Arrvindh (TASC 9009)

Alaa (next door)

Why are you here ?

- “Because It’s Required”
- “It Might Be Easy, Right?”
- “I Just Want to Get It Over With”
- “Because Everyone Else Is Doing It”
- “It’s Not Like I Have Anything Better to Do”

How do you get to 300 million petaflops?

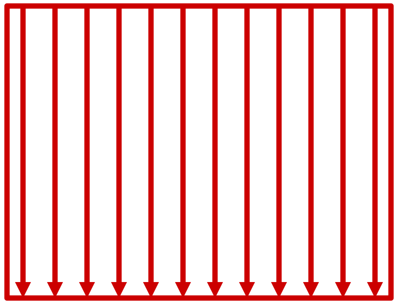
In CMPT 295 you will develop a machine that does 32 Gigaflops i.e,. 32 ops/step running at 1 Ghz frequency (1 billion steps/s)

Training GPT-3 reportedly took **several months**, leveraging a large-scale cluster of thousands of GPUs or TPUs to process its massive dataset and optimize its 175 billion parameters.

Message ChatGPT

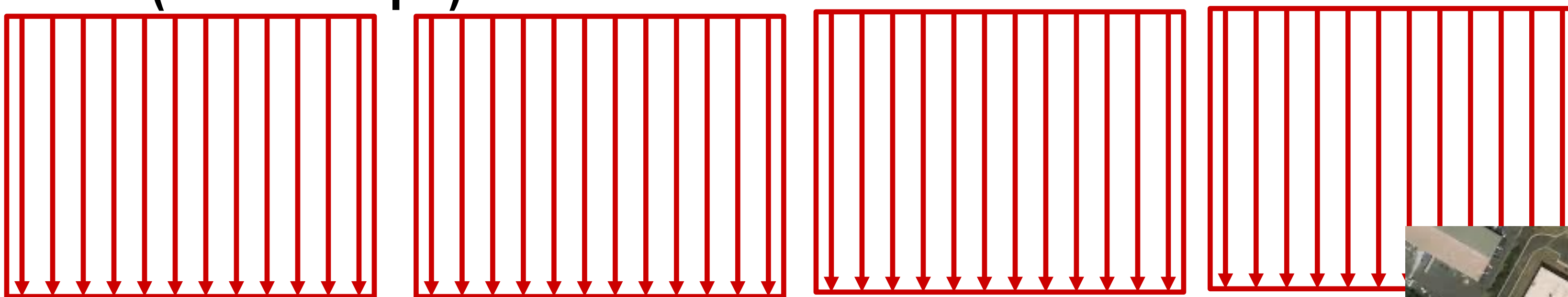
How do you get to 300 million petaflops?

1 chip = x1000 (32 teraflops)



How do you get to 300 million petaflops?

x1000 (32 teraflops)



x1000 machines (32 Petaflop/s) * 60s/m*60m/h* 24h

3 million Petaflops/day

300 million/3million = 100 days

Train: 300 million/3 = 100 days

Learning from first-principles

Logistics

- Assignment 1 will be released
  - Need to complete Lab 0 to be able to access
- Complete Lab 0 (ASAP!)
  - Tomorrow: TAs will begin Lab 1
  - Need it before we can grade anything
- 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.

Abstraction (Levels of Representation/Interpretation)

Python Program

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

C Program

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

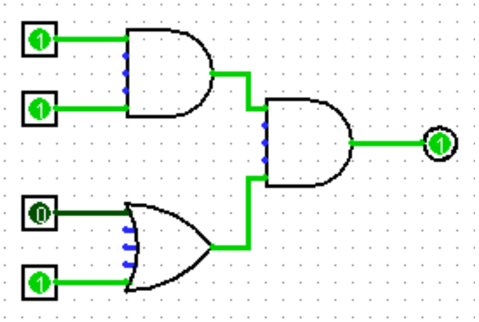
Binary

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

Assembly

```
square:
addi  sp,sp,-16
sw    ra,12(sp)
sw    s0,8(sp)
addi  s0,sp, 16
sw    a0,-12(s0)
lw    a0,-12(s0)
addi  a1,a0,2
mul   a0,a1,a0
lw    ra,12(sp)
lw    s0,8(sp)
addi  sp,sp,16
ret
```

Logic



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]]

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

Why different number systems?

- Binary System: foundation of computers (0s and 1s) because it aligns with a transistor’s switch state (off/on)
  - All data in computers—text, images, sound—can ultimately be represented as binary sequences.

- Hexadecimal System: compact representation; balance between human-readable and easy conversion to binary
  - 0xAB = 0b10101011 = 0d171.
- - Memory: hexadecimal matches neatly with word/block sizes in computer architecture (e.g., 8-bit, 16-bit systems).
- Realistic use: Identifying pointer properties.

Numerical Encoding

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

- <u>Examples</u>:
  - 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

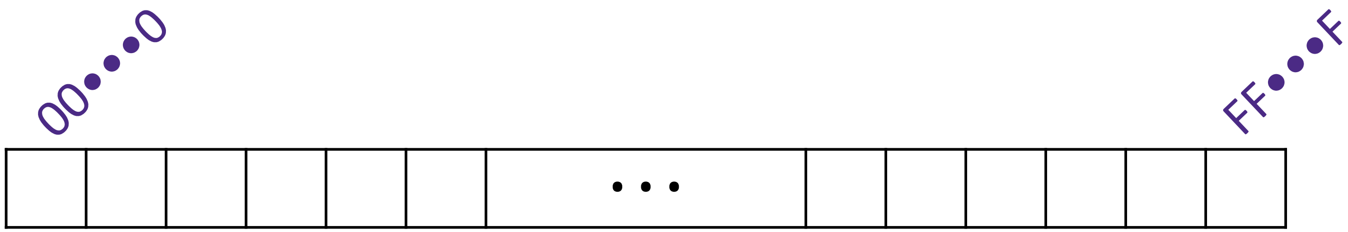
- Because storage is finite in reality, everything is stored as "fixed" length
  - Data is moved and manipulated in fixed-length chunks
  - Multiple fixed lengths (*e.g.* 1 byte, 4 bytes, 8 bytes)
  - Leading zeros now *must* be included up to "fill out" the fixed length

- 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…**

Why is 1KB = 1024 bytes (not 1000 bytes)

