Memory, Data, & Addressing II

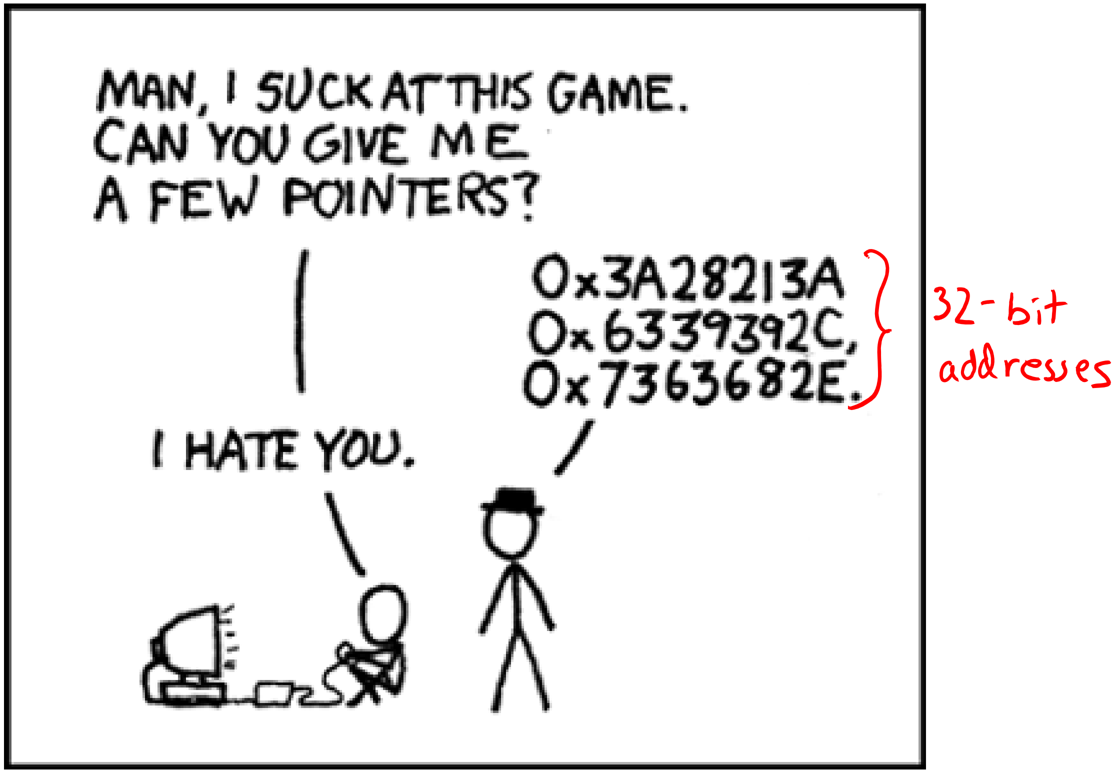
CSE 351 Winter 2020

Instructor:

Ruth Anderson

Teaching Assistants:

Jonathan Chen
Justin Johnson
Porter Jones
Josie Lee
Jeffery Tian
Callum Walker
Eddy (Tianyi) Zhou



http://xkcd.com/138/

Administrivia

- Lab 0 due today @ 11:59 pm
  - *You will be revisiting this program throughout this class!*
- hw2 due Monday, hw3 due Wednesday @ 11:00 am
  - Autograded, unlimited tries, no late submissions
- Lab 1a released today, due next Friday (1/17)
  - Pointers in C
  - Reminder: last submission graded, *individual* work

Late Days

- You are given 5 late lab days for the whole quarter
  - Tokens can only apply to Labs
  - No benefit to having leftover tokens
- Count lateness in *days* (even if just by a second)
  - Special: weekends count as *one day*
  - No submissions accepted more than two days late
- Late penalty is 20% deduction of your score per day
  - Only late labs are eligible for penalties
  - Penalties applied at end of quarter to *maximize* your grade
- Use at own risk – don’t want to fall too far behind
  - Intended to allow for unexpected circumstances

