Memory, Data, & Addressing II

CSE 351 Autumn 2022

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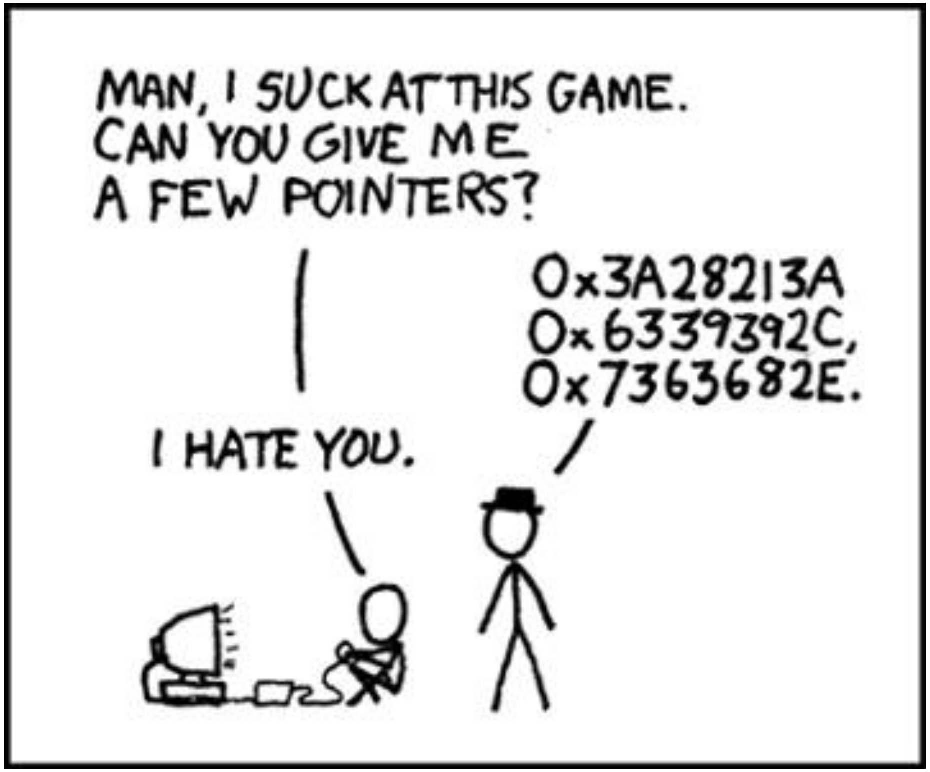

MAN, I SUCK AT THIS GAME. CAN YOU GIVE ME A FEW POINTERS?
0x3A28213A 0x6339392C, 0x7363682E.
I HATE YOU.

http://xkcd.com/138/

Relevant Course Information

- Lab 0 due today @ 11:59 pm
  - *You will revisit the concepts from this program in future labs!*
- hw2 due Wednesday, hw3 due Friday
  - Autograded, unlimited tries, no late submissions
- Lab 1a released today, due next Monday (10/10)
  - 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

