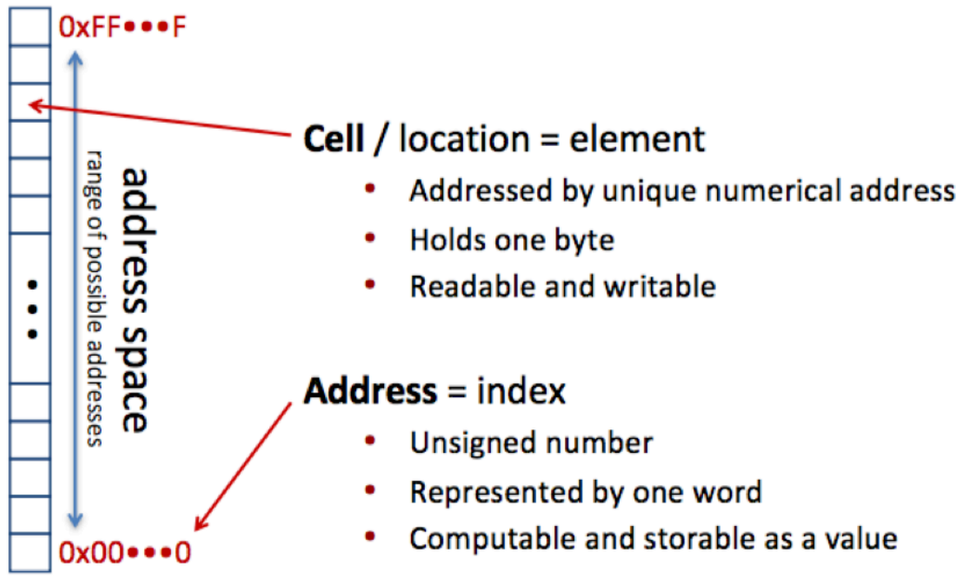
Programming with Memory

via C, pointers, and arrays

Why not just registers?

- Represent larger structures
- Computable addressing
- Indirection

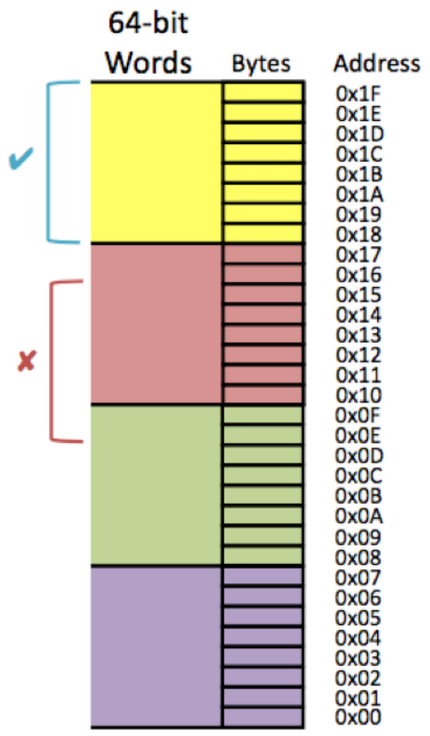
byte-addressable memory = mutable byte array



multi-byte values in memory

Store across contiguous byte locations.

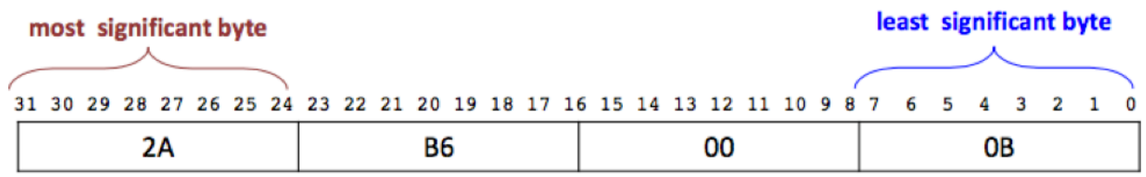
Alignment (Why?)



Bit order within byte always same.

Byte ordering within larger value?

Endianness: To store a multi-byte value in memory, which byte is stored first (at a lower address)?



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

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

Little Endian: least significant byte first

- low order byte at low address, high order byte at high address
- used by **x86**, ...