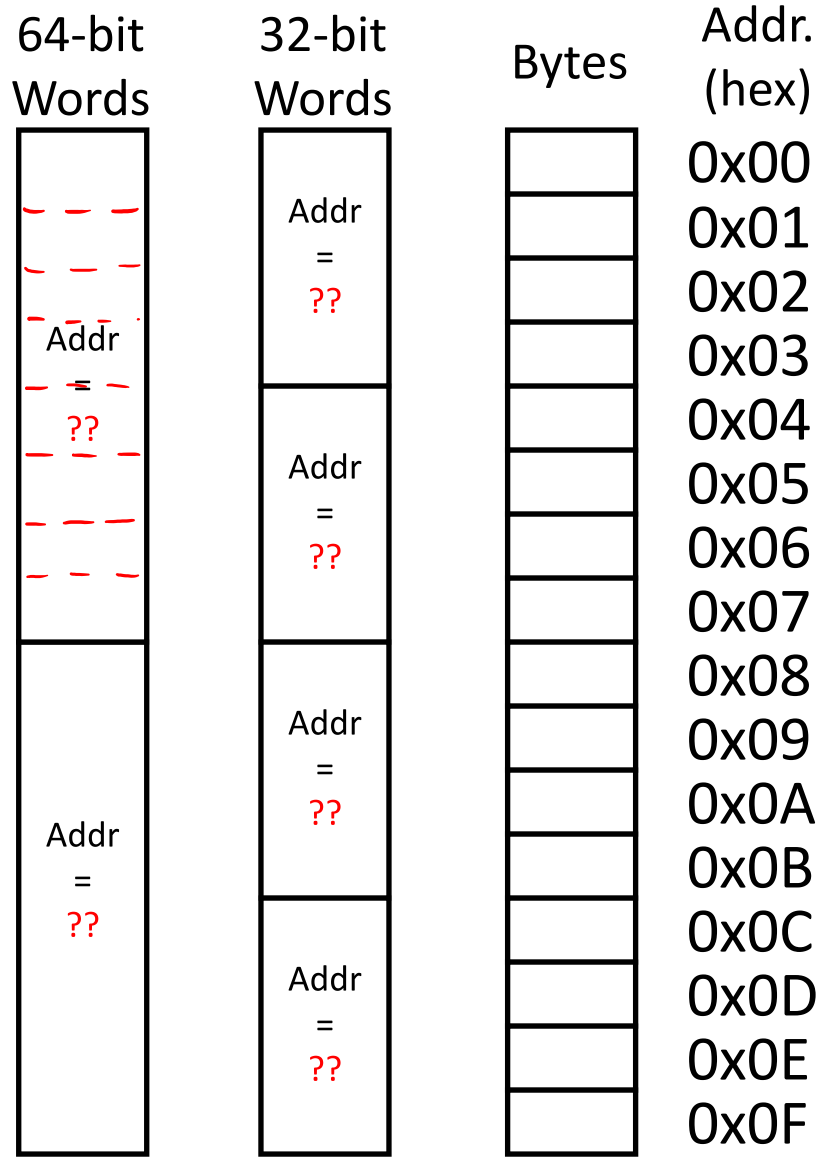
- Computers typically organize memory in powers of 2, since addressing grows as a power of 2.
- Consider,
- 1 bit address has two values 0,1 and hence can address a memory with 2 bytes.
- 2 bits address can have values 0,1,2,3 and hence can address memory with 4 bytes.
- 10 bits address can have values 0 – 1023 and hence can address memory with 1024 bytes (1KB).

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 $\mathbf{10^{19}}$ bytes**
    = 18 billion billion bytes = 18 EB (exabytes)
  - Actual physical address space: **48 bits**

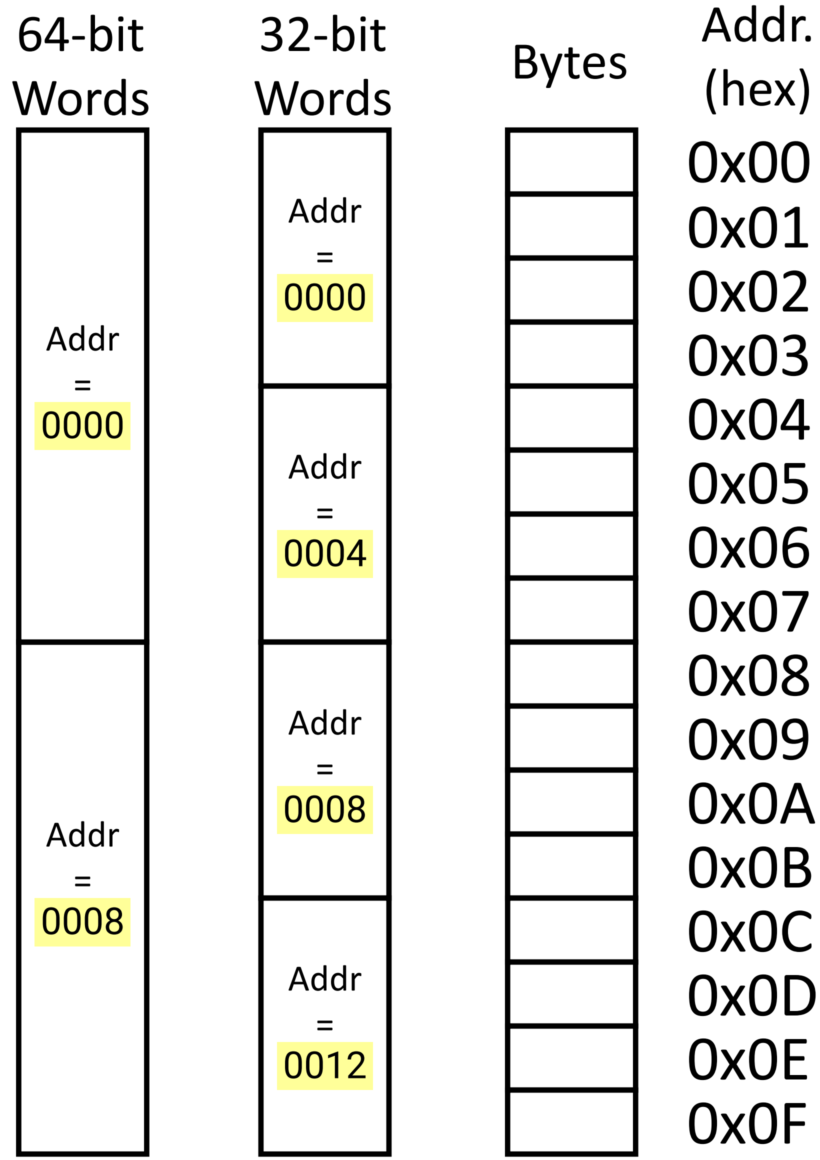
Word-Oriented Memory Organization

- 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

```
int i_int;
char ch = 'a';
long long int i_long_long;
short s_num = 0xBEEF;
uintptr_t int_ptr = (uintptr_t)&i_int;
printf("Sizeof data : %ld, Address, of
data %p, Addr. Binary)
```

