# System Programming

## 03. C. Memory II (ch 2.1)

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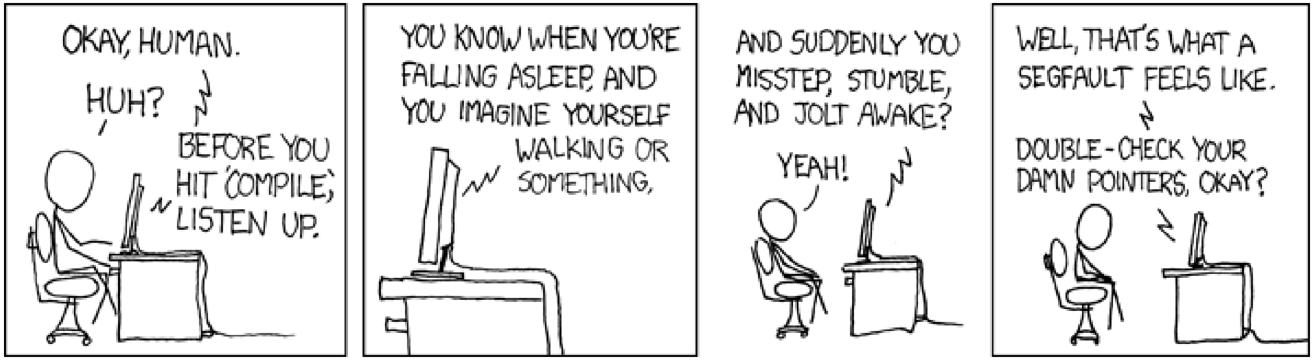
These slides are based on the slides prepared by Dan Grossman, Ruth Anderson.

# Compiler Complaint

- http://xkcd.com/371/



# Roadmap

Memory & data
Integers & floats
x86 assembly
Procedures & stacks
Executables
Arrays & structs
Memory & caches
Processes
Virtual memory
Memory allocation
Java vs. C

**C:**

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

**Java:**

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
 mpg =
    c.getMPG();
```

**Assembly language:**

```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

**Machine code:**

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

**OS:**

Windows 8 Mac

**Computer system:**


# Memory, Data, and Addressing

- Representing information as bits and bytes
- Organizing and addressing data in memory
- Manipulating data in memory using C
- Boolean algebra and bit-level manipulations

# Addresses and Pointers in C

- `&` = "address of" operator
- `*` = "value at address" or "dereference" operator

```
int* ptr;
```

Declares a variable, `ptr`, that is a pointer to (i.e. holds the address of) an `int` in memory

```
int x = 5;
int y = 2;
```

Declares two variables, `x` and `y`, that hold `int`s, and sets them to 5 and 2, respectively

```
ptr = &x;
```

Sets `ptr` to the address of `x` ("`ptr` points to `x`")

```
y = 1 + *ptr;
```

"Dereference `ptr`"

Sets `y` to "1 plus the value stored at the address held by `ptr`. Because `ptr` points to `x`, this is equivalent to `y=1+x;`

What is `*(&y)` ?

# Assignment in C (1)

- A variable is represented by a memory location
- Declaration ≠ initialization (initially holds "garbage")
- `int x, y;`
  - `x` is at address 0x04, `y` is at 0x18

| 0x00 | 0x01 | 0x02 | 0x03 | | |
|---|---|---|---|---|---|
| A7 | 00 | 32 | 00 | 0x00 | |
| 00 | 01 | 29 | F3 | 0x04 | x |
| EE | EE | EE | EE | 0x08 | |
| FA | CE | CA | FE | 0x0C | |
| 26 | 00 | 00 | 00 | 0x10 | |
| 00 | 00 | 10 | 00 | 0x14 | |
| 01 | 00 | 00 | 00 | 0x18 | y |
| FF | 00 | F4 | 96 | 0x1C | |
| DE | AD | BE | EF | 0x20 | |
| 00 | 00 | 00 | 00 | 0x24 | |

# Assignment in C (2)

**32-bit example (pointers are 32-bits wide)**

- A variable is represented by a memory location
- Declaration ≠ initialization (initially holds "garbage")
- `int x, y;`
  - `x` is at address 0x04, `y` is at 0x18

| 0x00 | 0x01 | 0x02 | 0x03 | | |
|---|---|---|---|---|---|
| | | | | 0x00 | |
| 00 | 01 | 29 | F3 | 0x04 | x |
| | | | | 0x08 | |
| | | | | 0x0C | |
| | | | | 0x10 | |
| | | | | 0x14 | |
| 01 | 00 | 00 | 00 | 0x18 | y |
| | | | | 0x1C | |
| | | | | 0x20 | |
| | | | | 0x24 | |

# Assignment in C (3)

**32-bit example (pointers are 32-bits wide)**

- left-hand side = right-hand side;
  - LHS must evaluate to a memory *location*
  - RHS must evaluate to a *value* (could be an address)
  - Store RHS value at LHS location
- `int x, y;`
- `x = 0;`

| 0x00 | 0x01 | 0x02 | 0x03 | | |
|---|---|---|---|---|---|
| | | | | 0x00 | |
| 00 | 00 | 00 | 00 | 0x04 | x |
| | | | | 0x08 | |
| | | | | 0x0C | |
| | | | | 0x10 | |
| | | | | 0x14 | |
| 01 | 00 | 00 | 00 | 0x18 | y |
| | | | | 0x1C | |
| | | | | 0x20 | |
| | | | | 0x24 | |

