Memory, Data, & Addressing II

CSE 351 Winter 2022

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http://xkcd.com/138/

Relevant Course Information

- Binary Homework and Pre-Course Survey due tonight
  - Autograded, unlimited tries, no late submissions
- Lab 0 due Monday @ 11:59 pm
  - *You will revisit the concepts from this program!*
- Lab 1a released today, due a week from Wed (1/19)
  - Pointers in C
  - Last submission graded, can optionally work with a partner
    - One student submits, then add their partner to the submission
  - Short answer "synthesis questions" for after the lab

Zoom Lecture Questions Doc

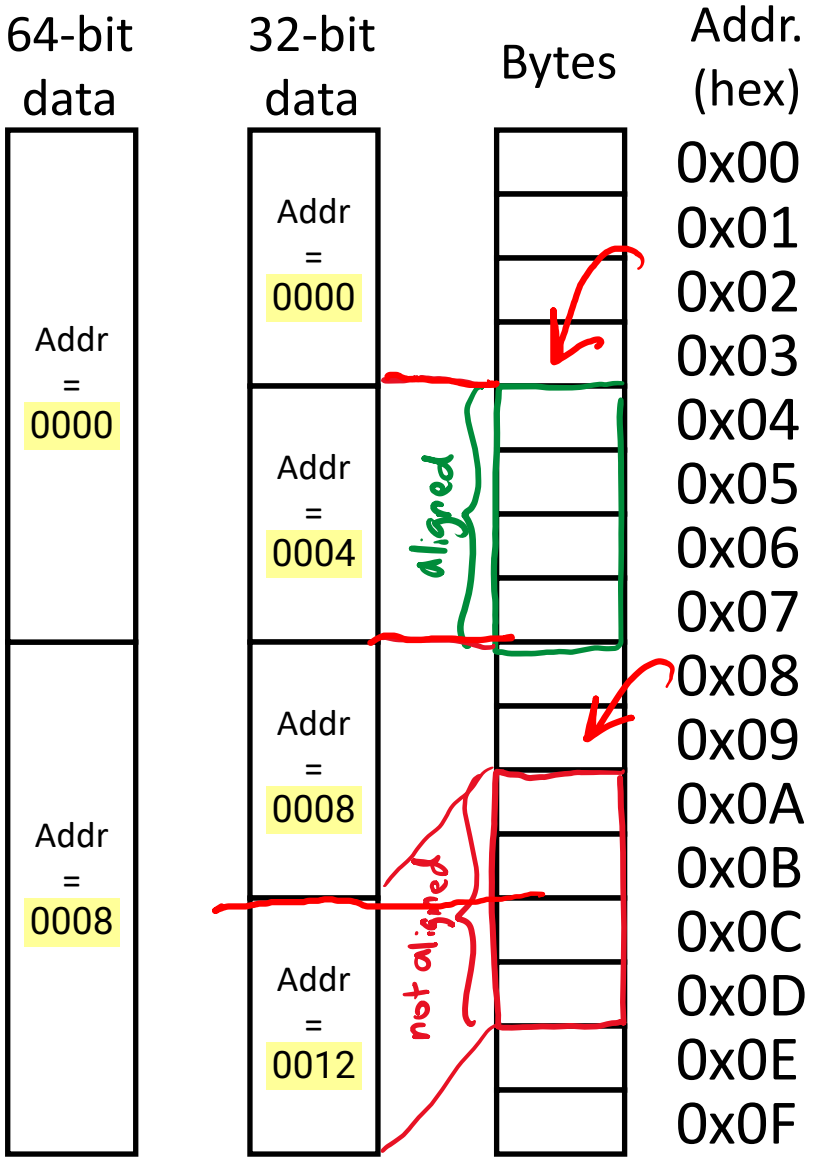
- If you have a question that isn't *directly* related to the topic at hand, we'll provide a Google Doc where you can ask it.
  - https://tinyurl.com/cse351-22wi-zoom-questions
  - TAs will monitor the doc and answer questions asynchronously.
  - If you're not sure where your question fits, go ahead and ask it in Zoom chat. We'll refer you to the questions doc if we think it would be better suited there.

Late Days

- You are given 5 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 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

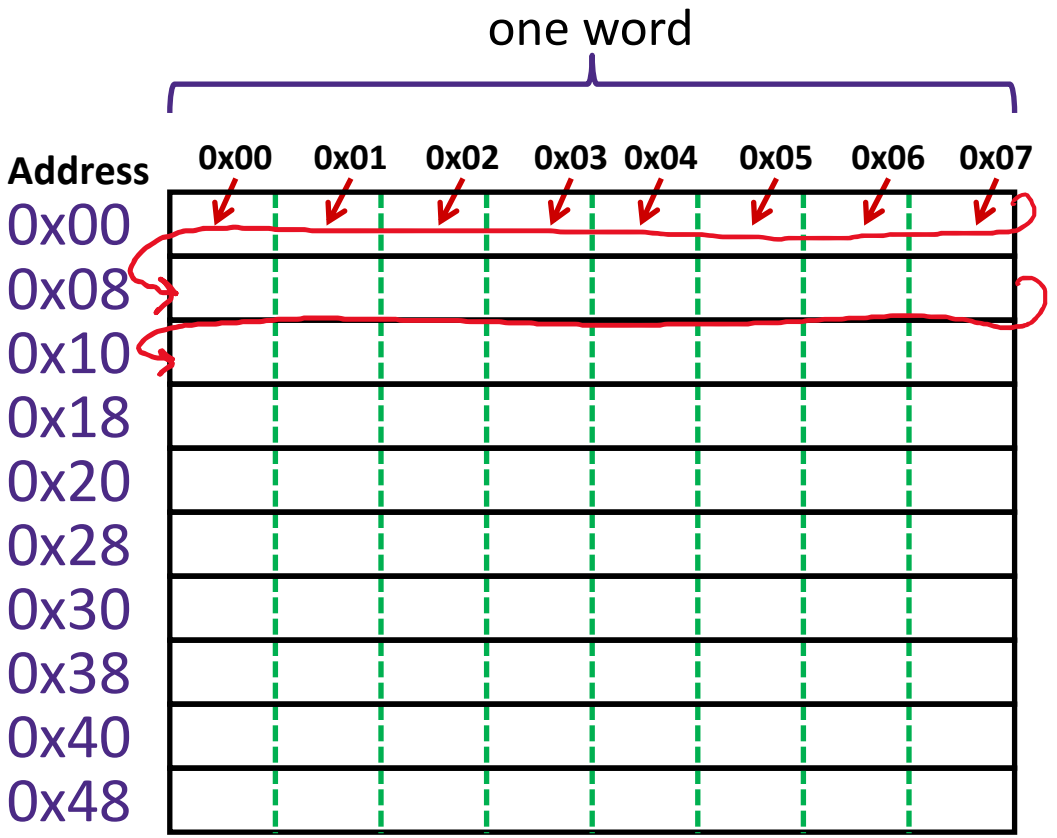
Alignment

- The address of a chunk of memory is considered aligned if its address is a multiple of its size
  - View memory as a series of consecutive chunks of this particular size and see if your chunk doesn't cross a boundary



A Picture of Memory (64-bit view)

- A "64-bit (8-byte) word-aligned" view of memory:
  - In this type of picture, each row is composed of 8 bytes
  - Each cell is a byte
  - An aligned, 64-bit chunk of data will fit on one row



