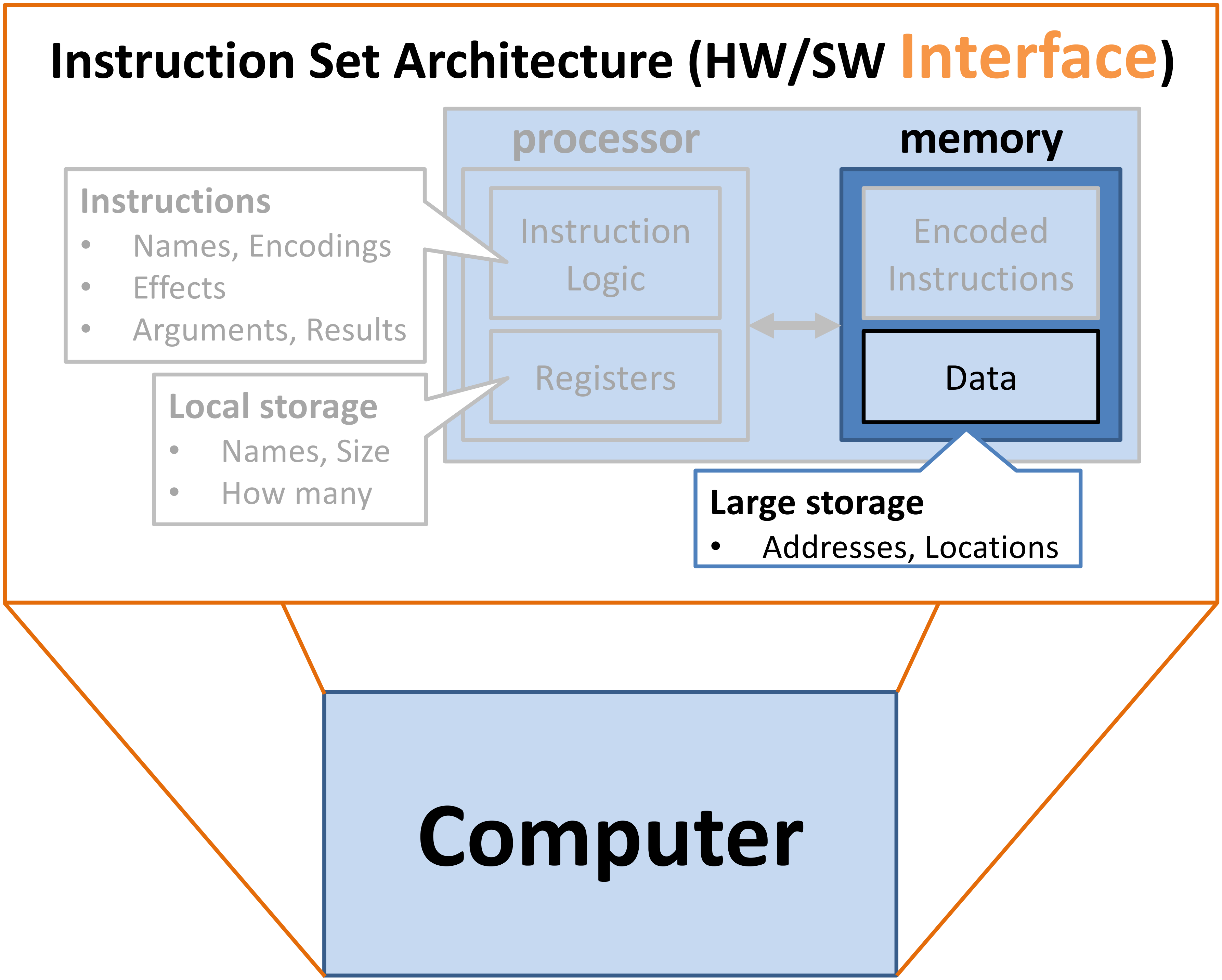
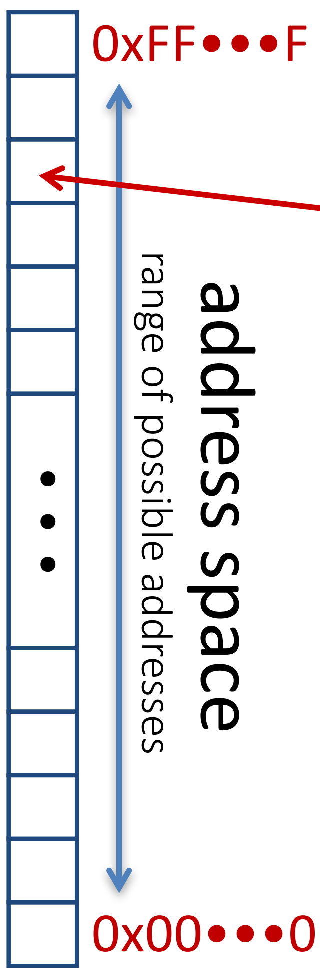
Programming with Memory

