CS 31: Intro to Systems C Programming
L11: Pointers and Functions

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Announcements

• Midterm is in-class on Thursday.

• Let me know if you have not received an email from accommodations.

• HW 2 is due today (before class)
Reading Quiz

• Note the red border!

• 1 minute per question

• No talking, no laptops, phones during the quiz

Check your frequency:
• Iclicker2: frequency AA
• Iclicker+: green light next to selection

For new devices this should be okay,
For used you may need to reset frequency

Reset:
1. hold down power button until blue light flashes (2secs)
2. Press the frequency code: AA
   vote status light will indicate success
• Pointers and memory
  – allocating memory
  – &: address of
  – *: value at
• Functions & the stack
C Pointers Introduction

What is a pointer?
What is a pointer?

A pointer is like a mailing address, it tells you where something is located.

Every object (including simple data types) reside in the memory of the machine.

A pointer is an “address” telling you where that variable is located in memory.
Pointers

• **Pointer**: A variable that stores a reference (index) to a memory location.

• **Pointer**: sequence of bits that should be interpreted as an index into memory.

• Where have we seen this before?
Recall: Arrays

\[
\text{int january_temps[31]; // Daily high temps}
\]

Array variable name means, to the compiler, the \textbf{beginning of the memory chunk.} (address)
Recall: Addressing Mode: Memory

\texttt{movl (%rcx), %rax}

- Use the address in register \%rcx to access memory, store result in register \%rax

<table>
<thead>
<tr>
<th>CPU Registers</th>
</tr>
</thead>
<tbody>
<tr>
<td>name</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>%rax</td>
</tr>
<tr>
<td>%rcx</td>
</tr>
<tr>
<td>...</td>
</tr>
</tbody>
</table>

1. Index into memory using the address in rcx.

2. Copy value at that address to rax.
Recall: Program Counter

Program Counter (PC): Memory address of next instr

Instruction Register (IR): Instruction contents (bits)

X86_64 refers to the PC as %rip.

Instruction Pointer

Register File

64-bit Register #0

64-bit Register #1

64-bit Register #2

64-bit Register #3

...
Pointers in C

• Like any other variable, must be declared:
  – Using the format: `type *name;`

• Example:
  – `int *mymem;`
  – promise to the compiler:
    • This variable holds a memory address. *If you follow what it points to in memory (dereference it), you’ll find an integer.*

• A note on syntax:
  – `int *mymem;`     `int *mymem;`     `int *mymem;`
  – These all do the same thing. (note the * position)
Dereferencing a Pointer

• To follow the pointer, we *dereference* it.

• *Dereferencing re-uses the * symbol.*

• If iptr is declared as an integer pointer, *iptr* will follow the address it stores to find an integer in memory.
Putting a * in front of a variable...

- When you *declare* the variable:
  - Declares the variable to be a pointer
  - It stores a memory address

- When you *get the value* at mem. location in the pointer (*dereference)*:
  - Like putting () around a register name
  - We follows the pointer out to memory, get the value
  - Data we access will be of the specified type
    - e.g., pointer (mem. address) to an int, pointer (mem. address) to a float .., etc.
Memory - Stack

• At high addresses, we keep the stack.

• This stores local (automatic) variables.
  – The kind we’ve been using in C so far.
  – e.g., int x;
Memory - Stack

• The stack grows upwards towards lower addresses (negative direction).

• Example: Allocating array
  – int array[4];

• (Note: this differs from Python.)
• The heap stores dynamically allocated variables.

• When programs explicitly ask the OS for memory, it comes from the heap.
  – malloc() function
Which region would we expect the PC register (program counter) to point to?

A. OS
B. Text
C. Data
D. Heap
E. Stack
Which region would we expect the PC register (program counter) to point to?

A. OS
B. Text
C. Data
D. Heap
E. Stack
What should happen if we try to access an address that’s NOT in one of these regions?

A. The address is allocated to your program.
B. The OS warns your program.
C. The OS kills your program.
D. The access fails, try the next instruction.
E. Something else
What should happen if we try to access an address that’s NOT in one of these regions?

A. The address is allocated to your program.
B. The OS warns your program.
C. The OS kills your program.
D. The access fails, try the next instruction.
E. Something else
Segmentation Violation

- Each region also known as a memory segment.