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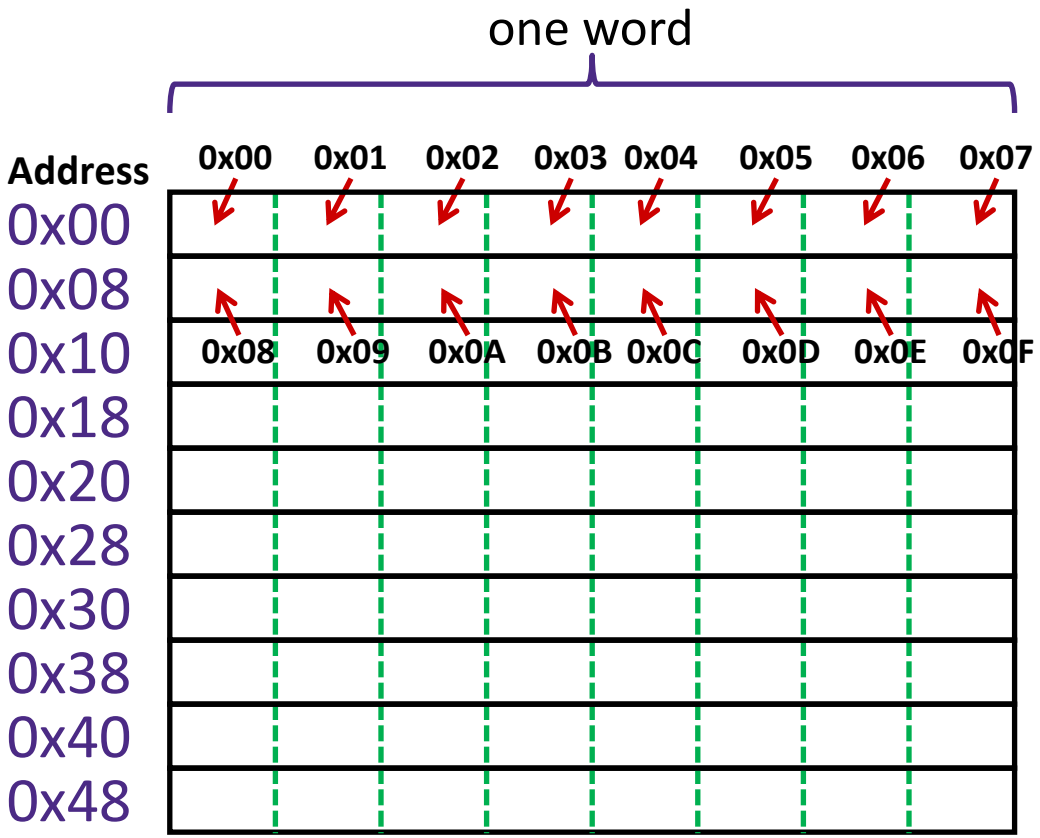
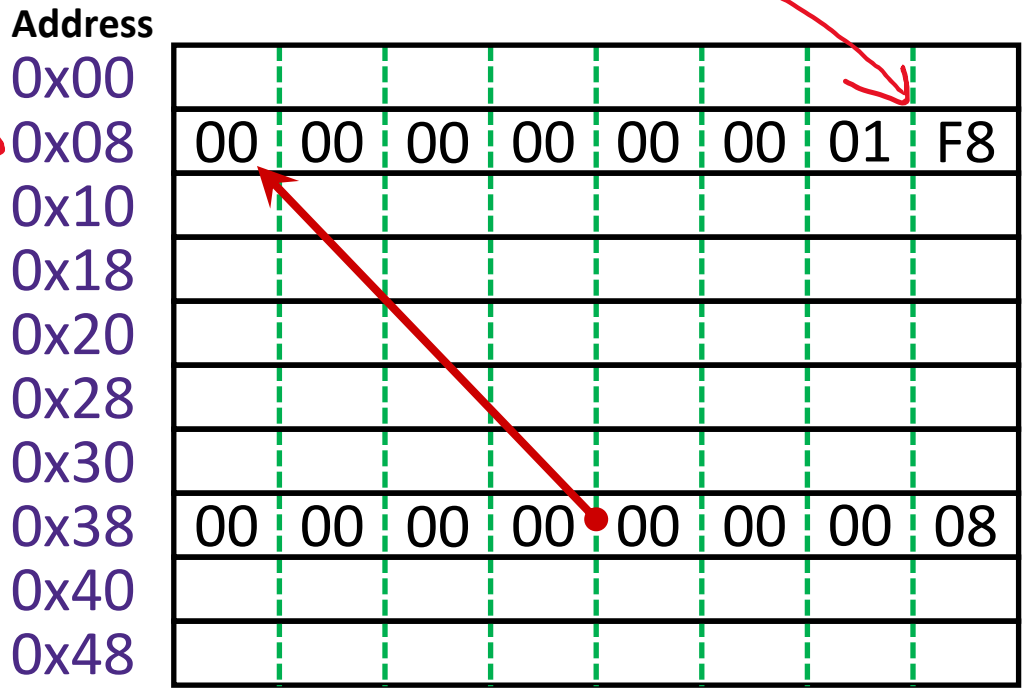


Addresses and Pointers

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

big-endian

- An *address* refers to a location in memory
- A *pointer* is a data object that holds an address
  - Address can point to *any* data
- 8-byte value 504 stored at address 0x08
  - $504_{10} = 1F8_{16}$ = 0x 00 … 00 01 F8
- Pointer stored at 0x38 points to address 0x08

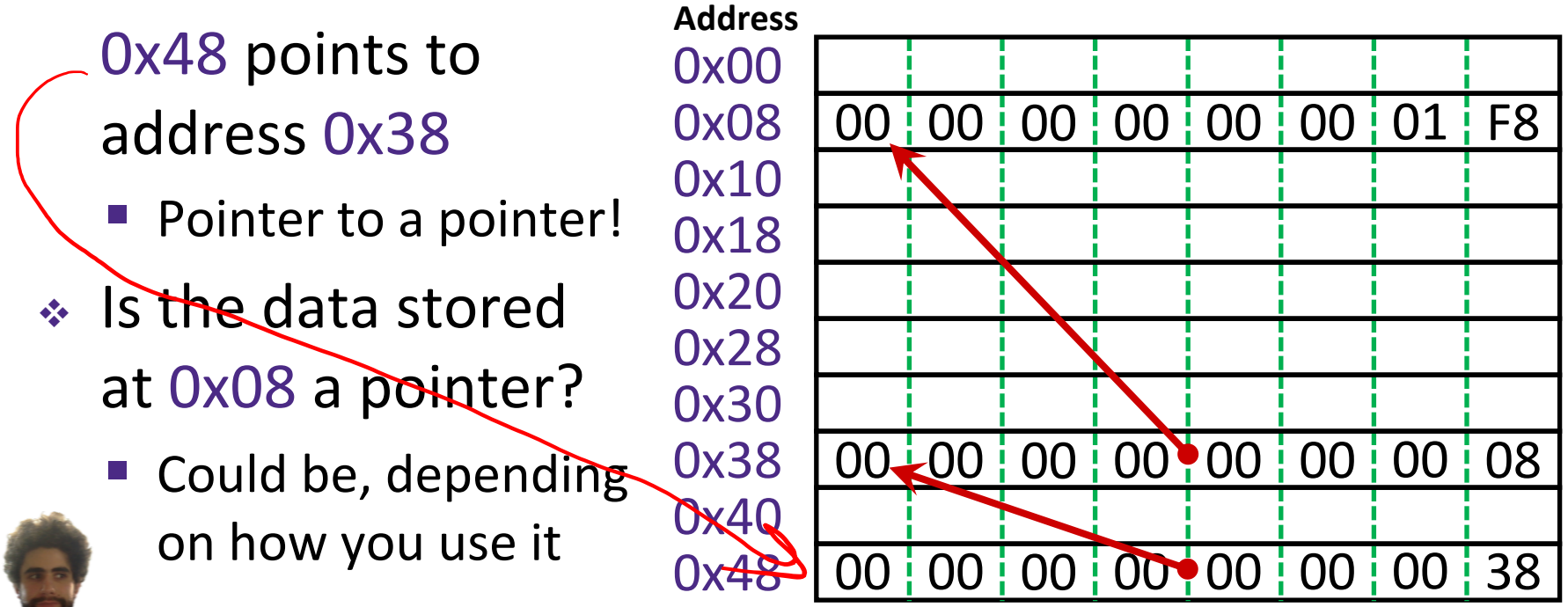


Addresses and Pointers

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

big-endian

- An *address* refers to a location in memory
- A *pointer* is a data object that holds an address
  - Address can point to *any* data
- Pointer stored at 0x48 points to address 0x38
  - Pointer to a pointer!
- Is the data stored at 0x08 a pointer?
  - Could be, depending on how you use it