via C, pointers, and arrays


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

byte-addressable memory = mutable byte array



Cell / location = element

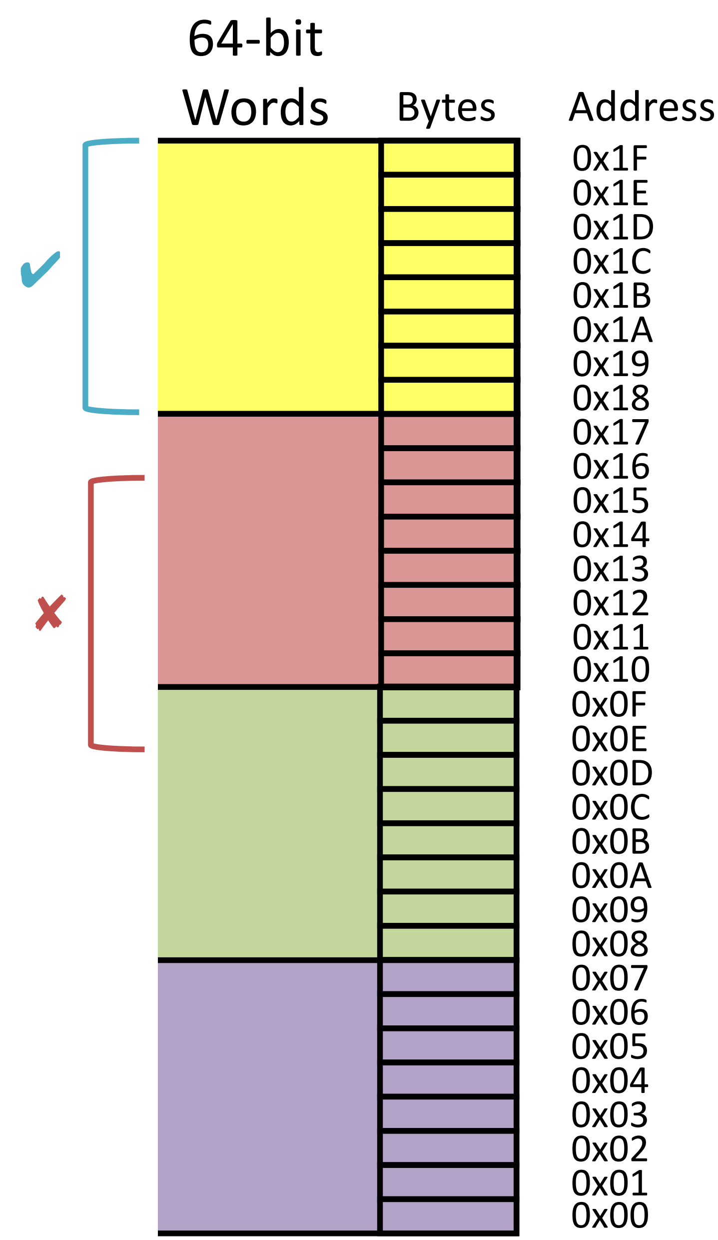
- Addressed by unique numerical address
- Holds one byte
- Readable and writable

Address = index

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

multi-byte values in memory

Store across contiguous byte locations.