Review Questions

1) If the word size of a machine is 64-bits, which of the following is usually true? (pick all that apply)
   a) 64 bits is the size of a pointer T
   b) 64 bits is the size of an integer F
   c) 64 bits is the width of a register T
2) (True/False) By looking at the bits stored in memory, I can tell if a particular 4-bytes is being used to represent an integer, floating point number, or instruction.
3) If the size of a pointer on a machine is 6 bits, the address space is how many bytes? 0b _ _ _ _ _ _

represent 2^6 things → 2^6 addresses → 2^6 bytes of data
64 B

Memory, Data, and Addressing

- Representing information as bits and bytes
  - Binary, hexadecimal, fixed-widths
- Organizing and addressing data in memory
  - Memory is a byte-addressable array
  - Machine “word” size = address size = register size
  - Endianness – ordering bytes in memory
- **Manipulating data in memory using C**
  - **Assignment**
  - **Pointers, pointer arithmetic, and arrays**
- Boolean algebra and bit-level manipulations

Addresses and Pointers in C

* is also used with variable declarations

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

datatype

```
int* ptr;
```

equivalent: 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 ints, and *initializes* them to 5 and 2, respectively

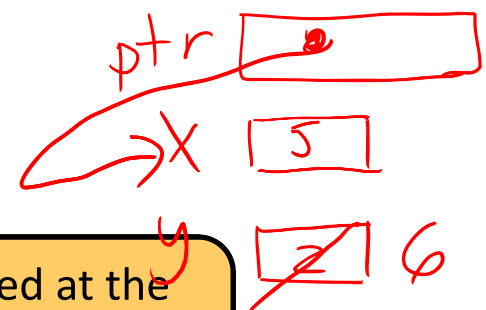
```
ptr = &x;
```

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) ?

returns value stored in y (equivalent to just using y)

Assignment in C

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

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

Assignment in C

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

little-endian

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

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

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

Assignment in C

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

- left-hand side = right-hand side;
  - LHS must evaluate to a *location*
  - RHS must evaluate to a *value* (could be an address)
  - Store RHS value at LHS location
- `int x, y;`
- `x = 0;` (pad) 0x 00 00 00 00
  - ↑ int (4 bytes)

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

Assignment in C

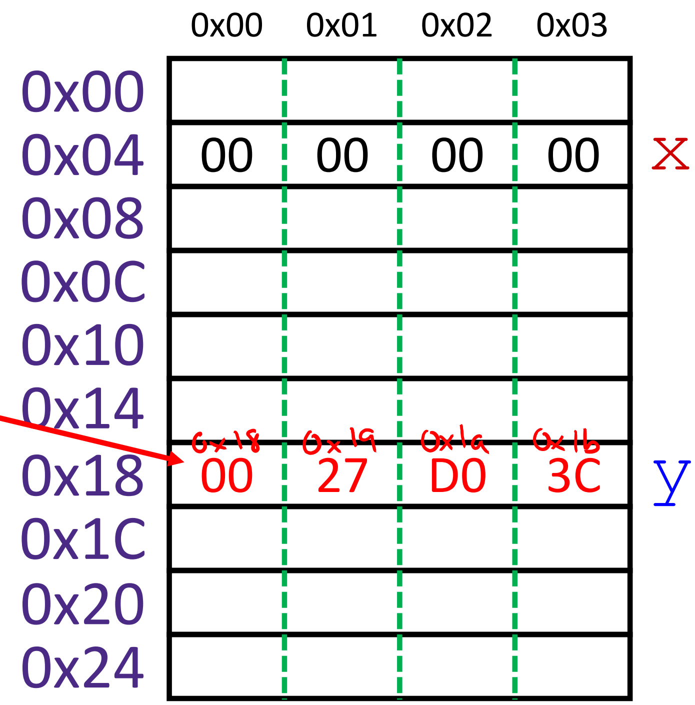
32-bit example
(pointers are 32-bits wide)

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

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

least significant byte

little endian!