# Assignment in C (3)

**32-bit example (pointers are 32-bits wide)**

- left-hand side = right-hand side;
  - LHS must evaluate to a memory *location*
  - RHS must evaluate to a *value* (could be an address)
  - Store RHS value at LHS location
- `int x, y;`
- `x = 0;`
- `y = 0x3CD02700;`

little endian!

| 0x00 | 0x01 | 0x02 | 0x03 | | |
|---|---|---|---|---|---|
| | | | | 0x00 | |
| 00 | 00 | 00 | 00 | 0x04 | x |
| | | | | 0x08 | |
| | | | | 0x0C | |
| | | | | 0x10 | |
| | | | | 0x14 | |
| 00 | 27 | D0 | 3C | 0x18 | y |
| | | | | 0x1C | |
| | | | | 0x20 | |
| | | | | 0x24 | |

# Assignment in C (4)

**32-bit example (pointers are 32-bits wide)**

- left-hand side = right-hand side;
  - LHS must evaluate to a memory *location*
  - RHS must evaluate to a *value* (could be an address)
  - Store RHS value at LHS location
- `int x, y;`
- `x = 0;`
- `y = 0x3CD02700;`
- `x = y + 3;`
  - Get value at `y`, add 3, store in

| 0x00 | 0x01 | 0x02 | 0x03 | | |
|---|---|---|---|---|---|
| | | | | 0x00 | |
| 03 | 27 | D0 | 3C | 0x04 | x |
| | | | | 0x08 | |
| | | | | 0x0C | |
| | | | | 0x10 | |
| | | | | 0x14 | |
| 00 | 27 | D0 | 3C | 0x18 | y |
| | | | | 0x1C | |
| | | | | 0x20 | |
| | | | | 0x24 | |

# Assignment in C (5)

**32-bit example (pointers are 32-bits wide)**

& = "address of"
* = "dereference"

- left-hand side = right-hand side;
  - LHS must evaluate to a memory *location*
  - RHS must evaluate to a *value* (could be an address)
  - Store RHS value at LHS location
- `int x, y;`
- `x = 0;`
- `y = 0x3CD02700;`
- `x = y + 3;`
  - Get value at `y`, add 3, store in `x`
- `int* z;`
  - `z` is at address 0x20

| 0x00 | 0x01 | 0x02 | 0x03 | | |
|---|---|---|---|---|---|
| | | | | 0x00 | |
| 03 | 27 | D0 | 3C | 0x04 | x |
| | | | | 0x08 | |
| | | | | 0x0C | |
| | | | | 0x10 | |
| | | | | 0x14 | |
| 00 | 27 | D0 | 3C | 0x18 | y |
| | | | | 0x1C | |
| DE | AD | BE | EF | 0x20 | z |
| | | | | 0x24 | |

Declaration: initially contains garbage

# Assignment in C (6)

**32-bit example (pointers are 32-bits wide)**

`&` = "address of"
`*` = "dereference"

- left-hand side = right-hand side;
  - LHS must evaluate to a memory *location*
  - RHS must evaluate to a *value* (could be an address)
  - Store RHS value at LHS location
- `int x, y;`
- `x = 0;`
- `y = 0x3CD02700;`
- `x = y + 3;`
  - Get value at `y`, add 3, store in `x`
- `int* z = &y + 3;`
  - Get address of `y`, "add 3", store in `z`

Pointer arithmetic

| 0x00 | 0x01 | 0x02 | 0x03 | | |
|---|---|---|---|---|---|
| | | | | 0x00 | |
| 03 | 27 | D0 | 3C | 0x04 | x |
| | | | | 0x08 | |
| | | | | 0x0C | |
| | | | | 0x10 | |
| | | | | 0x14 | |
| 00 | 27 | D0 | 3C | 0x18 | y |
| | | | | 0x1C | |
| 24 | 00 | 00 | 00 | 0x20 | z |
| | | | | 0x24 | |

# Pointer Arithmetic

- Pointer arithmetic is scaled by the size of target type
  - In this example, `sizeof(int)` = 4
- `int* z = &y + 3;`
  - Get address of `y`, add `3*sizeof(int)`, store in `z`
  - `&y = 0x18`
  - `24 + 3*(4) = 36`

- Pointer arithmetic can be dangerous!
  - Can easily lead to bad memory accesses
  - Be careful with data types and *casting*

# Assignment in C (7)

**32-bit example (pointers are 32-bits wide)**

& = "address of"
* = "dereference"

- `int x, y;`
- `x = 0;`
- `y = 0x3CD02700;`
- `x = y + 3;`
  - Get value at `y`, add 3, store in `x`
- `int* z = &y + 3;`
  - Get address of `y`, add **12**, store in `z`
- `*z = y;`
  - What does this do?

| 0x00 | 0x01 | 0x02 | 0x03 | | |
|---|---|---|---|---|---|
| | | | | 0x00 | |
| 03 | 27 | D0 | 3C | 0x04 | x |
| | | | | 0x08 | |
| | | | | 0x0C | |
| | | | | 0x10 | |
| | | | | 0x14 | |
| 00 | 27 | D0 | 3C | 0x18 | y |
| | | | | 0x1C | |
| 24 | 00 | 00 | 00 | 0x20 | z |
| | | | | 0x24 | |

# Assignment in C (8)

**32-bit example (pointers are 32-bits wide)**

`&` = "address of"
`*` = "dereference"

- `int x, y;`
- `x = 0;`
- `y = 0x3CD02700;`
- `x = y + 3;`
  - Get value at `y`, add 3, store in `x`
- `int* z = &y + 3;`
  - Get address of `y`, add **12**, store in `z`

