The Hardware/Software Interface

Memory, Data, & Addressing II

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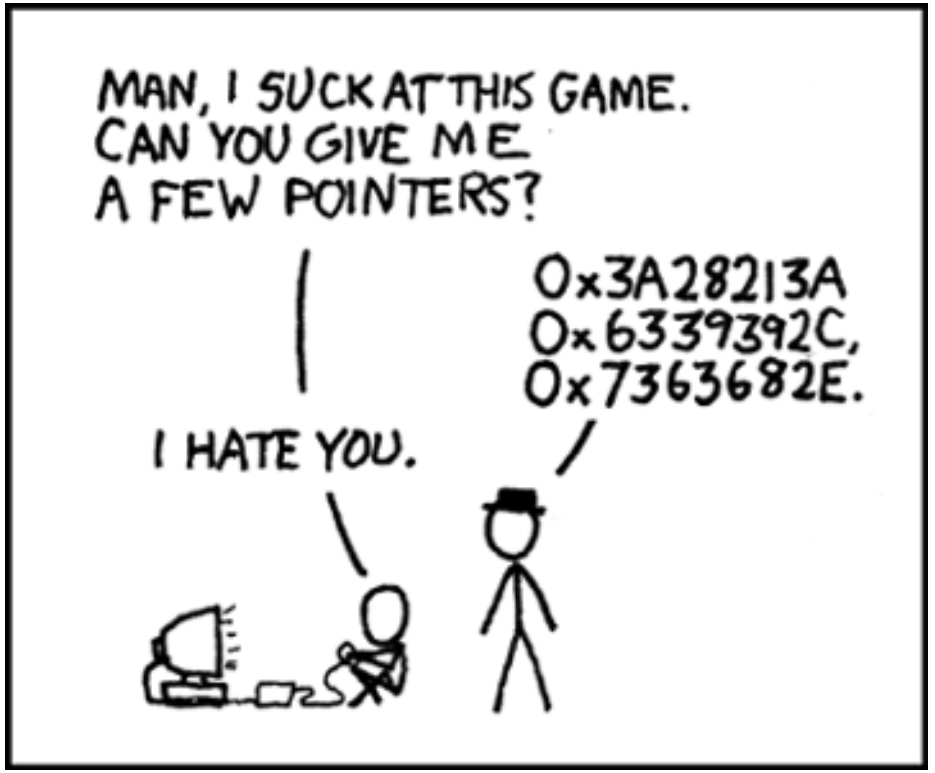


http://xkcd.com/138/

Relevant Course Information

- Lab 0 due today @ 11:59 pm
  - *You will revisit the concepts & behavior from this program in future labs!*
- HW1 due tonight, HW2 due Wednesday, HW3 due Friday @ 11:59 pm
  - Autograded, unlimited tries, no late submissions
- Lab 1a released today, due next Monday (10/6)
  - Pointers in C
  - Last submission graded, can optionally work with a partner
    - One student submits, then adds their partner to the submission (*for every submission*)
  - Short answer "synthesis questions" for after the lab

Late Days

- You are given 6 late day tokens 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 10% 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

Lecture Outline (1/4)

- **Pointers**
- Pointer Arithmetic
- Arrays in C Introduction
- C “Strings”

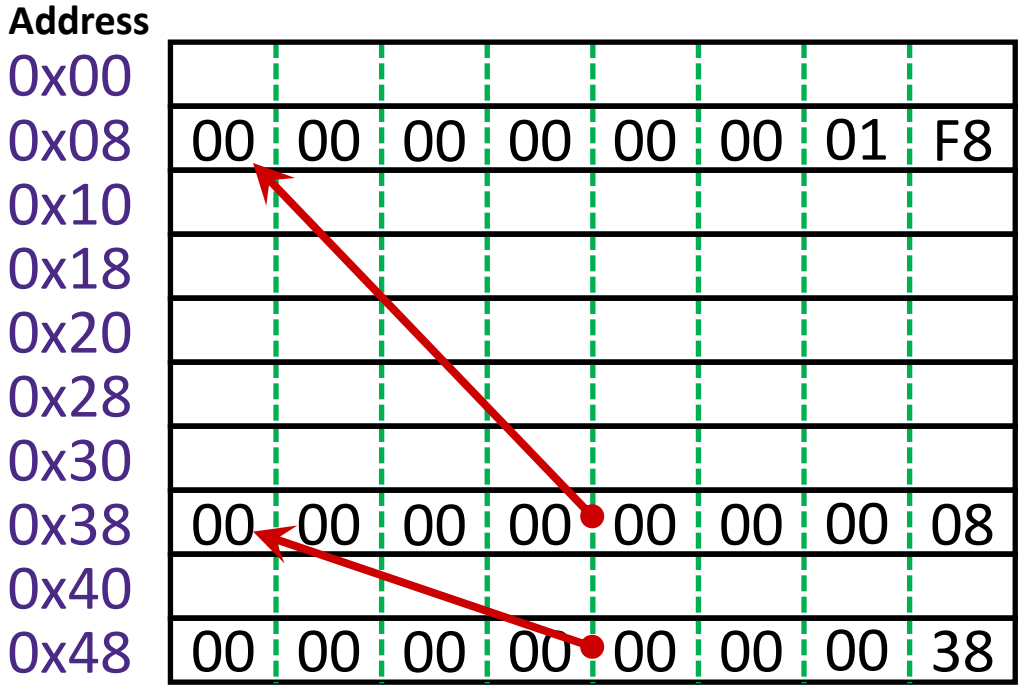
Data Types and Sizes (Revisited)

- A pointer is a data type that stores an address
  - Address size = word size

C Data Type	Java "Equivalent"	Size in bytes (x86-64)
`char`	`byte`	1
`short`	`short`	2
`int`	`int`	4
`long`		8
`long long`	`long`	8
`float`	`float`	4
`double`	`double`	8
`long double`		16
pointer (`type*`)	reference	8

