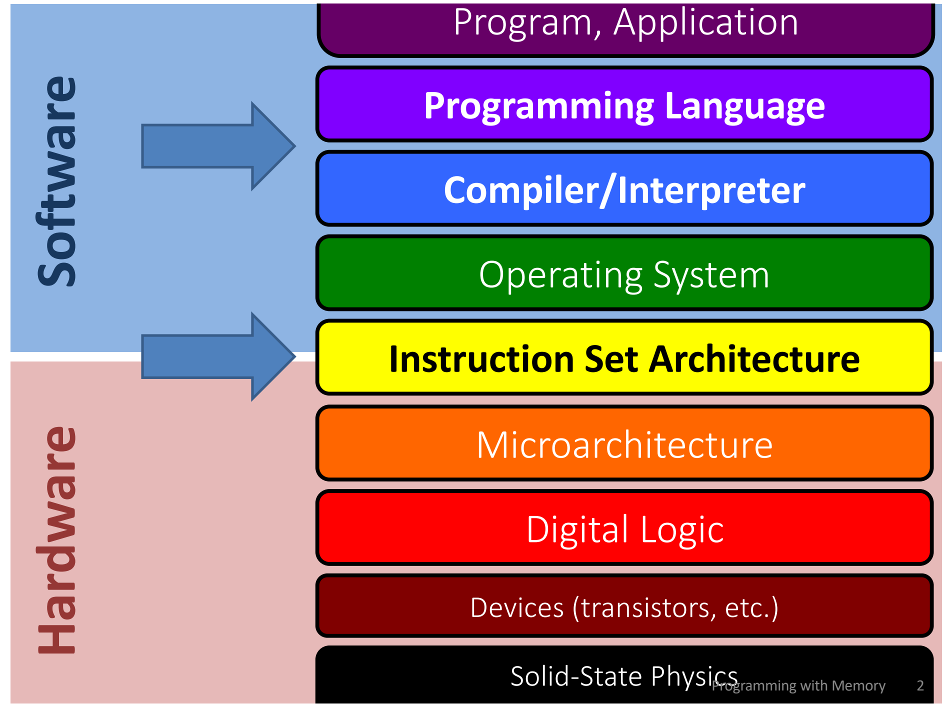
CS 240 Spring 2020
Foundations of Computer Systems
Ben Wood

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



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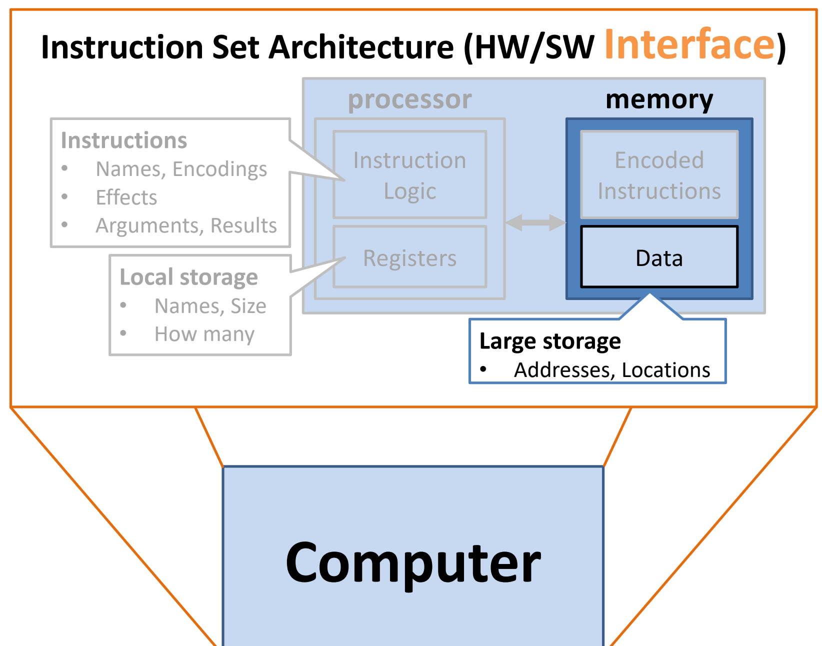
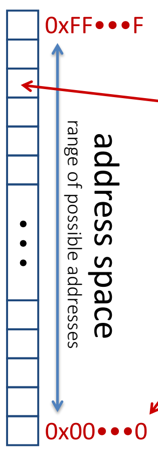
Programming with Memory

pointers and arrays in C



Byte-addressable memory = mutable byte array



Location / cell = element

- Addressed by unique numerical address
- Holds one byte
- Readable and writable

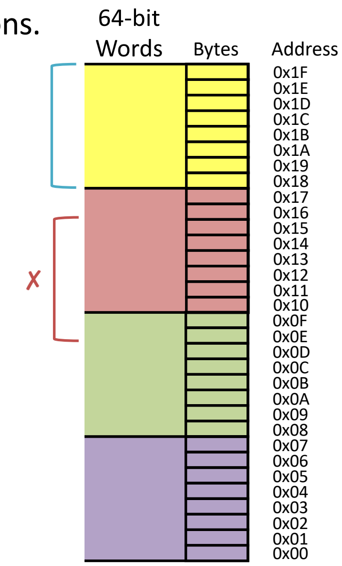
Address = index

- Unsigned number
- Represented by one word
- Computable and storable as a value

Multi-byte values in memory

Store across contiguous byte locations.