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 10% 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];
  ```

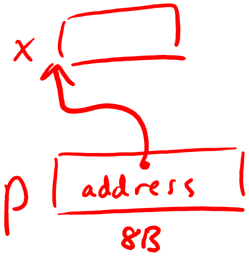
- How much space does the variable p take up?

  A. 1 byte

  B. 2 bytes

  C. 4 bytes

  [✓ D. 8 bytes]



- Which of the following expressions evaluate to an address?

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

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

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

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

  E. $ar[1] \rightarrow \text{int}$

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

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 "mystery data")
- `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 “mystery data”)
- `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)

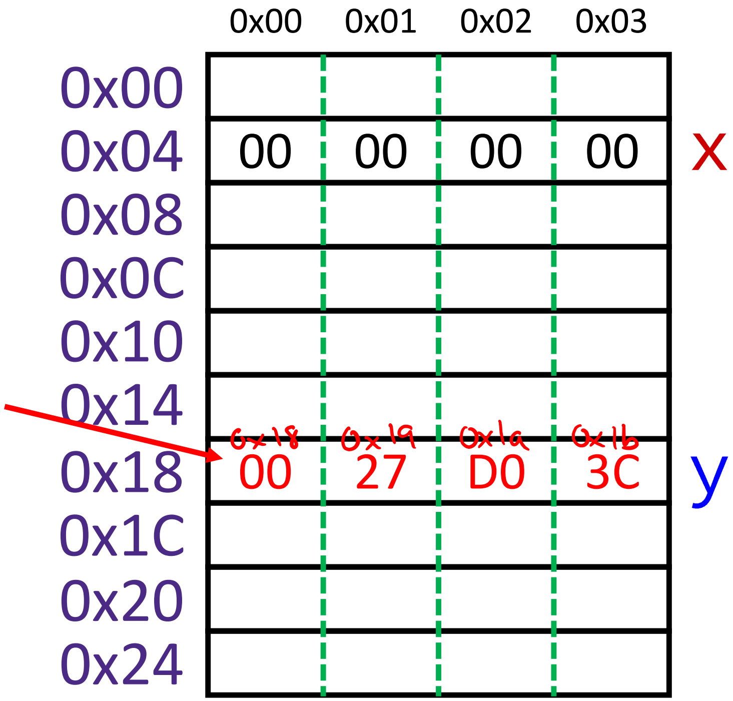
& = "address of"
* = "dereference"

- 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!



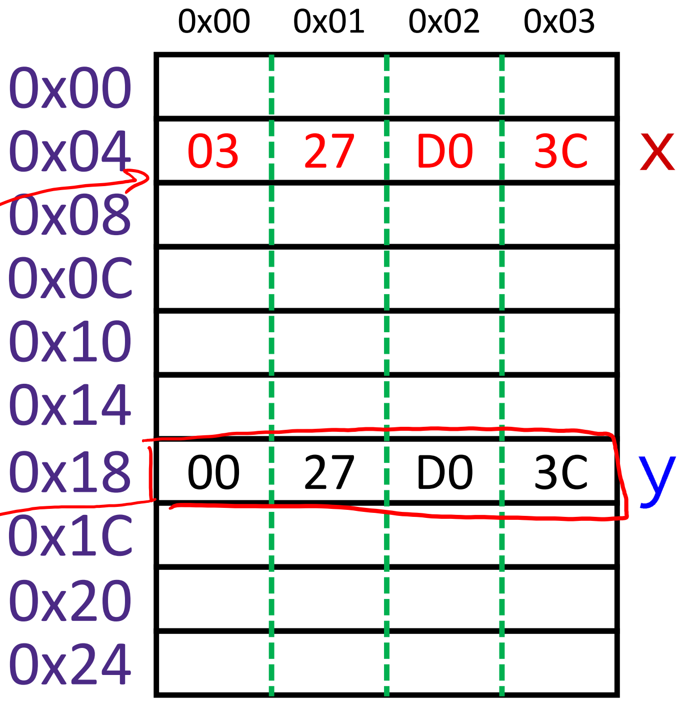
	0x00	0x01	0x02	0x03	
0x00					
0x04	00	00	00	00	x
0x08					
0x0C					
0x10					
0x14					
0x18	0x18 00	0x19 27	0x1a D0	0x1b 3C	y
0x1C					
0x20					
0x24					