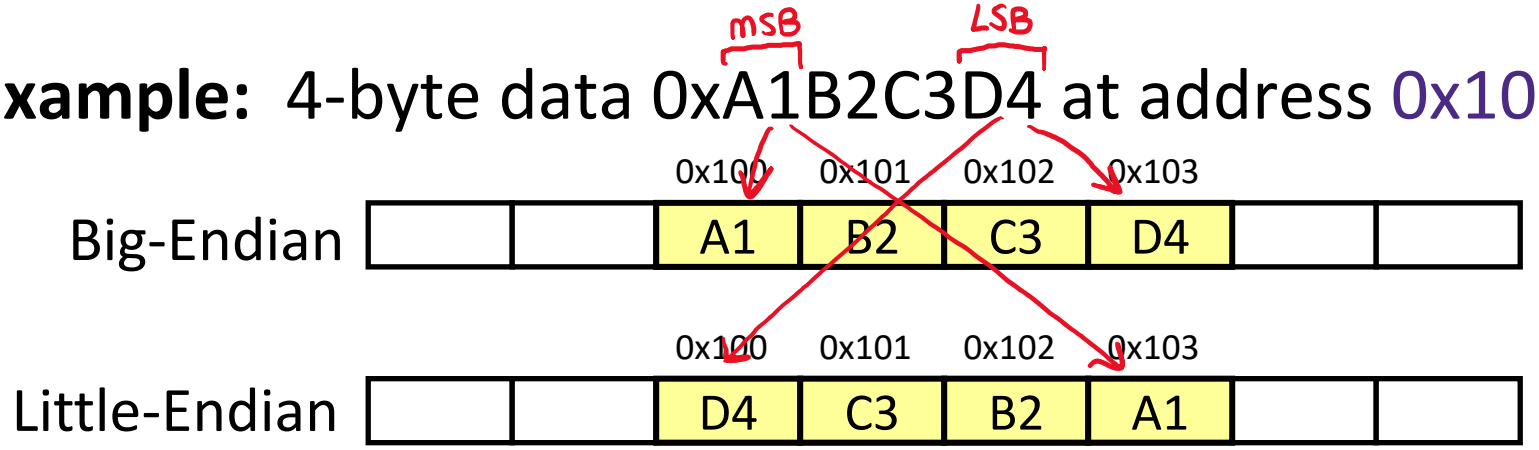
Byte Ordering (Review)

- How should bytes within a word be ordered *in memory?*
  - Want to keep consecutive bytes in consecutive addresses
  - **Example:** store the 4-byte (32-bit) `int`:
    `0x A1 B2 C3 D4`

- By convention, ordering of bytes called *endianness*
  - The two options are big-endian and little-endian
    - In which address does the least significant *byte* go?
    - Based on *Gulliver's Travels*: tribes cut eggs on different sides (big, little)

Byte Ordering

- Big-endian (SPARC, z/Architecture)
  - Least significant byte has highest address
- Little-endian (x86, x86-64)
  - Least significant byte has lowest address
- Bi-endian (ARM, PowerPC)
  - Endianness can be specified as big or little
- **Example:** 4-byte data 0xA1B2C3D4 at address 0x100



Endianness

- *Endianness only applies to memory storage*
- Often programmer can ignore endianness because it is handled for you
  - Bytes wired into correct place when reading or storing from memory (hardware)
  - Compiler and assembler generate correct behavior (software)
- Endianness still shows up:
  - Logical issues: accessing different amount of data than how you stored it (*e.g.*, store `int`, access byte as a `char`)
  - Need to know exact values to debug memory errors
  - Manual translation to and from machine code (in 351)

Summary

- Memory is a long, *byte-addressed* array
  - Word size bounds the size of the *address space* and memory
  - Different data types use different number of bytes
  - Address of chunk of memory given by address of lowest byte in chunk
  - Object of K bytes is *aligned* if it has an address that is a multiple of K
- Pointers are data objects that hold addresses
- Endianness determines memory storage order for multi-byte data

Reading Review

- Terminology:
  - address-of operator (&), dereference operator (*), NULL
  - box-and-arrow memory diagrams
  - pointer arithmetic, arrays
  - C string, null character, string literal

- Questions from the Reading?

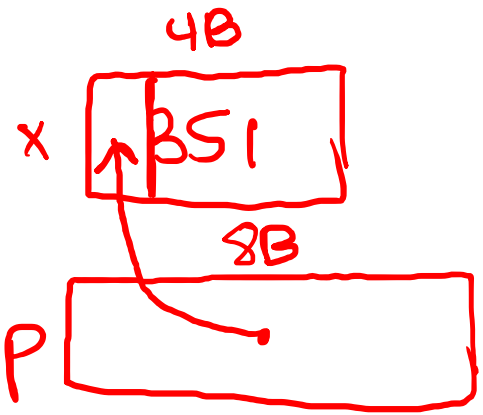
Review Questions

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

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

- How much space does the variable p take up?

  A. 1 byte
  B. 2 bytes
  C. 4 bytes
  D. 8 bytes



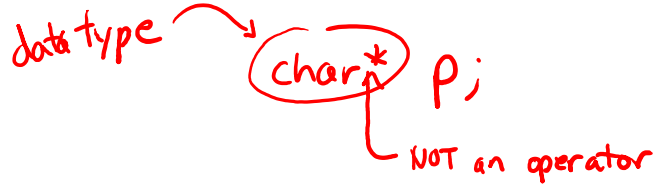
- Which of the following expressions evaluate to an address?