The target of a pointer is also a memory location

- `*z = y;`
  - Get value of `y`, put in address stored in `z`

| 0x00 | 0x01 | 0x02 | 0x03 | | |
|---|---|---|---|---|---|
| | | | | 0x00 | |
| 03 | 27 | D0 | 3C | 0x04 | x |
| | | | | 0x08 | |
| | | | | 0x0C | |
| | | | | 0x10 | |
| | | | | 0x14 | |
| 00 | 27 | D0 | 3C | 0x18 | y |
| | | | | 0x1C | |
| 24 | 00 | 00 | 00 | 0x20 | z |
| 00 | 27 | D0 | 3C | 0x24 | |

# Arrays in C (1)

Arrays are adjacent locations in memory storing the same type of data object

`a` is a name for the array's address

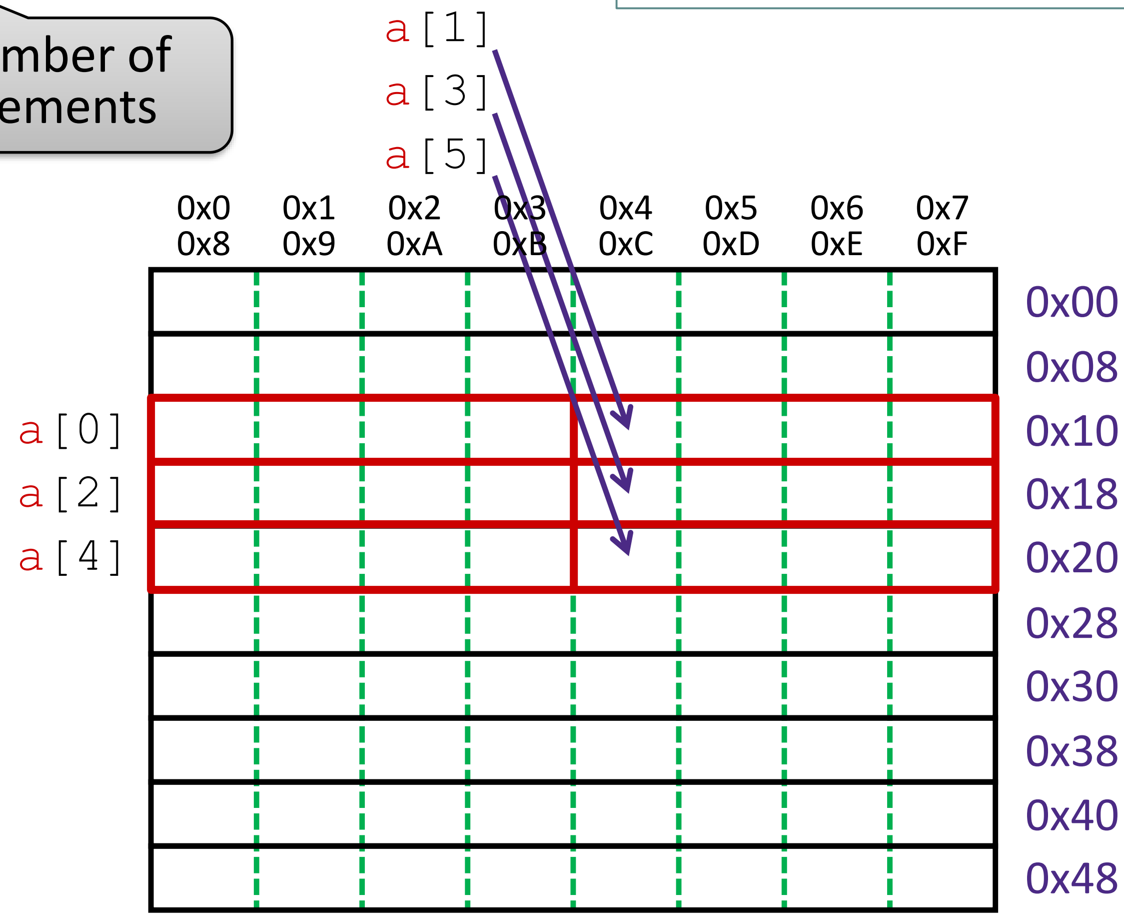
Declaration: `int a[6];`

element type

name

number of elements

64-bit example
(pointers are 64-bits wide)



