

CS 33

Introduction to C Part 3

Some of the slides in this lecture are either from or adapted from slides provided by the authors of the textbook “Computer Systems: A Programmer’s Perspective,” 2nd Edition and are provided from the website of Carnegie-Mellon University, course 15-213, taught by Randy Bryant and David O’Hallaron in Fall 2010. These slides are indicated “Supplied by CMU” in the notes section of the slides.

Meet Your TAs!!

- Come to CIT 3rd-floor atrium on Thursday at 5
- Eat tasty cookies!
- Talk to the course staff!
- Talk to fellow students in the course!

Arrays and Parameters

```
int main() {  
    int array1[4] = {0, 1, 2, 3};  
    printf("%d, %d\n", func(array1), array1[1]);  
    return 0;  
}  
  
void func(int arg[]) {  
    int array2[6] = {4, 5, 6, 7, 8, 9};  
    arg[1] = 0;  
    arg = array2;  
    return arg[3];  
}
```

```
$ ./a.out  
7 0
```

In this example, we've declared *array1* and *array2* in *main* and *func*. Both declarations allocate storage for arrays of *ints*. Both *array1* and *array2* refer (by pointing to the first elements) to the storage allocated for the arrays. These are literal (constant) values – they can't be changed.

In the definition of *func*, *arg* is a parameter that acts as a variable that's initialized with whatever is passed to *func*. In the slide, *func* is called with *array1* as the argument. Thus *arg* is initialized with *array1*, which means it's initialized with a pointer to the first element of the array referred to by *array1*. But this initial value of *arg* is not permanent – we're free to change it, as we do when we assign *array2* to *arg*.

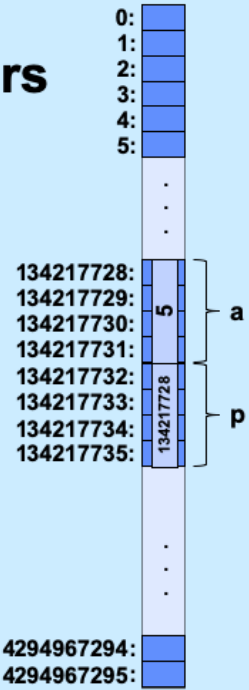
Arrays and Parameters

```
void func(int arg[]) {  
    /* arg points to the caller's array */  
    int local[7];    /* seven ints */  
    arg++;            /* legal */  
    arg = local;      /* legal */  
    local++;          /* illegal */  
    local = arg;      /* illegal */  
}
```

Dereferencing C Pointers

```
int main() {  
    int *p; int a = 4;  
    p = &a;  
    (*p)++;  
    printf("%d %u\n", *p, p);  
}
```

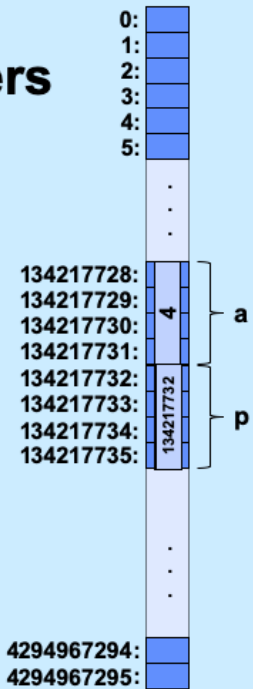
```
$ ./a.out  
5 134217728
```



Dereferencing C Pointers

```
int main() {  
    int *p; int a = 4;  
    p = &a;  
    *p++;  
    printf("%d %u\n", *p, p);  
}
```

```
$ ./a.out  
134217732 134217732
```



Operator precedence is hard to remember! ("`++`" takes precedence over "`*`".)

Dereferencing C Pointers

```
int main() {  
    int *p; int a = 4;  
    p = &a;  
    ++*p;  
    printf("%d %u\n", *p, p);  
}
```

```
$ ./a.out  
5 134217728
```

Quiz 1

```
int proc(int arg[]) {  
    arg++;  
    return arg[1];  
}  
  
int main() {  
    int A[3]={0, 1, 2};  
    printf("%d\n",  
        proc(A));  
}
```

What's printed?

- a) 0
- b) 1
- c) 2
- d) indeterminate

Strings

- **Strings are arrays of characters terminated by '\0' ("null")**
 - the '\0' is included at the end of string constants
 - » "Hello"

H	e	l	l	o	\0
---	---	---	---	---	----

Note that '\0' is represented as a byte containing all zeroes.

