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
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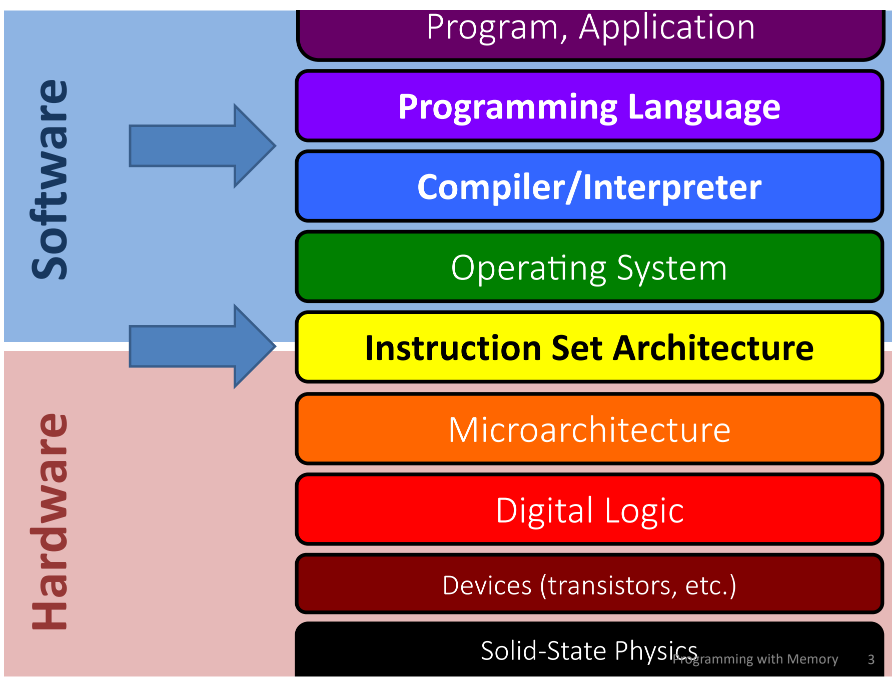
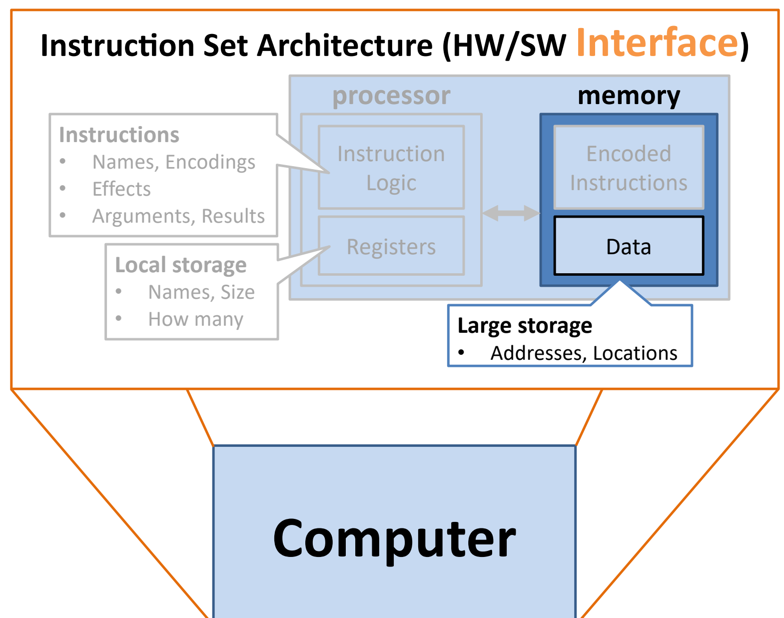
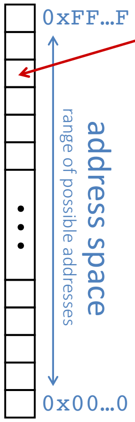
Programming with Memory

the memory model
pointers and arrays in C





Byte-addressable memory = mutable byte array



Location / cell = element
- Identified by unique numerical **address**
- Holds one byte