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



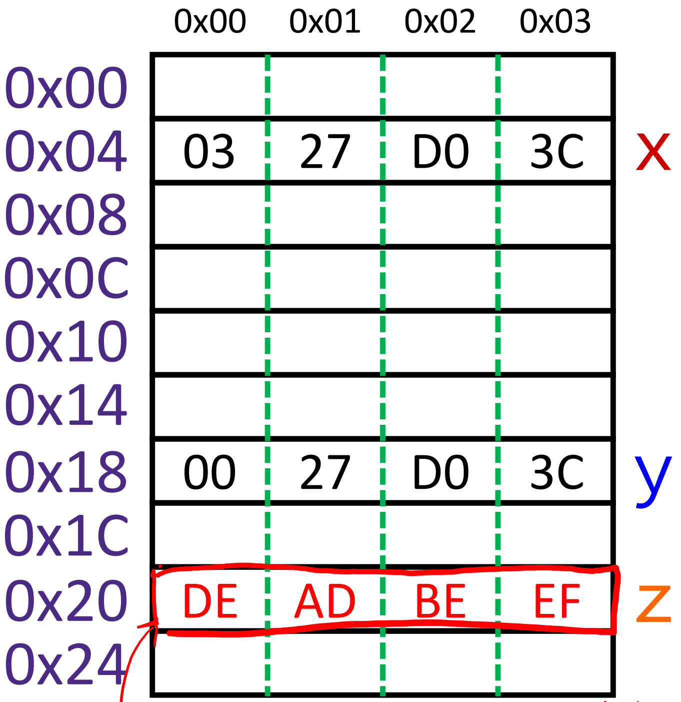
	0x00	0x01	0x02	0x03	
0x00					
0x04	03	27	D0	3C	x
0x08					
0x0C					
0x10					
0x14					
0x18	00	27	D0	3C	y
0x1C					
0x20					
0x24					

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! ("mystery data")

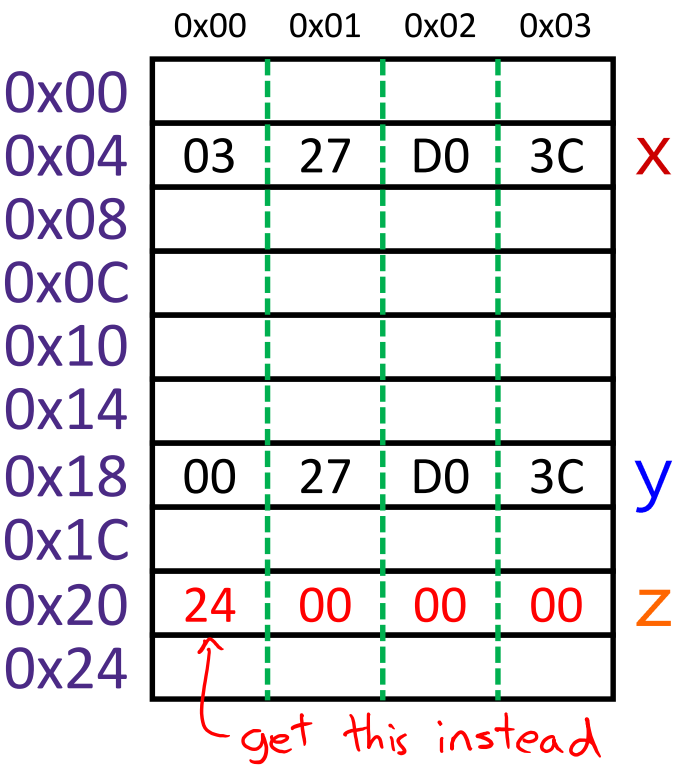
Assignment in C

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
  - 0x18 (above `&y`)
  - 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					

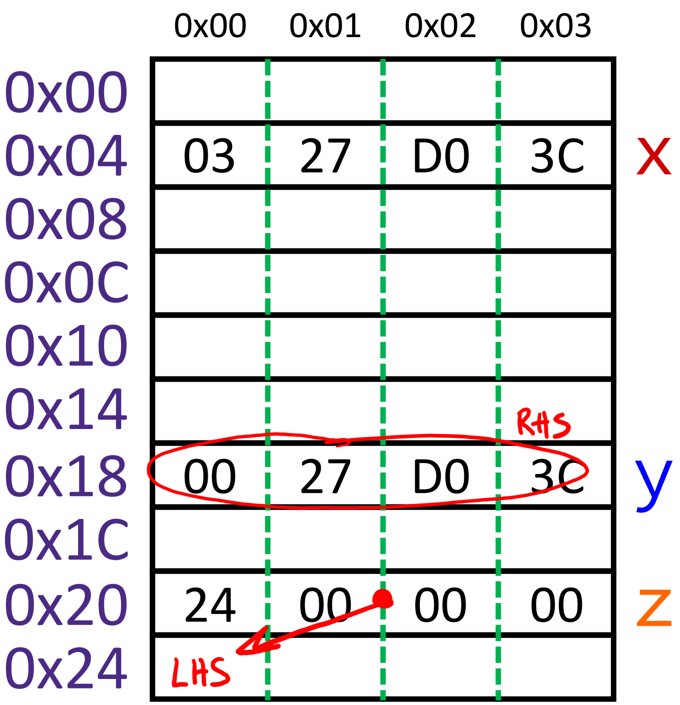
(scale by sizeof(int)=4)

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

