CSE 374 Programming Concepts and Tools

Lecture 09 - Dynamic Memory Allocation

This week

Monday: Exam 1

- Grades released next week

Today: **Dynamic Memory Allocation**

Next lecture: Memory Leaks

Today

Reviewing C pointers

Output Parameters

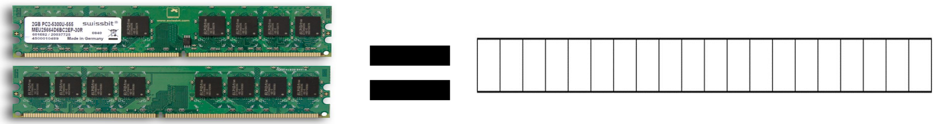
- Pointers and their lifetimes

Dynamic Memory Allocation

- Heap vs stack

`malloc` and **`free`**

Review



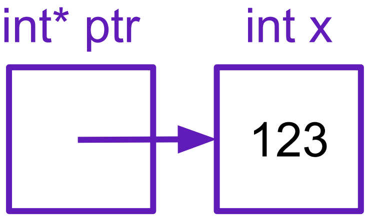
All data is binary - a sequence of 1's and 0's

- A single digit is called a **bit**
- Bits come in groups of 8, called a **byte**

Computers store data in files or in memory.

Memory is like a large **array of bytes**.

An address refers to a location in memory.



A **pointer** is a data object that holds an address.

- Address can point to *any* data, because they simply point to any space in memory

Review: Pointers

Storing in memory an address to another location in memory

`int x = 4;` // Variable called ‘x’ of type ‘int’ given value ‘4’

`int* xPtr = &x;` // Variable called ‘xPtr’ of type ‘int pointer’ given value ‘location of x’

`int xCopy = *xPtr;`

// Variable called ‘xCopy’ of type ‘int’ given value ‘value found at address xPtr’ (read)

`*xPtr = 123;` // Assigning the value '123' to the ‘value found at address xPtr’ (write)

`int* noPtr = NULL;` // variable called ‘noPtr; of type ‘int pointer’ given value of ‘null’

Output Parameters

Lifetime and pointers

Review: Using Pointers as Output Parameters

C pointers offer a powerful mechanism for **returning multiple values** from a function.

- Pass the memory address of variables to be modified as function arguments.

```
void initialize(int *a, char *c, int* b);
int main(void) {
    int a = 0;
    char c;                 // c is undefined (don’t do this)
    initialize(&a, &c);     // a = 10, c = 'A'
}
void initialize(int *a, char *c) {
    *a = 10;
    *c = 'A';
}
```

Example 1: Lifetimes and Pointers

```
void foo(int* x_ptr);
void main() {
  int x = 42;
  foo(&x);
}
void foo(int* x_ptr) {
  printf("x has %d\n", *x_ptr);
}
```

When we get to `printf()`...

- Is `x_ptr` alive?
- Is `x` alive?

Example 1: Lifetimes and Pointers

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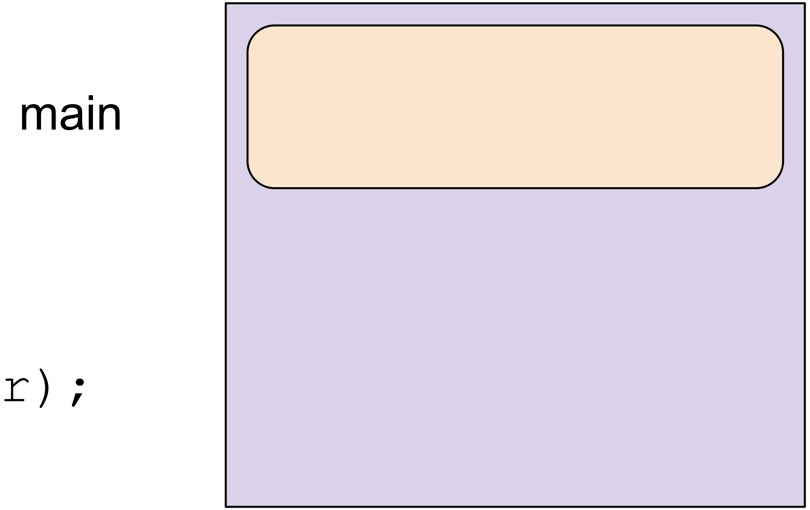

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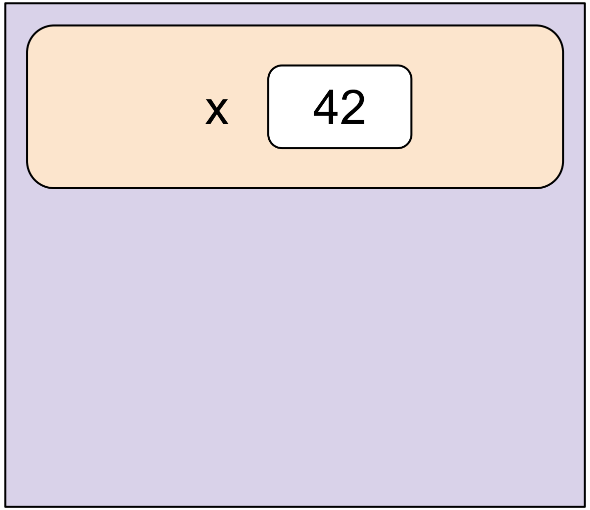
Is x_ptr alive? Is x alive?

