Memory, Data, & Addressing II

CSE 351 Spring 2020

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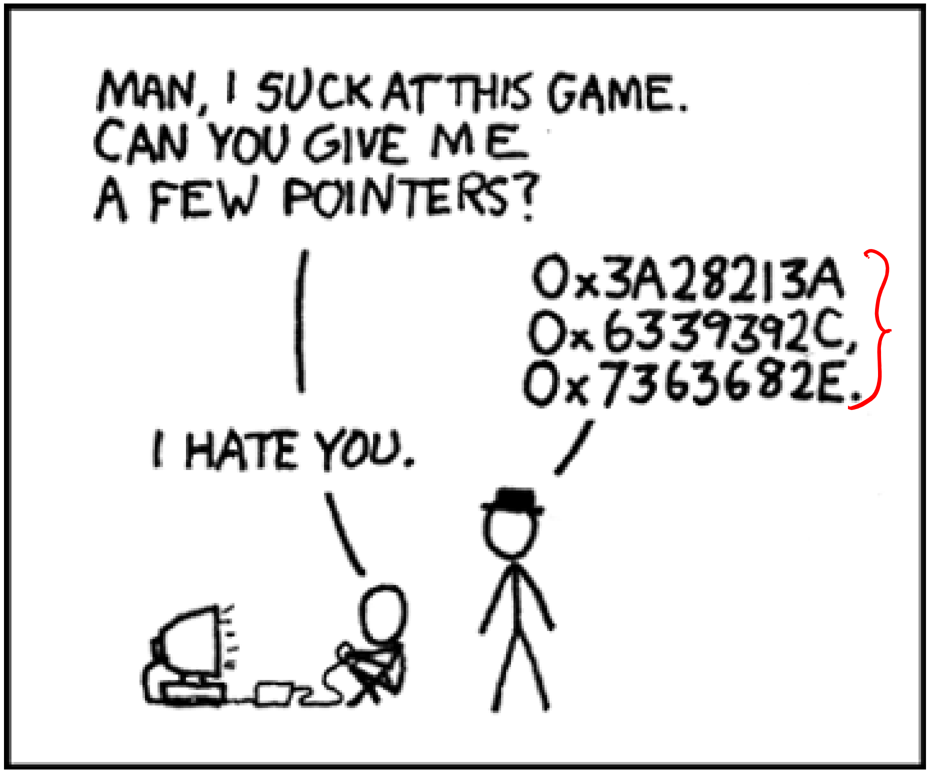


32-bit addresses

http://xkcd.com/138/

Administrivia

- Assignments – Nothing Due this week!
- Lecture Video to watch before Monday (4/06)
  - Not a full lecture, but part of one to help us retain time in lectures for small group interaction.
  - Posted later today, should be watched before lecture on Monday
- Pre-Course Survey, hw0, hw1, hw2 due Mon (4/06) – 11:59pm
- Lab 0 due Tuesday (4/07) – 11:59pm
- hw3 due Wednesday (4/08) – 11am
  - Autograded, unlimited tries, no late submissions
- Lab 1a released today, due next Monday (4/13)
  - Pointers in C
  - Reminder: last submission graded, *individual* work
- Feedback for today: https://catalyst.uw.edu/webq/survey/rea2000/387932

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

Addresses and Pointers in C

* is also used with variable declarations

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

datatype

equivalent

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

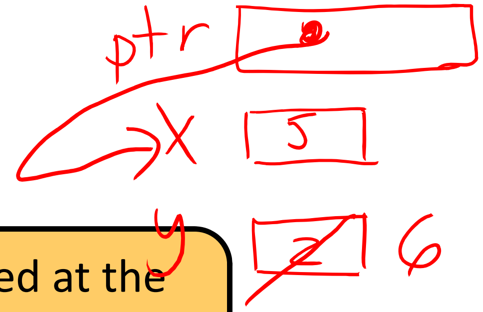
Declares a variable, `ptr`, that is a pointer to (*i.e.* holds the address of) an `int` in memory

```
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`")