  A. `x + 10` → int
  B. `p + 10` → char*
  C. `&x + 10` → int*
  D. `*(&p)` → char**
  E. `ar[1]` → int
  F. `&ar[2]` → int*
  ```

Pointer Operators

- & = "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!

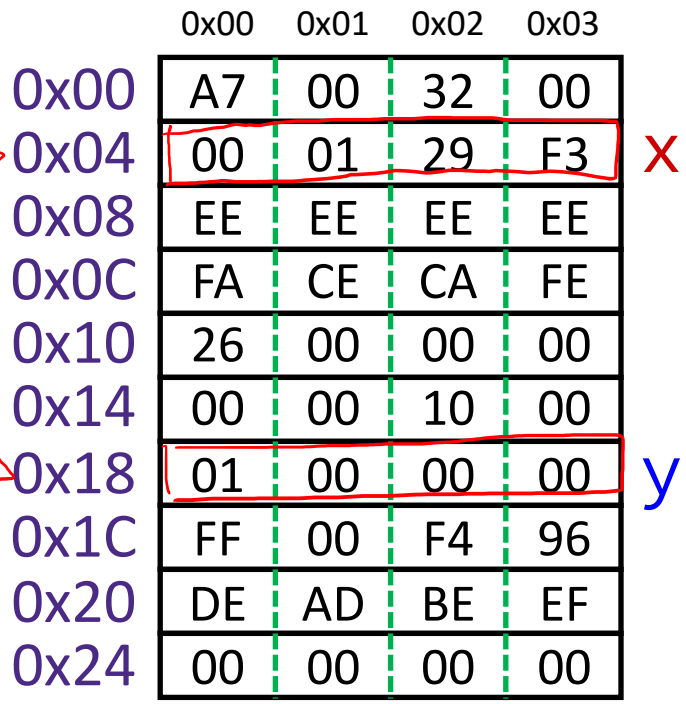


Assignment in C

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

little-endian

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



current state of memory

Assignment in C

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(pointers are 32-bits wide)

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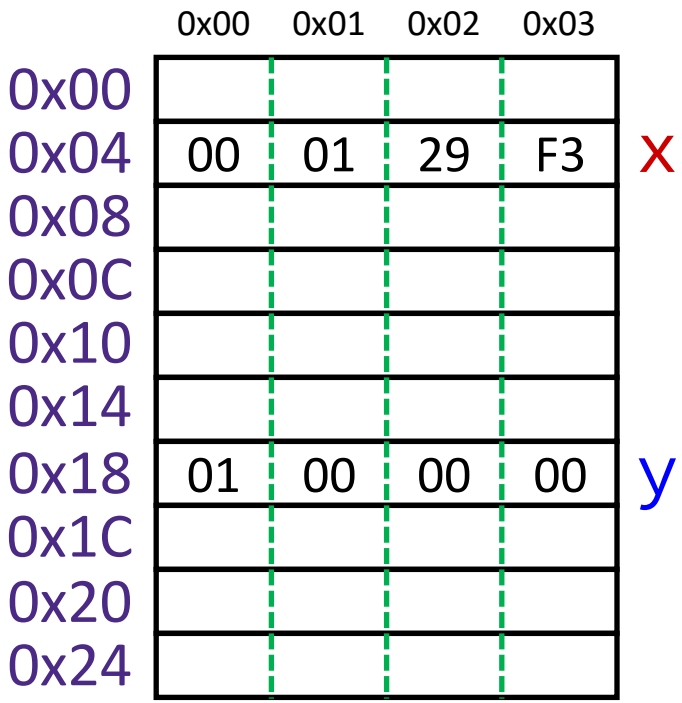
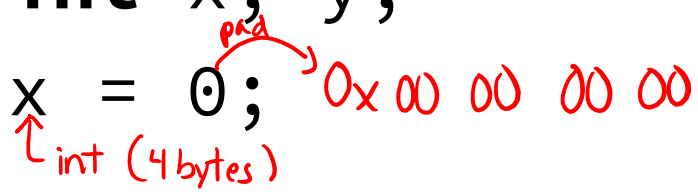


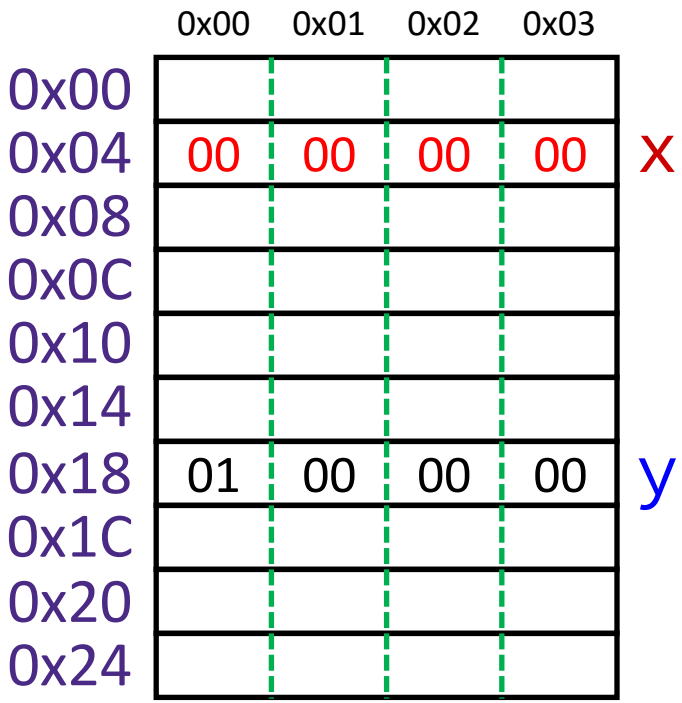
Assignment in C

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;`





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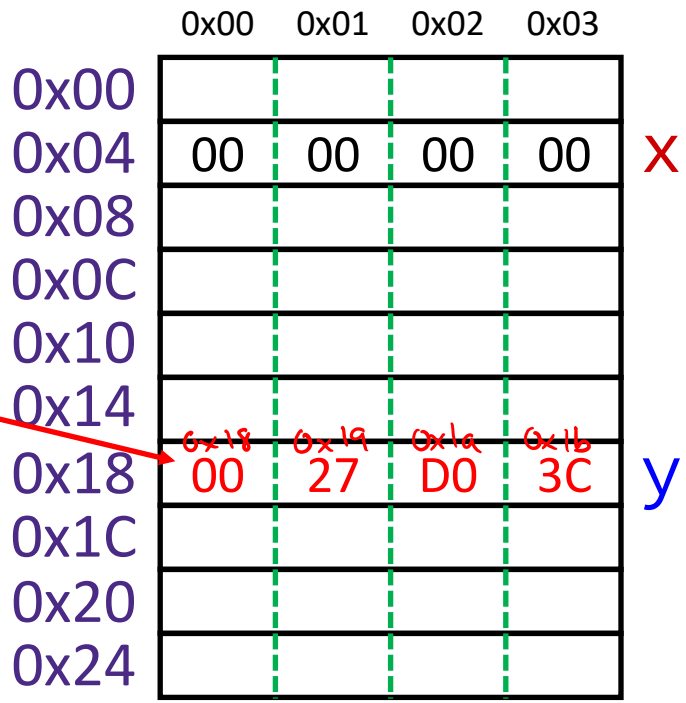
  - Store RHS value at LHS location
- `int x, y;`
- `x = 0;`
- `y = 0x3CD02700;`

least significant byte

little endian!



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  - LHS must evaluate to a *location*
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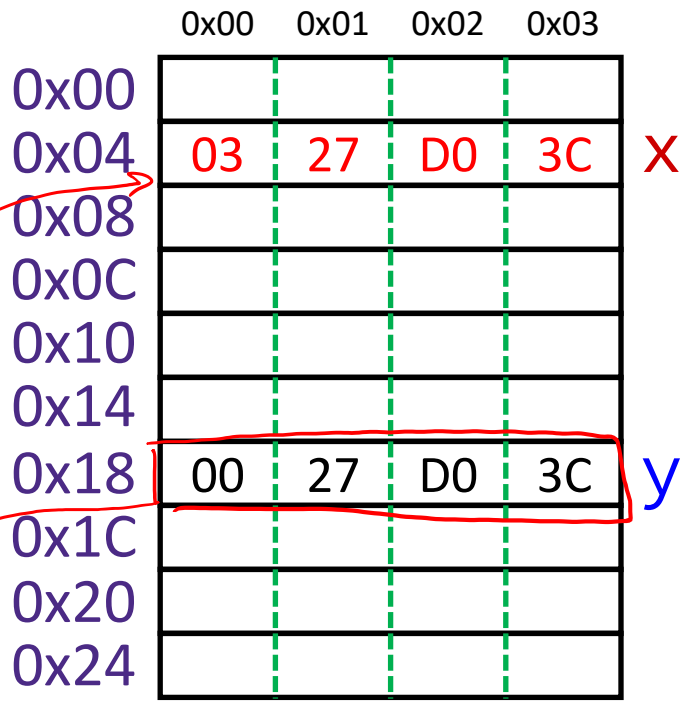
  - Store RHS value at LHS location
- `int x, y;`
- `x = 0;`
- `y = 0x3CD02700;`
- `x = y + 3;`
  - Get value at y, add 3, store in x



Assignment in C

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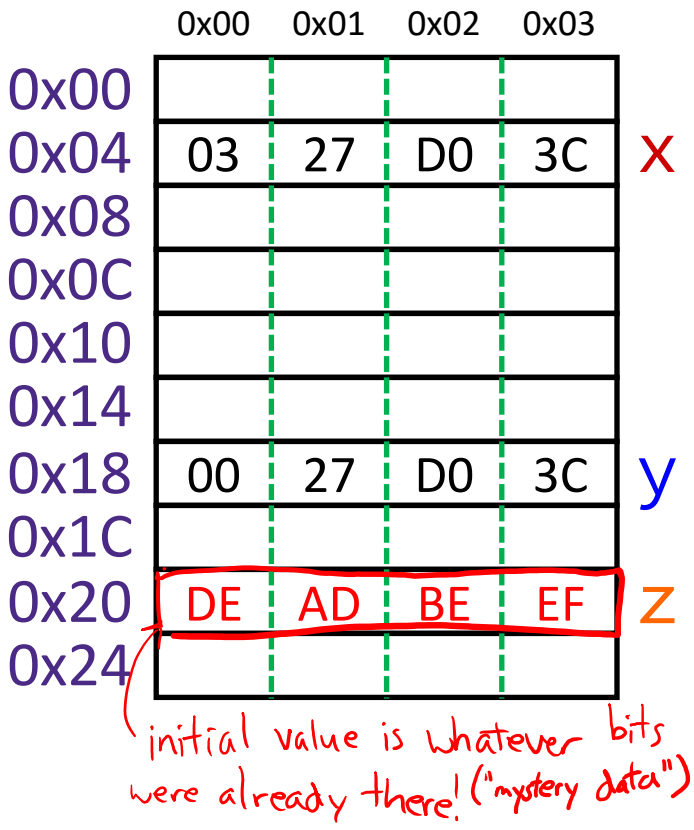