main



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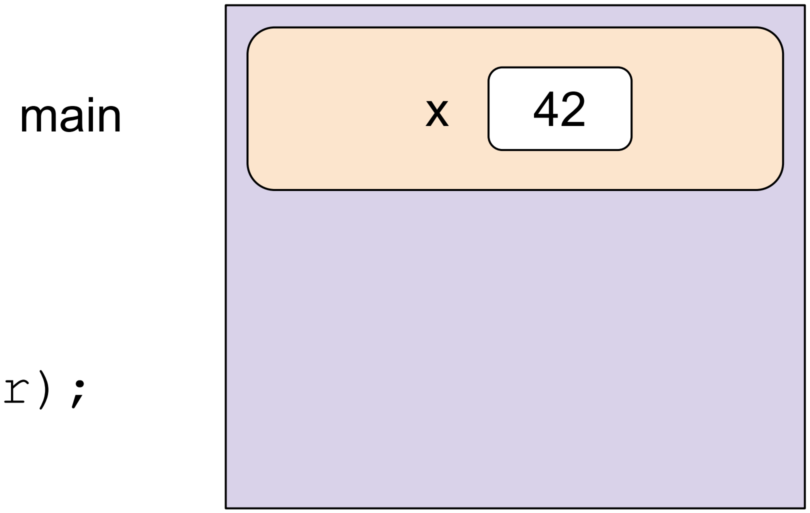
Is `x_ptr` alive? Is `x` alive?



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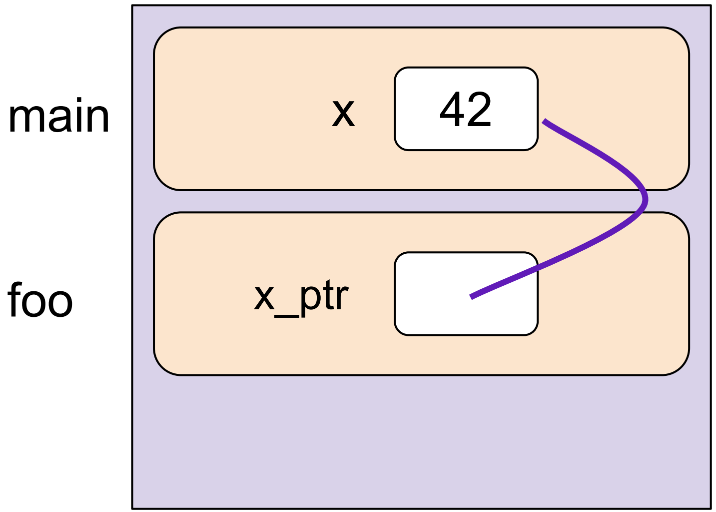

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  int x = 42;
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}
void foo(int* x_ptr) {
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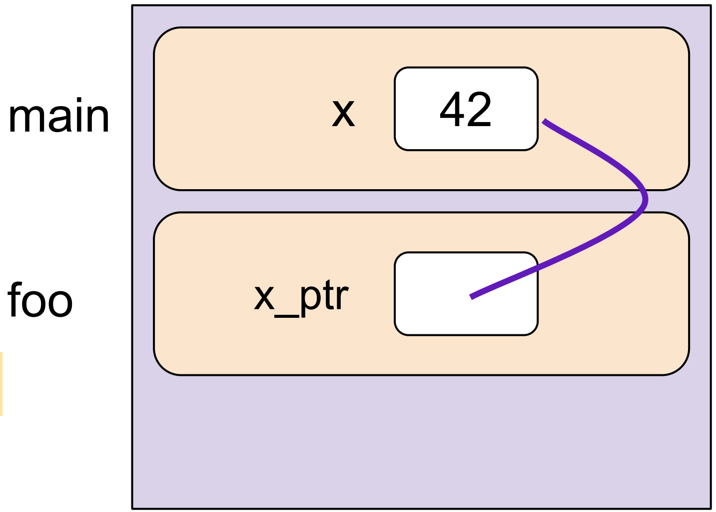
Is `x_ptr` alive? Is `x` alive?



Yes, `x_ptr` and `x` are both alive.

Example 2: Lifetimes and Pointers

```
int* foo();
void main() {
  int* x_ptr = foo();
  printf("x has %d\n", *x_ptr);
}
int* foo() {
  int x = 42;
  return &x;
}
```

When we get to `printf()`...

- Is `x_ptr` alive?
- Is `x` alive?