Addresses and Pointers Example

- *Address* – refers to a location in memory
- *Pointer* – data object that stores/holds an address
- In this example, assume a 64-bit machine using big-endian
  1) Store 504 = 0x1F8 as 8 bytes at addr 0x08
  2) Store pointer pointing to 0x08 at addr 0x38
  3) Store pointer pointing to 0x38 at addr 0x48
     - Pointer to a pointer!
  - Was the original data (504) a pointer?
    - Could be, depending on how you use it



Pointers in C (Review, 1/3)

- Declaration: **`type*`** `ptr;` or **`type`** `*ptr;` (equivalent)
  - Word size (*e.g.*, 8 bytes on a 64-bit machine) to store addresses

- & = "address of" operator
  - ```
    int  q;
    int* p = &q;  // stores address of q in p
    ```

- * = "value at address" or "dereference" operator
  - ```
    int  q = 351;
    int* p = &q;
    int  r = *p;  // store the data pointed at by p in r
    ```

Pointers in C (Review, 2/3)

- Declaration: **`type*`** `ptr;` or **`type`** `*ptr;` (equivalent)
- `&` = "address of" operator
- `*` = "value at address" or "dereference" operator

- Operator confusion
  - The pointer operators are *unary* (*i.e.*, take 1 operand)
  - These operators both have *binary* forms
    - `x & y` is bitwise AND (we'll talk about this next lecture)
    - `x * y` is multiplication
  - `*` is also used as part of the data type in pointer variable declarations – this is NOT an operator in this context!

Pointers in C (Review, 3/3)

- Declaration: **`type*`** `ptr;` or **`type`** `*ptr;` (equivalent)
- & = "address of" operator
- `*` = "value at address" or "dereference" operator

- `NULL` is a constant for a pointer to "nothing"
  - Example: **`int*`** `p = NULL;`
  - Dereferencing `NULL` always results in a runtime error

Box-and-Arrow Diagrams

- Visual representation of C code with pointers
  - Boxes are variables, arrows connect pointers to target (NULL shown as Ø)
  - Useful for planning code and debugging

```
int x = 3, y;
int* p = &x;
int** pp = &p;
y = **pp + 2;
p = NULL;
y = *p - 2;
```

Lecture Outline (2/4)

- Pointers
- **Pointer Arithmetic**
- Arrays in C Introduction
- C “Strings”

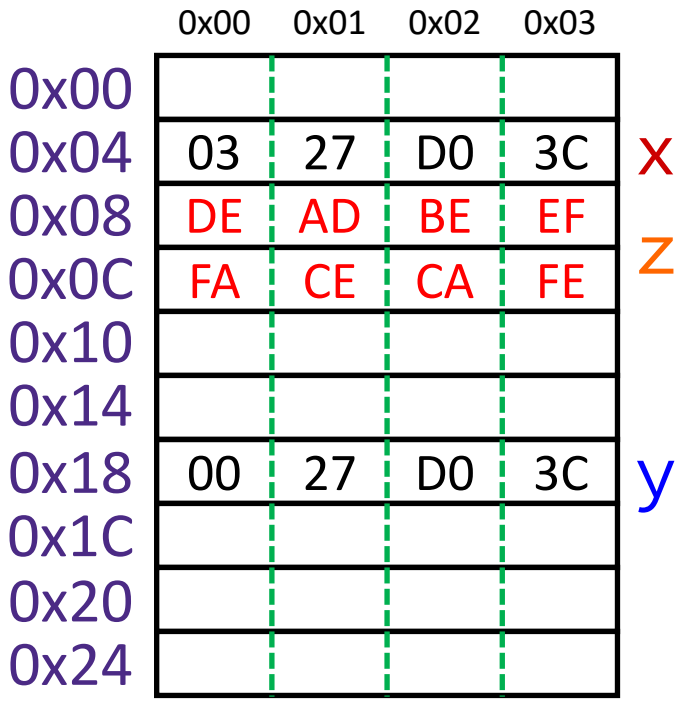
Pointer Arithmetic (Review)

- Pointer arithmetic is arithmetic (*e.g.*, +, –) performed on an expression that represents an address (*e.g.*, a pointer variable name)
  - The effect of the arithmetic operator is scaled by the size of the target type
    - Can consider this a change in units from bytes to the target type
    - Most commonly, adding constants to pointers and subtracting two pointers of the same type
- Examples:
  - For **`int*`** `p1`, `p1=p1+1` will increase its value by 4 (incremented by 1 **`int`**)
  - For **`long*`** `p2`, `p2=p2+1` will increase its value by 8 (incremented by 1 **`long`**)
  - For **`int*`** `p3` and **`int*`** `p4`, `p4-p3` will return the number of ***`int`***`s` between the two addresses
- ⚠️ Not all arithmetic operations are valid on pointers!

Assignment Example (Revisited, 1/3)

- Syntax: left-hand side (LHS) = right-hand side (RHS);
- Effect: store *value* of RHS into the *location* given by LHS

- Example: Little-endian, *partial* state of memory
  - `int x = 0, y = 0x3CD02700;`
  - `x = y + 3;`
  - `int* z;  // at address 0x08`