- `int x, y;`
- `x = 0;`
- `y = 0x3CD02700;`
- `x = y + 3;`
  - Get value at y, add 3, store in x
- `int* z;` ← pointer to an int
  - z is at address 0x20



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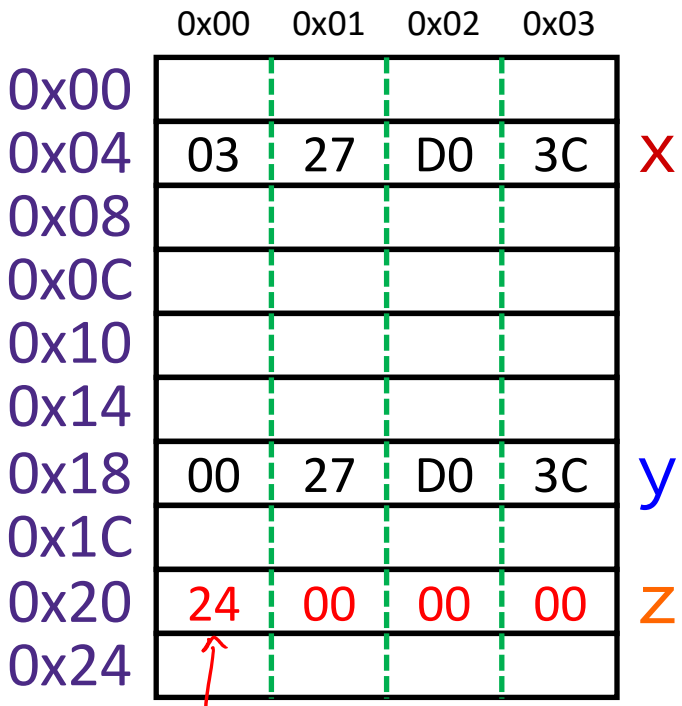
  - Store RHS value at LHS location
- `int x, y;`
- `x = 0;`
- `y = 0x3CD02700;`
- `x = y + 3;`
  - Get value at `y`, add 3, store in `x`
- `int* z = &y + 3;` // expect 0x1b (0x18)
  - Get address of y, "add 3", store in z



Pointer arithmetic (scale by sizeof(int) = 4)

Assignment in C

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

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* = "dereference"

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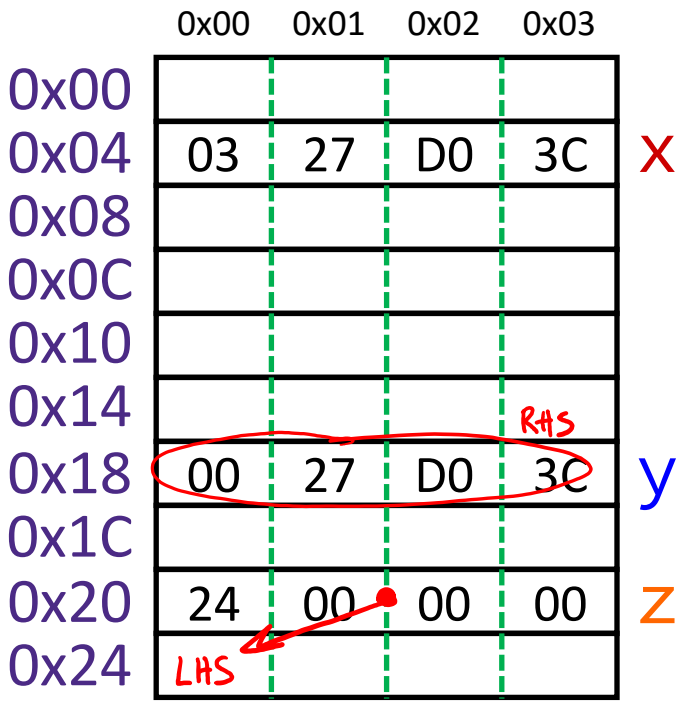
- `x = y + 3;`
  - Get value at y, add 3, store in x
- `int* z = &y + 3;`
  - Get address of y, add **12**, store in z
- `*z = y;`



Assignment in C

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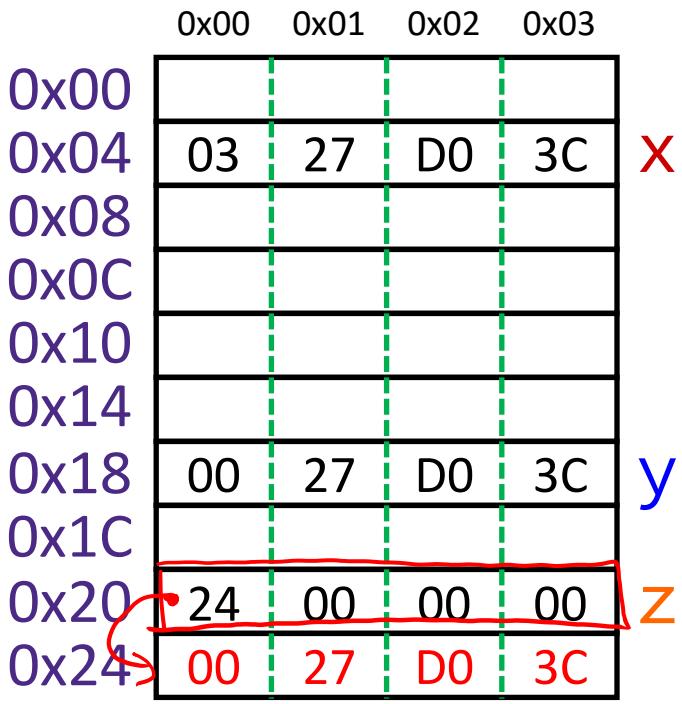
- `x = y + 3;`
  - Get value at y, add 3, store in x
- `int* z = &y + 3;`
  - Get address of y, add **12**, store in z
- `*z = y;`
  - Get value of y, put in address stored in z

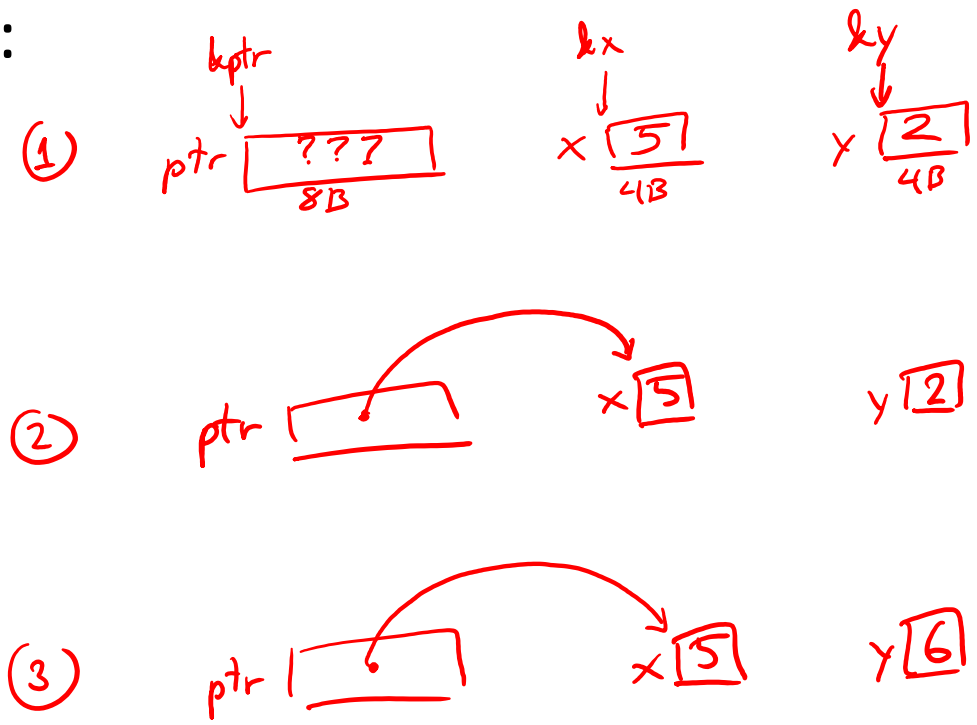
The target of a pointer is also a location



Addresses and Pointers in C (Review)

- Draw out a box-and-arrow diagram for the result of the following C code:

```
1  int* ptr;
   int x = 5;
   int y = 2;
2  ptr = &x;
3  y = 1 + (*ptr);
```



Arrays in C

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

a (array name) returns the array's address

4 bytes each

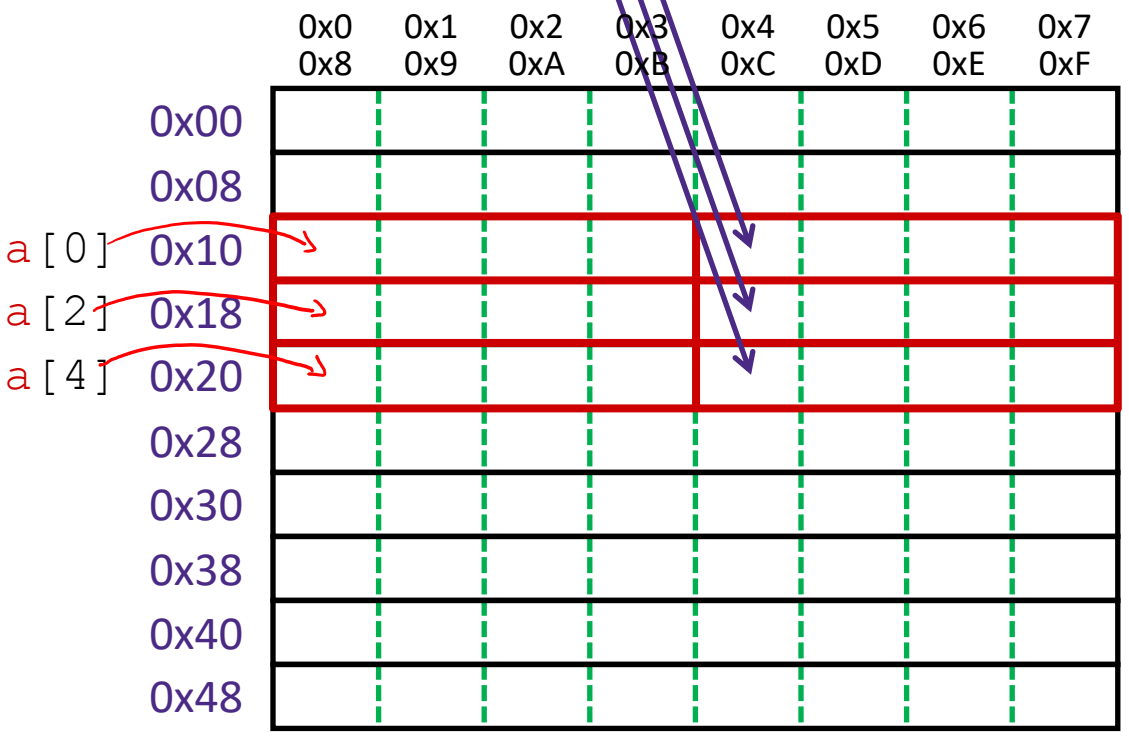
Declaration: `int a[6];` // &a is 0x10

element type

name

number of elements

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



Arrays in C

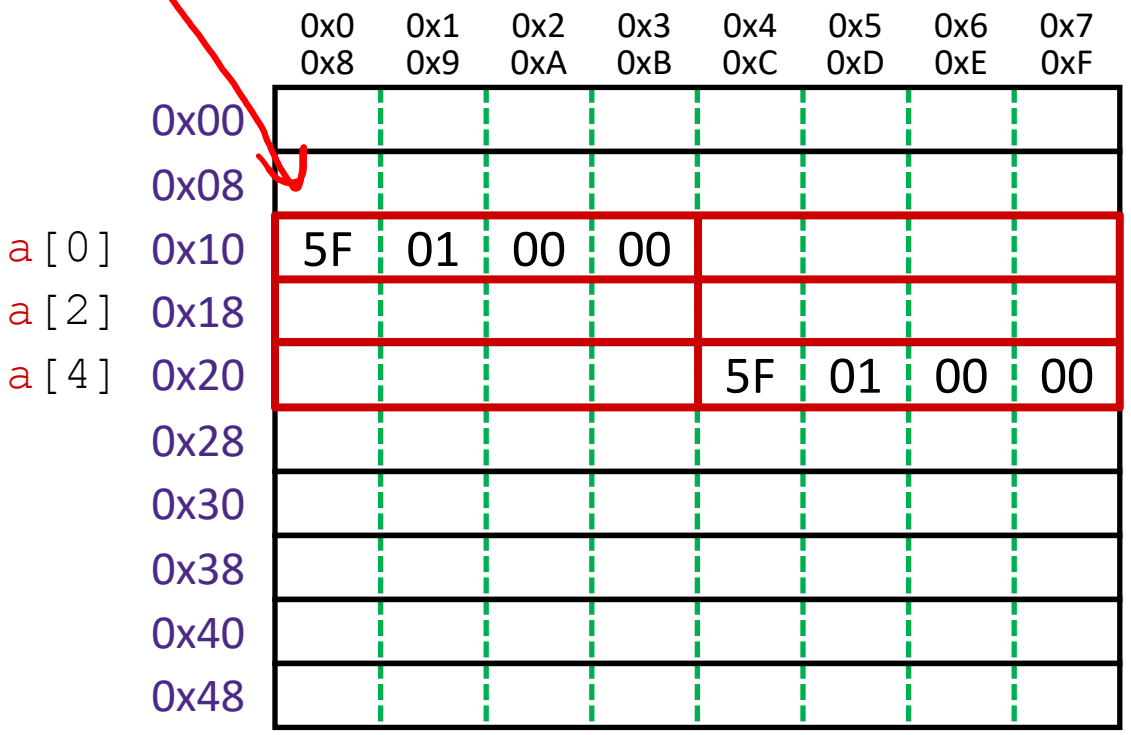
Declaration: `int a[6];`

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

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];
```

