

Memory, Data, & Addressing II

CSE 351 Spring 2021

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<http://xkcd.com/138/>

Administrivia

- ❖ hw1 due tonight, Friday (4/02) @ 11:59 pm
- ❖ Lab 0 and hw2 due Monday (4/05) @ 11:59 pm
- ❖ hw3 due Wednesday (4/07) @ 11:59 pm
- ❖ Lab 1a coming soon! due next Monday (4/12)
 - Pointers in C
 - Submitted via Gradescope
 - Reminder: last submission graded, *individual* work
- ❖ Questions Doc: You must log on with your @uw google account to access!!
 - <https://tinyurl.com/CSE351-21sp-Questions>
 - Then open the “TODAY's Lecture Questions” doc for 11:30/2:30

Late Days

- ❖ You are given **7 late days** for the whole quarter
 - Late days can only apply to Labs & Unit Summaries
 - No benefit to having leftover late days
- ❖ 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 work is 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**

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

Reading Review

❖ Terminology:

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

Review Questions

- ❖

```
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]`

Addresses and Pointers in C

- ❖ `&` = “address of” operator
- ❖ `*` = “value at address” or “dereference” operator

`*` is also used with variable declarations

```
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)` ?

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

- ❖ A variable is represented by a location
- ❖ Declaration \neq 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 \neq 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					

Assignment in C

- ❖ 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

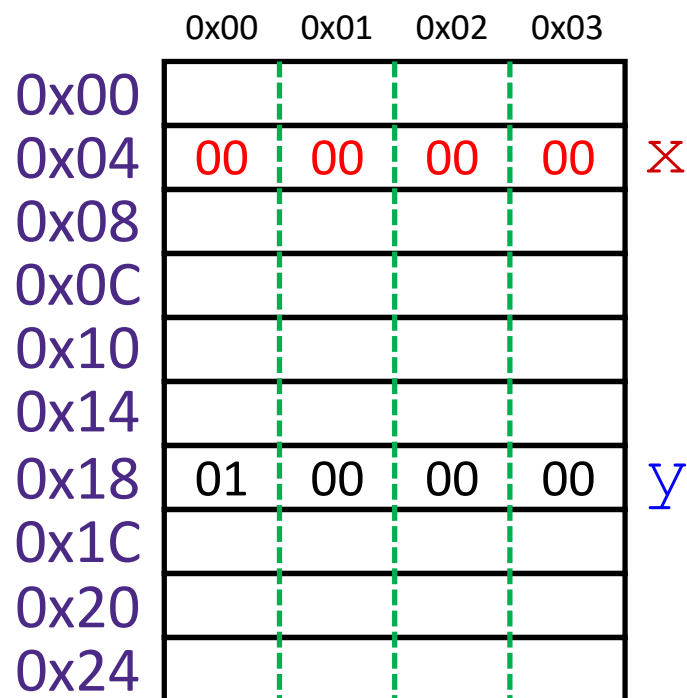
❖ `int x, y;`

❖ `x = 0;`

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

& = "address of"

* = "dereference"



Assignment in C

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

& = "address of"
* = "dereference"