Example 2: Lifetimes and Pointers

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int* foo();
void main() {
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}
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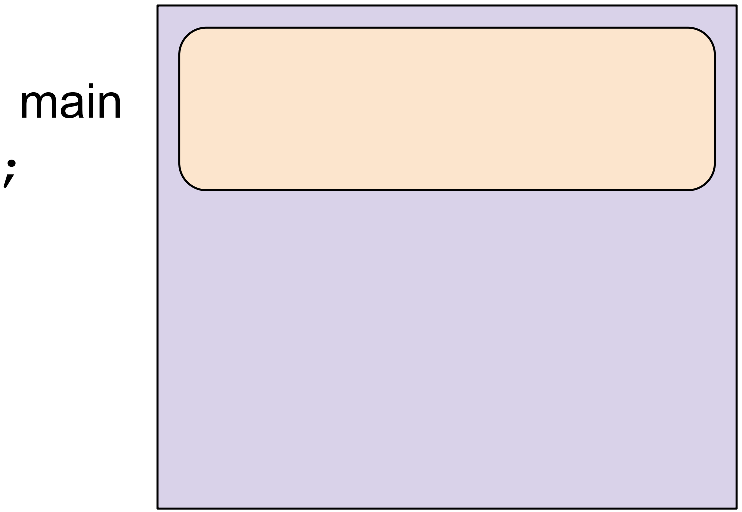
  return &x;
}
```

Is `x_ptr` alive? Is `x` alive?



Example 2: Lifetimes and Pointers

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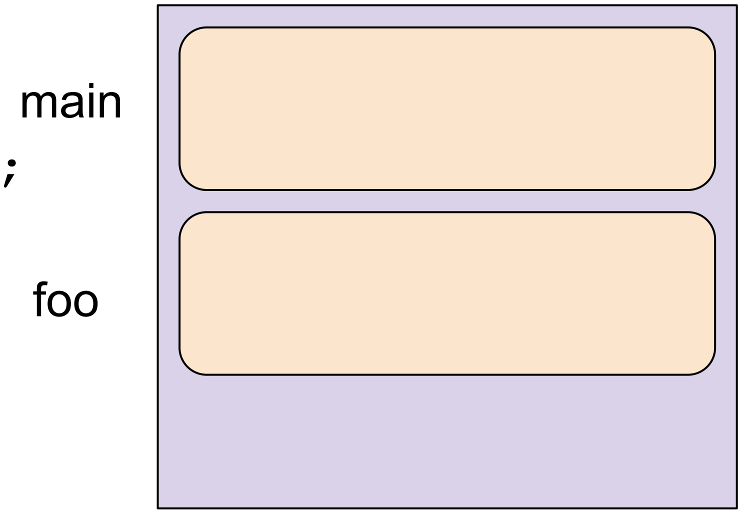
  return &x;
}
```

Is `x_ptr` alive? Is `x` alive?



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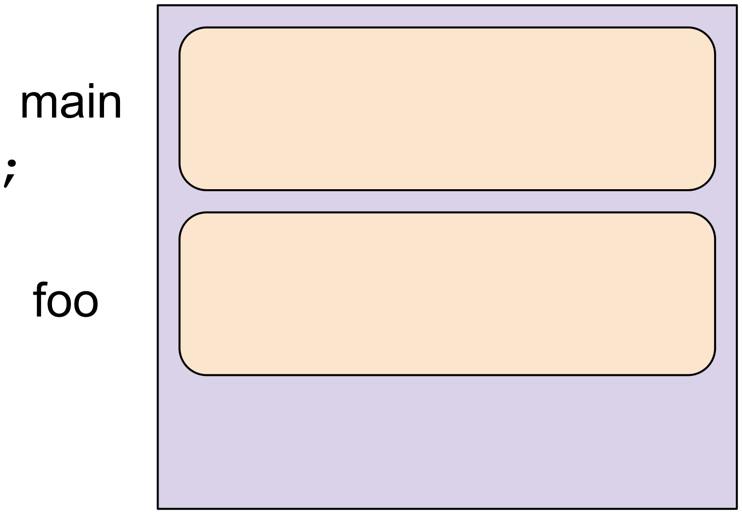

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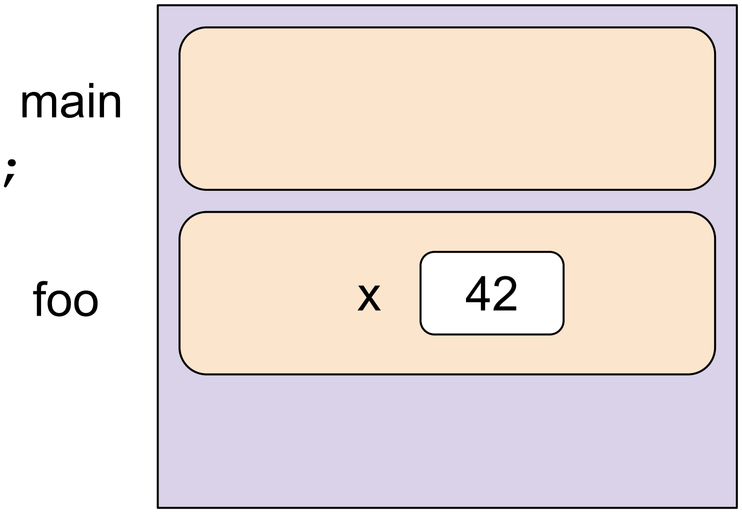

