
ALIENWARE
ALIENWARE
51Wh
Standard

Logistics

- Assignment 1 has been released
  - Need to complete Lab 0 to be able to access

- Complete Lab 0 (ASAP!)
  - deadline Sep 13
  - Need it before we can grade anything
  - Need it for assigning midterm slot

- SFU has informed that classes will not be recorded.
  - Class slides will be available as Class.pptx on syllabus page at the end of lecture day (i.e, if you are sick please follow BCCDC instructions)

Abstraction

The process of removing details or attributes in the study of systems to focus attention on details of greater importance.

Great Idea #1: Abstraction (Levels of Representation/Interpretation)

Python Program

```
def square(num):
    return num * num
```

C Program

```
int square(int num) {
return num * num;
}
```

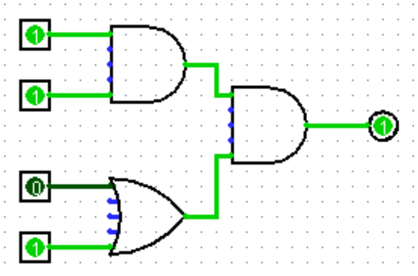
Binary

0x00000317
0x00830067
0xff010113
0x00112623
0x00812423
0x01010413
0xfea42a23
....

Assembly

```
square(int):
        addi    sp, sp, -16
        sw      ra, 12(sp)
        sw      s0, 8(sp)
        addi    s0, sp, 16
        sw      a0, -12(s0)
        lw      a0, -12(s0)
        mul     a0, a0, a0
        lw      s0, 8(sp)
        lw      ra, 12(sp)
        addi    sp, sp, 16
        ret
```

Logic



Great Idea #2: Performance Cost of Abstraction

- c = (a + b) OR c = (a + b) + d
- c = a + b OR c = a[i] + b[i]
- c = a[i] + b[i] OR c = a[c[i]] + a[c[i]]

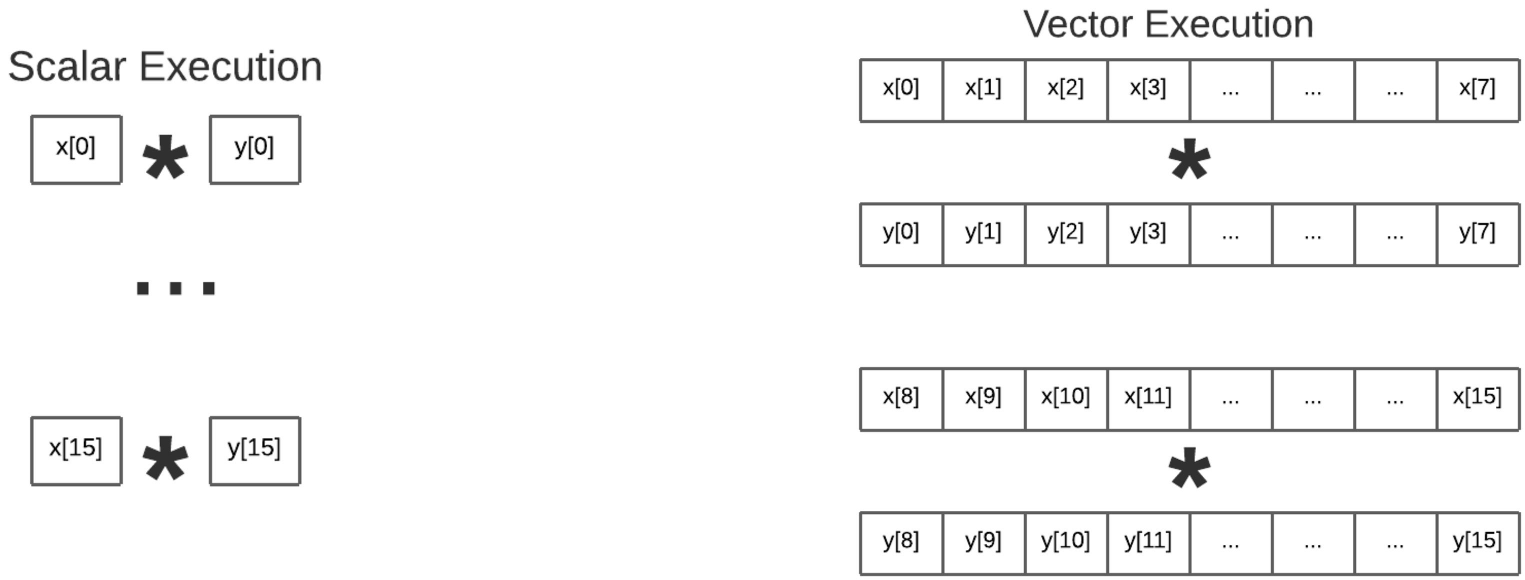
Great Idea #3: Memory Behavior

```
for (i = 0; i < 4; i++) {
  for (j = 0; j < 4; j++) {
      A[i][j]
```

```
for (i = 0; i < 4; i++) {
  for (j = 0; j < 4; j++) {
      A[j][i]
```

Great Idea #4: Parallelism

```
for (i = 0; i < N; i++){
  output[i] = x[i] * y[i];
}
```



Base Comparison

- Why does all of this matter?
  - *Humans* think about numbers in **base 10**, but *computers* “think” about numbers in **base 2**
  - Binary encoding is what allows computers to do all of the amazing things that they do!
- You should have this table memorized by the end of the 1st class
  - Might as well start now!

Base 10	Base 2	Base 16
0	0000	0
1	0001	1
2	0010	2
3	0011	3
4	0100	4
5	0101	5
6	0110	6
7	0111	7
8	1000	8
9	1001	9
10	1010	A
11	1011	B
12	1100	C
13	1101	D
14	1110	E
15	1111	F

Numerical Encoding

- **AMAZING FACT: You can represent *anything* countable using numbers!**
  - Need to agree on an encoding
  - Kind of like learning a new language

- Examples:
  - Decimal Integers: 0→0b0, 1→0b1, 2→0b10, etc.
  - English Letters: CSE→0x435345, yay→0x796179
  - Emoticons: 😃 0x0, 😞 0x1, 😎 0x2, 😇 0x3, 😈 0x4, 🙋 0x5