Strings

```
int main() {  
    printf("%s", "Hello");  
    return 0;  
}
```

```
$ ./a.out  
Hello$
```

Since we didn't explicitly output a newline character, the prompt for the next command goes on the same line as the string that was printed.

Strings

```
int main() {  
    printf("%s\n", "Hello");  
    return 0;  
}
```

```
$ ./a.out  
Hello  
$
```

We've added the newline character to the format specifier of `printf` – the prompt now appears on the next line.

Strings

```
void printString(char s[]) {  
    int i;  
    for(i=0; s[i]!='\0'; i++)  
        printf("%c", s[i]);  
}  
  
int main() {  
    printString("Hello");  
    printf("\n");  
    return 0;  
}
```

Tells C that this function does not return a value

We can also print a single character at a time. Note the test for the null character to determine whether we've reached the end of the string.

2-D Arrays

- **Suppose T is a datatype (such as `int`)**
- **$T\ n[6]$**
 - declares n to be an array of (six) T
 - the type of n is $T[6]$
- **Thus $T[6]$ is effectively a datatype**
- **Thus we can have an array of $T[6]$**
- **$T\ m[7][6]$**
 - m is an array of (seven) $T[6]$
 - $m[i]$ is of type $T[6]$
 - $m[i][j]$ is of type T

Note that even though we might think of “`int [6]`” as being a datatype, to declare “ n ” to be of that type, we must write “`int n[6]`” — the size of the array goes just after the identifier.

3-D Arrays

- How do we declare an array of eight $T[7][6]$?

$T \ p[8][7][6]$

- p is an array of (eight) $T[7][6]$
- $p[i]$ is of type $T[7][6]$
- $p[i][j]$ is of type $T[6]$
- $p[i][j][k]$ is of type T

2-D Arrays

```
#define NUM_ROWS 3
#define NUM_COLS 4
...
int main() {
    int row, col;
    int m[NUM_ROWS][NUM_COLS];
    for(row=0; row<NUM_ROWS; row++)
        for(col=0; col<NUM_COLS; col++)
            m[row][col] = row*NUM_COLS+col;
    printMatrix(NUM_ROWS, NUM_COLS, m);
    return 0;
}
```

```
$ ./a.out
```

0	1	2	3
4	5	6	7
8	9	10	11

Here we initialize a 2D array, then call a function (described in the next slide) to print it.

2-D Arrays

It must be told the
dimensions

```
void printMatrix(int nr, int nc,
                 int m[nr][nc]) {
    int row, col;
    for(row=0; row<nr; row++) {
        for(col=0; col<nc; col++)
            printf("%6d", m[row][col]);
        printf("\n");
    }
}
```

We print the array by rows.

Memory Layout

```
#define NUM_ROWS 3  
#define NUM_COLS 3
```

Row-Major Order

m[0][0]

m[0][1]

m[0][2]

m[1][0]

m[1][1]

m[1][2]

m[2][0]

m[2][1]

m[2][2]

row 0

row 1

row 2

C arrays are stored in *row-major order*, as shown in the slide. The idea is that the left index references the row, the right index references the column. Thus C arrays are stored row-by-row. Thus to index into a 2D array, we need to know how large each row is (i.e., how many columns there are). But it's not necessary, for indexing purposes, to know how many rows there are.

2-D Arrays

Alternatively ...

```
void printMatrix(int nr, int nc,
                int m[][nc]) {
    int row, col;
    for(row=0; row<nr; row++) {
        for(col=0; col<nc; col++)
            printf("%6d", m[row][col]);
        printf("\n");
    }
}
```

In general we don't need to specify the size of the leftmost dimension of an array argument. In the current 2D example, what's important is that the compiler know the size of each row so that it can generate code to compute where a particular element is.

2-D Arrays

Or ...

```
void printMatrix(int nr, int nc,
                int m[][nc]) {
    int i;
    for(i=0; i<nr; i++)
        printRow(nc, m[i]);
}
```

```
void printRow(int nc, int a[]) {
    int i;
    for(i=0; i<nc; i++)
        printf("%6d", a[i]);
    printf("\n");
}
```

Note that `m` is an array of arrays (in particular, an array of 1-D arrays).

