Memory, Data, & Addressing II

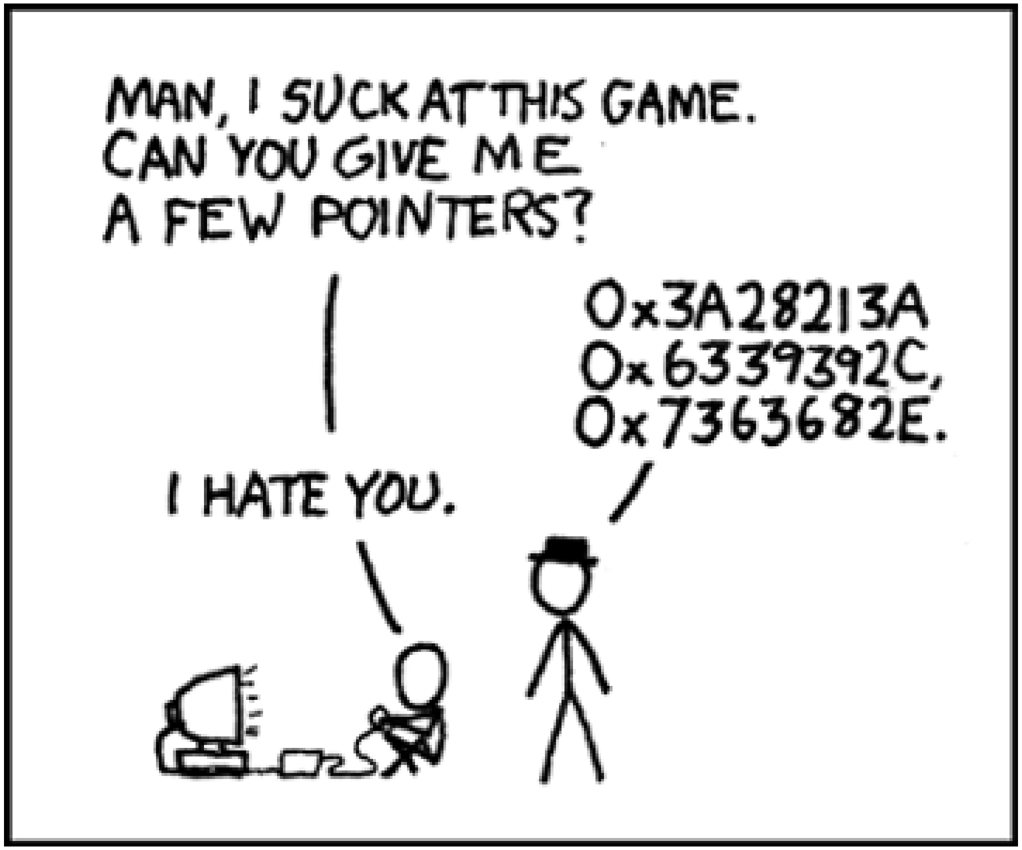
CSE 351 Autumn 2020

Instructor:

Justin Hsia

Teaching Assistants:

Aman Mohammed
Ami Oka
Callum Walker
Cosmo Wang
Hang Do
Jim Limprasert
Joy Dang
Julia Wang
Kaelin Laundry
Kyrie Dowling
Mariam Mayanja
Shawn Stanley
Yan Zhe Ong


MAN, I SUCK AT THIS GAME. CAN YOU GIVE ME A FEW POINTERS?
0x3A28213A 0x6339392C, 0x7363682E.
I HATE YOU.

http://xkcd.com/138/

Administrivia

- Lab 0 due today @ 11:59 pm
  - *You will revisit this concepts from program!*
- hw2 due Wednesday, hw3 due Friday @ 11:00 am
  - Autograded, unlimited tries, no late submissions
- Lab 1a released today, due next Monday (10/12)
  - Pointers in C
  - Reminder: last submission graded, *individual* work

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

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

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

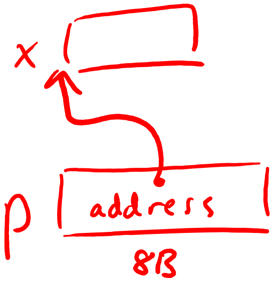
- How much space does the variable p take up?

  A. 1 byte

  B. 2 bytes

  C. 4 bytes

  [✓ D. 8 bytes]



- Which of the following expressions evaluate to an address?

  A. $\overset{\text{int}}{\texttt{x}} + 10$ → int

  [✓ B.] $\overset{\text{char*}}{\texttt{p}} + 10$ → char *

  [✓ C.] $\overset{\text{int*}}{\texttt{\&x}} + 10$ → int *

  [✓ D.] $*(\underline{\overset{\text{char**}}{\texttt{\&p}}})$ → char *

  E. ar[1] → int

  [✓ F.] $\underline{\texttt{\&}\overset{\text{int}}{\texttt{ar[2]}}}$ → int *

Pointer Operators

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

- Operator confusion

  &x

  *p

  - 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!

data type

char* p;