Memory, Data, & Addressing I

Binary Encoding Additional Details

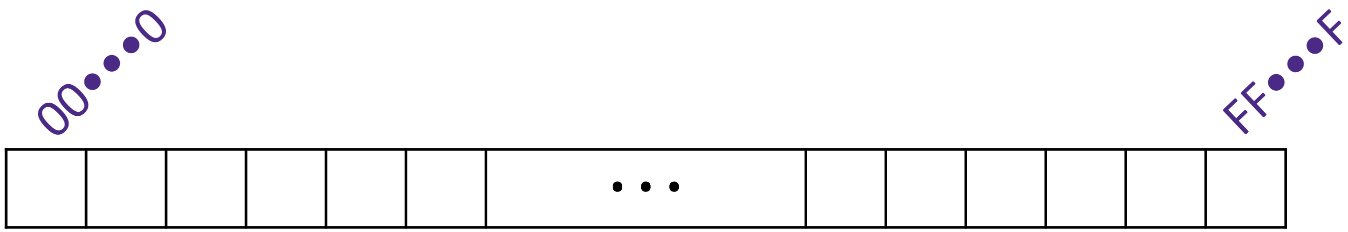
- Because storage is finite in reality, everything is stored as “fixed” length
  - Data is moved and manipulated in fixed-length chunks
  - Multiple fixed lengths (*e.g.* 1 byte, 4 bytes, 8 bytes)
  - Leading zeros now *must* be included up to “fill out” the fixed length

- Example: the “eight-bit” representation of the number 4 is 0b00000100

Least Significant Bit (LSB)

Most Significant Bit (MSB)

Byte-Oriented Memory Organization



- Conceptually, memory is a single, large array of bytes, each with a unique *address* (index)
  - **Each address is just a number represented in *fixed-length* binary**
- Programs refer to bytes in memory by their *addresses*
  - Domain of possible addresses = *address space*
  - **Pointer: We can store addresses as data to "remember" where other data is in memory**

- But not all values fit in a single byte… (*e.g.* 295)
  - Many operations actually use multi-byte values

Peer Instruction Question

- If we choose to use 4-bit addresses, how big is our address space?
  - *i.e.* How much space can we "refer to" using our addresses?

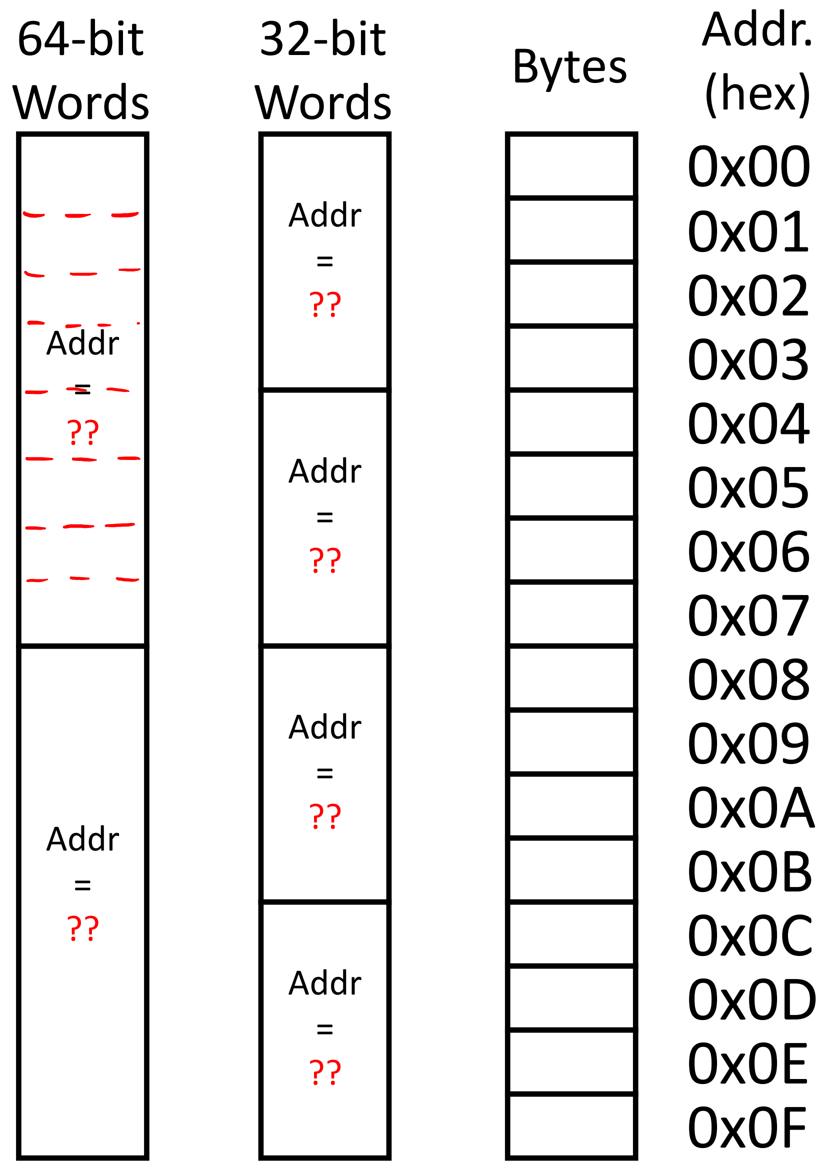
A. 16 bits
B. 16 bytes
C. 4 bits
D. 4 bytes
E. We're lost…

Machine "Words"

- We have *chosen* to tie word size to address size/width
  - word size = address size = register size
  - word size = w bits → 2^w addresses
- Current x86 systems use **64-bit (8-byte) words**
  - Potential address space: $\mathbf{2^{64}}$ addresses
    2^{64} bytes ≈ **1.8 x 10^{19} bytes**
    = 18 billion billion bytes = 18 EB (exabytes)
  - Actual physical address space: **48 bits**