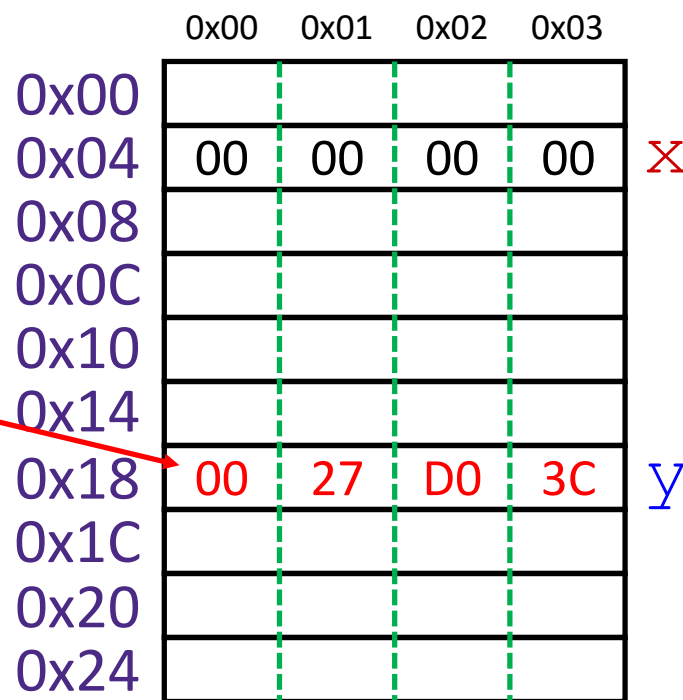
- ❖ left-hand side = right-hand side;
 - LHS must evaluate to a *location*
 - RHS must evaluate to a *value* (could be an address)
 - Store RHS value at LHS location

❖ `int x, y;`

❖ `x = 0;`

❖ `y = 0x3CD02700;`

little endian!



Assignment in C

- ❖ 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;`

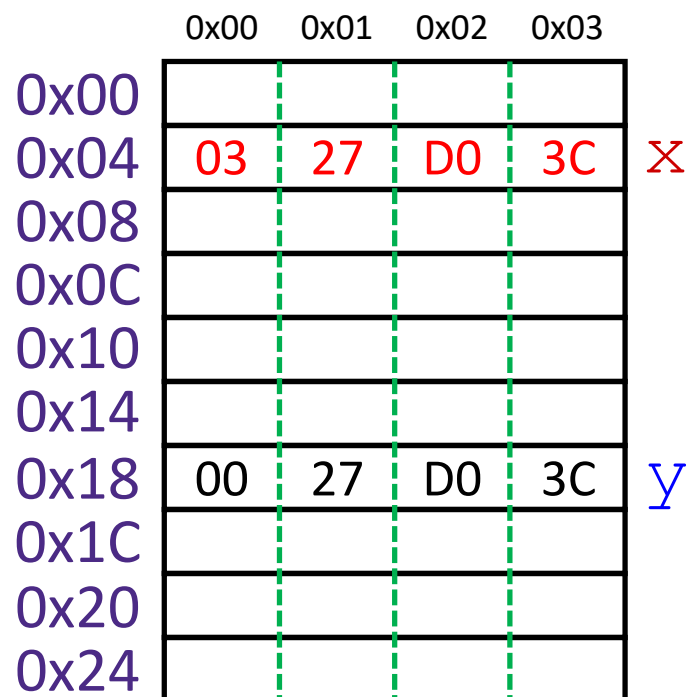
❖ `x = y + 3;`

- Get value at `y`, add 3, store in `x`

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

& = "address of"

* = "dereference"



Assignment in C

- ❖ 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;`

- `z` is at address `0x20`

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

& = "address of"

* = "dereference"

