Computer Architecture and Systems Programming

(252-0061-00)

Timothy Roscoe

Herbstsemester 2012

You will have seen…

- Courses:
  - Programming & software engineering
  - Parallel programming
  - Data structures and algorithms
- Languages: Eiffel, Java, C#, …
- Constructs and techniques:
  - Object-orientation
  - Design-by-contract
  - Locks, atomicity, OpenMP, etc.

This course covers in *depth*…

- Programming in C
  - *Still* the systems programming language of choice
- Programming in Assembly Language
  - What the machine understands
- What *really* happens at the bit-level
  - Machine instructions
  - Memory systems
  - I/O devices
- Basic elements of processor design
- What makes things go fast (and slow)

Hold on tight!

Course Components

- Lectures
  - Higher level concepts and ideas
- Recitations
  - Applied concepts, important tools and skills for labs, clarification of lectures, exam coverage, C tutorial
- Lab exercises
  - The heart of the course
  - 1 week each (sometimes 2 weeks)
  - Provide in-depth understanding of aspects of systems
  - Programming and measurement
- Exam (100% of grade)
  - Test your understanding of concepts

Language

- I'll teach in English (and C…)
  - If I speak too fast, or say something unclear, raise your hand!
  - Please ask questions!
- Assistants' groups are 5 x German, 2 x English
  - So far…
- Examination:
  - Paper will be in English
  - Answers may be in German or English

Logistics

- Lectures here in CAB G.61
  - Tuesday, Wednesday 10:00 – 12:00
- Recitations – very important!
  - Thursday 13:00 – 15:00, IFW various rooms
  - Learn C, simulator, tools
  - Briefings for Lab exercises
  - Knowledge needed for exams, but not in the lectures!
- There **will** be a session this Thursday
  - Sign up sheets at the front of the room today
  - Check the course web page on Wednesday

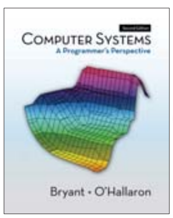
More logistics

- Web site:
  http://www.systems.ethz.ch/courses/fall2012/SPCA
  – Lecture notes should appear in advance on web site
  – The notes are not intended to be understood without lectures…
- Procedure for answering additional questions:
  1. Ask your friends
  2. Check the web
  3. Ask your teaching assistant
  4. Ask *another* teaching assistant
  5. Email me (troscoe@inf.ethz.ch)

Acknowledgements

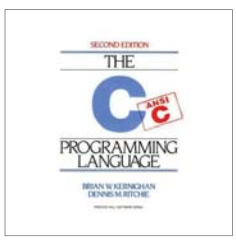
- Course based on CS 15-213 at Carnegie Mellon University
  – Lots of material gratefully borrowed from CMU
- New material: multicore, devices, etc.
  – All my fault ☺

Textbooks



Key book for the course!

- Randal E. Bryant and David R. O'Hallaron,
  – "Computer Systems: A Programmer's Perspective", 2nd edition, Prentice Hall 2010.
  – http://csapp.cs.cmu.edu
- Brian Kernighan and Dennis Ritchie,
  – "The C Programming Language, Second Edition", Prentice Hall, 1988



Motivation

- Most CS courses emphasize abstraction
  – Abstract data types (objects, contracts, etc.)
  – Asymptotic analysis (worst-case, complexity)
- These abstractions have limitations
  – Often don't survive contact with reality
  – Especially in the presence of bugs
  – Need to understand details of underlying implementations

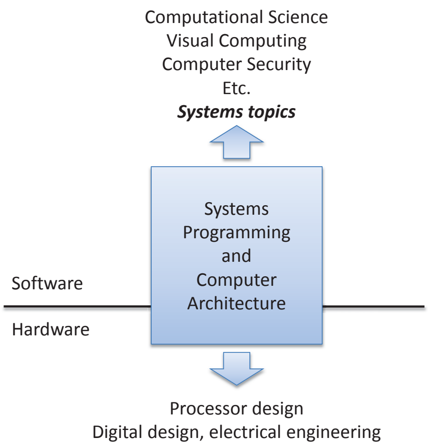
Goals

- Become more effective programmers
  – Find and eliminate bugs efficiently
  – Understand and tune for program performance
- Prepare for later systems classes at ETHZ
  – Compilers, Operating Systems, Networks, Computer Architecture, Embedded Systems

"Systems" as a field

- Encompasses:
  – Operating systems
  – Database systems
  – Networking protocols and routing
  – Compiler design and implementation
  – Distributed systems
  – Cloud computing & online services
- On and above *hardware/software* boundary

You are here:



Lecture 1:
Introduction, Bits and Bytes

Computer Architecture and
Systems Programming
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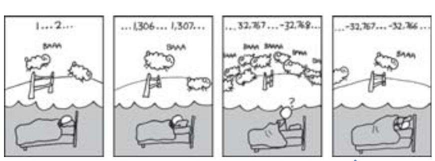
Motivation: 5 realities

Reality #1:

`int`'s are not integers.
`float`'s are not real numbers.