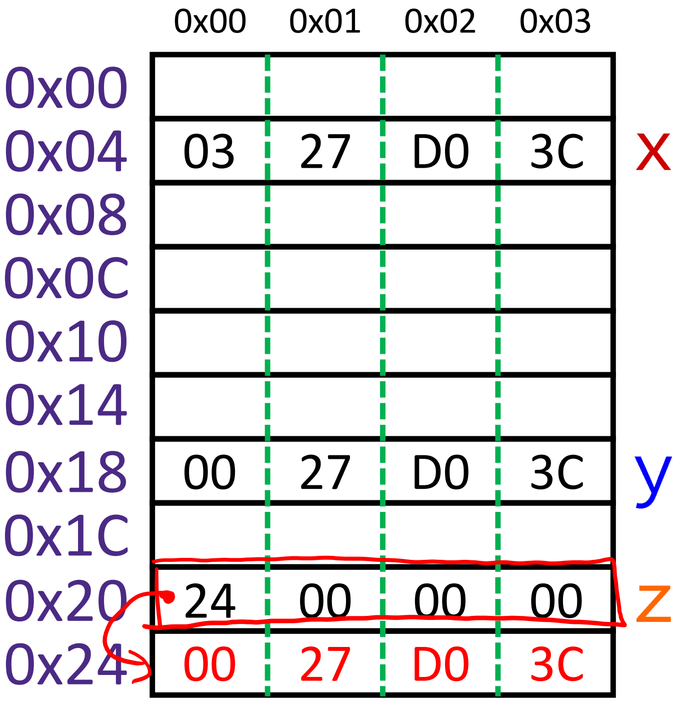
32-bit example
(pointers are 32-bits wide)

& = "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	

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

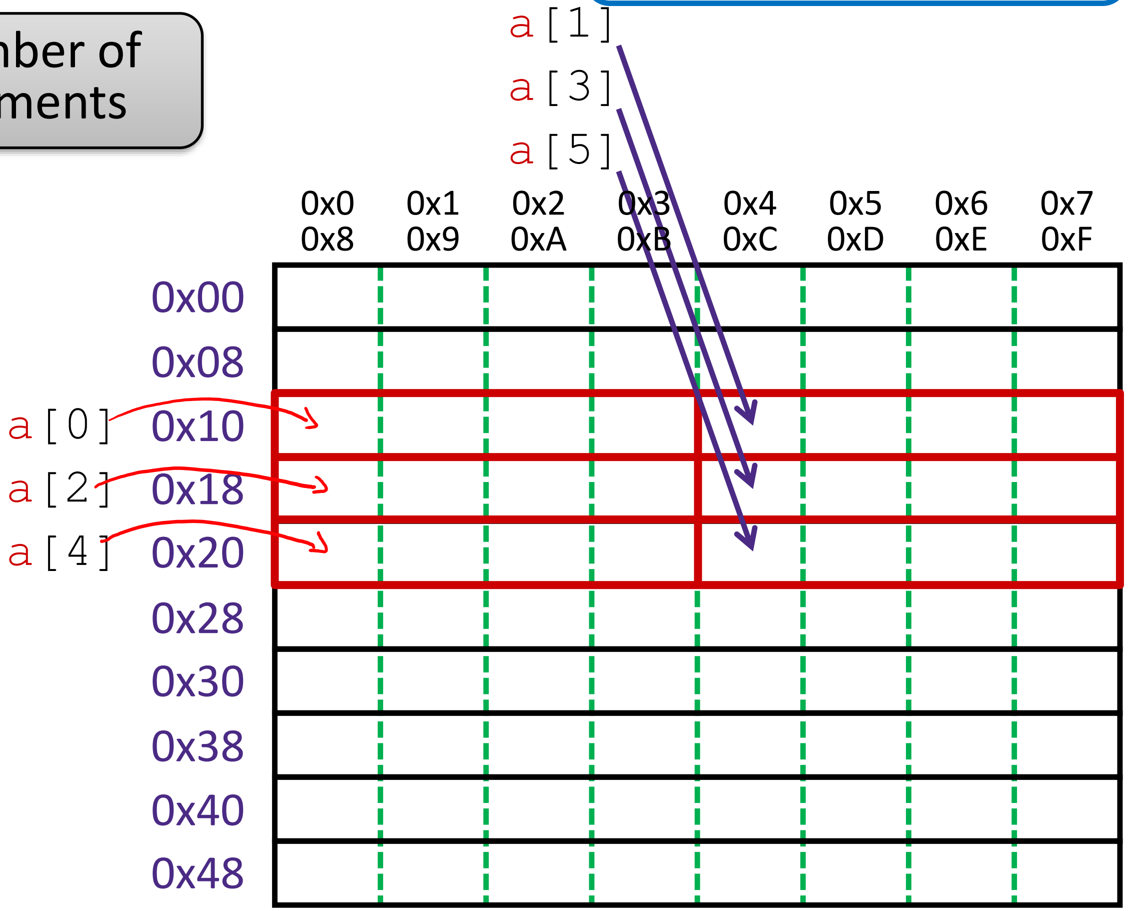
Declaration: `int a[6];` // &a is 0x10

element type

name

number of elements

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



Arrays in C

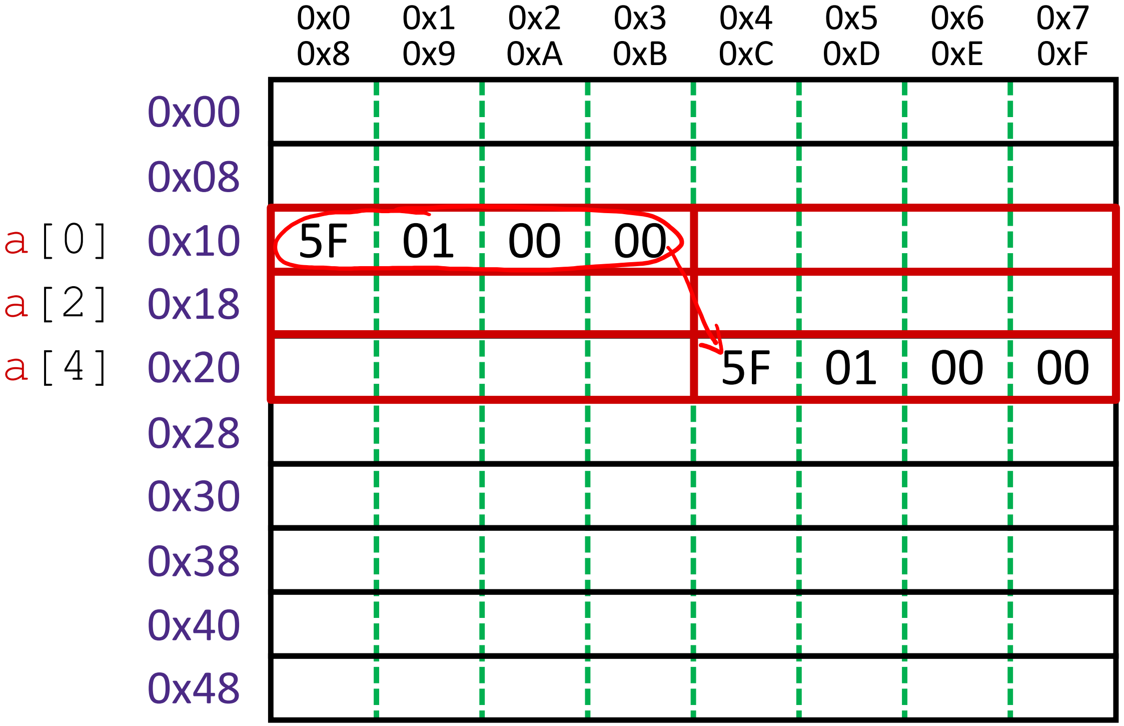
Arrays are adjacent locations in memory storing the same type of data object

`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;
```