	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					

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;`

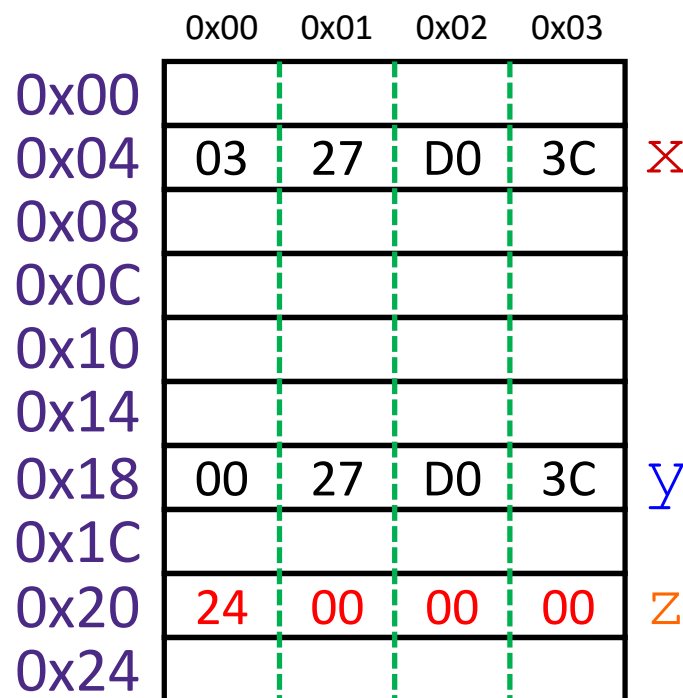
❖ `y = 0x3CD02700;`

❖ `x = y + 3;`

- Get value at `y`, add 3, store in `x`

❖ `int* z = &y + 3;`

- Get address of `y`, "add 3", store in `z`



Pointer arithmetic

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 $3 * \text{sizeof}(\mathbf{int})$, store in `z`
 - $\&y = 0x18 = 1 * 16^1 + 8 * 16^0 = 24$
 - $24 + 3 * (4) = 36 = 2 * 16^1 + 4 * 16^0 = 0x24$
- ❖ **Pointer arithmetic can be dangerous!**
 - Can easily lead to bad memory accesses
 - Be careful with data types and *casting*

Assignment in C

- ❖ `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?

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

& = "address of"

* = "dereference"

	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

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

The target of a pointer is also a location

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

& = "address of"
* = "dereference"

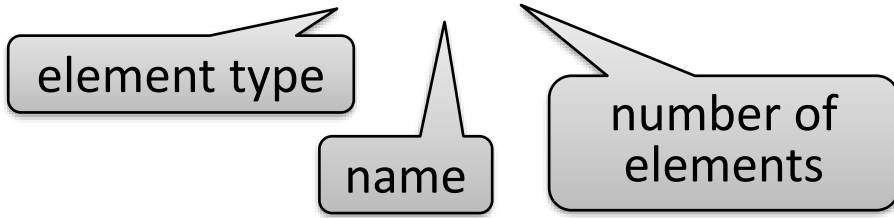
	0x00	0x01	0x02	0x03	
0x00					
0x04	03	27	D0	3C	x
0x08					
0x0C					
0x10					
0x14					
0x18	00	27	D0	3C	y
0x1C					
0x20	24	00	00	00	z
0x24	00	27	D0	3C	