Bit order within byte always same.

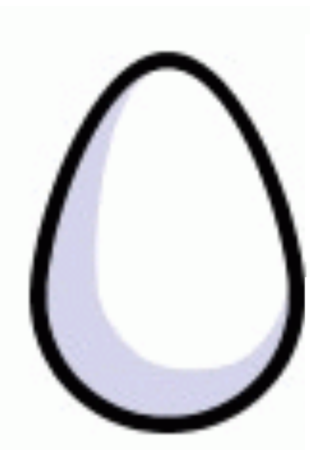
Endianness: To store a multi-byte value in memory, which byte is stored first (at a lower address)?

most significant byte — least significant byte

31 30 29 28 27 26 25 24	23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8	7 6 5 4 3 2 1 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 cell in memory

pointer = address represented as data

0x03	0x02	0x01	0x00	
				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

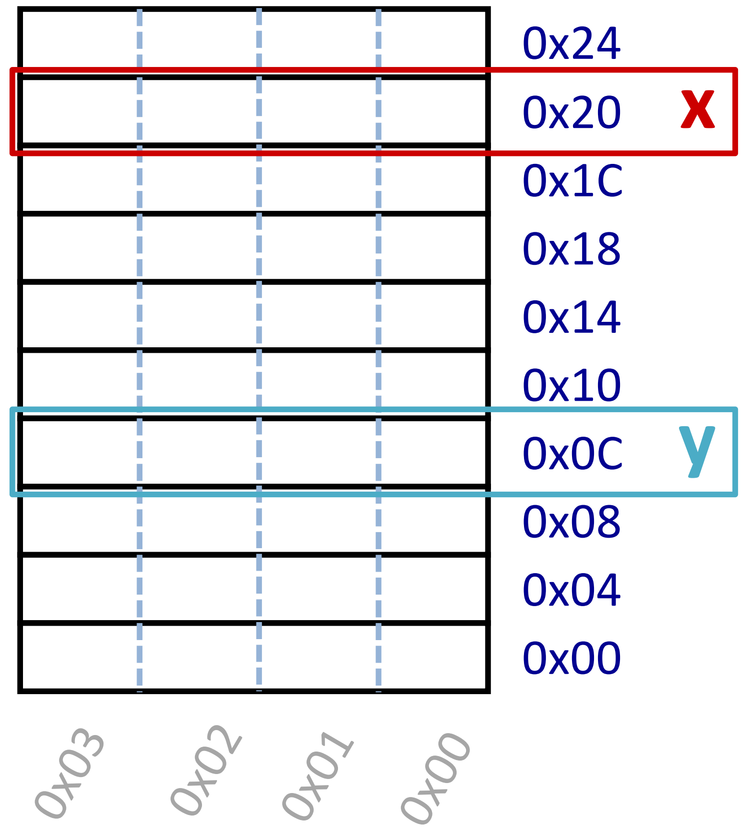
memory drawn as 32-bit values,
little endian order

C: variables are 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;
```

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

```
p = &x;
```

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

C: Address and Pointer Example

& = address of

** = contents at*

Declare a variable, p

```
int* 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.

Get the address of the memory location representing x

```
p = &x;
```

... and store it in p. Now, *"p points to x."*

Add 1 to the contents of memory at the address stored in p

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

... and store it in the memory location representing y.