# Arrays in C (2)

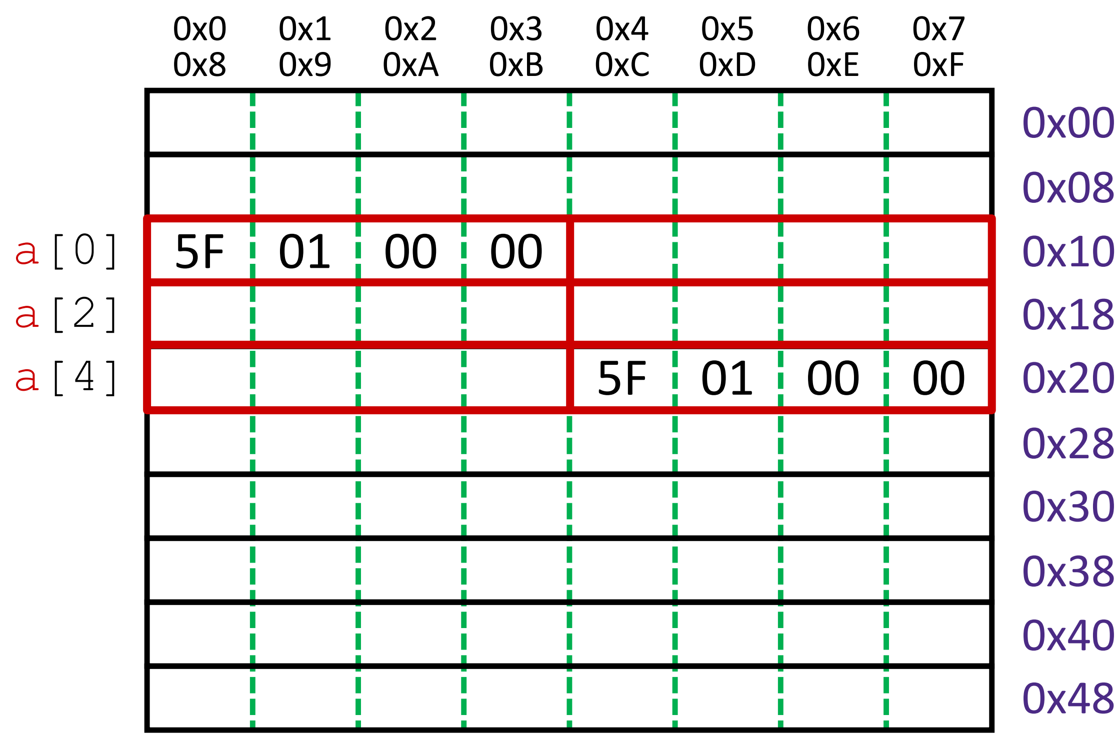
Arrays are adjacent locations in memory storing the same type of data object

`a` is a name for the array's address

The address of `a[i]` is the address of `a[0]` plus `i` times the element size in bytes

Declaration: `int a[6];`

Indexing:
```
a[0] = 0x015f;
a[5] = a[0];
```



# Arrays in C (3)

Arrays are adjacent locations in memory storing the same type of data object

`a` is a name for the array's address

The address of `a[i]` is the address of `a[0]` plus `i` times the element size in bytes

Declaration: `int a[6];`

Indexing:
```
a[0] = 0x015f;
a[5] = a[0];
```

No bounds checking:
```
a[6] = 0xBAD;
a[-1] = 0xBAD;
```

| | 0x0<br>0x8 | 0x1<br>0x9 | 0x2<br>0xA | 0x3<br>0xB | 0x4<br>0xC | 0x5<br>0xD | 0x6<br>0xE | 0x7<br>0xF | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | 0x00 |
| | | | | | AD | 0B | 00 | 00 | 0x08 |
| a[0] | 5F | 01 | 00 | 00 | | | | | 0x10 |
| a[2] | | | | | | | | | 0x18 |
| a[4] | | | | | 5F | 01 | 00 | 00 | 0x20 |
| | AD | 0B | 00 | 00 | | | | | 0x28 |
| | | | | | | | | | 0x30 |
| | | | | | | | | | 0x38 |
| | | | | | | | | | 0x40 |
| | | | | | | | | | 0x48 |

# Arrays in C (4)

Arrays are adjacent locations in memory storing the same type of data object

`a` is a name for the array's address

The address of `a[i]` is the address of `a[0]` plus `i` times the element size in bytes

Declaration: `int a[6];`

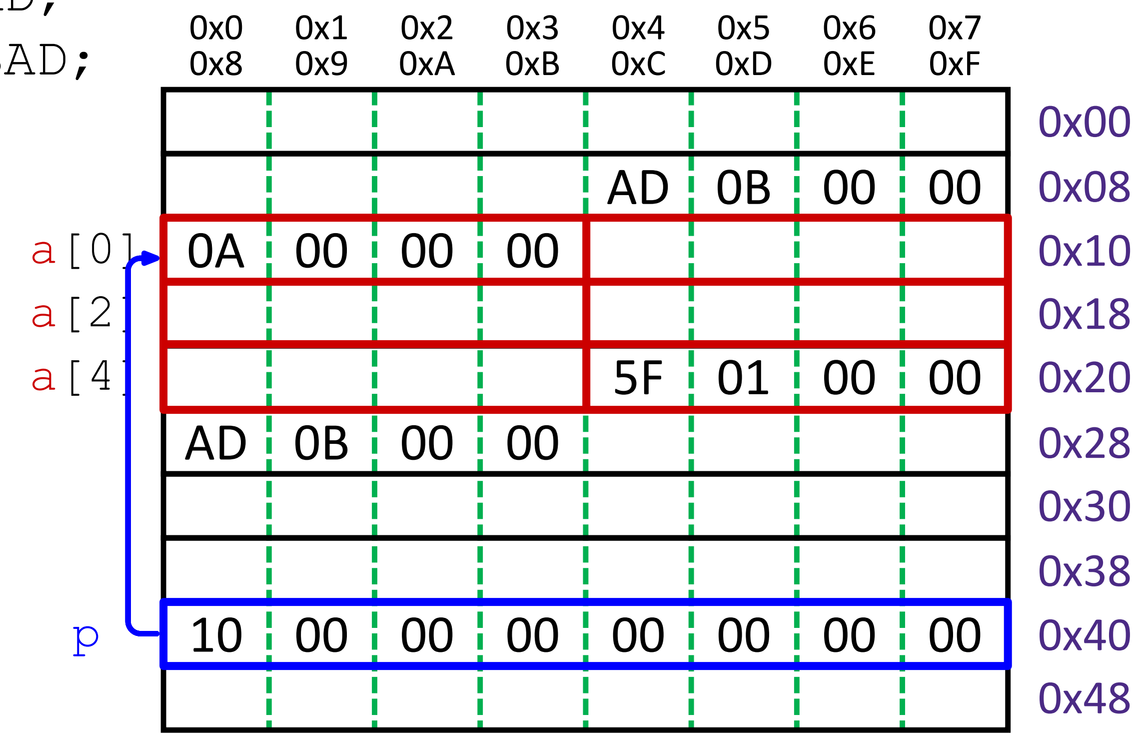
Indexing:
```
a[0] = 0x015f;
a[5] = a[0];
```