Alignment (Why?)



Bit order within byte always same.
Byte ordering within larger value?

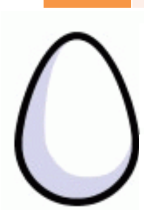
Endianness: To store a multi-byte value in memory, which byte is stored first (at a lower address)?

most significant byte — least significant byte

31–24	23–16	15–8	7–0
2A	B6	00	0B

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**, …

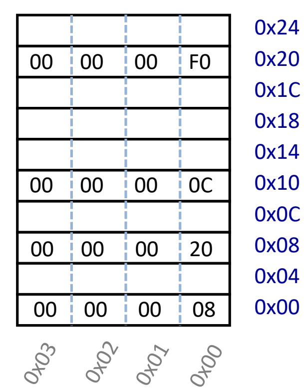
Big Endian: most significant byte first

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

Data, addresses, and pointers

address = index of a location in memory

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



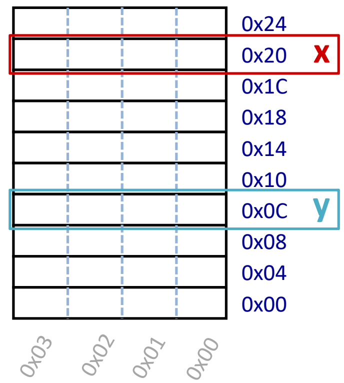
memory drawn as 32-bit values, little endian order

C: Variables are locations

Compiler maps variable name → 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: Pointer operations and types

address = index of a location in memory

pointer = a reference to a location in memory, represented as 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: Pointer example

& = address of
** = contents at*

```
int* p;


int x = 5;
int y = 2;


p = &x;



y = 1 + *p;
```


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;
```

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: Pointer example

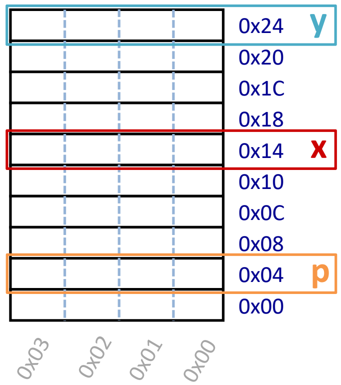
& = address of
** = contents at*

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: Pointer type syntax

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

The following are equivalent:

`int* ptr;` I prefer this

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.

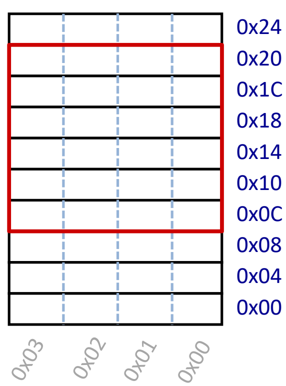
a is a name for the array's base address, can be used as an *immutable* pointer.

Declaration: `int a[6];`

element type

name

number of elements



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;
```

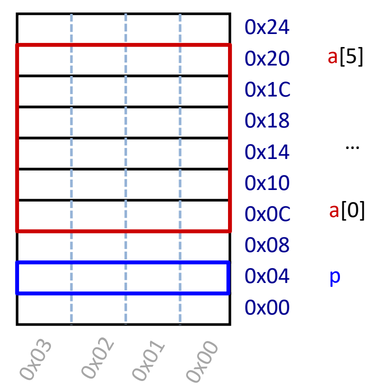
Pointers:
```
int* p;
```
equivalent {
```
p = a;
p = &a[0];
```
```
*p = 0xA;
```

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;
```



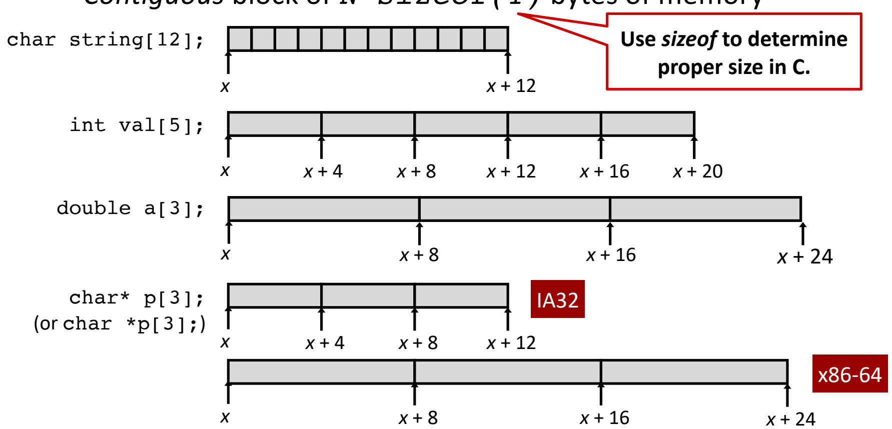
C: Array allocation

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

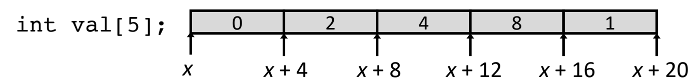
ex

Basic Principle

T A[*N*];

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

Identifier *A* has type



Expression	Type	Value
`val[4]`	`int`	`1`
`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.

}
```

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?