Alignment REPL

```
Sizeof data : 4, Addr: 0x7ffd38f84cac, Addr Binary
0000000000000000011111111111110100111000111110000100110010101100
 Sizeof data : 8, Address: 0x7ffd38f84c98, Addr in Binary
0000000000000000011111111111110100111000111110000100110010011000
 Sizeof data : 1, Addr: 0x7ffd38f84c97, Addr in Binary
0000000000000000011111111111110100111000111110000100110010010111
 Sizeof data : 2, Addr: 0x7ffd38f84c94, Addr in Binary
0000000000000000011111111111110100111000111110000100110010010100
```

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

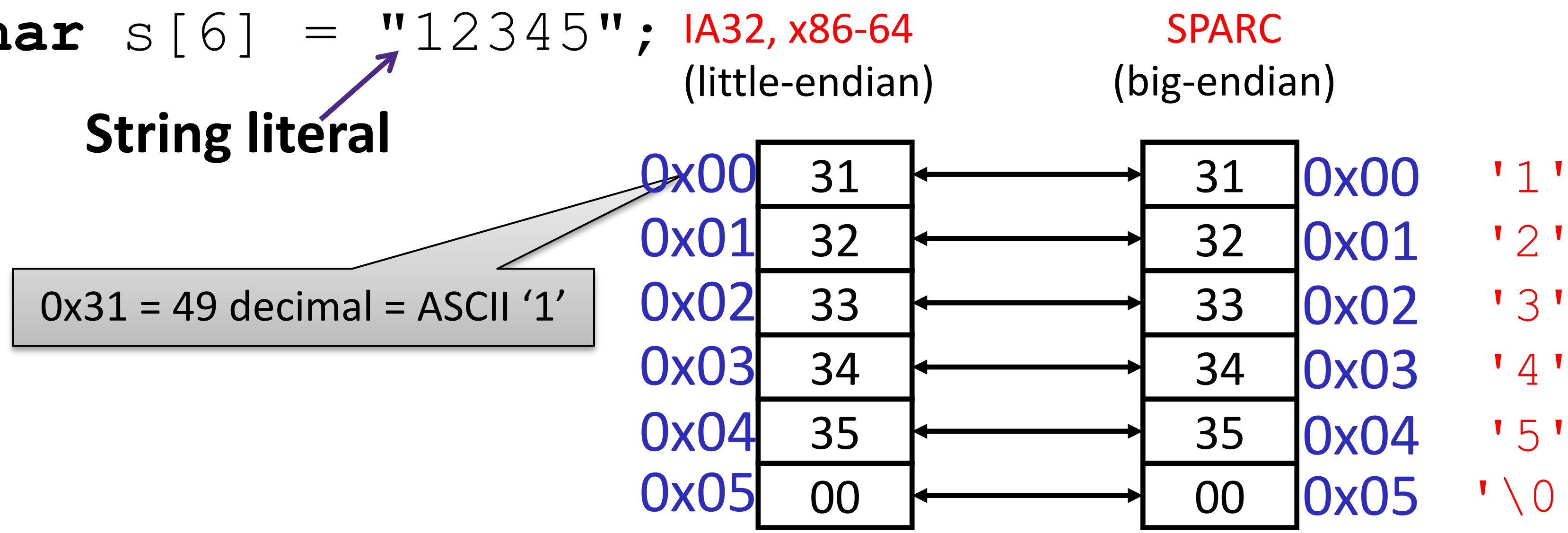
			0x100	0x101	0x102	0x103		
Big-Endian			a1	b2	c3	d4		