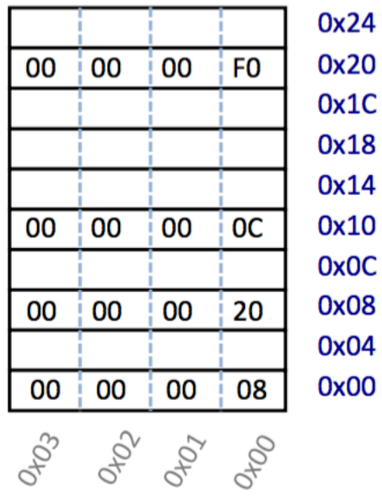
Big Endian: most significant byte first

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

Data, Addresses, and Pointers

address = index of a cell in memory

pointer = address represented as data



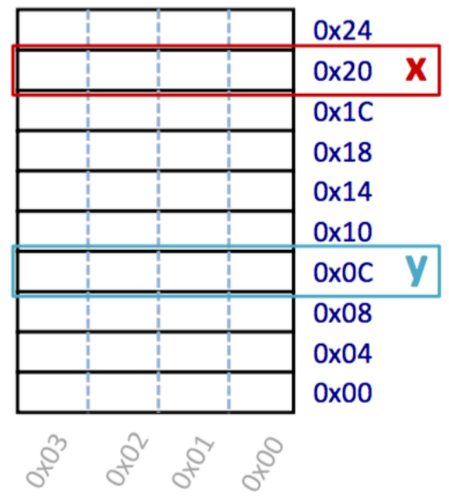
memory drawn as 32-bit values, little endian order

C: variables are memory locations (for now)

Compiler maps variable → memory location.

Declarations do not initialize!

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

x = 0; // store 0 at 0x20

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

// load the contents at 0x0C,
// add 3, and store sum at 0x20
x = y + 3;
```



C: Address and Pointer Primitives

address = index of a cell/location in memory

pointer = address represented as data

Expressions using addresses and pointers:

- &___ **address of** the memory location representing ___
- *___ **contents at** the memory address given by ___
  a.k.a. "dereference ___"

Pointer types:

- ___* address of a memory location holding a ___

C: Address and 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;
```
Get the address of the memory location representing x ... and store it in p. Now, "*p points to x.*"

```
y = 1 + *p;
```
Add 1 to the contents of memory at the address stored in p ... and store it in the memory location representing y.

C: Address and Pointer Example

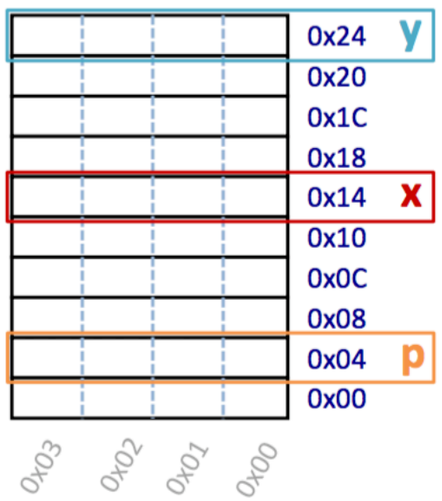
& = address of
** = contents at*

C assignment:

Left-hand-side = right-hand-side;

location value

```
int* p;      // p: 0x04
int x = 5;   // x: 0x14, store 5 at 0x14
int y = 2;   // y: 0x24, store 2 at 0x24
p = &x;      // store 0x14 at 0x04
// load the contents at 0x04  (0x14)
// load the contents at 0x14  (0x5)
// add 1 and store sum at 0x24
y = 1 + *p;
// load the contents at 0x04  (0x14)
// store 0xF0 (240) at 0x14
*p = 240;
```



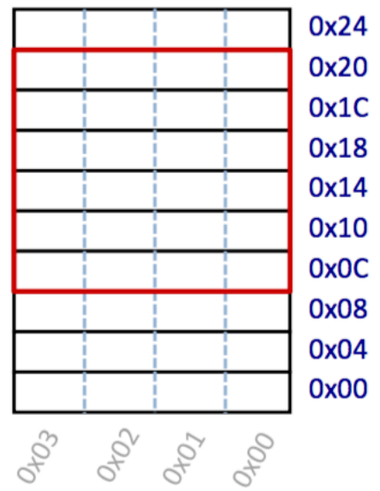
C: Arrays

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



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.

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

Declaration: `int a[6];`

Indexing:
```
a[0] = 0xf0;
a[5] = a[0];
```

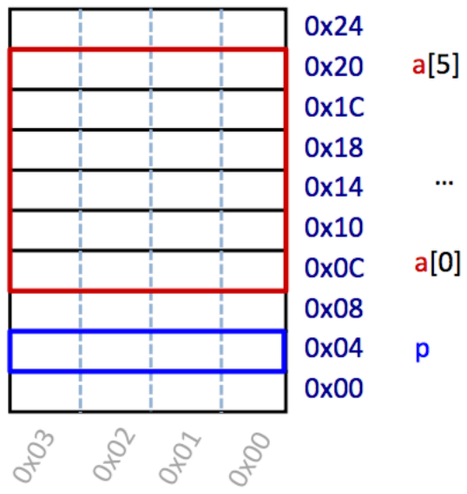
No bounds check:
```
a[6] = 0xBAD;
a[-1] = 0xBAD;
```

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

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

array indexing = address arithmetic
Both are scaled by the size of the type.

