In-Class Handout Version

15-213

"The Class That Gives CMU Its Zip!"

Bits and Bytes
Aug. 30, 2001

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.

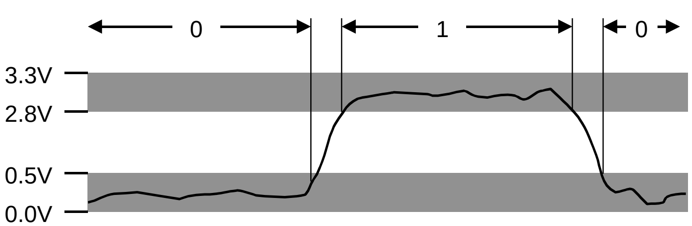
Binary Representations

Base 2 Number Representation

- Represent 15213_{10} as 11101101101101_2
- Represent 1.20_{10} as $1.0011001100110011[0011]\ldots_2$
- 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

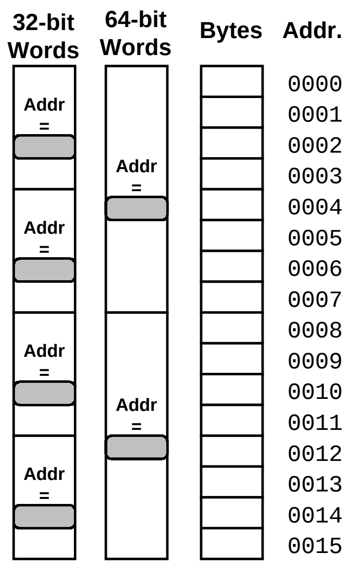
Machine Has "Word Size"

- 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 ≈ 1.8 X 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

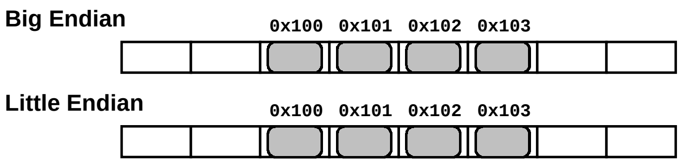
- How should bytes within multi-byte word be ordered in memory

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`



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));
```

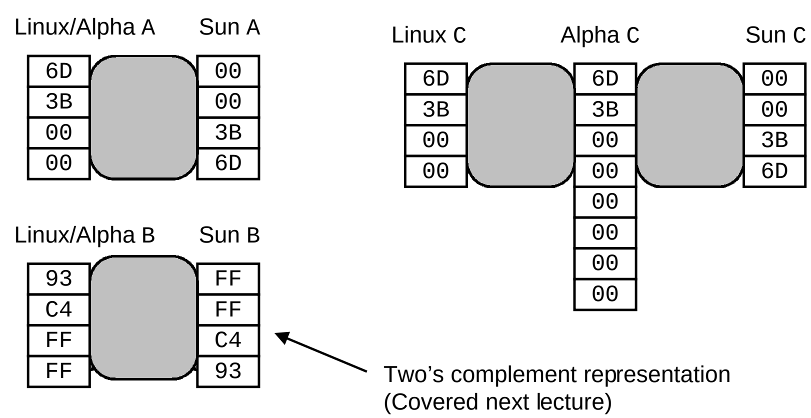
Result:

```
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



Representing Pointers

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

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

Alpha P
A0
FC
FF
FF
01
00
00
00

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

Linux Address								
Hex:	B	F	F	F	F	8	D	4
Binary:	1011	1111	1111	1111	1111	1000	1101	0100

Linux P
D4
F8
FF
BF

Different compilers & machines assign different locations to objects

Representing Floats

```
Float F = 15213.0;
```

Linux/Alpha F	Sun F
00	46
B4	6D
6D	B4
46	00

IEEE Single Precision Floating Point Representation								
Hex:	4	6	6	D	B	4	0	0
Binary:								
15213:			1110	1101	1011	01		

