CS 110
Computer Architecture
C Memory Management

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Course website: https://faculty.sist.shanghaitech.edu.cn/liust/courses/CS110.html

School of Information Science and Technology (SIST)

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Administrative

- HW2 and Lab2 released

- Start early on labs so that checking can be faster

- Those who haven't enrolled in Piazza
  (https://piazza.com/shanghaitech.edu.cn/spring2026/cs110,
  access code: ctpkbtnt4gf) and
  Gradescope (https://www.gradescope.com/courses/1243230,
  access code: PK3GX6) please enroll yourselves ASAP using
  your ShanghaiTech email!

- Discussion 2 on makefile, gdb & git, etc.(useful for your HWs) by
  TA Yuxuan Li at **SPST 4-122 18:00-19:40** on Friday

- The similarity check is conducted automatically for each HW, proj., etc.
  Please comply with the course rules!

- We grade only on your most recent valid activated submissions before
  ddl for all assignments!

Outline

- Pointer

- Array

- Pointer arithmetic

- C memory management

  - Stack

  - Heap

Address vs. Value

- Consider memory to be a single huge array of bytes

  - Each cell/byte of the array has an address associated with it

  - Each cell also stores some value

- Don't confuse the address referring to a memory location with the value stored there

- Byte-addressable

  - int: 4 bytes (by convention)

  - char: 1 byte (C standard)

  - address itself: machine-dependent

  (4 bytes throughout this course, 4 GiB memory)

  - RV32I instructions: 4 bytes

Memory ...

Bytes

...	...	...	0x9a **4**
0x78	0x56	0x34	0x12
3	**2**	**1**	**0**

4
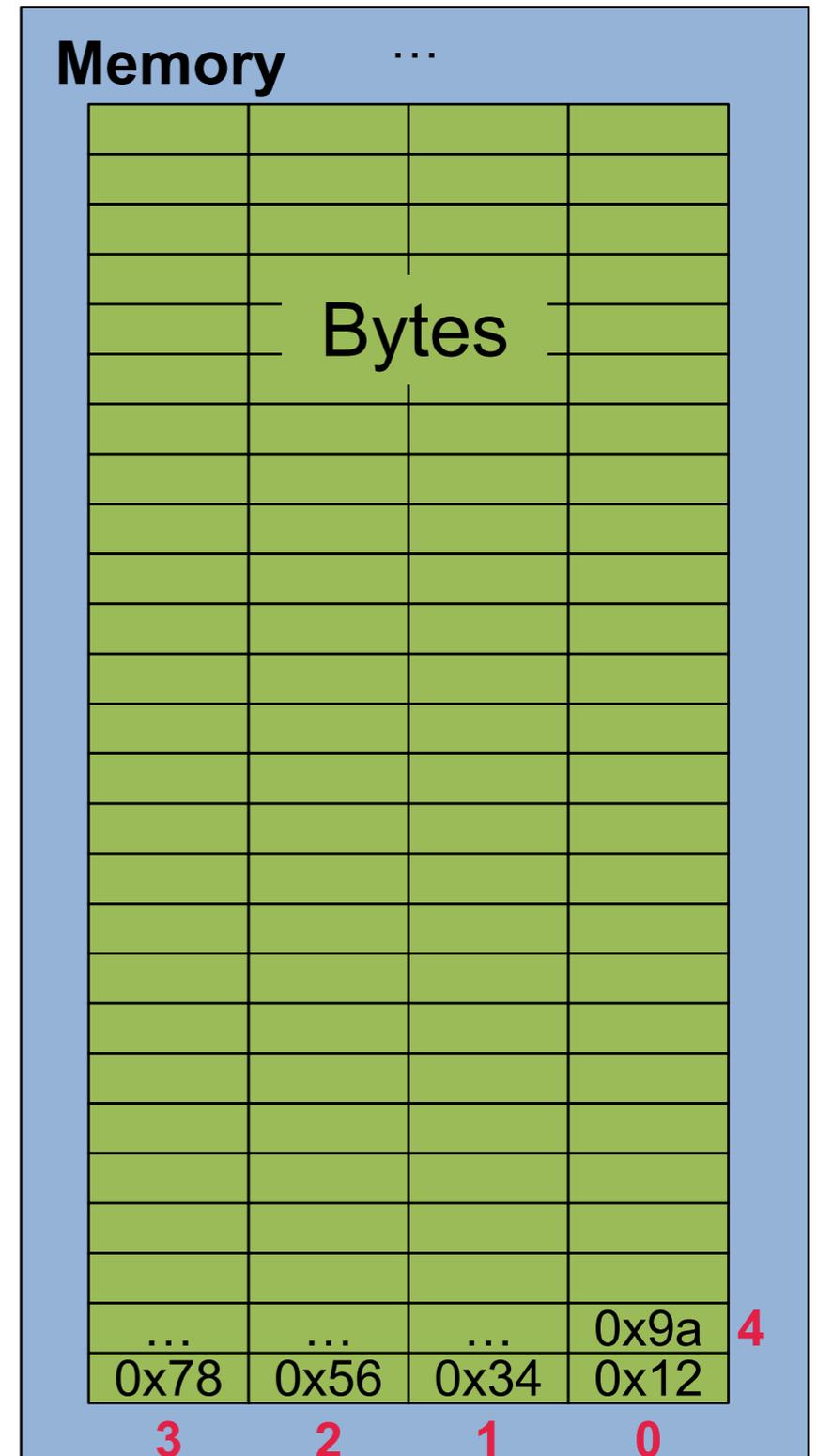
Pointers

- An address refers to a particular memory location;

- Pointer: A variable that contains the address of a variable;

- Pointer syntax and basic usage

int *p;

Tells compiler that variable p is the address of an int;

* called the "dereference operator" in this context;

p = &X;

Tells compiler to assign address of X to p;