- Accessing memory outside a segment is not allowed.

- Can also happen if you try to access a segment in an invalid way.
  - OS not accessible to users
  - Text is usually read-only
Place the variables/instructions in the c code into main memory

```c
int ARRAYSIZE = 100;

int main(void){
    int x, y;
    char *cptr;
    float values;
    values = malloc(5 * sizeof(int));

    return 0;
}
```
So we declared a pointer…

• How do we make it point to something?
  1. Assign it the address of an existing variable
  2. Copy some other pointer
  3. Allocate some memory and point to it
The Address Of (&)

- You can create a pointer to anything by taking its address with the `address of` operator (&).
The Address Of (&)

```c
int main(void) {
    int x = 7;
    int *iptr = &x;

    return 0;
}
```
What would this print?

```c
int main(void) {
    int x = 7;
    int *iptr = &x;
    int *iptr2 = &x;

    printf("%d %d ", x, *iptr);
    *iptr2 = 5;
    printf("%d %d ", x, *iptr);

    return 0;
}
```

A. 7 7 7 7   B. 7 7 7 5   C. 7 7 5 5   D. Something else
What would this print?

```c
int main(void) {
    int x = 7;
    int *iptr = &x;
    int *iptr2 = &x;

    printf("%d %d ", x, *iptr);
    *iptr2 = 5;
    printf("%d %d ", x, *iptr);

    return 0;
}
```

A. 7 7 7 7  
B. 7 7 7 5  
C. 7 7 5 5  
D. Something else
So we declared a pointer…

- How do we make it point to something?
  1. Assign it the address of an existing variable
  2. Copy some other pointer
  3. Allocate some memory and point to it
Copying a Pointer

We can perform assignment on pointers to copy the stored address.

```c
int x = 7;
int *iptr, *iptr2;
iptr = &x;
iptr2 = iptr;
```
Pointer Types

• By default, we can only assign a pointer if the type matches what C expects.

```c
int x = 7;  // Correct
int *iptr = &x;  // Correct
```

```c
int x = 7;  // Incorrect
float *fptr = &x;  // Incorrect
```

“Warning: initialization from incompatible pointer type”
(Don’t ignore this message!)
Recall: Dereferencing a Pointer

• To follow the pointer, we **dereference** it.

• **Dereferencing re-uses the * symbol.**

• If `iptr` is declared as an integer pointer, `*iptr` will follow the address it stores to find an integer in memory.
There exists a special type, `void *`, which represents a “generic pointer” type.

- Can be assigned to any pointer variable
- `int *iptr = (void *) &x;` // Doesn’t matter what x is

This is useful for cases when:

1. You want to **create a generic “safe value”** that you can assign to any pointer variable.
2. You want to pass a pointer to / return a pointer from a function, but you don’t know its type.
3. You **know better than the compiler** that what you’re doing is safe, and you want to eliminate the warning (usually not the case for cs31 😊)
NULL: A special pointer value.

• You can assign NULL to any pointer, regardless of what type it points to (it’s a void *).
  – `int *iptr = NULL;`
  – `float *fptr = NULL;`

• NULL is equivalent to pointing at memory address 0x0. This address is NEVER in a valid segment of your program’s memory.
  – *This guarantees a segfault if you try to dereference it.*

💡 In your C programs, start by initializing pointers to NULL.
Given these two setup statements, how many of the following dereference operations are invalid?

Setup:
```
int *ptr, x, y;
char *chptr, ch;
ptr = &x;       // ptr stores address of int x
chptr = &ch;   // chptr stores address of char ch
```

Dereference operations:
```
1) *ptr = 6;
2) *chptr = ‘a’;
3) y = *ptr + 4;
4) ptr = NULL, *ptr = 6;
```

A: 0   B: 1   C: 2   D: 3
Given these two setup statements, how many of the following dereference operations are invalid?

