Organisation und Architektur von Rechnern

Lecture 02

Instructor:

Reinhard v. Hanxleden

http://www.informatik.uni-kiel.de/rtsys/teaching/v-sysinf2

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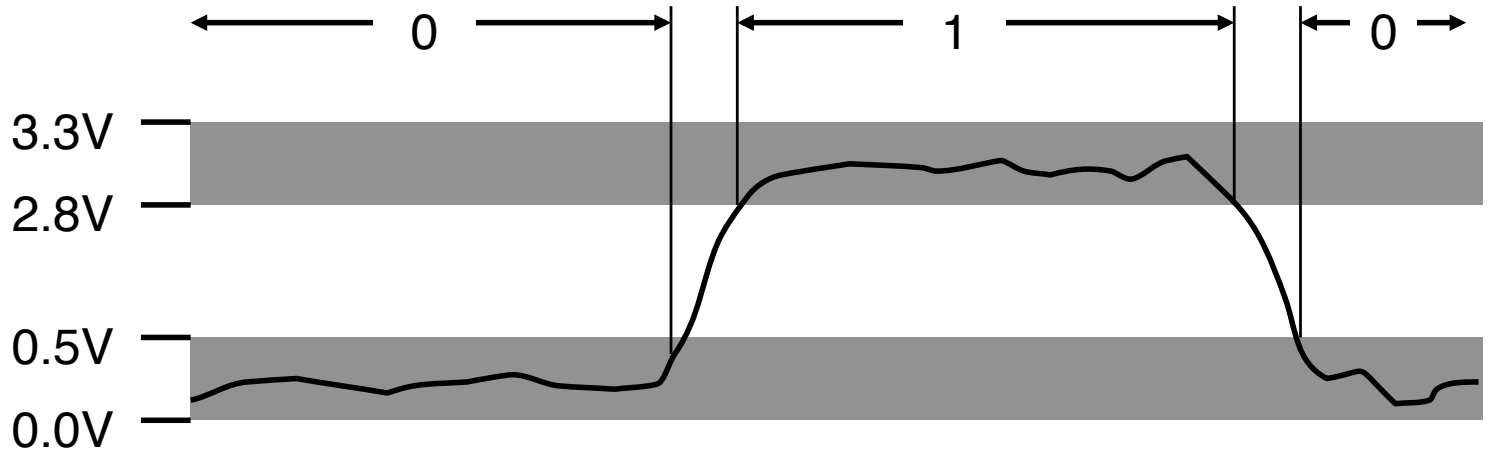
Binary Representations

- **Base 2 Number Representation**
  - Represent 15213_{10} as 11101101101101_2
  - Represent 1.20_{10} as $1.00110011001100110011[0011]\ldots_2$
  - 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

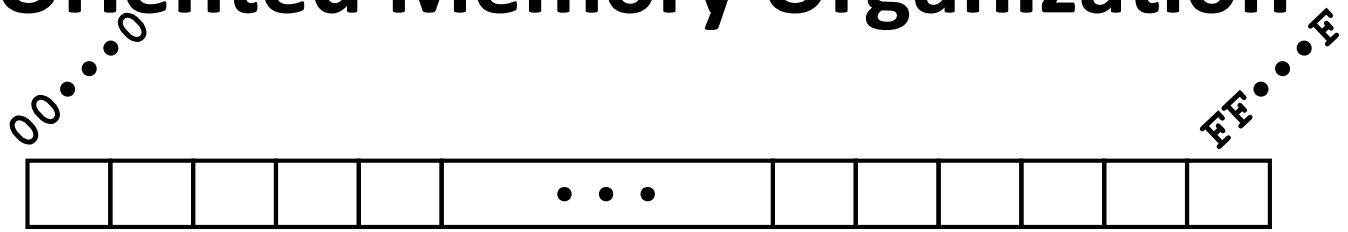


Encoding Byte Values

- **Byte = 8 bits**
  - Binary 00000000_2 to 11111111_2
  - Decimal: 0_{10} to 255_{10}
    - First digit must not be 0 in C
  - 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