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

Endianness and Strings

C (char = 1 byte)

```
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

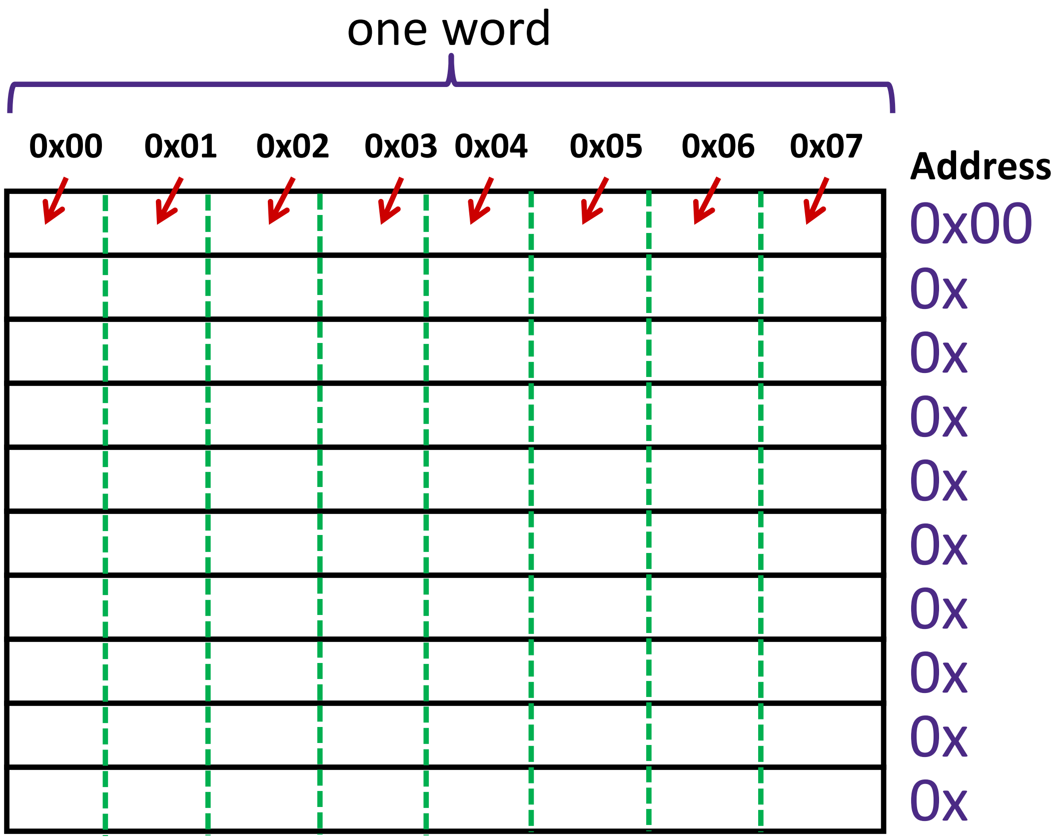
```
int x = 12345; // 0x00003039
printf("int x = %d;\n",x);
show_int(x);  // show_bytes((char *) &x, sizeof(int));
```

- 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



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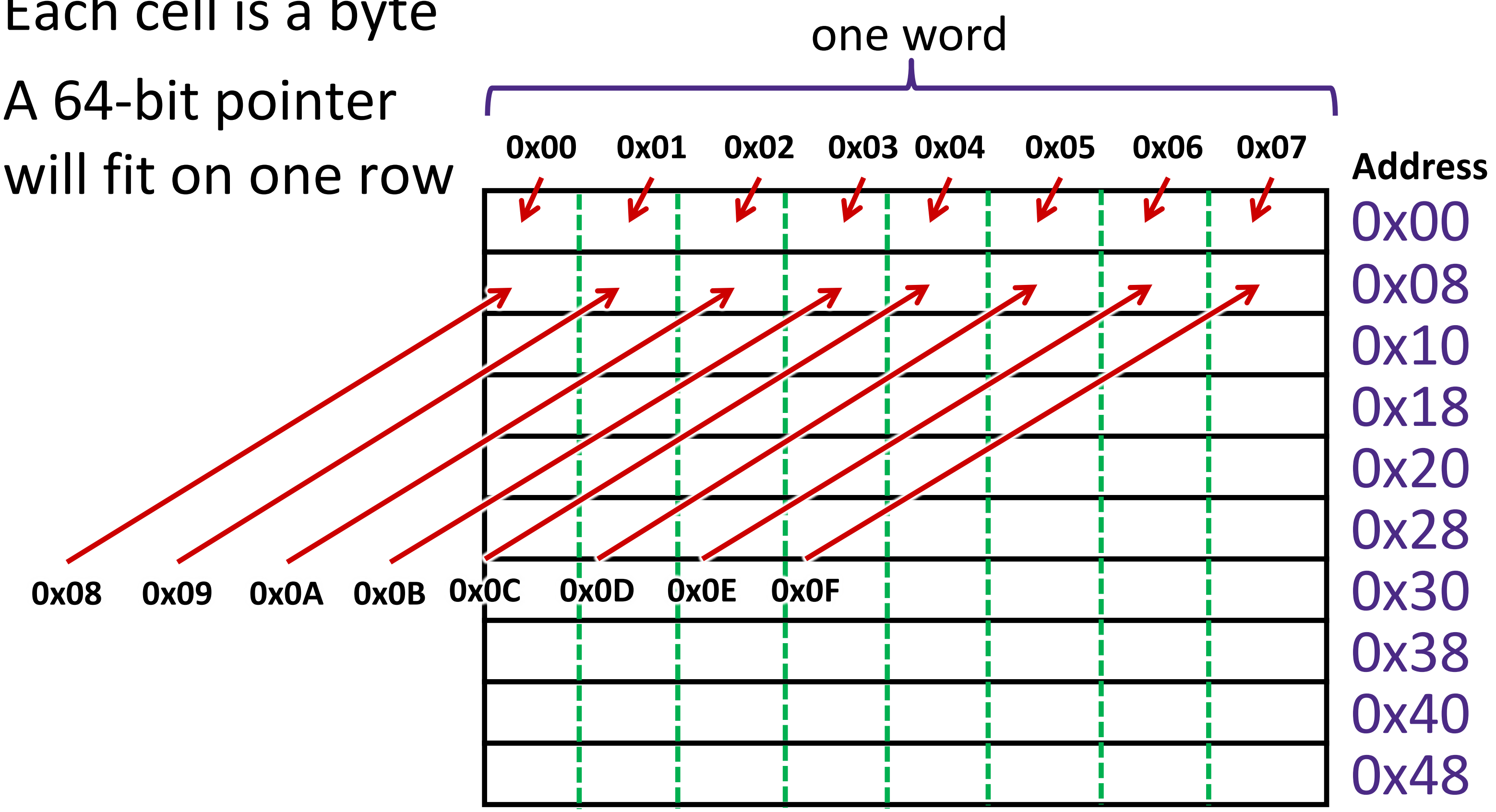