Setup:

```c
int *ptr, x, y;
char *chptr, ch;
ptr = &x;       // ptr stores address of int x
chptr = &ch;   // chptr stores address of char ch
```

Dereference operations:

```c
*ptr = 6;        // dereference ptr (get value at mem. address of x) and update x to a
*chptr = ‘a’;    // dereference chptr (get value at mem. address of ch), and update ch to a
y = *ptr + 4;    // dereference ptr (get value at mem. address of x) which is now 6, add 4, and store it in y. y = 10
ptr = NULL, *ptr = 6;   // set ptr to NULL and try to dereference the pointer. This will result in an error
```

A: 0   B: 1   C: 2   D: 3
What will this do?

```c
int main(void) {
    int *ptr;
    printf("%d", *ptr);
}
```

A. Print 0  
B. Print a garbage value  
C. Segmentation fault  
D. Something else
What will this do?

```c
int main(void) {
    int *ptr;
    printf("%d", *ptr);
}
```

A. Print 0  
B. Print a garbage value  
C. Segmentation fault  
D. Something else

Takeaway: If you’re not immediately assigning it something when you declare it, initialize your pointers to NULL.
Why Pointers?

- Using pointers seems like a lot of work, and if used incorrectly, things can go wrong.
- Pointers also add a level of “indirection” to retrieve / store a value

- Two main benefits:
  1. “Pass by pointer” function parameters
     - By passing a pointer into a function, the function can dereference it so that the changes persist to the caller.
  2. Dynamic memory allocation
     - A program can allocate memory on demand, as it needs it during execution
Why Pointers?

• Using pointers seems like a lot of work, and if used incorrectly, things can go wrong.
• Pointers add a level of “indirection” to retrieve / store a value

• Two main benefits:
  1. “Pass by pointer” function parameters
     * Pointer variable points to a memory location
     * Dereferencing a pointer can change value at that location
  2. Dynamic memory allocation
     * A program can allocate memory on demand, as it needs it during execution
So we declared a pointer…

• How do we make it point to something?
  1. Assign it the address of an existing variable
  2. Copy some other pointer
  3. Allocate some memory and point to this block of memory.
Allocating (Heap) Memory

- The standard C library (#include `<stdlib.h>`) includes functions for allocating memory:

```c
void* malloc(size_t size)
   // Allocate size bytes on the heap and return a pointer to the beginning of the memory block. (size_t is an unsigned int of 8 bytes on x86_64)

void free(void *ptr)
   // Release the malloc() ed block of memory starting at ptr back to the system.
```
Recall: void *

- **void** is a special type that represents “generic pointer”.

- This is useful for cases when:
  1. You want to create a generic “safe value” that you can assign to any pointer variable.
  2. *You want to pass a pointer to / return a pointer from a function, but you don’t know its type.*
  3. You know better than the compiler that what you’re doing is safe, and you want to eliminate the warning.

- When `malloc()` gives you bytes, it doesn’t know or care what you use them for...
Allocation Size

```c
void* malloc(size_t size)
    // Allocate size bytes on the heap and return a pointer to the beginning of
    // the memory block.
```

- How much memory should we ask for?

- Use C’s `sizeof()` operator:
  ```c
  int *iptr = NULL;
iptr = malloc(sizeof(int));
  ```
**sizeof()**

- Despite the (')s, *it's an operator, not a function*
  - Other operators:
    - addition / subtraction (+ / -)
    - address of (&)
    - indirection (*) (dereference a pointer)

- Works on any type to tell you how much memory it needs.

- Size value is determined *at compile time (static).*
Example

```c
int *iptr = NULL;

iptr = malloc(sizeof(int));

*iptr = 5;
```
Create an integer pointer, named iptr, on the stack.
Assign it NULL.

```c
int *iptr = NULL;

iptr = malloc(sizeof(int));

*iptr = 5;
```
Allocate space for an integer on the heap (4 bytes), and return a pointer to that space.

Assign that pointer to `iptr`.

```c
int *iptr = NULL;

iptr = malloc(sizeof(int));

*iptr = 5;
```
Example

```c
int *iptr = NULL;

iptr = malloc(sizeof(int));

*iptr = 5;
```

Use the allocated heap space by dereferencing the pointer.
Free up the heap memory we used.

```c
int *iptr = NULL;
iptr = malloc(sizeof(int));
*iptr = 5;
free(iptr);
```
Example

```c
int *iptr = NULL;
iptr = malloc(sizeof(int));
*iptr = 5;
free(iptr);
iptr = NULL;
```

Clean up this pointer, since it’s no longer valid.
Why is `sizeof()` important?

```c
struct student {
    char name[40];
    int age;
    double gpa;
}

struct student *bob = NULL;
bob = malloc(sizeof(struct student));
```

We never want to hard-code a number here!
You’re designing a system. What should happen if a program requests memory and the system doesn’t have enough available?