Byte-Oriented Memory Organization



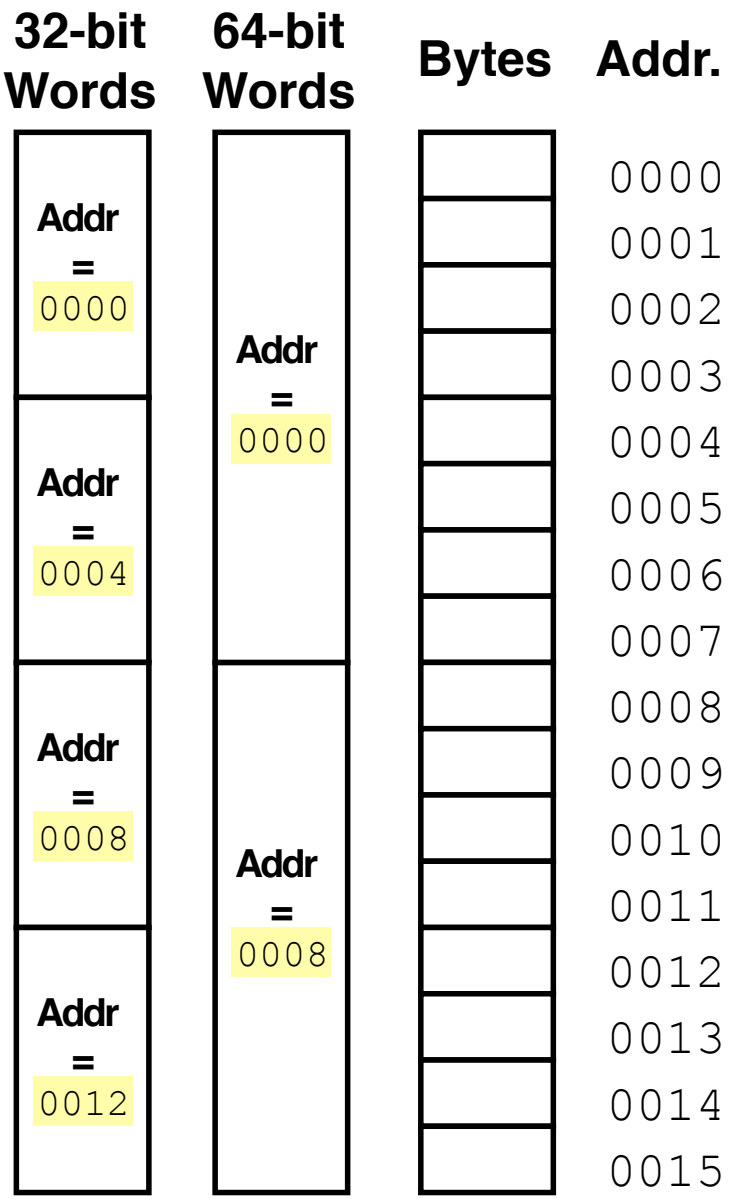
- **Programs Refer to Virtual Addresses**
  - Conceptually very large array of bytes
  - Actually implemented with hierarchy of different memory types
  - System provides address space private to particular "process"
    - Program being executed
    - Program can clobber its own data, but not that of others
- **Compiler + Run-Time System Control Allocation**
  - Where different program objects should be stored
  - All allocation within single virtual address space

Machine Words

- **Machine Has "Word Size"**
  - Nominal size of integer-valued data
    - Including addresses
  - Most current machines use 32 bits (4 bytes) words
    - Limits addresses to 4GB
    - Becoming too small for memory-intensive applications
  - High-end systems use 64 bits (8 bytes) words
    - Potential address space ≈ 1.8 X 10^{19} bytes
    - x86-64 machines support 48-bit addresses: 256 Terabytes
  - 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	Typical 32-bit	Intel IA32
	x86-64	
char	1	1
	1	
short	2	2
	2	
int	4	4
	4	
long	4	4
	8	
long long	8	8
	8	
float	4	4
	4	
double	8	8
	8	
long double	8	10/12
	10/16	
char *	4	4
	8	