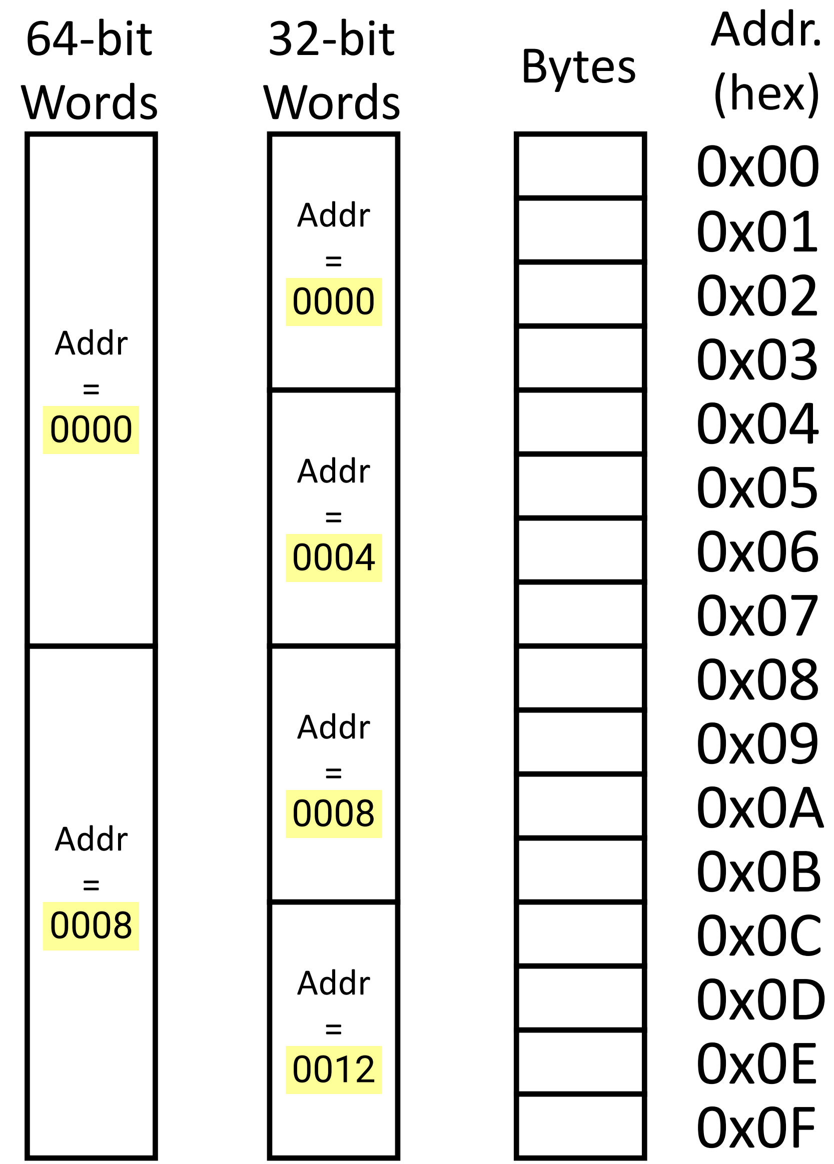
Word-Oriented Memory Organization

- Addresses still specify locations of *bytes* in memory
  - Addresses of successive words differ by word size (in bytes): *e.g.* 4 (32-bit) or 8 (64-bit)
  - Address of word 0, 1, ... 10?



Word-Oriented Memory Organization

- Addresses still specify locations of *bytes* in memory
  - Addresses of successive words differ by word size (in bytes): *e.g.* 4 (32-bit) or 8 (64-bit)
  - Address of word 0, 1, … 10?
- Address of word
  = address of *first* byte in word
  - The address of *any* chunk of memory is given by the address of the first byte
  - ***Alignment***



Data Representations

- Sizes of data types (in bytes)

Java Data Type	C Data Type	32-bit	x86-64
boolean	bool	1	1
byte	char	1	1
char		2	2
short	short int	2	2
int	int	4	4
float	float	4	4
	long int	4	8
double	double	8	8
long	long	8	8
	long double	8	16
(reference)	**pointer ***	**4**	**8**

address size = word size

To use "`bool`" in C, you must `#include <stdbool.h>`

Memory Alignment

- **Aligned**: Primitive object of K bytes must have an address that is a multiple of K
  - More about alignment later in the course

K	Type
1	`char`
2	`short`
4	`int, float`
8	`long, double,` pointers

- For good memory system performance, data has to be aligned.

Alignment REPL

- https://replit.com/@ashriram/Alignment#main.cpp

Byte Ordering

- How should bytes within a word be ordered *in memory?*
  - **Example:** store the 4-byte (32-bit) `int`:
    `0x a1 b2 c3 d4`

- By convention, ordering of bytes called *endianness*
  - The two options are big-endian and little-endian
    - In which address does the least significant *byte* go?
    - Based on *Gulliver's Travels*: tribes cut eggs on different sides (big, little)

Byte Ordering

- Big-endian (SPARC, z/Architecture)
  - Least significant byte has highest address
- Little-endian (x86, x86-64, **RISC-V**)
  - Least significant byte has lowest address
- Bi-endian (ARM, PowerPC)
  - Endianness can be specified as big or little

- **Example:** 4-byte data 0xa1b2c3d4 at address 0x100

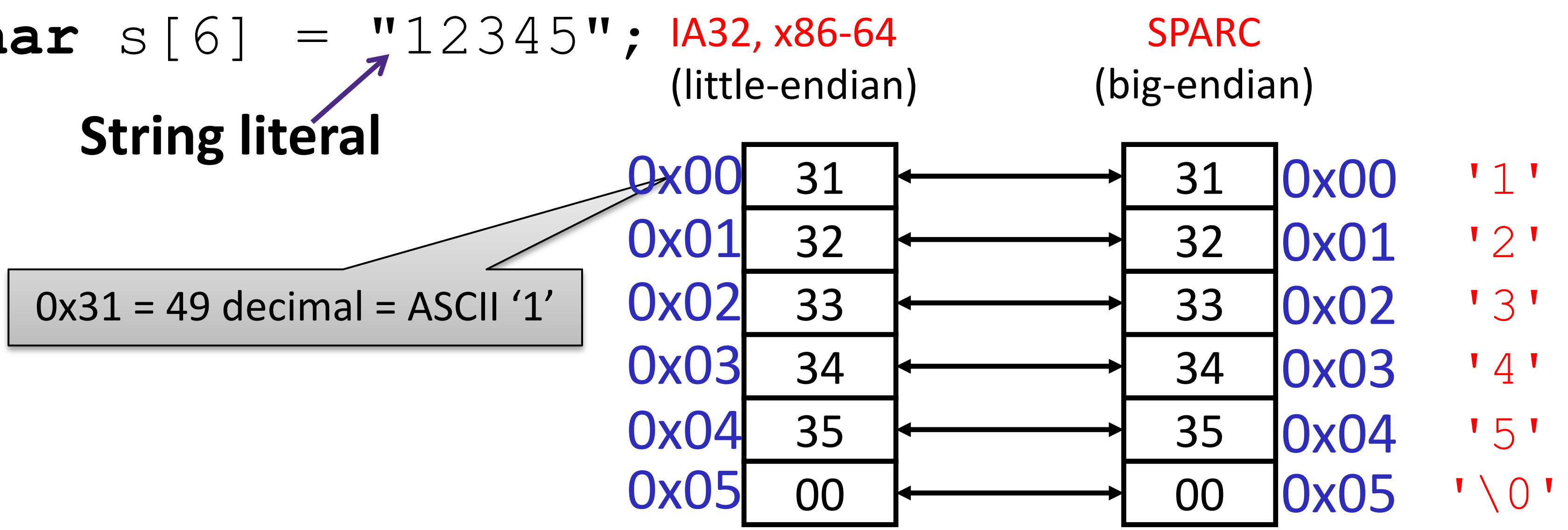
			0x100	0x101	0x102	0x103		
Big-Endian			a1	b2	c3	d4		