No bounds checking:
```
a[6] = 0xBAD;
a[-1] = 0xBAD;
```

Pointers:
```
int* p;
```

equivalent
```
p = a;
p = &a[0];
```

```
*p = 0xA;
```



# Arrays in C (5)

Arrays are adjacent locations in memory storing the same type of data object

`a` is a name for the array's address

The address of `a[i]` is the address of `a[0]` plus `i` times the element size in bytes

Declaration: `int a[6];`

Indexing:
```
a[0] = 0x015f;
a[5] = a[0];
```

No bounds checking:
```
a[6] = 0xBAD;
a[-1] = 0xBAD;
```

Pointers:
```
int* p;
p = a;
p = &a[0];
*p = 0xA;
```
equivalent: `p = a;` / `p = &a[0];`

array indexing = address arithmetic
(both scaled by the size of the type)

```
p[1] = 0xB;
*(p+1) = 0xB;

p = p + 2;
```
equivalent: `p[1] = 0xB;` / `*(p+1) = 0xB;`

| | 0x0 0x8 | 0x1 0x9 | 0x2 0xA | 0x3 0xB | 0x4 0xC | 0x5 0xD | 0x6 0xE | 0x7 0xF | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | 0x00 |
| | | | | | AD | 0B | 00 | 00 | 0x08 |
| a[0] | 0A | 00 | 00 | 00 | 0B | 00 | 00 | 00 | 0x10 |
| a[2] | | | | | | | | | 0x18 |
| a[4] | | | | | 5F | 01 | 00 | 00 | 0x20 |
| | AD | 0B | 00 | 00 | | | | | 0x28 |
| | | | | | | | | | 0x30 |
| | | | | | | | | | 0x38 |
| p | 10 | 00 | 00 | 00 | 00 | 00 | 00 | 00 | 0x40 |
| | | | | | | | | | 0x48 |

# Arrays in C (6)

Arrays are adjacent locations in memory storing the same type of data object

`a` is a name for the array's address

The address of `a[i]` is the address of `a[0]` plus `i` times the element size in bytes

Declaration: `int a[6];`

Indexing:
```
a[0] = 0x015f;
a[5] = a[0];
```

No bounds checking:
```
a[6] = 0xBAD;
a[-1] = 0xBAD;
```

Pointers: `int* p;`

equivalent {
```
p = a;
p = &a[0];
```
}
```
*p = 0xA;
```

array indexing = address arithmetic
(both scaled by the size of the type)

equivalent {
```
p[1] = 0xB;
*(p+1) = 0xB;
```
}
```
p = p + 2;
```

```
*p = a[1] + 1;
```

| | 0x0<br>0x8 | 0x1<br>0x9 | 0x2<br>0xA | 0x3<br>0xB | 0x4<br>0xC | 0x5<br>0xD | 0x6<br>0xE | 0x7<br>0xF | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | 0x00 |
| | | | | | AD | 0B | 00 | 00 | 0x08 |
| a[0] | 0A | 00 | 00 | 00 | 0B | 00 | 00 | 00 | 0x10 |
| a[2] | 0C | 00 | 00 | 00 | | | | | 0x18 |
| a[4] | | | | | 5F | 01 | 00 | 00 | 0x20 |
| | AD | 0B | 00 | 00 | | | | | 0x28 |
| | | | | | | | | | 0x30 |
| | | | | | | | | | 0x38 |
| p | 18 | 00 | 00 | 00 | 00 | 00 | 00 | 00 | 0x40 |
| | | | | | | | | | 0x48 |

# Fill in the blanks!

Arrays are adjacent locations in memory storing the same type of data object

`a` is a name for the array's address

The address of `a[i]` is the address of `a[0]` plus `i` times the element size in bytes