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  printf("x has %d\n", *x_ptr);
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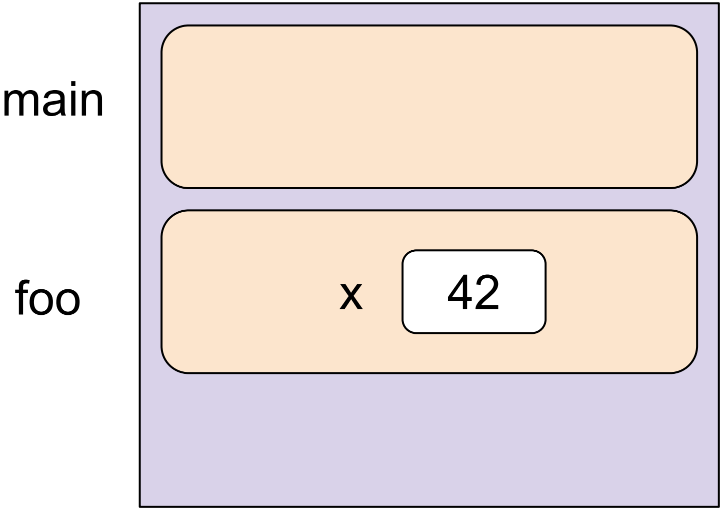
}
```

Is `x_ptr` alive? Is `x` alive?



Example 2: Lifetimes and Pointers

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   int* x_ptr = foo();
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   return &x;
}
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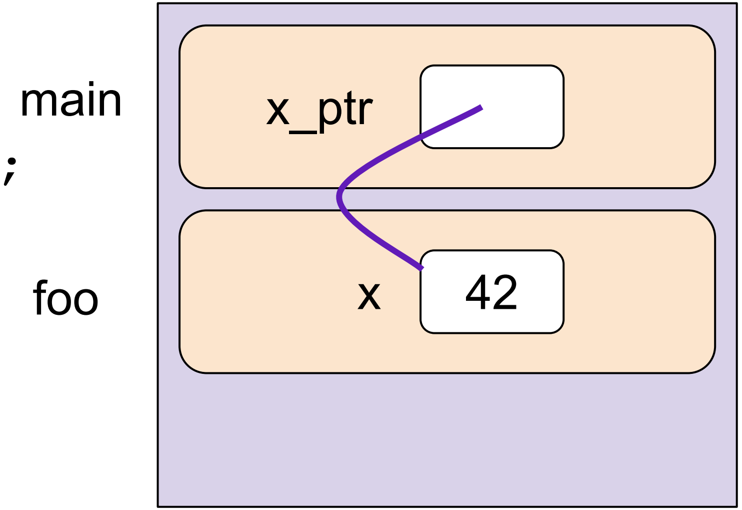

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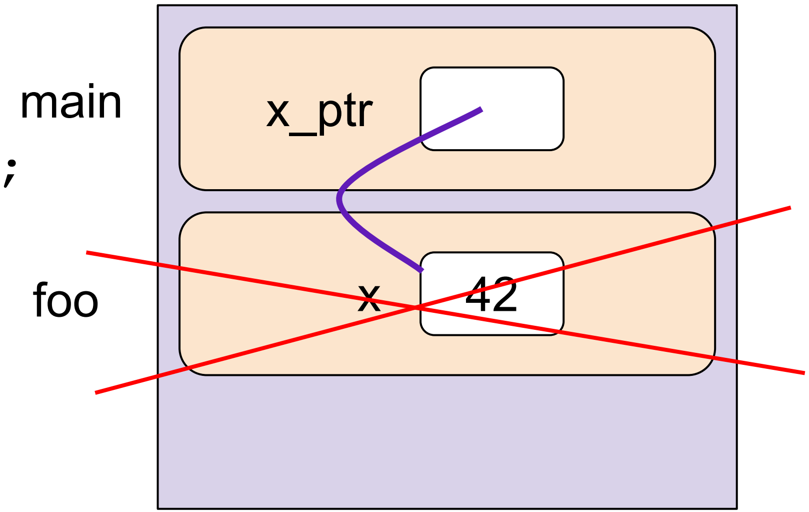
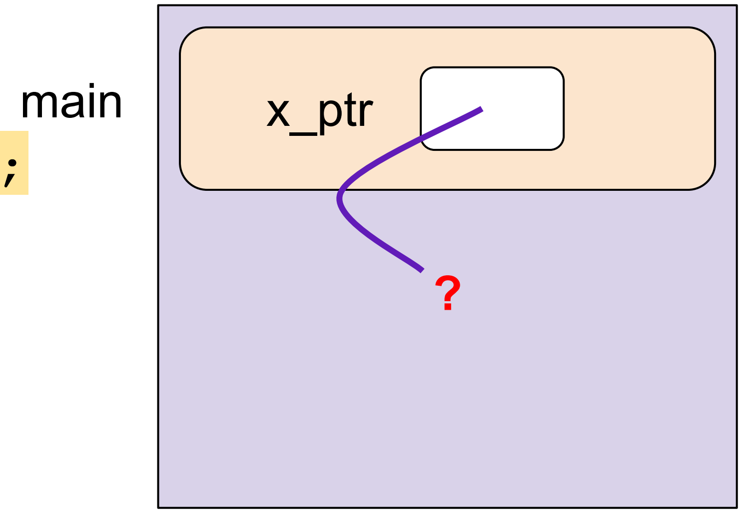


Example 2: Lifetimes and Pointers

