

15-213

“The Class That Gives CMU Its Zip!”

Bits and Bytes

Aug. 31, 2000

Topics

- **Why bits?**
- **Representing information as bits**
 - **Binary/Hexadecimal**
 - **Byte representations**
 - » **numbers**
 - » **characters and strings**
 - » **Instructions**
- **Bit-level manipulations**
 - **Boolean algebra**
 - **Expressing in C**

Why Don't Computers Use Base 10?

Base 10 Number Representation

- That's why fingers are known as “digits”
- Natural representation for financial transactions
 - Floating point number cannot exactly represent \$1.20
- Even carries through in scientific notation
 - 1.5213×10^4

Implementing Electronically

- Hard to store
 - ENIAC (First electronic computer) used 10 vacuum tubes / digit
- Hard to transmit
 - Need high precision to encode 10 signal levels on single wire
- Messy to implement digital logic functions
 - Addition, multiplication, etc.

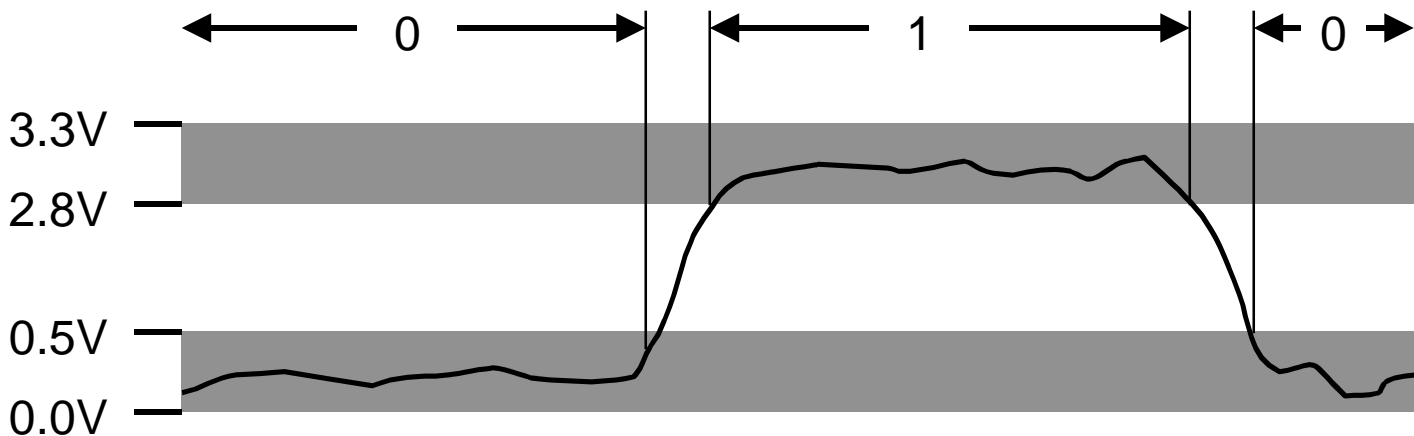
Binary Representations

Base 2 Number Representation

- Represent 15213_{10} as 11101101101101_2
- Represent 1.20_{10} as $1.0011001100110011[0011]\dots_2$
- Represent 1.5213×10^4 as $1.1101101101101_2 \times 2^{13}$

Electronic Implementation

- Easy to store with bistable elements
- Reliably transmitted on noisy and inaccurate wires



- **Straightforward implementation of arithmetic functions**

Byte-Oriented Memory Organization

Programs Refer to Virtual Addresses

- Conceptually very large array of bytes
- Actually implemented with hierarchy of different memory types
 - SRAM, DRAM, disk
 - Only allocate for regions actually used by program
- In Unix and Windows NT, address space private to particular “process”
 - Program being executed
 - Program can clobber its own data, but not that of others

Compiler + Run-Time System Control Allocation

- Where different program objects should be stored
- Multiple mechanisms: static, stack, and heap
- In any case, all allocation within single virtual address space

Encoding Byte Values

Byte = 8 bits

- Binary 00000000_2 to 11111111_2
- Decimal: 0_{10} to 255_{10}
- Hexadecimal 00_{16} to FF_{16}
 - Base 16 number representation
 - Use characters '0' to '9' and 'A' to 'F'
 - Write $FA1D37B_{16}$ in C as $0xFA1D37B$
 - » Or $0xfa1d37b$