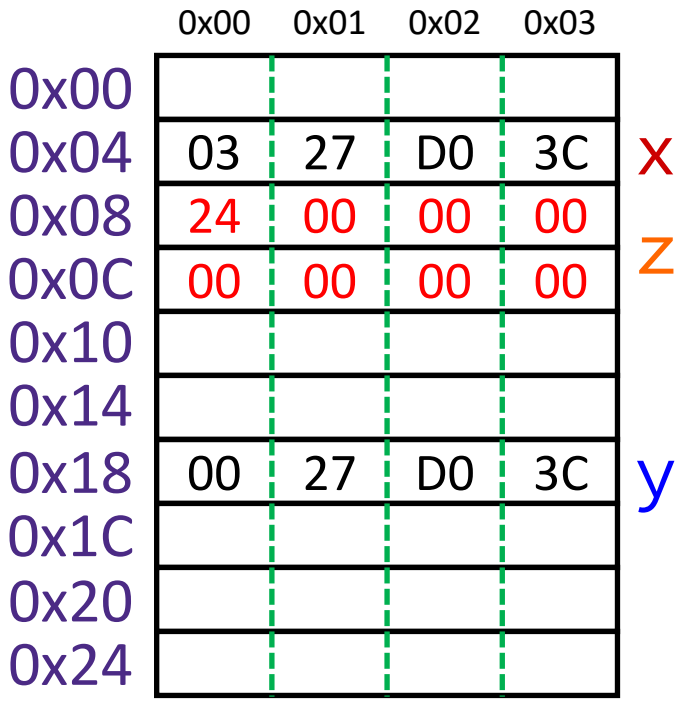


Assignment Example (Revisited, 2/3)

- Syntax: left-hand side (LHS) = right-hand side (RHS);
- Effect: store *value* of RHS into the *location* given by LHS

- Example: Little-endian, *partial* state of memory
  - `int x = 0, y = 0x3CD02700;`
  - `x = y + 3;`
  - `int* z;`
  - `z = &y + 3;`
    - Get address of y, "add 3", store in z

Pointer arithmetic



Assignment Example (Revisited, 3/3)

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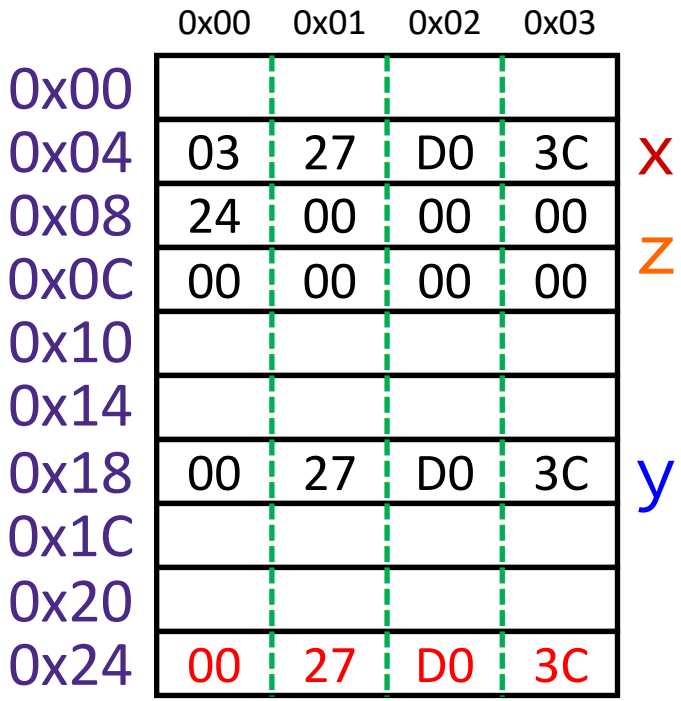
- Example: Little-endian, *partial* state of memory
  - `int x = 0, y = 0x3CD02700;`
  - `x = y + 3;`
  - `int* z;`
  - `z = &y + 3;`
    - Get address of y, add 12, store in z
  - `*z = y;`
    - Get value of y, put in address stored in z

The target of a pointer is also a location



Pointer Arithmetic Warning

- Pointer arithmetic is arithmetic (*e.g.*, +, –) performed on an expression that represents an address (*e.g.*, a pointer variable name)
  - The effect of the arithmetic operator is scaled by the size of the target type
    - Can consider this a change in units from bytes to the target type
    - Most commonly, adding constants to pointers and subtracting two pointers of the same type

- ⚠️ Pointer arithmetic can be dangerous and can easily lead to bad memory accesses if you are not careful!
  - Be careful with data types and *casting*
    - Example: For `int* p`, the expression `(short*)p + 1` will actually scale by 2 instead of 4 because we are now treating the value in `p` as if it was a `short*`

Polling Questions (1/2)

- ```
  int x = 351;
  char* p = &x;
  int ar[3];
  ```

- How much space does the variable p take up?

  A. 1 byte

  B. 2 bytes

  C. 4 bytes

  D. 8 bytes

- Which of the following expressions evaluate to an address?

  A. `x + 10`

  B. `p + 10`

  C. `&x + 10`

  D. `*(&p)`

  E. `ar[1]`

  F. `&ar[2]`
  ```

Aside: Java References

- In Java, everything that is not a primitive data type is an *object*
  - An object variable is actually a *"reference"* – a restricted pointer