A. The OS kills the requesting program.
B. The OS kills another program to make room.
C. malloc gives it as much memory as is available.
D. malloc returns NULL.
E. Something else.
Running out of Memory

• If you’re ever unsure of malloc / free’s behavior:
  $ man malloc

• According to the C standard:
  “The malloc function returns a pointer to the allocated memory that is suitably aligned for any kind of variable. **On error, this function returns NULL.**”

• Further down in the “Notes” section of the manual:
  “[On Linux], when malloc returns non-NULL there is no guarantee that memory is really available. **If the system is out of memory, one or more processes will be killed by the OOM killer.**”
You should check for NULL after every malloc:

```c
struct student *bob = NULL;
bob = malloc(sizeof(struct student));

if (bob == NULL) {
    /* Handle this. Often, print and exit. */
}
```
What do you expect to happen to the 100-byte chunk if we do this?

// What happens to these 100 bytes?

int *ptr = malloc(100);

ptr = malloc(2000);

A. The 100-byte chunk will be lost.
B. The 100-byte chunk will be automatically freed (garbage collected) by the OS.
C. The 100-byte chunk will be automatically freed (garbage collected) by C.
D. The 100-byte chunk will be the first 100 bytes of the 2000-byte chunk.
E. The 100-byte chunk will be added to the 2000-byte chunk (2100 bytes total).
“Memory Leak”

• Memory that is allocated, and not freed, for which there is no longer a pointer.

• In many languages (Java, Python, ...), this memory will be cleaned up for you.
  – “Garbage collector” finds unreachable memory blocks, frees them.
  – (This can be a time consuming feature)
  – C doesn’t does NOT do this for you!
Why doesn’t C do garbage collection?

A. It’s impossible in C.

B. It requires a lot of resources.

C. It might not be safe to do so. (break programs)

D. It hadn’t been invented at the time C was developed.

E. Some other reason.
Memory Bookkeeping

• To free a chunk, you MUST call `free` with the same pointer that `malloc` gave you. (or a copy)

• The standard C library keeps track of the chunks that have been allocated to your program.
  – This is called “metadata” – data about your data.

• Wait, where does it store that information?
  – It’s not like it can use `malloc` to get memory...
int *iptr = malloc(8);
int *iptr = malloc(8);
```c
int *iptr = malloc(8);
```

C Library:

"Let me record this allocation’s info here."
Size of allocation
Maybe other info

<table>
<thead>
<tr>
<th>Heap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meta</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>First Byte</td>
</tr>
<tr>
<td>...</td>
</tr>
</tbody>
</table>
```c
int *iptr = malloc(8);
```

### Metadata

<table>
<thead>
<tr>
<th>Heap</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Meta</td>
<td>Data</td>
<td>Meta</td>
<td>Data</td>
</tr>
<tr>
<td>First Byte</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>Last Byte</td>
</tr>
<tr>
<td>Meta</td>
<td>Data</td>
<td>Meta</td>
<td>Data</td>
</tr>
</tbody>
</table>

There could be another chunk after yours.
int *iptr = malloc(8);

stay within the memory chunks you allocate.
If you corrupt the metadata, you will get weird behavior.
Valgrind is your new best friend! 😊

```c
int *iptr = malloc(8);
```
Pointers as Arrays

"Why did you allocate 8 bytes for an int pointer?
  \[\texttt{int } *\texttt{iptr }= \texttt{malloc}(8);\]

• Recall: an array variable acts like a pointer to a block of memory. The number in [] is an offset from bucket 0, the first bucket.

• We can treat pointers in the same way!
Pointers as Arrays

```c
int *iptr = NULL;
iptr = malloc(4 * sizeof(int));
```
Pointers as Arrays

```c
int *iptr = NULL;
iptr = malloc(4 * sizeof(int));
```
Pointers as Arrays

```c
int *iptr = NULL;
iptr = malloc(4 * sizeof(int));
```

The C compiler knows how big an integer is.

As an alternative way of dereferencing, you can use []’s like an array.