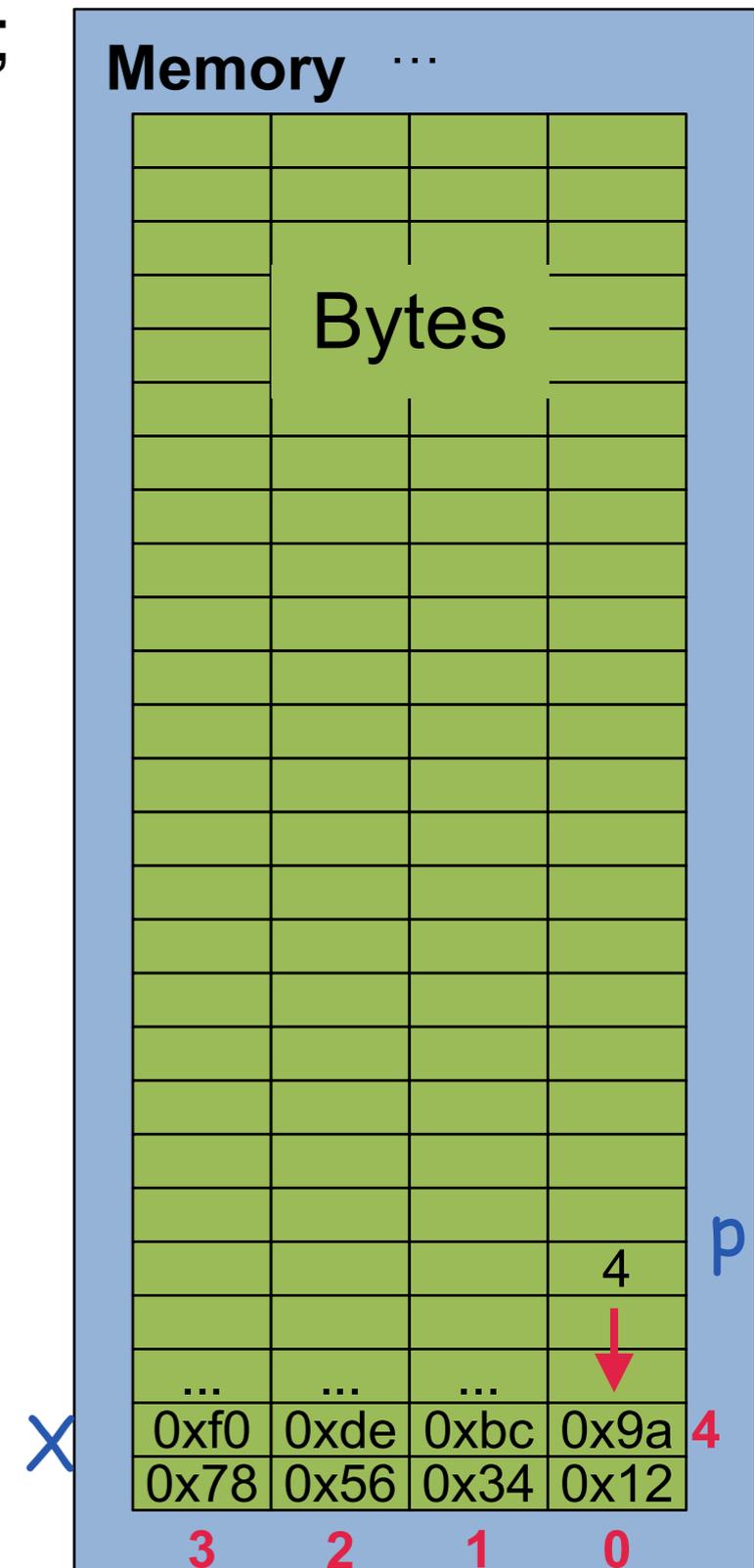& called the "address operator" in this context;

z = *p;

Tells compiler to assign value at address p to z;

*p = 5;

Change the value at p to 5 and use pointer to write;

Memory ...

Bytes

			p
			4
...	...	...	
0xf0	0xde	0xbc	0x9a
0x78	0x56	0x34	0x12
3	2	1	0

X   4

Pointers and Parameters Passing

- C passes parameters "by value"
  - Procedure/function/method gets a copy of the parameter, *so changing the copy cannot change the original*

```
void add_one (int x)
{x = x + 1;}
int y = 3;
add_one(y);
```

```
void add_one (int *p)
 {*p = *p + 1;}
int y = 3;
add_one(&y);
```

y remains
equal to 3

y equals
to 4 now

6

Pointers and Structures

```c
typedef struct {
    int x;
    int y;
} Point;


Point p1={1,2};
Point p2;
Point *paddr;
paddr = &p1;
```

```c
/* dot notation */
int h = p1.x;
p2.y = p1.y;


/* arrow notation */
int h = paddr->x; or
int h = (*paddr).x;


/* This works too */
p2 = p1;
```

7

Types of Pointers

- Pointers are used to point to any kind of data (**int**, **char**, a **struct**, and a **function**, etc.)

- Normally a pointer only points to one type (**int**, **char**, a **struct**, and a **function**, etc.).

  - **void *** is a type that can point to anything (generic pointer, more in memory management later)

  - Be careful, use **void *** sparingly to help avoid program bugs, and security issues, and other bad things!

Why Pointers in C?

- At time C was invented (early 1970s), compilers often didn't produce efficient code

  – Computers 100,000 times faster today, compilers better

- C designed to let programmer say what they want code to do without compiler getting in way

  – If we want to pass a large struct or array, it's easier/faster/etc. to pass a pointer than the whole thing

  – In general, pointers allow cleaner, more compact code

  – Even give compilers hints which registers to use!

- **Today's compilers produce much better code, so may not need to use pointers in application code**

- Low-level system code still needs low-level access via pointers

9

Pointers in C

- So what are the drawbacks?

  – Pointers are probably the single largest source of bugs in C, so be careful anytime you deal with them

    - Most problematic with dynamic memory management—coming up later

    - Dangling references and memory leaks

C Pointer Dangers

- Declaring a pointer just allocates space to hold the pointer – it does not allocate the thing being pointed to!

- Local variables in C are not initialized, they may contain anything (a.k.a. "garbage")

- What does the following code do?

```
void f(void)
{
    int *ptr;
    *ptr = 5;
}
```

Undefined Behavior

Not even working in some environments

ptr not initialized.

11

Outline

- Pointer

- **Array**

- Pointer arithmetic

- C memory management

  - Stack

  - Pointer

C Arrays

- Declaration:

  `int ar[2];`

  Declare a 2-element integer array: just a block of memory

  `int ar[] = {795, 635};`

  Declare and initialize a 2-element integer array

- Must specify size (or provide info. that can infer the size)

C Strings

- String in C is just an array of characters

  char string[] = "abc";

- How do you tell how long a string is?

  - Last character is followed by a '\0' (NULL) byte (a.k.a. "null terminator") (RTFM)

```
int strlength(char s[])
{
    int n = 0;
    while (s[n] != 0)
      n++;
    return n;
}
```

C11 standard: The declaration

    char s[] = "abc", t[3] = "abc";

defines "plain" char array objects s and t whose members are initialized with character string literals. This declaration is identical to

    char s[] = { 'a', 'b', 'c', '\0' },
       t[] = { 'a', 'b', 'c' };

Array/Pointer Duality

- Key Concept: Array variable is a "pointer" to the first (lowest addressed, i.e., 0th) element

- So, array variables almost identical to pointers
  - Not usually the other way (example next slide)

- Consequences:
  - ar is an array variable, but works like a pointer
  - ar[0] is the same as *ar
  - ar[2] is the same as *(ar+2)
  - Can use pointer arithmetic to conveniently access arrays

Array/Pointer Duality

- Be really careful!

char string1[] = "abc";
char *string2 = "abc";

- **CAN** modify *string1[x]*
- **CANNOT** modify *string2[x]*
- **CAN** access *string2* by string2[x]