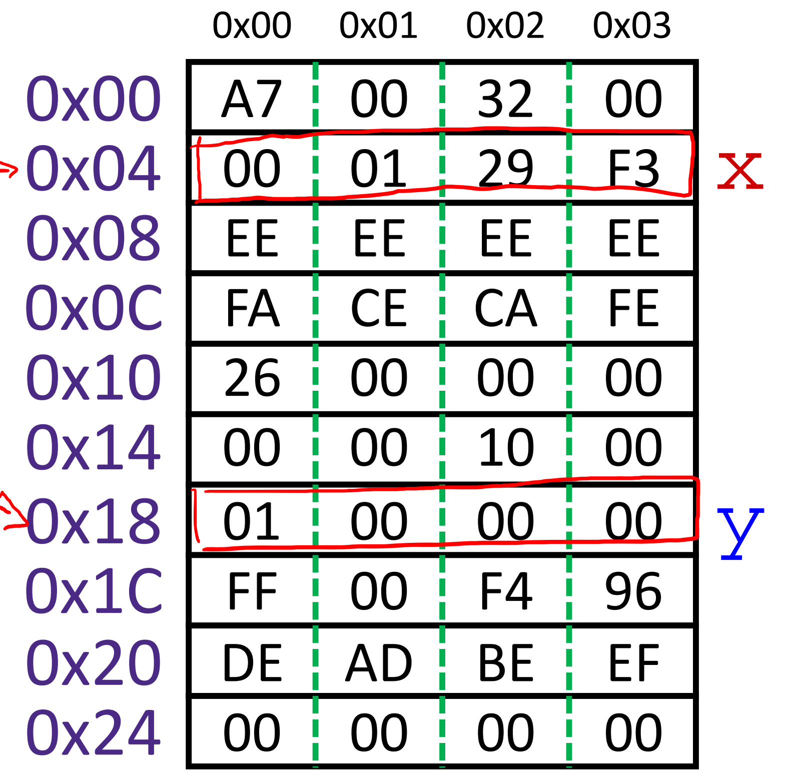
NOT an operator

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	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	

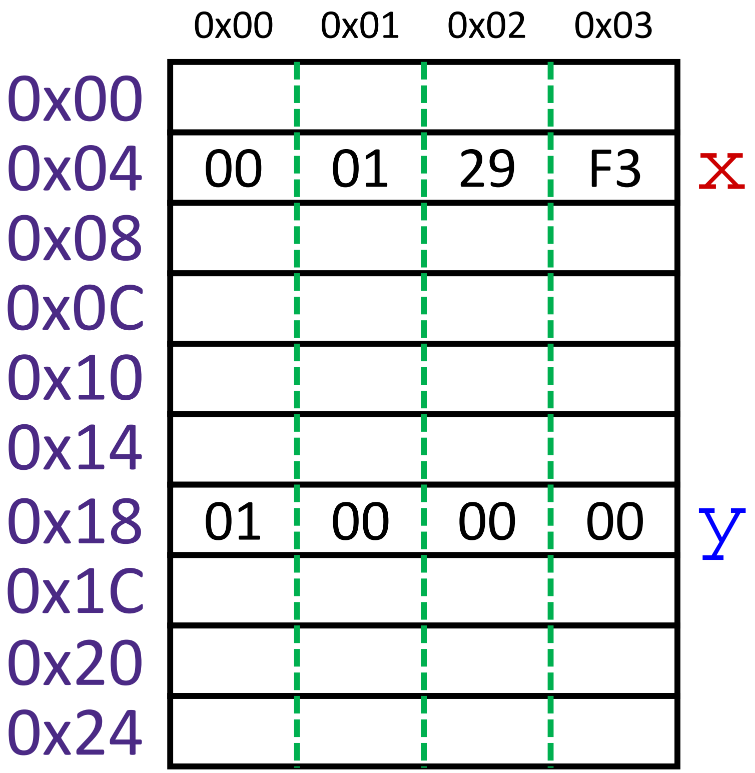
current state of memory

Assignment in C

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

little-endian

- A variable is represented by a location
- 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					

