Memory, Data, & Addressing II

CSE 351 Spring 2019

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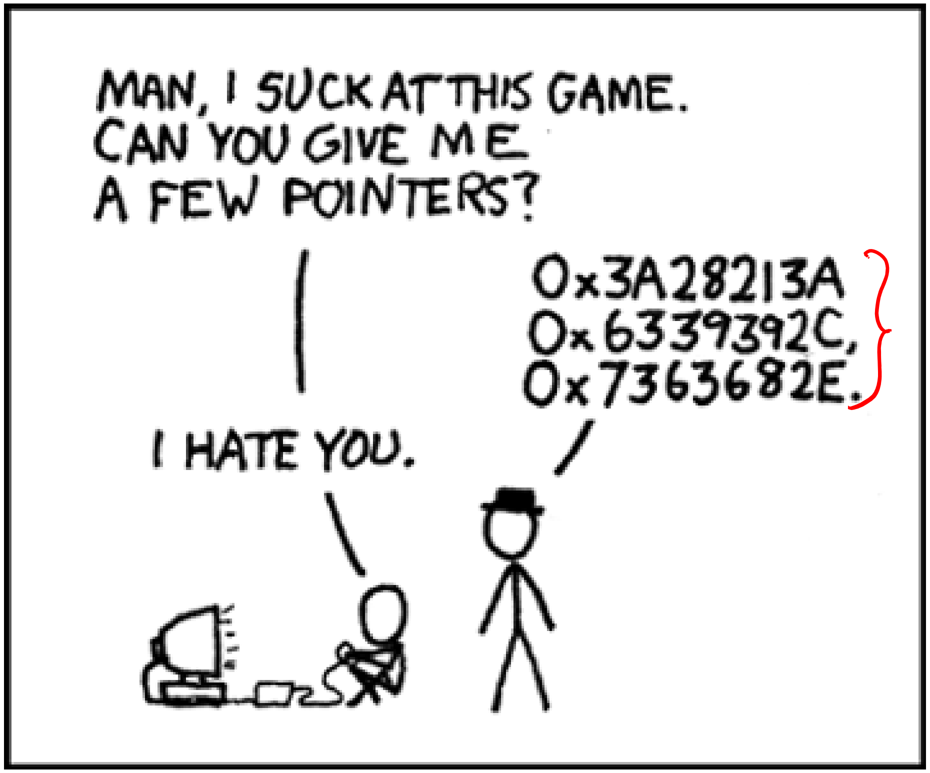


32-bit addresses

http://xkcd.com/138/

Administrivia

- Lab 0 due Monday @ 11:59 pm
    - *You will be revisiting this program throughout this class!*
- Homework 1 due Wednesday
    - Reminder: autograded, 20 tries, no late submissions
- Lab 1a released Monday, due next Monday (4/15)
    - Pointers in C
    - Reminder: last submission graded, *individual* work

Lab Late Days

- All submissions due at 11:59 pm
  - Count lateness in *days* (**even if just by a second**)
    - Special: weekends count as *one day*
  - No submissions accepted more than two “late days” late
- You are given 5 lab late days for the whole quarter
  - Late days only apply to Labs (not HW)
  - No benefit to having leftover late days
  - If you use more than 5 late days, late penalty is 20% deduction per day
  - 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 A pointer is just an address in memory. A 64 bit machine has 2^64 address space
   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? 2 2 2 2 2

   2^6

Memory, Data, and Addressing

- Hardware - High Level Overview
- Representing information as bits and bytes
  - Memory is a byte-addressable array
  - Machine "word" size = address size = register size
- Organizing and addressing data in memory
  - Endianness – ordering bytes 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

* is also used with variable declarations

datatype

equivalent

```
int* ptr;
int *ptr;
```

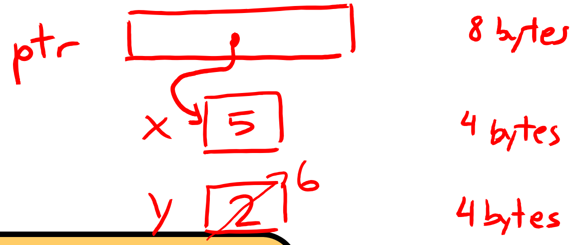
Declares a variable, `ptr`, that is a pointer to (*i.e.* holds the address of) an `int` in memory

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

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

```
ptr = &x;
```

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



5

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

"Dereference `ptr`"

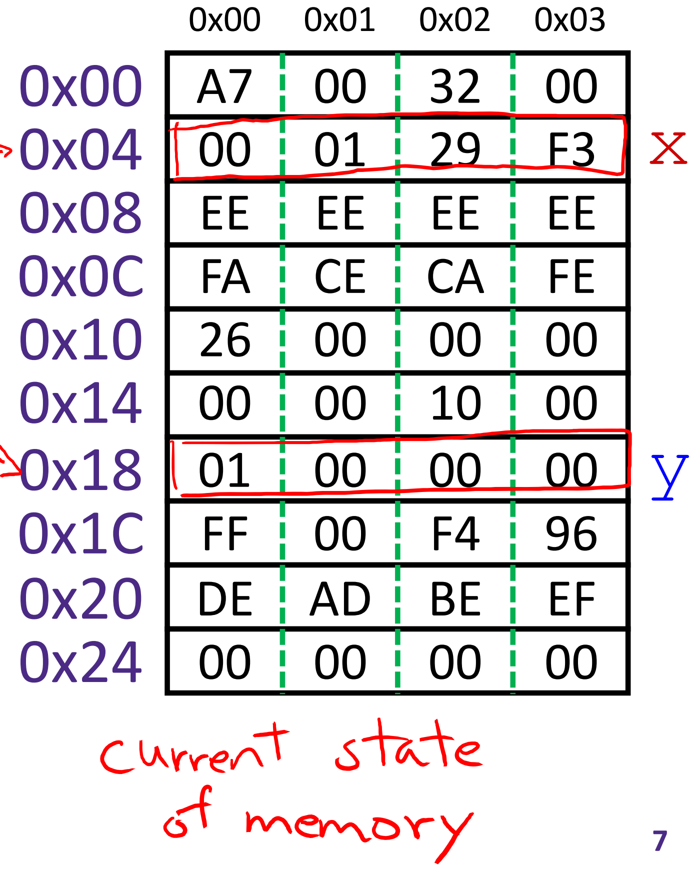
Sets `y` to "1 plus the value stored at the address held by `ptr`. Because `ptr` points to `x`, this is equivalent to `y=1+x;`

What is `*(&y)` ?