```
int* foo();
void main() {
  int* x_ptr = foo();
  printf("x has %d\n", *x_ptr);
}
int* foo() {
  int x = 42;
  return &x;
}
```

Is `x_ptr` alive? Is `x` alive?



`x_ptr` is alive, but `x` is not alive.

Dangling Pointer

When a pointer points to a dead local variable, it is "dangling"

Dereferencing a dangling pointer is undefined behavior

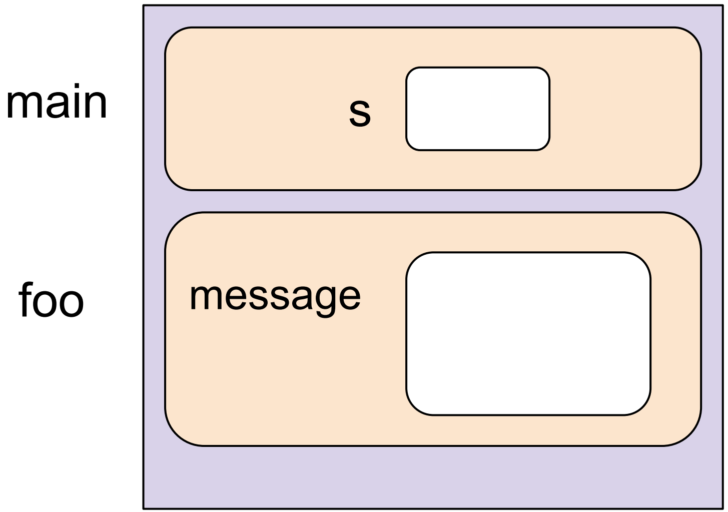
- Undefined behavior means that anything *could* happen
- Your program could crash (best case) or silently fail (worse case)

Luckily, `gcc` can often catch this kind of error with a warning

- But not always – you cannot rely on gcc to catch all of these errors!

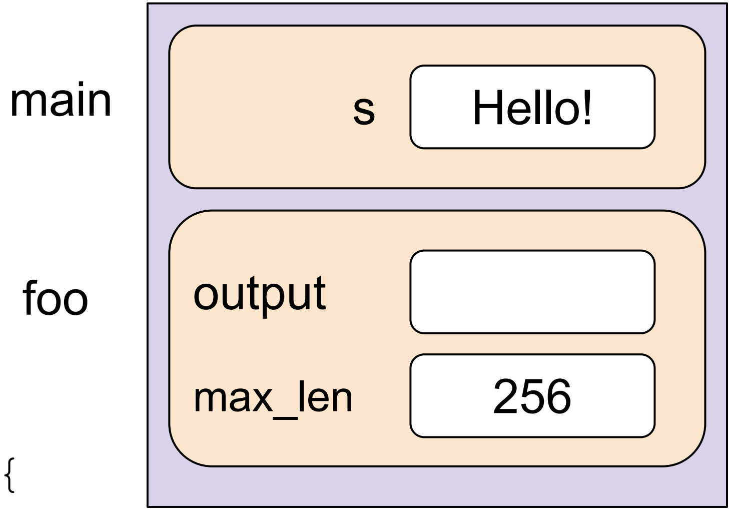
Example: Returning a String

```
char* foo();
int main() {
  char* s = foo();
  printf("String: %s\n", s);
}
char* foo() {
  char message[256] = "Hello!";
  return message;
}
```



Fix: Output Parameter

```
#include<stdio.h>
#include<string.h>
void foo(int max_len, char* output);
int main() {
  char s[256];
  foo(256, s);
  printf("String: %s\n", s);
}
void foo(int max_len, char* output) {
  strncpy(output, "Hello!", max_len);
}
```



Output Parameters

We can't *return* a pointer to a local variable

Instead, take in a pointer as a parameter, used for output

- Remember, pointers can be used for reading and writing

```
void foo(int max_len, char* output);
```

Avoid returning/using dangling pointers pointing at data that has gone out of scope…

```
int* bad() {
    int num = 8;
    return &num;
}
```

Dynamic Memory Allocation

Memory Allocation

Allocation refers to any way of asking for the operating system to set aside space in memory.

How much space? Based on variable type & your system.

- to get specific sizes for your system use `sizeof(<datatype>)` function in `stdlib.h`
- C also provides fixed-width integer types like `uint32_t` or `int64_t`

Type	Storage Size (64-bit system)	Value Range
`char`	1 byte	-128 to 127 or 0 to 255 (unsigned)
`short`	2 bytes	-32,768 to 32,767
`int`	4 bytes	-2,147,483,648 to 2,147,483,647
`unsigned int`	4 bytes	0 to 4,294,967,295
`long`	8 bytes	-9223372036854775808 to 9223372036854775807
`float`	4 bytes	1.2E-38 to 3.4E+38
`double`	8 bytes	2.3E-308 to 1.7E+308
`long long`	8 bytes	3.4E-4932 to 1.1E+4932
Pointer (any)	8 bytes	–

* pointers require space needed for an address – dependent on your system - 4 bytes for 32-bit, 8 bytes for 64-bit

Review: Working memory

As a program executes it interacts with the computer's working memory:

- **Code**: space for the code compiled instructions
- **Globals**: space for global variables, static constants, string literals, etc.
- **Heap**: holds dynamically allocated variables (`new` or `malloc` variables)
- **Stack**: holds current instructions, each function in a frame

Memory Allocation So Far

So far, we have seen two kinds of memory allocation:

- Global Variables – static memory allocation
  - space for global variables is set aside at compile time, stored in memory in the global/static variables segment of memory, not stack
  - space set aside for global variables is determined by C based on data type
  - space is preserved for entire lifetime of program, never relinquished while running

```
int counter = 0;      // global var
int main(int argc, char** argv) {
  counter++;
  printf("count = %d\n",counter);
  return EXIT_SUCCESS;
}
```

Memory Allocation So Far

- Local variables – automatic memory allocation
  - space for local variables is set aside at start of function, stored in **stack**
  - space set aside for local variables is determined by C based on data type
  - space is deallocated on return

