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
   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 7 bits, the address space is how many bytes? $2^7 = 128$ B

Memory, Data, & Addressing II

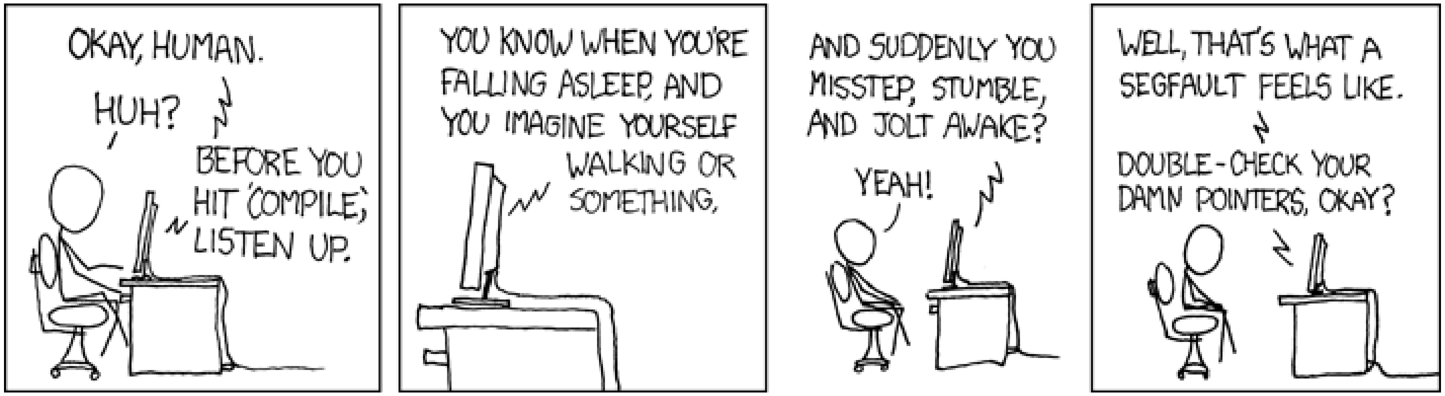
CSE 351 Autumn 2016

Instructor:

Justin Hsia

Teaching Assistants:

Chris Ma
Hunter Zahn
John Kaltenbach
Kevin Bi
Sachin Mehta
Suraj Bhat
Thomas Neuman
Waylon Huang
Xi Liu
Yufang Sun



http://xkcd.com/371/

Administrivia

- Lab 0 due today @ 5pm
  - Credit/no credit – we'll talk about topics in depth later
- Lab 1 released tomorrow @ 6pm
  - Some progress due Monday 10/10, Lab 1 due Friday 10/14
- Survey results:
  - Hoping to get out
    - Linux/Unix, C, Assembly
    - How a computer works
  - Concerns
    - Fast-paced & course load
    - Having little background in this area
    - Not familiar with C or Linux

Memory, Data, and Addressing

- Representing information as bits and bytes
- Organizing and addressing data in memory
- Manipulating data in memory using C
- Boolean algebra and bit-level manipulations