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

Assignment in C

- A variable is represented by a location in memory
- 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	

current state of memory

Assignment in C

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

little-endian

- A variable is represented by a location in memory
- 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					

Assignment in C

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

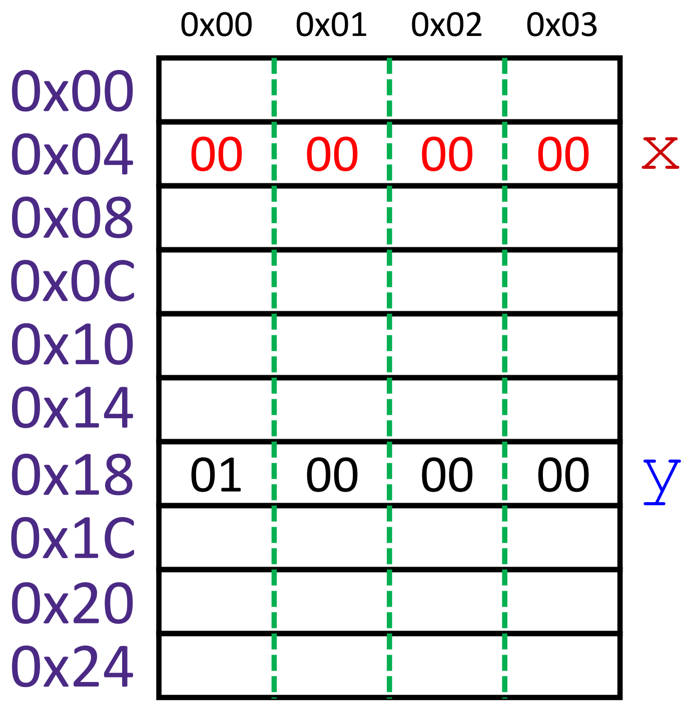
`&` = "address of"
`*` = "dereference"

- 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;`

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

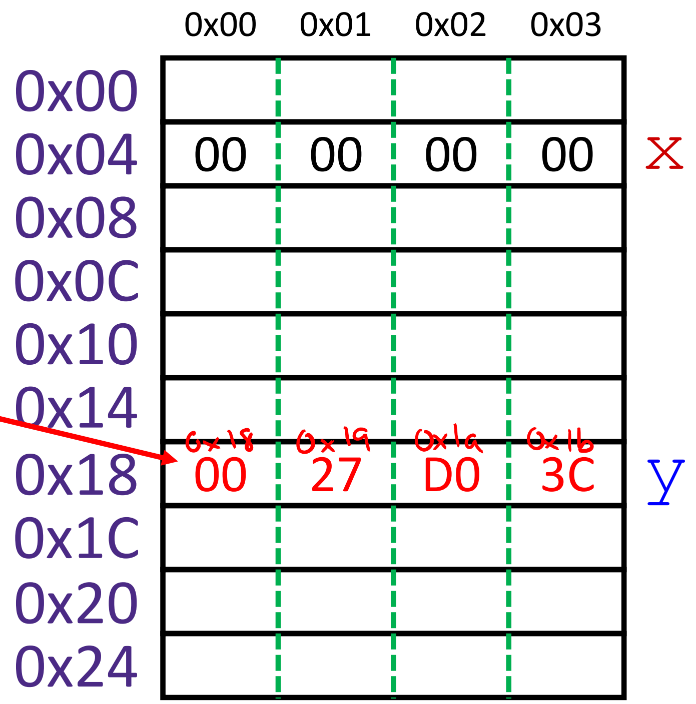
32-bit example
(pointers are 32-bits wide)

& = "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!



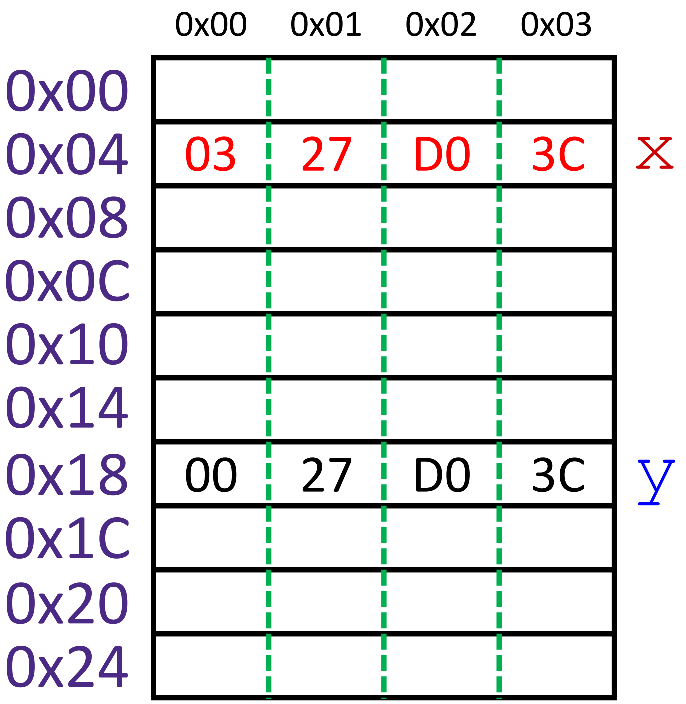
	0x00	0x01	0x02	0x03	
0x00					
0x04	00	00	00	00	x
0x08					
0x0C					
0x10					
0x14					
0x18	0x18 00	0x19 27	0x1a D0	0x1b 3C	y
0x1C					
0x20					
0x24					