Excercise

- What do these below mean? Be really careful!

```
int arr[] = { 3, 5, 6, 7, 9 };
int *p = arr;
int (*p1)[5] = &arr;
int *p2[5];
int (*p)( void );
int (*func_arr[5])(float x);
```
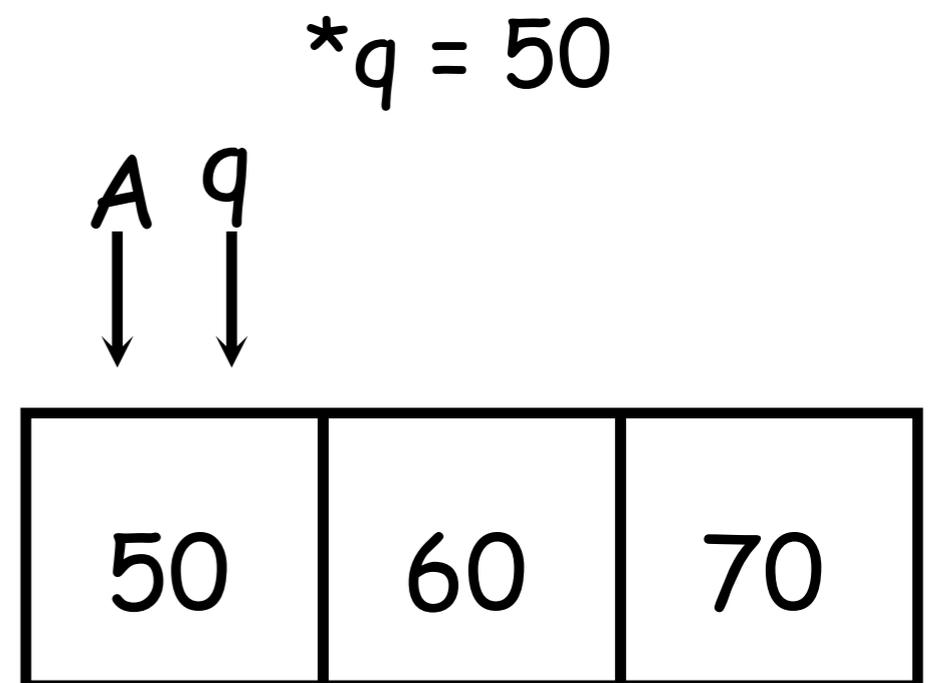
Changing a Pointer Argument?

- What if want function to change a pointer?
- What gets printed?

```
void inc_ptr(int *p)
{   p = p + 1;   }


int A[3] = {50, 60, 70};
int *q = A;
inc_ptr( q);
printf( "q = %d\n",*q);
```

$*q = 50$

A   q

| 50 | 60 | 70 |

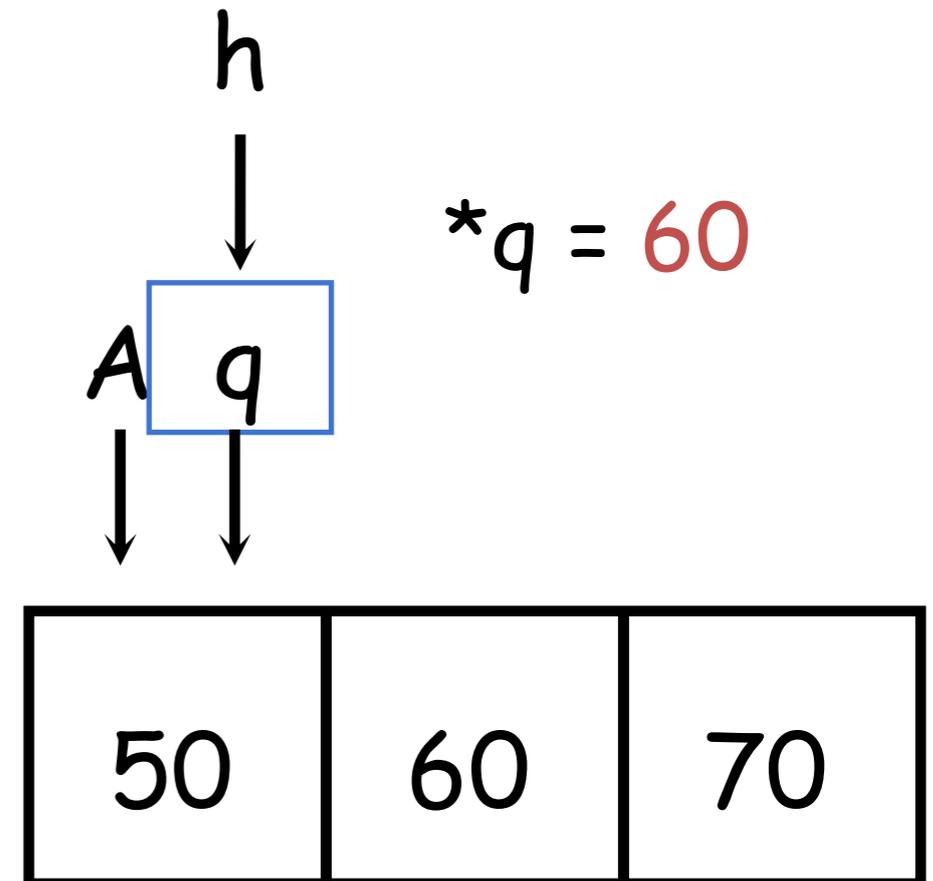# Pointer to a Pointer

- Solution! Pass a pointer to a pointer, declared as **h

- Now what gets printed?

```
void inc_ptr(int **h)
{   *h = *h + 1;   }


int A[3] = {50, 60, 70};
int *q = A;
inc_ptr(&q);
printf("*q = %d\n", *q);
```

h

*q = 60

A q

| 50 | 60 | 70 |

Arguments in main()

- To get arguments to the main function, use:

  int main(int argc, char *argv[])

  - *argc* contains the number of strings on the command line (the executable counts as one, plus one for each argument). Here *argc* is 5:

    % clang -ansi introC_1_1.c -o introC_1_1.out

  - argv is a pointer array, pointing to multiple strings

Example

% clang -ansi introC_1_1.c -o introC_1_1.out

- argc = 5 /* number arguments */

argv[0] = "clang",
argv[1] = "-ansi",
argv[2] = "introC_1_1.c",

argv[3] = "-o",

argv[4] = "introC_1_1.out"

More C Pointer & Array Dangers

- An array in C does not know its own length, and its bounds are not checked!

  – Consequence: We can accidentally access off the end of an array

  – Suggestion: We must pass the array and its size to any procedure that is going to manipulate it

- Out of boundary errors:

  – These are VERY difficult to find;
  Be careful!

Use Defined Constants

- Array size n; want to access from 0 to n-1, so you should use counter AND utilize a variable for declaration and incrementation

  - Bad pattern
    ```
    int i, ar[10];
    for(i = 0; i < 10; i++){ ... }
    ```
  - Better pattern
    ```
    const int ARRAY_SIZE = 10;
    int i, a[ARRAY_SIZE];
    for(i = 0; i < ARRAY_SIZE; i++){ ... }
    ```

- SINGLE SOURCE OF TRUTH

  - You avoid maintaining two copies of the number 10

  - DRY: "Don't Repeat Yourself"

Summary: Arrays and Pointers

Passing arrays

- Array = pointer to the initial (0th) array element

  a[i]=(*(a+(i)))

- An array is passed to a function as a pointer

  – The array size is lost!

- Usually bad style to interchange arrays and pointers

  – Avoid pointer arithmetic!