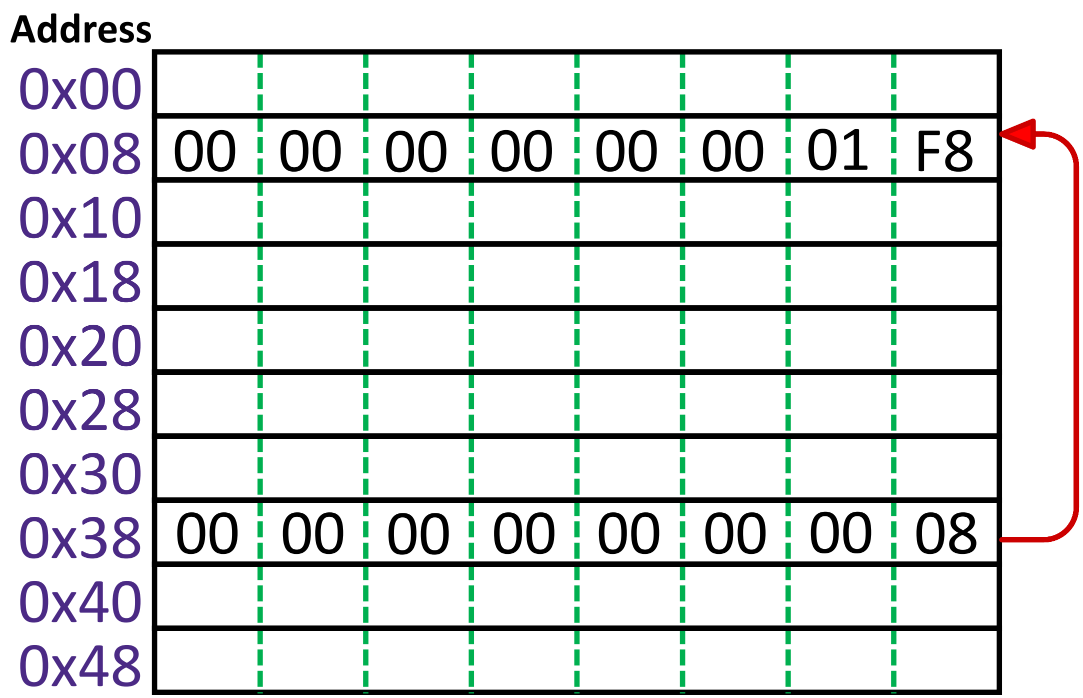


Addresses and Pointers

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

Address								
0x00								
0x08	00	00	00	00	00	00	01	F8
0x10								
0x18								
0x20								
0x28								
0x30								
0x38	00	00	00	00	00	00	00	08
0x40								
0x48	00	00	00	00	00	00	00	38

Memory, Data, & Addressing II

Arrays in C

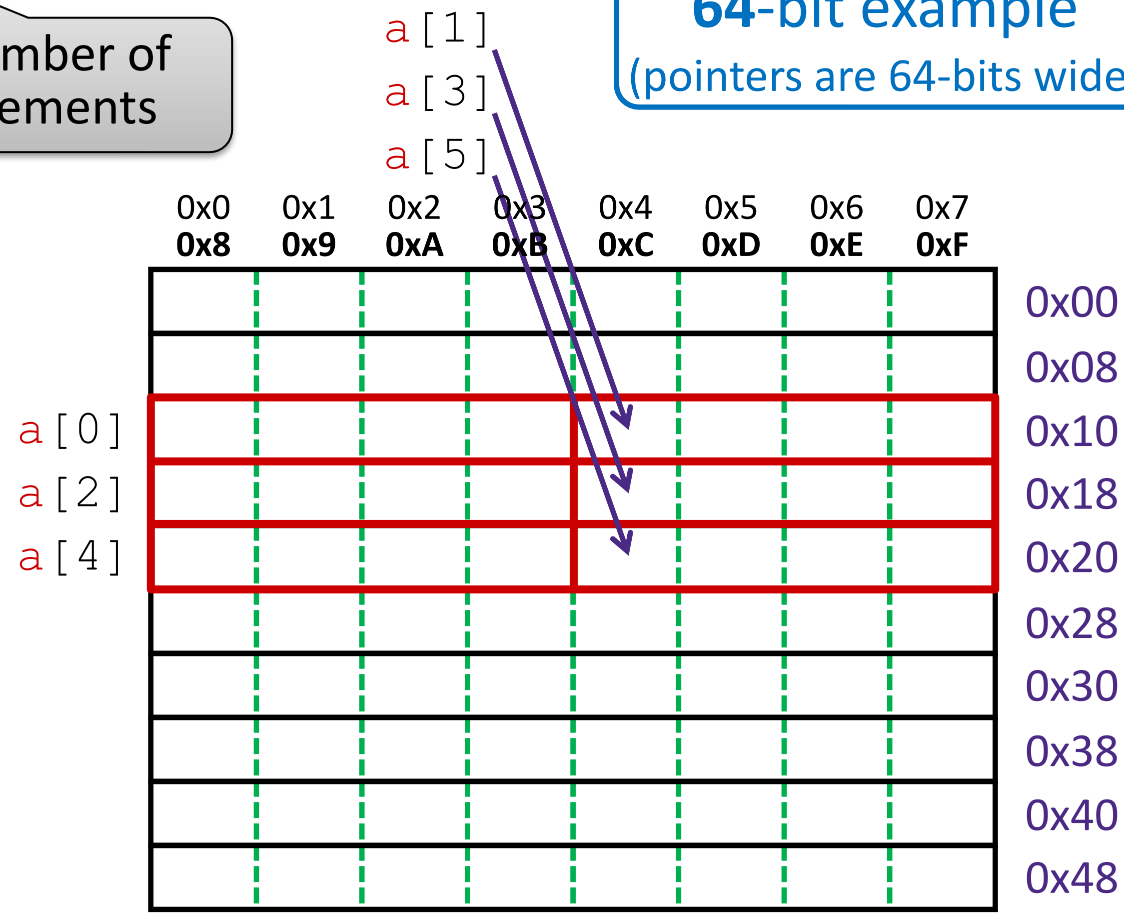
Arrays are adjacent locations in memory storing the same type of data object

a (array name) returns the array's address