Declaration: `int a[6];`

Indexing:
```
a[0] = 0x015f;
a[5] = a[0];
```

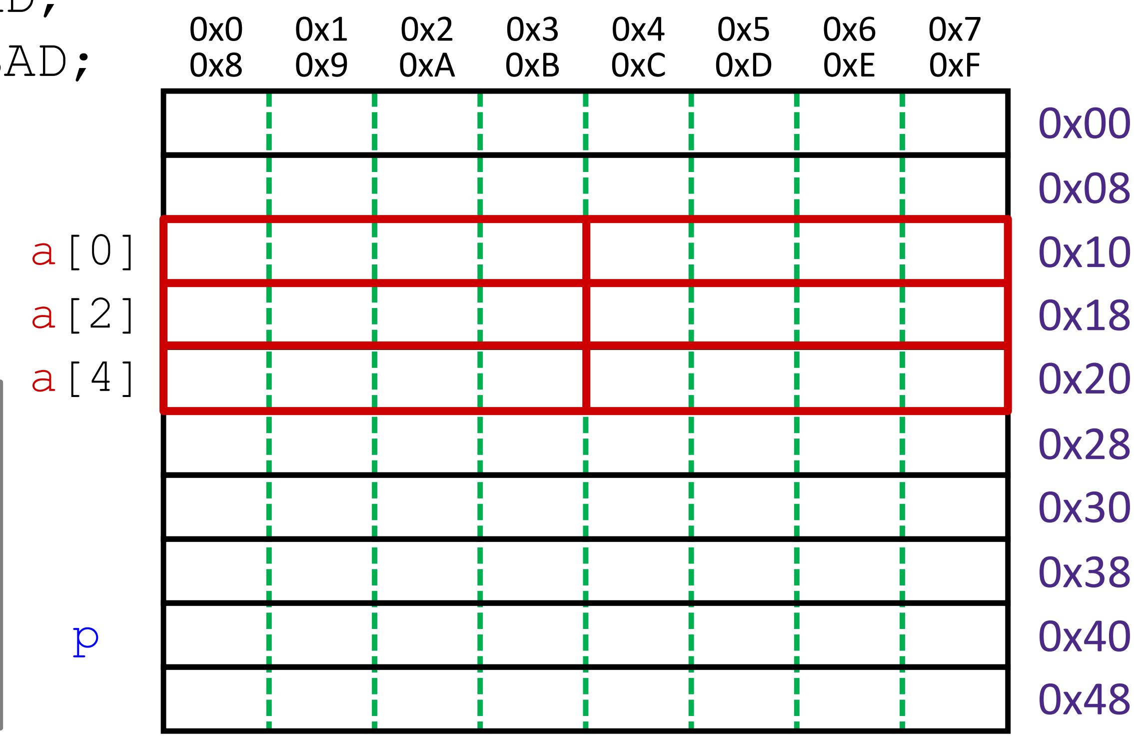
No bounds checking:
```
a[6] = 0xBAD;
a[-1] = 0xBAD;
```

Pointers: `int* p;`

equivalent {
```
p = a;
p = &a[0];
```
}
```
*p = 0xA;
```

array indexing = address arithmetic
(both scaled by the size of the type)

equivalent {
```
p[1] = 0xB;
*(p+1) = 0xB;
```
}
```
p = p + 2;
```




```
*p = a[1] + 1;
```

**Question:** The variable values after Line 3 executes are shown on the right. What are they after Line 4 & 5?

```
1   void main() {
2       int a[] = {5,10};
3       int *p = a;
4        p =  p + 1;
5       *p = *p + 1;
6   }
```

| | Data (decimal) | Address (decimal) |
|---|---|---|
| a[0] | 5 | 100 |
| a[1] | 10 | |
| | ⋮ | |
| p | 100 | |

| | p | *p | a[0] | a[1] | | p | *p | a[0] | a[1] |
|---|---|---|---|---|---|---|---|---|---|
| **(A)** | 101 | 10 | 5 | 10 | then | 101 | 11 | 5 | 11 |
| **(B)** | 104 | 10 | 5 | 10 | then | 104 | 11 | 5 | 11 |
| **(C)** | 100 | 6 | 6 | 10 | then | 101 | 6 | 6 | 10 |
| **(D)** | 100 | 6 | 6 | 10 | then | 104 | 6 | 6 | 10 |

# Representing strings

- C-style string stored as an array of bytes (`char *`)
  - Elements are one-byte ASCII codes for each character
  - No “String” keyword, unlike Java

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 32 | **space** | 48 | **0** | 64 | **@** | 80 | **P** | 96 | **`** | 112 | **p** |
| 33 | **!** | 49 | **1** | 65 | **A** | 81 | **Q** | 97 | **a** | 113 | **q** |
| 34 | **”** | 50 | **2** | 66 | **B** | 82 | **R** | 98 | **b** | 114 | **r** |
| 35 | **#** | 51 | **3** | 67 | **C** | 83 | **S** | 99 | **c** | 115 | **s** |
| 36 | **$** | 52 | **4** | 68 | **D** | 84 | **T** | 100 | **d** | 116 | **t** |
| 37 | **%** | 53 | **5** | 69 | **E** | 85 | **U** | 101 | **e** | 117 | **u** |
| 38 | **&** | 54 | **6** | 70 | **F** | 86 | **V** | 102 | **f** | 118 | **v** |
| 39 | **’** | 55 | **7** | 71 | **G** | 87 | **W** | 103 | **g** | 119 | **w** |
| 40 | **(** | 56 | **8** | 72 | **H** | 88 | **X** | 104 | **h** | 120 | **x** |
| 41 | **)** | 57 | **9** | 73 | **I** | 89 | **Y** | 105 | **I** | 121 | **y** |
| 42 | ***** | 58 | **:** | 74 | **J** | 90 | **Z** | 106 | **j** | 122 | **z** |
| 43 | **+** | 59 | **;** | 75 | **K** | 91 | **[** | 107 | **k** | 123 | **{** |
| 44 | **,** | 60 | **<** | 76 | **L** | 92 | **** | 108 | **l** | 124 | **\|** |
| 45 | **-** | 61 | **=** | 77 | **M** | 93 | **]** | 109 | **m** | 125 | **}** |
| 46 | **.** | 62 | **>** | 78 | **N** | 94 | **^** | 110 | **n** | 126 | **~** |
| 47 | **/** | 63 | **?** | 79 | **O** | 95 | **_** | 111 | **o** | 127 | **del** |