Not same as integer representation, but consistent across machines

Representing Strings

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

Strings in C

- 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

Linux/Alpha S	Sun S
31	31
35	35
32	32
31	31
33	33
00	00

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;
}
```

Alpha sum	Sun sum	PC sum
00	81	55
00	C3	89
30	E0	E5
42	08	8B
01	90	45
80	02	0C
FA	00	03
6B	09	45
		08
		89
		EC
		5D
		C3

- **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 fully binary compatible**

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

- **~A = 1 when A=0**

~	
0	1
1	0

Exclusive-Or (Xor)

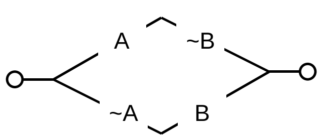
- **A^B = 1 when either A=1 or B=1, but not both**

^	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&~B | ~A&B
= A^B

Properties of & and | Operations

Integer Arithmetic

- ⟨Z, +, *, –, 0, 1⟩ **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

- ⟨{0,1}, |, &, ~, 0, 1⟩ **forms a "Boolean algebra"**
- **Or is "sum" operation**
- **And is "product" operation**
- **~ is "complement" operation (not additive inverse)**
- **0 is identity for sum**
- **1 is identity for product**

Properties of Rings & Boolean Algebras

Boolean Algebra — **Integer Ring**

- ***Commutativity***
  - A | B = B | A — A + B = B + A
  - A & B = B & A — A * B = B * A
- ***Associativity***
  - (A | B) | C = A | (B | C) — (A + B) + C = A + (B + C)
  - (A & B) & C = A & (B & C) — (A * B) * C = A * (B * C)
- ***Product distributes over sum***
  - A & (B | C) = (A & B) | (A & C) — A * (B + C) = A * B + B * C
- ***Sum and product identities***
  - A | 0 = A — A + 0 = A
  - A & 1 = A — A * 1 = A
- ***Zero is product annihilator***
  - A & 0 = 0 — A * 0 = 0
- ***Cancellation of negation***
  - ~ (~ A) = A — – (– A) = A

Ring ≠ Boolean Algebra

Boolean Algebra — **Integer Ring**

- **Boolean:** ***Sum distributes over product***
  - A | (B & C) = (A | B) & (A | C) — A + (B * C) ≠ (A + B) * (B + C)
- **Boolean:** ***Idempotency***
  - A | A = A — A + A ≠ A
  - – "A is true" or "A is true" = "A is true"
  - A & A = A — A * A ≠ A
- **Boolean:** ***Absorption***
  - A | (A & B) = A — A + (A * B) ≠ A
  - – "A is true" or "A is true and B is true" = "A is true"
  - A & (A | B) = A — A * (A + B) ≠ A
- **Boolean:** ***Laws of Complements***
  - A | ~A = 1 — A + –A ≠ 1
  - – "A is true" or "A is false"
- **Ring:** ***Every element has additive inverse***
  - A | ~A ≠ 0 — A + –A = 0

Properties of & and ^

Boolean Ring

- ⟨{0,1}, ^, &, *I*, 0, 1⟩
- Identical to integers mod 2
- *I* is identity operation: *I* (A) = A

  A ^ A = 0

Property — **Boolean Ring**

- Commutative sum — A ^ B = B ^ A
- Commutative product — A & B = B & A
- Associative sum — (A ^ B) ^ C = A ^ (B ^ C)
- Associative product — (A & B) & C = A & (B & C)
- Prod. over sum — A & (B ^ C) = (A & B) ^ (B & C)
- 0 is sum identity — A ^ 0 = A
- 1 is prod. identity — A & 1 = A
- 0 is product annihilator — A & 0 = 0
- Additive inverse — A ^ A = 0

Relations Between Operations

DeMorgan's Laws

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

  A & B = ~(~A | ~B)

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

  A | B = ~(~A & ~B)

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

Exclusive-Or using Inclusive Or

A ^ B = (~A & B) | (A & ~B)

» Exactly one of A and B is true

A ^ B = (A | B) & ~(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
& 01010101    | 01010101    ^ 01010101    ~ 01010101
```

Representation of Sets

- Width *w* bit vector represents subsets of {0, …, *w*–1}
- $a_j = 1$ **if** $j \in A$
  - **01101001** { }
  - **01010101** { }
- **&** Intersection **01000001**
- **|** Union **01111101**
- **^** Symmetric difference **00111100**
- **~** Complement **10101010**

Bit-Level Operations in C

Operations &, |, ~, ^ 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)

- **~0x41 -->**
  $\sim 01000001_2$ --> 10111110_2
- **~0x00 -->**
  $\sim 00000000_2$ --> 11111111_2

- **0x69 & 0x55 -->**
  01101001_2 & 01010101_2 --> 01000001_2
- **0x69 | 0x55 -->**
  01101001_2 | 01010101_2 --> 01111101_2

Contrast: Logic Operations in C

Contrast to Logical Operators

- **&&, ||, !**
  - View 0 as "False"
  - Anything nonzero as "True"
  - Always return 0 or 1
  - Early termination

Examples (char data type)

- **!0x41 -->**
- **!0x00 -->**
- **!!0x41 -->**

- **0x69 && 0x55 -->**
- **0x69 || 0x55 -->**
- **p && *p** (avoids null pointer access)

Shift Operations

Left Shift: x << y

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

Right Shift: x >> 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
<< 3	
Log. >> 2	
Arith. >> 2	

Argument x	10100010
<< 3	
Log. >> 2	
Arith. >> 2	

Cool Stuff with Xor

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

  A ^ 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^B	B
2		
3		
End		