Hex	Decimal	Binary
0	0	0000
1	1	0001
2	2	0010
3	3	0011
4	4	0100
5	5	0101
6	6	0110
7	7	0111
8	8	1000
9	9	1001
A	10	1010
B	11	1011
C	12	1100
D	13	1101
E	14	1110
F	15	1111

Machine Words

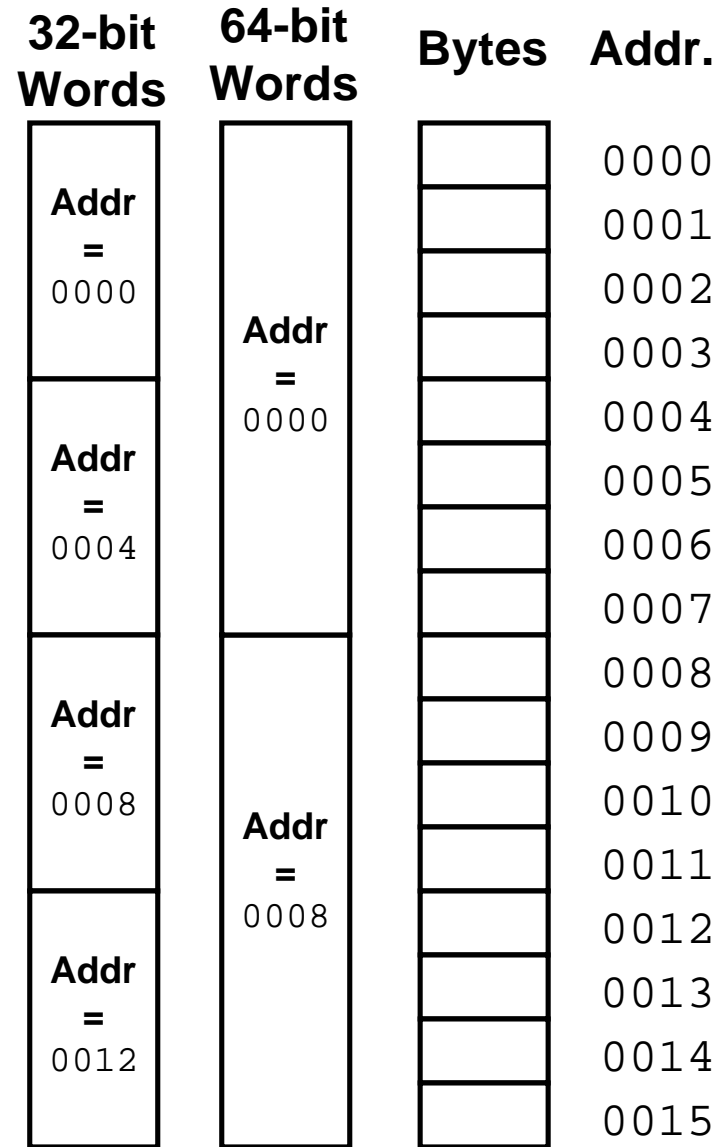
Machine Has “Word Size”

- **Nominal size of integer-valued data**
 - Including addresses
- **Most current machines are 32 bits (4 bytes)**
 - Limits addresses to 4GB
 - Becoming too small for memory-intensive applications
- **High-end systems are 64 bits (8 bytes)**
 - Potentially address $\approx 1.8 \times 10^{19}$ bytes
- **Machines support multiple data formats**
 - Fractions or multiples of word size
 - Always integral number of bytes

Word-Oriented Memory Organization

Addresses Specify Byte Locations

- Address of first byte in word
- Addresses of successive words differ by 4 (32-bit) or 8 (64-bit)



Data Representations

Sizes of C Objects (in Bytes)

C Data Type	Compaq Alpha	Typical 32-bit	Intel IA32
int	4	4	4
long int	8	4	4
char	1	1	1
short	2	2	2
float	4	4	4
double	8	8	8
long double	8	8	10/12
char *	8	4	4