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



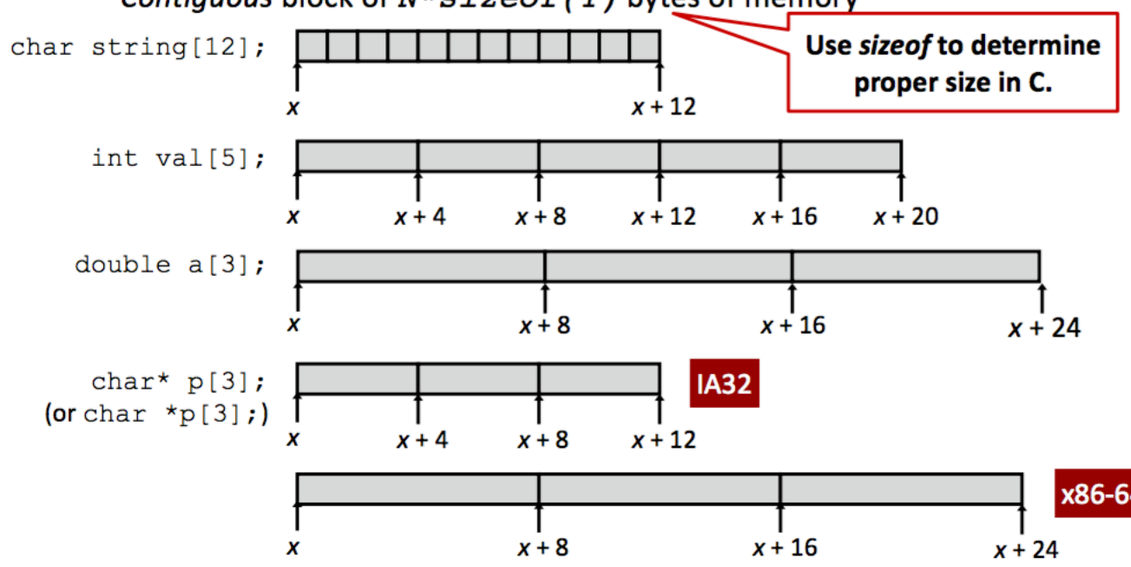
C: Array Allocation

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



C: Array Access

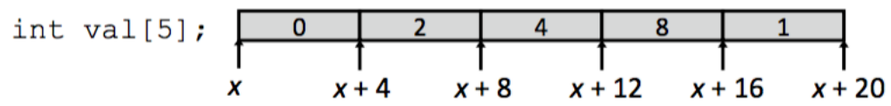
ex

Basic Principle

T *A*[*N*];

Array of length *N* with elements of type *T* and name *A*

Identifier *A* can be used as a pointer to array element 0: *A* has type *T**



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

C: Null-terminated strings

ex

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

Why?

0x48	0x61	0x72	0x72	0x79	0x20	0x50	0x6F	0x74	0x74	0x65	0x72	0x00
'H'	'a'	'r'	'r'	'y'	' '	'P'	'o'	't'	't'	'e'	'r'	'\0'

Does Endianness matter for strings?

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




}
```

C: * *and* [ ]

ex

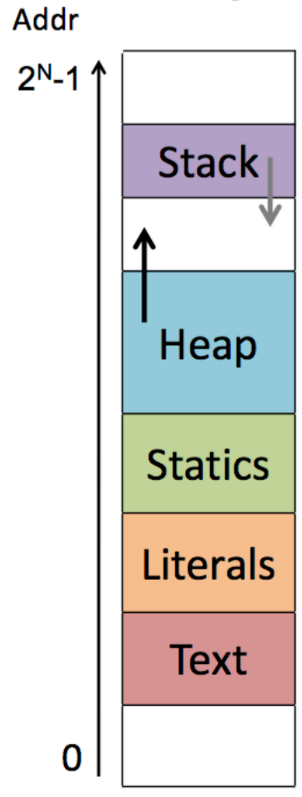
C programmers often use * where you might expect []:

e.g., char*:

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

```
int strcmp(char* a, char* b);
int string_length(char* str) {
  // Try with pointer arithmetic, but no array indexing.




}
```

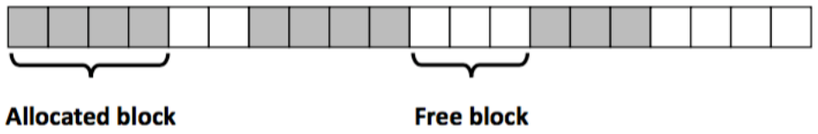
Memory Layout



Perm	Contents	Managed by	Initialized
RW	Procedure context	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);
```

pointer to allocated block to free

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


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 error (no space), returns `NULL`.