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 = 0x3CD0270~~0~~3;
- x = y + 3;
  - Get value at `y`, add 3, store in `x`



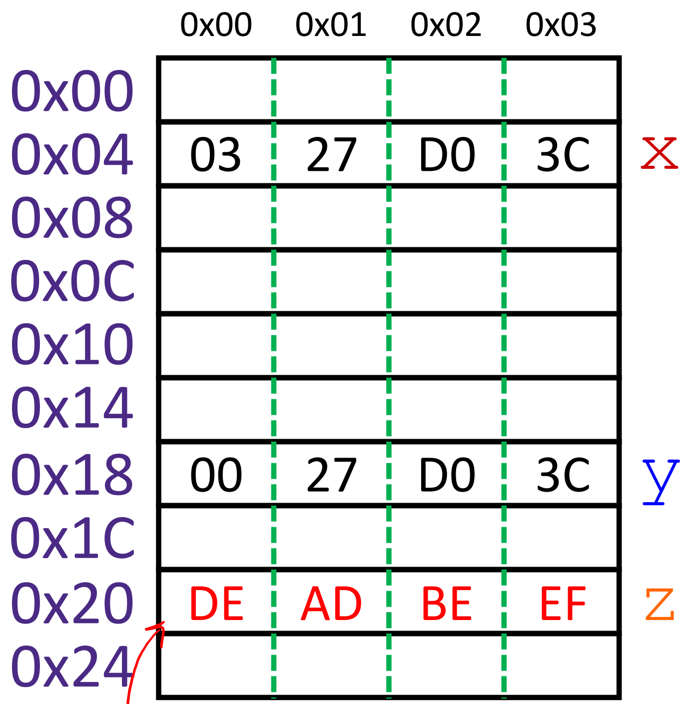
	0x00	0x01	0x02	0x03	
0x00					
0x04	03	27	D0	3C	x
0x08					
0x0C					
0x10					
0x14					
0x18	00	27	D0	3C	y
0x1C					
0x20					
0x24					

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)

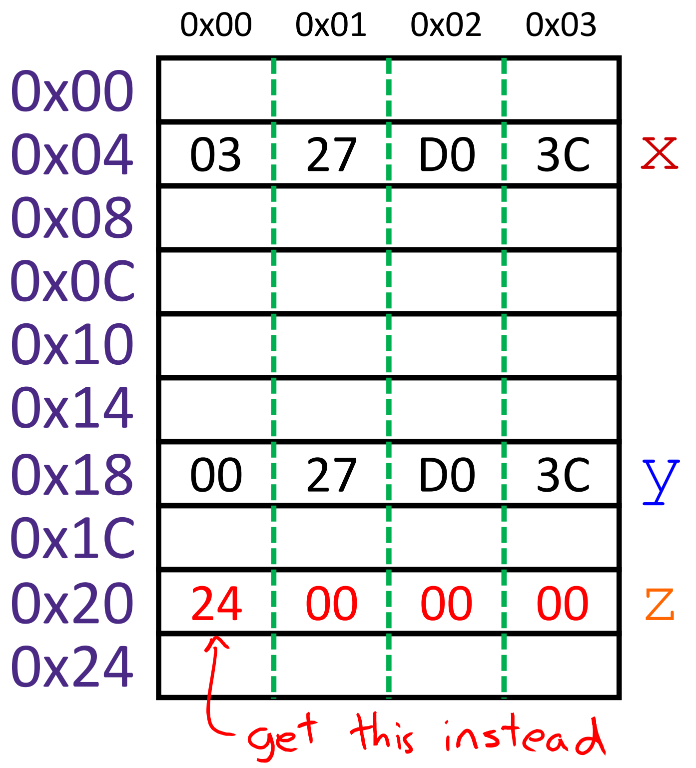
`&` = "address of"
`*` = "dereference"

- 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`

0x18

- **`int*`** `z = &y + 3;` // expect 0x1b
  - 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

Pointer Arithmetic

- Pointer arithmetic is scaled by the size of target type
  - In this example, `sizeof(int)` = 4

as z is an int pointer

- `int* z = &y + 3;`
  - Get address of `y`, add `3*sizeof(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