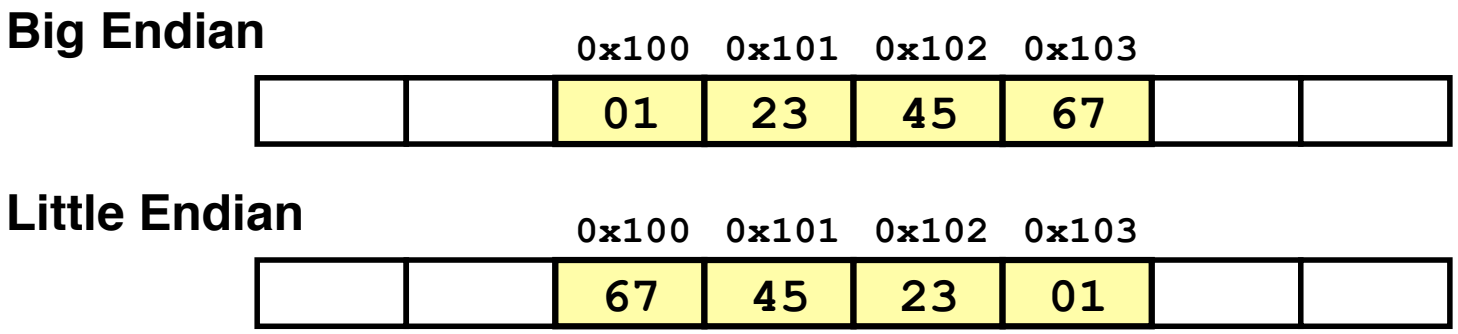
- Or any other pointer

Byte Ordering

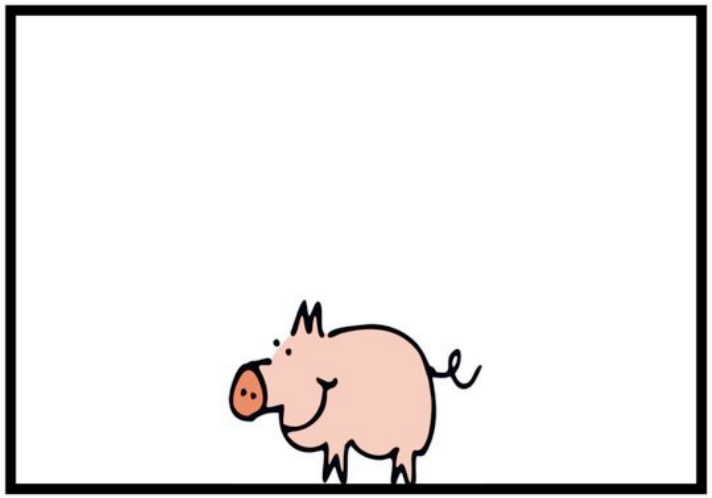
- **How should bytes within multi-byte word be ordered in memory?**
- **Conventions**
  - Big Endian: Sun, PPC Mac, Internet
    - Least significant byte has highest address
  - Little Endian: x86
    - Least significant byte has lowest address

Byte Ordering Example

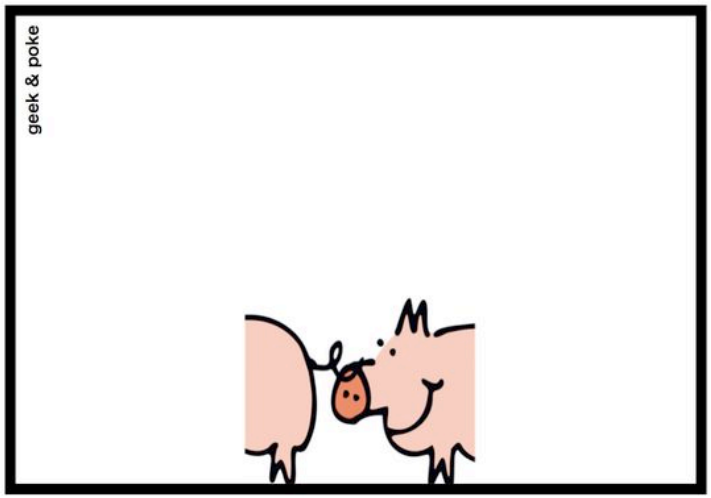
- **Big Endian**
  - Least significant byte has highest address
- **Little Endian**
  - Least significant byte has lowest address
- **Example**
  - Variable `x` has 4-byte representation `0x01234567`
  - Address given by `&x` is `0x100`



SIMPLY EXPLAINED



BIG-ENDIAN



LITTLE-ENDIAN

Reading Byte-Reversed Listings

- **Disassembly**
  - Text representation of binary machine code
  - Generated by program that reads the machine code
- **Example Fragment**

Address	Instruction Code	Assembly Rendition
8048365:	5b	pop %ebx
8048366:	81 c3 ab 12 00 00	add $0x12ab,%ebx
804836c:	83 bb 28 00 00 00 00	cmpl $0x0,0x28(%ebx)

Deciphering Numbers

- **Value:** 0x12ab
- **Pad to 32 bits:** 0x000012ab
- **Split into bytes:** 00 00 12 ab
- **Reverse:** ab 12 00 00

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 (Little Endian):

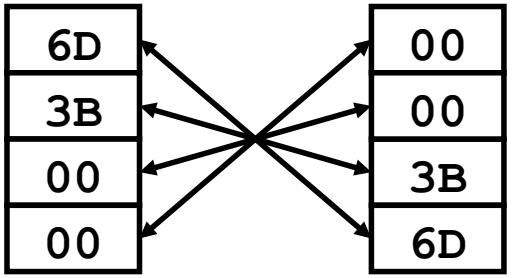
```
int a = 15213;
0x11ffffcb8   0x6d
0x11ffffcb9   0x3b
0x11ffffcba   0x00
0x11ffffcbb   0x00
```