`int`s are not integers, **`float`**s are not reals

- Is $x^2 \geq 0$?
  - floats: Yes!



http://xkcd.com/571

  - ints:
    - 40000 * 40000 → 1600000000
    - 50000 * 50000 → ??
- Is (x + y) + z = x + (y + z)?
  - unsigned & signed ints: Yes!
  - floats:
    - (1e20 + -1e20) + 3.14 → 3.14
    - 1e20 + (-1e20 + 3.14) → ??

Code security example

```
/* Kernel memory region holding user-accessible data */
#define KSIZE 1024
char kbuf[KSIZE];

/* Copy at most maxlen bytes from kernel region to user buffer */
int copy_from_kernel(void *user_dest, int maxlen) {
    /* Byte count len is minimum of buffer size and maxlen */
    int len = KSIZE < maxlen ? KSIZE : maxlen;
    memcpy(user_dest, kbuf, len);
    return len;
}
```

- Similar to code found in a version of FreeBSD's implementation of **`getpeername`**
- There are legions of smart people trying to find vulnerabilities in programs

Typical usage

```
/* Kernel memory region holding user-accessible data */
#define KSIZE 1024
char kbuf[KSIZE];

/* Copy at most maxlen bytes from kernel region to user buffer */
int copy_from_kernel(void *user_dest, int maxlen) {
    /* Byte count len is minimum of buffer size and maxlen */
    int len = KSIZE < maxlen ? KSIZE : maxlen;
    memcpy(user_dest, kbuf, len);
    return len;
}
```

```
#define MSIZE 528

void getstuff() {
    char mybuf[MSIZE];
    copy_from_kernel(mybuf, MSIZE);
    printf("%s\n", mybuf);
}
```


Malicious usage

```
/* Kernel memory region holding user-accessible data */
#define KSIZE 1024
char kbuf[KSIZE];

/* Copy at most maxlen bytes from kernel region to user buffer */
int copy_from_kernel(void *user_dest, int maxlen) {
    /* Byte count len is minimum of buffer size and maxlen */
    int len = KSIZE < maxlen ? KSIZE : maxlen;
    memcpy(user_dest, kbuf, len);
    return len;
}
```

```
#define MSIZE 528

void getstuff() {
    char mybuf[MSIZE];
    copy_from_kernel(mybuf, -MSIZE);
    . . .
}
```


Computer arithmetic

- Does not generate random values
  - Arithmetic operations have important mathematical properties
- Cannot assume all "usual" mathematical properties
  - Due to finiteness of representations
  - Integer operations satisfy "ring" properties
    - Commutativity, associativity, distributivity
  - Floating point operations satisfy "ordering" properties
    - Monotonicity, values of signs
- Observation
  - Need to understand which abstractions apply in which contexts
  - Important issues for compiler writers and serious application programmers

Reality #2:

You've Got to Know Assembly

You've got to know assembly

- Chances are, you'll never write program in assembly
  - Compilers are much better & more patient than you are
- But: understanding assembly is **key** to machine-level execution model
  - Behavior of programs in presence of **bugs**
    - High-level language model breaks down
  - Tuning program **performance**
    - Understand optimizations done/not done by the compiler
    - Understanding sources of program inefficiency
  - Implementing **system software**
    - Compiler has machine code as target
    - Operating systems must manage process state
  - Creating / fighting **malware**
    - x86 assembly is the language of choice!

Assembly code example

- Time Stamp Counter
  - Special 64-bit register in Intel-compatible machines
  - Incremented every clock cycle
  - Read with `rdtsc` instruction
- Application
  - Measure time (in clock cycles) required by procedure

```
double t;
start_counter();
P();
t = get_counter();
printf("P required %f clock cycles\n", t);
```

Code to read counter

- Write small amount of assembly code using GCC's asm facility
- Inserts assembly code into machine code generated by compiler

```
static unsigned cyc_hi = 0;
static unsigned cyc_lo = 0;

/* Set *hi and *lo to the high and low order bits
   of the cycle counter.
*/
void access_counter(unsigned *hi, unsigned *lo)
{
    asm("rdtsc; movl %%edx,%0; movl %%eax,%1"
        : "=r" (*hi), "=r" (*lo)
        :
        : "%edx", "%eax");
}
```


Reality #3:

Memory matters.
RAM is an unrealistic abstraction.