Addresses and Pointers in C

`*` is also used with variable declarations

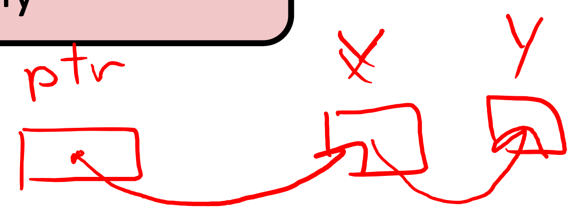
- `&` = "address of" operator
- `*` = "value at address" or "dereference" operator

```
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 sets 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)` ?

Assignment in C

- A variable is represented by a memory location
- Declaration ≠ initialization (initially holds "garbage")
- `int x, y;`
  - `x` is at address 0x04, `y` is at 0x18

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

Assignment in C

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

- A variable is represented by a memory location
- Declaration ≠ initialization (initially holds "garbage")
- `int x, y;`
  - `x` is at address 0x04, `y` is at 0x18

0x00	0x01	0x02	0x03		
				0x00	
00	01	29	F3	0x04	x
				0x08	
				0x0C	
				0x10	
				0x14	
01	00	00	00	0x18	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 memory *location*
  - RHS must evaluate to a *value* (could be an address)
  - Store RHS value at LHS location
- `int x, y;`
- `x = 0;`

0x00	0x01	0x02	0x03		
				0x00	