```
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

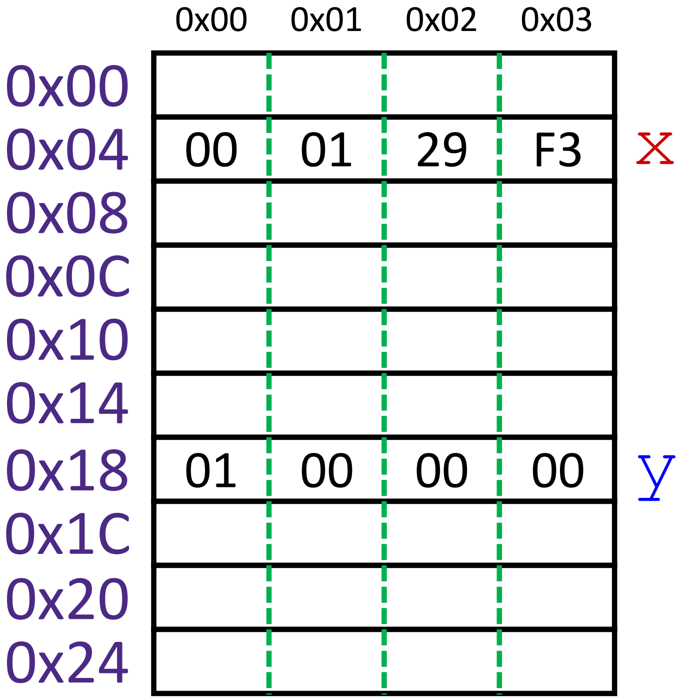
	0x00	0x01	0x02	0x03	
0x00	A7	00	32	00	
0x04	00	01	29	F3	x
0x08	EE	EE	EE	EE	
0x0C	FA	CE	CA	FE	
0x10	26	00	00	00	
0x14	00	00	10	00	
0x18	01	00	00	00	y
0x1C	FF	00	F4	96	
0x20	DE	AD	BE	EF	
0x24	00	00	00	00	

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					

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

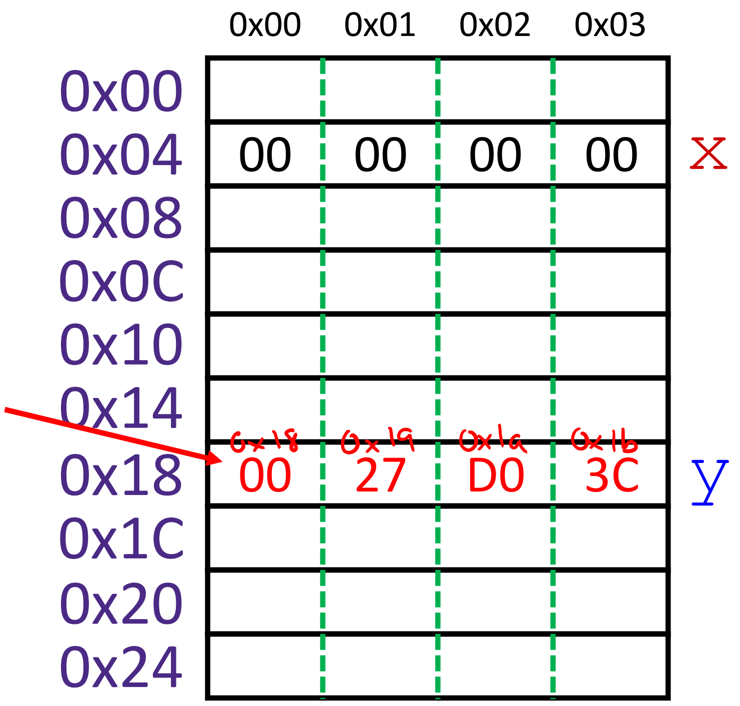
32-bit example
(pointers are 32-bits wide)

`&` = “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!



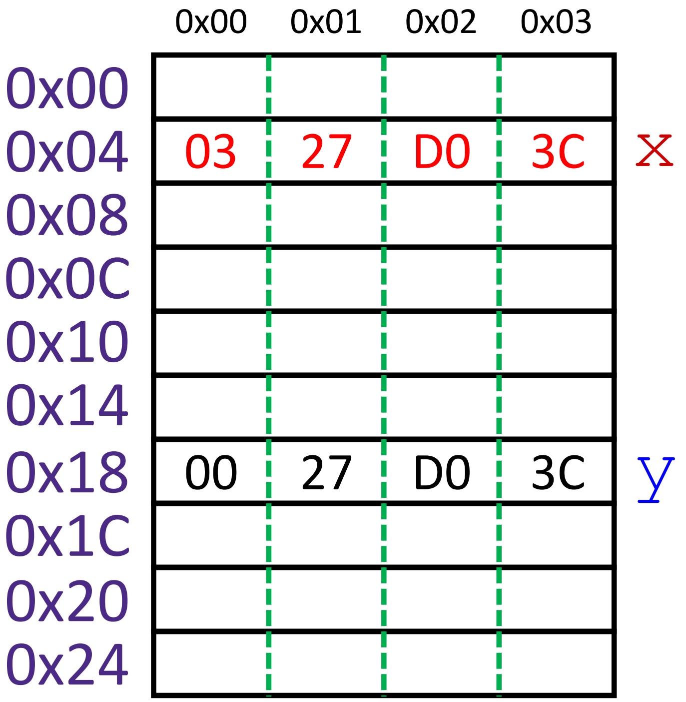
	0x00	0x01	0x02	0x03	
0x00					
0x04	00	00	00	00	x
0x08					
0x0C					
0x10					
0x14					
0x18	0x18 00	0x19 27	0x1a D0	0x1b 3C	y
0x1C					
0x20					
0x24					