Declaration: `int a[6];`

- element type
- name
- number of elements

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

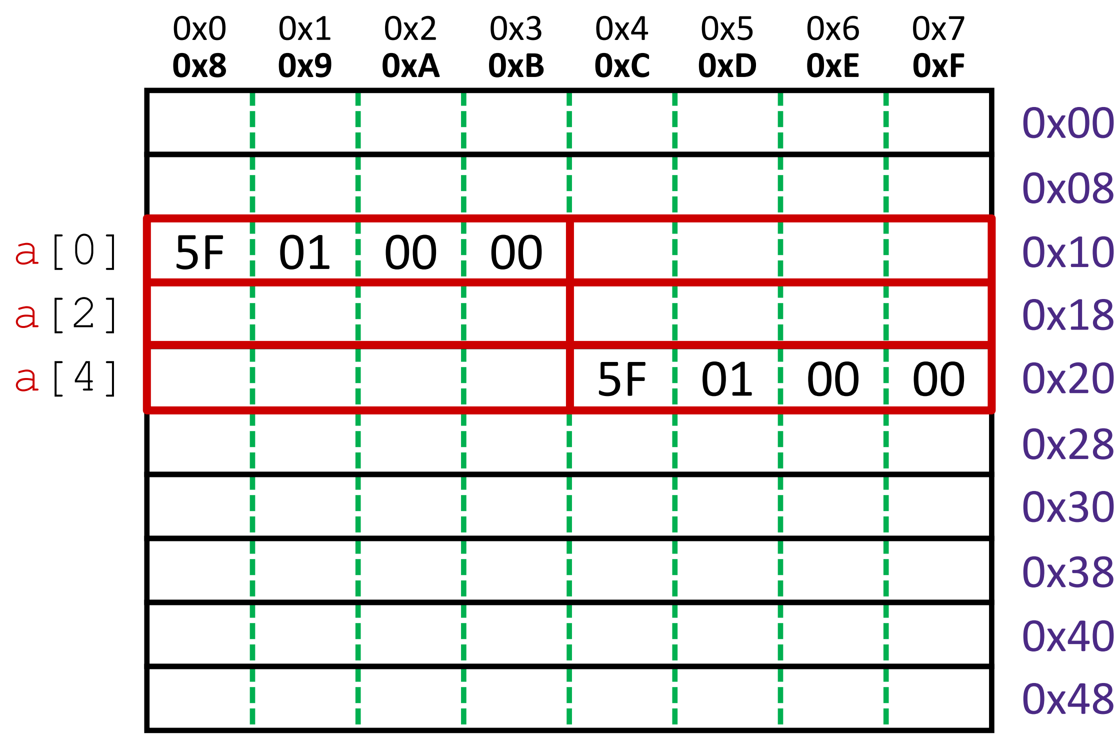
Declaration: `int a[6];`

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

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



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a[0] = 0x015f;
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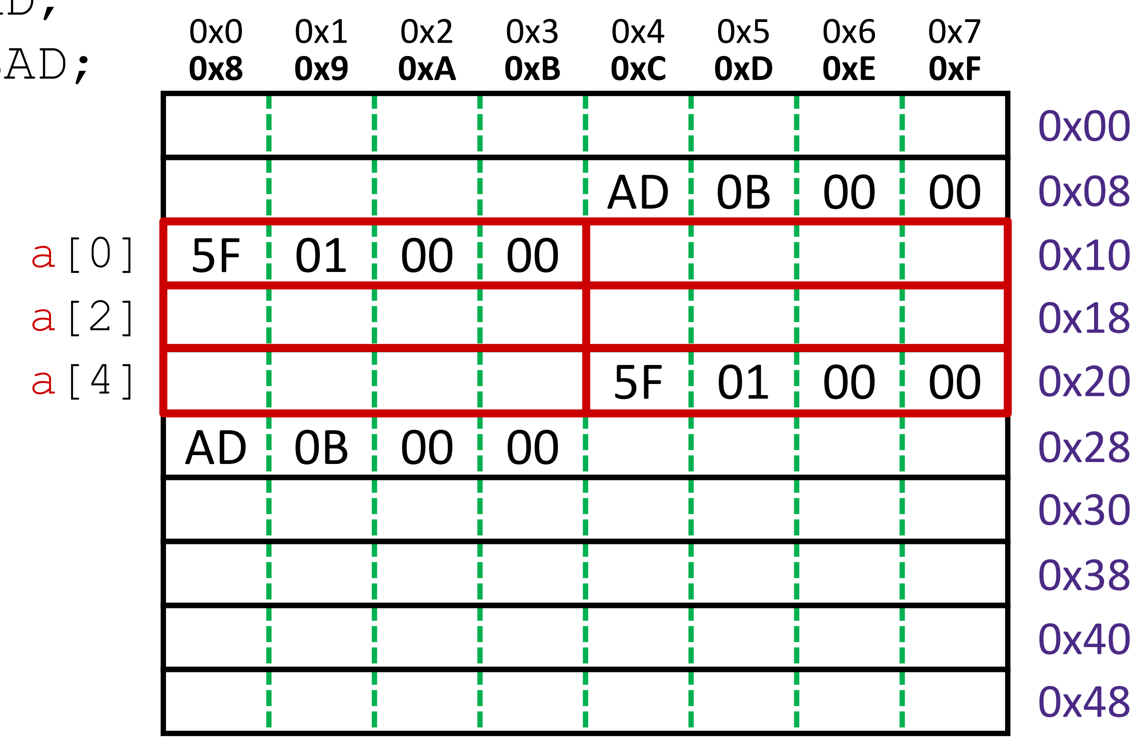
```