			0x100	0x101	0x102	0x103		
Little-Endian			d4	c3	b2	a1		

C (char = 1 byte)

Endianness and Strings

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



- 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

Show bytes demo

https://replit.com/@ashriram/ShowBytes#main.cpp

show_bytes Execution Example

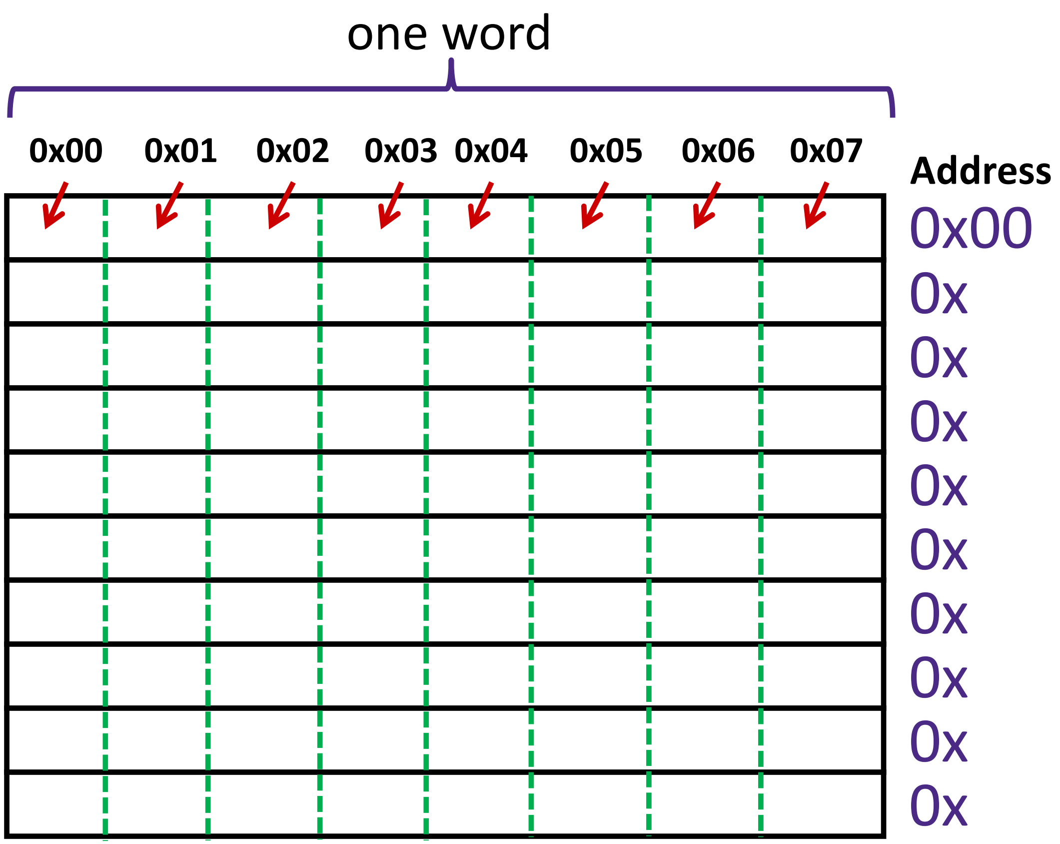
```
int x = 12345; // 0x00003039
printf("int x = %d;\n",x);
show_int(x);  // show_bytes((char *) &x,
sizeof(int));
```