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 = 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

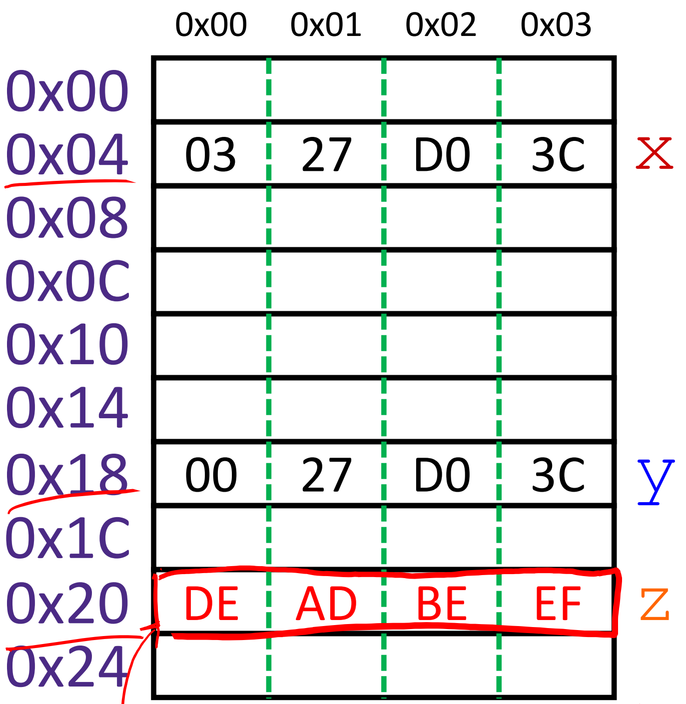
32-bit example
(pointers are 32-bits wide)

`&` = "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

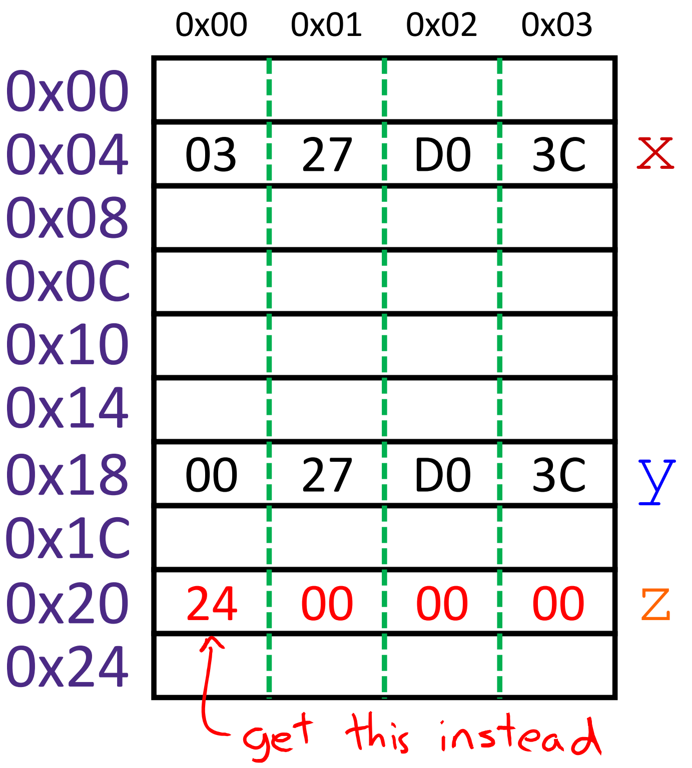
32-bit example
(pointers are 32-bits wide)

