Tutorial 01: Number Systems

Computer Science Department
CS2208: Introduction to Computer Organization and Architecture
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Instructor: Mahmoud R. El-Sakka
Office: MC-419
Email: elsakka@csd.uwo.ca
Phone: 519-661-2111 x86996

Number Systems

- In positional notation number systems
  - Numbers are ***represented*** (***encoded***) using digits
  - Each digit has a *value* and a *place*
  - Each *place* has a *weight*
    - for example, in decimal, we have the *ones place*, *tens place*, *hundreds place*, …

Number Systems

- A radix or base is
  - the number of unique digits, ***including zero***, used to represent numbers in a positional numeral system.

- With the use of a *radix point*, the notation can be extended to include *fractions* and *real numbers*.

Number Systems

- Examples of positional numeral systems
  - Decimal is base-10 ➔ {0, 1, 2, 3, 4, 5, 6, 7, 8, and 9}

  - Binary is base-2 ➔ {0, and 1}
  - Quaternary is base-4 ➔ {0, 1, 2, and 3}
  - Octal is base-8 ➔ {0, 1, 2, 3, 4, 5, 6, and 7}
  - Hexadecimal is base-16 ➔ {0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E and F}

  - Trinary is base-3 ➔ {0, 1, and 2}
  - Quinary is base-5 ➔ {0, 1, 2, 3, and 4}
  - Senary is base-6 ➔ {0, 1, 2, 3, 4, and 5}
  - Septenary is base-7 ➔ {0, 1, 2, 3, 4, 5, and 6}
  - Nonary is base-9 ➔ {0, 1, 2, 3, 4, 5, 6, 7, and 8}
  - Duodecimal is base-12 ➔ {0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, and B}
  - Sexagesimal is base-60 ➔ {0, 1, 2, 3, 4, 5, …, 58 and 59}

You need to know how to convert values from one system to the other

Conversion from any other base system to decimal

- If the original number in base b is:

$$(a_{n-1}\ a_{n-2}\ \ldots\ a_i\ \ldots\ a_1\ a_0\ .\ a_{-1}\ a_{-2}\ \ldots\ a_{-m})_b$$

- The *decimal* value of this number is defined as

$$N_{10} = (a_{n-1}b^{n-1} + \ldots + a_i b^i + \ldots + a_1 b^1 + a_0 b^0 + a_{-1} b^{-1} + a_{-2} b^{-2} + \ldots + a_{-m} b^{-m})_{10}$$

Conversion from any other base system to decimal

- *Example 1*: Convert $2E8_{16}$ to *decimal*

$$2E8_{16} = 2\times16^2 + E\times16^1 + 8\times16^0$$
$$= 2\times256 + 14\times16 + 8\times1$$
$$= 512 + 224 + 8$$
$$= 744_{10}$$

This question can be asked as follow:
Convert the hexadecimal value 2E8 to *decimal*

Calculators are not allowed during exams.
You need to improve your mental math skills.

During exams, calculations will be simplified.

Yet, when you answer the assignment/quiz questions, you may want to use calculators, as simplifying the calculations are not considered in the assignment/quiz.

10 = A
11 = B
12 = C
13 = D
14 = E
15 = F

Conversion from any other base system to decimal

- *Example 2*: Convert 361_8 to *decimal*

$$361_8 = 3\times8^2 + 6\times8^1 + 1\times8^0$$
$$= 3\times64 + 6\times8 + 1\times1$$
$$= 192 + 48 + 1$$
$$= 241_{10}$$

This question can be asked as follow:
Convert the octal value 361 to *decimal*

Conversion from any other base system to decimal

- ***Example 3***: Convert 0.361_8 to *decimal*

$$0.361_8 = 3\times 8^{-1} + 6\times 8^{-2} + 1\times 8^{-3}$$
$$= 3\times 0.125 + 6\times 0.015625 + 1\times 0.001953125$$
$$= 0.375 + 0.09375 + 0.001953125$$
$$= 0.470703125_{10}$$

Another method:

$$0.361_8 = 361_8 / 1000_8$$
$$= (3\times 8^2 + 6\times 8^1 + 1\times 8^0) / (1\times 8^3)$$
$$= (3\times 64 + 6\times 8 + 1\times 1) / (1\times 512)$$
$$= (192 + 48 + 1) / (512)$$
$$= 241 / 512$$
$$= 0.470703125_{10}$$

Conversion from any other base system to decimal

- ***Example 4***: 12.112_3 to *decimal*

12.112_3

$= 1\times3^1 + 2\times3^0 + 1\times3^{-1} + 1\times3^{-2} + 2\times3^{-3}$

$= 1 \times 3 + 2 \times 1 + 1 \times 0.33333 + 1 \times 0.11111 + 2 \times 0.03703$