C: Address and Pointer Example

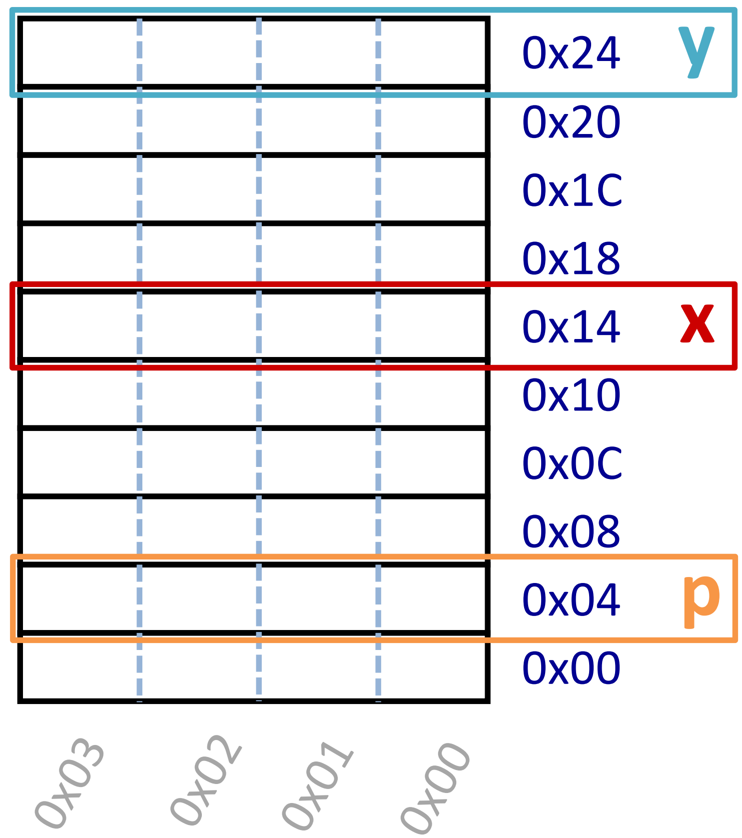
& = address of
** = contents at*

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: Pointer Type Syntax

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

The following are equivalent:

```c
int* ptr;
```

```c
int * ptr;
```

```c
int *ptr;
```

C: Arrays

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

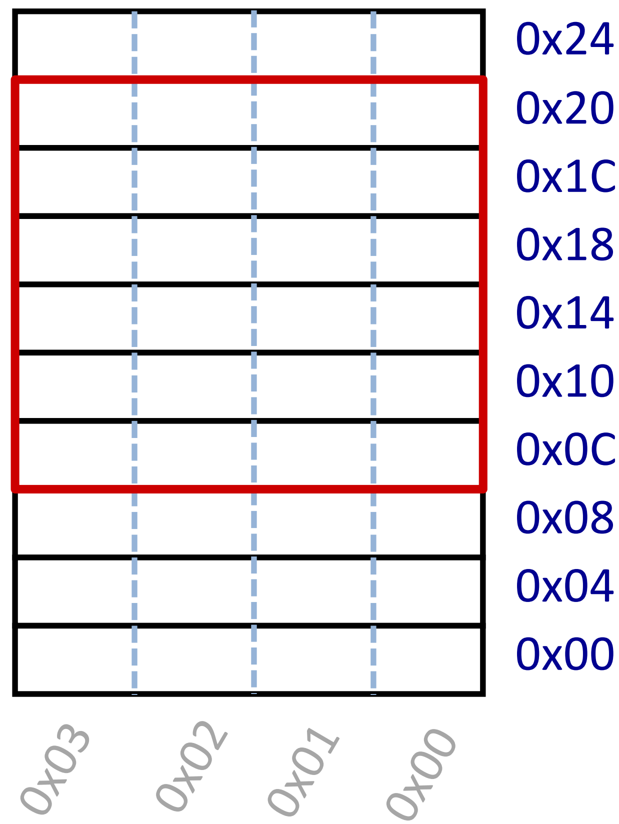
a is a name for the array's base address, can be used as an *immutable* pointer.