Memory matters

- Memory is **not unbounded**
  - It must be allocated and managed
  - Many applications are memory-dominated
- Memory referencing bugs especially pernicious
  - Effects are distant in both time and space
- Memory performance is **not uniform**
  - Cache and virtual memory effects can greatly affect program performance
  - Adapting program to characteristics of memory system can lead to major speed improvements

Memory referencing bug

```
double fun(int i)
{
  volatile double d[1] = {3.14};
  volatile long int a[2];
  a[i] = 1073741824; /* Possibly out of bounds */
  return d[0];
}
```

```
fun(0)  ->     3.14
fun(1)  ->     3.14
fun(2)  ->     3.1399998664856
fun(3)  ->     2.00000061035156
fun(4)  ->     3.14, then segmentation fault
```

Explanation:

Saved State	4
d7 … d4	3
d3 … d0	2
a[1]	1
a[0]	0

Location accessed by `fun(i)`

Memory referencing errors

- C and C++ do not provide any memory protection
  - Out of bounds array references
  - Invalid pointer values
  - Abuses of malloc/free
- Can lead to nasty bugs
  - Whether or not bug has any effect depends on system and compiler
  - Action at a distance
    - Corrupted object logically unrelated to one being accessed
    - Effect of bug may be first observed long after it is generated
- How can I deal with this?
  - Program in C#, or ML, or Scala, or Haskell, or…
  - Understand what possible interactions may occur
  - Use or develop tools to detect referencing errors

Memory system performance

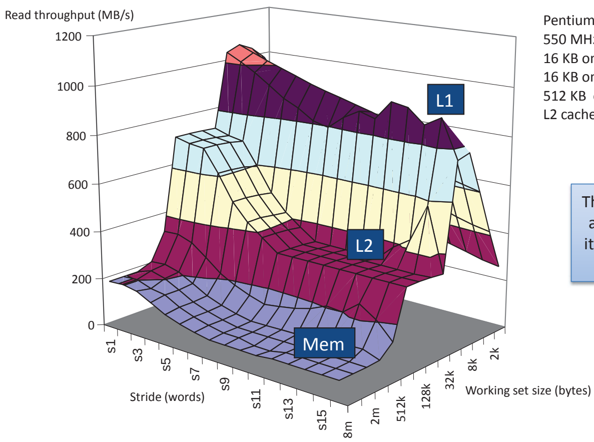
```
void copyij(int src[2048][2048],
            int dst[2048][2048])
{
  int i,j;
  for (i = 0; i < 2048; i++)
    for (j = 0; j < 2048; j++)
      dst[i][j] = src[i][j];
}
```

```
void copyji(int src[2048][2048],
            int dst[2048][2048])
{
  int i,j;
  for (j = 0; j < 2048; j++)
    for (i = 0; i < 2048; i++)
      dst[i][j] = src[i][j];
}
```

21 times slower
(Pentium 4)

- Hierarchical memory organization
- Performance depends on access patterns
  - Including how step through multi-dimensional array

The Memory Mountain



Pentium III Xeon
550 MHz
16 KB on-chip L1 d-cache
16 KB on-chip L1 i-cache
512 KB off-chip unified
L2 cache

This processor is a little old, but it's the same on new ones!

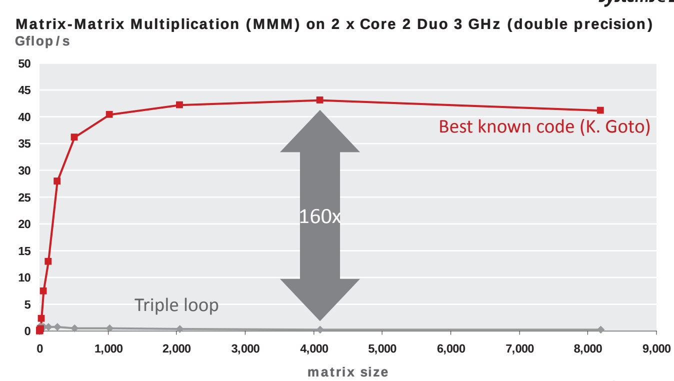
Reality #4:

There's much more to performance than asymptotic complexity

There's much more to performance than asymptotic complexity

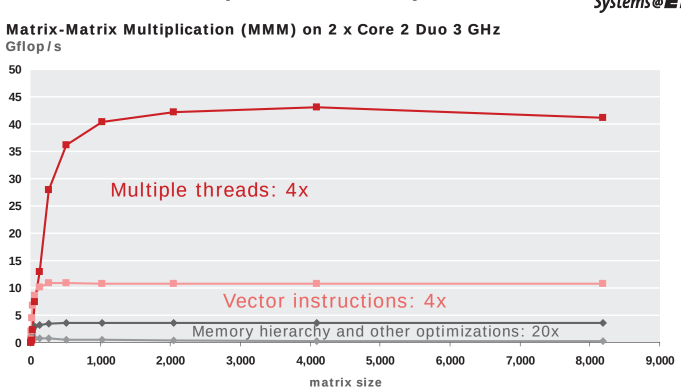
- Constant factors matter too!
- Even exact op count does not predict performance
  - Easily see 10:1 performance range depending on how code written
  - Must optimize at multiple levels: algorithm, data representations, procedures, and loops
- Must understand system to optimize performance
  - How programs compiled and executed
  - How to measure program performance and identify bottlenecks
  - How to improve performance without destroying code modularity and generality

Example: matrix multiplication



- Standard desktop computer, vendor compiler, using optimization flags
- Both implementations have exactly the same operations count ($2n^3$)
- What is going on?

MMM plot: analysis



- Reason for 20x: Blocking or tiling, loop unrolling, array scalarization, instruction scheduling, search to find best choice
- ***Effect: less register spills, less L1/L2 cache misses, less TLB misses***

Reality #5:

Computers don't just execute programs

Computers don't just run programs

- They need to get data in and out
  - I/O system critical to program reliability and performance
- They communicate with each other over networks
  - Many system-level issues arise in presence of network
    - Concurrent operations by autonomous processes
    - Coping with unreliable media
    - Cross platform compatibility
    - Complex performance issues

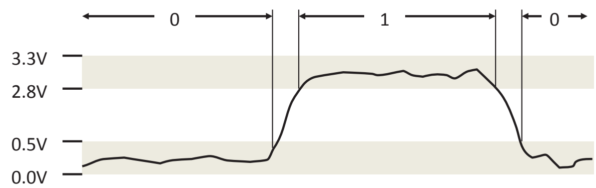
To start: Bits, Bytes and Integers

Bits, Bytes, and Integers

- Topics
  - Representing information as bits
  - Bit-level manipulations
    - Boolean algebra
    - Expressing in C
  - Representations of Integers
    - Basic properties and operations
    - Implications for C

Binary representations

- Base 2 number representation
  - Represent 15213_{10} as 11101101101101_2
  - Represent 1.20_{10} as $1.0011001100110011[0011]..._2$
  - 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	Dec	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

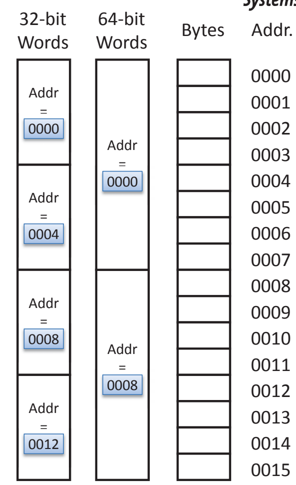
- Programs refer to *virtual addresses*
  - Conceptually, a very large array of bytes
  - Secretly, a hierarchy of different memory types
  - System provides *address space* private to particular "process"
    - Program being executed
    - Program can clobber its own data, but not that of others
- Compiler + runtime system control allocation
  - Where different program objects should be stored
  - All allocation within single virtual address space

Machine words

- Machines have a "word size"
  - Nominal size of integer-valued data
    - Including addresses
  - Many current machines use 32-bit (4 byte) words
    - Limits addresses to 4GB
    - Becoming too small for memory-intensive applications
  - Modern machines often use 64-bit (8 byte) 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

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



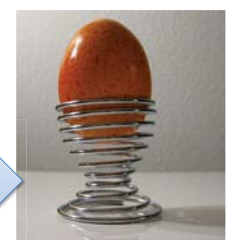
Data representations

- Sizes of C objects (in bytes)

C data type	Typical 32-bit	ia32	Intel 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

Byte ordering

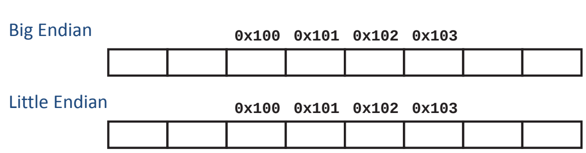
- How should bytes within multi-byte word be ordered in memory?
  - Big Endian: Sun, PPC, Internet
    - Least significant byte has highest address
  - Little Endian: x86
    - Least significant byte has lowest address
- Origin: "Gullivers Reisen" (Gulliver's Travels)
- Which end to crack a soft-boiled egg?