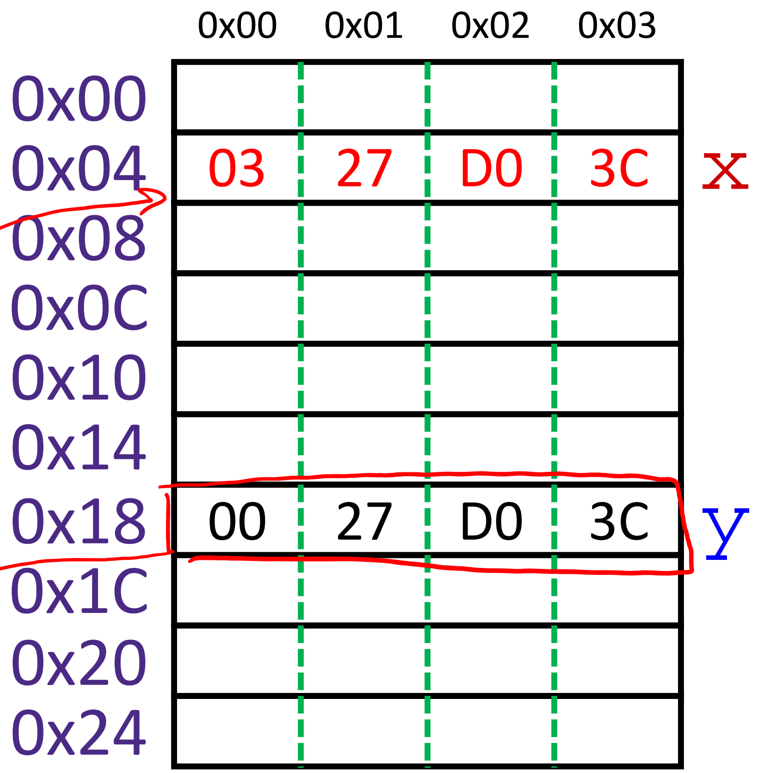
Assignment in C

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;`

  0x3CD02703
  - Get value at `y`, add 3, store in `x`



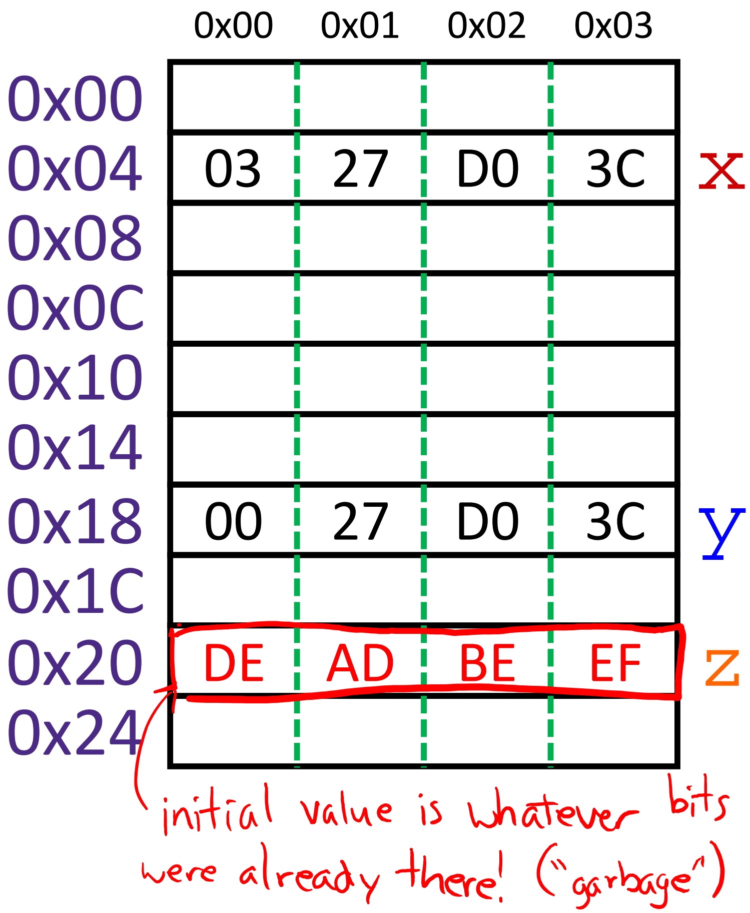
	0x00	0x01	0x02	0x03	
0x00					
0x04	03	27	D0	3C	x
0x08					
0x0C					
0x10					
0x14					
0x18	00	27	D0	3C	y
0x1C					
0x20					
0x24					

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

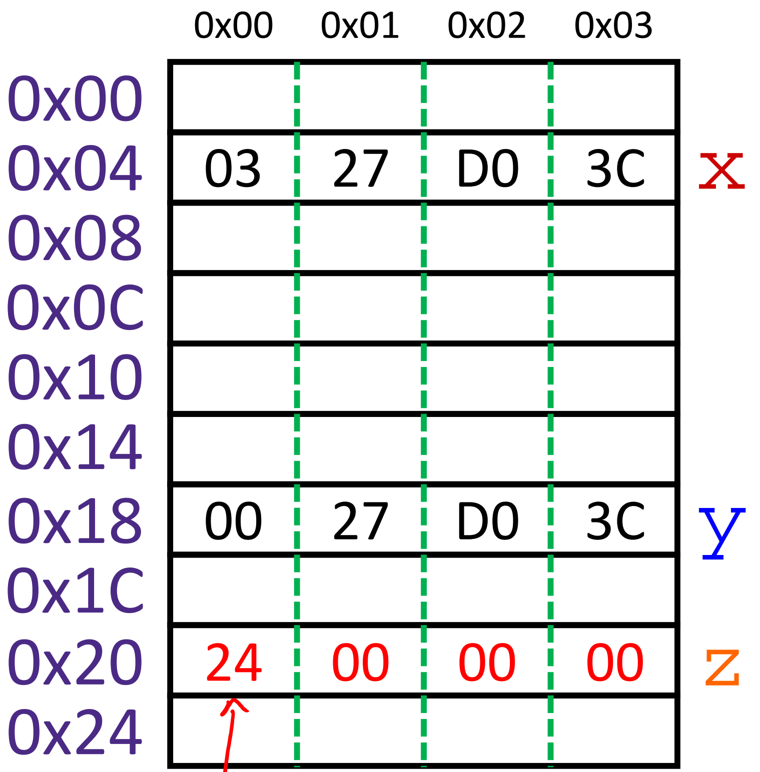
32-bit example
(pointers are 32-bits wide)

& = "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

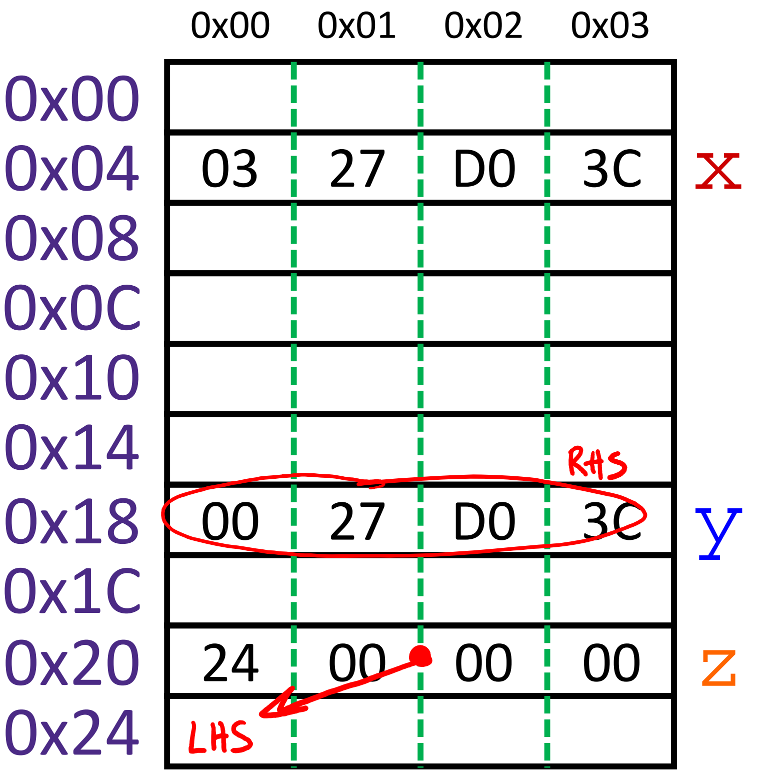
(scale by sizeof(int)=4)