**ASCII:** American Standard Code for Information Interchange

# Null-terminated Strings

- **Example:** "Life is good" stored as a 13-byte array

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Decimal:* | 76 | 105 | 102 | 101 | 32 | 105 | 115 | 32 | 103 | 111 | 111 | 100 | 0 |
| *Hex:* | 0x4c | 0x69 | 0x66 | 0x65 | 0x20 | 0x69 | 0x73 | 0x20 | 0x67 | 0x6f | 0x6f | 0x64 | 0x00 |
| *Text:* | L | i | f | e | | i | s | | g | o | o | d | \0 |

- Last character followed by a 0 byte (`'\0'`) (a.k.a. "null terminator")
  - Must take into account when allocating space in memory
  - Note that `'0'` ≠ `'\0'` (i.e. character 0 has non-zero value)
- How do we compute the length of a string?
  - Traverse array until null terminator encountered

# Endianness and Strings

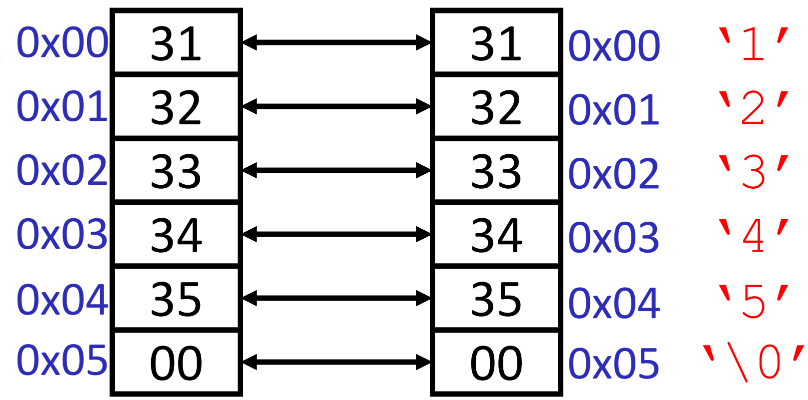
C (char = 1 byte)

```
char s[6] = "12345";
```

String literal

IA32, x86-64 (little endian)

SPARC (big endian)




0x31 = 49 decimal = ASCII ‘1’

- Byte ordering (endianness) is not an issue for 1-byte values
  - The whole array does not constitute a single value
  - Individual elements are values; chars are single bytes
- Unicode characters – up to 4 bytes/character
  - ASCII codes still work (just add leading zeros)
  - Unicode can support the many characters in all languages in the world
  - Java and C have libraries for Unicode (Java commonly uses 2 bytes/char)

# Examining Data Representations

- Code to print byte representation of data
  - Any data type can be treated as a *byte array* by **casting** it to `char`
  - C has unchecked casts !! DANGER !!

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

**`printf` directives:**

| | |
|---|---|
| `%p` | Print pointer |
| `\t` | Tab |
| `%x` | Print value as hex |
| `\n` | New line |

# Examining Data Representations

- Code to print byte representation of data
  - Any data type can be treated as a *byte array* by **casting** it to `char`
  - C has unchecked casts !! DANGER !!

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

```
void show_int(int x) {
   show_bytes( (char *) &x, sizeof(int));
}
```

# show_bytes Execution Example

```
int a = 12345; // 0x00003039
printf("int a = 12345;\n");
show_int(a);  // show_bytes((char *) &a, sizeof(int));
```

- Result (Linux x86-64):
  - **Note:** The addresses will change on each run (try it!), but fall in same general range

```
int a = 12345;
0x7fffb7f71dbc      0x39
0x7fffb7f71dbd      0x30
0x7fffb7f71dbe      0x00
0x7fffb7f71dbf      0x00
```

# Summary

- Assignment in C results in value being put in memory location
- Pointer is a C representation of a data address
  - `&` = "address of" operator
  - `*` = "value at address" or "dereference" operator
- Pointer arithmetic scales by size of target type
  - Convenient when accessing array-like structures in memory
  - Be careful when using – particularly when *casting* variables
- Arrays are adjacent locations in memory storing the same type of data object
  - Strings are null-terminated arrays of characters (ASCII)

# Memory, Data, and Addressing

- Representing information as bits and bytes
- Organizing and addressing data in memory
- Manipulating data in memory using C
- **Boolean algebra and bit-level manipulations**

# Boolean Algebra

- Developed by George Boole in 19th Century
  - Algebraic representation of logic (True → 1, False → 0)
  - AND: `A&B=1` when both A is 1 and B is 1
  - OR: `A|B=1` when either A is 1 or B is 1
  - XOR: `A^B=1` when either A is 1 or B is 1, but not both
  - NOT: `~A=1` when A is 0 and vice-versa
  - DeMorgan's Law: `~(A|B) = ~A & ~B`
    `~(A&B) = ~A | ~B`

AND

| & | 0 | 1 |
|---|---|---|
| 0 | **0** | **0** |
| 1 | **0** | **1** |

OR

| \| | 0 | 1 |
|---|---|---|
| 0 | **0** | **1** |
| 1 | **1** | **1** |

XOR

| ^ | 0 | 1 |
|---|---|---|
| 0 | **0** | **1** |
| 1 | **1** | **0** |

NOT

| ~ | |
|---|---|
| 0 | **1** |
| 1 | **0** |

# General Boolean Algebras

- Operate on bit vectors
  - Operations applied bitwise
  - All of the properties of Boolean algebra apply

```
  01101001      01101001      01101001
& 01010101    | 01010101    ^ 01010101    ~ 01010101
```