- 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
```

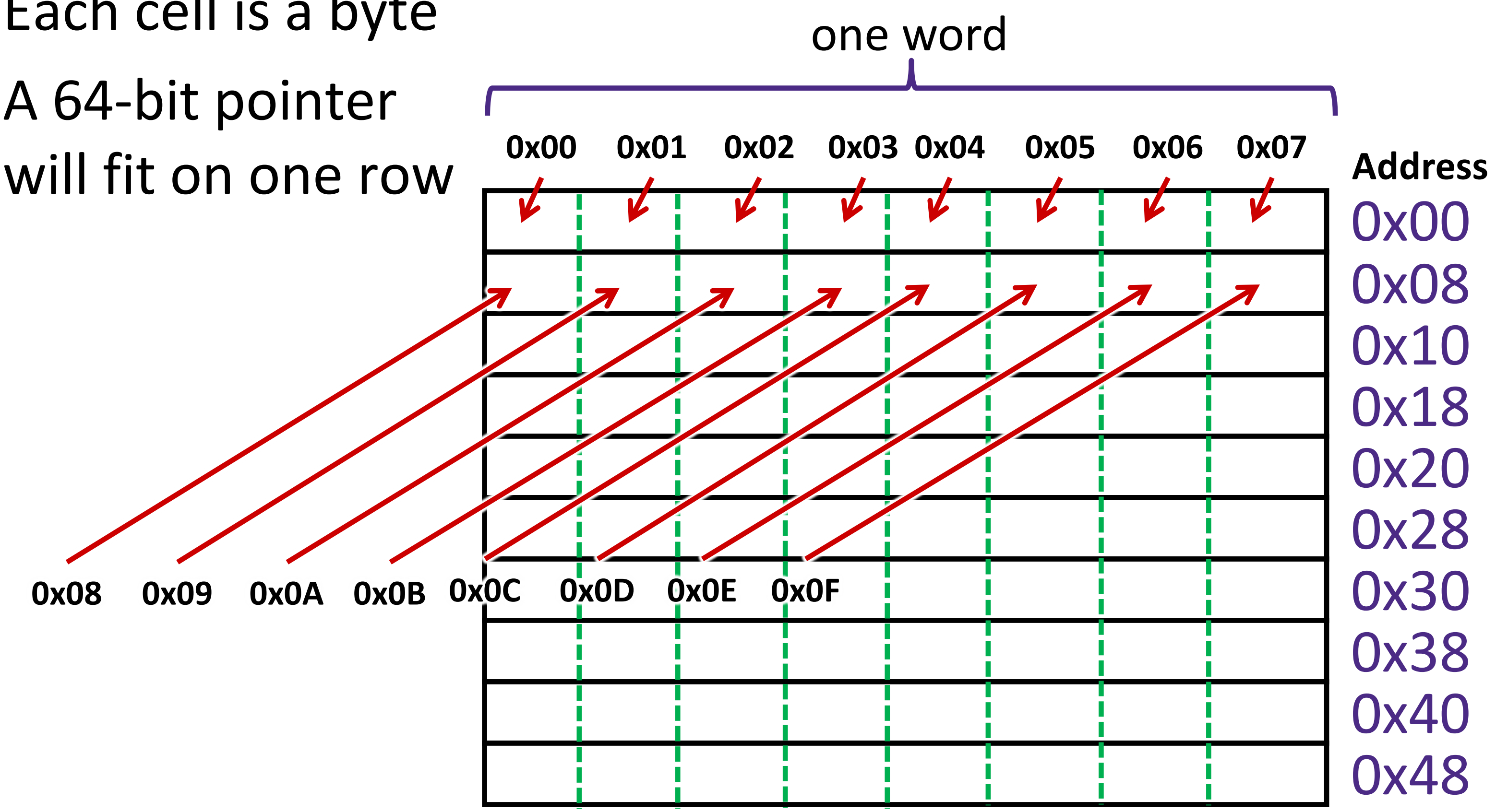
A Picture of Memory (64-bit view)

- A "64-bit (8-byte) word-aligned" view of memory:
  - In this type of picture, each row is composed of 8 bytes
  - Each cell is a byte
  - A 64-bit pointer will fit on one row



A Picture of Memory (64-bit view)

- A "64-bit (8-byte) word-aligned" view of memory:
  - In this type of picture, each row is composed of 8 bytes
  - Each cell is a byte
  - A 64-bit pointer will fit on one row

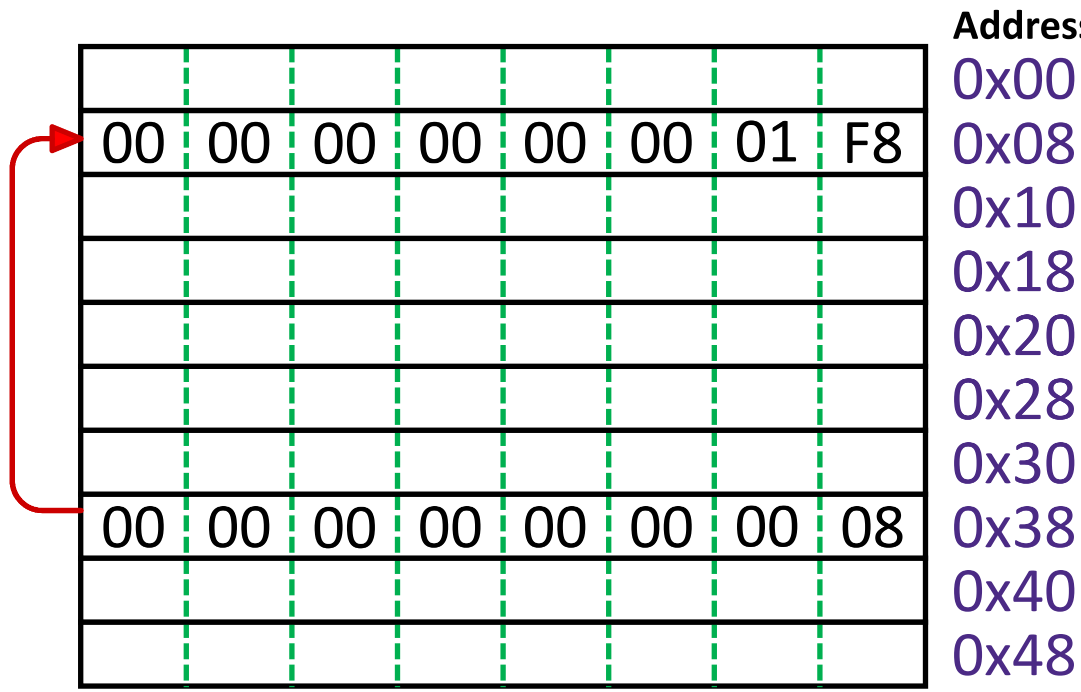


Addresses and Pointers

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

big-endian

- An *address* is a location in memory
- A *pointer* is a data object that holds an address
  - Address can point to *any* data
- Value 504 stored at address 0x08
  - $504_{10} = 1F8_{16}$
    = 0x 00 … 00 01 F8
- Pointer stored at 0x38 points to address 0x08

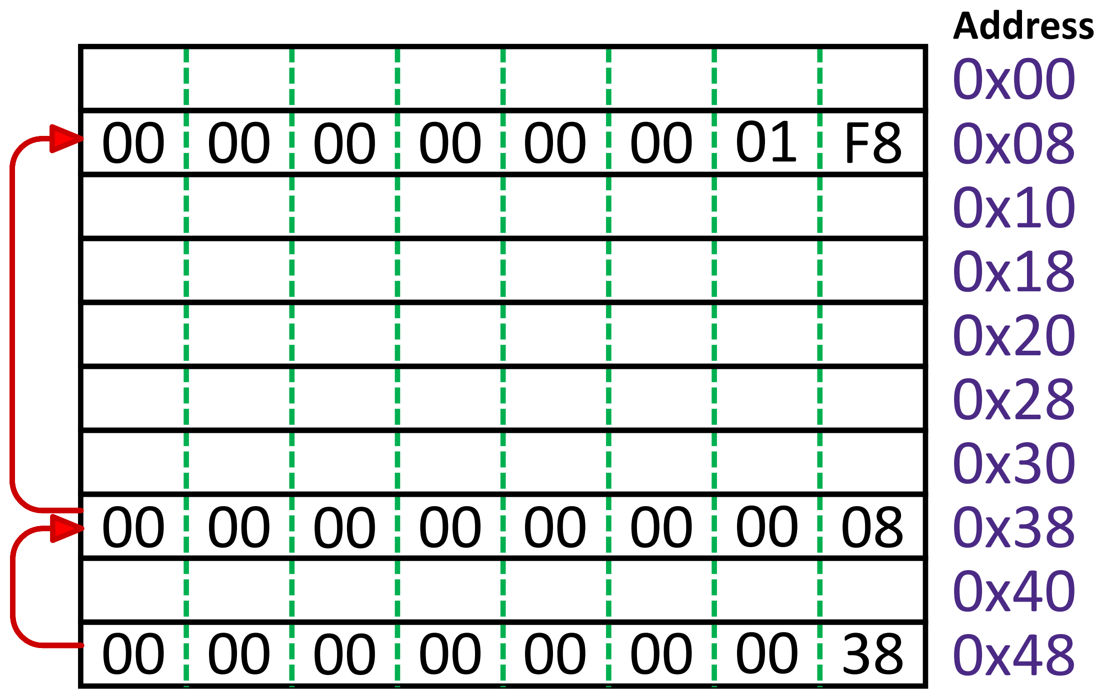


Addresses and Pointers

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

big-endian

- An *address* is a location in memory