"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

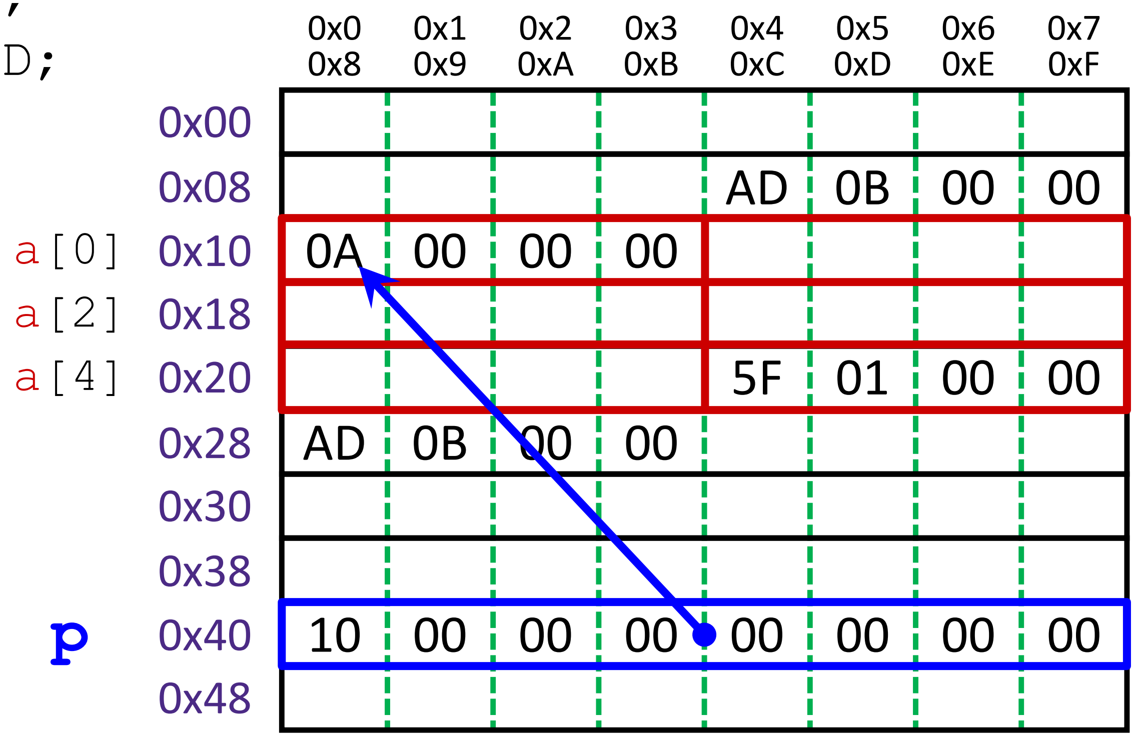
&a[i] is the address of a[0] plus i times the element size in bytes