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

0x18

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
- `int* z = &y + 3;`

  4 bytes

  - 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					

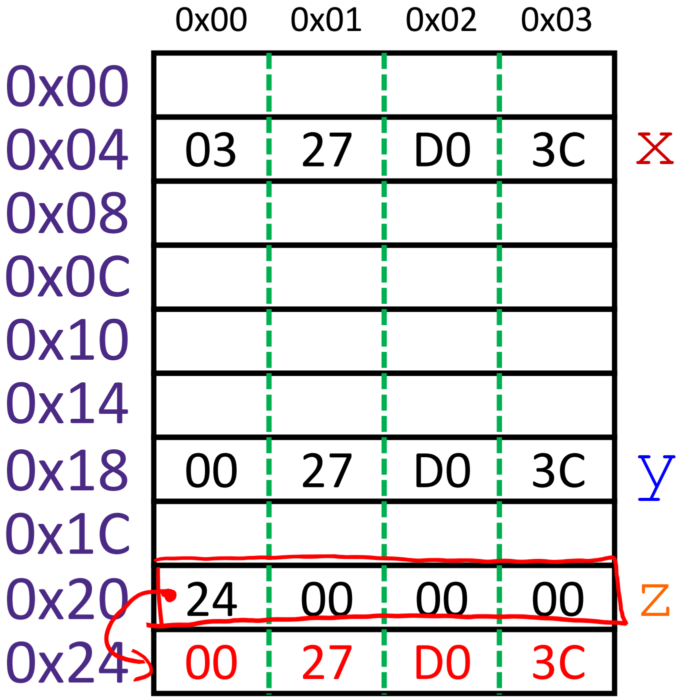
Assignment in C

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	

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

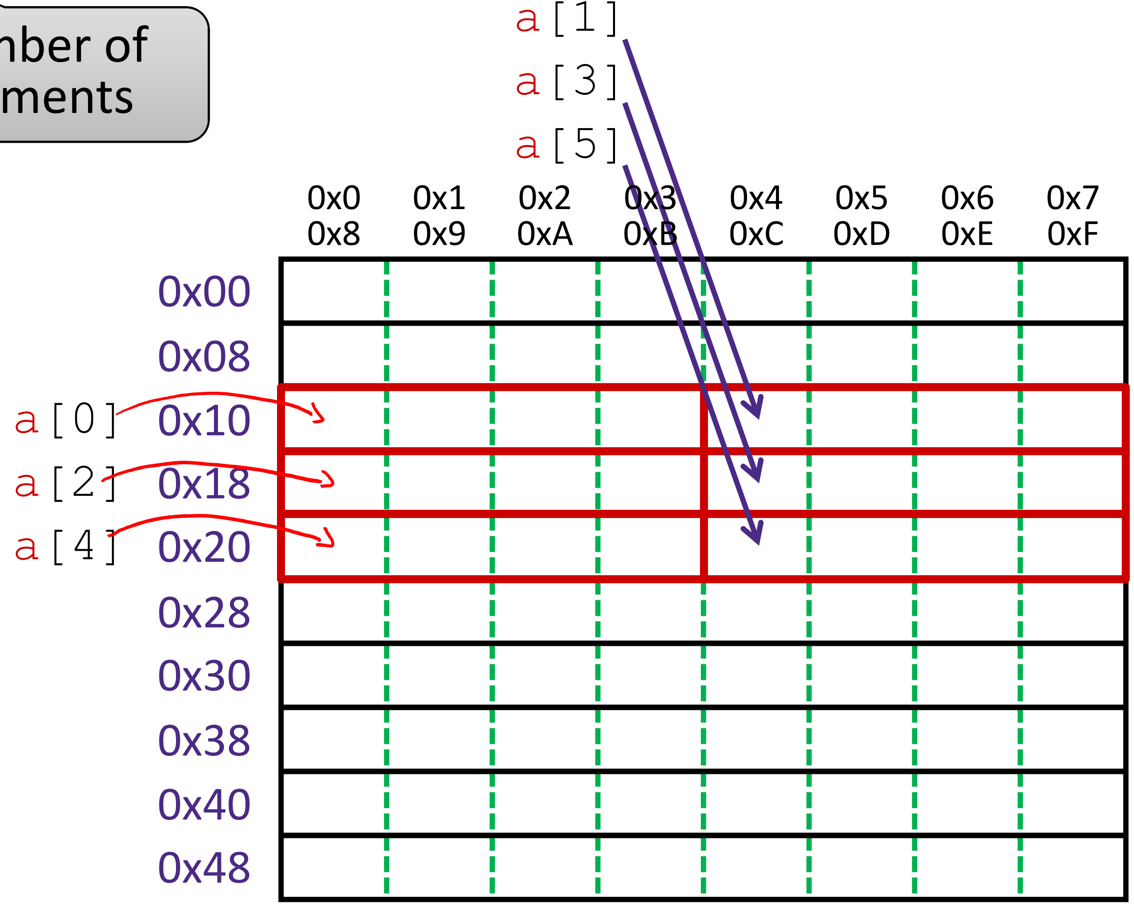
Declaration: **`int`** `a[6];` // &a is 0x10