Assignment in C

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

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

- left-hand side = right-hand side;
  - LHS must evaluate to a *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`

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

Assignment in C

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

`&` = "address of"

`*` = "dereference"

- left-hand side = right-hand side;
  - LHS must evaluate to a *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;` — pointer to an int
  - `z` is at address 0x20

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

initial value is whatever bits were already there! ("garbage")

Assignment in C

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

& = "address of"
* = "dereference"

- left-hand side = right-hand side;
  - LHS must evaluate to a *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;` // expect 0x1b (handwritten: `&y` = 0x18)
  - Get address of `y`, "add 3", store in `z`

Pointer arithmetic

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

get this instead (arrow pointing to 24)

Pointer Arithmetic

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

    4 bytes
  - `&y = 0x18 =` $1*16^1 + 8*16^0 = 24$
  - $24 + 3*(4) = 36 = 2*16^1 + 4*16^0 =$ `0x24`

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

Assignment in C

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					
0x04	03	27	D0	3C	x
0x08					
0x0C					
0x10					
0x14					
0x18	00	27	D0	3C	y
0x1C					
0x20	24	00	00	00	z
0x24					

Assignment in C

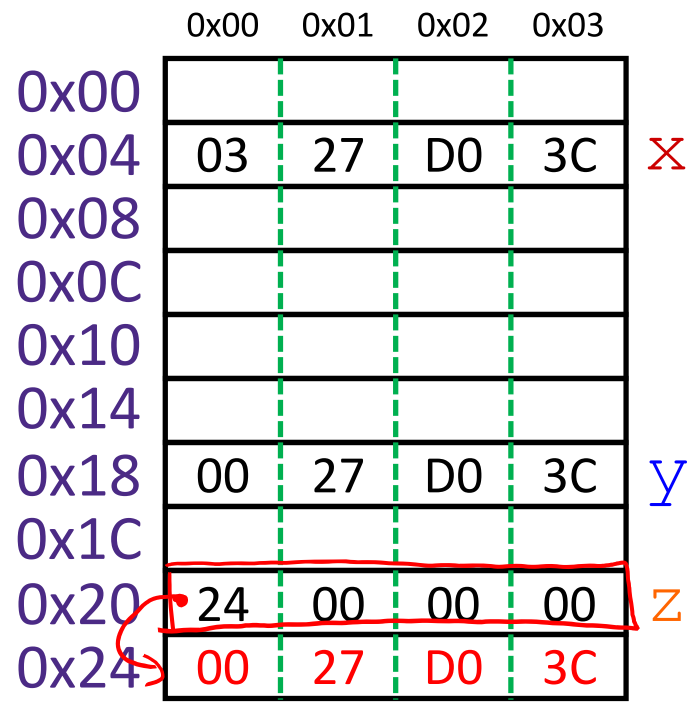
32-bit example
(pointers are 32-bits wide)