$= 3 + 2 + 0.33333 + 0.11111 + 0.07406 = 5.5185_{10}$

Another method:

$12.112_3 = 12112_3 / 1000_3$

$= (1\times3^4 + 2\times3^3 + 1\times3^2 + 1\times3^1 + 2\times3^0) / (1\times3^3)$

$= (81 + 54 + 9 + 3 + 2) / 27$

$= 149 / 27 = 5.5185_{10}$

Conversion from decimal to any other base system

- ***Division Method (for integer numbers)***
  - Initialize the quotient by the value of the *decimal number*
  - *Repeat*:
    - Divide the quotient from the previous stage by the new base to get
      - A new quotient (the whole number)
      - A *remainder*
    - The *remainder* here is *the next **least** significant digit* in the new number

    Until the new quotient becomes 0.

Conversion from decimal to any other base system

- *Example 5*: Convert 14_{10} to binary

  Binary means the new base is 2

  - $14/2 = 7$ Remainder: 0 ➔ This is the ***least*** significant binary digit
    Quotient $= 7 \neq 0$ ➔ continue
  - $7/2 = 3$ Remainder: 1 ➔ This is the ***2nd least*** significant binary digit
    Quotient $= 3 \neq 0$ ➔ continue
  - $3/2 = 1$ Remainder: 1 ➔ This is the ***3rd least*** significant binary digit
    Quotient $= 1 \neq 0$ ➔ continue
  - $1/2 = 0$ Remainder: 1 ➔ This is the ***4th least*** significant binary digit
    Quotient $= 0$ ➔ exit the *repeat-until* control structure
  - $14_{10} = 1110_2$

Note that, it is 1110_2
It is NOT 0111_2

Conversion <u>from decimal</u> to any other base system

- ***<u>Example 6</u>***: Convert 2477_{10} to hexadecimal:

  Hexadecimal means the new base is 16

  - $2477/16 = 154$ Remainder: 13 ➔ This is the ***<u>least</u>*** significant Hex digit
    Quotient $= 154 \neq 0$ ➔ continue
  - $154/16 = 9$ Remainder: 10 ➔ This is the ***<u>2nd least</u>*** significant Hex digit
    Quotient $= 9 \neq 0$ ➔ continue
  - $9/16 = 0$ Remainder: 9 ➔ This is the ***<u>3rd least</u>*** significant Hex digit
    Quotient $= 0$ ➔ exit the *repeat-until* control structure

  - $2477_{10} = 9AD_{16}$

Note that, it is $9AD_{16}$
It is NOT $DA9_{16}$

10 = A	13 = D
11 = B	14 = E
12 = C	15 = F

Conversion from decimal to any other base system

- ***Multiplication Method (for fraction numbers)***
  - Initialize the fraction by the value of the *fractional decimal number*
  - *Repeat*:
    - Multiply the fraction from the previous stage by the new base to get
      - A *whole number*
      - A new *fraction*
    - The *whole number* here is *the next digit to the right after the radix point* in the new number

    Until the new fraction becomes 0.

This condition might be *reached* or *not*.

If reached,

then we will have 100% accurate result.

If not,

then we have to approximate the result.

Conversion from decimal to any other base system

- *Example 7*: Convert 0.017578125_{10} to hexadecimal

  Hexadecimal means the new base is 16

  - $0.01757812 \times 16 = 0.28125$
    whole number: 0 ➔ *the next digit to the right after the radix point*
    fraction $= 0.28125 \neq 0$ ➔ continue

  - $0.28125 \times 16 = 4.5$
    whole number: 4 ➔ *the next digit to the right after the radix point*
    fraction $= 0.5 \neq 0$ ➔ continue

  - $0.5 \times 16 = 8.0$
    whole number: 8 ➔ *the next digit to the right after the radix point*
    fraction $= 0.0$ ➔ exit the *repeat-until* control structure

  - $0.017578125_{10} = 0.048_{16}$

Conversion <u>from decimal</u> to any other base system

- ***Example 8***: Convert 255.017578125_{10} to hexadecimal:

  Hexadecimal means the new base is 16

  $255.017578125_{10} = 255_{10} + 0.017578125_{10}$

  Using the ***division method***: $255_{10} \rightarrow FF_{16}$

  Using the ***multiplication method***: $0.017578125_{10} \rightarrow 0.048_{16}$

$255.017578125_{10} = FF.048_{16}$

Conversion <u>from decimal</u> to any other base system

- *Example 9*: Convert 0.85_{10} to hexadecimal
  Hexadecimal means the new base is 16
  - $0.85 \times 16 = 13.6$
    whole number: 13 ➔ *the next digit to the right after the radix point*
    fraction $= 0.6 \neq 0$ ➔ continue
  - $0.6 \times 16 = 9.6$
    whole number: 9 ➔ *the next digit to the right after the radix point*
    fraction $= 0.6 \neq 0$ ➔ continue
  - $0.6 \times 16 = 9.6$
    whole number: 9 ➔ *the next digit to the right after the radix point*
    fraction $= 0.6 \neq 0$ ➔ continue
  - …
  - $0.85_{10} = 0.D99999\ldots9_{16}$
  - Can be approximated in 4 digits after the radix point, for example, as
    - ***$0.D999_{16}$ (using truncation)*** or as
    - ***$0.D99A_{16}$ (using rounding)***

Conversion between <u>any two bases</u>, <u>other than decimal</u>

- This task can be done in two steps:
  - Convert from the source base to the decimal
  - Convert from the decimal to the destination base

Conversion between any two bases, other than decimal

- ***Example 10***: Convert $2E8_{16}$ to *octal*

$$2E8_{16} = 2\times16^2 + E\times16^1 + 8\times16^0$$
$$= 2\times256 + 14\times16 + 8\times1$$
$$= 512 + 224 + 8 = 744_{10}$$

10 = A	13 = D
11 = B	14 = E
12 = C	15 = F

744/8 = 93 Remainder: 0 ➔ This is the ***least*** significant octal digit
Quotient = 93 ≠ 0 ➔ continue

93/8 = 11 Remainder: 5 ➔ This is the ***2nd least*** significant octal digit
Quotient = 11 ≠ 0 ➔ continue

11/8 = 1 Remainder: 3 ➔ This is the ***3rd least*** significant octal digit
Quotient = 1 ≠ 0 ➔ continue

1/8 = 0 Remainder: 1 ➔ This is the ***4th least*** significant octal digit
Quotient = 11 ≠ 0 ➔ exit the *repeat-until* control structure

$$\mathbf{2E8_{16} = 744_{10} = 1350_8}$$

Conversion between any two bases, other than decimal (Special cases)

- ***Binary to octal or hexadecimal:***
  - ***Binary to octal conversion***
    - Group bits in three's, *starting from the binary point* (*pad the last group with 0's, if needed*)
    - Convert each of these three-bit group into an octal digit
  - ***Binary to hexadecimal conversion***
    - Group bits in four's, *starting from the binary point* (*pad the last group with 0's, if needed*)
    - Convert each of these four-bit group into a hexadecimal digit

Conversion between <u>any two bases</u>, <u>other than decimal</u> (Special cases)

- ***Example 11***: Convert 11001111_2 to *octal*

11001111_2

$\rightarrow 011\ \ 001\ \ 111_2$

$\rightarrow 317_8$

0 = 000
1 = 001
2 = 010
3 = 011
4 = 100
5 = 101
6 = 110
7 = 111

Conversion between any two bases, other than decimal (Special cases)

- *Example 12*: Convert 1111010101_2 to hexadecimal

1111010101_2

→ $0011\ \ 1101\ \ 0101_2$

→ $3D5_{16}$

0 = 0000	8 = 1000
1 = 0001	9 = 1001
2 = 0010	A = 1010
3 = 0011	B = 1011
4 = 0100	C = 1100
5 = 0101	D = 1101
6 = 0110	E = 1110
7 = 0111	F = 1111

Conversion between <u>any two bases</u>, <u>other than decimal</u> (Special cases)

- ***<u>Octal or hexadecimal to binary</u>:***
  - ***Octal to binary conversion***
    - Expanding each octal digit into three bits
  - ***Hexadecimal to binary conversion***
    - Expanding each hexadecimal digit into four bits

Conversion between <u>any two bases</u>, <u>other than decimal</u> (Special cases)

- *Example 13*: Convert 743_8 to binary

743_8

$\rightarrow 111\ \ 100\ \ 011_2$

$\rightarrow 111100011_2$

0 = 000
1 = 001
2 = 010
3 = 011
4 = 100
5 = 101
6 = 110
7 = 111

Conversion between any two bases, other than decimal (Special cases)

- *Example 14*: Convert $FA9_{16}$ to binary

$FA9_{16}$

$\rightarrow 1111\ \ 1010\ \ 1001_2$

$\rightarrow 111110101001_2$

0 = 0000	8 = 1000
1 = 0001	9 = 1001
2 = 0010	A = 1010
3 = 0011	B = 1011
4 = 0100	C = 1100
5 = 0101	D = 1101
6 = 0110	E = 1110
7 = 0111	F = 1111

Conversion between any two bases, other than decimal (Special cases)

