In a byte-addressable design, how many distinct addresses are used across 64 bits of memory?

- 1
- 4
- 8
- 64

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CS 240
Foundations of Computer Systems

WELLESLEY

CS 240 Stage 2!

Hardware-Software Interface

Memory addressing, C language, pointers
Assertions, debugging
Machine code, assembly language, program translation
Control flow
Procedures, stacks
Data layout, security, linking and loading

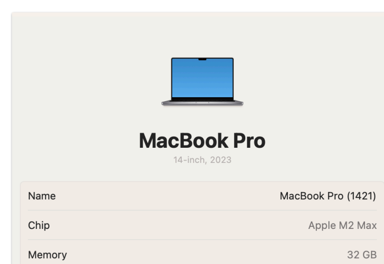
CS 240
Foundations of Computer Systems

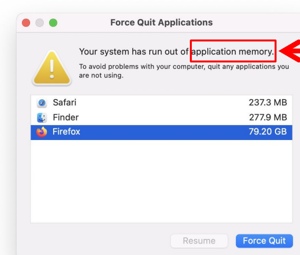
WELLESLEY

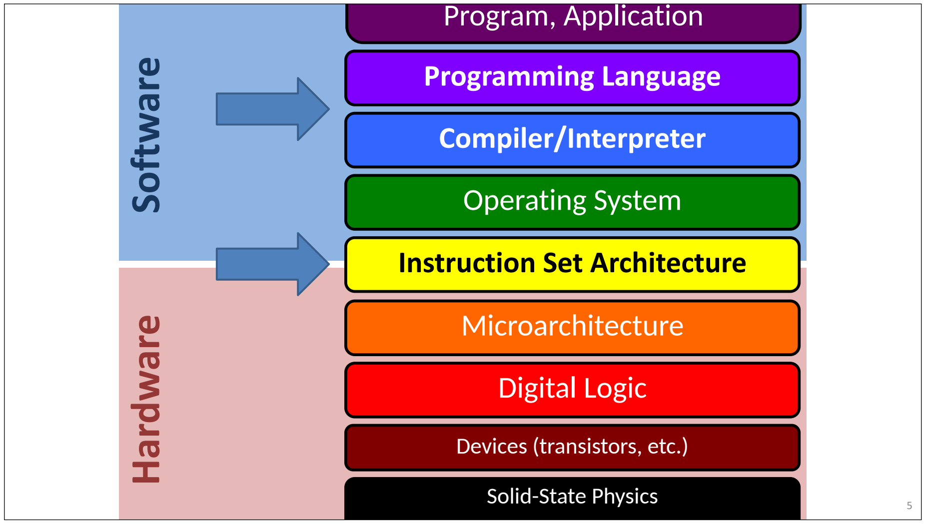
Programming with Memory

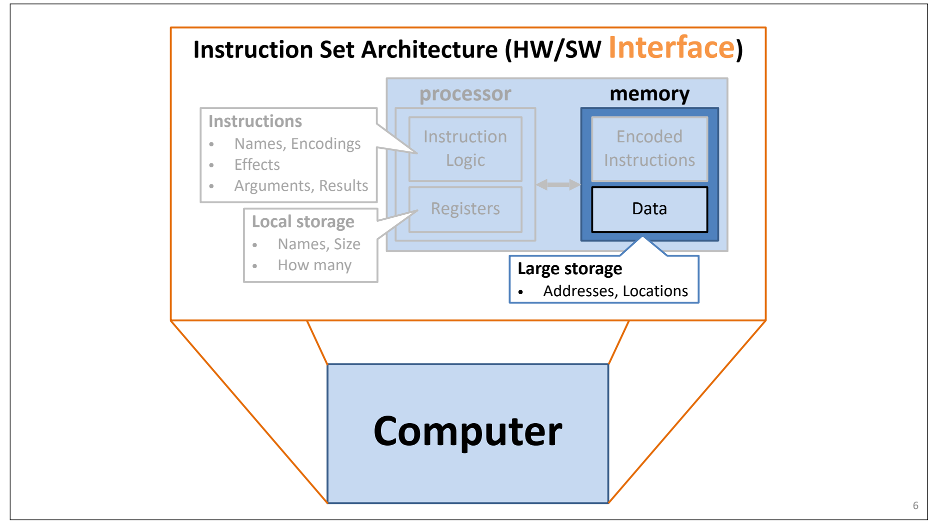
the memory model
pointers and arrays in C