Really **int *array**

Must explicitly pass the size

```
int foo(int array[],
    unsigned int size)
{
    … array[size - 1] …
}

int
main(void)
{
    int a[10], b[5];
    … foo(a, 10)… foo(b, 5) …
}
```
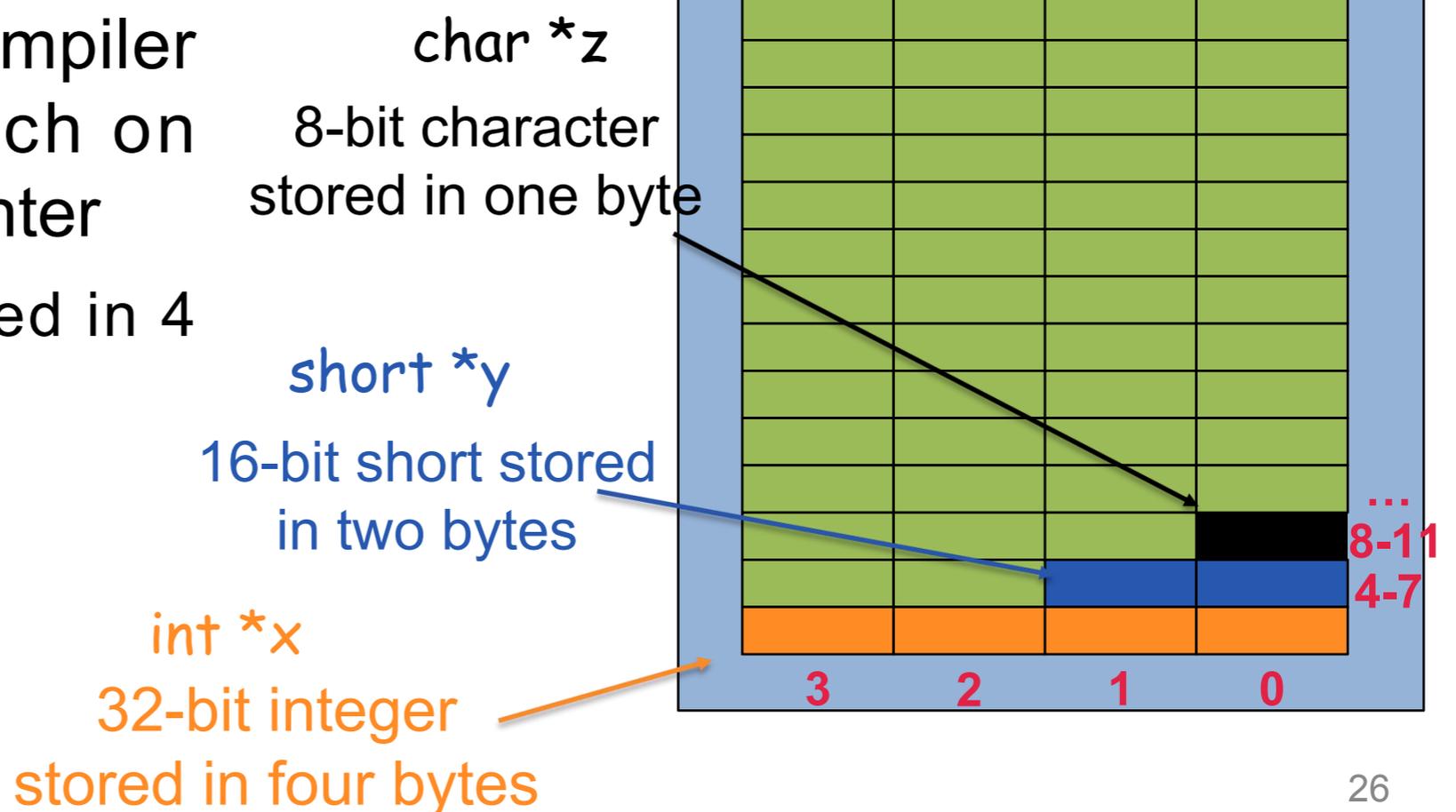
Outline

- Pointer

- Array

- **Pointer arithmetic**

- C memory management

  - Stack

  - Pointer

Pointing to Different-Sized Objects

- Modern machines are "byte-addressable"
  - Hardware's memory composed of 8-bit storage cells, each has a unique address
- A pointer is just an abstracted memory address
- Type declaration tells compiler how many bytes to fetch on each access through pointer
  - E.g., 32-bit integer stored in 4 consecutive 8-bit bytes
- Alignment

Memory

Byte-addressable

char *z
8-bit character stored in one byte

short *y
16-bit short stored in two bytes

int *x
32-bit integer stored in four bytes

...
8-11
4-7

3   2   1   0

26

Pointing to Different-Sized Objects

- Modern machines are "byte-addressable"

  – Hardware's memory composed of 8-bit storage cells, each has a unique address

- A pointer is just an abstracted memory address

- Type declaration tells compiler how many bytes to fetch on each access through pointer

  – E.g., 32-bit integer stored in 4 consecutive 8-bit

- Alignment

char *z

8-bit character stored in one byte

```
%1 = alloca i32, align 4
%2 = alloca i32, align 4
%3 = alloca i32, align 4
%4 = alloca i32, align 4
store i32 0, i32* %1, align 4
store i32 1234, i32* %2, align 4
store i32 4321, i32* %3, align 4
%5 = load i32, i32* %2, align 4
%6 = load i32, i32* %3, align 4
%7 = add nsw i32 %5, %6
store i32 %7, i32* %4, align 4
```