00	00	00	00	0x04	x
				0x08	
				0x0C	
				0x10	
				0x14	
01	00	00	00	0x18	y
				0x1C	
				0x20	
				0x24	

Assignment in C

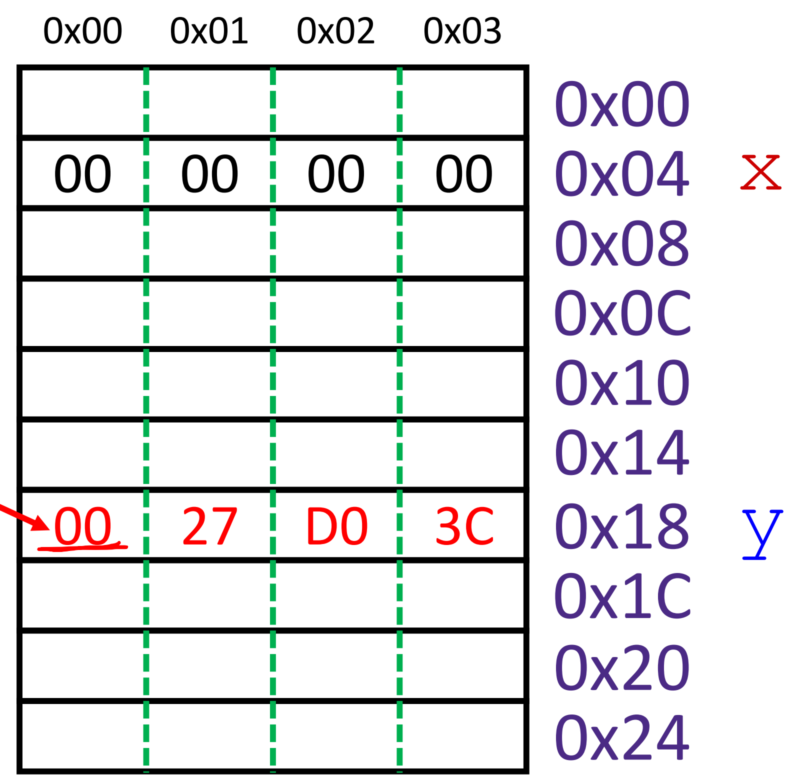
32-bit example
(pointers are 32-bits wide)

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

- left-hand side = right-hand side;
  - LHS must evaluate to a memory *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

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

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

- left-hand side = right-hand side;
  - LHS must evaluate to a memory *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	Address	Variable
				0x00	
03	27	D0	3C	0x04	x
				0x08	
				0x0C	
				0x10	
				0x14	
00	27	D0	3C	0x18	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 memory *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

0x00	0x01	0x02	0x03	Address	Variable
				0x00	
03	27	D0	3C	0x04	x
				0x08	
				0x0C	
				0x10	
				0x14	
00	27	D0	3C	0x18	y
				0x1C	
DE	AD	BE	EF	0x20	z
				0x24	

Assignment in C

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(pointers are 32-bits wide)

`&` = "address of"