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;
```

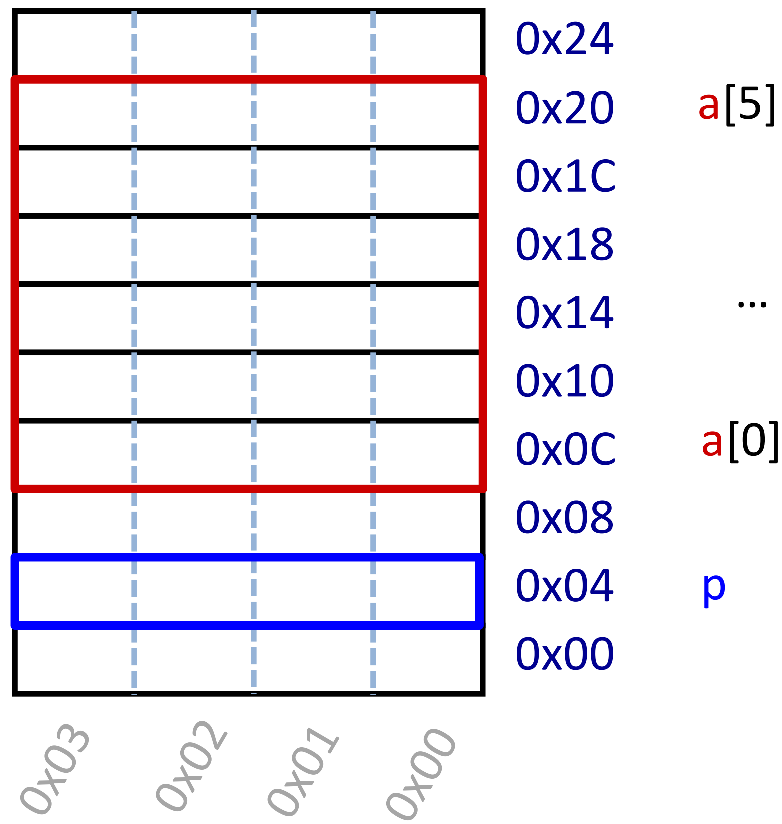
Pointers:
```
int* p;
```
equivalent {
```
p = a;
p = &a[0];
```
```
*p = 0xA;
```

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;
```