2D as 1D

0	1	2	3
4	5	6	7

=

0	1	2	3	4	5	6	7
---	---	---	---	---	---	---	---

```
int A2D[2][4];
```

```
int A1D[8];
```

```
int AccessAs1D(int A[], int Row, int Col, int RowSize) {  
    return A[Row*RowSize + Col];  
}
```

```
int main(void) {  
    int A2D[2][4] = {{0, 1, 2, 3}, {4, 5, 6, 7}};  
    int *A1D = &A2D[0][0];  
    int x = AccessAs1D(A1D, 1, 2, 4);  
    printf("%d\n", x);  
    return 0;  
}
```

```
$ ./a.out  
6  
$
```

While it's convenient to think of something as being a 2D array, its elements are stored linearly in memory. Thus, as shown in the slide where we are calling *AccessAs1D* to get the value of *A2D[1][2]*, given a pointer to a 2D array, we can access its elements as if it were a 1D array.

Quiz 2

Consider the array

`int A[3][3];`

– which element is adjacent to `A[0][0]` in memory?

a) `A[0][1]`

b) `A[1][0]`

c) none of the above

Quiz 3

Consider the array

```
int A[3][3];
```

```
int *B = &A[0][0];
```

```
B[8] = 8;
```

– which element of A was modified?

a) A[0][3]

b) A[2][2]

c) A[3][0]

d) none of the above

Number Representation

- **Hindu-Arabic numerals**
 - **developed by Hindus starting in 5th century**
 - » **positional notation**
 - » **symbol for 0**
 - **adopted and modified somewhat later by Arabs**
 - » **known by them as “Rakam Al-Hind” (Hindu numeral system)**
 - **1999 rather than MCMXCIX**
 - » **(try doing long division with Roman numerals!)**

Which Base?

- **1999**
 - **base 10**
 - » $9 \cdot 10^0 + 9 \cdot 10^1 + 9 \cdot 10^2 + 1 \cdot 10^3$
 - **base 2**
 - » 11111001111
 - $1 \cdot 2^0 + 1 \cdot 2^1 + 1 \cdot 2^2 + 1 \cdot 2^3 + 0 \cdot 2^4 + 0 \cdot 2^5 + 1 \cdot 2^6 + 1 \cdot 2^7 + 1 \cdot 2^8 + 1 \cdot 2^9 + 1 \cdot 2^{10}$
 - **base 8**
 - » 3717
 - $7 \cdot 8^0 + 1 \cdot 8^1 + 7 \cdot 8^2 + 3 \cdot 8^3$
 - » why are we interested?
 - **base 16**
 - » 7CF
 - $15 \cdot 16^0 + 12 \cdot 16^1 + 7 \cdot 16^2$
 - » why are we interested?

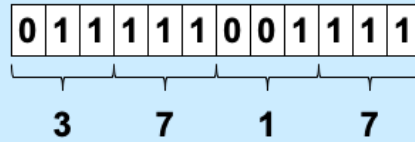
Base 2 is known as “binary” notation.

Base 8 is known as “octal” notation.

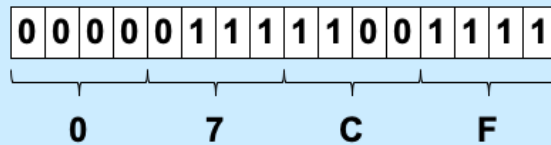
Base 10 is known as “decimal” notation.

Base 16 is known as “hexadecimal” notation. Note that “hexa” is derived from the Greek language and “decimal” is derived from the Latin language. Many people feel you shouldn’t mix languages when you invent words, but IBM, who coined the term “hexadecimal” in the 1960s, didn’t think their corporate image could withstand “sexadecimal”.

Words ...



12-bit computer word



16-bit computer word

Note that a byte consists of two hexadecimal digits, which are sometimes known as “nibbles”. A 32-bit computer word would then have eight nibbles; a 64-bit computer word would have sixteen nibbles.

Note that for the moment we consider only unsigned integers: i.e., integers whose values are nonnegative.

Algorithm ...

```
void baseX(unsigned int num, unsigned int base) {
    char digits[] = {'0', '1', '2', '3', '4', '5', '6', ... };
    char buf[8*sizeof(unsigned int)+1];
    int i;

    for (i = sizeof(buf) - 2; i >= 0; i--) {
        buf[i] = digits[num%base];
        num /= base;
        if (num == 0)
            break;
    }

    buf[sizeof(buf) - 1] = '\0';
    printf("%s\n", &buf[i]);
}
```

This routine prints the base *base* representation of *num*. The “%” operator yields the remainder. E.g., “10%3” evaluates to 1: the remainder after dividing 10 by 3. (Note that the “...” is not heretofore unexplained C syntax, but is shorthand for “fill this in to the extent needed.”)