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



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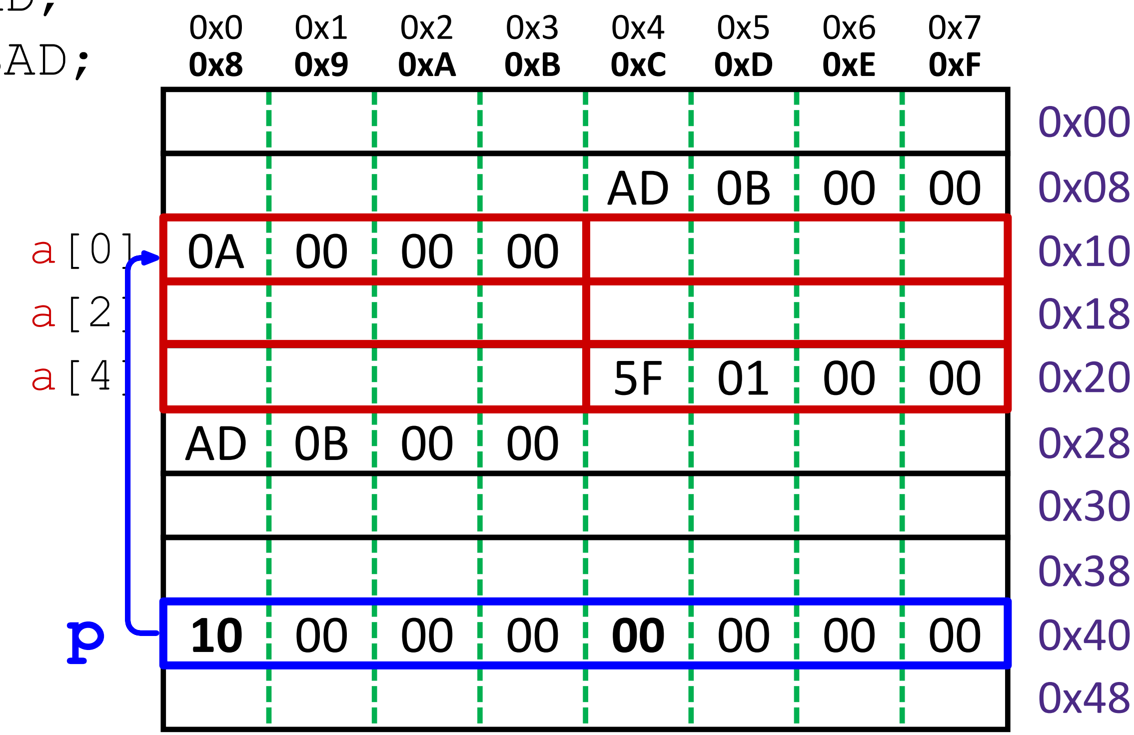
```

Pointers: `int* p;`

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



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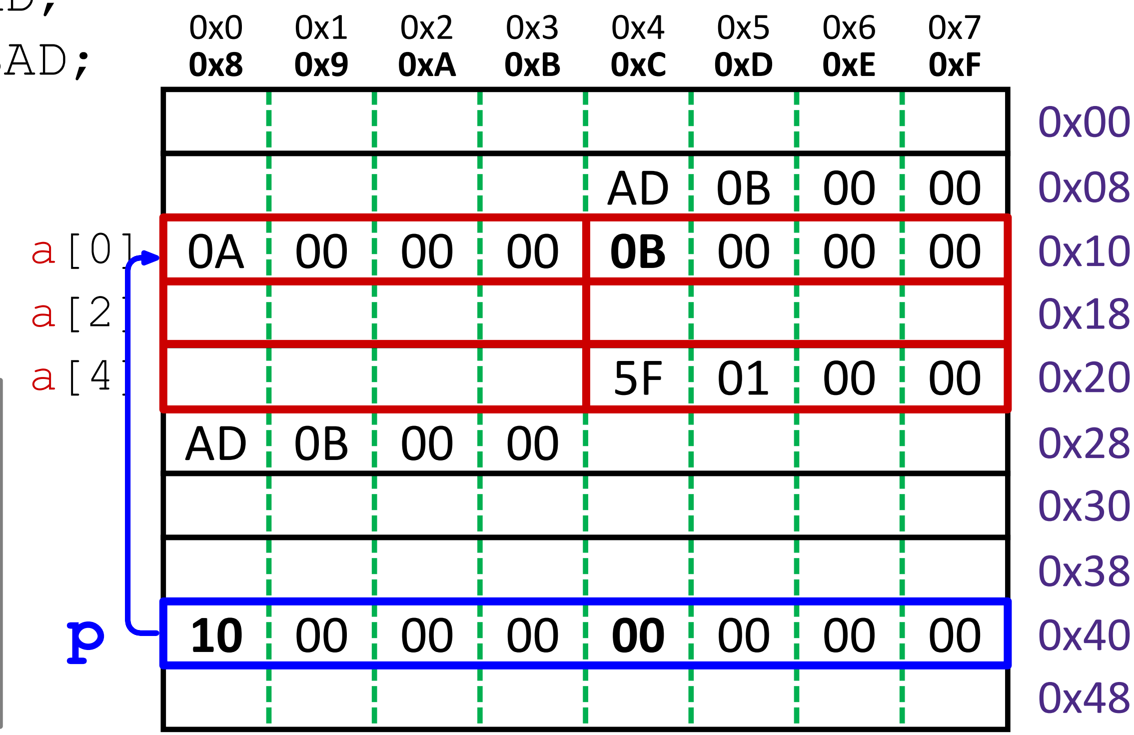
```

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;
```



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Pointers:
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```
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```
}
```
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```

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```
p[1] = 0xB;
*(p+1) = 0xB;
```
}
```
p = p + 2;
```

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

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

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;`
  - 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	

Assignment in C

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

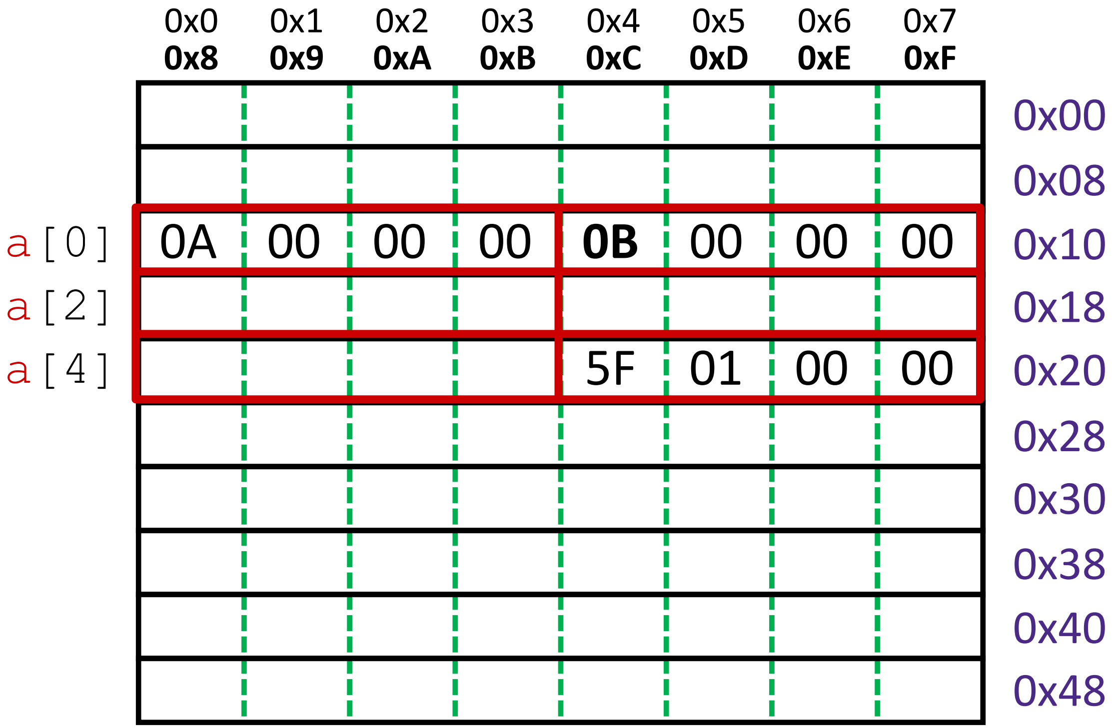
`&` = "address of"
`*` = "dereference"

- 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					

int a[6];



a = &a[0]

a+i = a[i] e.g., *(a+i) = 5 is same as a[i] = 5

Pointer Cast Example

- [PTYPE]* ptr = variable+ offset
  - PTYPE controls how many bytes are read by *ptr
  - Variable type controls scaling factor k for offset
  - Ptr is the integer value variable + offset*sizeof(type)