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;`



	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

The target of a pointer is also a location

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

	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	

Addresses and Pointers in C

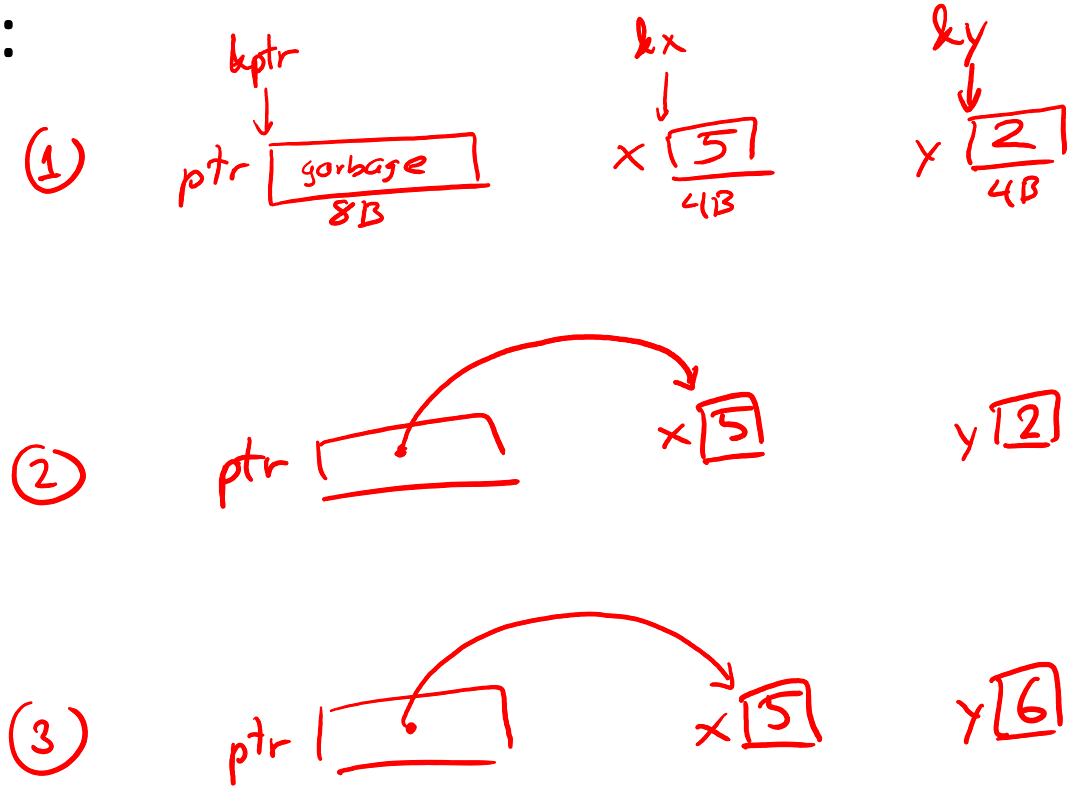
- Draw out a box-and-arrow diagram for the result of the following C code:

```
    int* ptr;

(1) int x = 5;

    int y = 2;