`&` = "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 location

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



Arrays in C

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

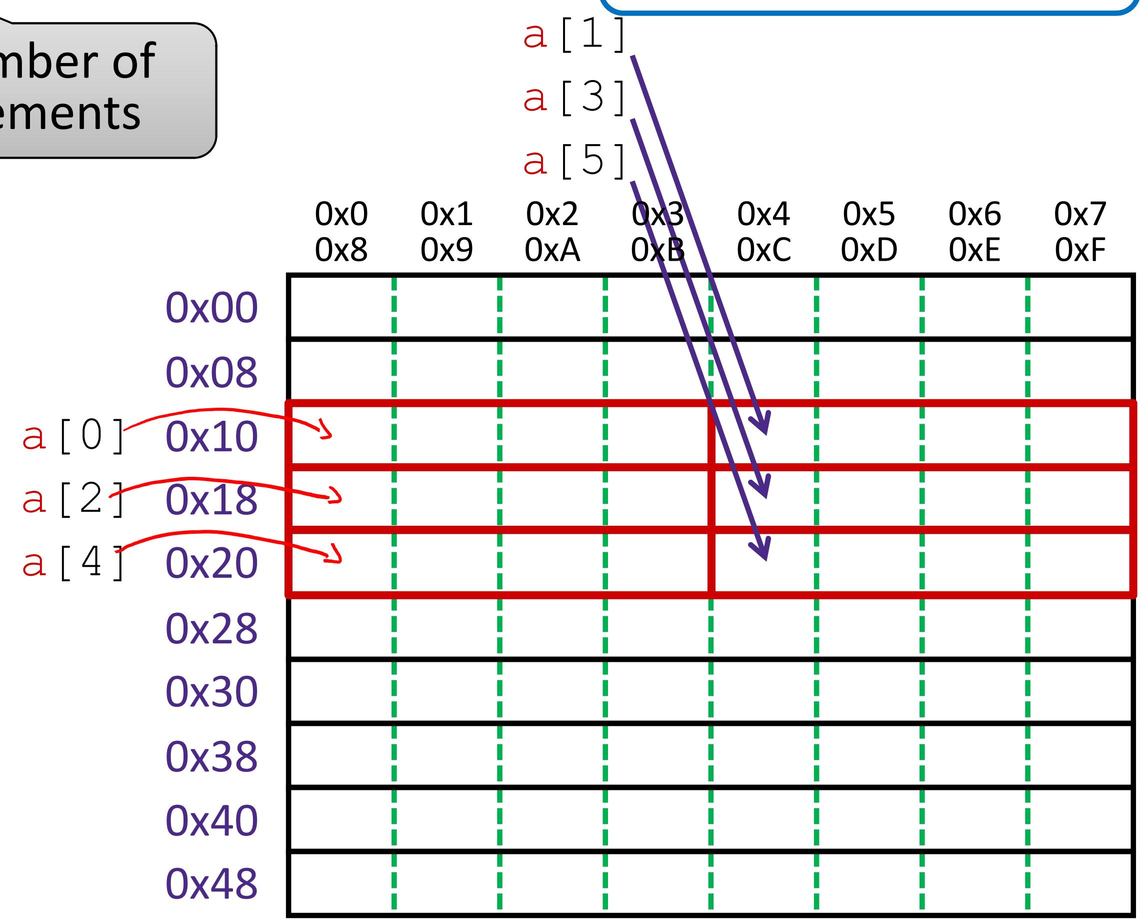
a (array name) returns the array's address

Declaration: `int a[6];` // &a is 0x10

(4 bytes each → int)

element type (int) · name (a) · number of elements (6)

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



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

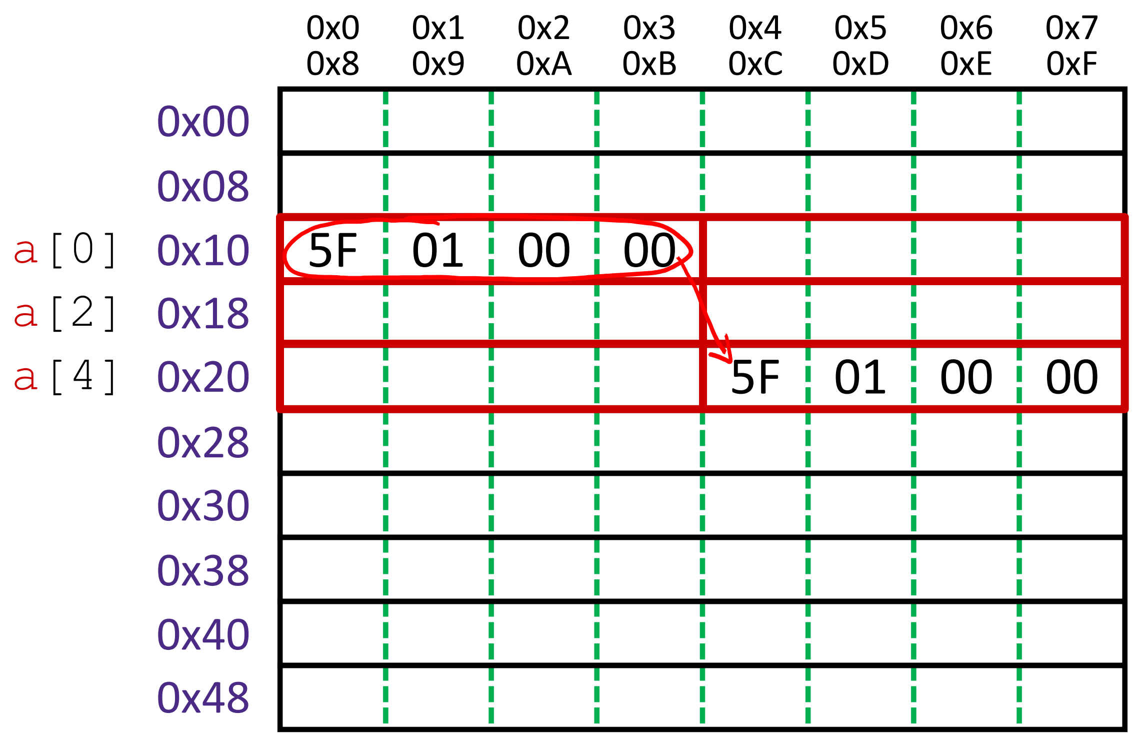
`a` (array name) returns the array's address