- A *pointer* is a data object that holds an address
  - Address can point to *any* data
- Pointer stored at 0x48 points to address 0x38
  - Pointer to a pointer!
- Is the data stored at 0x08 a pointer?
  - Could be, depending on how you use it



Memory, Data, & Addressing II

Review

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
   b) 64 bits is the size of an integer
   c) 64 bits is the width of a register
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?

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;`
  - 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					
0x04	03	27	D0	3C	x
0x08					
0x0C					
0x10					
0x14					
0x18	00	27	D0	3C	y
0x1C					
0x20	24	00	00	00	z
0x24					

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

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

Assignment in C

- `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`

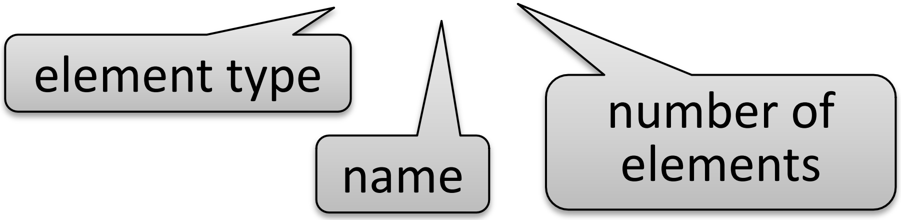
	0x00	0x01	0x02	0x03	
0x00					
0x04	03	27	D0	3C	x
0x08					
0x0C					
0x10					
0x14					
0x18	00	27	D0	3C	y
0x1C					