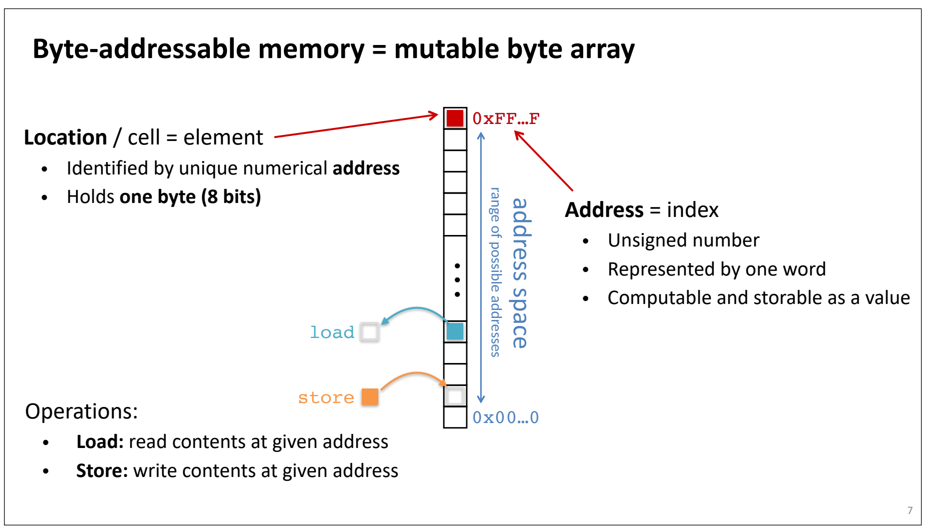
Big picture: systems programmers need to *optimize use of compute resources*

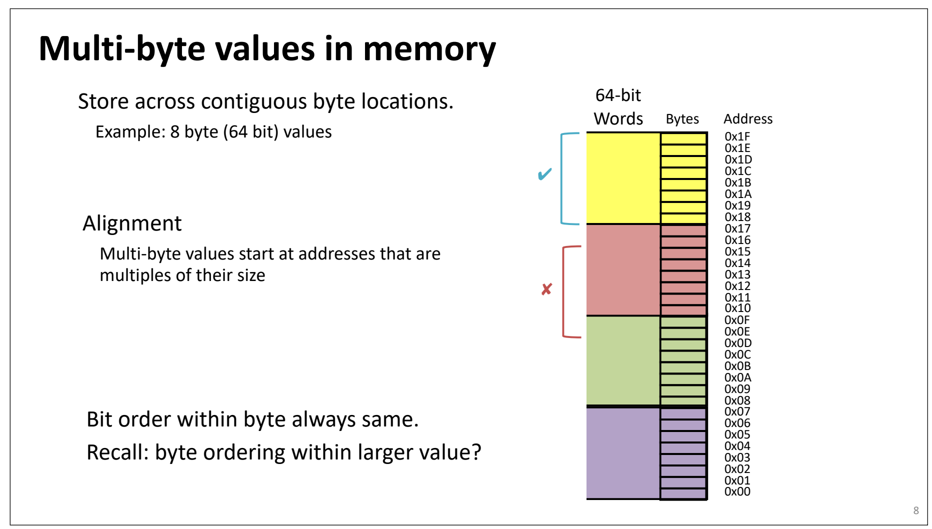





Software
Hardware
Program, Application
Programming Language
Compiler/Interpreter
Operating System
Instruction Set Architecture
Microarchitecture
Digital Logic
Devices (transistors, etc.)
Solid-State Physics
5


Instruction Set Architecture (HW/SW Interface)
processor
memory
Instructions
• Names, Encodings
• Effects
• Arguments, Results
Instruction Logic
Registers
Encoded Instructions
Data
Local storage
• Names, Size
• How many
Large storage
• Addresses, Locations
Computer
6


Byte-addressable memory = mutable byte array
Location / cell = element
• Identified by unique numerical address
• Holds one byte (8 bits)
0xFF…F
Address = index
• Unsigned number
• Represented by one word
• Computable and storable as a value
address space
range of possible addresses
load
store
0x00…0
Operations:
• Load: read contents at given address
• Store: write contents at given address
7


Multi-byte values in memory
Store across contiguous byte locations.
Example: 8 byte (64 bit) values
Alignment
Multi-byte values start at addresses that are multiples of their size
Bit order within byte always same.
Recall: byte ordering within larger value?
64-bit Words
Bytes
Address
✔
✘
0x1F
0x1E
0x1D
0x1C
0x1B
0x1A
0x19
0x18
0x17
0x16
0x15
0x14
0x13
0x12
0x11
0x10
0x0F
0x0E
0x0D
0x0C
0x0B
0x0A
0x09
0x08
0x07
0x06
0x05
0x04
0x03
0x02
0x01
0x00
8

Is an `int` stored at address 0x00000002 aligned?