Rules:

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

`void free(void* p)`

Deallocates the block at **`p`**, making its space available for new allocations.

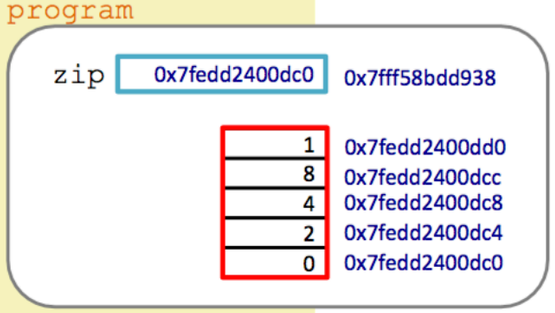
`p` must be a **`malloc`** result that has not yet been freed.

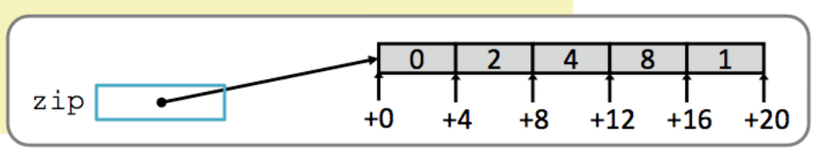
Rules:

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

C: Dynamic array allocation

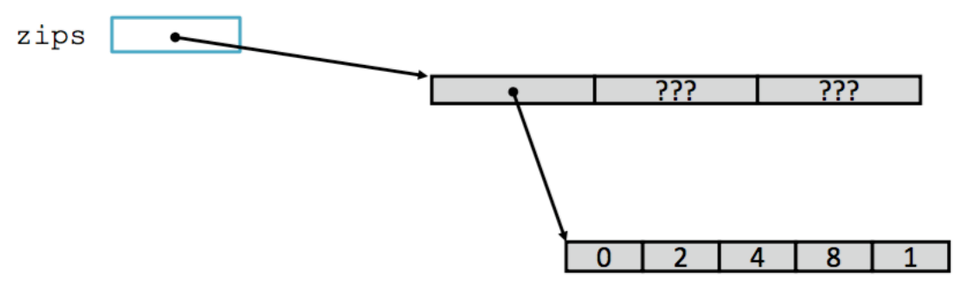
```
#define ZIP_LENGTH 5
int* zip = (int*)malloc(sizeof(int)*ZIP_LENGTH);
if (zip == NULL) {    // if error occurred
  perror("malloc");   // print error message
  exit(0);            // end the program
}

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: Arrays of pointers to arrays of …

```
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;
```



C: Memory-Related Perils and Pitfalls

Terrible things to do with pointers, part 1.

Dereferencing bad pointers

See later exercises for:

- Reading uninitialized memory
- Overwriting memory
- Referencing nonexistent variables
- Freeing blocks multiple times
- Referencing freed blocks

C: scanf reads formatted input

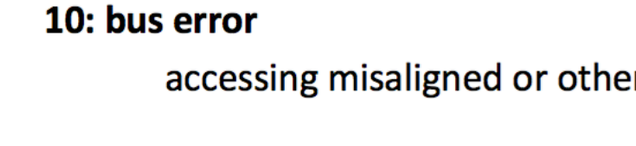
```
int val;

...

scanf("%d", &val);
```

Declared, but not initialized – holds anything.

Read one int from input.

Store it in memory at this address.

i.e., store it in memory at the address **where the contents of val is stored**: store into memory at 0xFFFFFF38.



C: classic bug using scanf

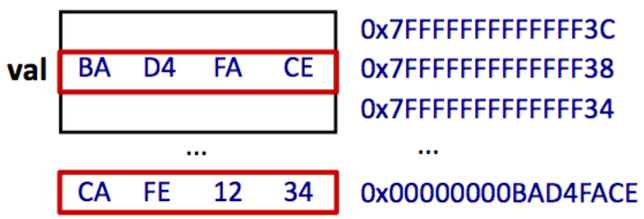

```
int val;

...

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

Declared, but not initialized – holds anything.

Read one int from input.

Store it in memory at this address.

i.e., store it in memory at the address **given by the contents of val**: store into memory at 0xBAD4FACE.



Best case: segmentation fault, or bus error, crash.

Bad case: silently corrupt data stored at address 0xBAD4FACE, and val still holds 0xBAD4FACE.
Worst case: arbitrary corruption

C: memory error messages

http://xkcd.com/371/

11: segmentation fault ("segfault", SIGSEGV)

accessing address outside legal area of memory

10: bus error

accessing misaligned or other problematic address

More to come on debugging!