{2} \frac{1}{1}$$

$$0.625_{10} = \frac{1}{.5} \frac{0}{.25} \frac{1}{.125} \frac{0}{.0625} \frac{0}{.03125}$$

## Decimal to Another Base

- To convert a decimal number,  $x$ , to base  $r$ :
  - Use the place values of base  $r$  (powers of  $r$ ). Starting with largest place values, fill in coefficients that sum up to desired decimal value without going over.

$$75_{10} = \frac{0}{256} \frac{4}{16} \frac{B}{1} \text{ hex}$$