Yes

No

Maybe

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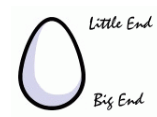
Endianness: details

In what order are the individual bytes of a multi-byte value stored in memory?

most significant byte (bits 31–24)	bits 23–16	bits 15–8	least significant byte (bits 7–0)
2A	B6	00	0B



Address	Contents
03	**2A**
02	B6
01	00
00	**0B**

Little Endian: least significant byte first

- low order byte at low address
- high order byte at high address
- used by **x86**, … and **CS240!**

Address	Contents
03	**0B**
02	00
01	B6
00	**2A**

Big Endian: most significant byte first

- high order byte at low address
- low order byte at high address
- used by networks, SPARC, …

Data, addresses, and pointers

+3	+2	+1	+0	
				0x24
				0x20
				0x1C
				0x18
				0x14
				0x10
				0x0C
				0x08
				0x04
				0x00

For these slides, we'll draw the bytes in this reverse order so that multi-byte values can be read directly

memory drawn as 32-bit values, little endian order

Data, addresses, and pointers

address = index of a location in memory

pointer = a reference to a location in memory, represented as an address stored as data

Let's store the number 240 at address `0x20`.

240_{10} = $F0_{16}$ = `0x00 00 00 F0`

At address `0x08` we store a pointer to the contents at address `0x20`.

At address `0x00`, we store a pointer to a pointer.

The number 12 is stored at address `0x10`.

Is it a pointer?

How do we know if values are pointers or not?

How do we manage use of memory?

+3	+2	+1	+0	
				0x24
00	00	00	F0	0x20
				0x1C
				0x18
				0x14
00	00	00	0C	0x10
				0x0C
00	00	00	20	0x08
				0x04
00	00	00	08	0x00

memory drawn as 32-bit values, little endian order

C: Variables are locations

The compiler creates a map from variable name → location.

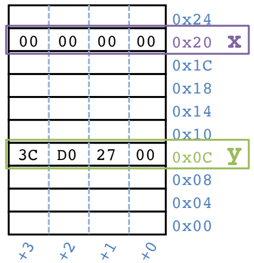
Declarations do not initialize!

```
int x; // x @ 0x20
int y; // y @ 0x0C

x = 0; // store 0 @ 0x20

// store 0x3CD02700 @ 0x0C
y = 0x3CD02700;

// 1. load the contents @ 0x0C
// 2. add 3
// 3. store sum @ 0x20
x = y + 3;
```



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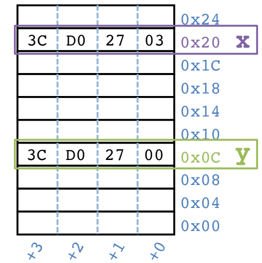


C: Pointer operations and types

address = index of a location in memory

pointer = a *reference* to a location in memory, an address stored as data

Expressions using addresses and pointers:

&___ **address of** the memory location representing ___
a.k.a. "reference to ___"

*___ **contents at** the memory address given by ___
a.k.a. "dereference ___"

Pointer types:

___* address of a memory location holding a ___
a.k.a. "a reference to a ___"

C: Types determine sizes

Used by CS Linux, most modern machines

Sizes of data types (in bytes)

Java Data Type	C Data Type	32-bit word	**64-bit word**
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 long	8	8
	long double	8	16
(reference)	(pointer) *	4	8

address size = word size

C: Pointer example

& = address of
** = contents at*

```
int* p;
```

Declare a variable, p that will hold the address of a memory location holding an int

```
int x = 5;
int y = 2;
```

Declare two variables, x and y, that hold ints, and store 5 and 2 in them, respectively.

```
p = &x;
```

Take the address of the memory representing x ... and store it in the memory location representing p. Now, *"p points to x."*

```
y = 1 + *p;
```

Add 1 to the contents of memory at the address given by the contents of the memory location representing p ... and store it in the memory location representing y.