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					

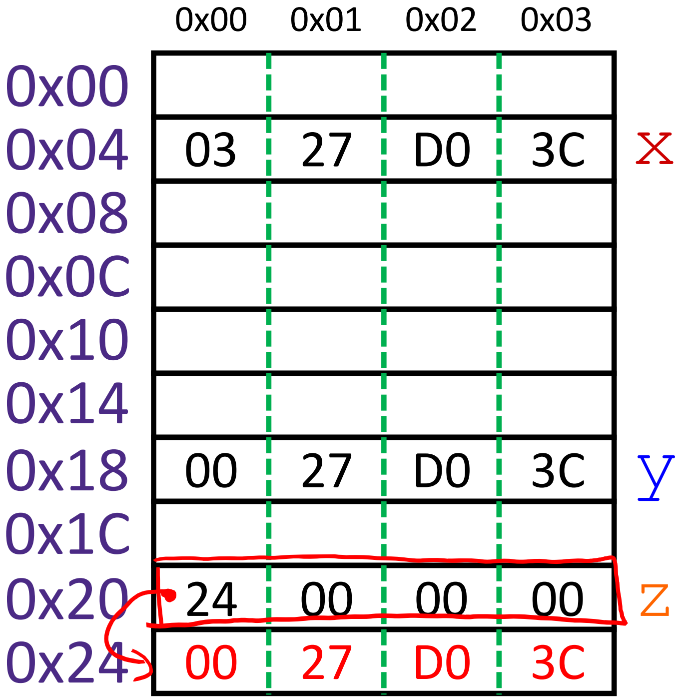
Assignment in C

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

The target of a pointer is also a location



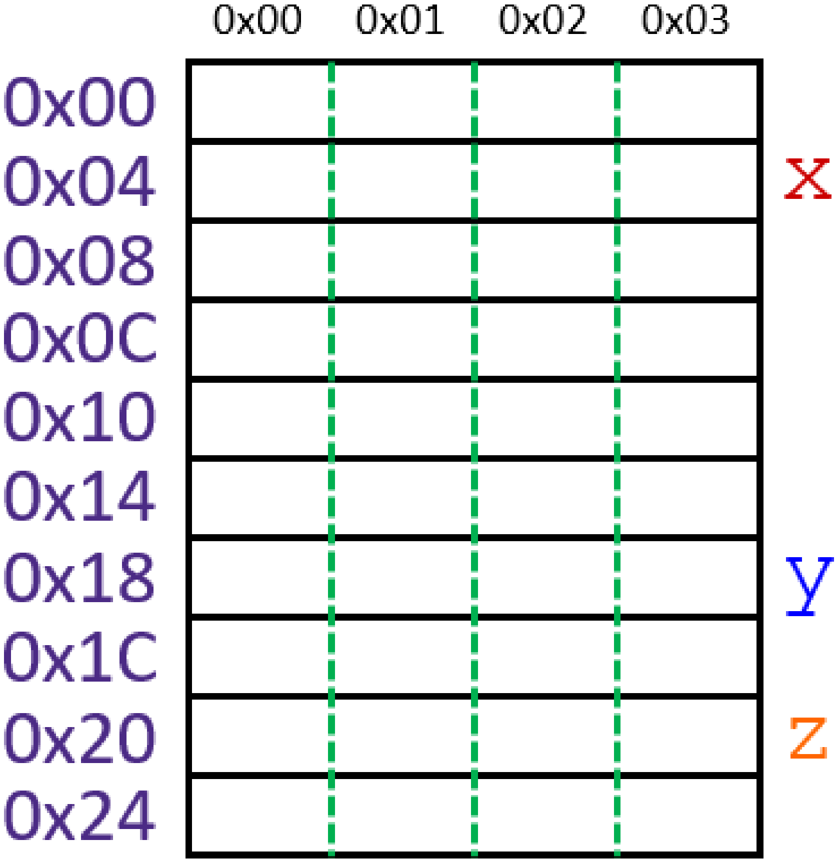
	0x00	0x01	0x02	0x03	
0x00					
0x04	03	27	D0	3C	x
0x08					
0x0C					
0x10					
0x14					
0x18	00	27	D0	3C	y
0x1C					
0x20	24	00	00	00	z
0x24	00	27	D0	3C	

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* (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 **12**, store in `z`
- `*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

4 bytes each

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

element type

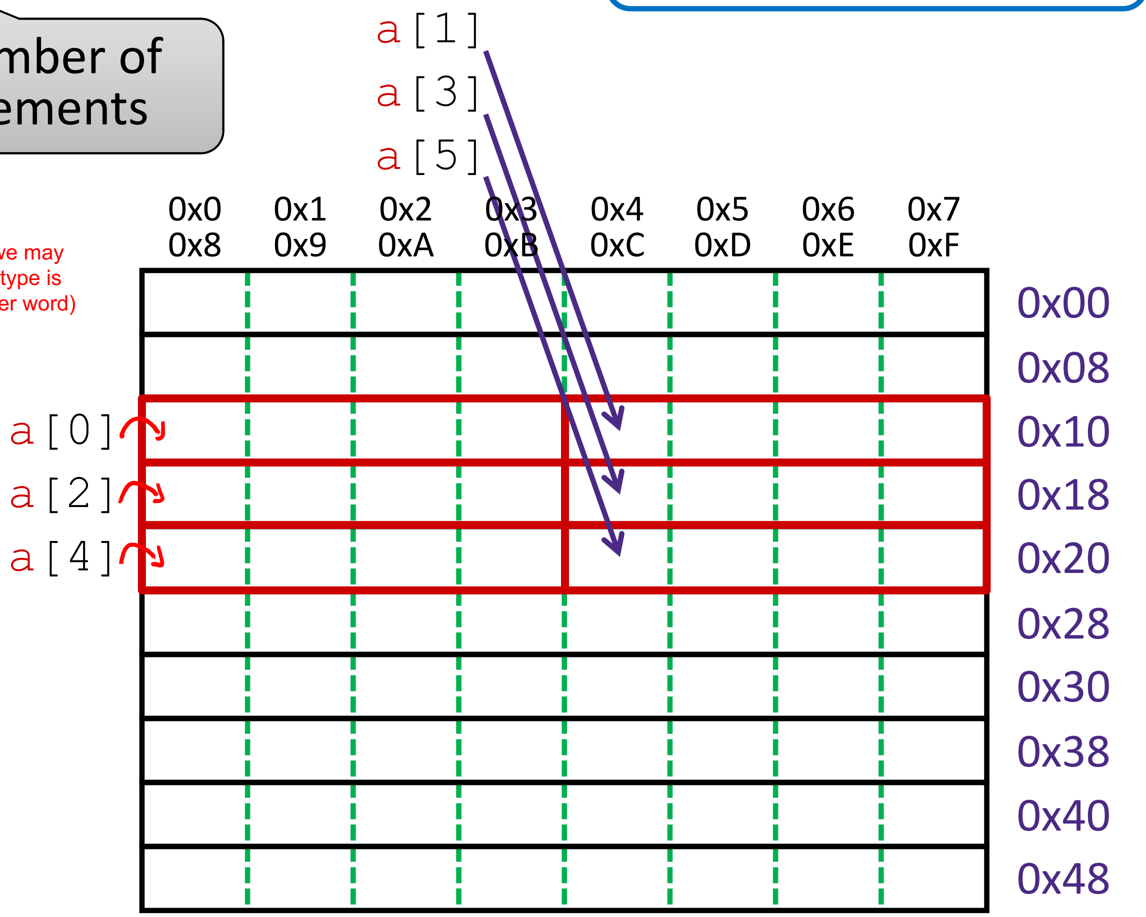
name

number of elements

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

Arrays are stored continuously in memory. Depending on size of the data type, we may be able to fit multiple entries of the area at one address. For example if the data type is int which typically is allotted 4 bytes and we have a 64-bit system (e.g. 8 bytes per word) we can fit two entries of the array per word!