```
int foo(int a) {
  int x = a + 1;      // local var
  return x;
}

int main(int argc, char** argv) {
  int y = foo(10);    // local var
  printf("y = %d\n",y);
  return EXIT_SUCCESS;
}
```

Dynamic Allocation

There are some situations where static and automatic allocation aren't sufficient:

- Need memory that persists *across* multiple function calls (but not for entire lifetime of program)
- Need more memory than can fit on the stack
- Memory size is not known in advance to the caller
- Something like…

```
char* ReadFile(char* filename) {
  int size = GetFileSize(filename);
  char* buffer = AllocateMem(size);

  ReadFileIntoBuffer(filename, buffer);
  return buffer;
}
```

You don't know how big the file size is!

Implicit vs. Explicit Allocation

What we want is ***dynamically***-allocated memory. The memory persists until either:

- A garbage collector collects it (*automatic memory management*)
  - **Implicit** memory allocator: programmer only allocates space, doesn't free it
  - Example: `new` in Java
- Your code explicitly deallocates it (*manual memory management*)
  - **Explicit** allocator: programmer allocates space and frees it up when finished
  - C requires you to manually manage memory
    - Gives you more control, but also causes headaches 🤕
  - Example: `malloc` and `free` in C

Memory is allocated on the **heap**, not the stack!

Multiple Ways to Store Program Data

Static global data

- *Fixed size* at compile-time
- Entire *lifetime of the program*

Stack-allocated data

- Local/temporary variables
- *Known lifetime* (deallocated on `return`)

Dynamic (heap) data

- Size known only at runtime (*i.e.* based on user-input)
- Lifetime known only at runtime (long-lived data structures)

```c
int count = 0;

void foo(int n) {
  int tmp;
  int local_array[n];

  int* dyn =
    (int*)malloc(n*sizeof(int));
}
```

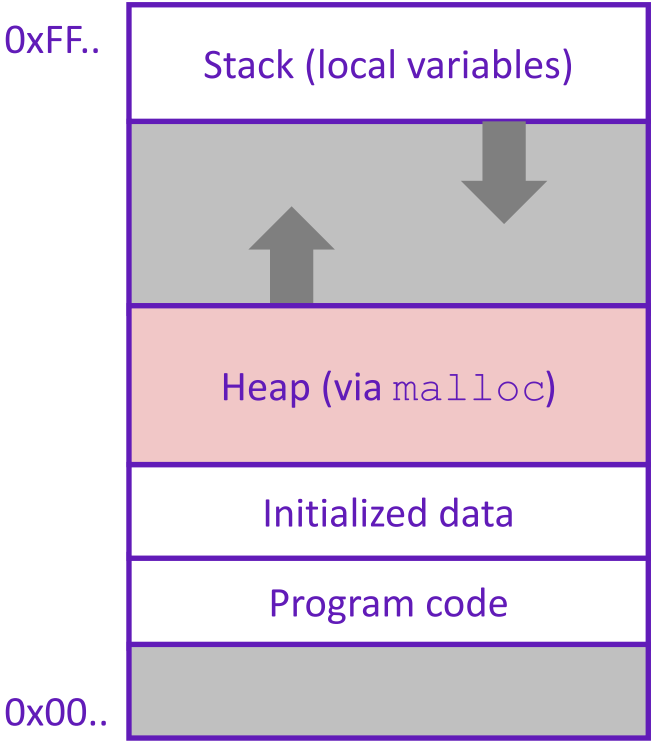
Address Space Visualization

Higher addresses on top, lower addresses on bottom

- Space is first set aside for program code
- Then for the initialized data (global variables, constants, string literals)

As program runs…

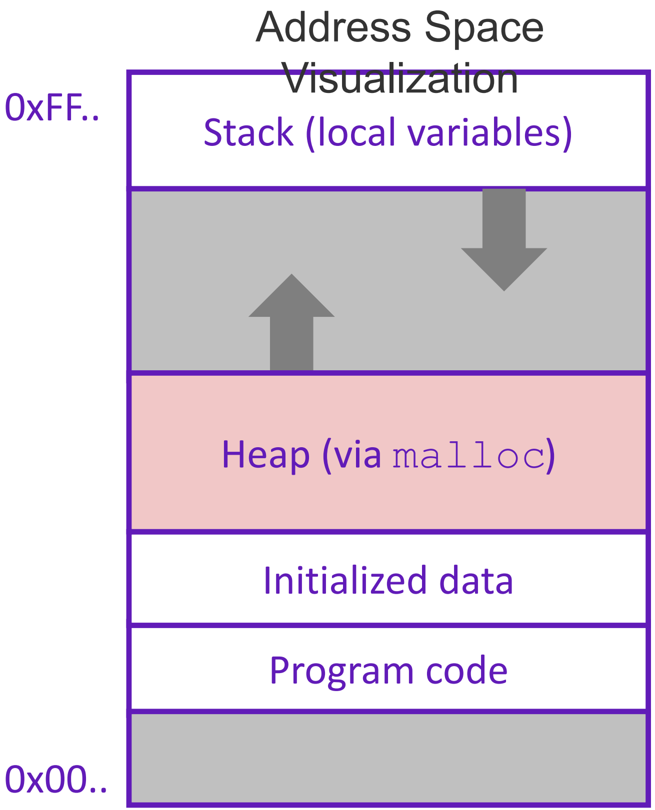
- Heap grows up as we dynamically allocate more memory
- Stack grows down as we call functions
- When the space between the stack and heap is full - **crash** (out of memory)



The Heap

The Heap is a large pool of available memory used to hold dynamically-allocated data

- **`malloc`** allocates chunks of data in the Heap; **`free`** deallocates those chunks
- **`malloc`** maintains bookkeeping data in the Heap to track allocated blocks
  - That's why bound checking is important! If we write beyond the allocated space, we might destroy the bookkeeping data.



Polling Time!

Please answer in the LP9 assignment on Gradescope!

Which of the following statements are **true**?

Select *all* that apply:

- ❏ The heap and stack grow towards each other but will *never* collide
- ❏ Temporary arrays should *not* be allocated on the heap
- ❏ Some languages handle memory cleanup automatically, freeing unused memory without requiring programmer intervention
- ❏ A data type will have the same size regardless of the machine you are using

`malloc` and `free`

Allocating Memory in C

Need to `#include <stdlib.h>`

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

- Allocates a continuous block of `size` *bytes* of **uninitialized** memory
- `void*` means a pointer to any type (e.g. `int`, `float`, `char`)
- Returns a pointer to the beginning of the allocated block
- Returns **`NULL`** if allocation failed or `size==0`
    - Allocation can fail if out of memory, very rare but always check before using!
- Consecutively allocated blocks are not necessarily adjacent
- Read/writing memory next to the returned block is **undefined behavior**

malloc()

General usage:

```
type* var = (type*) malloc(n * sizeof(type))
```

"Type casts" `void*` pointer to desired type

- Put the type you want to convert to in parentheses before the variable

`sizeof()` makes code portable to different machines

```
// allocate a 10-float array
float* arr = (float*) malloc(10*sizeof(float));
if (arr == NULL) {
  return 1; // exit with an error
}
...    // do stuff with arr
```

Special Case: Strings

When you allocate space for a string, you need to include space for the `\0`

This is a common mistake!

```
#include <stdlib.h>
#include <string.h>

char* str = "Hello World!\n"
char* copy = (char*) malloc(sizeof(char) * (strlen(str) + 1));
if (copy == NULL) {
  return 1;
}
strcpy(copy, str);
...   // do stuff with copy
```

Casting

C can convert a value of one type into another type using casting

Put the type you want to convert to in parentheses before the value

```
long x = 374;
int* ptr = (int*) x;
printf("%d\n", *ptr);
```

This will compile without warnings, but it is a really bad idea!

- This would dereference memory at location `374` (undefined behavior, likely result in a segfault)

Aside: errno (must #include <errno.h>)

How do you know if an error has occurred in C?

- C does not have Java-like exceptions

Usually, return a special error value (e.g. NULL)

stdlib functions set a global variable called errno

Can check error type by comparing to error code

- `if (errno == ENOMEM)  // Allocation failure`

Or call perror(message) to print to stderr

- `perror("malloc");  // "malloc: Cannot allocate memory"`

Reading Uninitialized Memory

Unlike Java, in C variables are un-initialized by default

- Meaning that they could hold any value before we first write to them
- Invalid read – reading from memory before you have written to it

```
int i;
printf("%d\n", i);  // Invalid read!
i = 374;
printf("%d\n", i);  // OK, was initialized to 374

float* fptr = (float*) malloc(sizeof(float));
if (fptr == NULL) {
  // Handle error ...
}
printf("%f\n", *fptr);  // Invalid read!
```

`calloc()`

General usage:

```
var = (type*) calloc(n, sizeof(type))
```

Like **`malloc`**, but also **zeroes out the memory** (i.e. calloc == *clear* and *allocate*)

- i.e. **initializes** memory to all 0s
- Slightly slower; but useful for non-performance-critical code
- Also in `stdlib.h`

```
// allocate a 10-double array
double* arr = (double*) calloc(10, sizeof(double));
if (arr == NULL) {
  // Handle error ...
}
printf("%f\n", arr[0]); // OK, will print 0.00000
```

`realloc()`

General usage:

```
p = (type*) realloc(p, newsize)
```

Creates a new allocation with given size, copies the contents of `p` into it and then frees `p`

- Saves a few lines of code and can sometimes be faster due to allocator optimizations
- Also in `stdlib.h`

```
// allocate a 10-int array
int* arr = (int*) calloc(10, sizeof(int));
if (arr == NULL) {
  // Handle error ...
}
// reallocate the memory
arr = (int*) realloc(arr, sizeof(int)*20);
```

Freeing Memory in C

Need to `#include <stdlib.h>`

```
void free(void* p)
```

- Releases whole block pointed to by `p` to the pool of available memory
- Pointer `p` must be the address *originally* returned by **`m/c/realloc`** (*i.e.* beginning of the block), otherwise system exception raised
- Address in the pointer is unaffected by call to free
  - Defensive programming: can set pointer to `NULL` after freeing it; freeing `NULL` has no effect
- Don't call `free` on a block that has already been released (double free)
  - Undefined behavior, best case: program crashes 😓

free()

Usage:

```
free(pointer);
```

Rule of thumb: for every call to `malloc` there should be one call to `free`

```
float* arr = (float*) malloc(10*sizeof(float));
if (arr == NULL)
  // Handle error ...
...              // do stuff with arr
free(arr);
arr = NULL;      // OPTIONAL, but recommended
free(arr);       // Bad! Double free is undefined
```

Polling Time!

Please answer in the LP9 assignment on Gradescope!

Which code snippet shows a **correct** use of **`malloc`** and **`free`**?

```
int x[] = {1, 2, 3};
int sum = x[0]+x[1]+x[2];
free(x);
```

A.