Memory

Byte-addressable

8-11

4-7

3 2 1 0

27
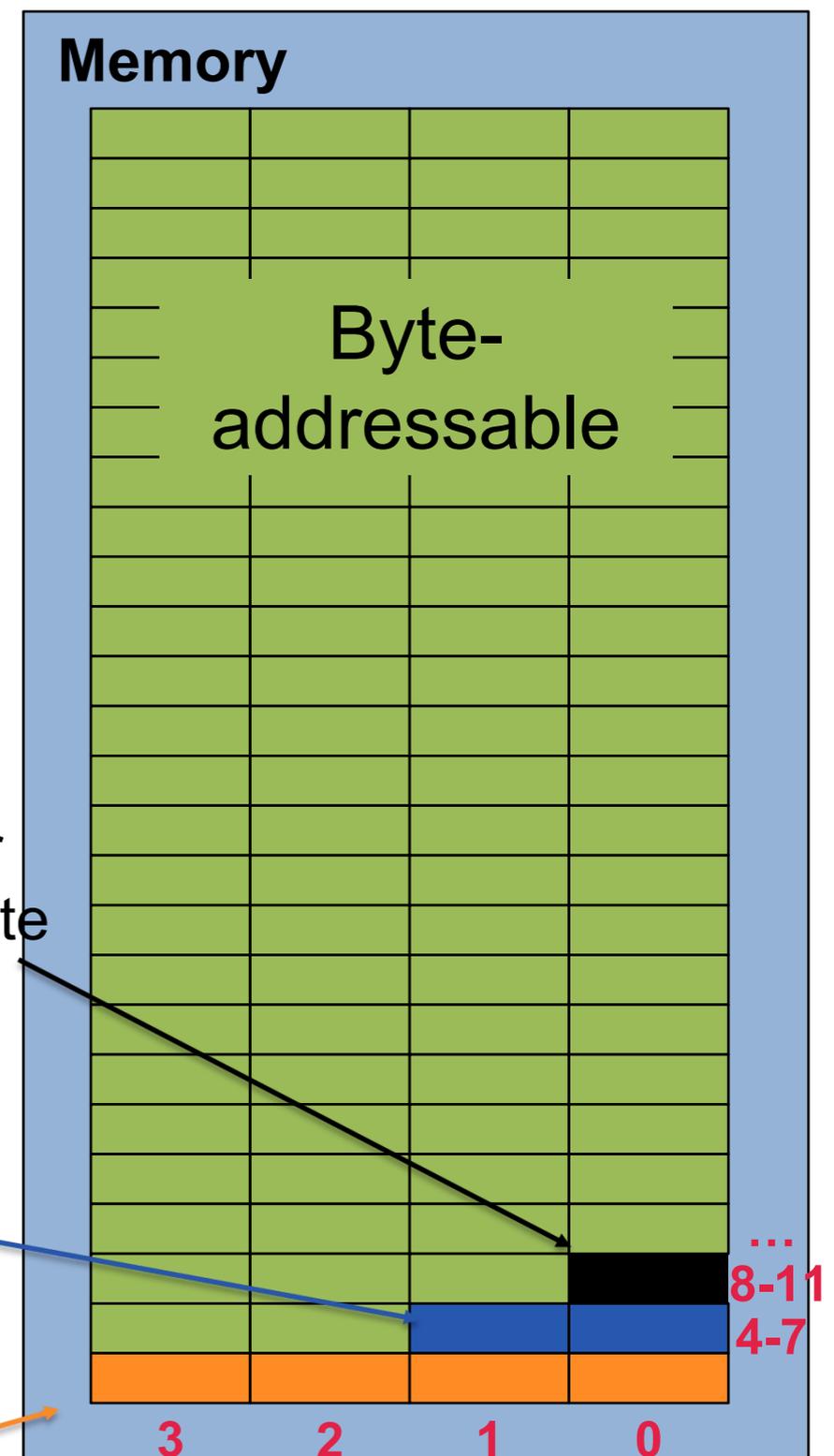
sizeof() Operator

- sizeof(type) returns number of bytes in object
  - But number of bits in a byte is not standardized
    - In olden times, when dragons roamed the earth, bytes could be 5, 6, 7, 9 bits long
- By definition, sizeof(char)==1
- Can take sizeof(variable), or sizeof(type)
- We'll see more of sizeof when we look at dynamic memory management

Excercise

```
int foo(int array[], unsigned int size)
{

  …
  printf("%d\n", sizeof(array));
}


int main(void)
{

  int a[10], b[5];
  … foo(a, 10)… foo(b, 5) …
  printf("%d\n", sizeof(a));
}
```

What does this print (32-bit address)? **4**

Because **array** is really a pointer (and a pointer is architecture dependent, likely to be 8 on modern 64-bit machines!)

What does this print (32-bit int)? **40**

29

Pointer Arithmetic

pointer + number   *pointer − number*

e.g., *pointer* **+ 1**   adds 1 to a pointer

```
char    *p;
char     a;
char     b;

p = &a;
p += 1;
```

In each, **p** now points to b

(Assuming compiler doesn't reorder variables in memory. Never code like this!!!!)

```
int    *p;
int     a;
int     b;

p = &a;
p += 1;
```

Adds 1*sizeof(char) to the memory address

Adds 1*sizeof(int) to the memory address

Pointer arithmetic should be used cautiously

Pointer Arithmetic--Exercise

int arr[] = { 3, 5, 6, 7, 9 };

int *p = arr;

int (*p1)[5] = &arr;

Are arr+1, p+1, p1+1 the same?

Arrays and Pointers

```
int  i;
int  array[10];

for (i = 0; i < 10; i++)
{
   array[i] = …;
}
```

```
int *p;
int  array[10];

for (p = array; p < &array[10]; p++)
{
   *p = …;
}
```

These code sequences have the same effect!

Concise strlen()

```
int(long) strlen(char *s)
{   char *p = s;
    while (*p++)
            ; /* Null body of while */
    return (p - s - 1);
}
```

What happens if there is no zero character at end of string?

Point past end of array?

- Array size n; want to access from 0 to n-1, but test for exit by comparing to address one element past the last member of the array

```
int ar[10]={},*p, *q, sum=0;
p = &ar[0]; q = &ar[10];
while (p!=q) /* sum = sum+*p; p = p+1*/
    sum += *p++;
```

- C defines that one element past end of array must be a valid address, i.e., not causing an error

Valid Pointer Arithmetic

- Add an integer to a pointer.

- Subtract 2 pointers (pointed to the same array/object)

- Compare pointers (<, <=, ==, !=, >, >=)

- Compare pointer to NULL (indicates that the pointer points to nothing)

- Everything else illegal since makes no sense:

- Adding two pointers

- Multiplying pointers

- Subtract pointer from integer

Summary

- "Lowest High-level language"
  - => closest to assembler

- Pointers: powerful but dangerous

- Pointer arithmetic and arrays useful but also dangerous

Summary

- Pointers and arrays are virtually same
- C knows how to increment pointers
- C is an efficient language, with little protection
  - Array bounds not checked
  - Variables not automatically initialized
- (Beware) The cost of efficiency is more overhead for the programmer.

"C gives you a lot of extra rope but be careful not to hang yourself with it!"

Outline

- Pointer

- Array

- Pointer arithmetic

- C memory management

  - Stack

  - Heap

C Memory Management

- To simplify, assume one program runs at a time

- A program's address space contains 4 regions:

  - stack: local variables inside functions, grows downward

  - heap: space requested for dynamic data via malloc(); resizes dynamically, grows upward

  - static data: variables declared outside functions, does not grow or shrink. Loaded when program starts, can be modified.

  - code (a.k.a. text): loaded when program starts, does not change

  - 0x0 unwritable/unreadable (NULL pointer)

Memory Address
(32 bits assumed here)

$FFFF\ FFFF_{hex}$

stack
heap
static data
code

~ $0000\ 0000_{hex}$
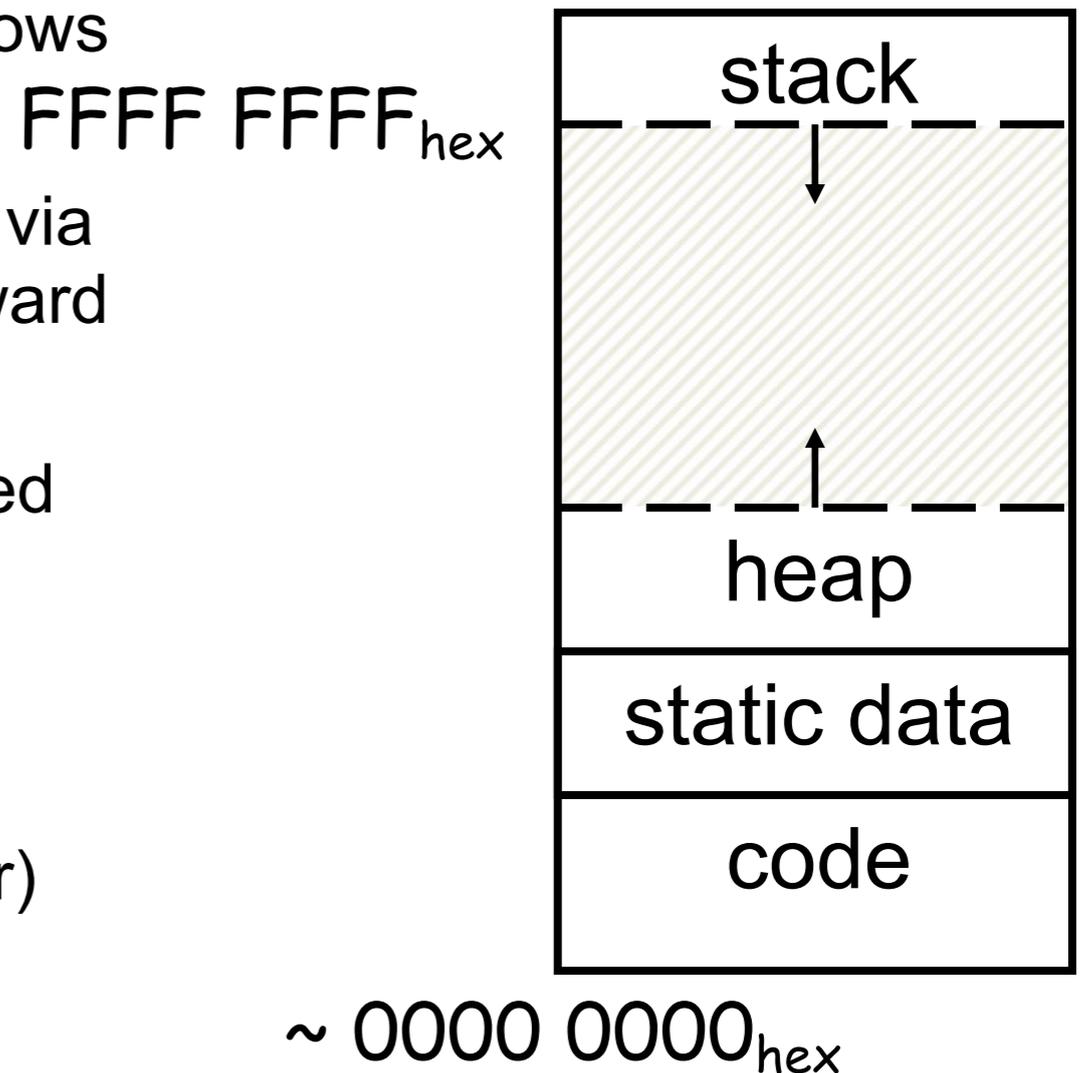
Where are Variables Allocated?