(2) ptr = &x;
                 5
(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

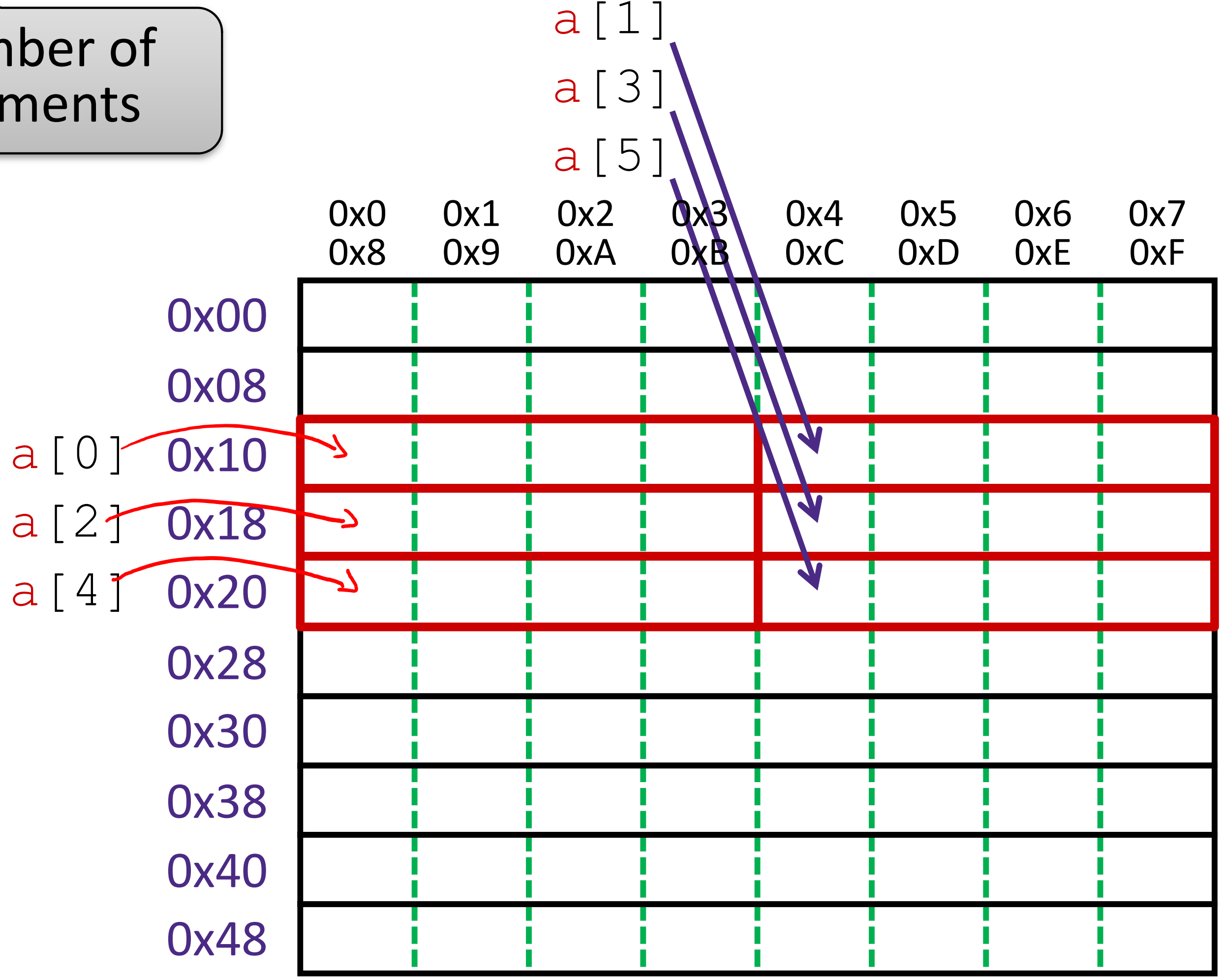
Declaration: `int a[6];` // &a is 0x10

element type

name

number of elements

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



Arrays in C

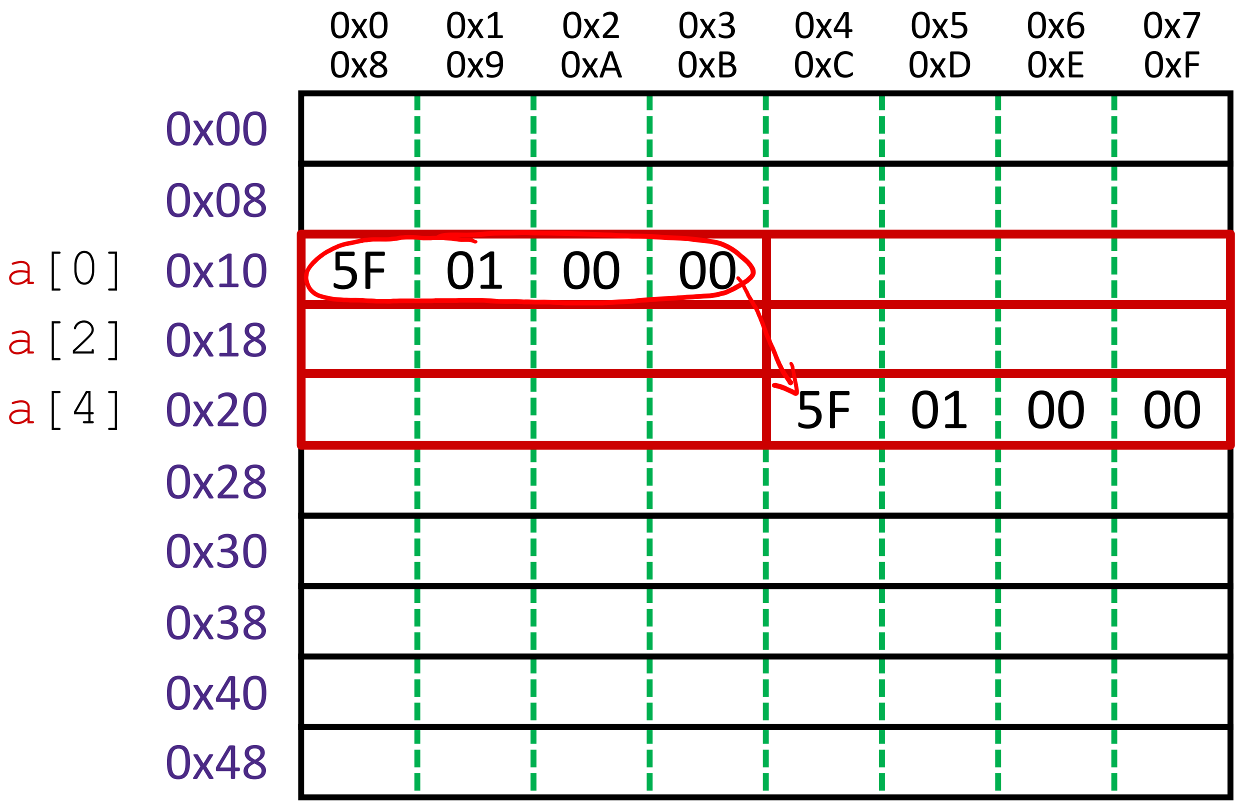
Arrays are adjacent locations in memory storing the same type of data object

`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];
```