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- left-hand side = right-hand side;
  - LHS must evaluate to a memory *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

	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					

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*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	
	03	27	D0	3C	0x04	x
					0x08	
					0x0C	
					0x10	
					0x14	
	00	27	D0	3C	0x18	y
					0x1C	
	24	00	00	00	0x20	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 memory location

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

0x00000024

Arrays in C

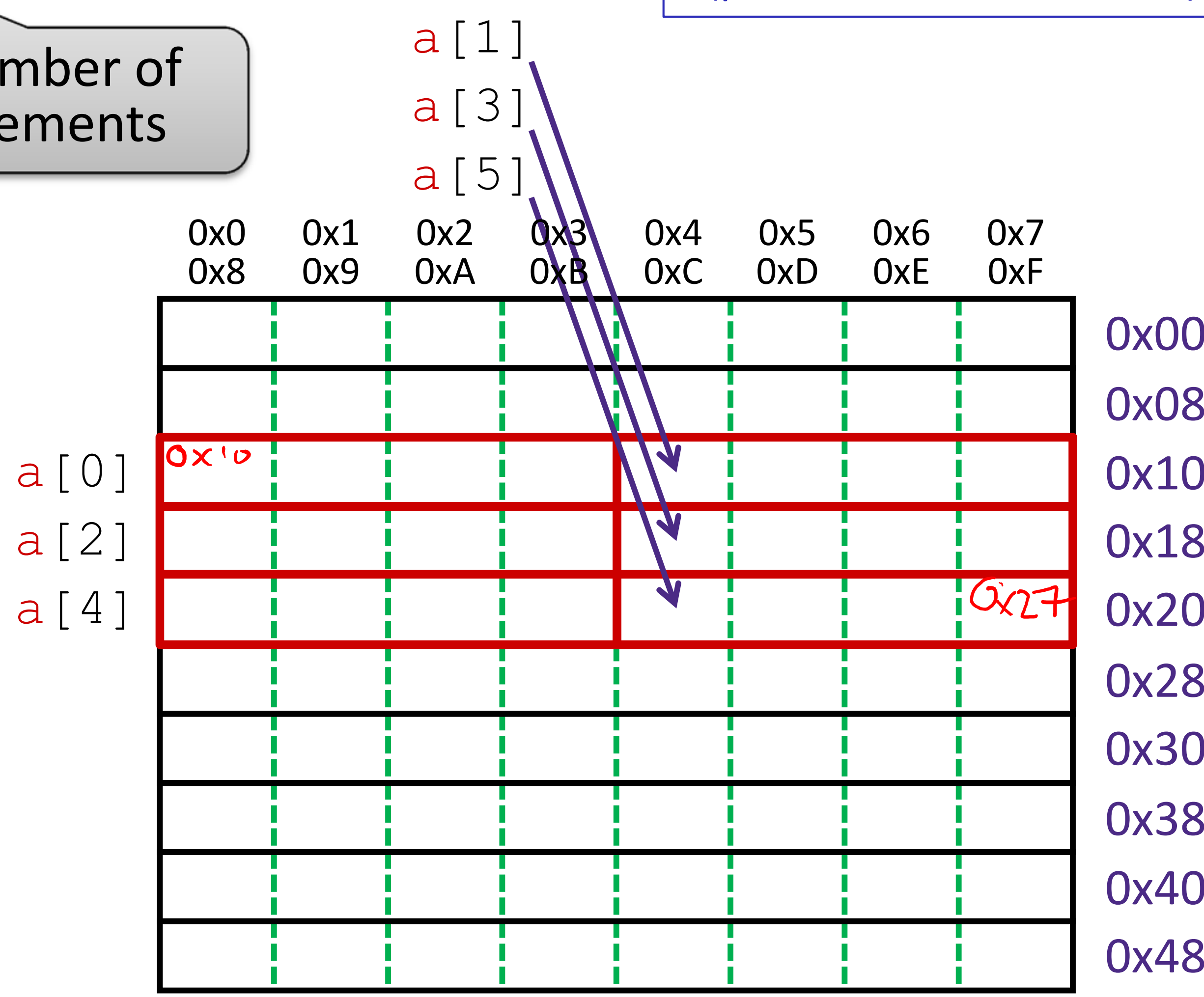
Arrays are adjacent locations in memory storing the same type of data object

a is a name for the array's address

Declaration: `int a[6];`

element type — name — number of elements

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



Arrays in C

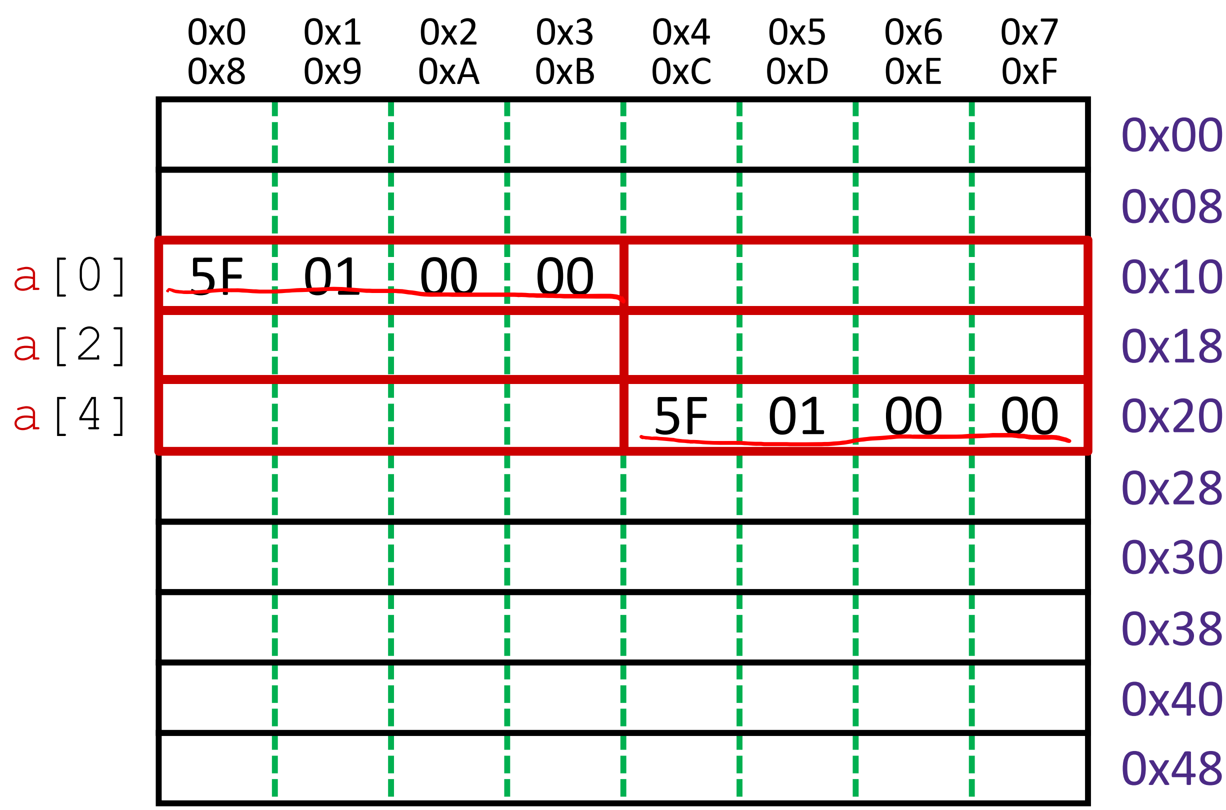
Arrays are adjacent locations in memory storing the same type of data object

`a` is a name for the array's address

The address of `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];
```