Arrays in C

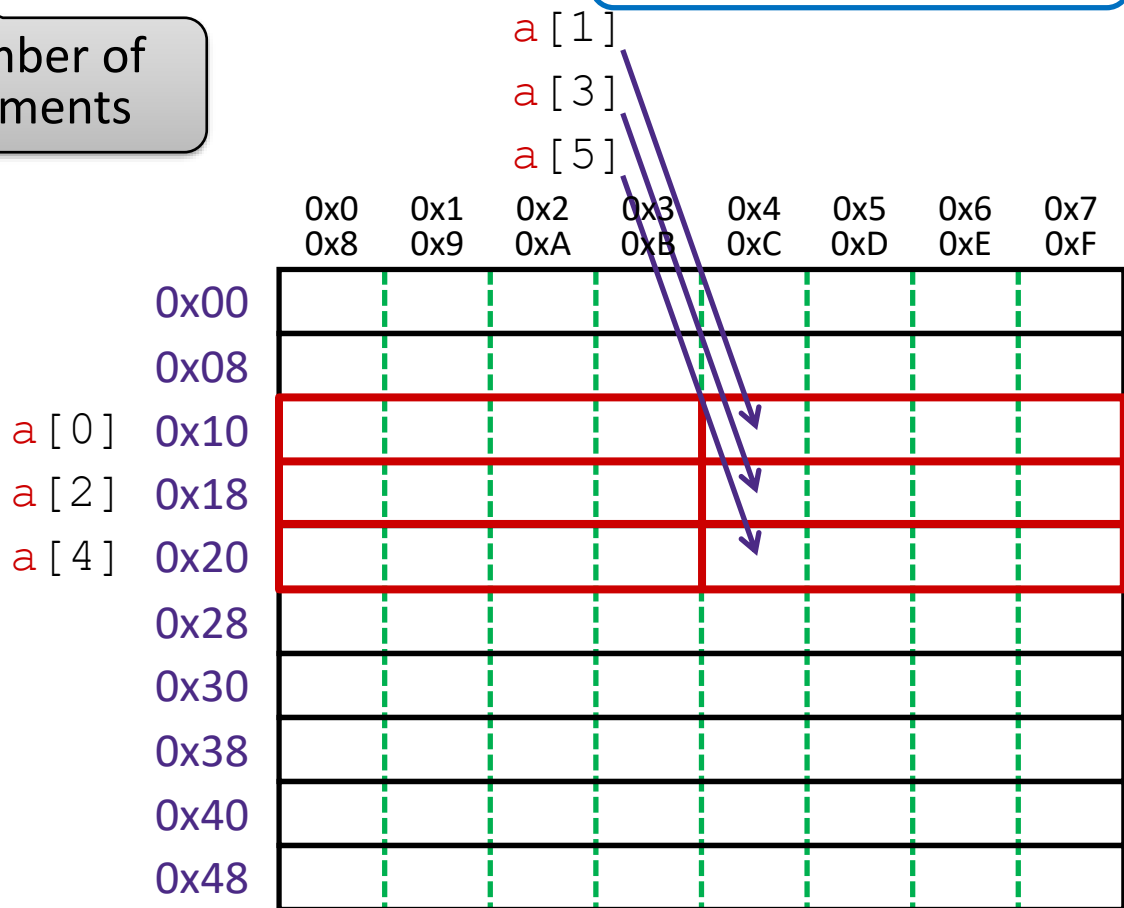
Arrays are adjacent locations in memory storing the same type of data object

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

Declaration: `int a[6];`



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

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

Arrays in C

Declaration: `int a[6];`

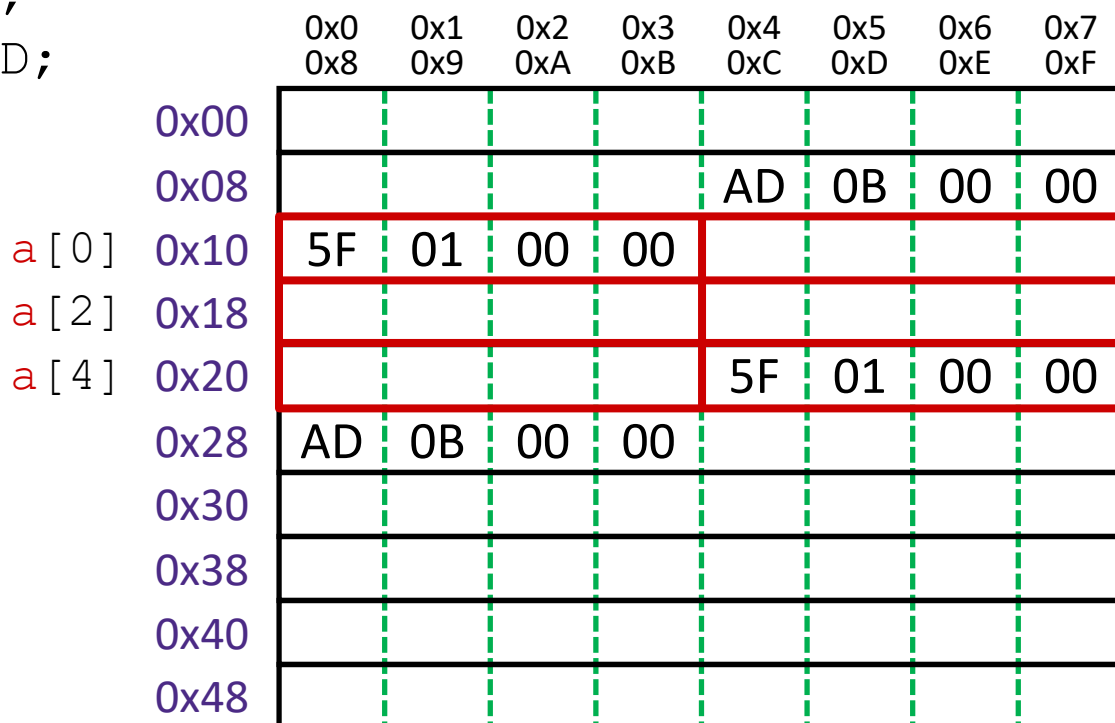
Indexing: `a[0] = 0x015f;`
`a[5] = a[0];`