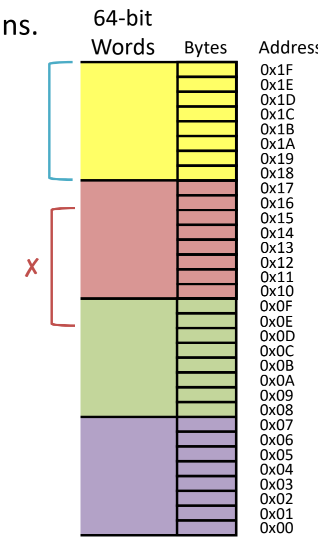
Address = index
- Unsigned number
- Represented by one word
- Computable and storable as a value

Operations:
- **Load:** read contents at given address
- **Store:** write contents at given address

Multi-byte values in memory

Store across contiguous byte locations.

Alignment (Why?)



Bit order within byte always same.

Byte ordering within larger value?

Endianness

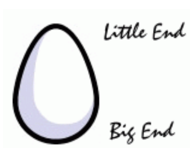
In what order are the individual bytes of a multi-byte value stored in memory?

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

Little Endian: least significant byte first
- low order byte at low address
- high order byte at high address
- used by **x86**, …



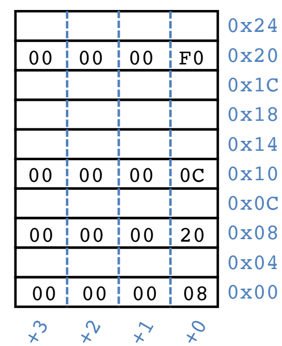
Address	Contents
03	0B
02	00
01	B6
00	2A

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

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

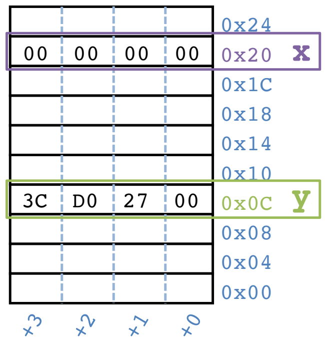
Compiler maps variable name → location.

Declarations do not initialize!

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

x = 0; // store 0 @ 0x20

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



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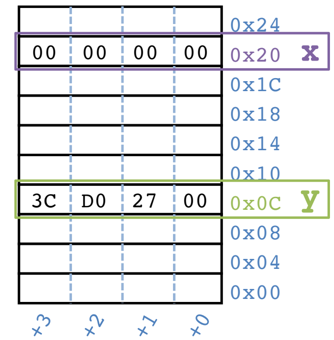
int y; // y @ 0x0C

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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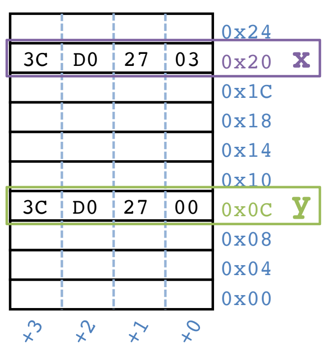


C: Pointer operations and types

address = index of a location in memory

pointer = a reference to a location in memory,
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: Types determine sizes

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 location 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

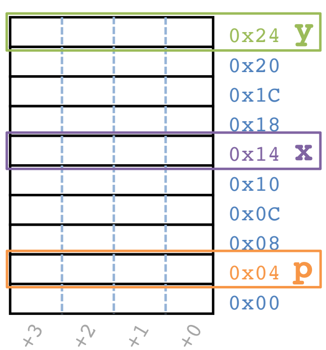
& = address of
** = contents at*

C assignment:
Left-hand-side **=** ***right-hand-side*;**
(Left-hand-side: location; right-hand-side: value)

```
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;
```



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**."