» Or any other pointer

Byte Ordering

Issue

- How should bytes within multi-byte word be ordered in memory

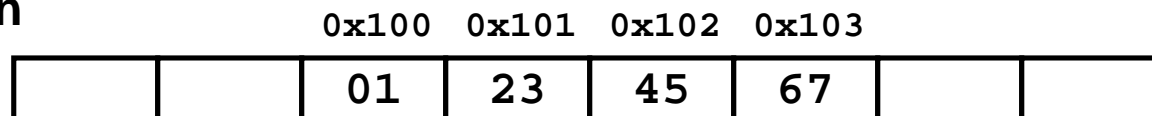
Conventions

- Alphas, PC's are "Little Endian" machines
 - Least significant byte has lowest address
- Sun's, Mac's are "Big Endian" machines
 - Least significant byte has highest address

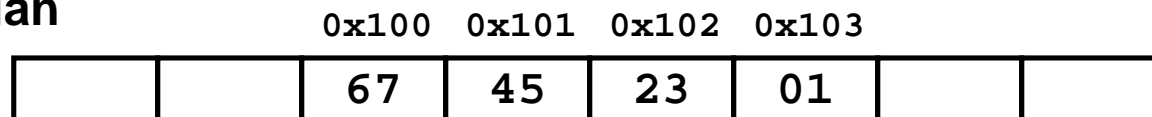
Example

- Variable `x` has 4-byte representation `0x01234567`
- Address given by `&x` is `0x100`

Big Endian



Little Endian



Examining Data Representations

Code to Print Byte Representation of Data

- Casting pointer to unsigned char * creates byte array

```
typedef unsigned char *pointer;

void show_bytes(pointer start, int len)
{
    int i;
    for (i = 0; i < len; i++)
        printf("0x%p\t0x%.2x\n",
               start+i, start[i]);
    printf("\n");
}
```

Printf directives:

%p: Print pointer

%x: Print Hexadecimal

show_bytes Execution Example

```
int a = 15213;  
printf("int a = 15213;\n");  
show_bytes((pointer) &a, sizeof(int));
```

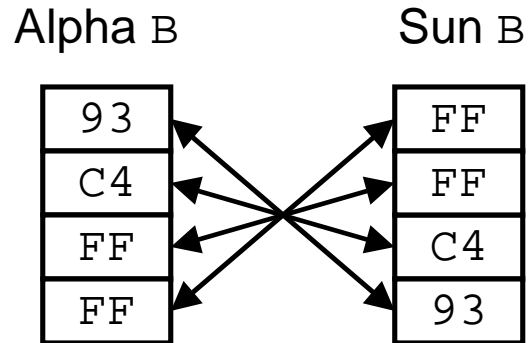
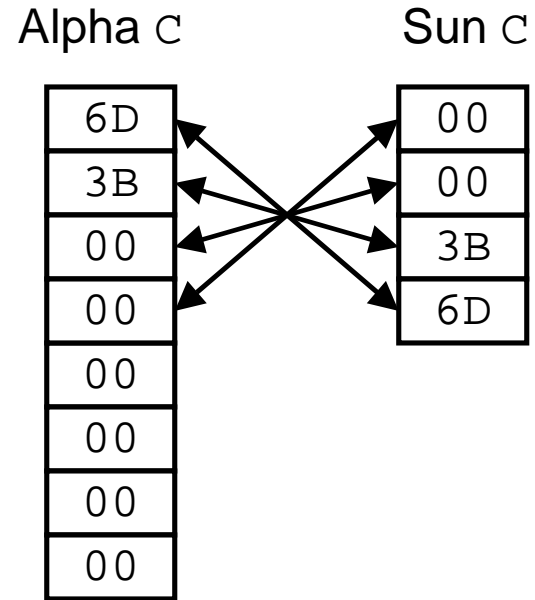
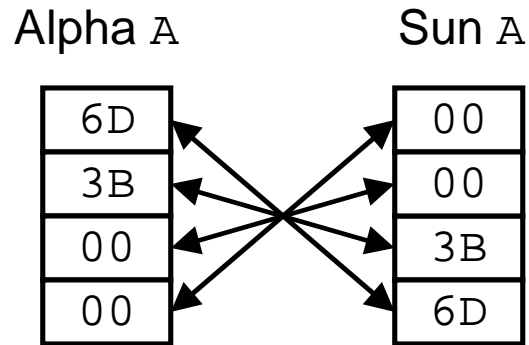
Result:

```
int a = 15213;  
0x11ffffcb8  0x6d  
0x11ffffcb9  0x3b  
0x11ffffcba  0x00  
0x11ffffcbb  0x00
```

Representing Integers

```
int A = 15213;  
int B = -15213;  
long int C = 15213;
```