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

Arrays in C

Declaration: `int a[6];`

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



Arrays in C

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

`a` (array name) returns the array's address

`&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 0x8	0x1 0x9	0x2 0xA	0x3 0xB	0x4 0xC	0x5 0xD	0x6 0xE	0x7 0xF
	0x00								
	0x08					AD ("a[-1]")	0B	00	00
a[0]	0x10	5F	01	00	00				
a[2]	0x18								
a[4]	0x20					5F	01	00	00
"a[6]"	0x28	AD	0B	00	00				
	0x30								
	0x38								
	0x40								
	0x48								

Arrays in C

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

`a` (array name) returns the array's address

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

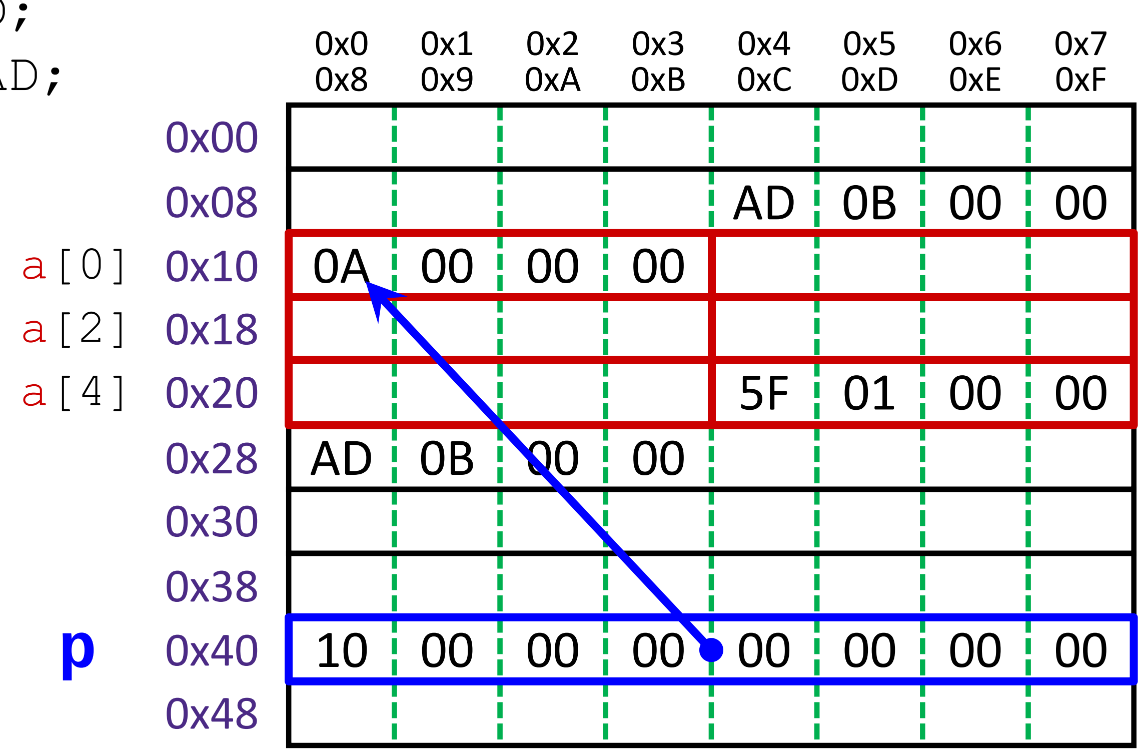
Declaration: `int a[6];`

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



Arrays in C

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

`a` (array name) returns the array's address