C: Pointer example

& = address of
** = contents at*

C assignment:

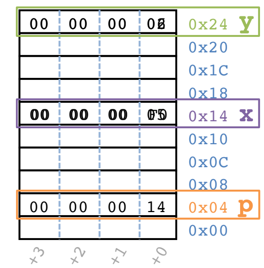
location → ***Left-hand-side* = *right-hand-side;*** ← value

What is the type of *p?
What is the type of &x?
What is `*(&y)` ?

```
int* p;      // p @ 0x04
int x = 5;   // x @ 0x14, store 5 @ 0x14
int y = 2;   // y @ 0x24, store 2 @ 0x24
p = &x;      // store 0x14 @ 0x04

// 1. load the contents @ 0x04  (=0x14)
// 2. load the contents @ 0x14  (=0x5)
// 3. add 1
// 4. store sum as contents @ 0x24
y = 1 + *p;

// 1. load the contents @ 0x04  (=0x14)
// 2. store 0xF0 as contents @ 0x14
*p = 240;
```



What is the result of printing the decimal values of `a` and `b` at the end of this code?

```
int a = 1;
int b = 5;
int* p = &a;
*p = *p + 1;
a = a + 1;

p = &b;
*p = *p * 2;
```

- 2, 10
- 3, 5
- 3, 10
- 6, 5
- None of the above

C: Pointer type syntax

Spaces between base type, *, and variable name mostly do not matter.

The following are **equivalent**:

```
int* ptr;
```

I see: "The variable **ptr** holds an **address of an int** in memory."

```
int * ptr;
```

```
int *ptr;
```

more common C style

Looks like: "Dereferencing the variable **ptr** will yield an **int**."

Or "The **memory location** where the variable **ptr** points holds an **int**."

Caveat: do not declare multiple variables unless using the last form.
`int* a, b;` means `int *a, b;` means `int* a; int b;`

C: Arrays

Arrays are adjacent memory locations storing the same type of data.

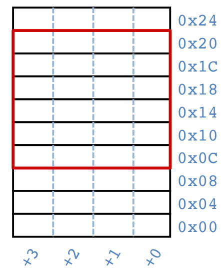
a is a name for the array's base address, can be used as an *immutable* pointer.

Declaration: `int a[6];`

element type

name

number of elements



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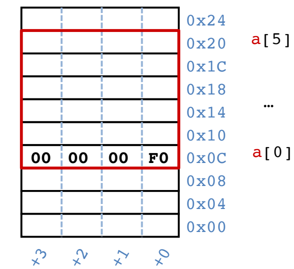
Address of `a[i]` is base address `a` plus `i` times element size in bytes.

Declaration: `int a[6];`

Indexing: `a[0] = 0xf0;`



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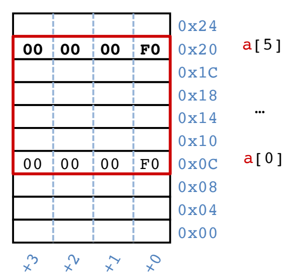
```



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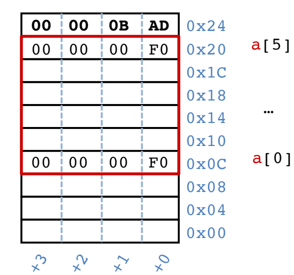
No bounds check: `a[6] = 0xBAD;`



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Indexing:
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```

No bounds check:
```
a[6] = 0xBAD;
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```

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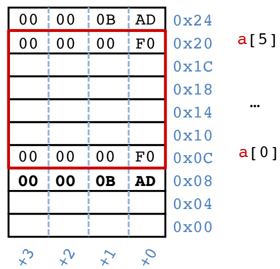