Decimal:	15213
Binary:	0011 1011 0110 1101
Hex:	3 B 6 D



Two's complement representation
(Covered next lecture)

Representing Pointers

```
int B = -15213;
int *P = &B;
```

Alpha P

A0
FC
FF
FF
01
00
00
00

Alpha Address									
Hex:	1	F	F	F	F	F	C	A	0
Binary:	0001	1111	1111	1111	1111	1111	1100	1010	0000

Sun P

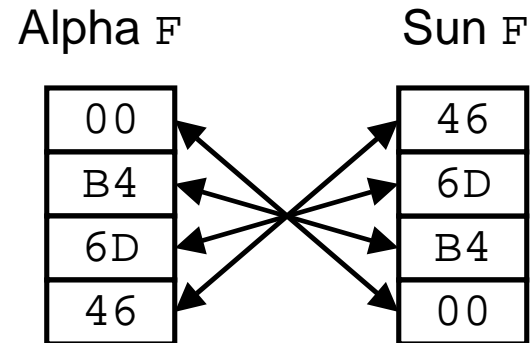
EF
FF
FB
2C

Sun Address								
Hex:	E	F	F	F	F	B	2	C
Binary:	1110	1111	1111	1111	1111	1011	0010	1100

Different compilers & machines assign different locations to objects

Representing Floats

Float F = 15213.0;



IEEE Single Precision Floating Point Representation

Hex: 4 6 6 D B 4 0 0

Binary: 0100 0110 0110 1101 1011 0100 0000 0000

15213: 1110 1101 1011 01



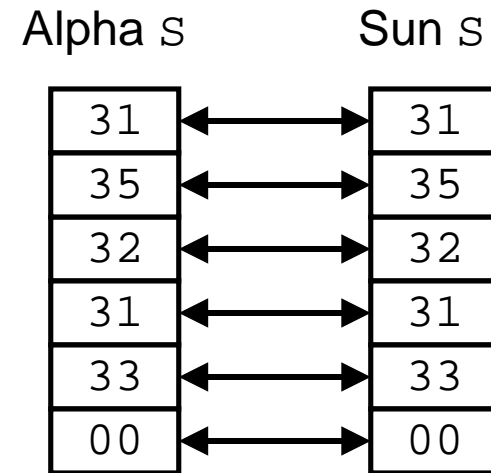
Not same as integer representation, but consistent across machines

Representing Strings

Strings in C

```
char s[6] = "15213";
```

- Represented by array of characters
- Each character encoded in ASCII format
 - Standard 7-bit encoding of character set
 - Other encodings exist, but uncommon
 - Character “0” has code $0x30$
 - » Digit i has code $0x30+i$
- String should be null-terminated
 - Final character = 0



Compatibility

- Byte ordering not an issue
 - Data are single byte quantities
- Text files generally platform independent
 - Except for different conventions of line termination character!

Machine-Level Code Representation

Encode Program as Sequence of Instructions

- Each simple operation
 - Arithmetic operation
 - Read or write memory
 - Conditional branch
- Instructions encoded as bytes
 - Alpha's, Sun's, Mac's use 4 byte instructions
 - » Reduced Instruction Set Computer (RISC)
 - PC's use variable length instructions
 - » Complex Instruction Set Computer (CISC)
- Different instruction types and encodings for different machines
 - Most code not binary compatible

Programs are Byte Sequences Too!

Representing Instructions

```
int sum(int x, int y)
{
    return x+y;
}
```

- For this example, Alpha & Sun use two 4-byte instructions
 - Use differing numbers of instructions in other cases
- PC uses 7 instructions with lengths 1, 2, and 3 bytes
 - Same for NT and for Linux
 - NT / Linux not binary compatible

Alpha sum

00
00
30
42
01
80
FA
6B

Sun sum

81
C3
E0
08
90
02
00
09

PC sum

55
89
E5
8B
45
0C
03
45
08
89
EC
5D
C3

Different machines use totally different instructions and encodings

Boolean Algebra

Developed by George Boole in 19th Century

- Algebraic representation of logic
 - Encode “True” as 1 and “False” as 0

And

- $A \& B = 1$ when both $A=1$ and $B=1$

$\&$	0	1
0	0	0
1	0	1

Or

- $A | B = 1$ when either $A=1$ or $B=1$

	0	1
0	0	1
1	1	1

Not

- $\sim A = 1$ when $A=0$

\sim	
0	1
1	0

Exclusive-Or (Xor)