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

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

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Arrays in C

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Pointers: `int* p;`

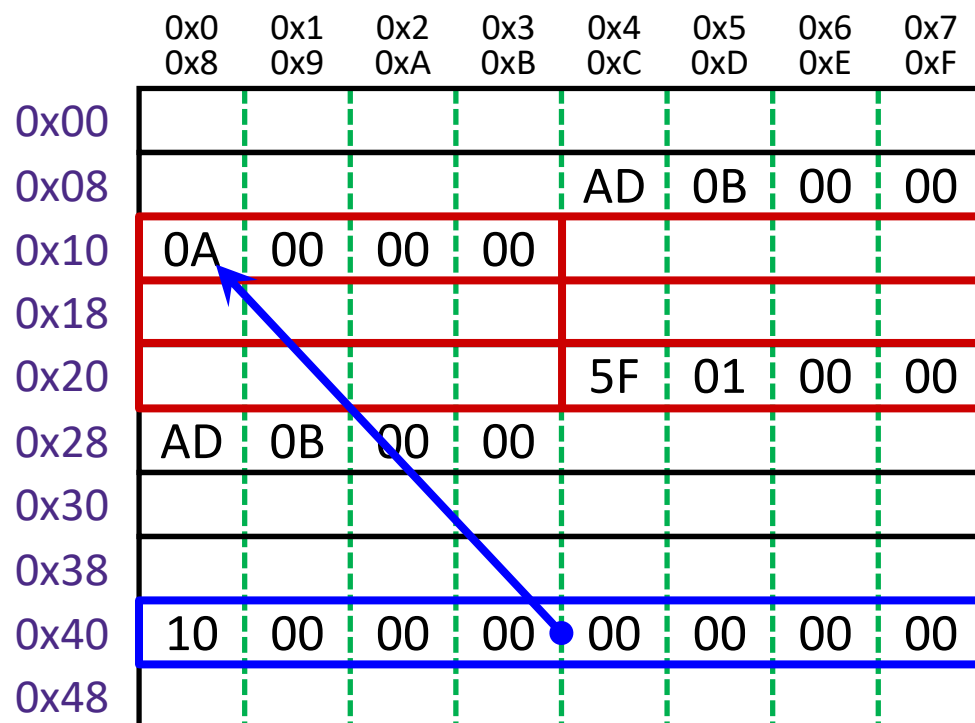
equivalent $\left\{ \begin{array}{l} p = a; \\ p = \&a[0]; \\ *p = 0xA; \end{array} \right.$ `a[0]`
`a[2]`
`a[4]`