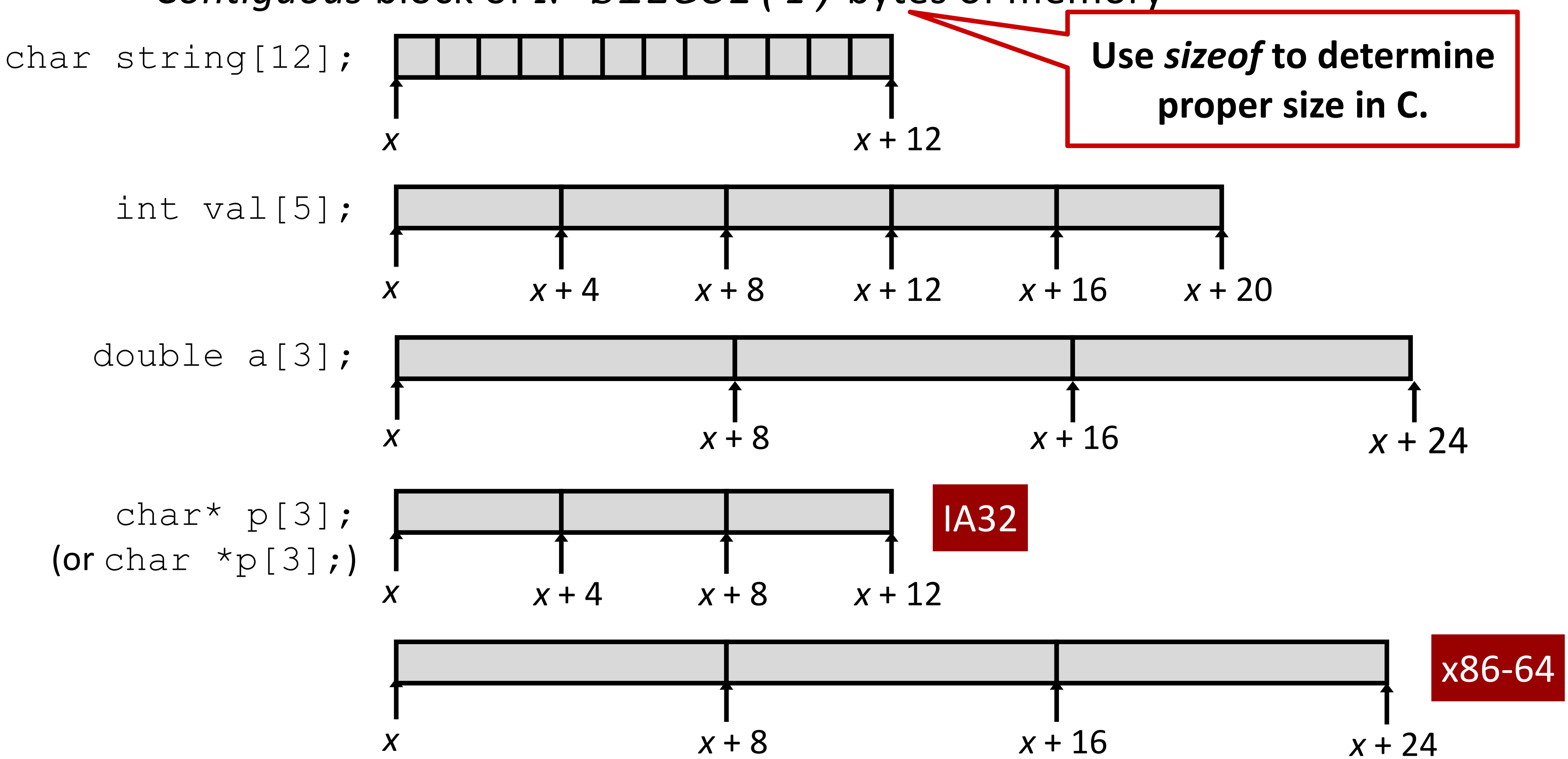
C: Array Allocation

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

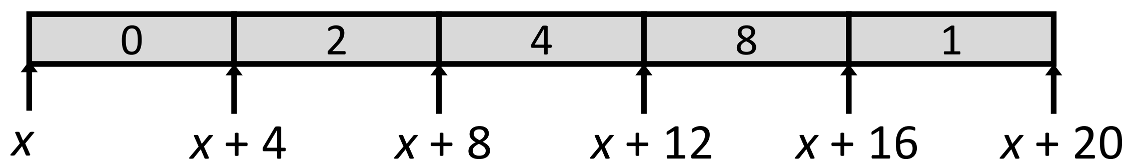
Basic Principle

T *A*[*N*];

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

Identifier *A* has type

```
int val[5];
```



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

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

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'

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



}
```

C: * *and* [ ]

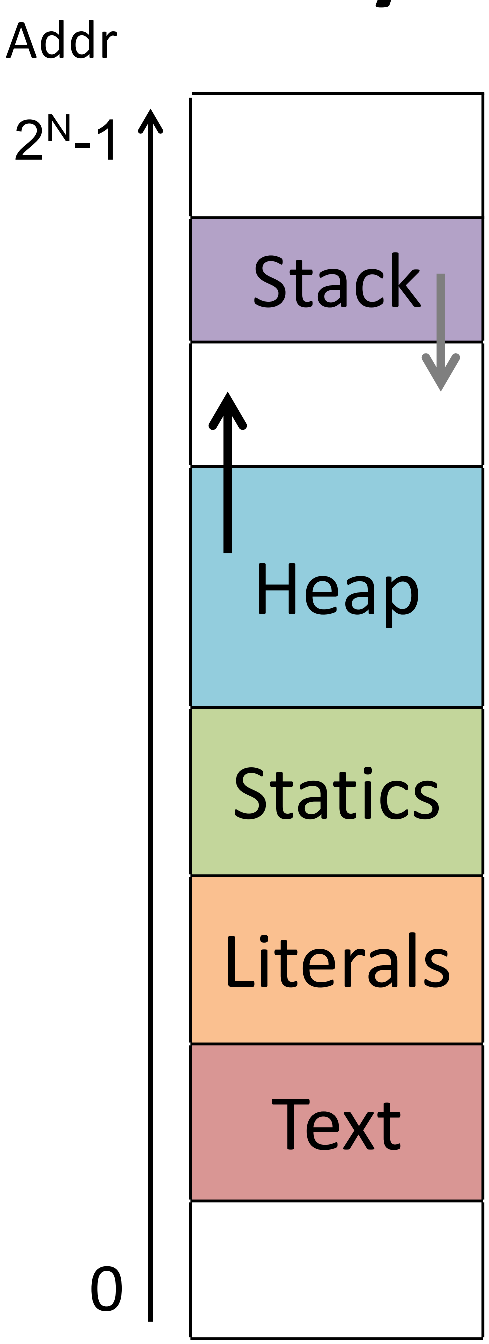
C programmers often use * where you might expect []:

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.









}
```