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```
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
					AD	0B	00	00	0x08
a[0]	5F	01	00	00					0x10
a[2]									0x18
a[4]					5F	01	00	00	0x20
	AD	0B	00	00					0x28
									0x30
									0x38
									0x40
									0x48

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Declaration: `int a[6];`

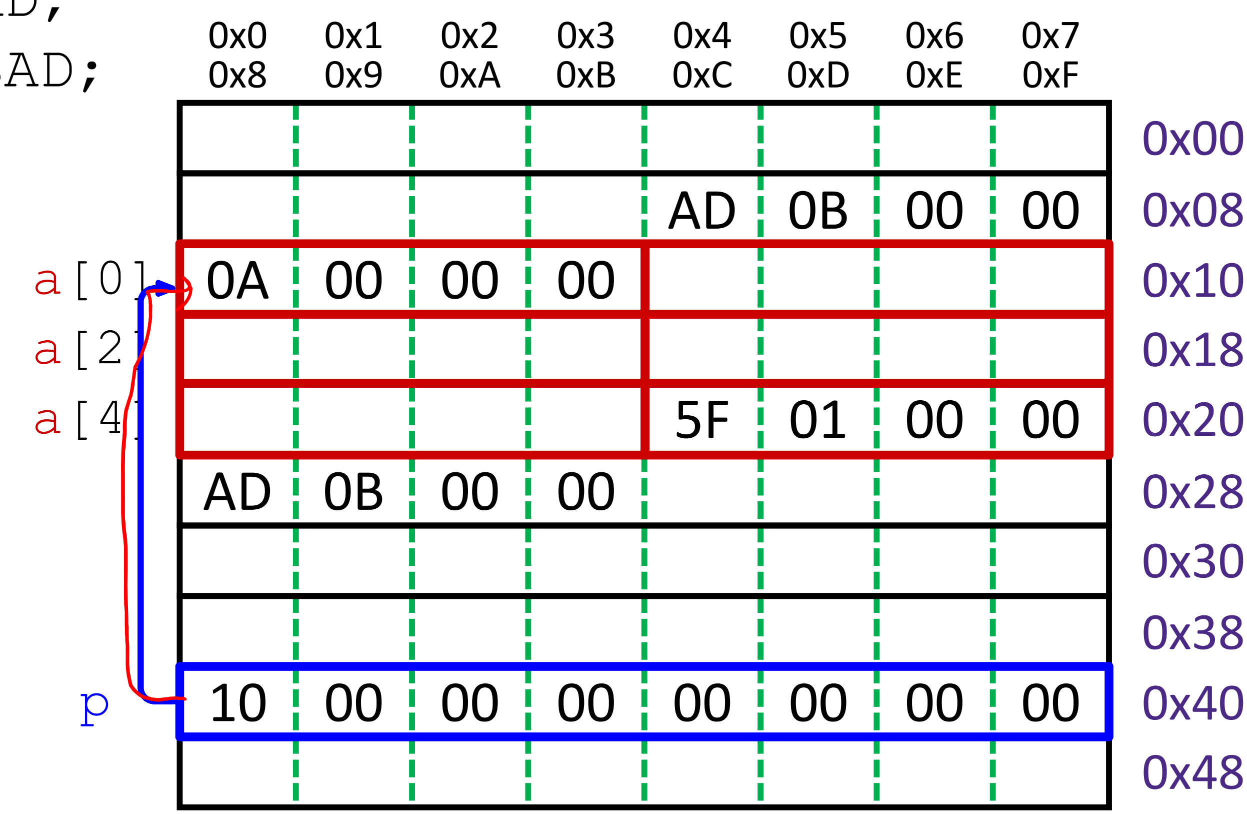
Indexing:
```
a[0] = 0x015f;
a[5] = a[0];
```

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

Pointers: `int* p;`

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

0x00 00 00 0A



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```
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```