`p`

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

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

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Arrays in C

Declaration: `int a[6];`

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`a[0]`
`a[2]`
`a[4]`

`p`

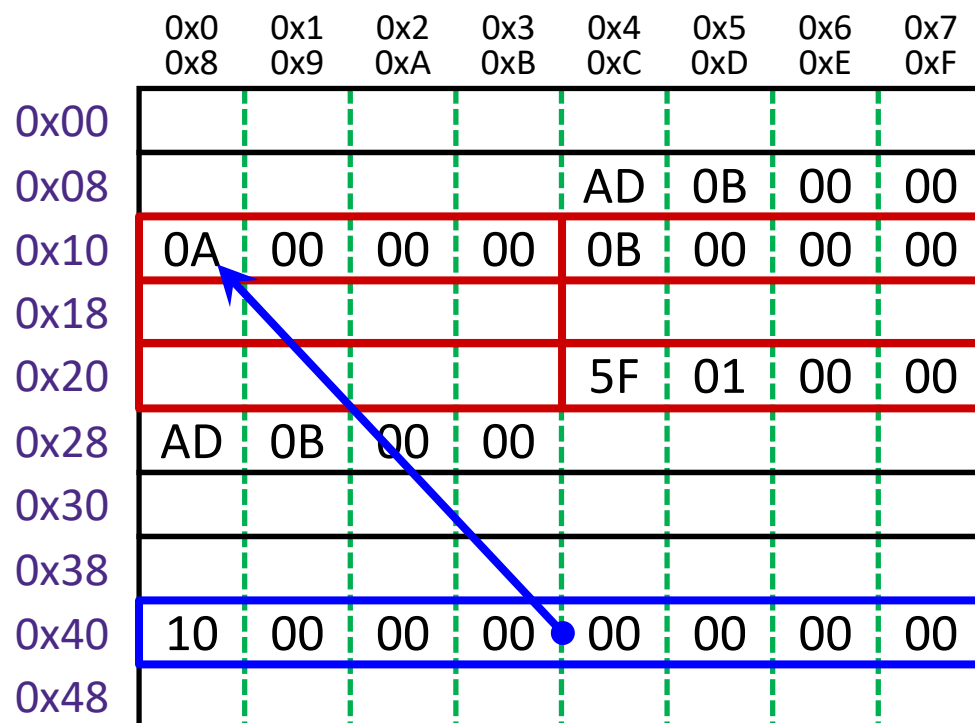
array indexing = address arithmetic
 (both scaled by the size of the type)

equivalent $\left\{ \begin{array}{l} p[1] = 0xB; \\ *(p+1) = 0xB; \\ p = p + 2; \end{array} \right.$

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

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

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

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Declaration: `int a[6];`

Indexing: `a[0] = 0x015f;`
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`a[-1] = 0xBAD;`

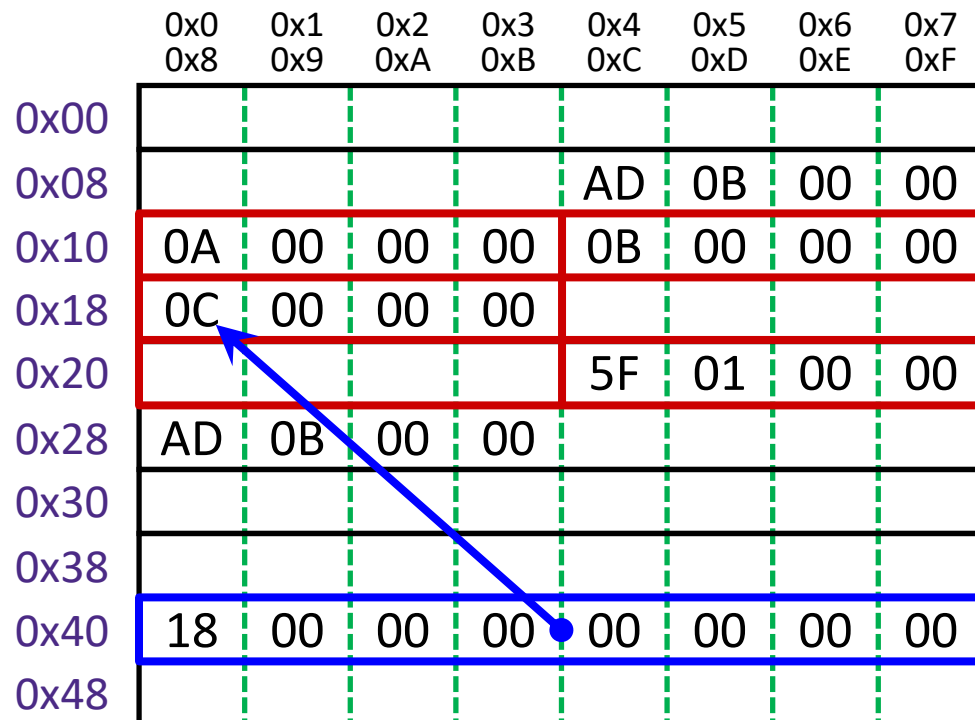
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equivalent $\left\{ \begin{array}{l} p = a; \\ p = \&a[0]; \\ *p = 0xA; \end{array} \right.$ `a[0]`
`a[2]`
`a[4]`