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

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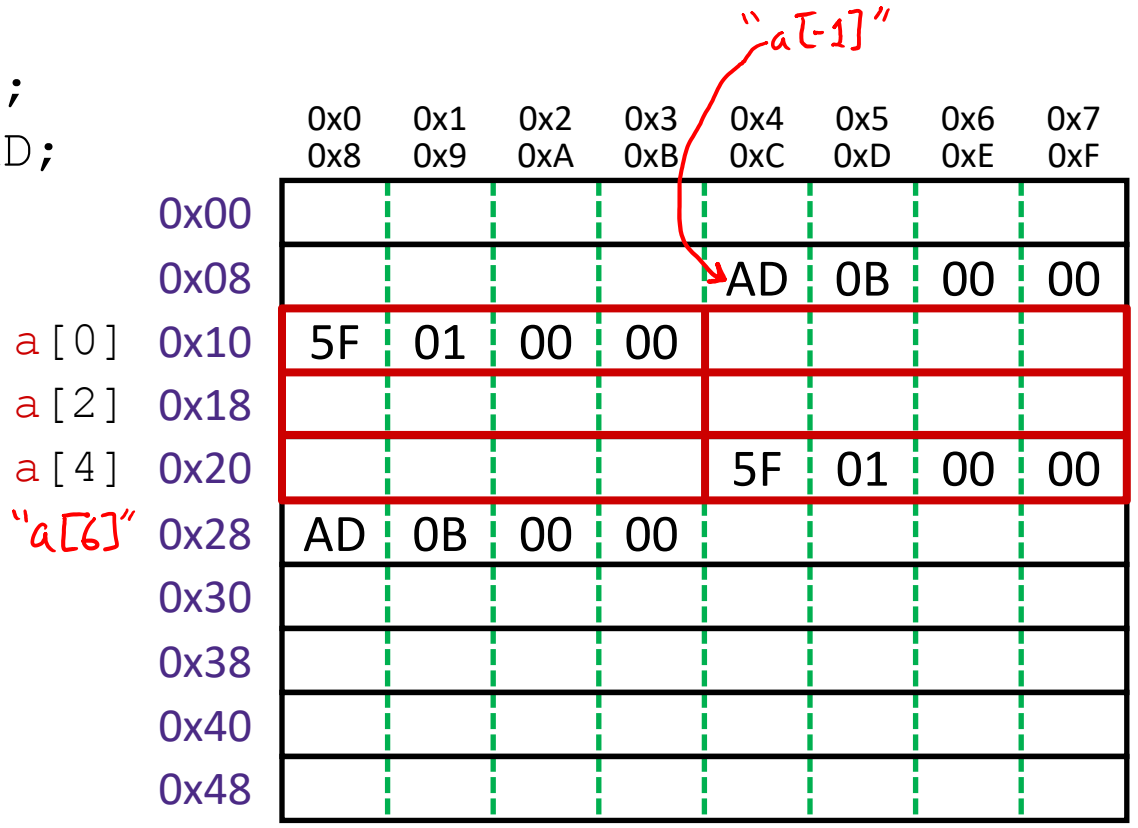
`&a[i]` is the address of `a[0]` plus `i` times the element size in bytes



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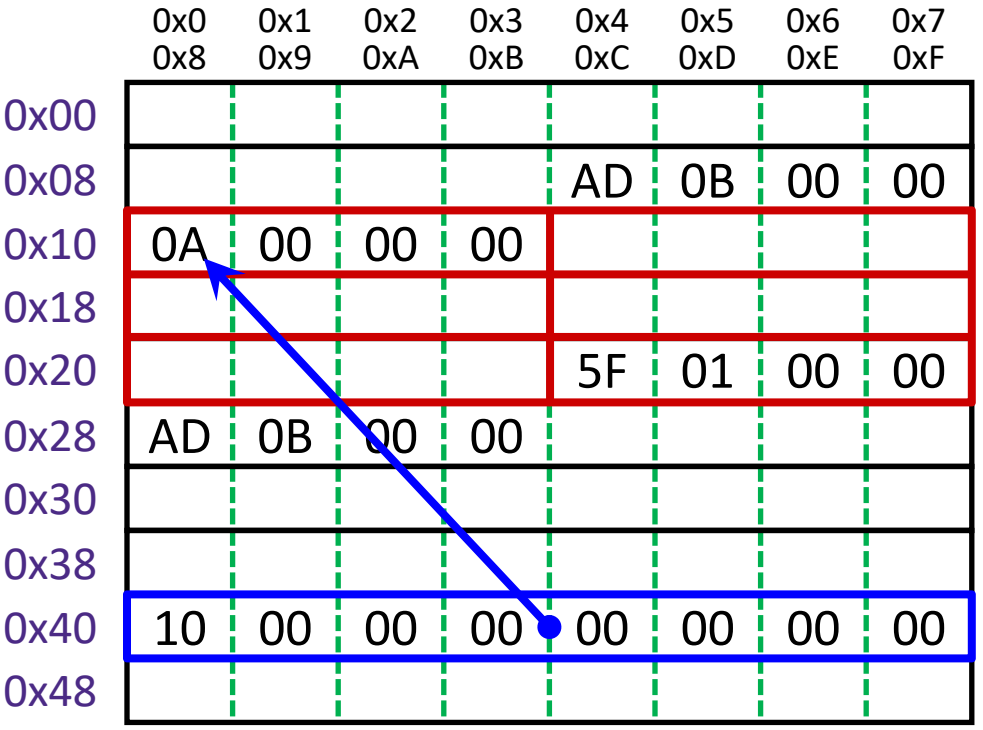
a[5] = a[0];
```

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

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

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



Arrays in C

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`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)

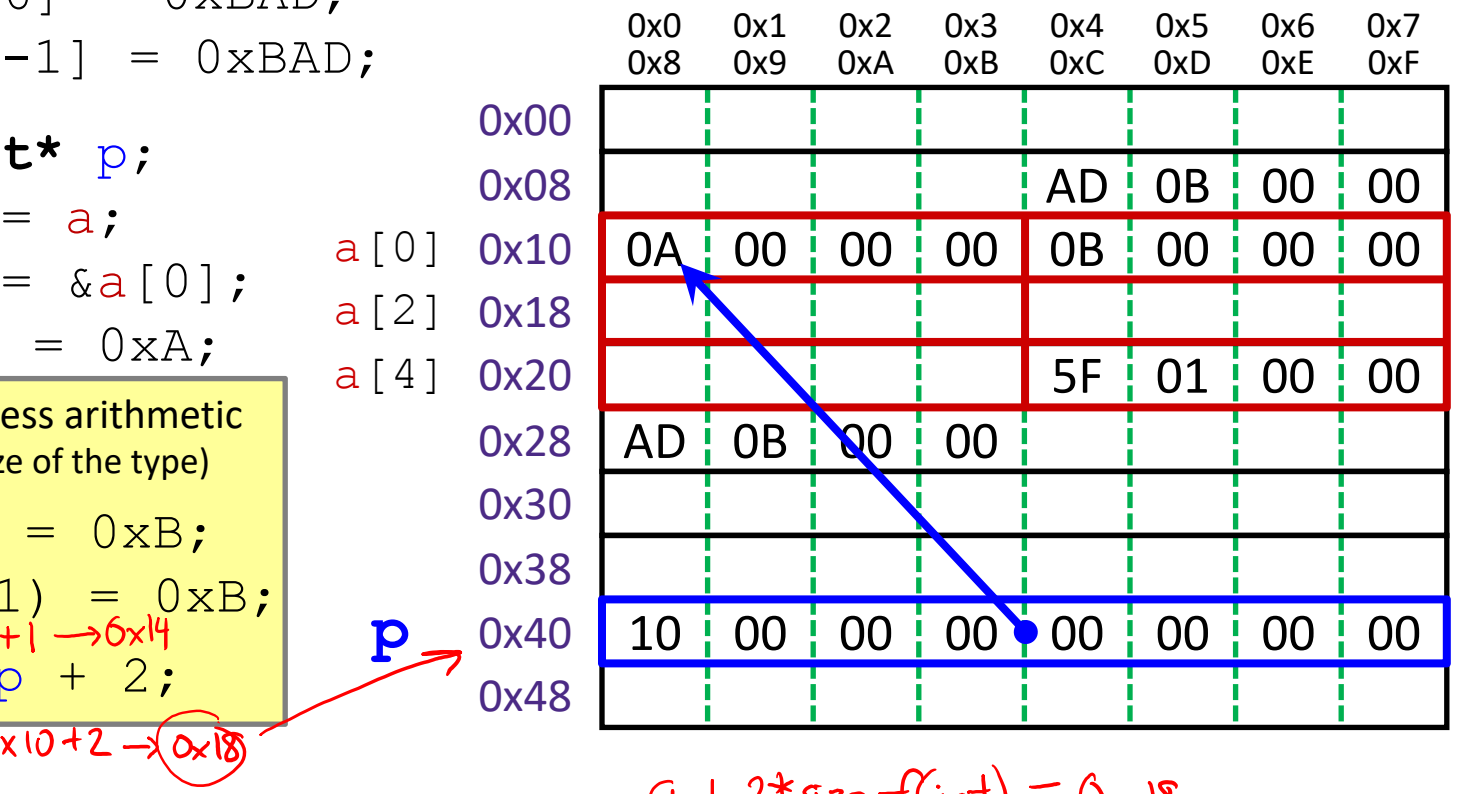
equivalent:
```
p[1] = 0xB;
*(p+1) = 0xB;
```

pointer arithmetic: 0x10 + 1 → 0x14