element type

name

number of elements

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



Arrays in C

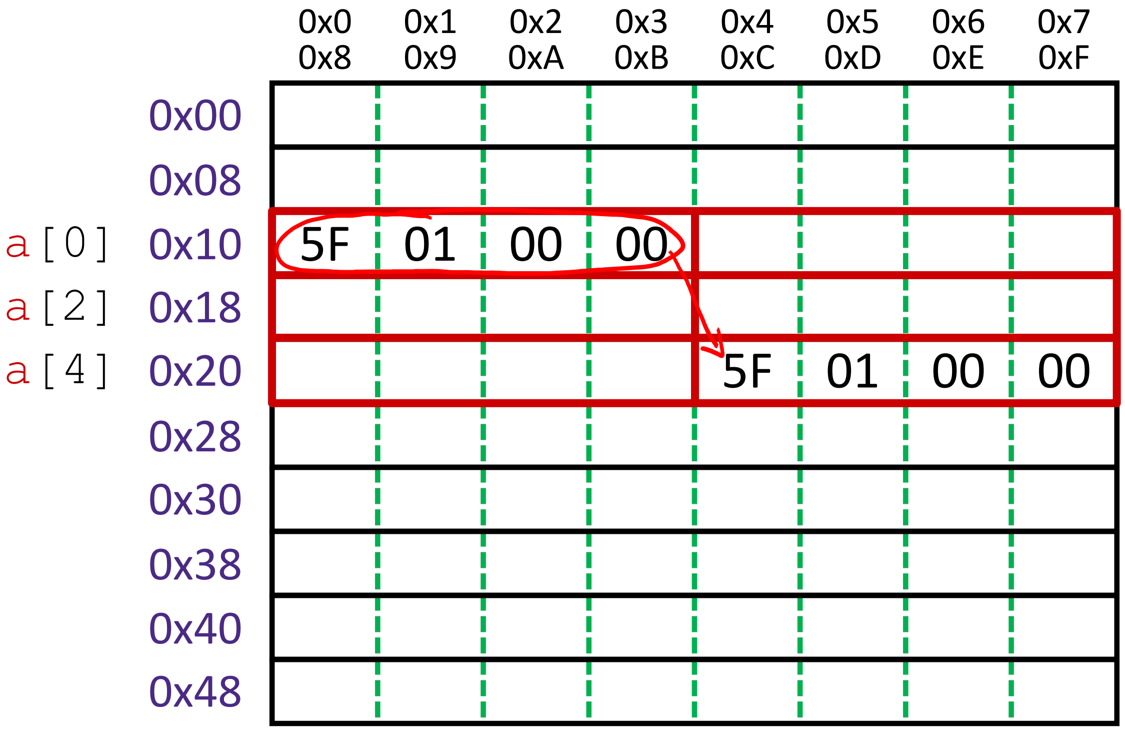
Arrays are adjacent locations in memory storing the same type of data object