Pointers:
```
int* p;
```

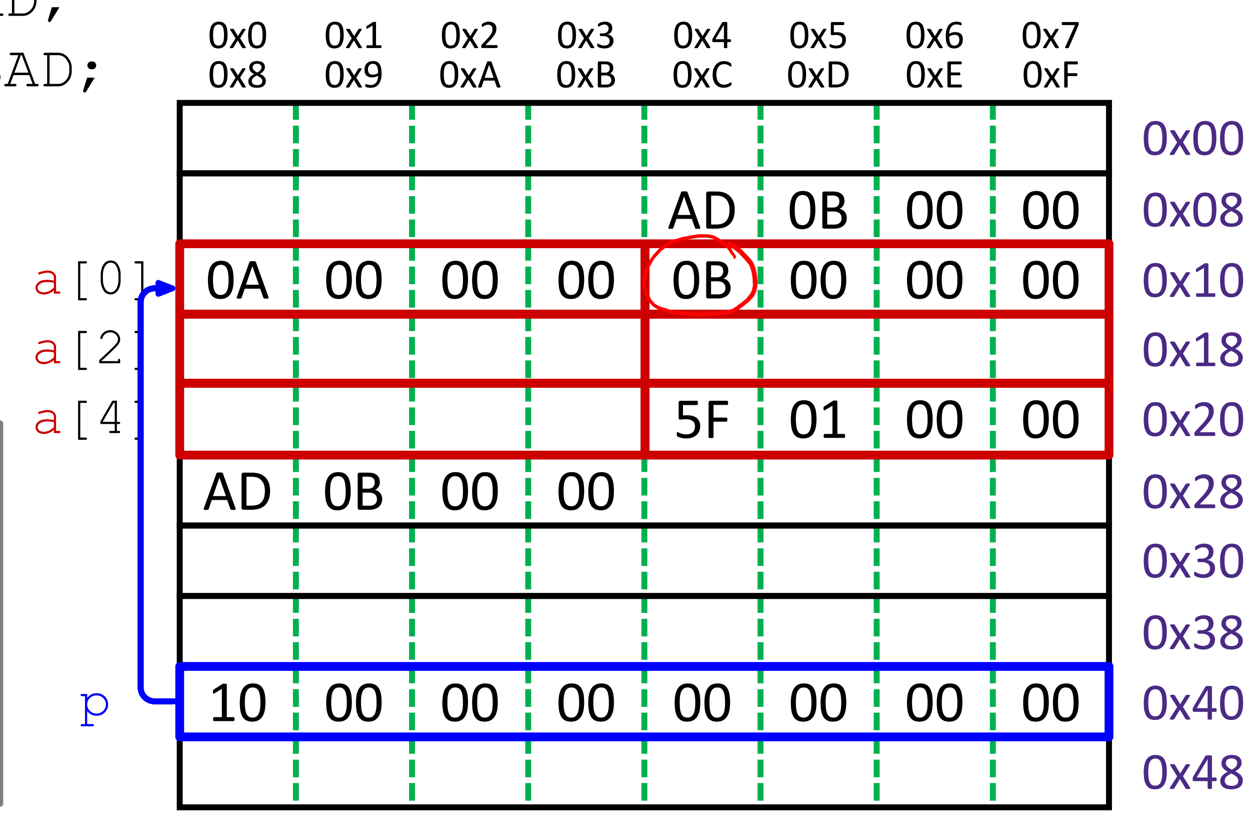
equivalent {
```
p = a;
p = &a[0];
```
}

```
*p = 0xA;
```