Again when the array is just initialized, garbage (NOT zeros) is stored in all the entries initially.



Arrays in C

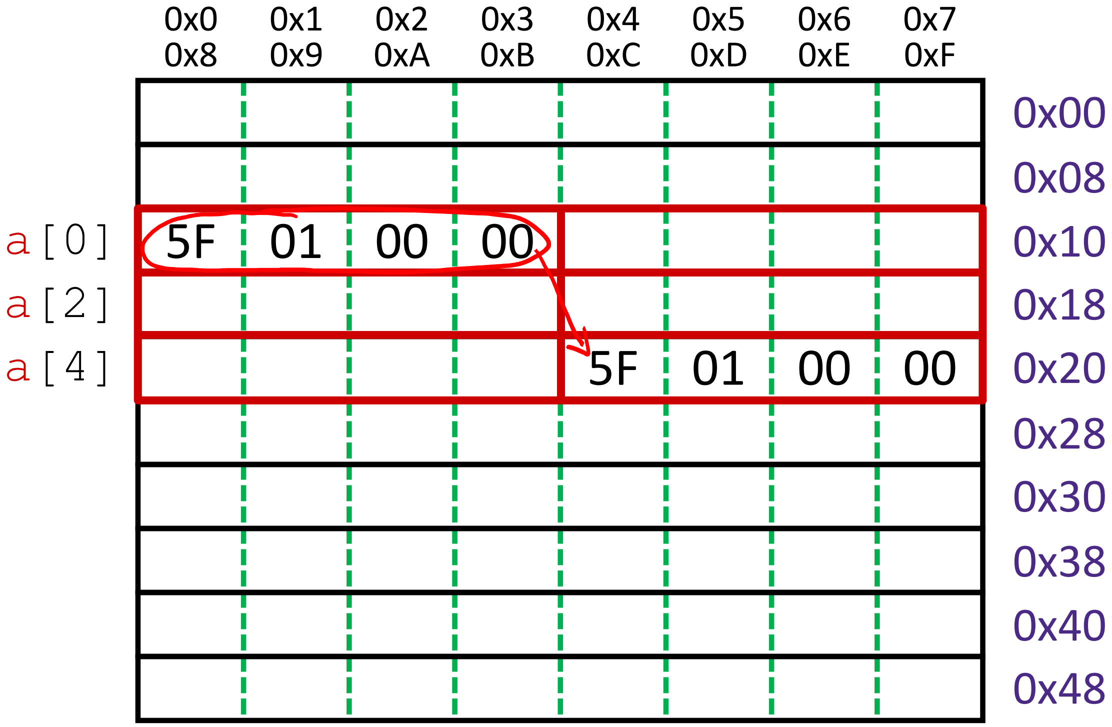
Arrays are adjacent locations in memory storing the same type of data object