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;`

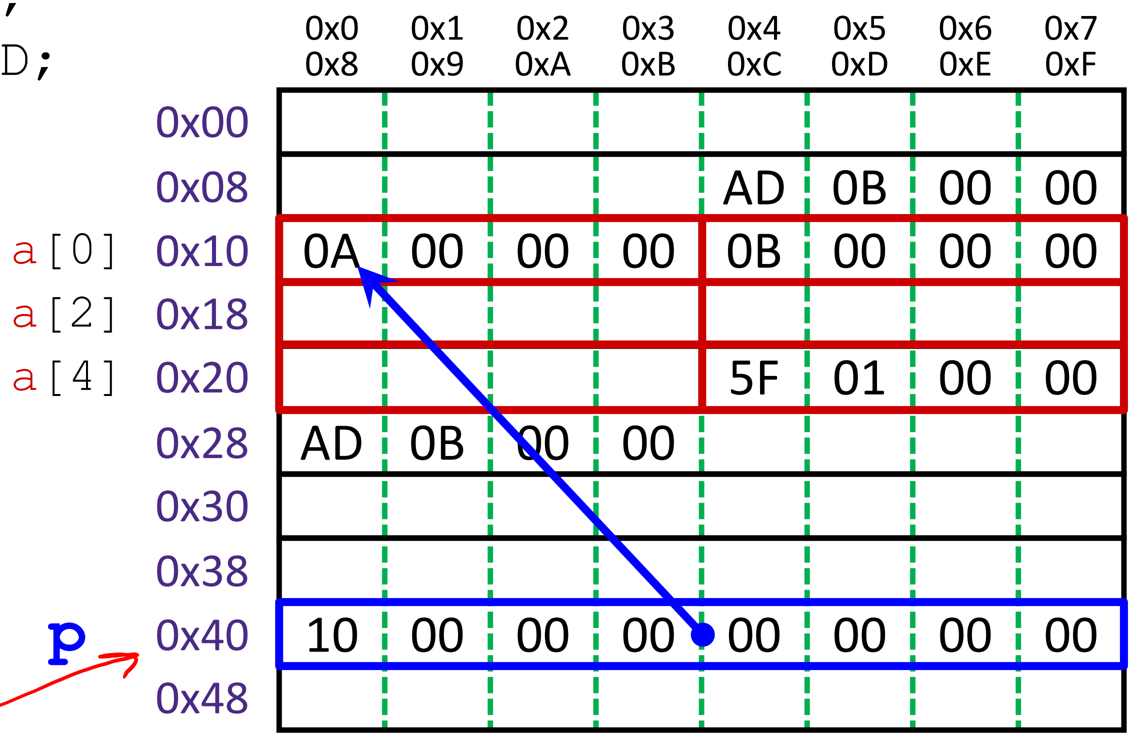
equivalent {
```
p = a;
p = &a[0];
```
}
```
*p = 0xA;
```

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 → 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;
```

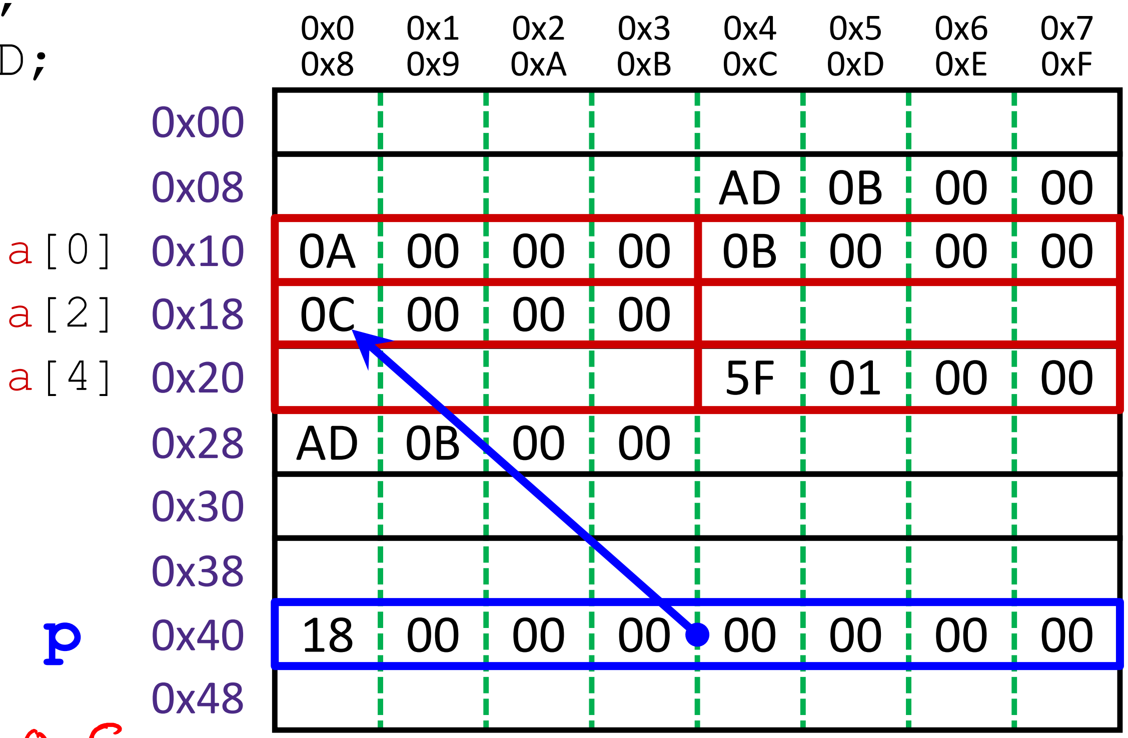
```
p = p + 2;
```

store at 0x18 →

0xB + 1 = 0xC

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

(no pointer arithmetic)



		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								

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

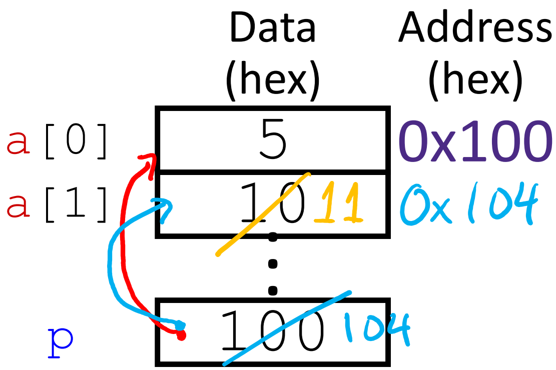
- Vote in Ed Lessons