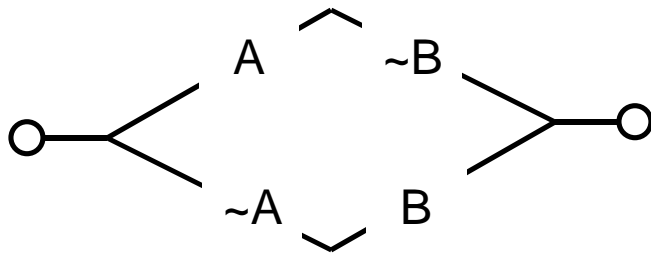
- $A \wedge B = 1$ when either $A=1$ or $B=1$, but not both

\wedge	0	1
0	0	1
1	1	0

Application of Boolean Algebra

Applied to Digital Systems by Claude Shannon

- 1937 MIT Master's Thesis
- Reason about networks of relay switches
 - Encode closed switch as 1, open switch as 0



Connection when
 $A \& \sim B \mid \sim A \& B$
 $= A \oplus B$

Properties of & and | Operations

Integer Arithmetic

- $\langle \mathbb{Z}, +, *, -, 0, 1 \rangle$ forms a “ring”
- Addition is “sum” operation
- Multiplication is “product” operation
- $-$ is additive inverse
- 0 is identity for sum
- 1 is identity for product

Boolean Algebra

- $\langle \{0,1\}, |, \&, \sim, 0, 1 \rangle$ forms a “Boolean algebra”
- Or is “sum” operation
- And is “product” operation
- \sim is “complement” operation (not additive inverse)
- 0 is identity for sum
- 1 is identity for product

Properties of Rings & Boolean Algebras

Boolean Algebra

- *Commutativity*

$$A | B = B | A$$

$$A \& B = B \& A$$

- *Associativity*

$$(A | B) | C = A | (B | C)$$

$$(A \& B) \& C = A \& (B \& C)$$

- *Product distributes over sum*

$$A \& (B | C) = (A \& B) | (A \& C)$$

- *Sum and product identities*

$$A | 0 = A$$

$$A \& 1 = A$$

- *Zero is product annihilator*

$$A \& 0 = 0$$

- *Cancellation of negation*

$$\sim (\sim A) = A$$

Integer Ring

$$A + B = B + A$$

$$A * B = B * A$$

$$(A + B) + C = A + (B + C)$$

$$(A * B) * C = A * (B * C)$$

$$A * (B + C) = A * B + B * C$$

$$A + 0 = A$$

$$A * 1 = A$$

$$A * 0 = 0$$

$$-(-A) = A$$

Ring \neq Boolean Algebra

Boolean Algebra

- Boolean: *Sum distributes over product*

$$A \mid (B \& C) = (A \mid B) \& (A \mid C)$$

- Boolean: *Idempotency*

$$A \mid A = A$$

– “A is true” or “A is true” = “A is true”

$$A \& A = A$$

- Boolean: *Absorption*

$$A \mid (A \& B) = A$$

– “A is true” or “A is true and B is true” = “A is true”

$$A \& (A \mid B) = A$$

- Boolean: *Laws of Complements*

$$A \mid \sim A = 1$$

– “A is true” or “A is false”

- Ring: *Every element has additive inverse*

$$A \mid \sim A \neq 0$$

Integer Ring

$$A + (B * C) \neq (A + B) * (B + C)$$

$$A + A \neq A$$

$$A * A \neq A$$

$$A + (A * B) \neq A$$

$$A * (A + B) \neq A$$

$$A + \sim A \neq 1$$

$$A + \sim A = 0$$

Properties of & and ^

Boolean Ring

- $\langle \{0,1\}, ^, \&, I, 0, 1 \rangle$
 - Identical to integers mod 2
 - I is identity operation: $I(A) = A$
- $$A \wedge A = 0$$

Property

- Commutative sum
- Commutative product
- Associative sum
- Associative product
- Prod. over sum
- 0 is sum identity
- 1 is prod. identity
- 0 is product annihilator
- Additive inverse