The C compiler will jump ahead the right number of bytes, based on the type.
Pointers as Arrays

```c
int *iptr = NULL;
iptr = malloc(4 * sizeof(int));
```
**Pointers as Arrays**

```c
int *iptr = NULL;
iptr = malloc(4 * sizeof(int));

1. Start from the base of iptr.
iptr[2] = 7;
```
Pointers as Arrays

```c
int *iptr = NULL;
iptr = malloc(4 * sizeof(int));

iptr[2] = 7;
```

1. Start from the base of `iptr`.
2. Skip forward by the size of two ints.
Pointers as Arrays

```c
int *iptr = NULL;
iptr = malloc(4 * sizeof(int));
```

1. Start from the base of `iptr`.
2. Skip forward by the size of two ints.
3. Treat the result as an int. (Access the memory location like a typical dereference.)
Pointers as Arrays

• This is one of the most common ways you’ll use pointers:
  – You need to dynamically allocate space for a collection of things (ints, structs, whatever).
  – You don’t know how many at compile time.

```c
float *student_gpas = NULL;
student_gpas = malloc(n_students * sizeof(int));
...
student_gpas[0] = ...;
student_gpas[1] = ...;
```
Pointer Arithmetic

- Addition and subtraction work on pointers.

- C automatically increments by the size of the type that’s pointed to.
int *iptr = NULL;

iptr = malloc(4 * sizeof(int));
int *iptr = NULL;
iptr = malloc(4 * sizeof(int));

int *iptr2 = iptr + 3;
`int *iptr = NULL;
iptr = malloc(4 * sizeof(int));`

`int *iptr2 = iptr + 3;`

Skip ahead by 3 times the size of `iptr`'s type (integer, size: 4 bytes).
Why Pointers?

• Using pointers seems like a lot of work, and if used incorrectly, things can go wrong.
• Pointers also add a level of “indirection” to retrieve / store a value

• Two main benefits:
  1. “Pass by pointer” function parameters
     • By passing a pointer into a function, the function can dereference it so that the changes persist to the caller.
  2. Dynamic memory allocation
     • A program can allocate memory on demand, as it needs it during execution
Function Arguments

• Arguments are **passed by value**
  – The function gets a separate _copy_ of the passed variable

```c
int func(int a, int b) {
    a = a + 5;
    return a - b;
}

int main(void) {
    int x, y; // declare two integers
    x = 4;
    y = 7;
    y = func(x, y);
    printf("%d, %d", x, y);
}
```

Function Arguments

- Arguments are **passed by value**
  - The function gets a separate copy of the passed variable

```c
int func(int a, int b) {
    a = a + 5;
    return a - b;
}

int main(void) {
    int x, y;  // declare two integers
    x = 4;
    y = 7;
    y = func(x, y);
    printf("%d, %d", x, y);
}
```

It doesn’t matter what `func` does with `a` and `b`. The value of `x` in `main` doesn’t change.
Pass by Pointer

• Want a function to modify a value on the caller’s stack? Pass a pointer!

• The called function can modify the memory location it points to.
  – passing the address of an argument to function:
  – pointer parameter holds the address of its argument
  – dereference parameter to modify argument’s value

• You’ve already used functions like this:
  – `readfile` library functions and `scanf`
  – pass address of (&) argument to these functions
Function Arguments

• Arguments can be pointers!
  — The function gets the address of the passed variable!

```c
void func(int *a) {
    *a = *a + 5;
}

int main(void) {
    int x = 4;
    func(&x);
    printf("%d", x);
}
```
• Arguments can be pointers!
  – The function gets the address of the passed variable!

```c
void func(int *a) {
    *a = *a + 5;
}

int main(void) {
    int x = 4;
    func(&x);  // x's address is passed to func
    printf("%d", x);
}
```
**Pointer Arguments**

- Arguments can be pointers!
  - The function gets the address of the passed variable!

```c
void func(int *a) {
    *a = *a + 5;
}

int main(void) {
    int x = 4; // x is at mem. address 0x1A
    func(&x);
    printf("%d", x);
}
```
void func(int *a) {
    *a = *a + 5;
}

int main(void) {
    int x = 4; // x is at mem. address 0x1A
    func(&x);
    printf("%d", x);
}

**Pointer Arguments**

- Arguments can be pointers!
  - The function gets the address of the passed variable!