- Examples of useful operations:

$$x \,\hat{}\, x = 0$$

```
  01010101
^ 01010101
  00000000
```

$$x \mid 1 = 1, \qquad x \mid 0 = x$$

```
  01010101
| 11110000
  11110101
```

# Representing & Manipulating Sets

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

```
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 } |

# Bit-Level Operations in C

- `&` (AND), `|` (OR), `^` (XOR), `~` (NOT)
  - View arguments as bit vectors, apply operations bitwise
  - Apply to any "integral" data type
    - `long`, `int`, `short`, `char`, `unsigned`

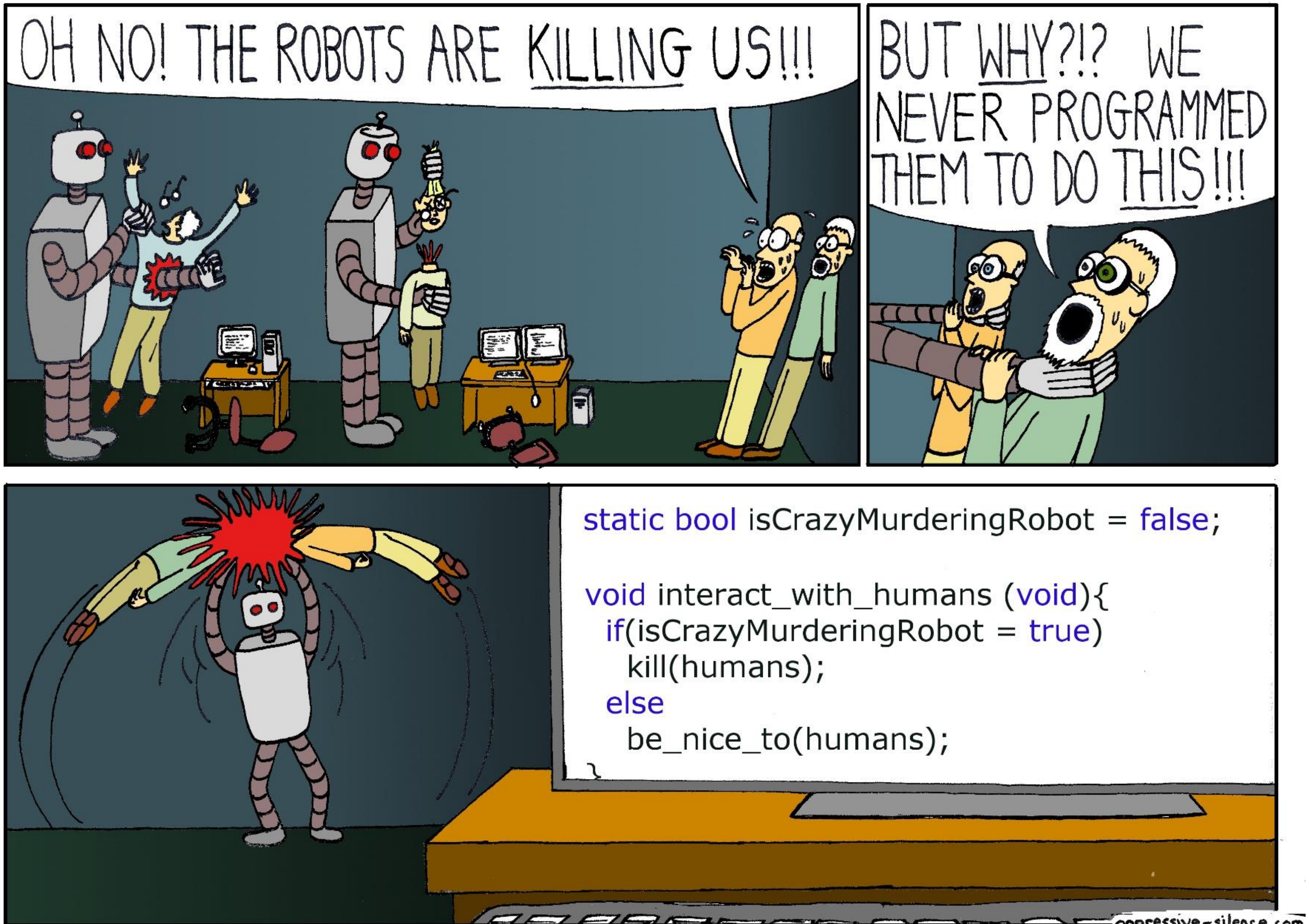
- Examples with `char a, b, c;`
  - ```
    a = (char) 0x41;      // 0x41->0b 0100 0001
    b = ~a;               //       0b           ->0x
    ```
  - ```
    a = (char) 0x69;      // 0x69->0b 0110 1001
    b = (char) 0x55;      // 0x55->0b 0101 0101
    c = a & b;            //       0b           ->0x
    ```
  - ```
    a = (char) 0x41;      // 0x41->0b 0100 0001
    b = a;                //       0b 0100 0001
    c = a ^ b;            //       0b           ->0x
    ```
    ```

# Contrast: Logic Operations in C

- Logical operators in C: `&&` (AND), `||` (OR), `!` (NOT)
  - **<u>0</u>** is False, **<u>anything nonzero</u>** is True
  - **<u>Always</u>** return 0 or 1
  - Early termination (a.k.a. short-circuit evaluation) of `&&`, `||`

- Examples (`char` data type)
  - `!0x41 -> 0x00`
  - `!0x00 -> 0x01`
  - `!!0x41 -> 0x01`
  - `p && *p++`
    - Avoids null pointer (0x0) access via *early termination*
    - Short for: `if (p) { *p++; }`

# Logic Operations!!!



# Q&A