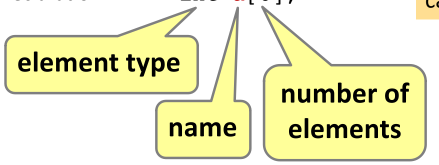
Caveat: do not declare multiple variables unless using the last form.
`int* a, b;` means `int *a, b;` means `int* a; int b;`

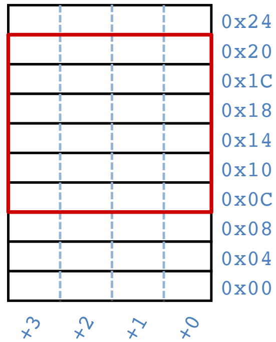
C: Arrays

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];`





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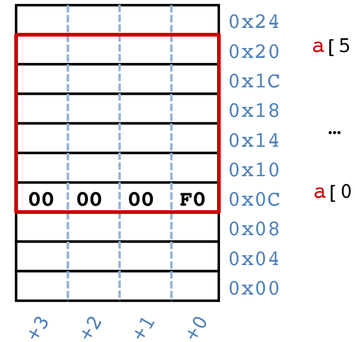
Address of `a[i]` is base address `a` plus `i` times element size in bytes.

Declaration: `int a[6];`

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



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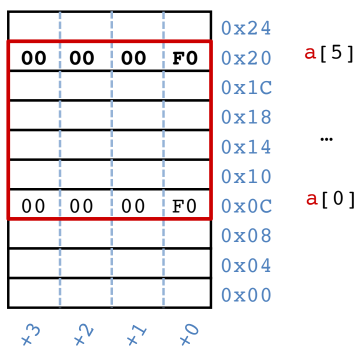

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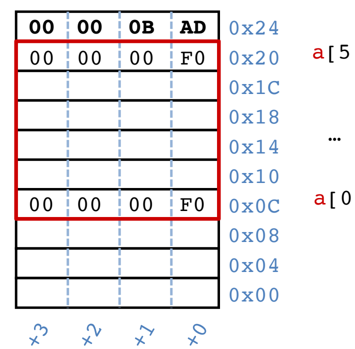

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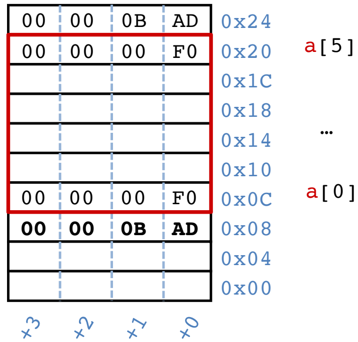

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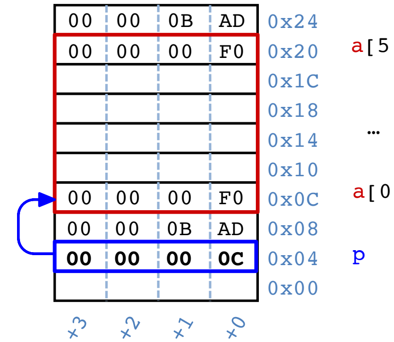

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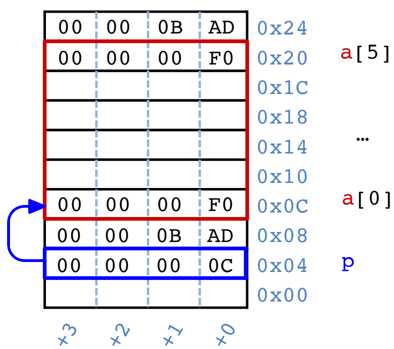

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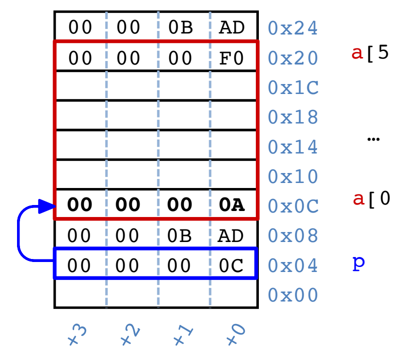