Dereference pointer, set value that a points to.
Pointer Arguments

• Arguments can be pointers!
  – The function gets the address of the passed variable!

```c
void func(int *a) {
    *a = *a + 5;
}

int main(void) {
    int x = 4;
    func(&x);
    printf("%d", x);
}
```

Prints: 9
Haven’t we seen this somewhere before?
• In lab 1/lab 4 with read_int, read_float.
  – This is why you needed an & when you pass the address of a variable.
  – e.g.,
    ```
    int value;
    status_code = read_int(&value);
    ```

• You’re asking read_int to modify a parameter, so you give it a pointer (the address of) that parameter.
  – read_int will dereference it and set it.
Pass by Pointer - Example

```c
int main(void){
    int x, y;
    x = 10; y = 20;
    //assume x at mem. address 0xF1
    foo(&x, y);
    ...
}

void foo(int *b, int c){
    c = 99
    *b = 8;  // Stack drawn here
}
```
int main(void) {
    int x, y;
    x = 10; y = 20;  // assume x at mem. address 0xF1
    foo(&x, y);
    ...
}

void foo(int *b, int c) {
    c = 99
    *b = 8;  // Stack drawn here
}

dereference parameter b to set argument x’s value

Pass by Pointer - Example
Passing Arrays

- An array argument’s value is its base address
- Array parameter “points to” its array argument
Passing Arrays

• An array argument’s value is its base address
• Array parameter “points to” its array argument

```c
int main(void)
{
    int array[10];
    foo(array, 10);
}

void foo(int arr[], int n)
{
    arr[2] = 6;
}
```
Passing Arrays

- An array argument’s value is its base address
- Array parameter “points to” its array argument

```c
int main(void){
    int array[10];
    foo(array, 10);
}
void foo(int arr[], int n){
    arr[2] = 6;
}
```
Passing Arrays

- An array argument’s value is its base address
- Array parameter “points to” its array argument

```c
int main(void){
    int array[10];
    foo(array, 10);
}
void foo( _______ , int n){
    arr[2] = 6;
}
```
Passing Arrays

- An array argument’s value is its base address
- Array parameter “points to” its array argument

```c
int main(void) {
    int array[10];
    foo(array, 10);
}

void foo(int *arr, int n) {
    arr[2] = 6;
}
```

*pass a pointer instead!*

```
0   1   2      …               9
```

`arr` is a pointer to the array; `n` is the size of the array. October 24, 2022
Can you return an array?

• Suppose you wanted to write a function that copies an array (of 5 integers).
  – Given: array to copy

```c
int copy_array(int array[]) {
    int result[5];
    result[0] = array[0];
    ...
    result[4] = array[4];
    return result;
}
```

As written above, this would be a terrible way of implementing this. (Don’t worry, compiler won’t let you do this anyway.)
Consider the memory…

copy_array(int array[]) {
    int result[5];
    result[0] = array[0];
    ...
    result[4] = array[4];
    return result;
}

(In main):
copy = copy_array(...)

```cpp
copy_array(int array[]) {
    int result[5];
    result[0] = array[0];
    ...
    result[4] = array[4];
    return result;
}
```

```cpp
(In main):
copy = copy_array(...)
```
Consider the memory...

copy_array(int array[]) {
    int result[5];
    result[0] = array[0];
    ...
    result[4] = array[4];
    return result;
}

(In main):
copy = copy_array(...)

Consider the memory...

copy_array(int array[]) {
    int result[5];
    result[0] = array[0];
    ...
    result[4] = array[4];
    return result;
}

(In main):

copy = copy_array(…)

Left with a pointer to nowhere.

When we return from copy_array, its stack frame is gone!
Using the Heap

```c
int *copy_array(int num, int array[]) {
    int *result = malloc(num * sizeof(int));
    result[0] = array[0];
    ...
    return result;
}
```

malloc memory is on the heap.

Doesn’t matter what happens on the stack (function calls, returns, etc.)
Pointers to Pointers

- Why stop at just one pointer?

```c
int **double_iptr;
```

- “A pointer to a pointer to an int.”
  - Dereference once: pointer to an int
  - Dereference twice: int

- Commonly used to:
  - Allow a function to modify a pointer (data structures)
  - Dynamically create an array of pointers.
  - (Program command line arguments use this.)