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

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

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



Arrays in C

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

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

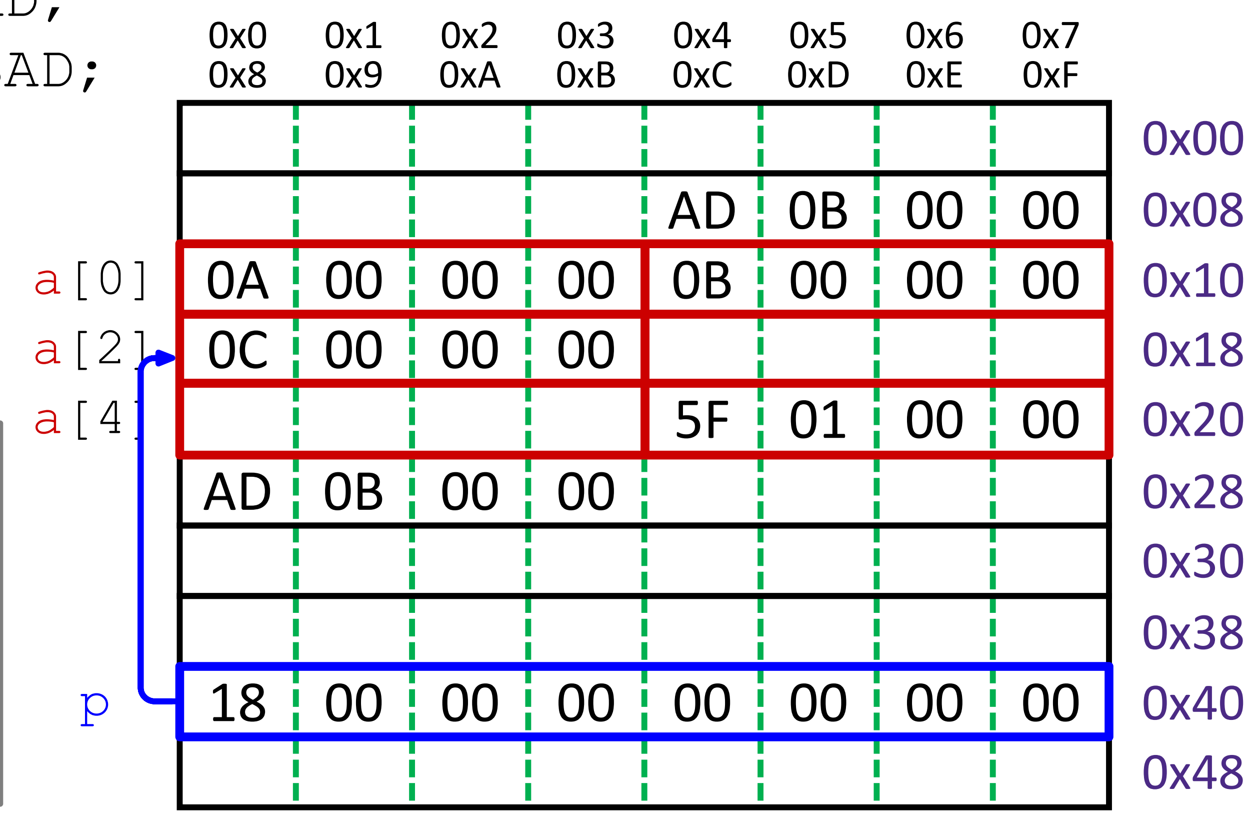
Pointers: `int* p;`

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;
```



http://PollEv.com/justinh

Question: The variable values after Line 3 executes are shown on the right. What are they after Line 4 & 5?

```
1   void main() {
2       int a[] = {5,10};
3       int *p = a;
4       p = p + 1;
5       *p = *p + 1;
6   }
```

	Data (decimal)	Address (decimal)
a[0]	5	100
a[1]	10	
⋮		
p	100	

	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

- **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

- 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";
```

String literal

0x31 = 49 decimal = ASCII ‘1’

Address	IA32, x86-64 (little endian)	SPARC (big endian)	Address	Char
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
- Unicode characters – up to 4 bytes/character
  - ASCII codes still work (just add leading zeros)
  - Unicode can support the many characters in all languages in the world
  - Java and C have libraries for Unicode (Java commonly uses 2 bytes/char)

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

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`
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```
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   int i;
   for (i = 0; i < len; i++)
      printf("%p\t0x%.2x\n", start+i, *(start+i));
   printf("\n");
}
```

```
void show_int(int x) {
   show_bytes( (char *) &x, sizeof(int));
}
```

show_bytes Execution Example

```
int a = 12345; // 0x00003039
printf("int a = 12345;\n");
show_int(a);  // show_bytes((char *) &a, sizeof(int));
```

- Result (Linux x86-64):
  - **Note:** The addresses will change on each run (try it!), but fall in same general range

```
int a = 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)