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No bounds check:
```
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```

Pointers:
```
int* p;
p = a;
p = &a[0];
```
equivalent (`p = a;` / `p = &a[0];`)

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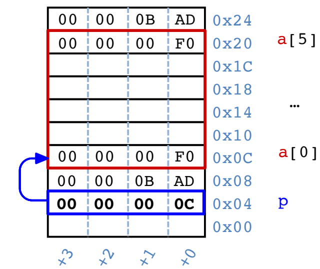

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*p = 0xA;
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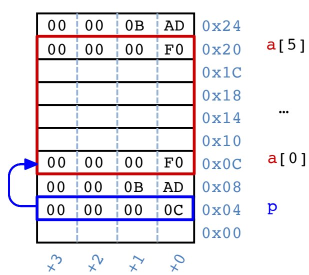

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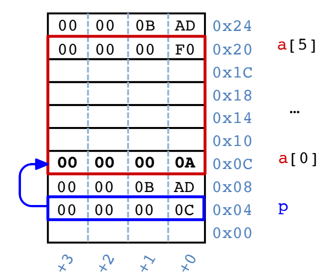

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```
No bounds check:
```
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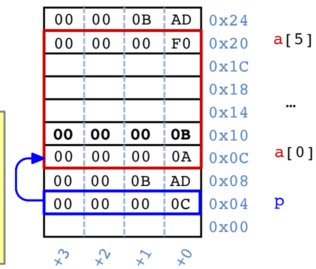
a[-1] = 0xBAD;
```
Pointers:
```
int* p;
p = a;          } equivalent
p = &a[0];
*p = 0xA;
```
```
p[1] = 0xB;     } equivalent
*(p + 1) = 0xB;
```
array indexing = address arithmetic

Both are scaled by the size of the type.



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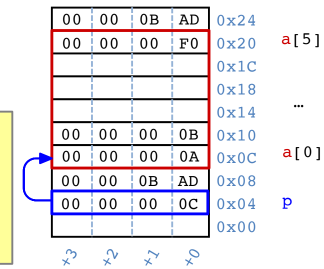

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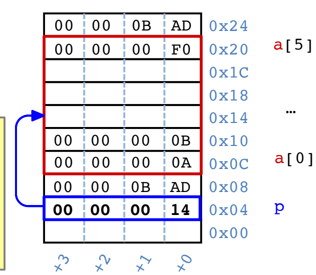

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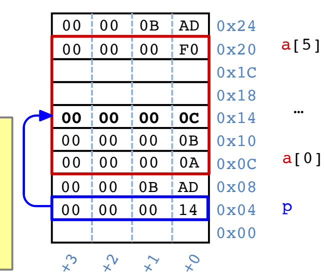