- If declared outside a function, allocated in "static" storage

- If declared inside function, allocated on the "stack" and freed when function returns

```
int myGlobal;
main() {
   int myTemp;
}
```

  - main() is treated like a function

- For the above two types, the memory management is automatic

  - Don't need to deallocating when no longer using them

 - A variable does not exist anymore once a function ends!

The Stack

- Every time a function is called, a new "stack frame" is allocated on the stack

- Stack frame includes:
  - Return address (who called me?)
  - Arguments
  - Space for local variables

- Stack frames: contiguous blocks of memory; stack pointer indicates start of stack frame

- When function ends, stack frame is tossed off the stack; frees memory for future stack frames

- Details covered later (RISC-V processor)

```
funcA() { funcB(); }
funcB() { funcC(); }
funcC() { funcD(); }
```
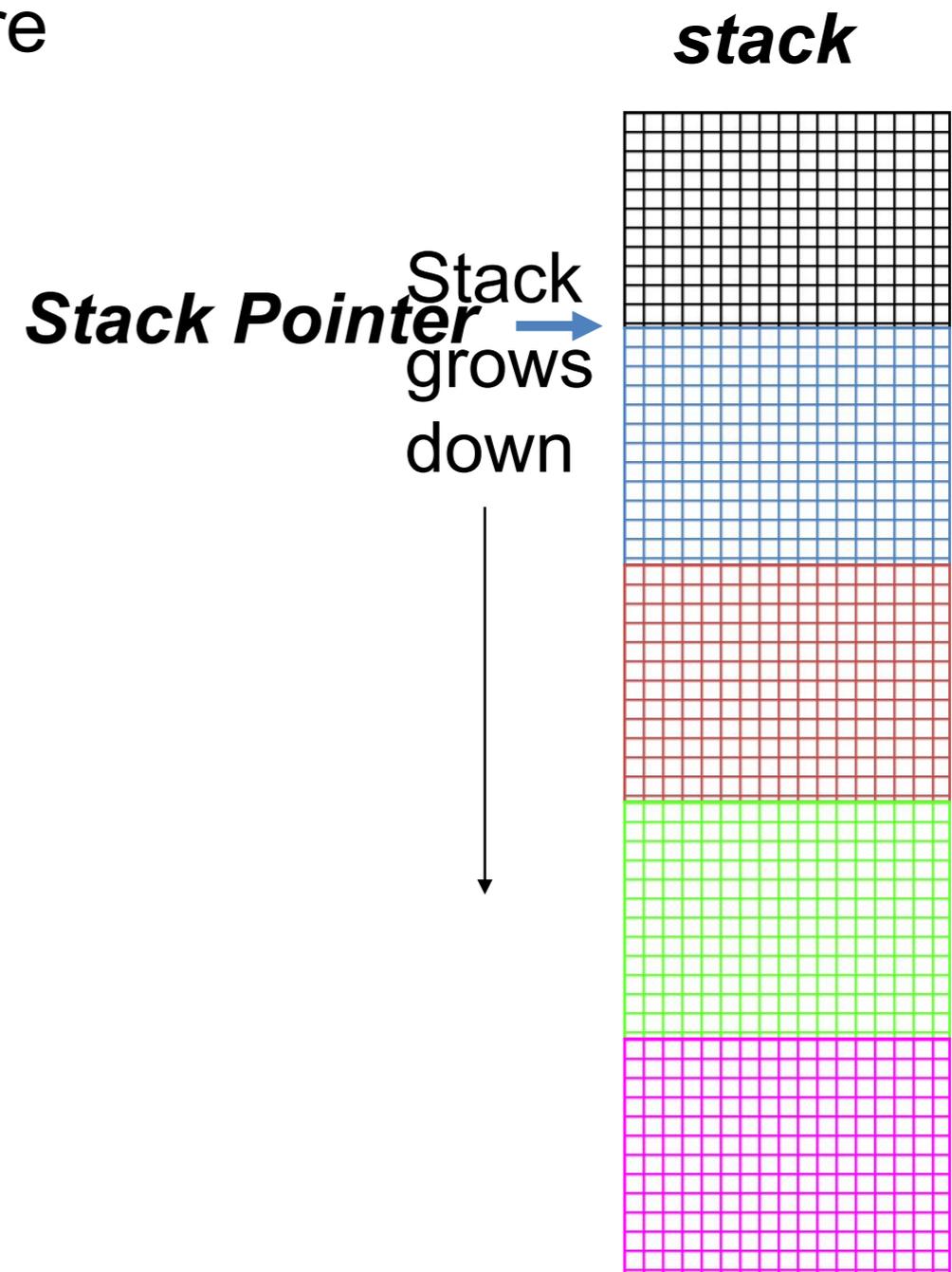
funcA frame
funcB frame
funcC frame
funcD frame