```
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 (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

ASCII: American Standard Code for Information Interchange

in C, use single quotes:

char c = '3';

↑ gets the value 51

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	116	97	121	32	115	97	102	101	32	87	65	0
Hex:	0x53	0x74	0x61	0x79	0x20	0x73	0x61	0x66	0x65	0x20	0x57	0x41	0x00
Text:	'S'	't'	'a'	'y'	' '	's'	'a'	'f'	'e'	' '	'W'	'A'	'\0'
	4 characters				1	4				1	2		1

string literal: "Stay safe WA" uses 13 bytes
(double quotes)

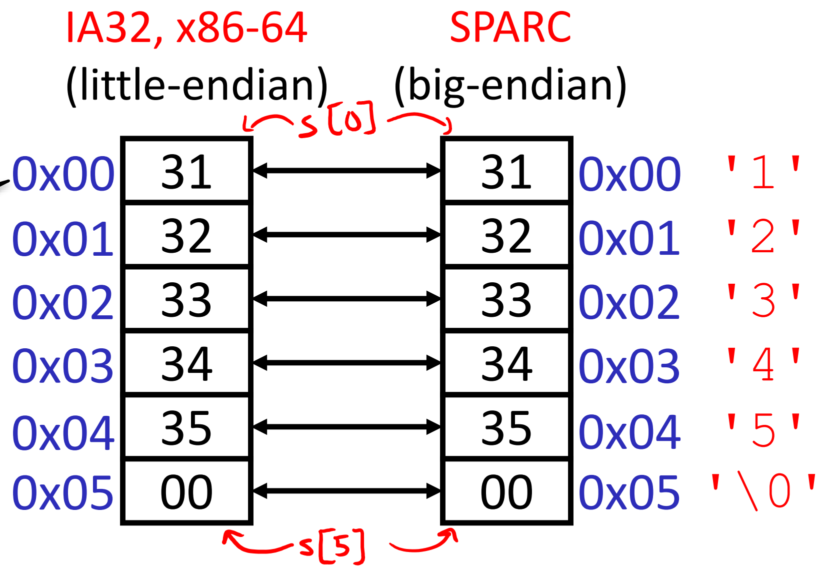
Endianness and Strings

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

- 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)