`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

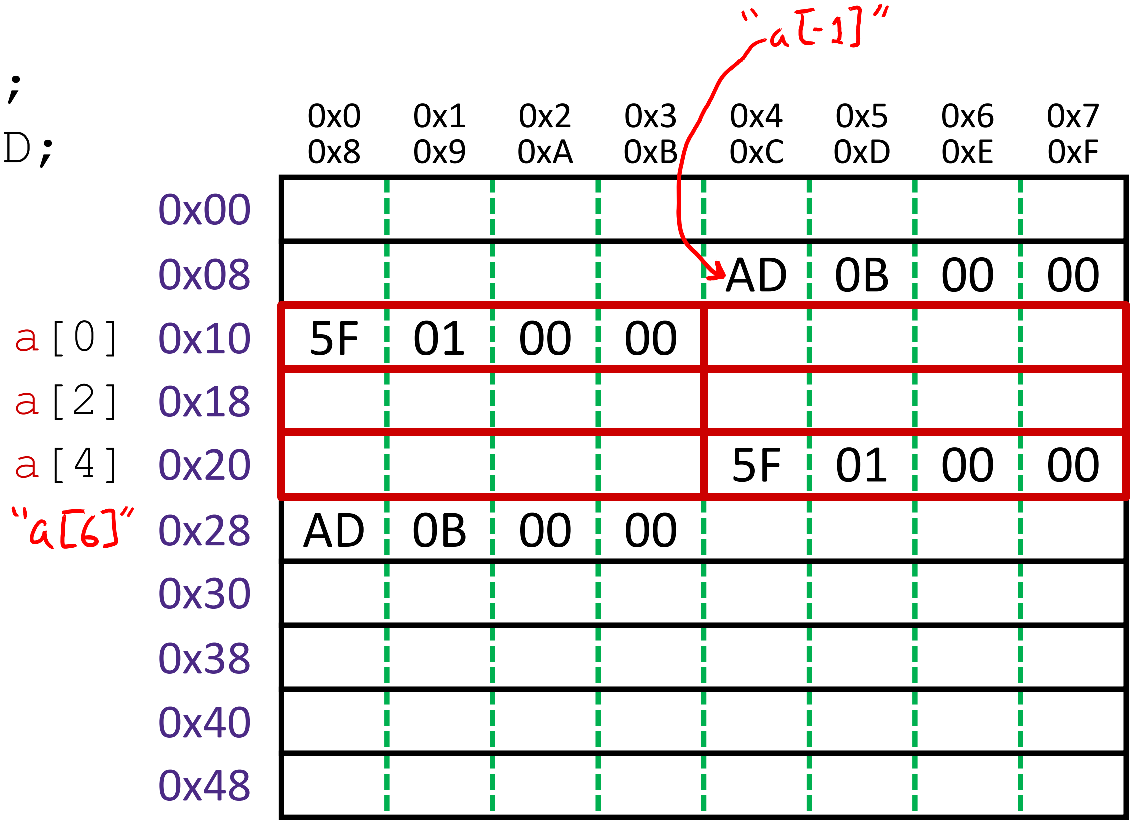
`a` (array name) returns the array's address

`&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;`



"a[-1]"

		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	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];`

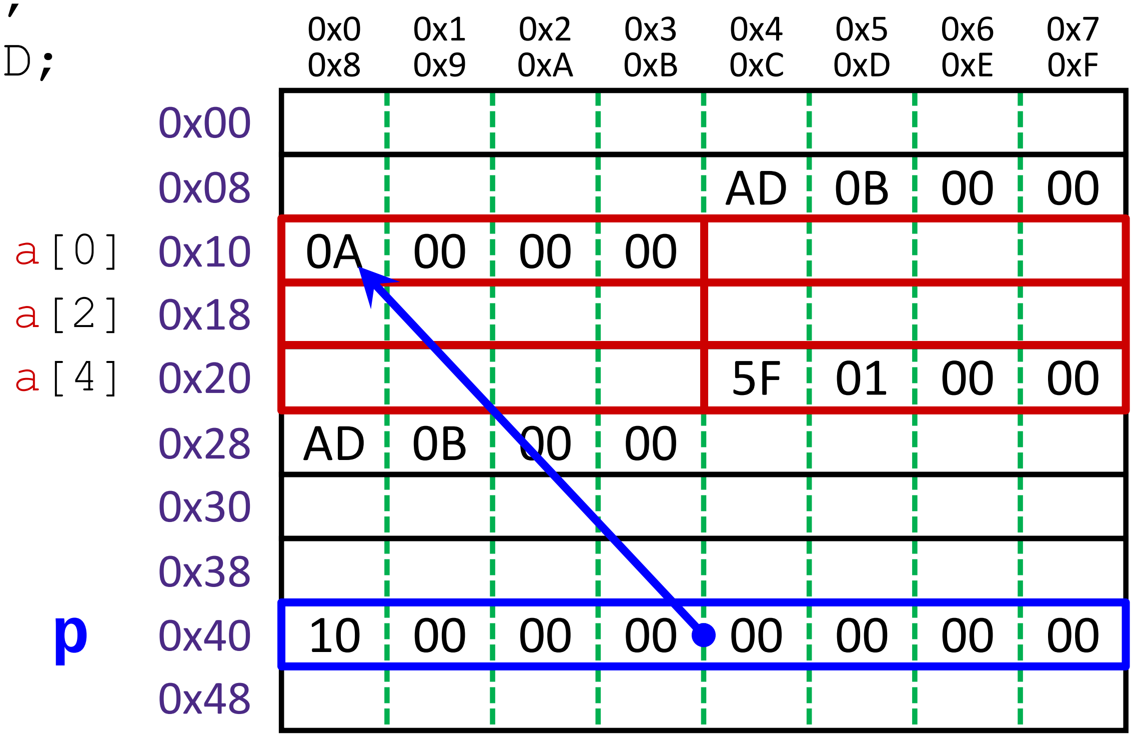
Indexing: `a[0] = 0x015f;`
`a[5] = a[0];`