Egg in "little endian" configuration (Wikipedia)

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`**



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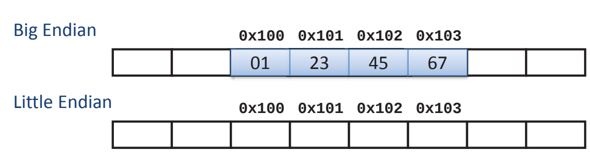

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Big Endian

		0x100	0x101	0x102	0x103		
		01	23	45	67		

Little Endian

		0x100	0x101	0x102	0x103		
		67	45	23	01		

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 4 bytes:	**0x000012ab**
Split into bytes:	**00 00 12 ab**
Reverse (endian):	**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 directives:
%p: print pointer
%x: print hexadecimal

show_bytes example

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

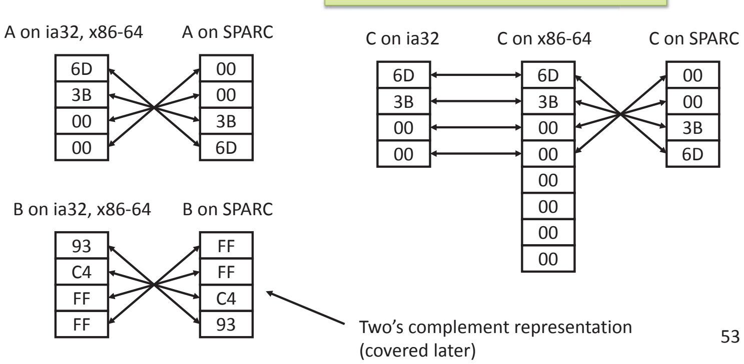
Result using Linux on Intel x86:

```
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;
```

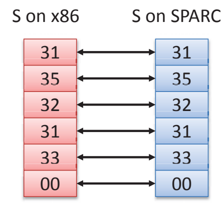
SPARC P	IA32 P	x86-64 P
EF	D4	0C
FF	F8	89
FB	FF	EC
2C	BF	FF
		FF
		7F
		00
		00

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 A=1 and B=1

&	0	1
0	0	0
1	0	1

(Inclusive) OR :
A|B = 1 when A=1 or B=1

|	0	1
0	0	1
1	1	1

NOT:
~A = 1 when A=0

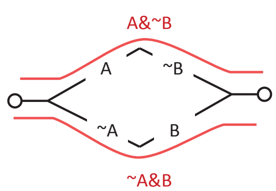
~	
0	1
1	0

Exclusive-OR (XOR) :
A^B = 1 when 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

- 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:

Operator	Operation	Result	Meaning
&	Intersection	01000001	{ 0, 6 }
|	Union	01111101	{ 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 | $01010101_2 \rightarrow 01111101_2$

Contrast: Logic operations in C

- `&&, ||, !`
  - 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
- Undefined behavior
  - 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

Java writes this ">>>".

Integer C puzzles

- Assume 32-bit word size, two's complement integers
- For each of the following C expressions, either:
  - Argue that is true for all argument values
  - Give example where not true

Initialization

```
int x = foo();
int y = bar();
unsigned ux = x;
unsigned uy = y;
```

```
• x < 0        ⇒  ((x*2) < 0)
• ux >= 0
• x & 7 == 7  ⇒  (x<<30) < 0
• ux > -1
• x > y        ⇒  -x < -y
• x * x >= 0
• x>0 && y>0 ⇒  x + y > 0
• x >= 0       ⇒  -x <= 0
• x <= 0       ⇒  -x >= 0
• (x|-x)>>31 == -1
• ux >> 3 == ux/8
• x >> 3 == x/8
• x & (x-1) != 0
```


Next time: Integers

- Representation: unsigned and signed
- Conversion, casting
- Expanding, truncating
- Addition, negation, multiplication, shifting