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

Arrays in C

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

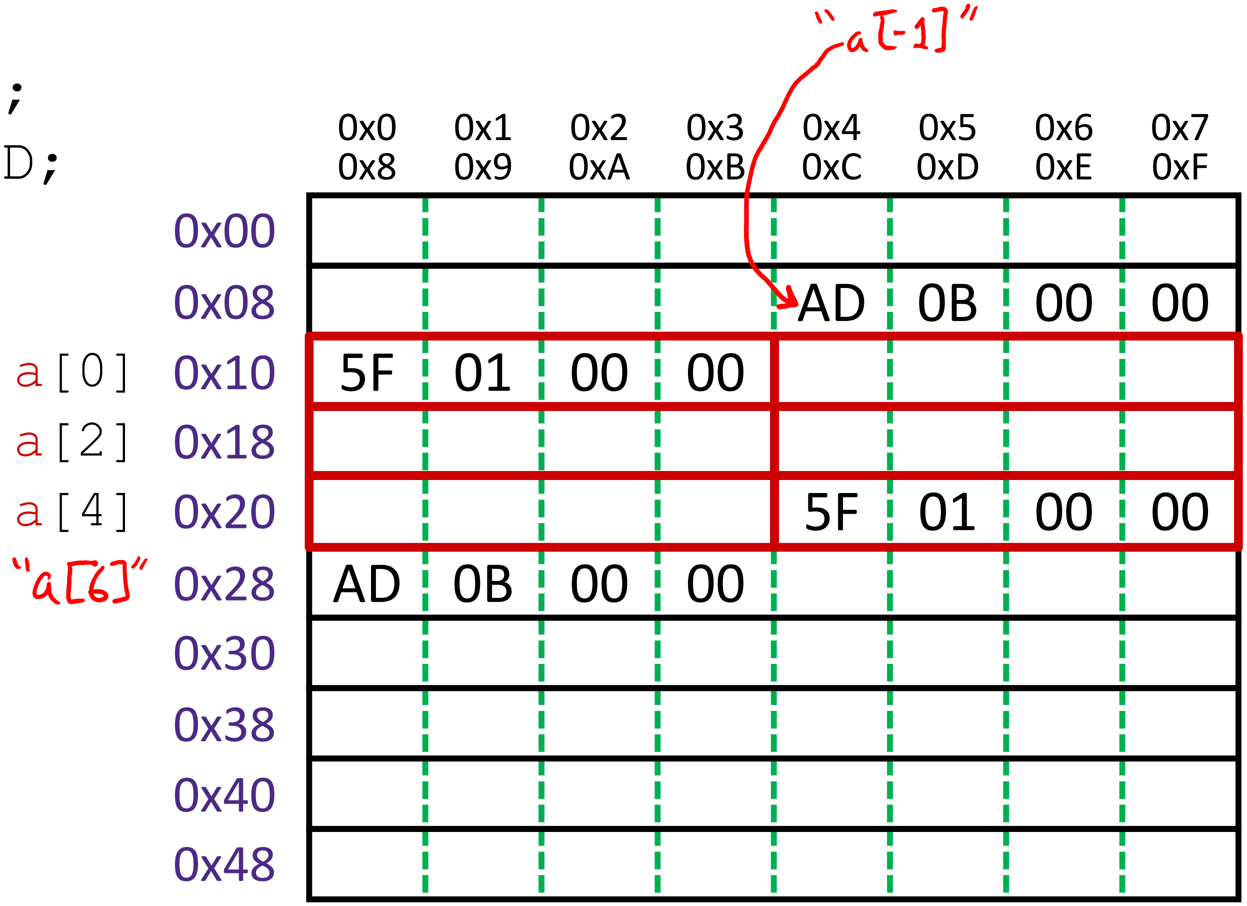
a (array name) returns the array's address

&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;