```
*p = a[1] + 1;
```

Assume p has type int *. Are `p[2] = 5` and `*(p + 2) = 5` equivalent? What about `p[2] = 5` and `*p + 2 = 5`?

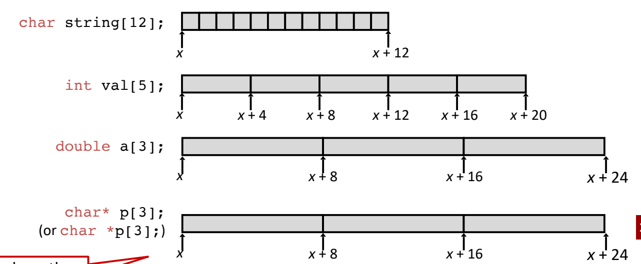
- No; No.
- No; Yes.
- Yes; No.
- Yes; Yes.

C: Array allocation

Basic Principle

T *A*[*N*];
Array of length *N* with elements of type *T* and name *A*
Contiguous block of *N**sizeof(*T*) bytes of memory

Use *sizeof* to determine proper size in C.



x86-64

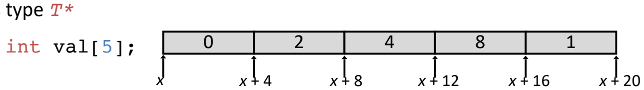
size depends on the machine word size

C: Array access

ex

Basic Principle

T *A*[*N*];
Array of length *N* with elements of type *T* and name *A*
Identifier *A* has type *T**



Expression	Type	Value
`val[4]`	`int`	1
`val`	`int *`	
`val+1`	`int *`	
`&val[2]`	`int *`	
`val[5]`	`int`	
`*(val+1)`	`int`	
`val + i`	`int *`	

Representing strings

A C-style string is represented by an array of bytes (`char`).
- Elements are one-byte ASCII codes for each character.
- ASCII = American Standard Code for Information Interchange

<table>
<tr><td>32</td><td>space</td><td>48</td><td>0</td><td>64</td><td>@</td><td>80</td><td>P</td><td>96</td><td>`</td><td>112</td><td>p</td></tr>
<tr><td>33</td><td>!</td><td>49</td><td>1</td><td>65</td><td>A</td><td>81</td><td>Q</td><td>97</td><td>a</td><td>113</td><td>q</td></tr>
<tr><td>34</td><td>”</td><td>50</td><td>2</td><td>66</td><td>B</td><td>82</td><td>R</td><td>98</td><td>b</td><td>114</td><td>r</td></tr>
<tr><td>35</td><td>#</td><td>51</td><td>3</td><td>67</td><td>C</td><td>83</td><td>S</td><td>99</td><td>c</td><td>115</td><td>s</td></tr>
<tr><td>36</td><td>$</td><td>52</td><td>4</td><td>68</td><td>D</td><td>84</td><td>T</td><td>100</td><td>d</td><td>116</td><td>t</td></tr>
<tr><td>37</td><td>%</td><td>53</td><td>5</td><td>69</td><td>E</td><td>85</td><td>U</td><td>101</td><td>e</td><td>117</td><td>u</td></tr>
<tr><td>38</td><td>&</td><td>54</td><td>6</td><td>70</td><td>F</td><td>86</td><td>V</td><td>102</td><td>f</td><td>118</td><td>v</td></tr>
<tr><td>39</td><td>’</td><td>55</td><td>7</td><td>71</td><td>G</td><td>87</td><td>W</td><td>103</td><td>g</td><td>119</td><td>w</td></tr>
<tr><td>40</td><td>(</td><td>56</td><td>8</td><td>72</td><td>H</td><td>88</td><td>X</td><td>104</td><td>h</td><td>120</td><td>x</td></tr>
<tr><td>41</td><td>)</td><td>57</td><td>9</td><td>73</td><td>I</td><td>89</td><td>Y</td><td>105</td><td>I</td><td>121</td><td>y</td></tr>
<tr><td>42</td><td>*</td><td>58</td><td>:</td><td>74</td><td>J</td><td>90</td><td>Z</td><td>106</td><td>j</td><td>122</td><td>z</td></tr>
<tr><td>43</td><td>+</td><td>59</td><td>;</td><td>75</td><td>K</td><td>91</td><td>[</td><td>107</td><td>k</td><td>123</td><td>{</td></tr>
<tr><td>44</td><td>,</td><td>60</td><td><</td><td>76</td><td>L</td><td>92</td><td>\</td><td>108</td><td>l</td><td>124</td><td>|</td></tr>
<tr><td>45</td><td>-</td><td>61</td><td>=</td><td>77</td><td>M</td><td>93</td><td>]</td><td>109</td><td>m</td><td>125</td><td>}</td></tr>
<tr><td>46</td><td>.</td><td>62</td><td>></td><td>78</td><td>N</td><td>94</td><td>^</td><td>110</td><td>n</td><td>126</td><td>~</td></tr>
<tr><td>47</td><td>/</td><td>63</td><td>?</td><td>79</td><td>O</td><td>95</td><td>_</td><td>111</td><td>o</td><td>127</td><td>del</td></tr>
</table>

C: Null-terminated strings

ex

C strings: arrays of ASCII characters ending with *null character*.

Why?

0x57	0x65	0x6C	0x6C	0x65	0x73	0x6C	0x65	0x79	0x20	0x43	0x53	0x00
'W'	'e'	'l'	'l'	'e'	's'	'l'	'e'	'y'	' '	'C'	'S'	'\0'

Does Endianness matter for strings?

```
int string_length(char str[]) {



}
```


How many bytes does it take to store the null-terminated string "hi bye"?

0

- 1
- 3
- 5
- 6
- 7
- 8

C: * *and* [ ]

ex

C programmers often use * where you might expect []:

e.g., char*:

- pointer to a char
- pointer to the first char in a string of unknown length