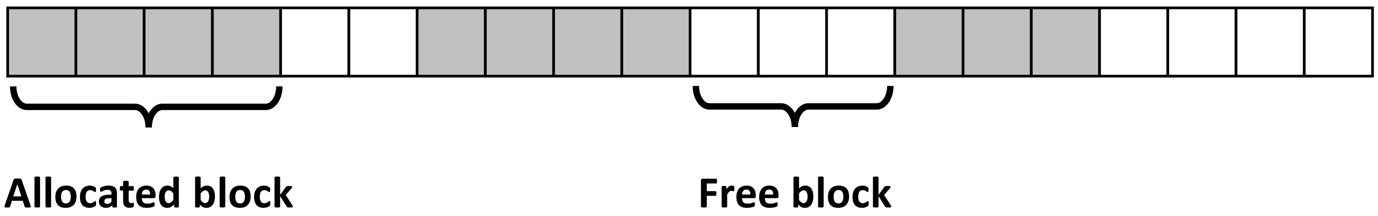
Memory Layout



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

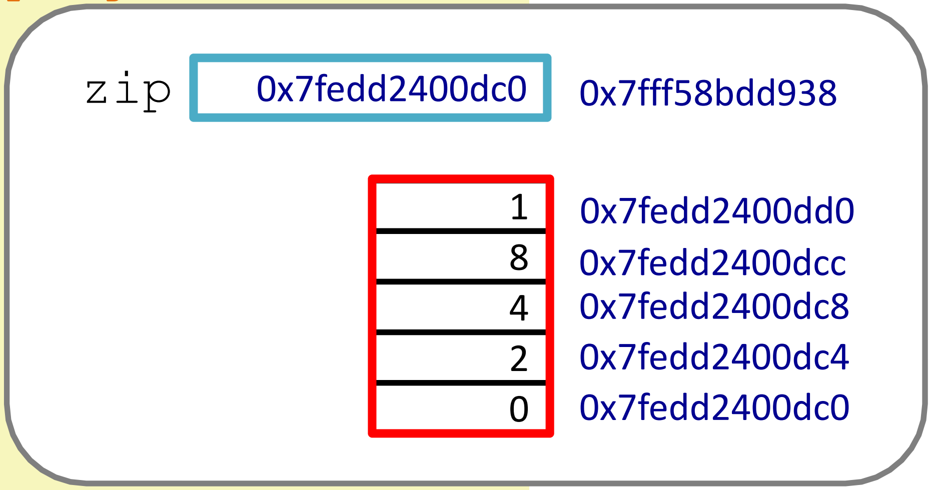
```
void free(void* ptr);
```

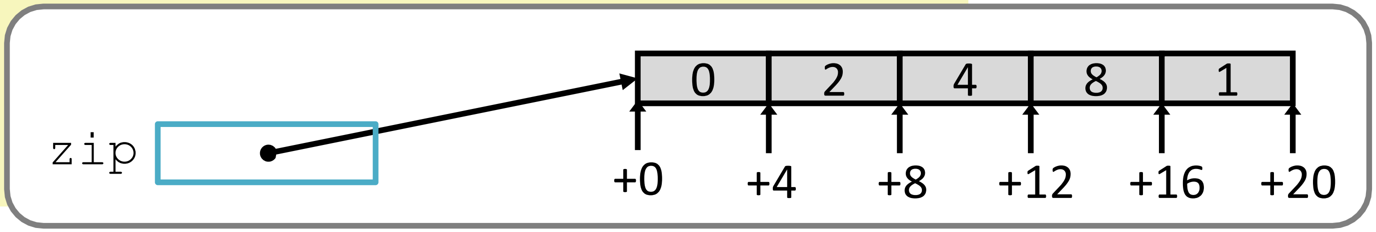
C: Dynamic array allocation

```
#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);          zip
```