`&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;
```
pointer arithmetic: 0x10 + 1 → 0x14
```
p = p + 2;
```
0x10 + 2 → 0x18

p[i] ⟺ *(p + i)

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

a + 2*sizeof(int) = 0x18

Arrays in C

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

`a` (array name) returns the array's address

`&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;
```

store at 0x18 →
```
*p = a[1] + 1;
```
0xB + 1 = 0xC

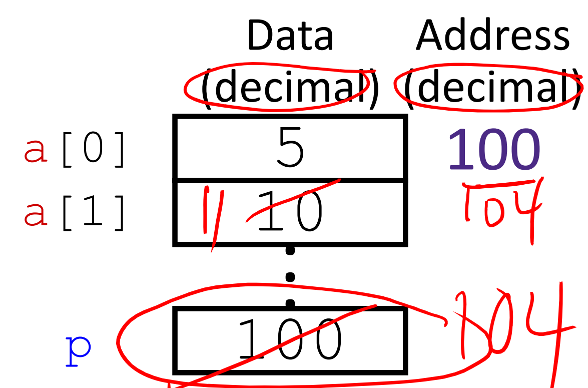
(no pointer arithmetic)

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

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

- Vote at http://pollev.com/rea

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



	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:** "Donald Trump" stored as a 13-byte array

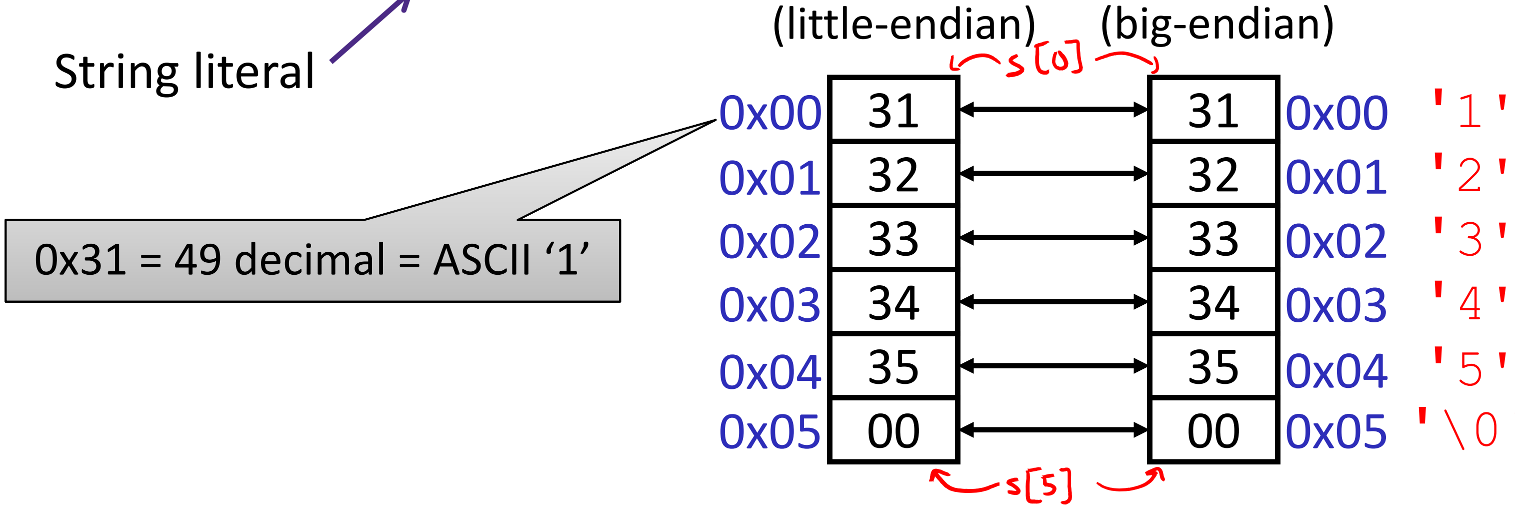
Decimal:	68	111	110	97	108	100	32	84	114	117	109	112	0
Hex:	0x44	0x6F	0x6E	0x61	0x6C	0x64	0x20	0x54	0x72	0x75	0x6D	0x70	0x00
Text:	D	o	n	a	l	d		T	r	u	m	p	\0