`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];
```



Arrays in C

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

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

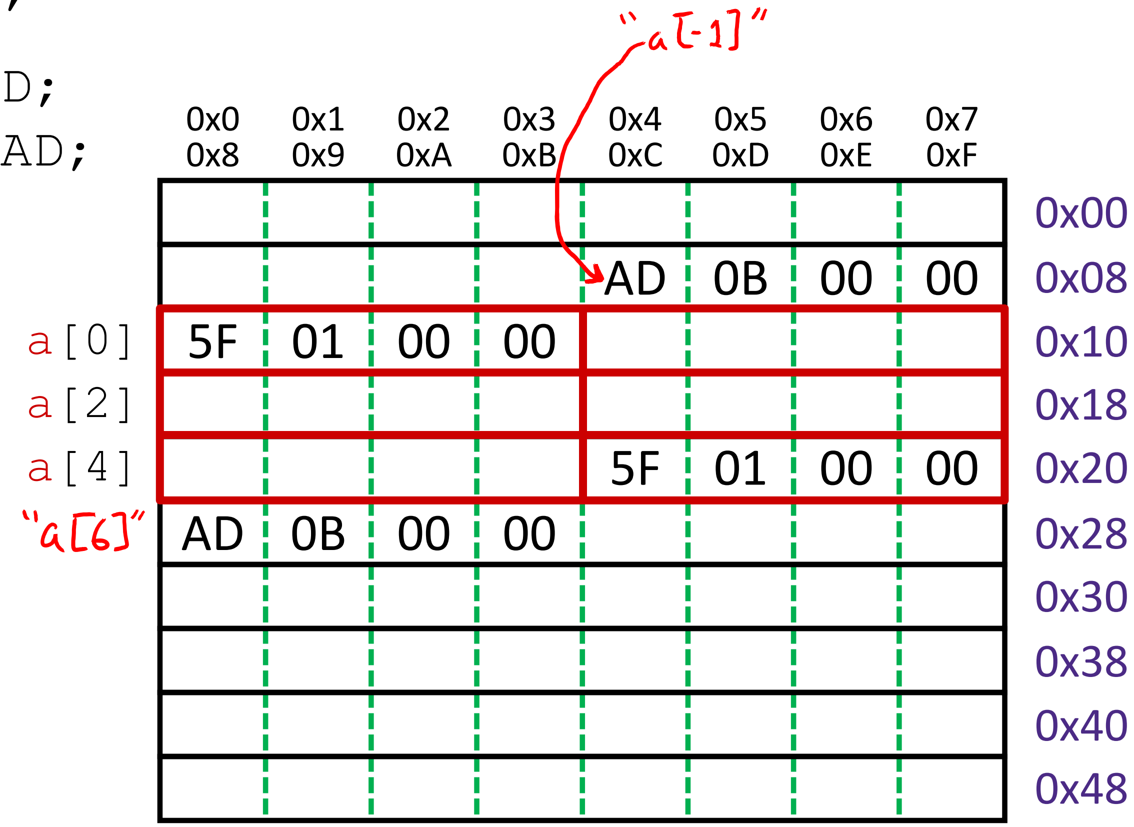
`&a[i]` is the address of `a[0]` plus `i` times the element size in bytes

Declaration: **`int`** `a[6];`

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

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

Can be dangerous: what if those adjacent addresses were being used for something else in the program? Then you'd be overwriting it!



	0x0 0x8	0x1 0x9	0x2 0xA	0x3 0xB	0x4 0xC	0x5 0xD	0x6 0xE	0x7 0xF	
									0x00
					AD	0B	00	00	0x08
a[0]	5F	01	00	00					0x10
a[2]									0x18
a[4]					5F	01	00	00	0x20
"a[6]"	AD	0B	00	00					0x28
									0x30
									0x38
									0x40
									0x48

Arrays in C

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

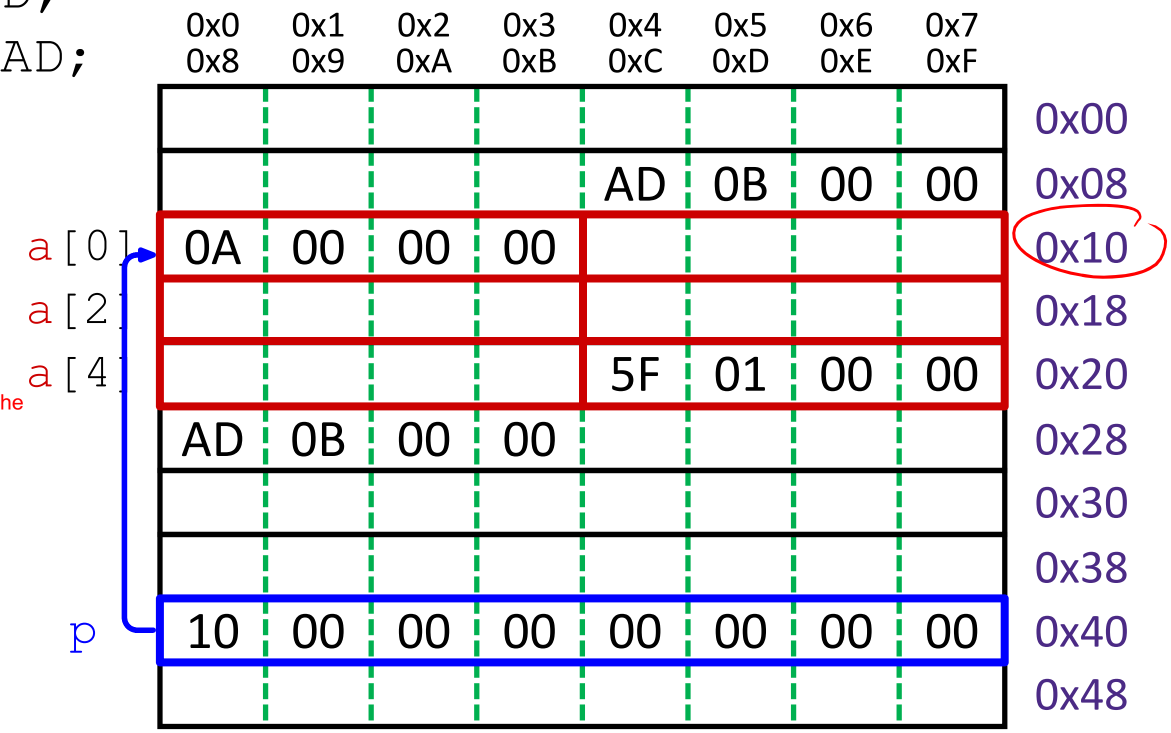
No bounds checking:
`a[6] = 0xBAD;`
`a[-1] = 0xBAD;`

Pointers: `int* p;`

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

`*p = 0xA;`

p stores the address of the start of the array! Again *p = 0xA sets the value at location *p (namely location a[0]) to 0xA



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

p[i] <=> *(p + i)

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;`

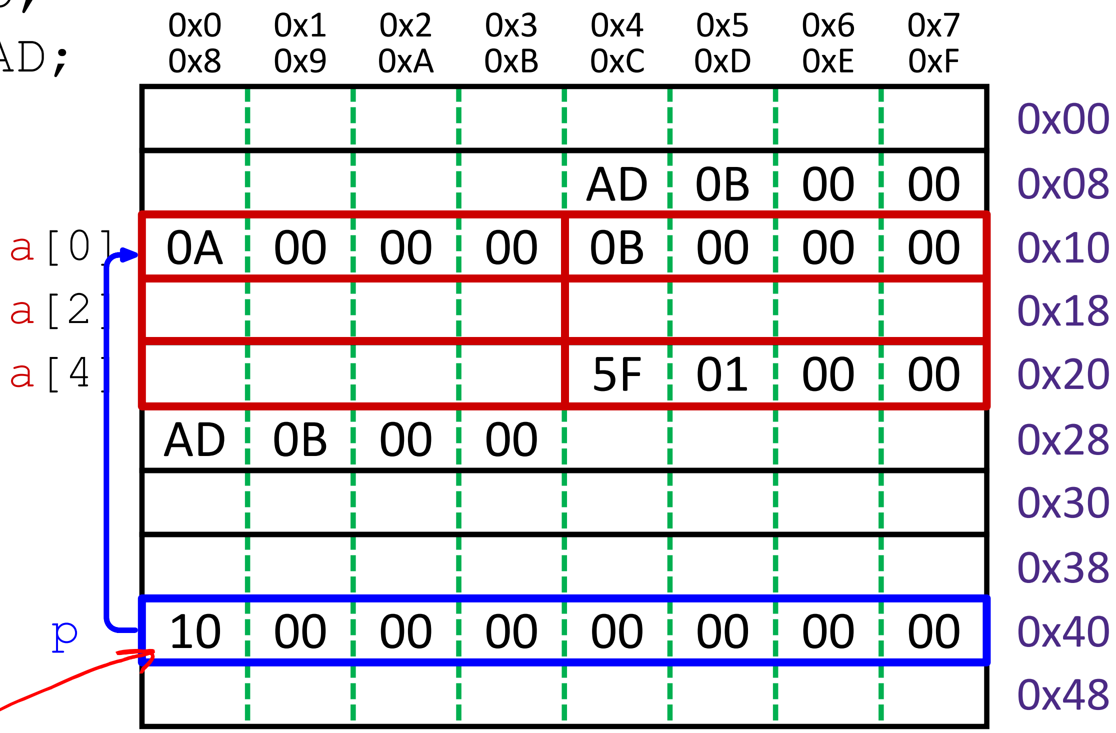
array indexing = address arithmetic
(both scaled by the size of the type)
see slide 13/14

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

pointer arithmetic: 0x10 + 1 → 0x14

`p = p + 2;`

0x10+2 → 0x18



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

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`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)

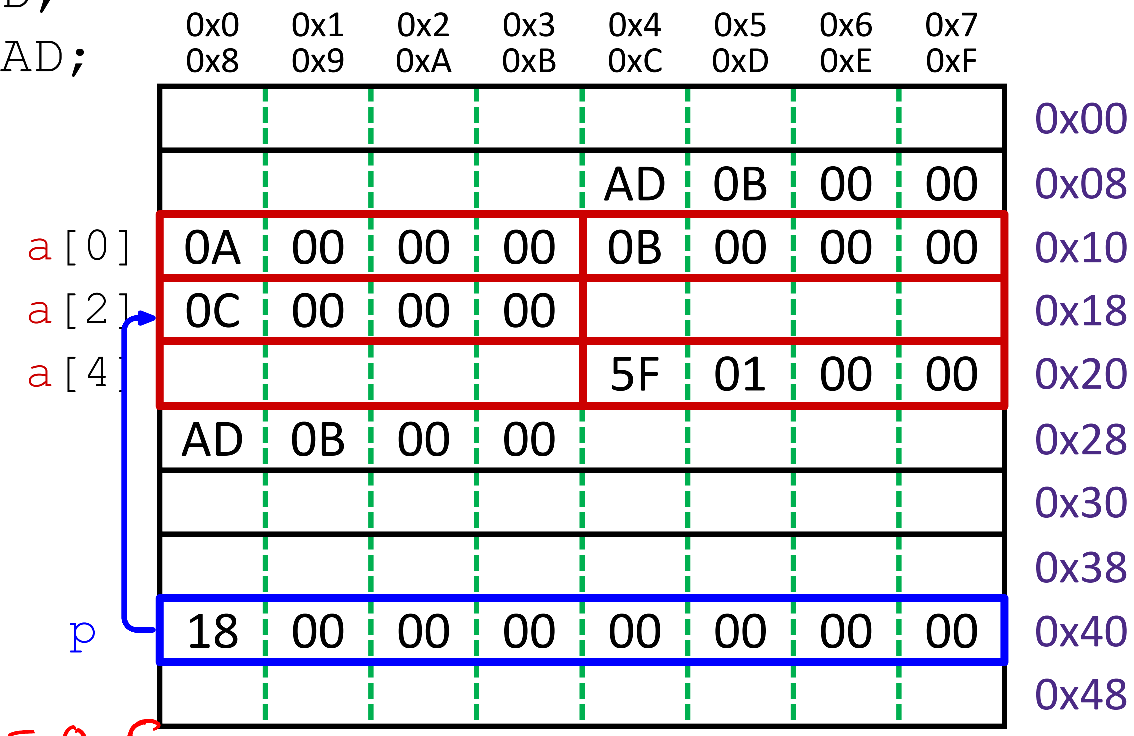
equivalent { `p[1] = 0xB;`
`*(p+1) = 0xB;` }

`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
					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

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;
```