- ***Octal to hexadecimal or hexadecimal to octal:***
  - Convert from the source base to the binary
    - Expanding each digit into three bits (in case of octal) or four bits (in case of hexadecimal)
  - Convert from the binary to the destination base
    - Group bits in three's (in case of octal) or four's (in case of hexadecimal), *starting from the binary point* (*pad the last group from both sides with 0's, if needed*)

Conversion between any two bases, other than decimal (Special cases)

- *Example 15*: Convert ABC_{16} to octal

ABC_{16}

$\rightarrow$ $1010\ 1011\ 1100_2$

$\rightarrow$ 101010111100_2

$\rightarrow$ $101\ 010\ 111\ 100_2$

$\rightarrow$ 5274_8

0 = 000
1 = 001
2 = 010
3 = 011
4 = 100
5 = 101
6 = 110
7 = 111

0 = 0000	8 = 1000
1 = 0001	9 = 1001
2 = 0010	A = 1010
3 = 0011	B = 1011
4 = 0100	C = 1100
5 = 0101	D = 1101
6 = 0110	E = 1110
7 = 0111	F = 1111

Conversion between <u>any two bases</u>, <u>other than decimal</u> (Special cases)

- *Example 16*: Convert $0.AB_{16}$ to octal

$0.AB_{16}$

$\rightarrow$ $0.1010\ \ 1011_2$

$\rightarrow$ 0.10101011_2

$\rightarrow$ $000.101\ \ 010\ \ 110_2$

$\rightarrow$ 0.526_8

0 = 000
1 = 001
2 = 010
3 = 011
4 = 100
5 = 101
6 = 110
7 = 111

0 = 0000	8 = 1000
1 = 0001	9 = 1001
2 = 0010	A = 1010
3 = 0011	B = 1011
4 = 0100	C = 1100
5 = 0101	D = 1101
6 = 0110	E = 1110
7 = 0111	F = 1111

Conversion between any two bases, other than decimal (Special cases)

- *Example 17*: Convert $AB.BA_{16}$ to octal

$AB.BA_{16}$

→ $1010\ 1011.1011\ 1010_2$

→ 10101011.1011101_2

→ $010\ 101\ 011.101\ 110\ 100_2$

→ 253.564_8

0 = 000
1 = 001
2 = 010
3 = 011
4 = 100
5 = 101
6 = 110
7 = 111

0 = 0000	8 = 1000
1 = 0001	9 = 1001
2 = 0010	A = 1010
3 = 0011	B = 1011
4 = 0100	C = 1100
5 = 0101	D = 1101
6 = 0110	E = 1110
7 = 0111	F = 1111

Conversion between any two bases, other than decimal (Special cases)

- ***Example 18***: Convert 123_8 to hexadecimal

123_8

$\rightarrow 001\ \ 010\ \ 011_2$

$\rightarrow 1010011_2$

$\rightarrow 0101\ \ 0\,011_2$

$\rightarrow 53_{16}$

0 = 000
1 = 001
2 = 010
3 = 011
4 = 100
5 = 101
6 = 110
7 = 111

0 = 0000	8 = 1000
1 = 0001	9 = 1001
2 = 0010	A = 1010
3 = 0011	B = 1011
4 = 0100	C = 1100
5 = 0101	D = 1101
6 = 0110	E = 1110
7 = 0111	F = 1111

Conversion between any two bases, other than decimal (Special cases)

- *Example 19*: Convert 0.123_8 to hexadecimal

0.123_8

→ $0.001\ 010\ 011_2$

→ 0.001010011_2

→ $0000.0010\ 1001\ 1000_2$

→ 0.298_{16}

0 = 000
1 = 001
2 = 010
3 = 011
4 = 100
5 = 101
6 = 110
7 = 111

0 = 0000	8 = 1000
1 = 0001	9 = 1001
2 = 0010	A = 1010
3 = 0011	B = 1011
4 = 0100	C = 1100
5 = 0101	D = 1101
6 = 0110	E = 1110
7 = 0111	F = 1111

Conversion between any two bases, other than decimal (Special cases)

- ***Example 20***: Convert 321.123_8 to hexadecimal

321.123_8

→ $011\ 010\ 001.001\ 010\ 011_2$

→ 11010001.001010011_2

→ $1101\ 0001.0010\ 1001\ 1000_2$

→ $D1.298_{16}$

0 = 000
1 = 001
2 = 010
3 = 011
4 = 100
5 = 101
6 = 110
7 = 111

0 = 0000	8 = 1000
1 = 0001	9 = 1001
2 = 0010	A = 1010
3 = 0011	B = 1011
4 = 0100	C = 1100
5 = 0101	D = 1101
6 = 0110	E = 1110
7 = 0111	F = 1111