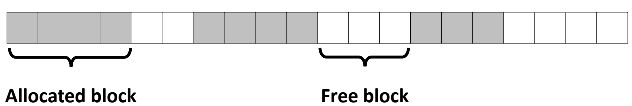
What happens if a programmer mixes up these "zeroey" values?

Memory address-space layout

Addr		Perm	Contents	Managed by	Initialized
2^N-1					
	Stack	RW	Procedure context	Compiler	Run time
	Heap	RW	Dynamic data structures	Programmer, malloc/free, new/GC	Run time
	Statics	RW	Global variables/ static data structures	Compiler/ Assembler/Linker	Startup
	Literals	R	String literals	Compiler/ Assembler/Linker	Startup
	Text	X	Instructions	Compiler/ Assembler/Linker	Startup
0					

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

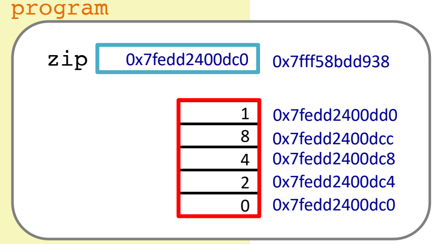
```
void* malloc(size_t size);
```

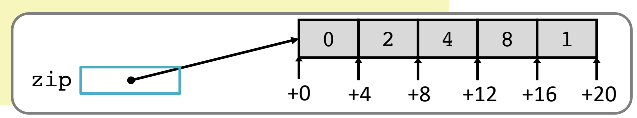
pointer to allocated block to free

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


C: 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);
```

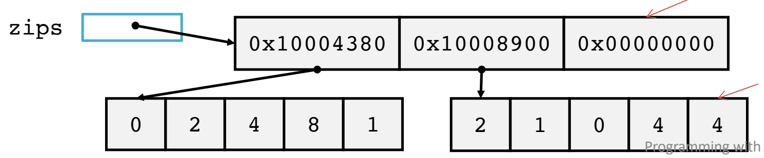




C: Array of pointers to arrays of `int`s

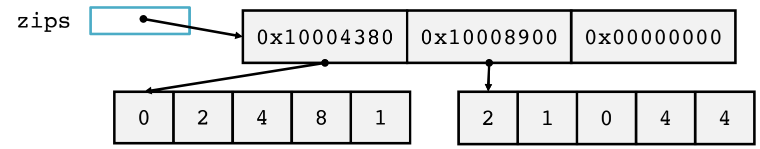
```
int** zips = (int**)malloc(sizeof(int*) * 3);

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 terminate with NULL?



Why no NULL?

Zip code




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

}
```


http://xkcd.com/138/

C: `scanf` reads formatted input

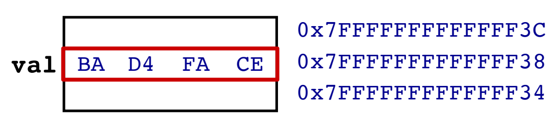
```
int val;
...
scanf("%d", &val);
```

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 **given by the contents of val**: store into memory at `0xBAD4FACE`.



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.

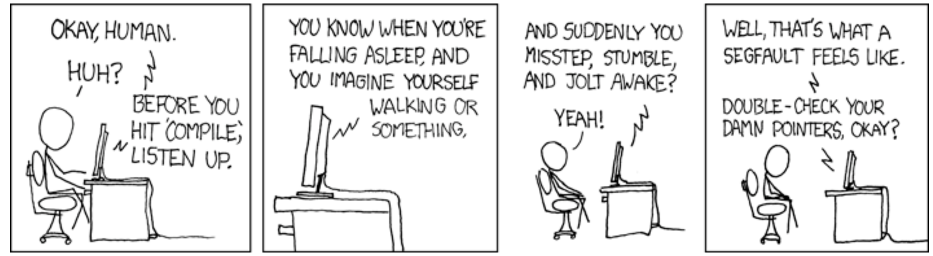
		0x7FFFFFFFFFFFFF3C
val	BA D4 FA CE	0x7FFFFFFFFFFFFF38
		0x7FFFFFFFFFFFFF34
	...	...
	CA FE 12 34	0x00000000BAD4FACE

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!

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.
- Many advances in programming language design since then have produced languages that fix C's problems while keeping strengths.