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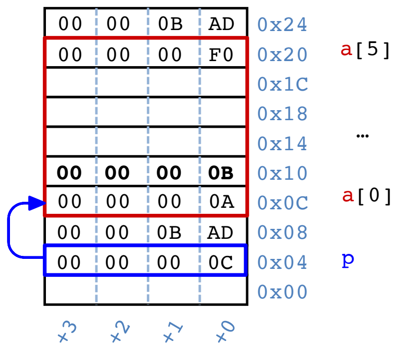
```

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

array indexing = address arithmetic

Both are scaled by the size of the type.



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

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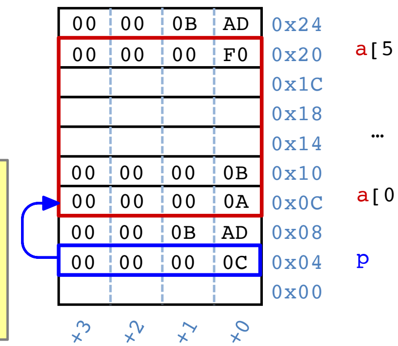

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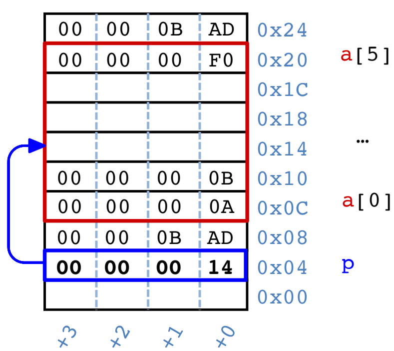

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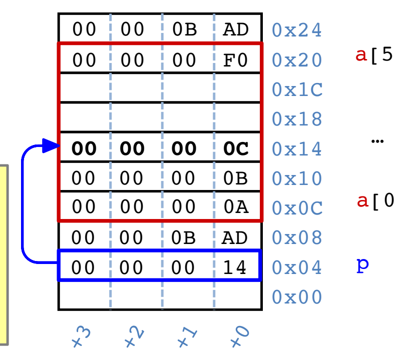



```
*p = a[1] + 1;
```

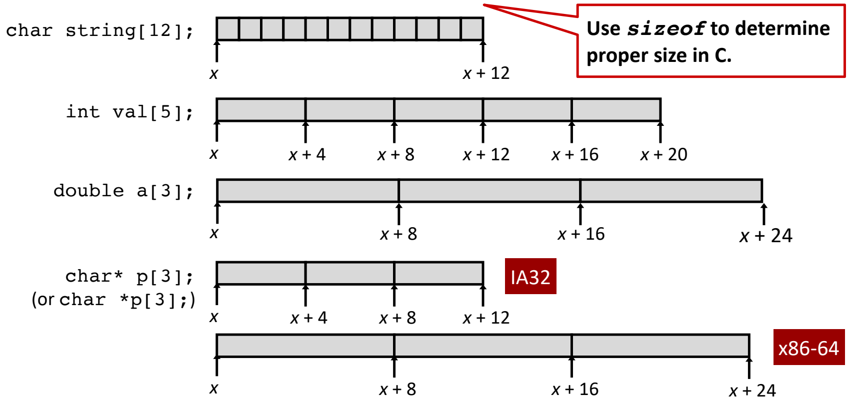
C: Array allocation

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

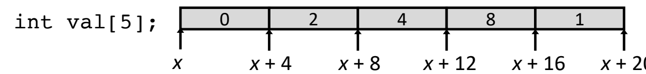
ex

Basic Principle

T *A*[*N*];

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

Identifier *A* has type *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

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

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[]) {



}
```

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.

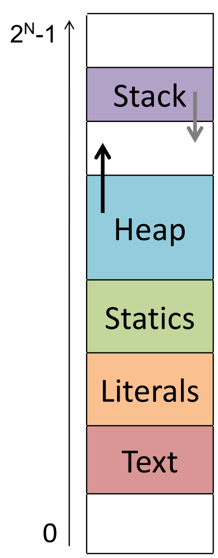
'\0'
Name: null character
Type: `char`
Size: 1 byte
Value: `0x00`
Usage: Terminator for C strings.

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?