```
int strcmp(char* a, char* b);
```


C: 0 vs. '\0' vs. NULL

0
Name: zero
Type: `int`
Size: 4 bytes
Value: `0x00000000`
Usage: The integer zero.

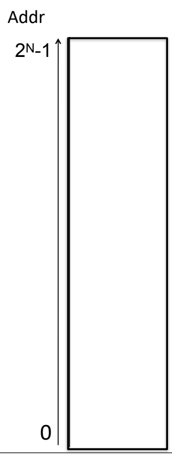
'\0'
Name: null character
Type: `char`
Size: 1 byte
Value: `0x00`
Usage: Terminator for C strings.

NULL
Name: null pointer / null reference / null address
Type: `void*`
Size: 1 word (= 8 bytes on a 64-bit architecture)
Value: `0x0000000000000000`
Usage: The absence of a pointer where one is expected.
Address 0 is inaccessible, so `*NULL` is invalid; it crashes.

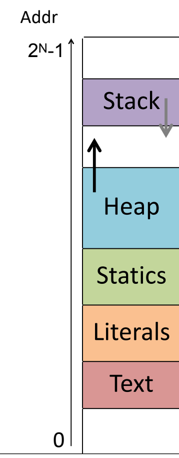
Is it important/necessary to encode the null character or the null pointer as 0x0?

What happens if a programmer mixes up these "zeroey" values?

Memory address-space layout

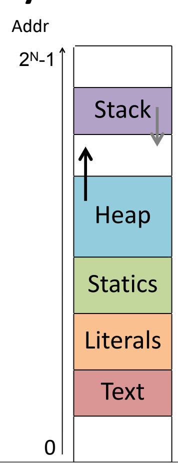


Memory address-space layout



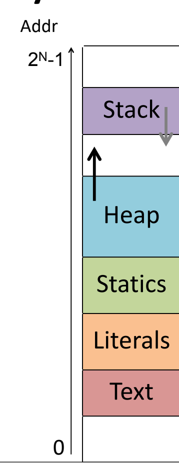
Perm	Contents	Managed by	Initialized
RW	Procedure context, local variables	Compiler	Run time

Memory address-space layout



Perm	Contents	Managed by	Initialized
RW	Procedure context, local variables	Compiler	Run time
RW	Global variables/ static data structures	Compiler/ Assembler/Linker	Startup
R	String literals	Compiler/ Assembler/Linker	Startup
X	Instructions	Compiler/ Assembler/Linker	Startup

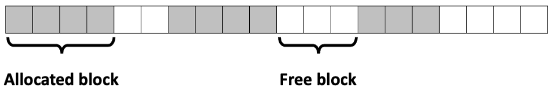
Memory address-space layout



Perm	Contents	Managed by	Initialized
RW	Procedure context, local variables	Compiler	Run time
RW	Dynamic data structures	Programmer, malloc/free, new/ GC	Run time
RW	Global variables/ static data structures	Compiler/ Assembler/Linker	Startup
R	String literals	Compiler/ Assembler/Linker	Startup
X	Instructions	Compiler/ Assembler/Linker	Startup

C: Dynamic memory allocation in the heap

Heap:



Managed by memory allocator:

pointer to newly allocated block of at least that size

number of contiguous bytes required

```
void* malloc(size_t size);

void free(void* ptr);
```

pointer to allocated block to free

C: standard memory allocator

```
#include <stdlib.h>      // include C standard library
void* malloc(size_t size)
```

Allocates a memory block of at least `size` bytes and returns its address.

If memory error (e.g., allocator has no space left), returns `NULL`.

Rules:

- Check for error result.
- Cast result to relevant pointer type.
- Use sizeof(...) to determine size.

```
void free(void* ptr)
```

Deallocates the block referenced by `ptr`, making its space available for new allocations.

`ptr` **must** be a `malloc` result that has not yet been `free`d.

Rules:

- `ptr` must be a `malloc` result that has not yet been freed.
- Do not use `*ptr` after freeing.

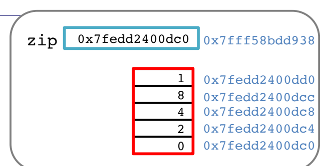
C: Dynamic array allocation

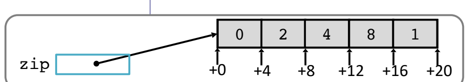
```
#define ZIP_LENGTH 5
int* zip = (int*)malloc(sizeof(int)*ZIP_LENGTH);
if (zip == NULL) {   // if error occurred
  perror("malloc");  // print error message
  exit(0);           // end the program
}

zip[0] = 0;
zip[1] = 2;
zip[2] = 4;
zip[3] = 8;
zip[4] = 1;

printf("zip is");
for (int i = 0; i < ZIP_LENGTH; i++) {
   printf(" %d", zip[i]);
}
printf("\n");

free(zip);
```





C: Array of pointers to arrays of `int`s

```
int** zips = (int**)malloc(sizeof(int*) * 3);