```
long* make_array(void) {
 return (long*)
malloc(5*sizeof(long));
}
// later...
long* val = make_array();
free(val);
```

B.

```
char* str =
   (char*) malloc(sizeof(char)*5);
free(str);
strcpy(str, ”Hello”);
```

C.

```
char** strings =
   (char**) malloc(sizeof(char)*5);
// use strings…
free(strings);
```

D.

Memory Allocation Example in C

```
void foo(int n, int m) {
  int i, *p;                                   //  declare local variables
  p = (int*) malloc(n*sizeof(int));            //  allocate block of n ints
  if (p == NULL) {                             //  check for allocation error
    perror("malloc");                          //  prints error message to stderr
    exit(1);
  }
  for (i=0; i<n; i++)                          //  initialize int array
    p[i] = i;
                                               //  add space for m ints to end of p block
  p = (int*) realloc(p,(n+m)*sizeof(int));
  if (p == NULL) {                             //  check for allocation error
    perror("realloc");
    exit(1);
  }
  for (i=n; i < n+m; i++)                      //  initialize new spaces
    p[i] = i;
  for (i=0; i<n+m; i++)                        //  print new array
    printf("%d\n", p[i]);
  free(p);                                     //  free p, pointer will be freed at end of
function
}
```

Demo: Memory Allocation

Activity: Practice using `malloc` and `free`!

Assignment Reminders

Ex6 and Ex7 due on Friday morning

Ex8 released today, due before class on Monday

HW3 has been released, you have until next Friday, July 24

- First C programming assignment!

All of these assignments can be found on our course's Gradescope page.

Bonus Slides 🎁

Wouldn't it be nice...

If we never had to free memory?

Do you free objects in Java?

- Reminder: *implicit* allocator

There are two main kinds of implicit allocators

- Garbage collection
- Reference counting (C++ smart pointers)

Garbage Collection (GC)

(Automatic Memory Management)

Garbage collection: automatic reclamation of heap-allocated storage – application never explicitly frees memory

```
void foo() {
    int* p = (int*) malloc(128);
    return;  /* p block is now unreachable! */
}
```

Used in many modern languages:

- Lisp, Haskell, Java, C#, Ruby, Python, JavaScript, Go, MATLAB, and more…

Variants ("conservative" garbage collectors) exist for C and C++, but cannot collect all garbage

Garbage Collection

How does the memory allocator know when memory can be freed?

- In general, we cannot know what is going to be used in the future since it depends on conditionals
- But, we can tell that certain blocks cannot be used if they are *unreachable* (via pointers in registers/stack/globals)

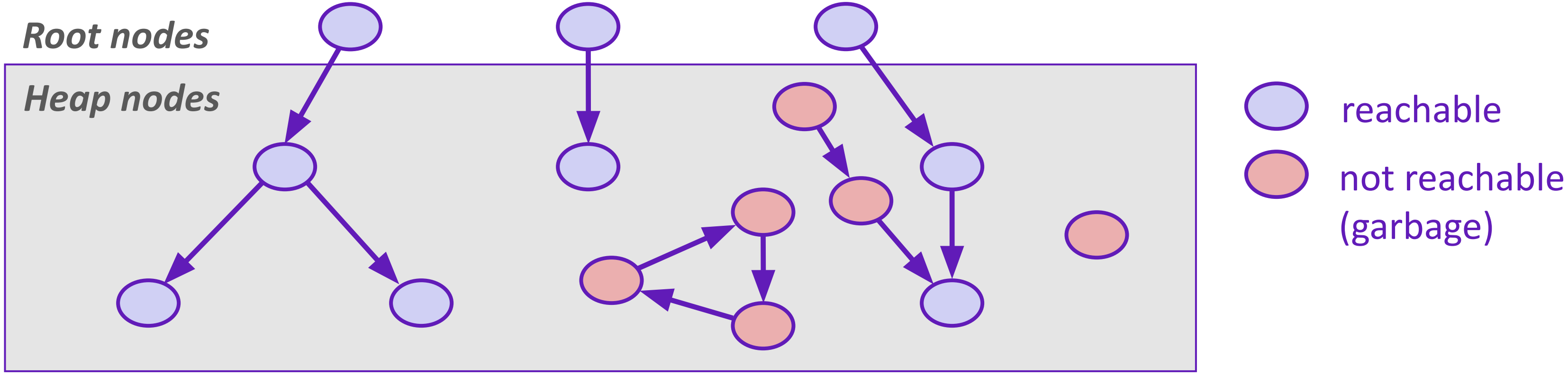
Memory allocator needs to know what is a pointer and what is not – how can it do this?

- Sometimes with help from the compiler

Memory as a Directed Graph

Each allocated heap block is a node in the graph

Each pointer is an edge in the graph



A node (block) is *reachable* if there is a path from any root to that node

- A root node is a global or local variable (or any other reachable object)

Non-reachable nodes are *garbage* (cannot be needed by the application)

Garbage Collection

Dynamic memory allocator can free blocks if there are no pointers to them

How can it know what is a pointer and what is not?

We'll make some *assumptions* about pointers:

- Memory allocator can distinguish pointers from non-pointers
- All pointers point to the start of a block in the heap
- Application cannot hide pointers
  (*e.g.* by coercing them to a long, and then back again)

Mark and Sweep

Interrupt the program at a regular interval

- "Stop the world" pauses

Deallocate any unreachable nodes

Resume program execution until the next pause and repeat