0x20	24	00	00	00	z
0x24	00	27	D0	3C	

Arrays in C

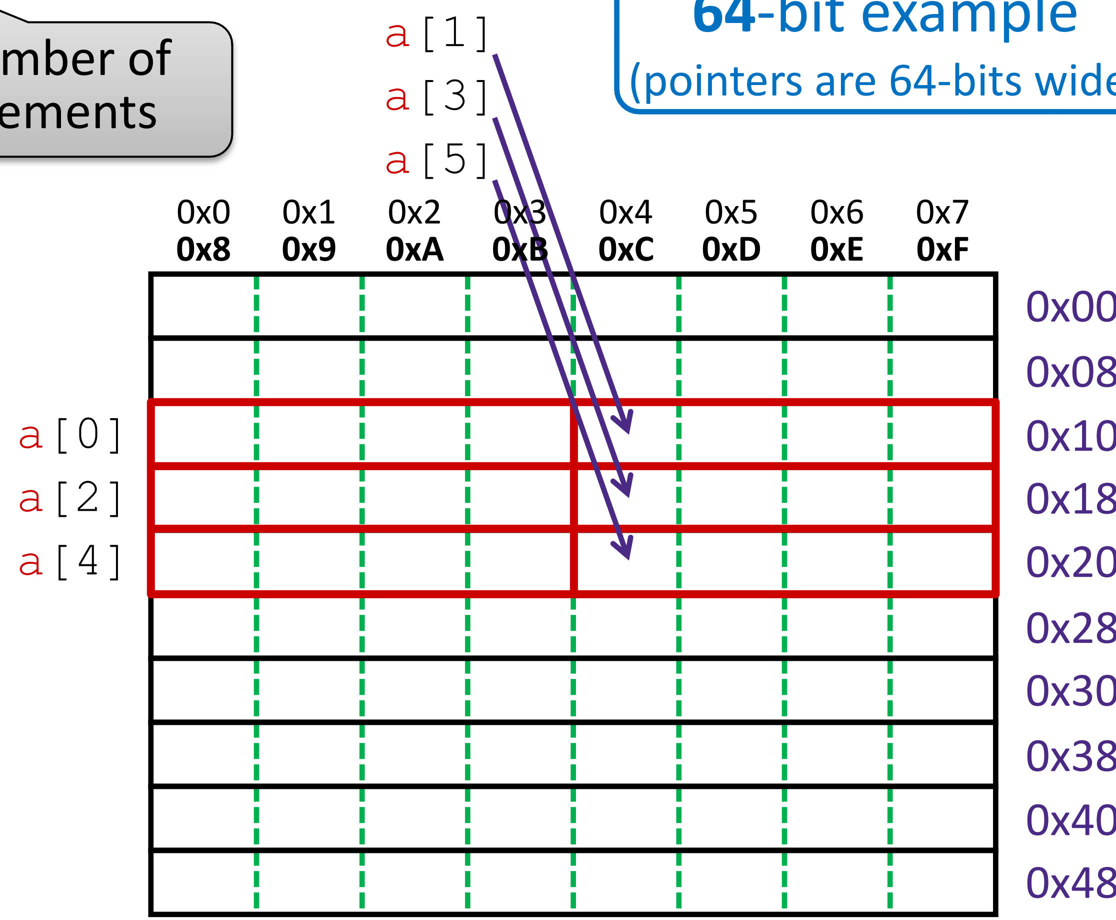
Arrays are adjacent locations in memory storing the same type of data object

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

Declaration: `int a[6];`



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



Arrays Basics

- **Pitfall:** An array in C does not know its own length, and its bounds are not checked!
  - We can accidentally access off the end of an array
  - We must pass the array **and its size** to any procedure that is going to manipulate it
- Mistakes with array bounds cause *segmentation faults* and *bus errors*
  - Be careful! These are VERY difficult to find (You'll learn how to debug these in lab)

Arrays in C

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

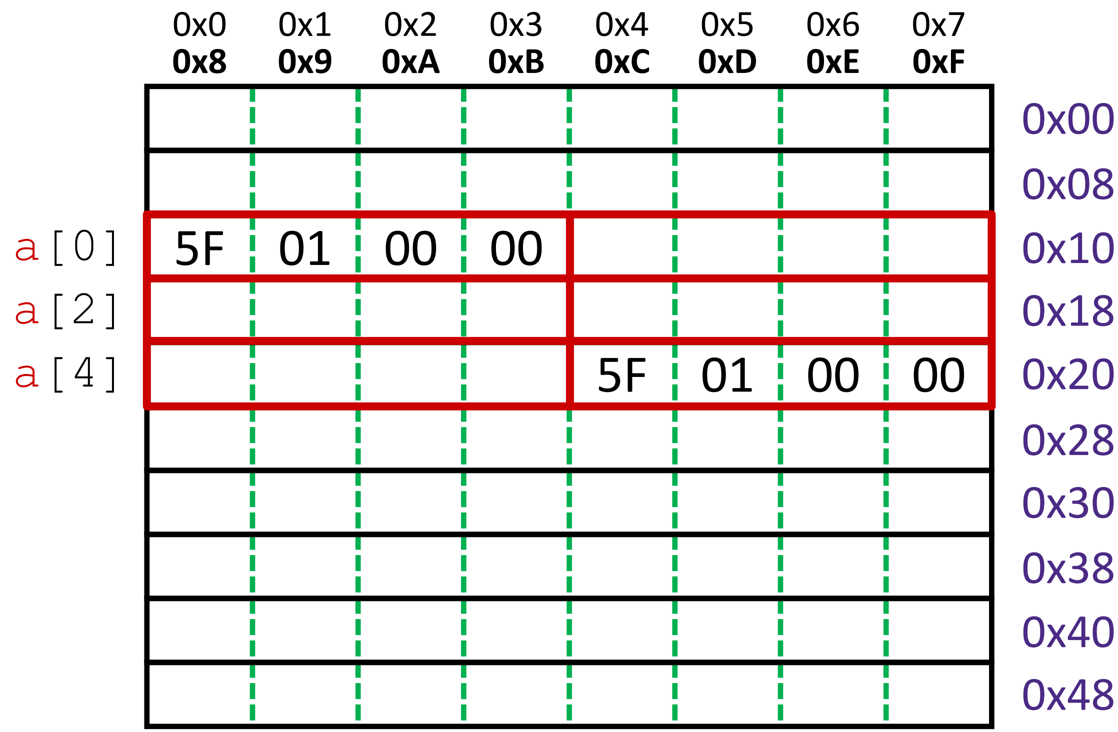
a (array name) returns the array's address

&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

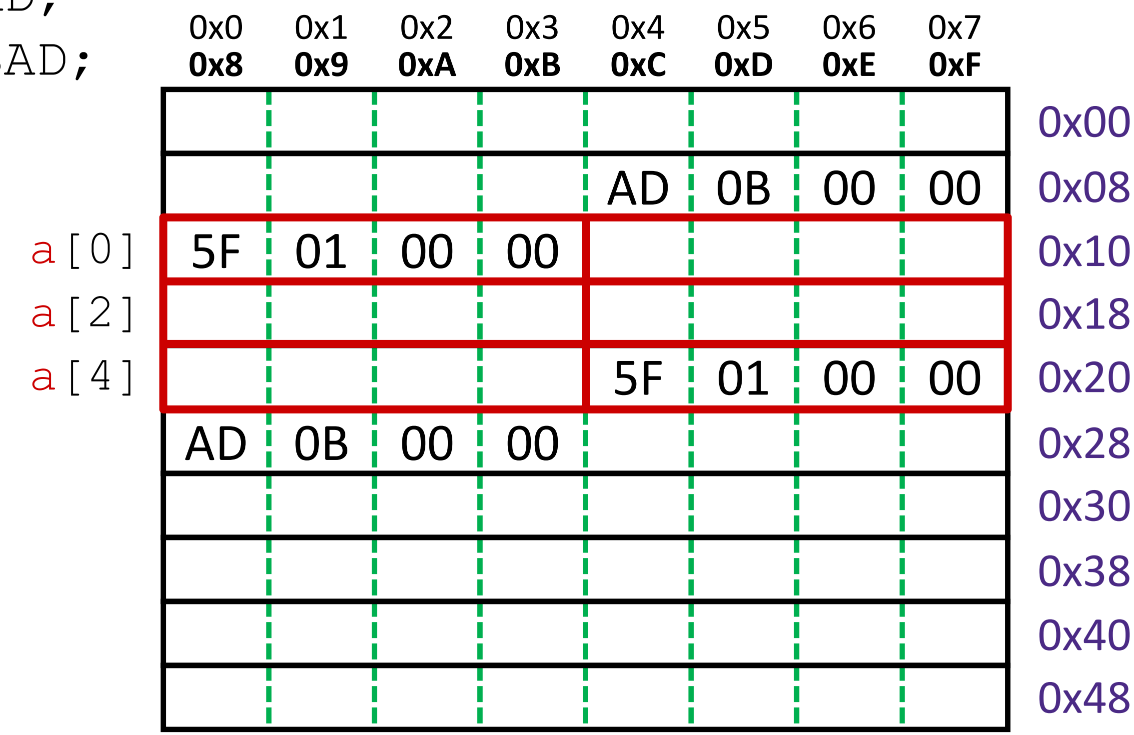
`a` (array name) returns the array's address

`&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;
```