Stack Pointer →

41
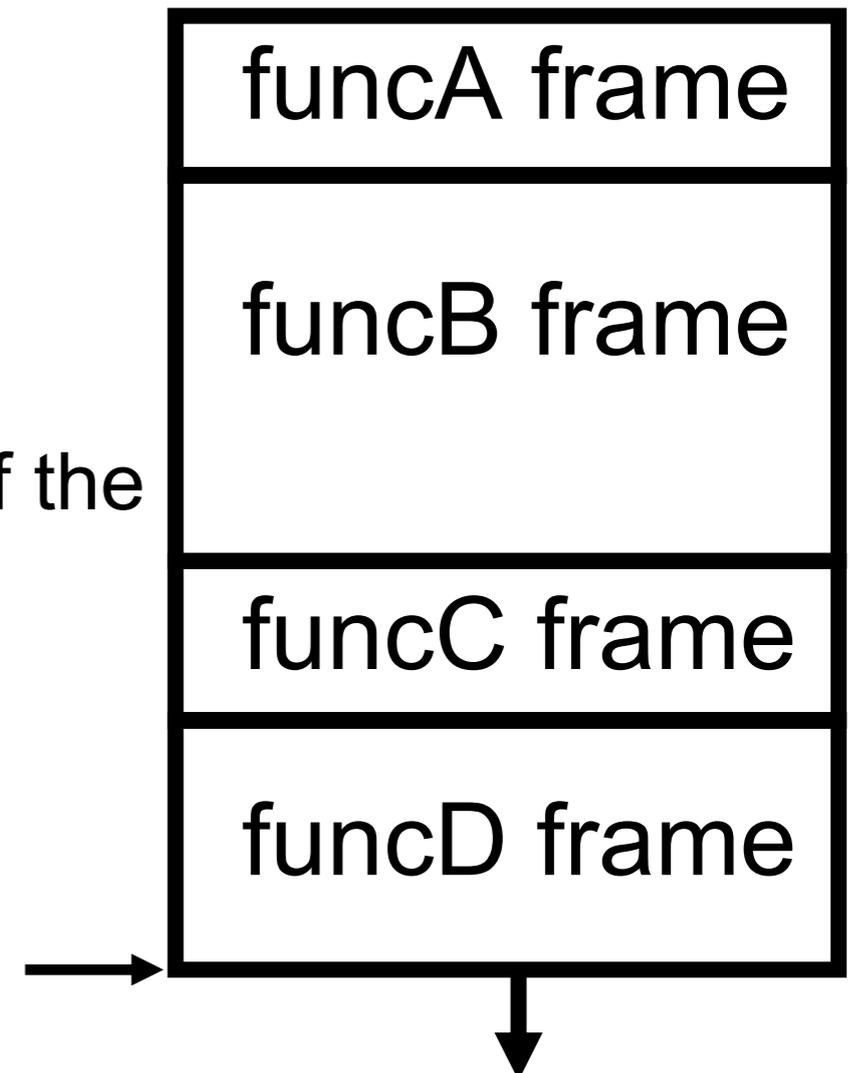
Stack Animation

- Last In, First Out (LIFO) data structure

stack

```
main ()
{ a(0);
}
        void a (int m)
        { b(1);
        }
            void b (int n)
            { c(2);
            }
                void c (int o)
                { d(3);
                }
                    void d (int p)
                    {
                    }
```
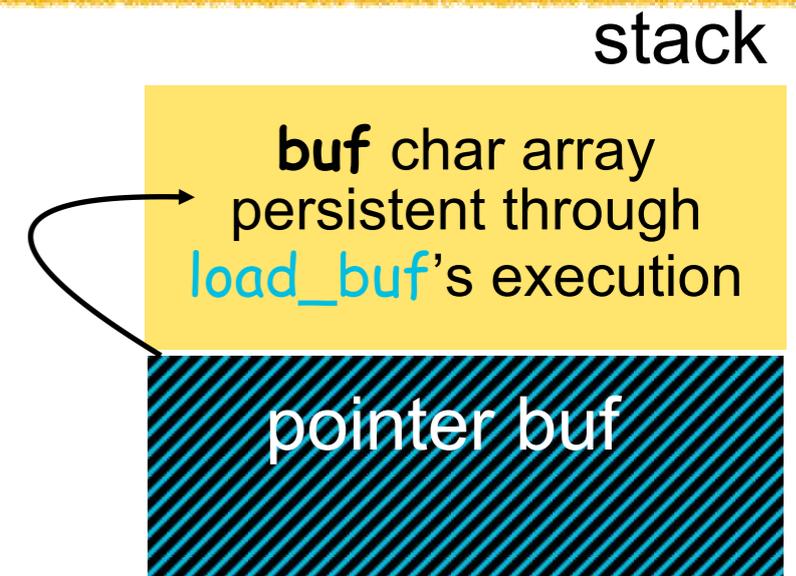
Stack Pointer → Stack
grows
down

42

Passing Pointers into the Stack

stack

- It is fine to pass a pointer to stack space further down.

```
#define BUFLEN 256
int main() {
    …
    char buf[BUFLEN];
    load_buf(buf, BUFLEN);
    …
}
```

buf char array persistent through load_buf's execution

pointer buf

- However, it is bad to return a pointer to something in the stack!

  - Memory will be overwritten when other functions called!

  - So your data would no longer exist, and writes can overwrite key pointers, causing crashes!

```
char* make_buf() {
    char buf[50];
    return buf;
}

int main(){
    …
    char *stackAddr =
    make_buf();
    …
}
```

stack

stackAddr points to overwritten memory

buf???

Carving on the moving boat to look for the sword

43

Managing the Heap

- The heap is dynamic memory – memory that can be allocated, resized, and freed during program runtime.
  - Useful for persistent memory across function calls
  - But biggest source of pointer bugs, memory leaks, …
- Large pool of memory, not allocated in contiguous order
  - Back-to-back requests for heap memory could result in blocks very far apart
- C supports four functions for heap management:

  - malloc()   allocate a block of uninitialized memory
  - calloc()   allocate a block of zeroed memory
  - free()   free previously allocated block of memory
  - realloc()   change size of previously allocated block (might move)

Managing the Heap

- **void *malloc(size_t n)**:
  - Allocate a block of uninitialized memory
  - **n** is an integer, indicating size of allocated memory block in bytes
  - **size_t** is an unsigned integer type big enough to "count" memory bytes
  - **sizeof** returns size of given type in bytes, produces more portable code
  - Returns **void*** pointer to block; **NULL** return indicates no more memory; always check for return **NULL** (**if (ip)**)
  - Think of pointer as a handle that describes the allocated block of memory; Additional control information stored in the heap around the allocated block! (Including size, etc.)

"Cast" operation, changes type of a variable.
Here changes **(void *)** *to* **(int *)**

- Examples:

int *ip1, *ip2;
ip1 = (int *) malloc(sizeof(int));
ip2 = (int *) malloc(20*sizeof(int)); //allocate an array of 20 ints.

typedef struct { … } TreeNode;
TreeNode *tp = (TreeNode *) malloc(sizeof(TreeNode));

Assuming size of objects can lead to misleading, unportable code. Use **sizeof()**!

45

Managing the Heap

- **void free(void *p)**:
  - Releases memory allocated by malloc()
  - **p** is pointer containing the address originally returned by **malloc()**

    ```
    int *ip;
    ip = (int *) malloc(sizeof(int));
    … .. ..
    free((void*) ip);   /* Can you free(ip) after ip++ ? */

    typedef struct {… } TreeNode;
    TreeNode *tp = (TreeNode *) malloc(sizeof(TreeNode));
        … .. ..
    free((void *) tp);
    ```

  - When you free memory, you must be sure that you pass the original address returned from **malloc()** to **free()**; Otherwise, system exception (or worse)!