- 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";
```



- 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

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");
}
```

format string

pointer arithmetic on char*

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

int*

4 bytes

"cast" (treat as)

show_bytes Execution Example

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

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

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

Summary

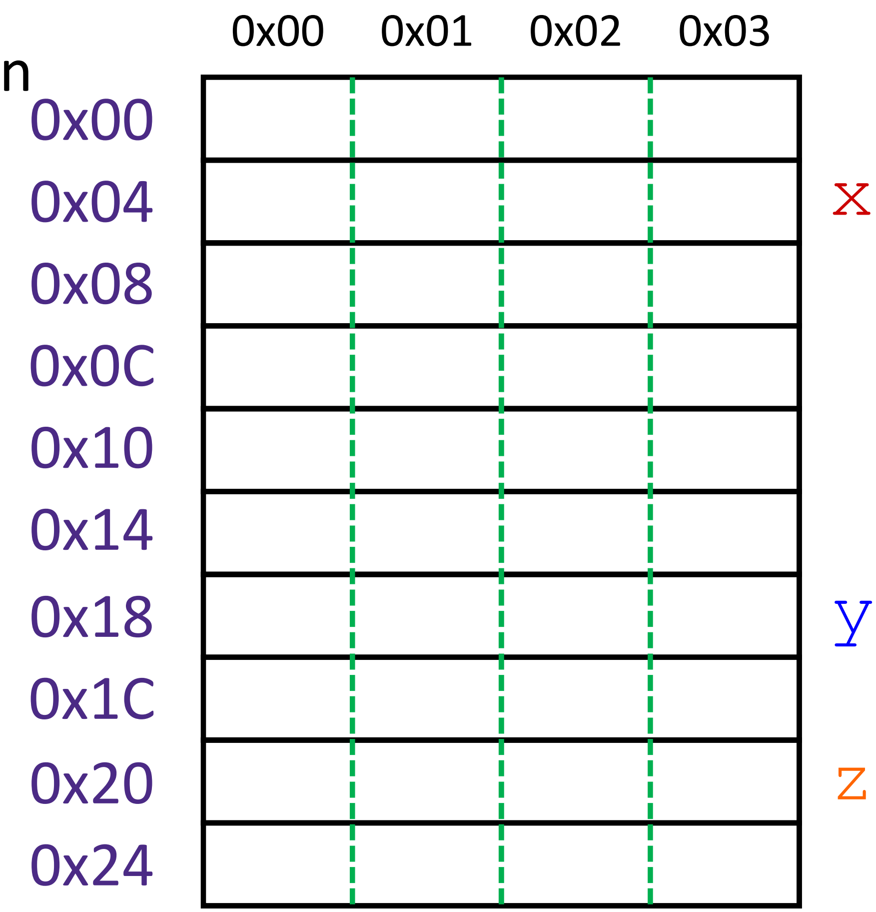
- Assignment in C results in value being put in memory location
- Pointer is a C representation of a data address
  - `&` = "address of" operator
  - `*` = "value at address" or "dereference" operator
- Pointer arithmetic scales by size of target type
  - Convenient when accessing array-like structures 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)

Assignment in C - Handout

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

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

- left-hand side = right-hand side;
  - LHS must evaluate to a *location*
  - RHS must evaluate to a *value*
  - Store RHS value at LHS location
- `int x, y;`
- `x = 0;`
- `y = 0x3CD02700;`
- `x = y + 3;`
- `int* z = &y + 3;`
- `*z = y;`



Arrays in C - Handout

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

`a` (array name) returns the array's address

`&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;
```