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

Pointers: `int* p;`

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

`*p = 0xA;`



		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				
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								

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;`

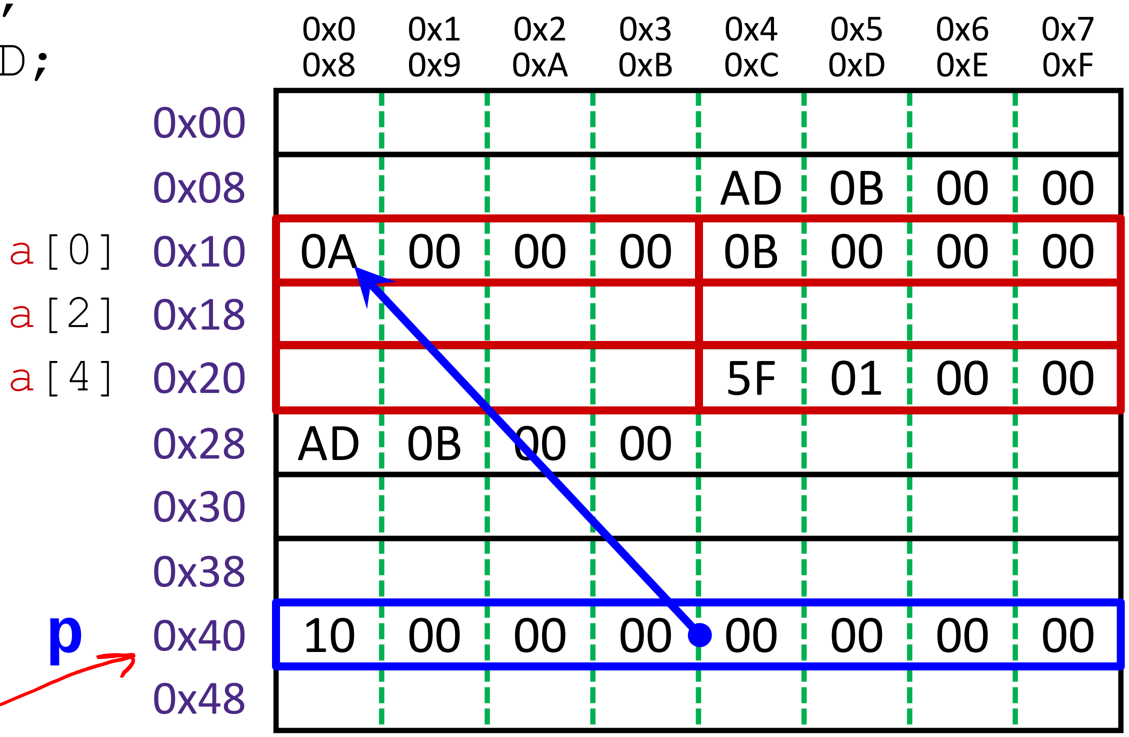
Pointers: `int* p;`

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 → $\boxed{0x18}$

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)

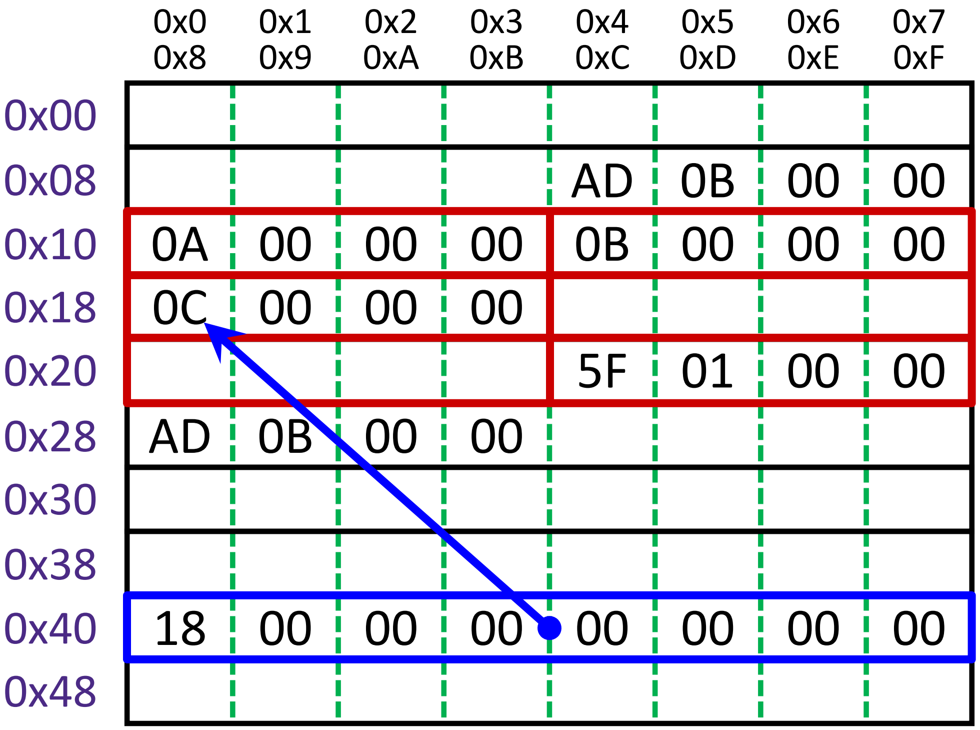
equivalent {
`p[1] = 0xB;`
`*(p+1) = 0xB;`
}