```
class Record { ... }
Record x = new Record();
```

- Reference restrictions:
  - No pointer arithmetic, just reassignment
    - Reassignment must adhere to rules set by typing system (*e.g.*, inheritance)
  - References can only be "dereferenced" in ways that match class definition
    - *e.g.*, calling a method, accessing a field in object
- All higher-level languages use pointers/addresses under the hood, but likely abstracted away from the programmer

Lecture Outline (3/4)

- Pointers
- Pointer Arithmetic
- **Arrays in C Introduction**
- C “Strings”

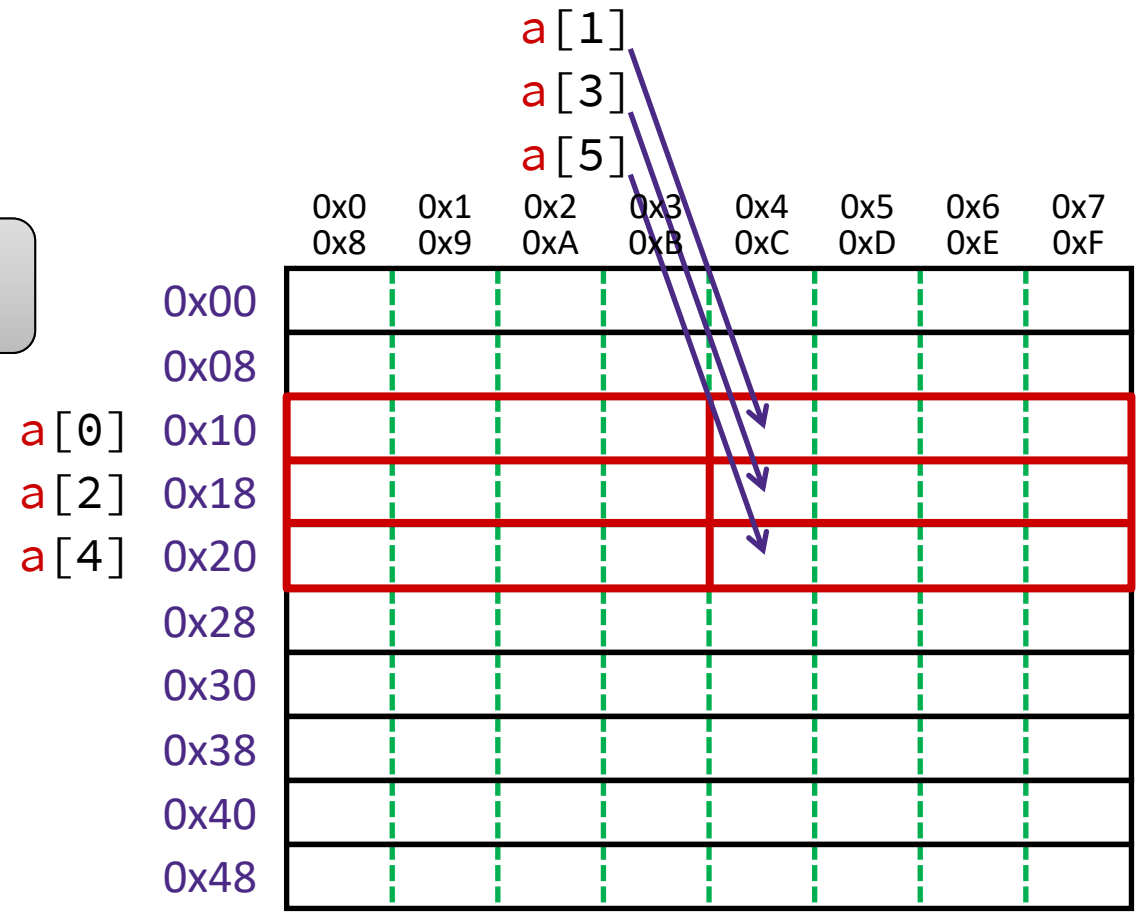
Arrays in C: Declaration (Review)

- **Arrays** are adjacent locations in memory storing the same type of data object
  - Declaration: `int a[6];`

element type

name

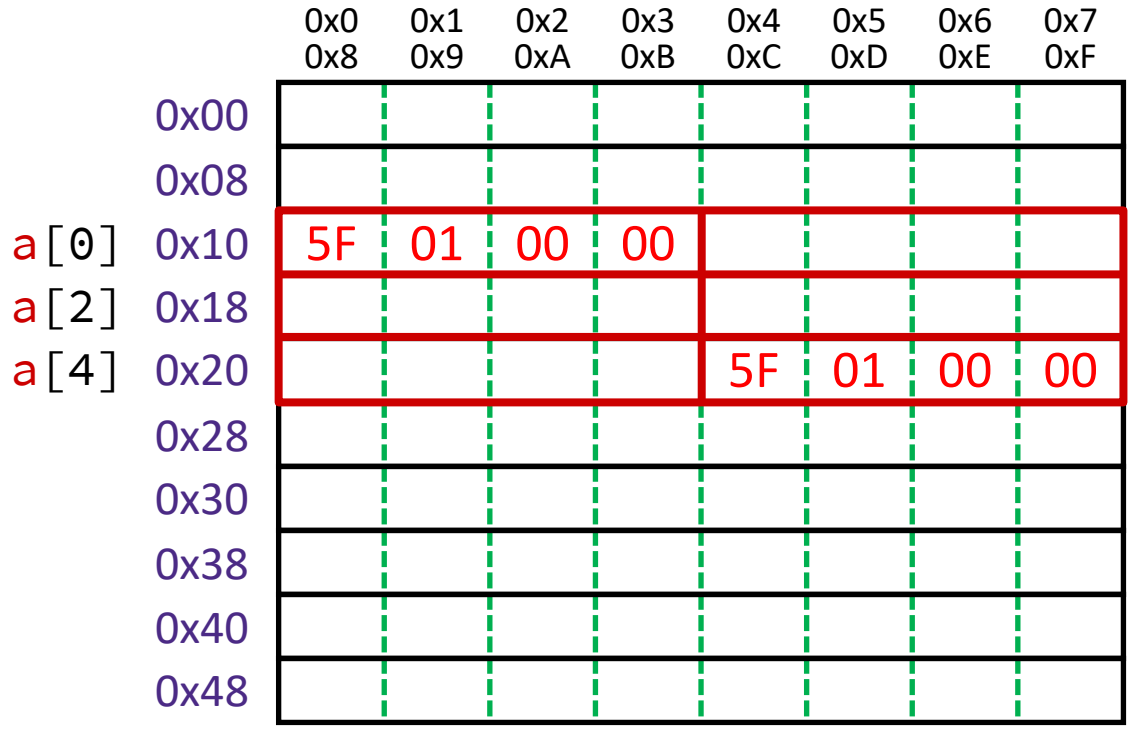
number of elements



Arrays in C: Indexing (Review)

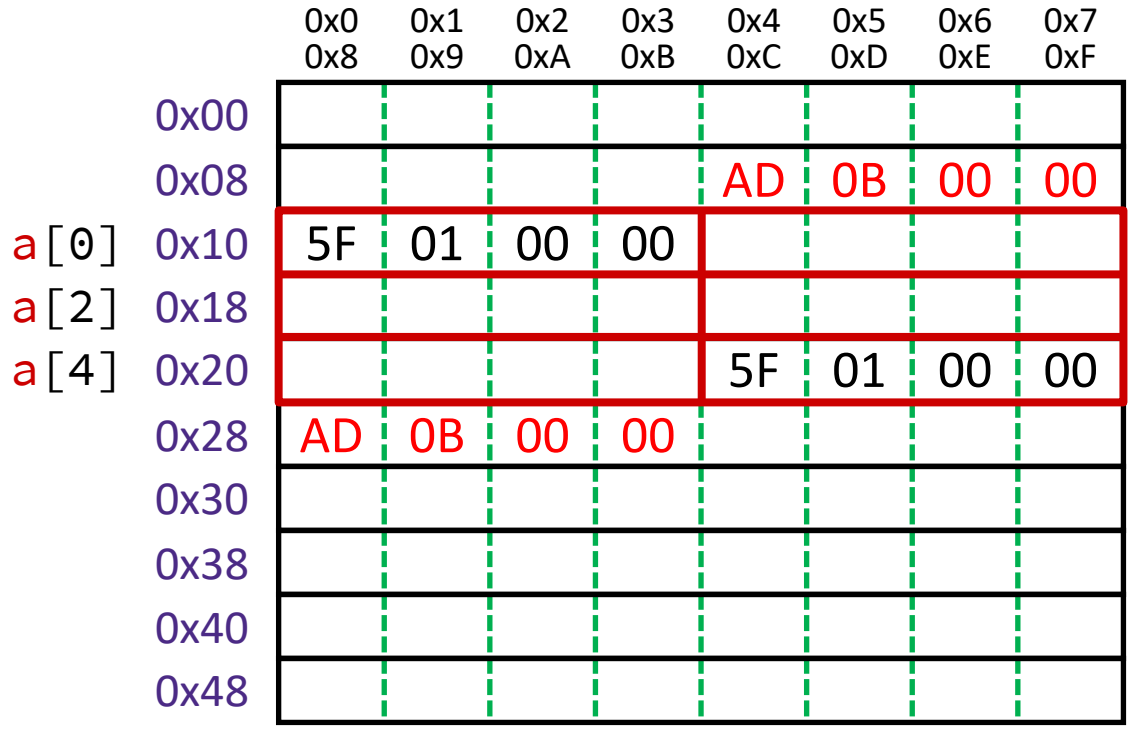
- **Arrays** are adjacent locations in memory storing the same type of data object
  - Declaration: `int a[6];`
  - Indexing:

```
a[0] = 0x15F;
a[5] = a[0];
```



Arrays in C: Lack of Bounds Checking (Review)

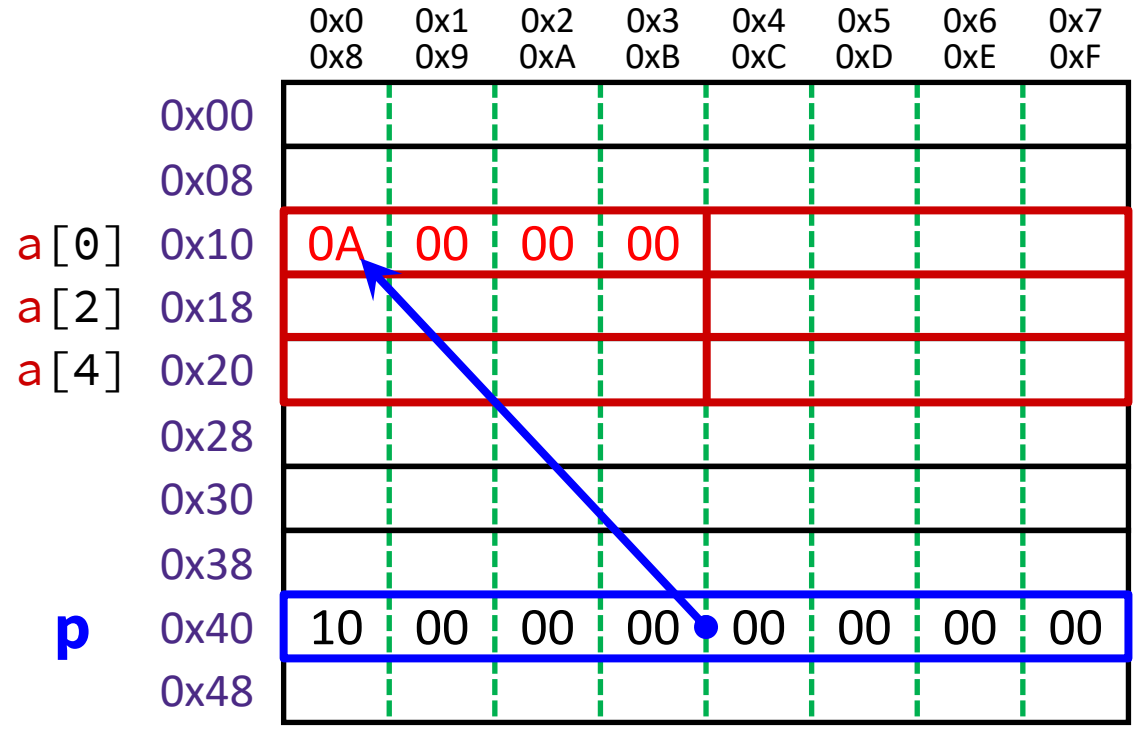
- **Arrays** are adjacent locations in memory storing the same type of data object
  - Declaration: `int a[6];`
  - Indexing:
    ```
    a[0] = 0x15F;
    a[5] = a[0];
    ```
  - No bounds checking:
    ```
    a[6] = 0xBAD;
    a[-1] = a[6];
    ```



Arrays and Pointers in C Example (1/4)

- Pointers are very handy when using arrays:
  - Using the name of an array in an expression evaluates to the array's address

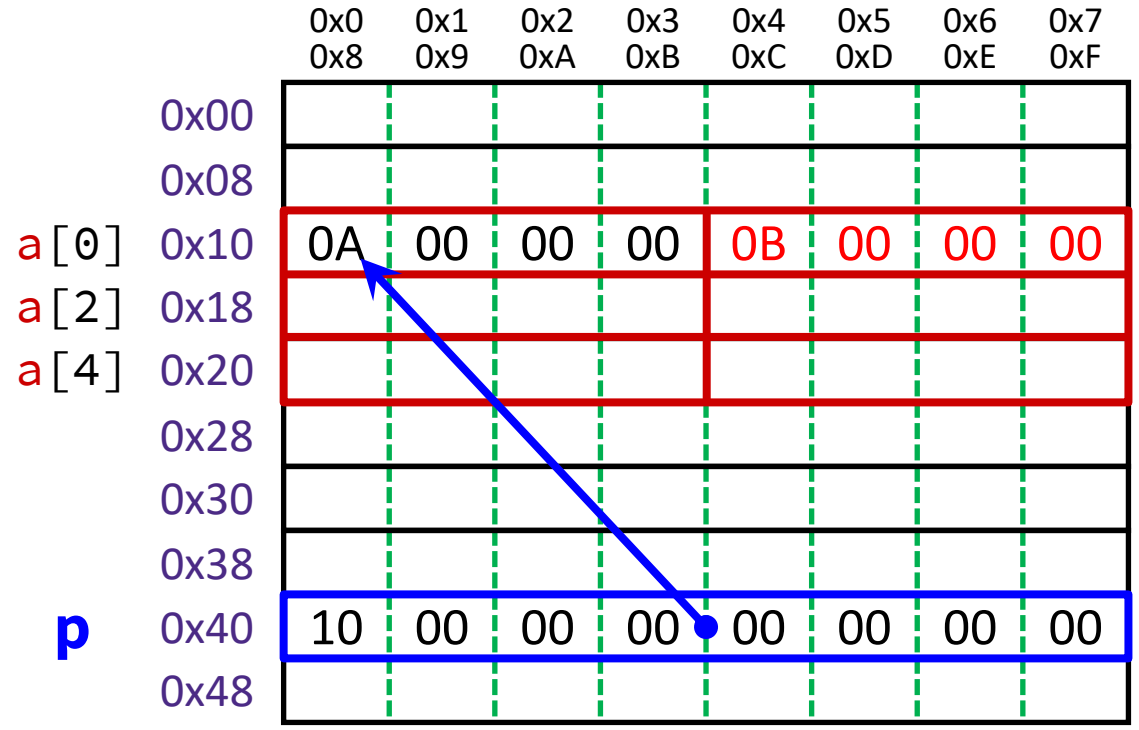
- Examples:
  - `int a[6];`
  - `int* p = a;  // or &a[0];`
  - `*p = 0xA;`



Arrays and Pointers in C Example (2/4)

- Pointers are very handy when using arrays:
  - Using the name of an array in an expression evaluates to the array's address