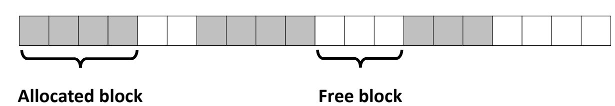
Memory address-space layout



	Perm	Contents	Managed by	Initialized
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

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* 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 `freed`.

Rules:

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

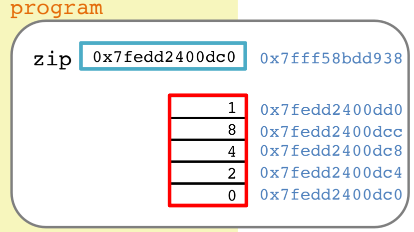
C: Dynamic array allocation

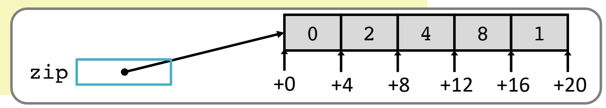
```
#define ZIP_LENGTH 5
int* zip = (int*)malloc(sizeof(int)*ZIP_LENGTH);
if (zip == NULL) {   // if error occurred
  perror("malloc");  // print error message
  exit(0);           // end the program
}

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 `ints`

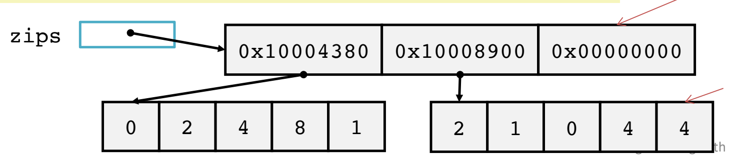
```
int** zips = (int**)malloc(sizeof(int*) * 3);

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;

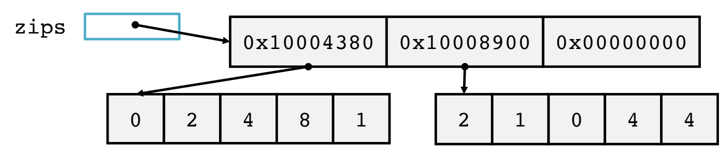
zips[2] = NULL;
```

Why terminate with `NULL`?



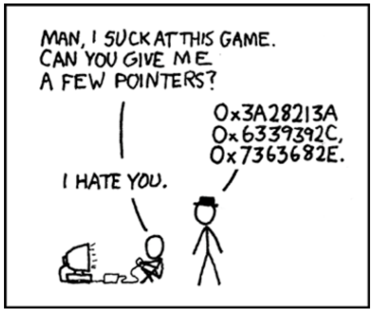
Why no `NULL`?

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` in decimal$_{10}$ format **from input.**

Store it in memory at this address.

Store in memory at the address given by the **address of `val`**: store input @ `0x7F…F38`.

		0x7FFFFFFFFFFFFF3C
val	CA FE 12 34	0x7FFFFFFFFFFFFF38
		0x7FFFFFFFFFFFFF34

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`.

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.

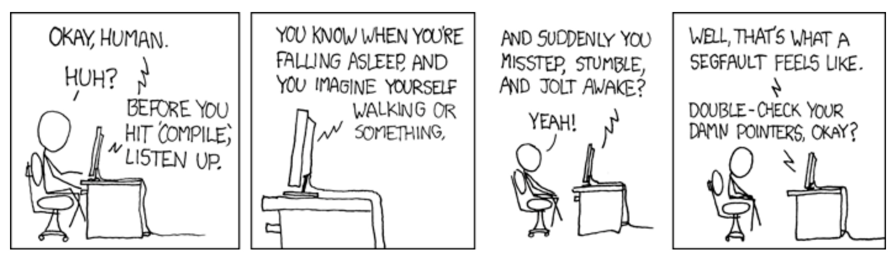
		0x7FFFFFFFFFFFFF3C
val	BA D4 FA CE	0x7FFFFFFFFFFFFF38
		0x7FFFFFFFFFFFFF34
	...	...
	CA FE 12 34	0x00000000BAD4FACE

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