		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

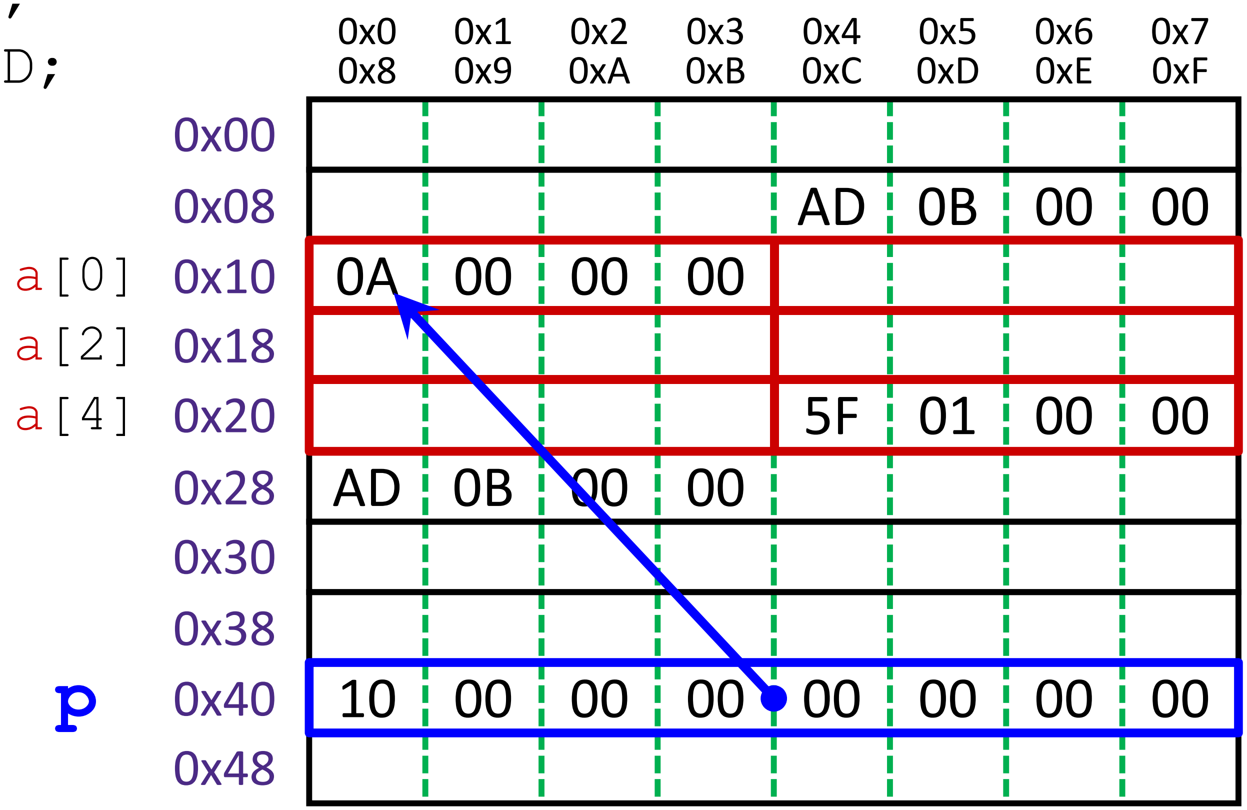
Declaration: `int a[6];`

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;`

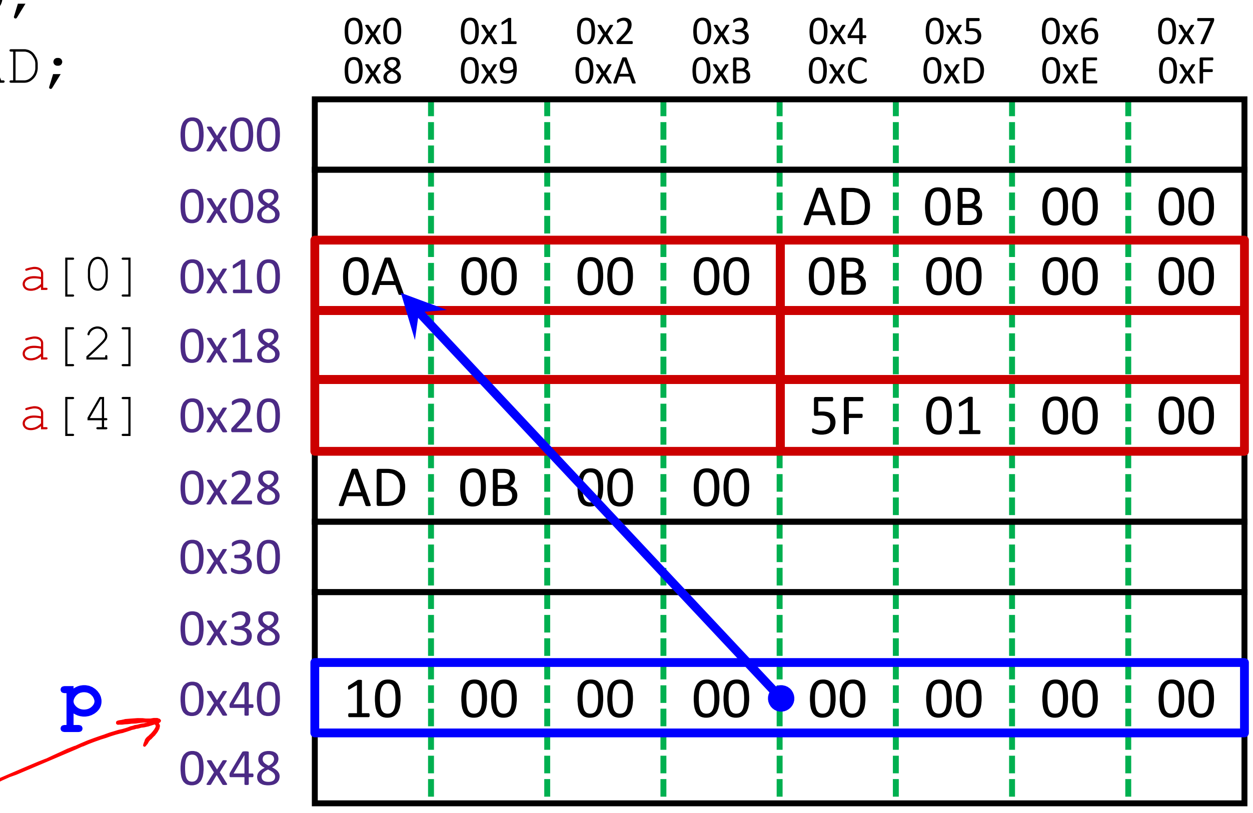
equivalent {
```
p = a;
p = &a[0];
```
}
```
*p = 0xA;
```

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 → 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;`