  - `a[i]` is actually `*(a + i)` and `&a[i]` is equivalent to `a+i`

- Examples:
  - `int a[6];`
  - `int* p = a;  // or &a[0];`
  - `*p = 0xA;`
  - `p[1] = 0xB;  // or *(p+1)`



Arrays and Pointers in C Example (3/4)

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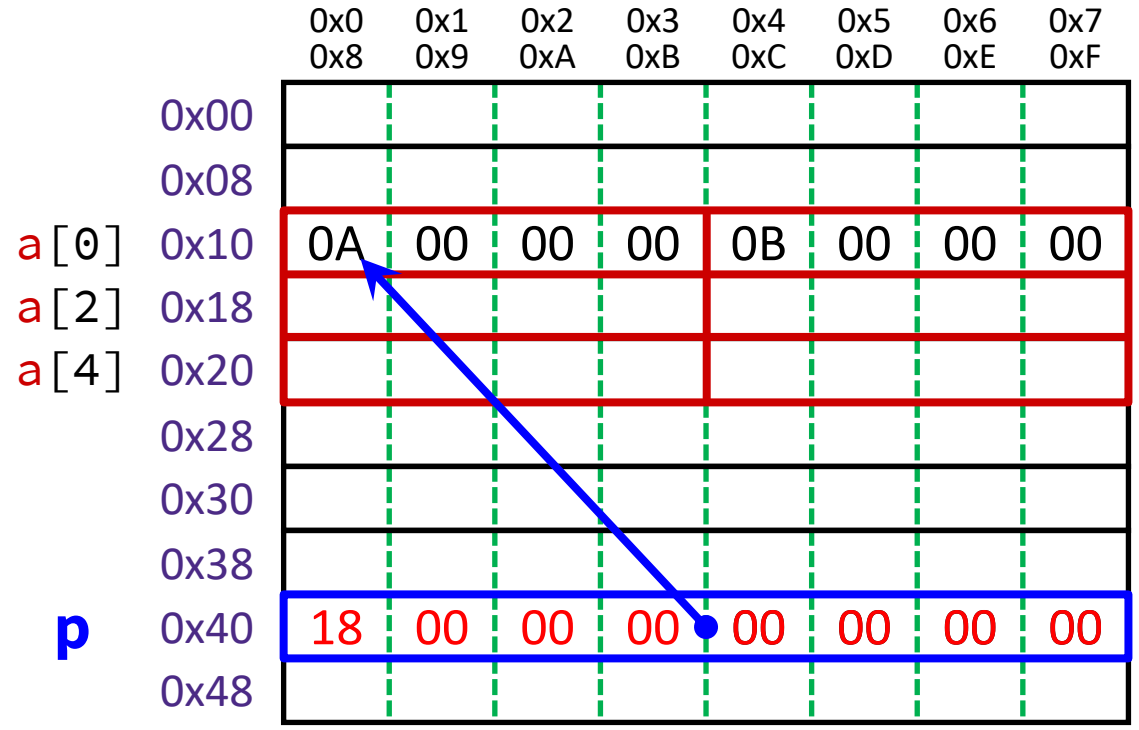
- Examples:
  - `int a[6];`
  - `int* p = a;  // or &a[0];`
  - `*p = 0xA;`
  - `p[1] = 0xB;  // or *(p+1)`
  - `p = p + 2;`



Arrays and Pointers in C Example (4/4)

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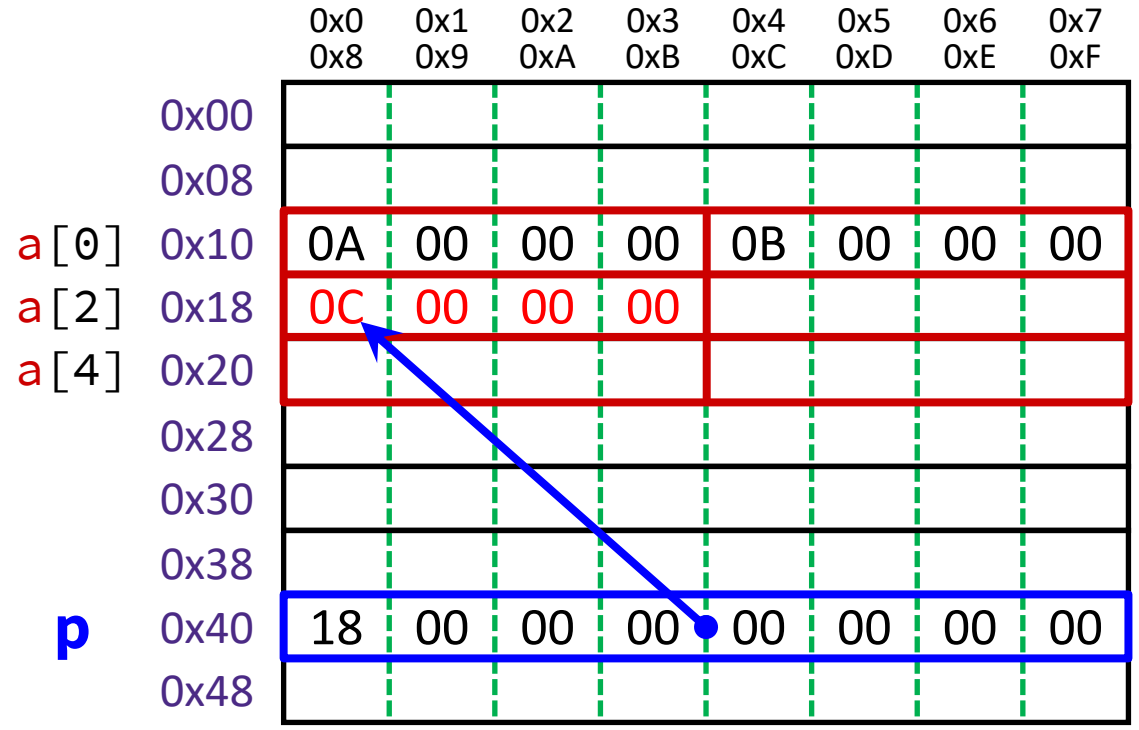
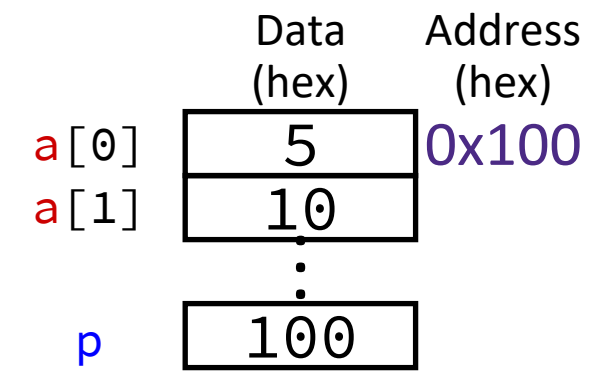
- Examples:
  - `int a[6];`
  - `int* p = a;  // or &a[0];`
  - `*p = 0xA;`
  - `p[1] = 0xB;  // or *(p+1)`
  - `p = p + 2;`
  - `*p = a[1] + 1;`



Polling Questions (2/2)

- The variable values after Line 3 executes are shown on the right. What are they after Line 5?