C: Dynamic array allocation

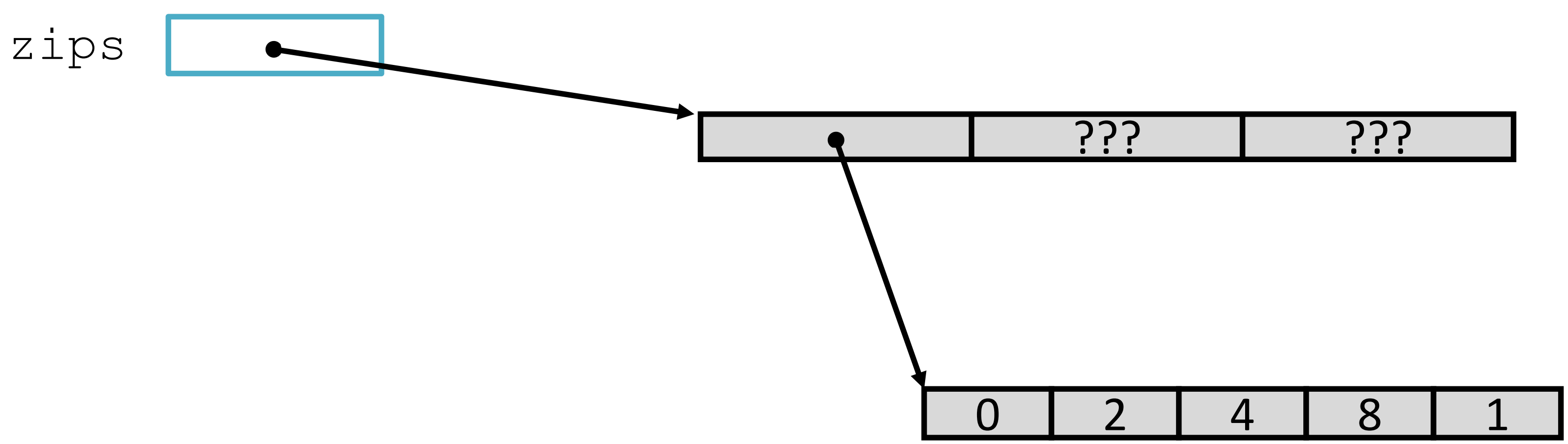
```
#define ZIP_LENGTH 5
int* zip = (int*)malloc(sizeof(int)*ZIP_LENGTH);
if (zip == NULL) {    // if error occurred
  perror("malloc");   // print error message
  exit(0);            // end the program
}

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: scanf reads formatted input

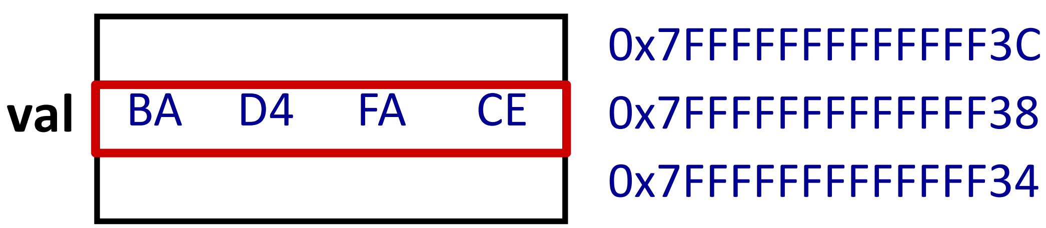
```
int val;

...

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.

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

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

11: segmentation fault ("segfault", SIGSEGV)

accessing address outside legal area of memory

10: bus error

accessing misaligned or other problematic address

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.