Or ...

```
$ bc
obase=16
1999
7CF
$
```

“bc” (it stands for basic calculator, or perhaps better calculator) is a standard Unix command that handles arbitrary-precision arithmetic. Among its features is the ability to specify which base to use for input and output of numbers. The default base for both input and output is ten. Setting *obase* to 16 sets the base for output to 16. Similarly, one can change the base for input numbers by setting *ibase*.

Quiz 4

- What's the decimal (base 10) equivalent of 23_{16} ?
 - a) 19
 - b) 33
 - c) 35
 - d) 37

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`
 - `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

Supplied by CMU.

Unsigned 32-Bit Integers

b_{31}	b_{30}	b_{29}	...	b_2	b_1	b_0
----------	----------	----------	-----	-------	-------	-------

$$\text{value} = \sum_{i=0}^{31} b_i \cdot 2^i$$

(we ignore negative integers for now)

If a computer word is to be interpreted as an unsigned integer, we can do so as shown in the slide for 32-bit integers. Thus integers are represented in binary (base-2) notation in the computer. We'll discuss representing negative integers in an upcoming lecture.

Storing and Viewing Ints

```
int main() {  
    unsigned int n = 57;  
    printf("binary: %b, decimal: %u, "  
          "hex: %x\n", n, n, n);  
    return 0;  
}
```

```
$ ./a.out  
binary: 111001, decimal: 57, hex: 39  
$
```

Here `n` is an *unsigned int* whose value is 57 (expressed in base 10). As we've seen, it's represented in the computer in binary. When we print its value using `printf`, we choose to view it in the base specified by the format code. `%b` means binary, `%u` means decimal (assuming an unsigned int), and `%x` means hexadecimal.

Note, in the arguments for *printf*, that the format string is in two parts. C allows you to do this: "string 1 " "string 2" is treated the same as "string1 string2".

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

Supplied by CMU.

General Boolean Algebras

- Operate on bit vectors
 - operations applied bitwise

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

- All of the properties of boolean algebra apply

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Example: Representing & Manipulating Sets

- Representation

- width- w bit vector represents subsets of $\{0, \dots, w-1\}$
- $a_j = 1$ iff $j \in A$

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 }

Supplied by CMU.

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 datatype)
 - `~0x41 → 0xBE`
`~010000012 → 101111102`
 - `~0x00 → 0xFF`
`~000000002 → 111111112`
 - `0x69 & 0x55 → 0x41`
`011010012 & 010101012 → 010000012`
 - `0x69 | 0x55 → 0x7D`
`011010012 | 010101012 → 011111012`

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Contrast: Logic Operations in C

- **Contrast to Logical Operators**

- `&&`, `||`, `!`

- » view 0 as “false”

- » anything nonzero as “true”

- » always return 0 or 1

- » early termination/short-circuited execution

- **Examples (char datatype)**

- `!0x41 → 0x00`

- `!0x00 → 0x01`

- `!!0x41 → 0x01`

- `0x69 && 0x55 → 0x01`

- `0x69 || 0x55 → 0x01`

- `p && *p` (avoids null pointer access)

Supplied by CMU.

Contrast: Logic Operations in C

- Contrast to Logical Operators

– &&, ||, !
» view “false”

**Watch out for && vs. & (and || vs. |)...
One of the more common oopsies in
C programming**

- Example

!0x41 → 0x00
!0x00 → 0x01
!!0x41 → 0x01

0x69 && 0x55 → 0x01

0x69 || 0x55 → 0x01

p && *p (avoids null pointer access)

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Quiz 5

- Which of the following would determine whether the next-to-the-rightmost bit of Y (declared as a char) is 1? (i.e., the expression evaluates to true if and only if that bit of Y is 1.)
 - a) `Y & 0x02`
 - b) `!((~Y) & 0x02)`
 - c) both of the above
 - d) none of the above

Recall that a char is an 8-bit integer.

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 left
- **Undefined Behavior**
 - shift amount < 0 or \geq word size

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

Supplied by CMU.

Why we need both logical and arithmetic shifts should be clear by the end of an upcoming lecture. If one is applying a right shift to an *int*, it will be an arithmetic right shift. Why this is so will be explained in the upcoming lecture (it has to do with the representation of negative numbers).