Boolean Ring

$$A \wedge B = B \wedge A$$

$$A \& B = B \& A$$

$$(A \wedge B) \wedge C = A \wedge (B \wedge C)$$

$$(A \& B) \& C = A \& (B \& C)$$

$$A \& (B \wedge C) = (A \& B) \wedge (A \& C)$$

$$A \wedge 0 = A$$

$$A \& 1 = A$$

$$A \& 0 = 0$$

$$A \wedge A = 0$$

Relations Between Operations

DeMorgan's Laws

- Express & in terms of |, and vice-versa

$$A \& B = \sim(\sim A | \sim B)$$

» A and B are true if and only if neither A nor B is false

$$A | B = \sim(\sim A \& \sim B)$$

» A or B are true if and only if A and B are not both false

Exclusive-Or using Inclusive Or

$$A \wedge B = (\sim A \& B) | (A \& \sim B)$$

» Exactly one of A and B is true

$$A \wedge B = (A | B) \& \sim(A \& B)$$

» Either A is true, or B is true, but not both

General Boolean Algebras

Operate on Bit Vectors

- Operations applied bitwise

01101001	01101001	01101001	01101001
<u>& 01010101</u>	<u> 01010101</u>	<u>^ 01010101</u>	<u>~ 01010101</u>
01000001	01111101	00111100	10101010

Representation of Sets

- Width w bit vector represents subsets of $\{0, \dots, w-1\}$

- $a_j = 1$ if $j \in A$

– 01101001 { 0, 3, 5, 6 }

– 01010101 { 0, 2, 4, 6 }

- **& Intersection** 01000001 { 0, 6 }
- **| Union** 01111101 { 0, 2, 3, 4, 5, 6 }
- **^ Symmetric difference** 00111100 { 2, 3, 4, 5 }
- **~ Complement** 10101010 { 1, 3, 5, 7 }

Bit-Level Operations in C

Operations $\&$, $|$, \sim , \wedge Available in C

- Apply to any “integral” data type
 - long, int, short, char
- View arguments as bit vectors
- Arguments applied bit-wise

Examples (Char data type)

- $\sim 0x41 \rightarrow 0xBE$
 $\sim 01000001_2 \rightarrow 10111110_2$
- $\sim 0x00 \rightarrow 0xFF$
 $\sim 00000000_2 \rightarrow 11111111_2$

- $0x69 \ \& \ 0x55 \rightarrow 0x41$
 $01101001_2 \ \& \ 01010101_2 \rightarrow 01000001_2$
- $0x69 \ | \ 0x55 \rightarrow 0x7D$
 $01101001_2 \ | \ 01010101_2 \rightarrow 01111101_2$

Contrast: Logic Operations in C

Contrast to Logical Operators

- `&&`, `||`, `!`
 - View 0 as “False”
 - Anything nonzero as “True”
 - Always return 0 or 1

Examples (char data type)

- `!0x41 --> 0x00`
- `!0x00 --> 0x01`
- `!!0x41 --> 0x01`

- `0x69 && 0x55 --> 0x01`
- `0x69 || 0x55 --> 0x01`

Shift Operations

Left Shift: $x \ll y$

- Shift bit-vector x left y positions
 - Throw away extra bits on left
 - Fill with 0's on right

Right Shift: $x \gg y$

- Shift bit-vector x right y positions
 - Throw away extra bits on right
- Logical shift
 - Fill with 0's on left
- Arithmetic shift
 - Replicate most significant bit on right
 - Useful with two's complement integer representation

Argument x	01100010
$\ll 3$	00010000
Log. $\gg 2$	00011000
Arith. $\gg 2$	00011000

Argument x	10100010
$\ll 3$	00010000
Log. $\gg 2$	00101000
Arith. $\gg 2$	11101000

Cool Stuff with Xor

- Bitwise Xor is form of addition
- With extra property that every value is its own additive inverse

$$A \oplus A = 0$$

```
void funny(int *x, int *y)
{
    *x = *x ^ *y;    /* #1 */
    *y = *x ^ *y;    /* #2 */
    *x = *x ^ *y;    /* #3 */
}
```

Step	*x	*y
Begin	A	B
1	$A \oplus B$	B
2	$A \oplus B$	$(A \oplus B) \oplus B = A \oplus (B \oplus B) = A \oplus 0 = A$
3	$(A \oplus B) \oplus A = (B \oplus A) \oplus A = B \oplus (A \oplus A) = B \oplus 0 = B$	A
End	B	A