Representing Integers

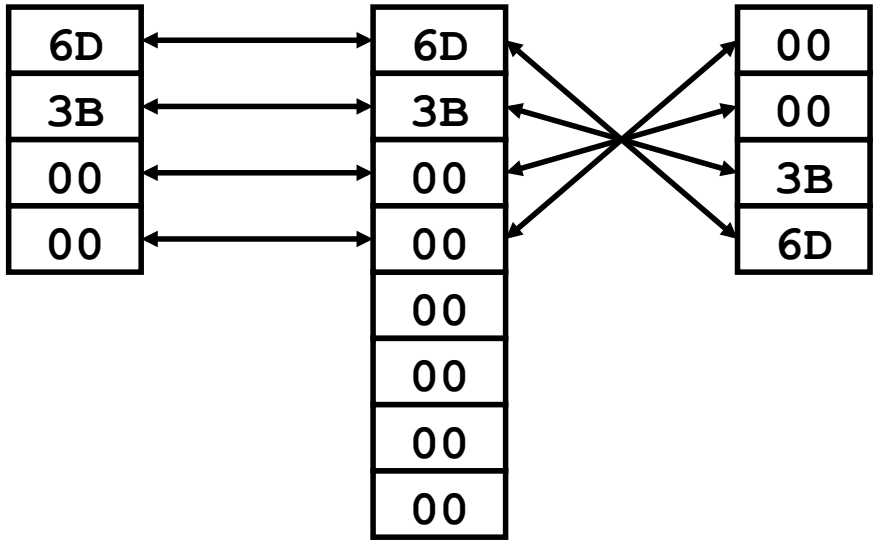
- `int A = 15213;`
- `int B = -15213;`
- `long int C = 15213;`

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

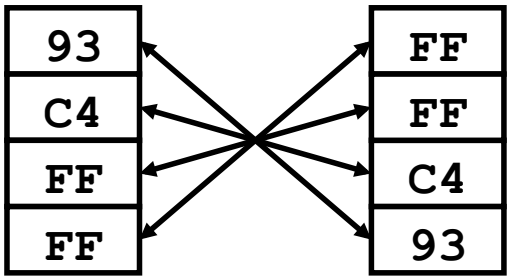
IA32, x86-64 `A` **Sun `A`**



IA32 `C` **x86-64 `C`** **Sun `C`**



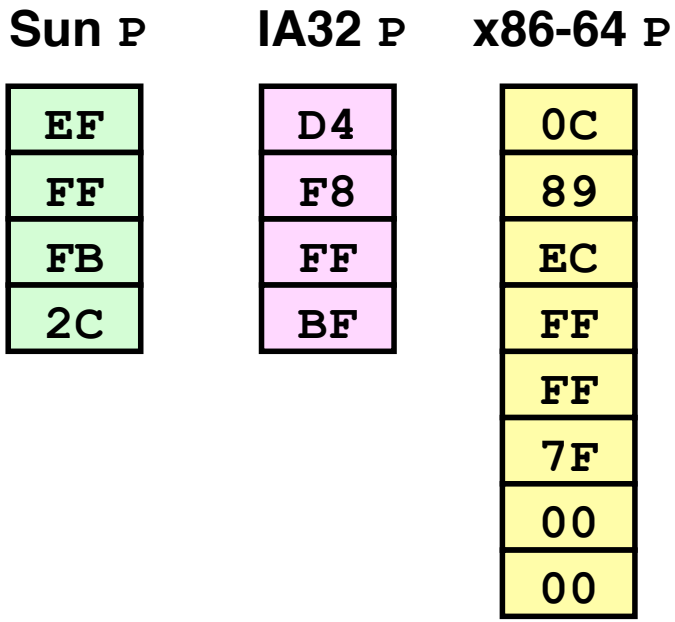
IA32, x86-64 `B` **Sun `B`**



Two's complement representation (Covered later)

Representing Pointers

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

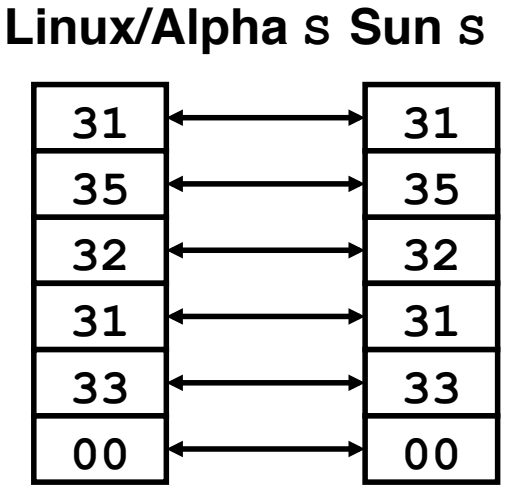


Different compilers & machines assign different locations to objects

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
    - 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