```
1  void main() {
2    int a[] = {0x5,0x10};
3    int* p = a;
4    p = p + 1;
5    *p = *p + 1;
6  }
```



	p	a[0]	a[1]
(A)	0x101	0x5	0x11
(B)	0x104	0x5	0x11
(C)	0x101	0x6	0x10
(D)	0x104	0x6	0x10

Lecture Outline (4/4)

- Pointers
- Pointer Arithmetic
- Arrays in C Introduction
- **C "Strings"**

Representing Strings: ASCII

- C-style string stored as an array of bytes (**`char*`**)
  - No "`String`" keyword, unlike Java
  - Elements are one-byte *ASCII codes* for each character
    - Characters in C indicated with single quotes (*e.g.*, `'3'`) and evaluate to decimal constants

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

Representing Strings: Null Character (Review)

- C-style string stored as an array of bytes (**`char*`**)
  - No "`String`" keyword, unlike Java
  - Elements are one-byte ASCII codes for each character
    - Characters in C indicated with single quotes (*e.g.*, `'3'`) and evaluate to decimal constants
  - Last character followed by a 0 byte (`'\0'`, the *null character*)
    - Note that `'0'` ≠ `'\0'`
    - Example: **`char`** `str[] = "hi, you";` contains the following values

Decimal:	104	105	44	32	121	111	117	0
Hex:	0x68	0x69	0x2C	0x20	0x79	0x6F	0x75	0x00
Text:	`'h'`	`'i'`	`','`	`' '`	`'y'`	`'o'`	`'u'`	`'\0'`

Representing Strings: Literals (Review)

- C-style string stored as an array of bytes (**`char*`**)
  - No "`String`" keyword, unlike Java
  - Elements are one-byte ASCII codes for each character
    - Characters in C indicated with single quotes (*e.g.*, `'3'`) and evaluate to decimal constants
  - Last character followed by a 0 byte (`'\0'`, the null character)
    - Note that `'0'` ≠ `'\0'`
    - Example: **`char`** `str[] = "hi, you";` contains `{'h','i',' ','y','o','u','\0'}`

- A ***string literal*** (or *string constant*) indicated by double quotes (*e.g.*, `"hi, you"`) and automatically stored as a char array in memory
  - Space for `'\0'` included
  - Cannot be manipulated (need to copy into another char array first)

Printing Strings

- To print a string, use `printf` with the format specifier `%s`
  - Argument is the address of the string
  - Prints out the characters until it finds the first null character

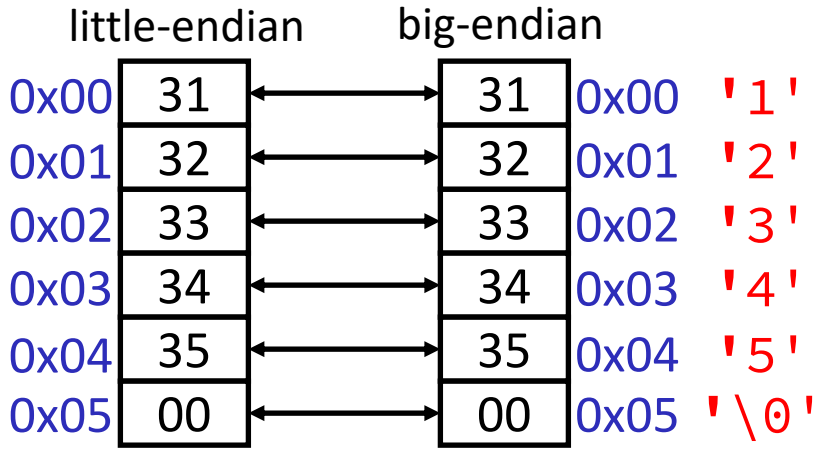
- Example:

```
// Curious about these numbers? See asciitable.com.
char str[] = {89, 111, 33, 0, 121, 111, 117};
// notice that it stops at ^
printf("%s\n", str);
```

Endianness and Strings

- Byte ordering (endianness) is not an issue for 1-byte values
  - The whole array does not constitute a single value
  - Individual elements are values; **char**s are single bytes

- Example:
  - `char s[6] = "12345";`



Examining Data Representations: Code

- Code to print byte representation of data
  - Treat any data type as a *byte array* by **casting** its address 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%.2hhX\n", start+i, *(start+i));
  printf("\n");
}
```

- `printf` legend:
  - Special characters: `\t` = Tab, `\n` = newline
  - Format specifiers: `%p` = pointer,
    `%.2hhX` = 1 byte (hh) in hex (X), padding to 2 digits (`.2`)

Examining Data Representations: Usage

- Code to print byte representation of data
  - Treat any data type as a *byte array* by **casting** its address to `char*`
  - C has unchecked casts (⚠️ DANGER ⚠️)

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

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

`show_bytes` Execution Example

```
int x = 123456;  // 0x00 01 E2 40
printf("int x = %d;\n", x);
show_int(x);     // show_bytes((char *) &x, sizeof(int));
```

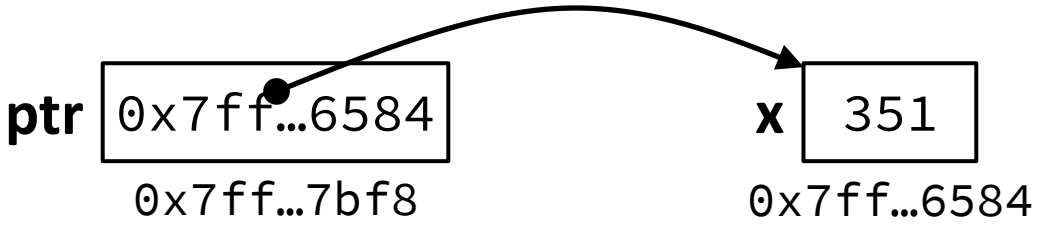
- Result (Linux x86-64):
  - **Note:** The addresses will change on each run (try it!), but fall in same general range

```
int x = 123456;
0x7fffb245549c  0x40
0x7fffb245549d  0xE2
0x7fffb245549e  0x01
0x7fffb245549f  0x00
```

Summary (1/2)

- Pointers are data objects that hold addresses
  - Type of pointer determines size of thing being pointed at, which could be another pointer
  - `&` = "address of" operator
  - `*` = "value at address" or "dereference" operator
  - `NULL` is a constant for a pointer to "nothing"

- Can visualize using box-and-arrow diagrams:



Summary (2/2)

- Arrays are adjacent locations in memory storing the same type of data
  - Strings are null-terminated arrays of characters (ASCII)
- Pointer arithmetic scales by size of target type
  - Convenient when accessing array-like structures in memory: `a[i]` ↔ `*(a + i)`
  - Be careful when using – particularly when *casting* variables