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

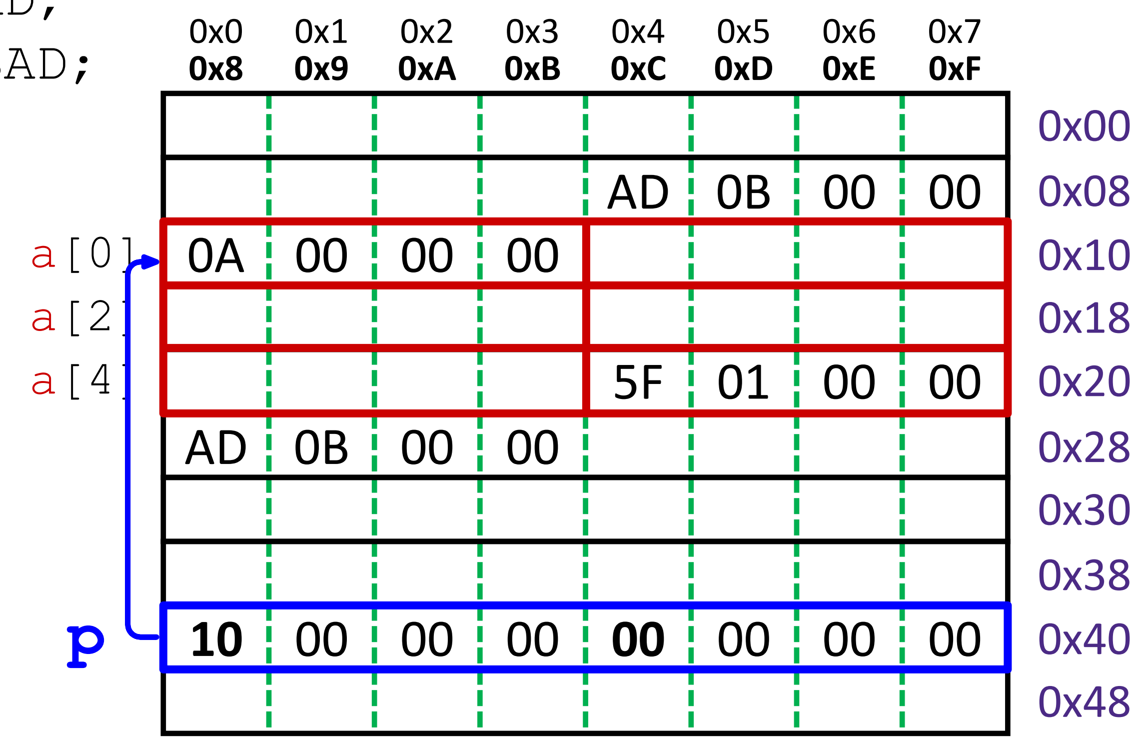
Declaration: `int a[6];`

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;
```



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];`

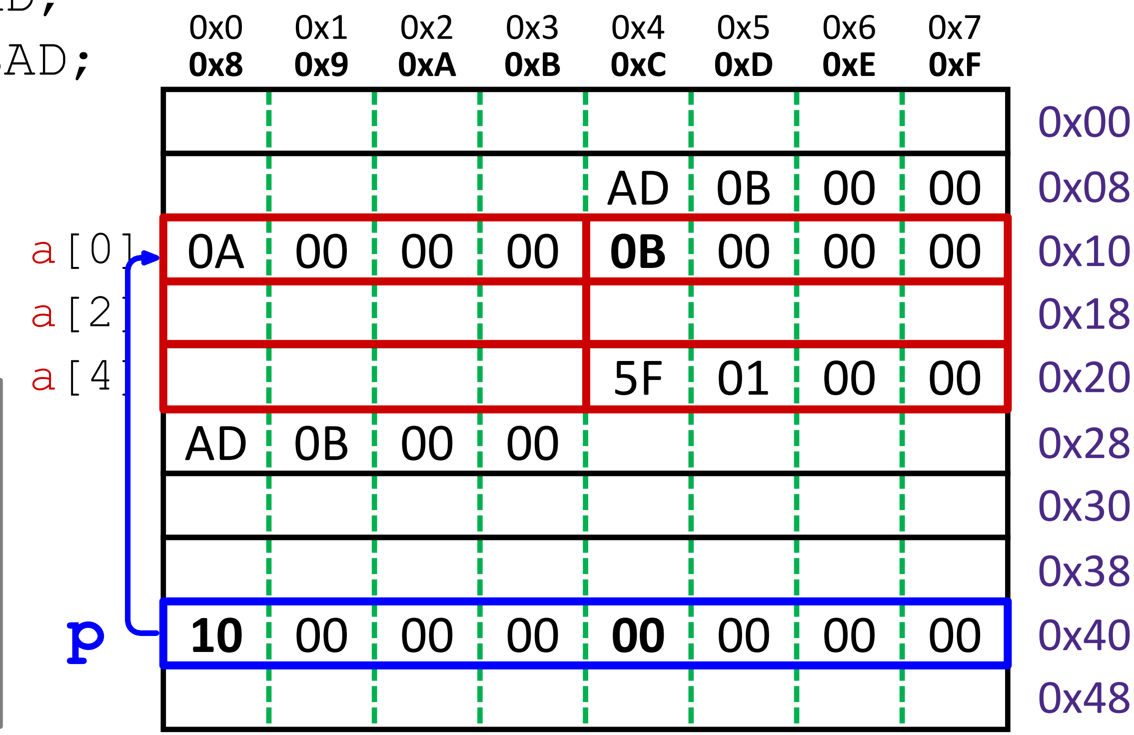
Indexing:
```
a[0] = 0x015f;
a[5] = a[0];
```

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;
```



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;
```

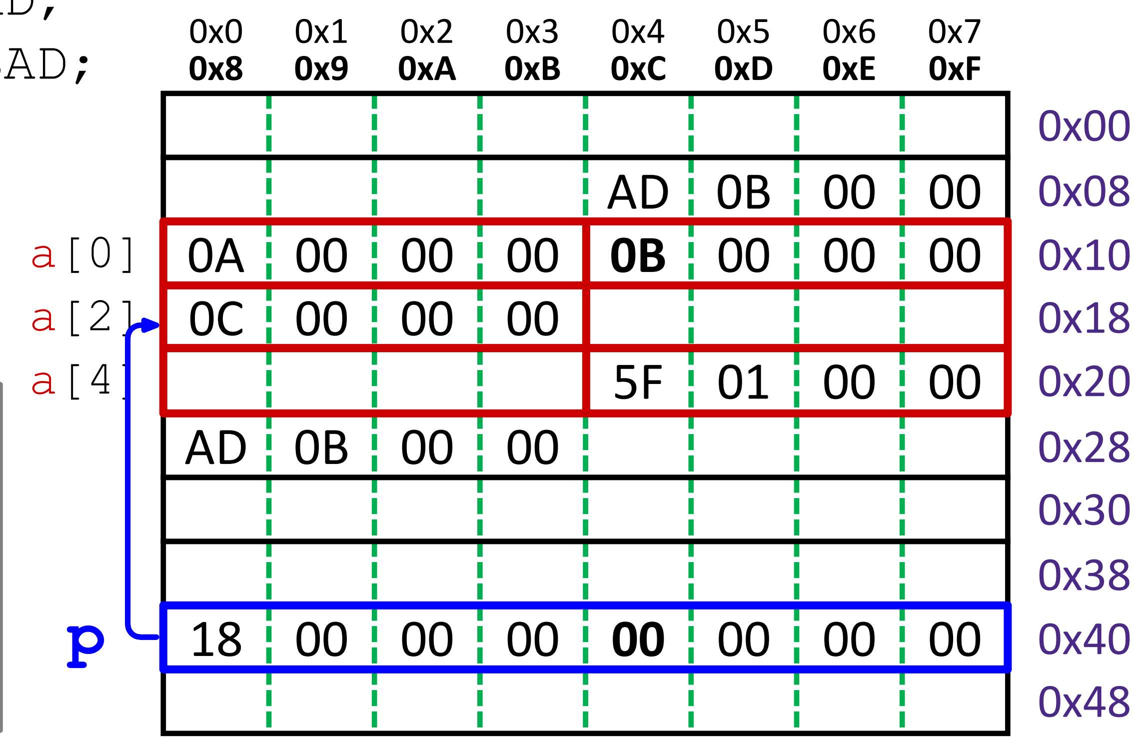
Pointers: `int* p;`

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;
```

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



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

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