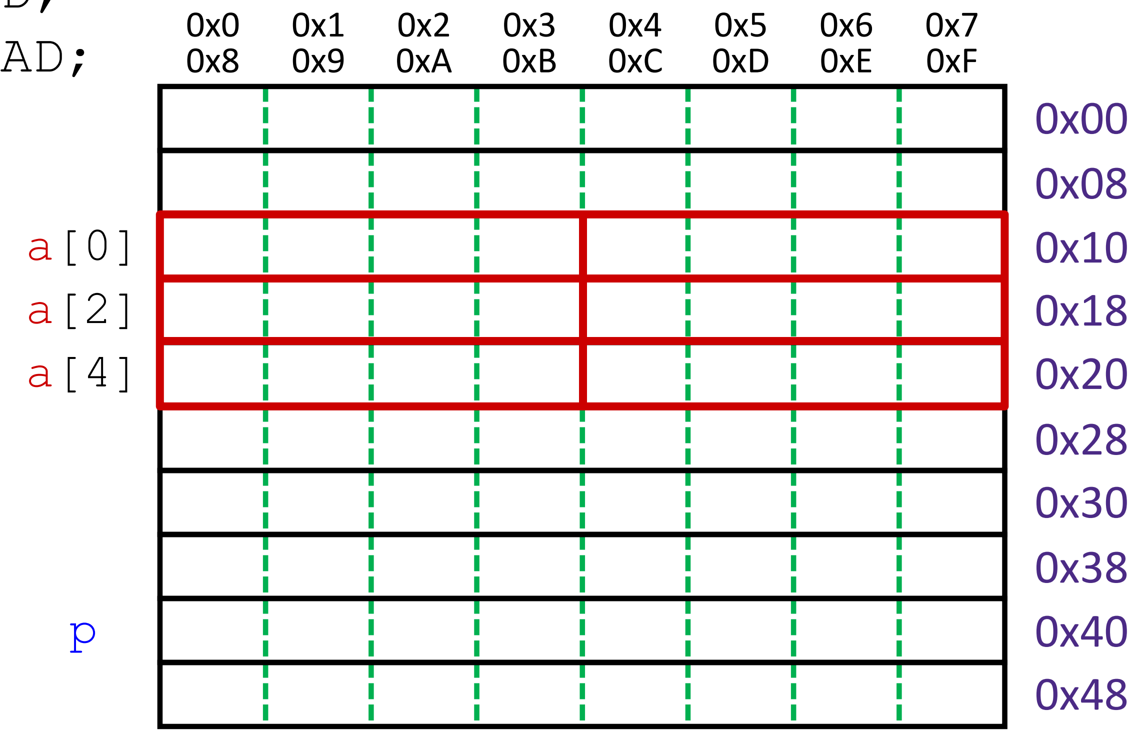
array indexing = address arithmetic
(both scaled by the size of the type)