Managing the Heap

- **void *realloc(void *p, size_t size)**:
  – Returns new address of the memory block.
    - In doing so, it may need to copy all data to a new location.

  realloc(NULL, size); // behaves like malloc
  realloc(ptr, 0); // behaves like free, deallocates heap block

  – **Always check** for return NULL

```
int *ip; ip = (int *) malloc(10*sizeof(int));
… … …                    /* check for NULL */
ip = (int *) realloc(ip, 20*sizeof(int));
/* contents of first 10 elements retained */
… … …                    /* check for NULL */
realloc(ip,0);       /* equivalent to free(ip); */
```
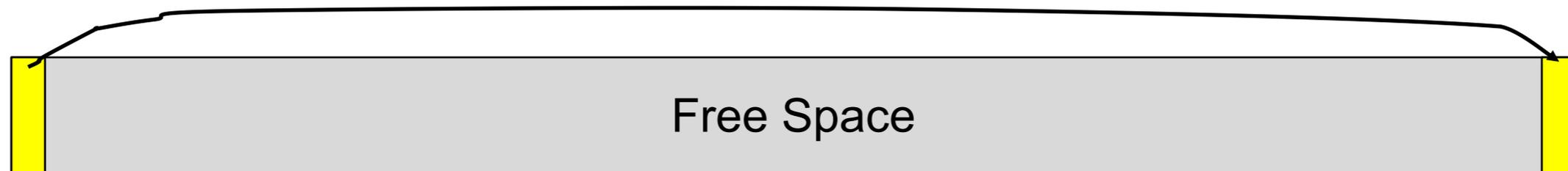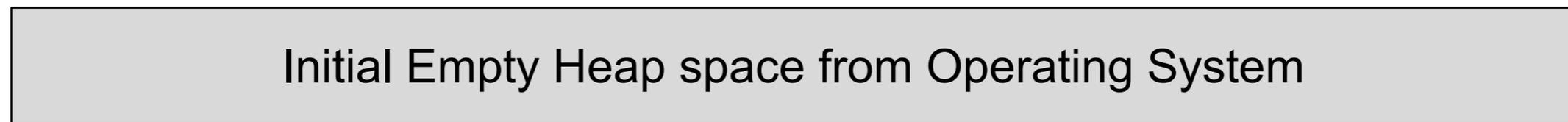
Keep track of this, since it might change.
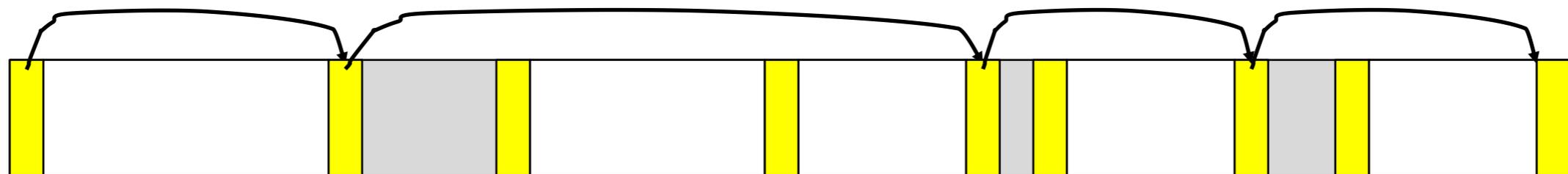
47

How are malloc/free implemented?

- Underlying operating system allows malloc library to ask for large blocks of memory to use in heap (stdlib.h)

Initial Empty Heap space from Operating System

Free Space

Malloc library creates linked list of empty blocks (one block initially)

Object 1　　　　　Free

First allocation chews up space from start of free space

After many mallocs and frees, have potentially long linked list of odd-sized blocks
Frees link block back onto linked list – might merge with neighboring free space

48

Faster ɱalloc implementations

- "Buddy allocators" always round up to power-of-2 sized chunks to simplify finding correct size and merging neighboring blocks

free

used	
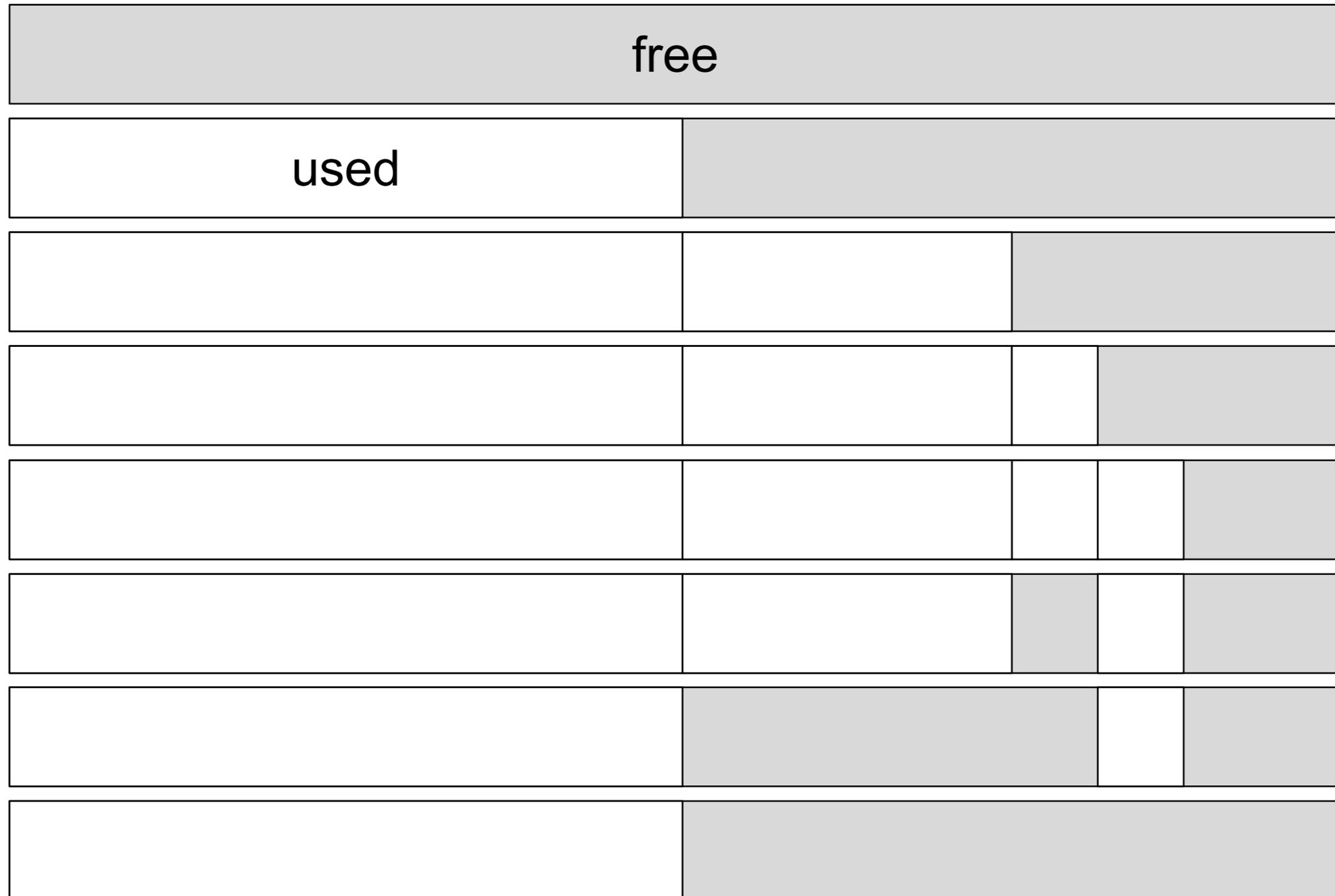
Observations/Summary

- Code, static storage are easy: they never grow or shrink
- Stack space is relatively easy: stack frames are created and destroyed in last-in, first-out (LIFO) order, avoid "dangling references"
- Managing the heap is tricky:
    - Memory can be allocated/deallocated at any time
    - "Memory leak": If you forget to deallocate memory
    - "Use after free": If you use data after calling free
    - "Double free": If you call free 2x on same memory