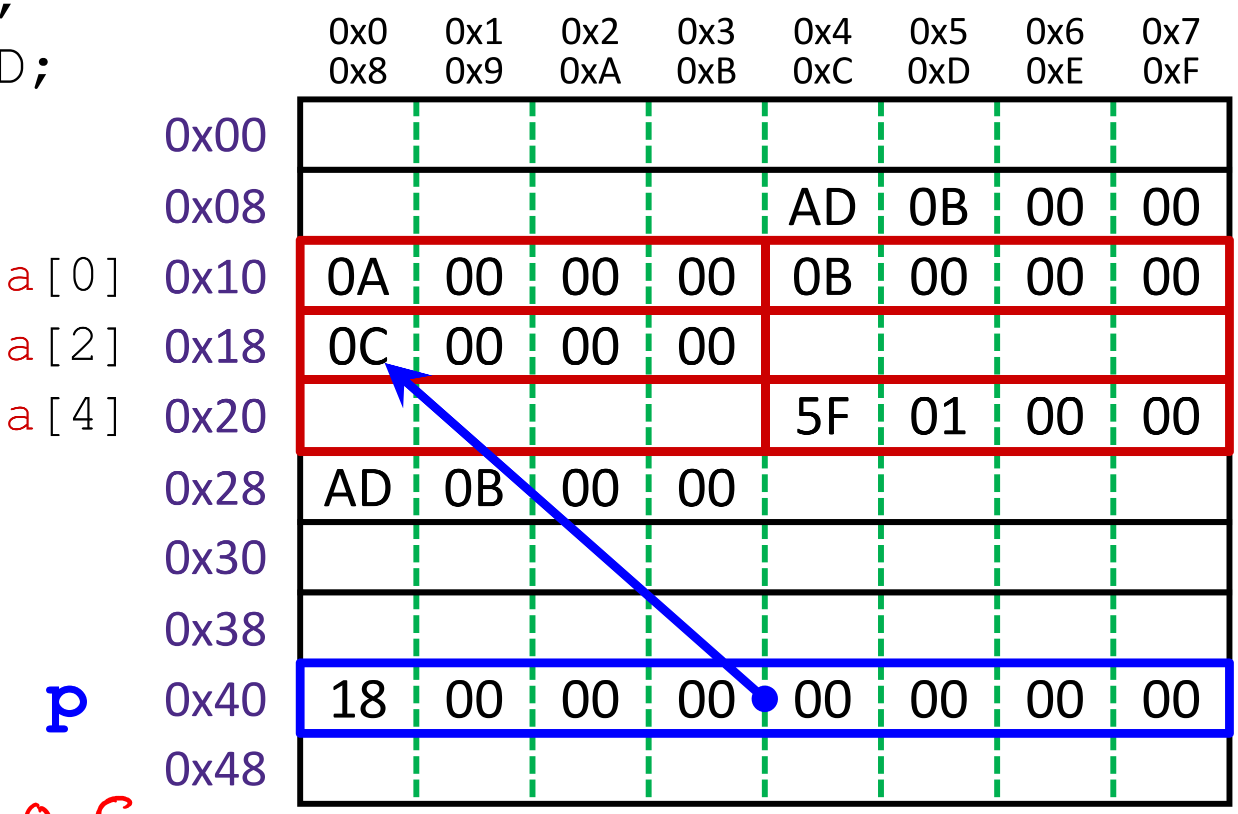
equivalent {
```
p = a;
p = &a[0];
```
}
```
*p = 0xA;
```

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 → 0xB + 1 = 0xC

```
*p = a[1] + 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	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 5?

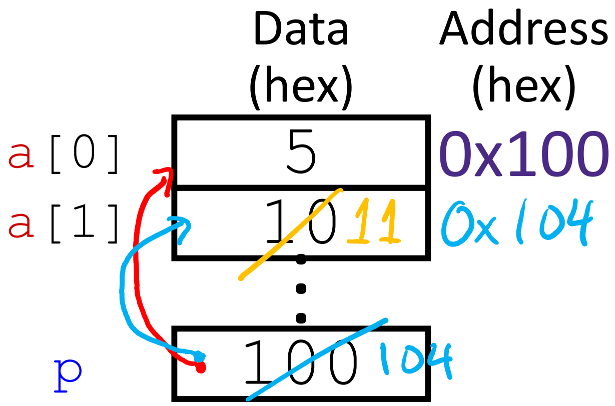
- Vote in Ed Lessons

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

int*

*sizeof(int)

int



	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*`**)
  - 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

- 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")

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

6 characters 1 4 1 1

string literal: "Please vote!" uses 13 bytes
(double quotes)

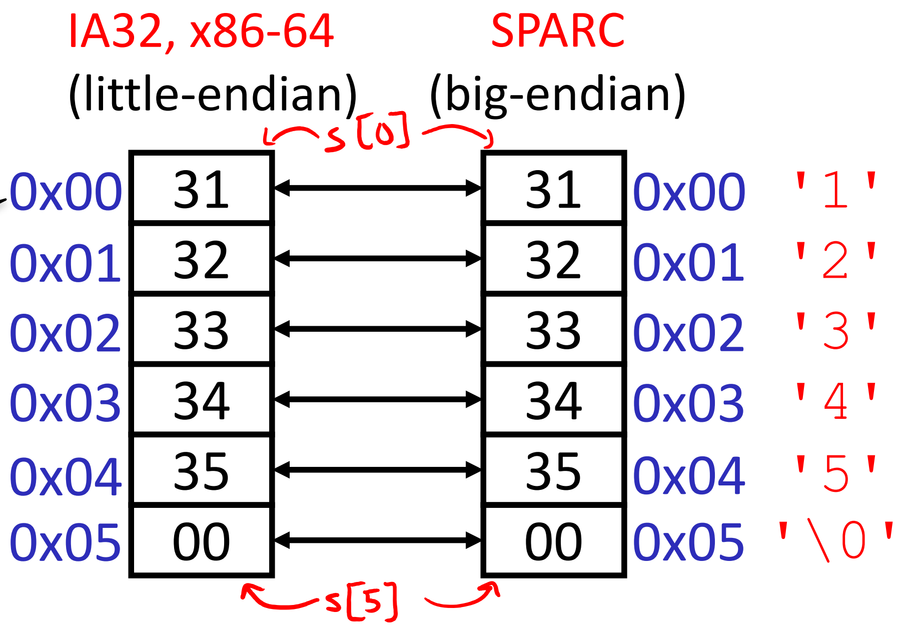
Endianness and Strings

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
  - 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");
}
```

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)