`p = p + 2;`

store at 0x18 →

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

0xB + 1 = 0xC



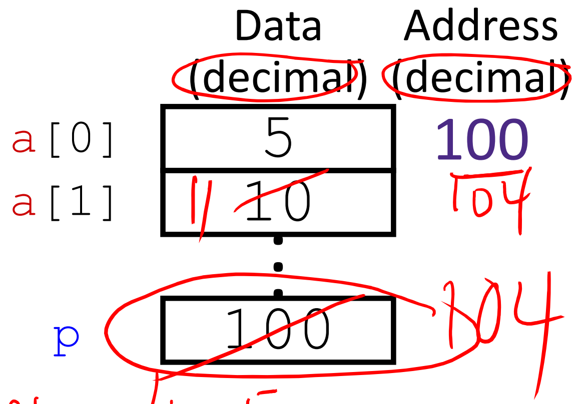
		0x0 0x8	0x1 0x9	0x2 0xA	0x3 0xB	0x4 0xC	0x5 0xD	0x6 0xE	0x7 0xF
	0x00								
	0x08					AD	0B	00	00
a[0]	0x10	0A	00	00	00	0B	00	00	00
a[2]	0x18	0C	00	00	00				
a[4]	0x20					5F	01	00	00
	0x28	AD	0B	00	00				
	0x30								
	0x38								
p	0x40	18	00	00	00	00	00	00	00
	0x48								

(no pointer arithmetic)

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    }
```



	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)

48 0

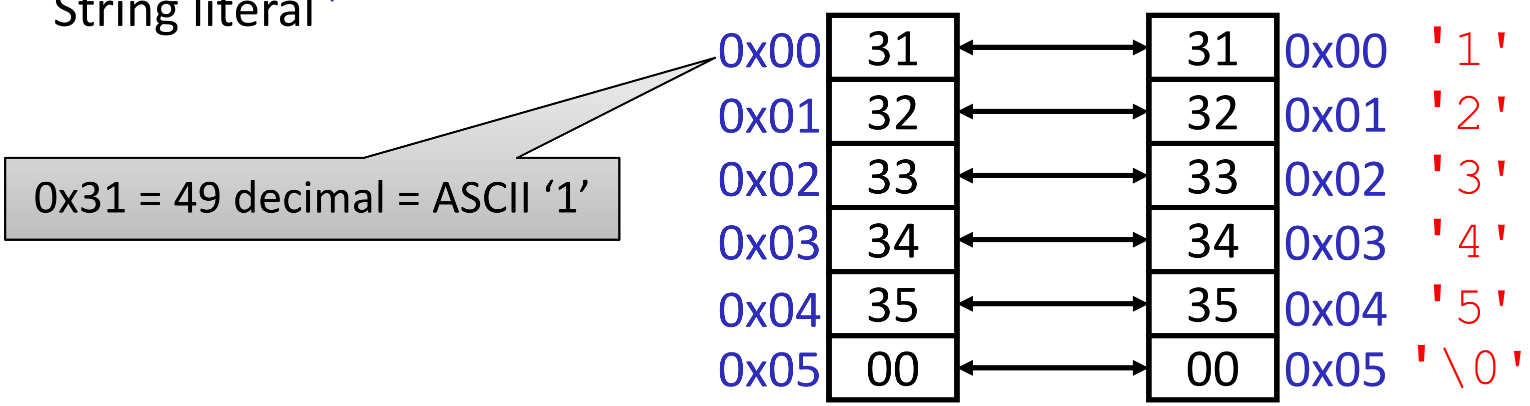
- How do we compute the length of a string?
  - Traverse array until null terminator encountered

Endianness and Strings

C (char = 1 byte)

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

String literal



0x31 = 49 decimal = ASCII ‘1’

	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
  - 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("\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)