```
short array[4] = {0xAAAA,0xBBBB,0xCCCC,0xDDDD};
short *s_ptr = (short*)&array;
int   *i_ptr =   (int*)&array;

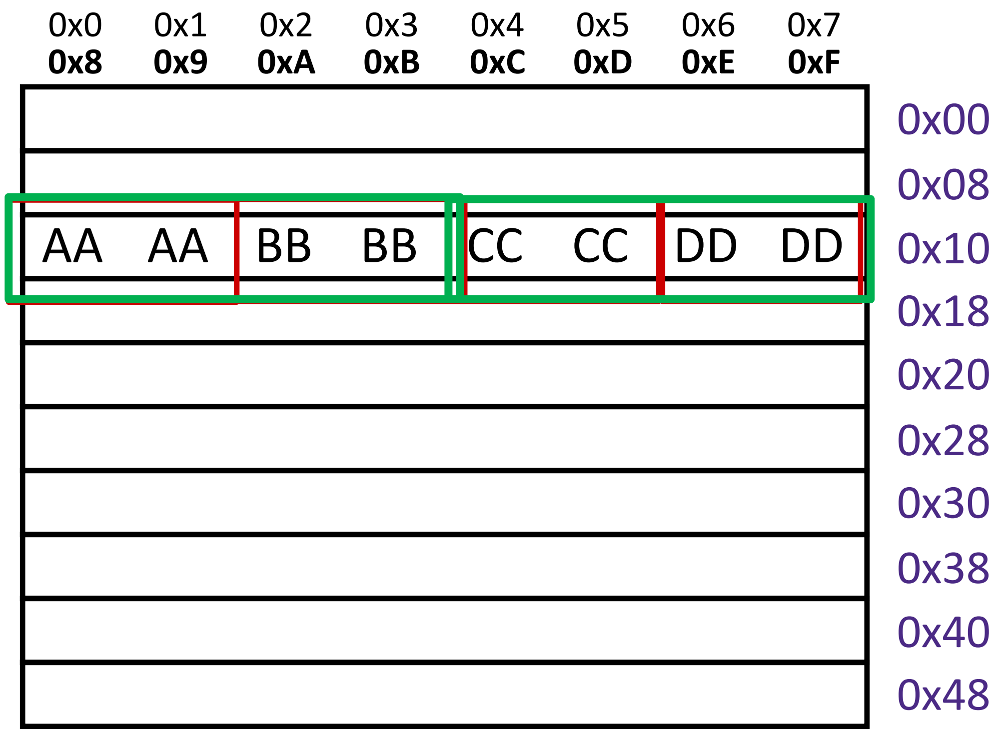
for(int i = 0; i < 4; i++)
printf("\n [%p], 0x%hx ", s_ptr+i, s_ptr[i]);

for (int i = 0; i < 2; i++)
printf("\n [%p], 0x%lx ", i_ptr+i, i_ptr[i]);
```

short array[4] = {0xAAAA,0xBBBB,0xCCCC,0xDDDD}

0x0 **0x8**	0x1 **0x9**	0x2 **0xA**	0x3 **0xB**	0x4 **0xC**	0x5 **0xD**	0x6 **0xE**	0x7 **0xF**	
								0x00
								0x08
AA	AA	BB	BB	CC	CC	DD	DD	0x10
								0x18
								0x20
								0x28
								0x30
								0x38
								0x40
								0x48

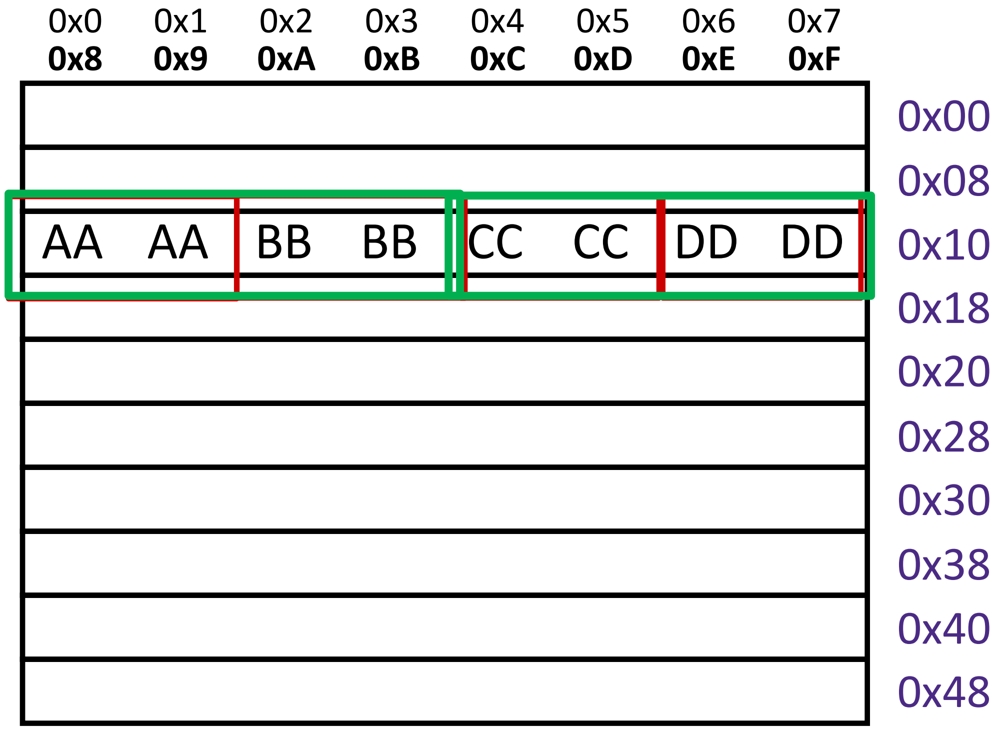
short array[4] = {0xAAAA,0xBBBB,0xCCCC,0xDDDD}



short *s_ptr = &array

int *i_ptr = &array

Pointer Cast Example



// s_ptr: as a short
[0x16f716f00], 0xaaaa
[0x16f716f02], 0xbbbb
[0x16f716f04], 0xcccc
[0x16f716f06], 0xdddd

// i_ptr: as a int
[0x16f716f00], 0xbbbbaaaa
[0x16f716f04], 0xddddcccc

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

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