equivalent {

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

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

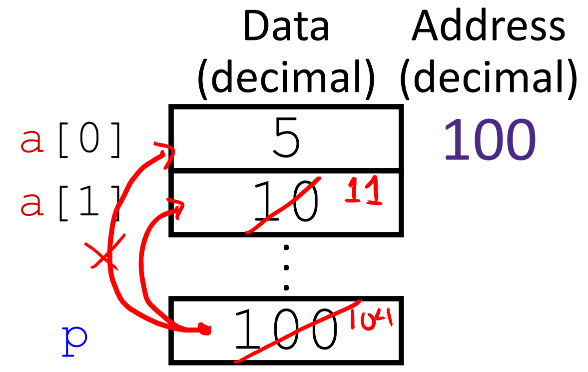
```
*p = a[1] + 1;
```



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; //sizeof(int) = 4
5       *p = *p + 1;
                10
6   }
```



	After Line 4					After Line 5			
	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

6 chars 1 char 5 chars

- **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

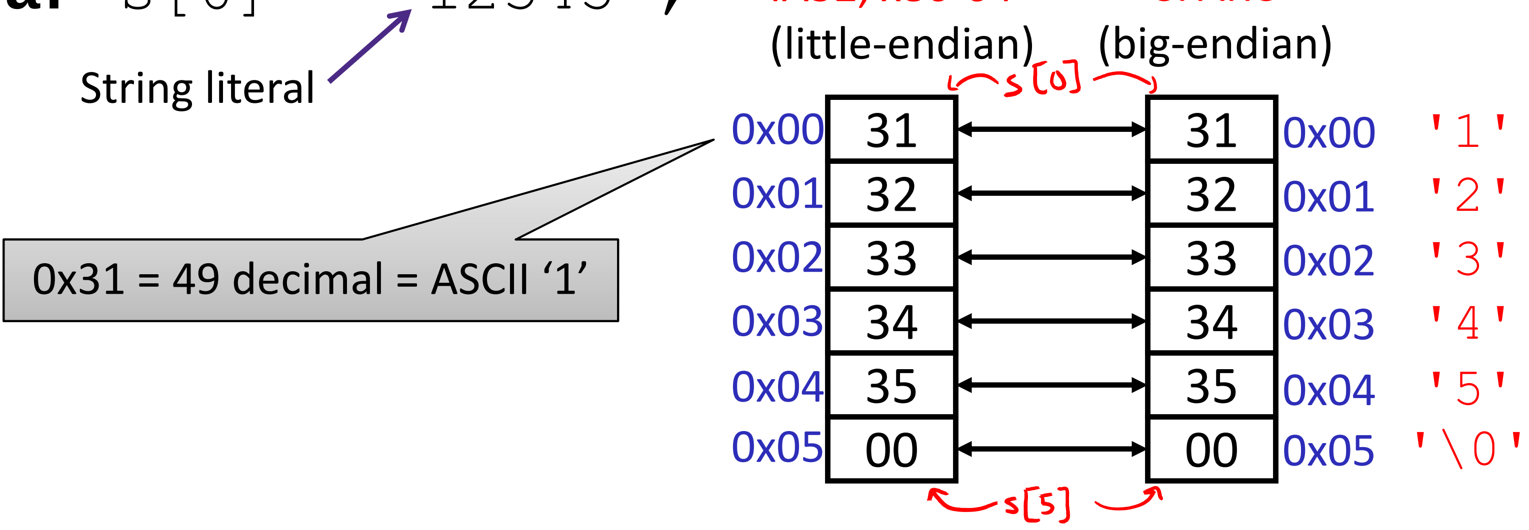
13 bytes total!

- 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";`



	IA32, x86-64 (little-endian)		SPARC (big-endian)		
0x00	31	↔	31	0x00	'1'
0x01	32	↔	32	0x01	'2'
0x02	33	↔	33	0x02	'3'
0x03	34	↔	34	0x03	'4'
0x04	35	↔	35	0x04	'5'
0x05	00	↔	00	0x05	'\0'

- Byte ordering (endianness) is not an issue for 1-byte values

because the reverse of a one element set is just itself

  - 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

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      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    First byte
0x7fffb7f71dbd      0x30    second byte
0x7fffb7f71dbe      0x00    third byte
0x7fffb7f71dbf      0x00    fourth byte
```

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)