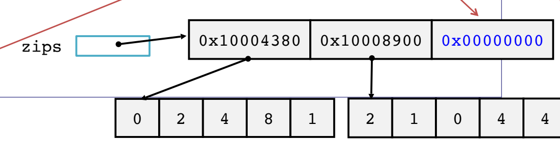
zips[0] = (int*)malloc(sizeof(int)*5);
int* zip0 = zips[0];
zip0[0] = 0;
zips[0][1] = 2;
zips[0][2] = 4;
zips[0][3] = 8;
zips[0][4] = 1;

zips[1] = (int*)malloc(sizeof(int)*5);
zips[1][0] = 2;
zips[1][1] = 1;
zips[1][2] = 0;
zips[1][3] = 4;
zips[1][4] = 4;

zips[2] = NULL;
```

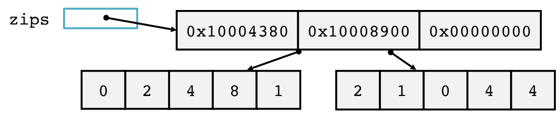
Why no NULL?

Why terminate with NULL?



Zip code

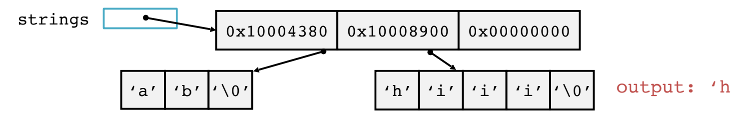
ex




```c
// return a count of all zips that end with digit endNum
int zipCount(int* zips[], int endNum) {



}
```


Group example: longest string starts with

ex



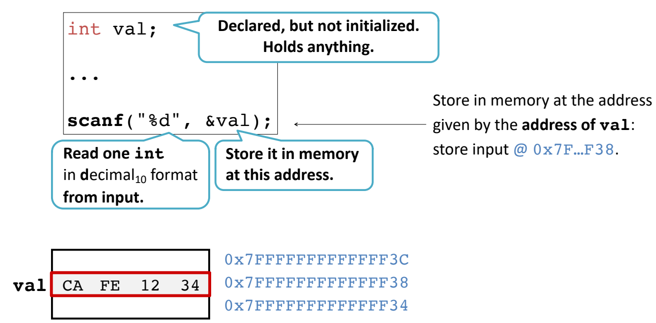

```c
// Return the starting character of the longest string in the
// null-terminated strings array.
// You can use: int strlen(char *str)
char longest_string_starts_with(char ** strings) {

}
```


Group example: longest string starts with

ex

```c
// Return the starting character of the longest string in the
// null-terminated strings array.
// You can use: int strlen(char *str)
char longest_string_starts_with(char ** strings) {
    int longest = 0;
    char c = '\0';
    while (*strings) {
        int l = strlen(*strings);
        if (l > longest) {
            longest = l;
            c = *(*strings);
        }
        strings++;
    }
    return c;
}
```


`scanf` reads formatted input



C: Classic bug using `scanf`

!!!

```
int val;
...
scanf("%d",  val);
```

Declared, but not initialized. Holds anything.

Read one `int` in decimal_{10} format from input.

Store it in memory at this address.

Store in memory at the address given by the **contents of `val`** (implicitly cast as a pointer): store input @ `0xBAD4FACE`.

		0x7FFFFFFFFFFFFF3C
val	BA D4 FA CE	0x7FFFFFFFFFFFFF38
		0x7FFFFFFFFFFFFF34
	...	...
	CA FE 12 34	0x00000000BAD4FACE

Best case: 🙌! **crash immediately** with segmentation fault/bus error.

Bad case: 🤬 **silently corrupt data** stored @ `0xBAD4FACE`, **fail to store input in `val`**, *and keep going.*

Worst case: 💻🔥🧨🚀 program does literally anything.

C: Memory error messages

11: **segmentation fault** ("**segfault**", SIGSEGV)
accessing address outside legal area of memory

10: **bus error** (SIGBUS)
accessing misaligned or other problematic address

More to come on debugging!

http://xkcd.com/371/

C: Why?

Why learn C?

- Think like actual computer (abstraction close to machine level) without dealing with machine code.
- Understand just how much Your Favorite Language provides.
- Understand just how much Your Favorite Language might cost.
- Classic.
- Still (more) widely used (than it should be).
- Pitfalls still fuel devastating reliability and security failures today.

Why not use C?

- Probably not the right language for your next personal project.
- It "gets out of the programmer's way" … even when the programmer is unwittingly running toward a cliff.
- Advances in programming language design since the 70's have produced languages that fix C's problems while keeping strengths.

Fill out the Pointers partner form (even if solo)

http://xkcd.com/138/

https://forms.gle/kmL62aTcm9Nh3xjG9