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

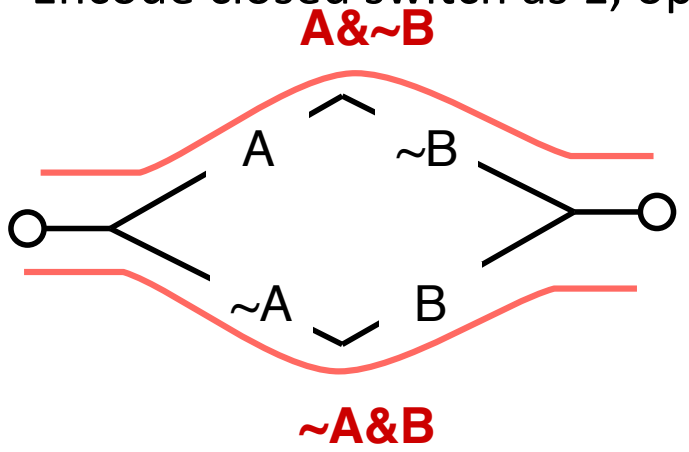
Exclusive-Or (Xor)

- **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

General Boolean Algebras

- **Operate on Bit Vectors**
  - Operations applied bitwise

```
  01101001     01101001     01101001
& 01010101   | 01010101   ^ 01010101   ~ 01010101
  01000001     01111101     00111100     10101010
```

- **All of the Properties of Boolean Algebra Apply**

Representing & Manipulating Sets

- **Representation**
  - Width ***w*** bit vector represents subsets of **{0, …, *w*–1}**
  - a_j **= 1** if $j \in A$

```
01101001                { 0, 3, 5, 6 }
76543210

01010101                { 0, 2, 4, 6 }
76543210
```

- **Operations**

&	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 &, |, ~, ^ Available in C**
  - Apply to any "integral" data type
    - `long, int, short, char, unsigned`
  - View arguments as bit vectors
  - Arguments applied bit-wise
- **Examples (Char data type)**
  - `~0x41` → `0xBE`

    $\sim 01000001_2 \rightarrow 10111110_2$
  - `~0x00` → `0xFF`

    $\sim 00000000_2 \rightarrow 11111111_2$
  - `0x69 & 0x55` → `0x41`

    $01101001_2 \;\&\; 01010101_2 \rightarrow 01000001_2$
  - `0x69 | 0x55` → `0x7D`

    $01101001_2 \mid 01010101_2 \rightarrow 01111101_2$

Contrast: Logic Operations in C

- **Contrast to Logical Operators**
  - `&&, ||, !`
    - View 0 as “False”
    - Anything nonzero as “True”
    - Always return 0 or 1
    - Early termination
- **Examples (char data type)**
  - `!0x41` → **0x00**
  - `!0x00` → **0x01**
  - `!!0x41` → **0x01**
  - `0x69 && 0x55` → **0x01**
  - `0x69 || 0x55` → **0x01**
  - `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
  - For unsigned values, use logical shift
  - For signed values, it is implementation-defined whether arithmetic or logical shift is used!
  - *Note:* Java distinguishes signed (>>) and unsigned (>>>) right shift – but has no unsigned integers
  - At assembler level, logical/arithmetic shift are different operations (x86: SHR vs. SAR)
- **Undefined Behavior if Shift Amount < 0 or ≥ Word Size**

Argument x	01100010
<< 3	00010*000*
Log. >> 2	*00*011000
Arith. >> 2	*00*011000

Argument x	10100010
<< 3	00010*000*
Log. >> 2	*00*101000
Arith. >> 2	*11*101000

Cool Stuff with Xor (Code example)

- 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 */
}
```

	*x	*y
Begin	A	B
1	A^B	B
2	A^B	(A^B)^B = A
3	(A^B)^A = B	A
End	B	A

Main Points

- **It's All About Bits & Bytes**
  - Numbers
  - Programs
  - Text
- **Different Machines Follow Different Conventions**
  - Word size
  - Byte ordering
  - Representations
- **Boolean Algebra is Mathematical Basis**
  - Basic form encodes "false" as 0, "true" as 1
  - General form like bit-level operations in C
    - Good for representing & manipulating sets