```
p = p + 2;
```

0x10 + 2 → 0x18

p[i] ⟺ *(p + i)



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)

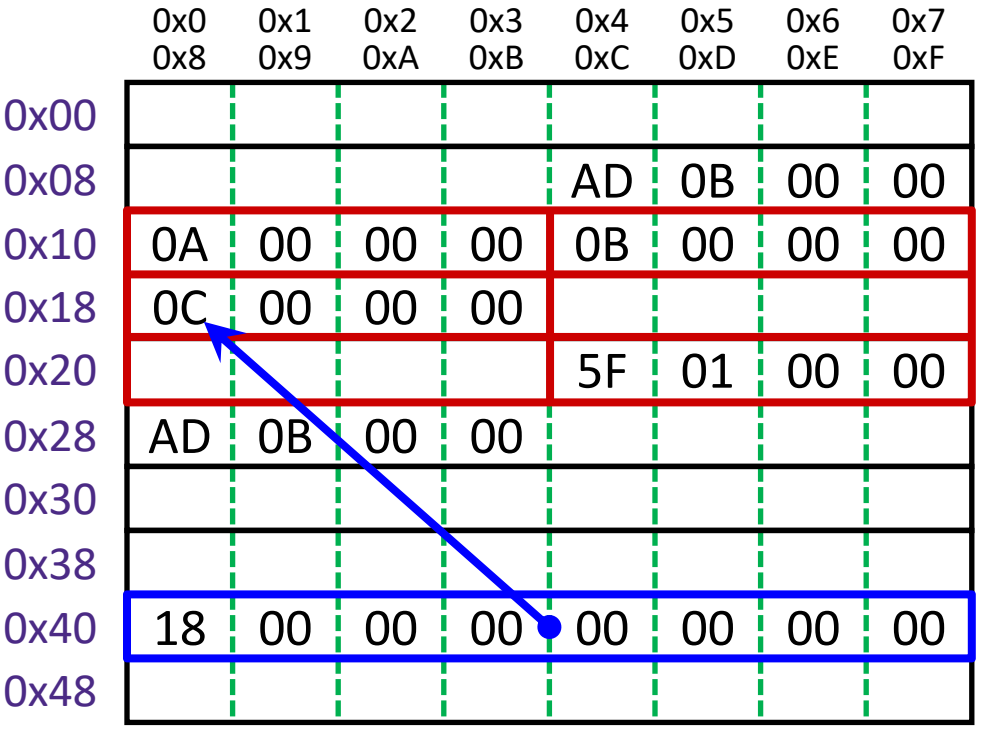
equivalent
```
p[1] = 0xB;
*(p+1) = 0xB;
```

```
p = p + 2;
```

store at 0x18

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

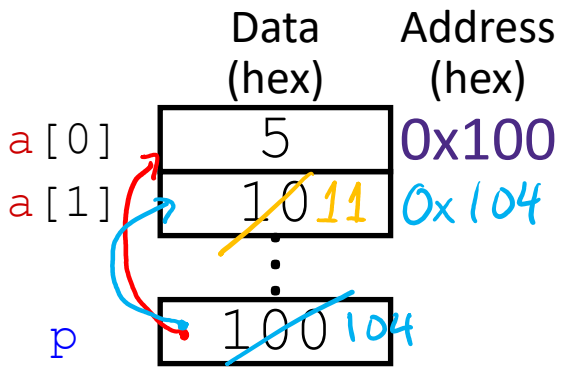
0xB + 1 = 0xC



(no pointer arithmetic)

Question: 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

Representing strings (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

decimal character

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

in C, use single quotes:

```
char c = '3';
```

↑ gets the value 51

ASCII: American Standard Code for Information Interchange

Representing strings (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
  - Last character followed by a 0 byte (`'\0'`)
    (a.k.a. the null character)

Decimal:	83	97	109	32	105	115	32	99	111	111	108	33	0
Hex:	0x53	0x61	0x6D	0x20	0x69	0x73	0x20	0x63	0x6F	0x6F	0x6C	0x21	0x00
Text:	'S'	'a'	'm'	' '	'i'	's'	' '	'c'	'o'	'o'	'l'	'!'	'\0'

String literal "Sam is cool!" uses 13B

double quotes

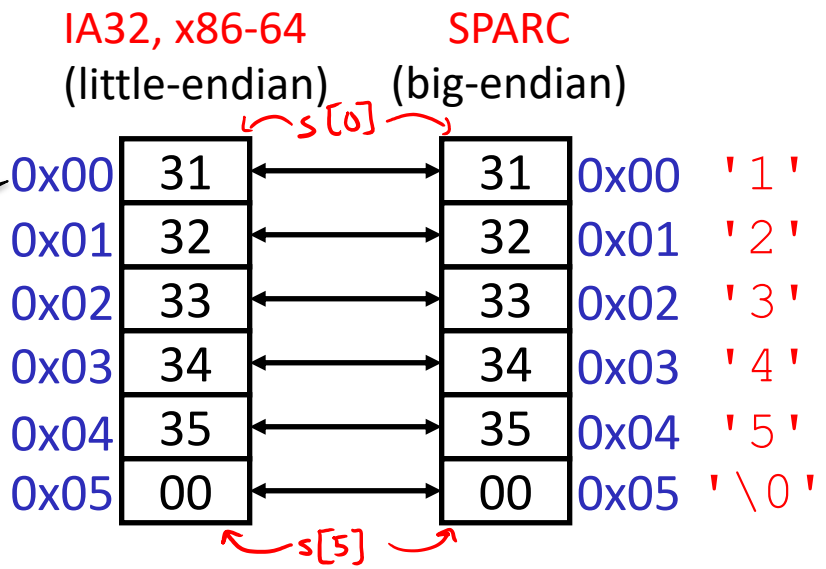
Endianness and Strings

C (char = 1 byte)

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

String literal

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

Examining Data Representations

- 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` directives:
  - `%p` Print pointer
  - `\t` Tab
  - `%.2hhX` Print value as char (hh) in hex (X), padding to 2 digits (.2)
  - `\n` New line

Examining Data Representations

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    printf("%p\t0x%.2hhX\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 = 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

- 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)