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

equivalent $\left\{ \begin{array}{l} p[1] = 0xB; \\ *(p+1) = 0xB; \\ p = p + 2; \end{array} \right.$ `p`

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

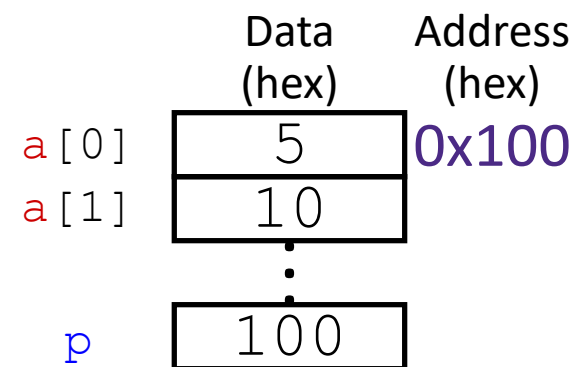


Question: The variable values after Line 3 executes are shown on the right. What are they after Line 5?

- No voting

```

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

- ❖ 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

Representing strings

- ❖ 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. “**null terminator**”)

<i>Decimal:</i>	80	108	101	97	115	101	32	118	111	116	101	33	0
<i>Hex:</i>	0x50	0x6C	0x65	0x61	0x73	0x65	0x20	0x76	0x6F	0x74	0x65	0x21	0x00
<i>Text:</i>	'P'	'l'	'e'	'a'	's'	'e'		'v'	'o'	't'	'e'	'!'	'\0'

Endianness and Strings

C (char = 1 byte)

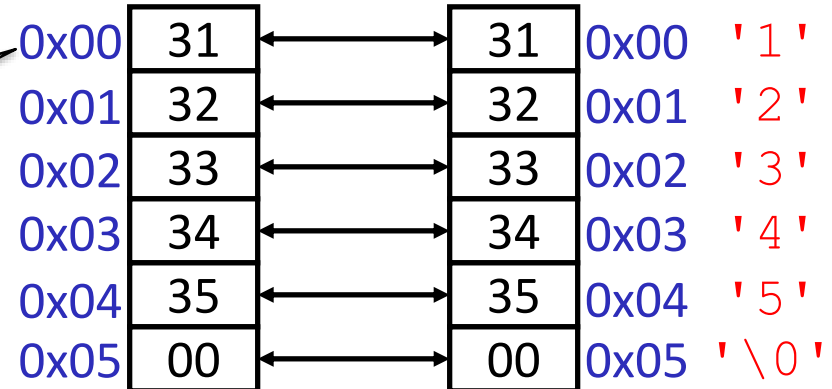
```
char s[6] = "12345";
```

String literal

0x31 = 49 decimal = ASCII '1'

IA32, x86-64
(little-endian)

SPARC
(big-endian)



- ❖ 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

- ❖ 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");
}
```

```
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

- ❖ 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)