CS 31: Intro to Systems
Pointers and Memory

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February 14, 2016
Reminders:

• Lab03 due tonight 11:59pm

• Written Assignment due at the beginning of class this Thursday

• Send me team info before 6pm tonight for Lab04

• Reminder: Ninja Session Sunday 7pm-11pm in SCI 256
Overview

• How to reference the location of a variable in memory

• Where variables are placed in memory

• How to make this information useful
  – Allocating memory
  – Calling functions with pointer arguments
The “P” Word

• Pointer: A variable that stores a reference to a memory location.

• We’ve seen a few things that look like pointers
  – Arrays
  – Putting () around a register
Recall: Arrays

```c
int myarray[31];  // Daily high temps
```

“myarray”
Location of [0] in memory.

- Array variable name means, to the compiler, the beginning of the memory chunk. (address)

- Index number is an offset from beginning.
In Assembly Language
Recall: Assembly While Loop

```assembly
movl $0 eax
movl $0 edx
loop:
    addl (%ecx), %eax
    addl $4, %ecx
    addl $1, %edx
    cmpl $5, %edx
    jne loop
```

Values to sum, in memory.

<p>| | | |</p>
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Update reference to next item.
**Recall: Assembly While Loop**

```
movl $0 eax
movl $0 edx
loop:
  addl (%ecx), %eax
  addl $4, %ecx
  addl $1, %edx
  cmpl $5, %edx
  jne loop
```

- **Using (dereferencing)** the memory address to access memory at that location.
- Manipulating the pointer to point to something else.
- Note: This did NOT read or write the memory that is pointed to.
Pointers in C

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

• Example:
  – int *mypytr;
  – This is a 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* myptr;  int * myptr;  int *mypytr;
  – These all do the same thing. (note the * position)
Declaring pointer variables

float f; //declares a float
int i = 0; //declares and initializes an int

float* fp; //declares a float pointer
int *ip = NULL; //declares and inits an int
    //int pointer

int *p1, *p2, p3; //declares two pointers
    //and an ordinary int
Pointers store addresses.

```c
float f = 0, *fp = NULL;
int i = 0, *ip = NULL;

printf("%f, %p\n", f, fp);
printf("%d, %p\n", i, ip);

> 0.000000, 0x0
> 0, 0x0
```
Pointer operators: * and &

* is the value-at-address operator.
  * AKA the dereference operator.

& is the address-of operator.

```c
float f, *fp;
fp = &f;
*fp = 0;
```
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 *use* the variable (dereference):
  - Like putting () around a register name
  - Follows the pointer out to memory
  - Acts like the specified type (e.g., int, float, etc.)
Suppose we set up a pointer like this. Which expression gives us 5, and which gives us a memory address?

```c
int *iptr = (that memory);
```

A. Memory address: *iptr, Value 10: iptr

B. Memory address: iptr, Value 10: *iptr
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

• First, let’s look at how memory is organized.
Memory

• Behaves like a big array of bytes, each with an address (bucket #).

• By convention, we divide it into regions.

• The region at the lowest addresses is usually reserved for the OS.
Memory - Text

• After the OS, we store the program’s code.

• Instructions generated by the compiler.
Memory – (Static) Data

- Next, there’s a fixed-size region for static data.

- This stores static variables that are known at compile time.
  - Global variables
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.)
Memory - Heap

- The heap stores dynamically allocated variables.

- When programs explicitly ask the OS for memory, it comes from the heap.
  - `malloc()` function
If we can declare variables on the stack, why do we need to dynamically allocate things on the heap?

A. There is more space available on the heap.

B. Heap memory is better. (Why?)

C. We may not know a variable’s size in advance.

D. The stack grows and shrinks automatically.

E. Some other reason.
Memory - Heap

• The heap grows downwards, towards higher addresses.

• I know you want to ask a question…
Memory - Heap

• “What happens if the heap and stack collide?”

• This picture is not to scale – the gap is huge.

• The OS works really hard to prevent this.
  – Would likely kill your program before it could happen.
Which region would we expect the PC register (prog. 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
Segmentation Violation

This program has performed an illegal operation and will be shut down.
If the problem persists, contact the program vendor.

SETUP caused an invalid page fault in module SETUP.EXE at 0167:0040351e.
Registers:
EAX=00000000  CS=0167  EIP=0040351e  EFLGS=00000000
EBX=00000000  SS=016f  ESP=0068ff58  EBP=0068ff78
ECX=00000001  DS=016f  ESI=00000000  FS=1b3f
EDX=0040349a  ES=016f  EDI=00440000  GS=0000
Bytes at CS:EIP:
0f b7 06 66 3b c3 0f 85 78 ff ff ff eb 1d 6a 08

kwebb@sesame ~ $ ./my_program
Segmentation fault
kwebb@sesame ~ $
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
Recap

• & gives us the address of a variable (a pointer)
• * allows us to follow the address to memory, accessing the item (dereference the pointer)

• Memory model:
  • So far, all variables on stack.

• Up next: using the heap.
  – We may not know the size of a variable in advance. (dynamic)
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() {
    int x = 7;
    int *iptr = &x;

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

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

    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;
```
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;
*iptr2 = 5;
```
Pointer Types

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

  \[
  \text{int } x = 7; \\
  \text{int } *\text{i.ptr} = &x; \\
  \text{int } x = 7; \\
  \text{float } *\text{f.ptr} = &x; \\
  \]

  \[
  \text{int } x = 7; \\
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  \text{int } x = 7; \\
  \text{float } *\text{f.ptr} = &x; \\
  \]

  \[
  \text{“Warning: initialization from incompatible pointer type” (Don’t ignore this!)} \\
  \]
There exists a special type, `void *`, which represents “generic pointer” type.

- Can be assigned to any pointer variable
  ```c
  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.
**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 deref it.
  - Generally a good ideal to initialize pointers to `NULL`. 
int main() {
    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.
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
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

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”.
  - Can be assigned to any pointer variable

- 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…
The `sizeof()` operator

```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));
  ```
Example

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

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

Create an integer pointer, named iptr, on the stack.

Assign it NULL.
Example

```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.
int *iptr = NULL;

iptr = malloc(sizeof(int));

*iptr = 5;

Use the allocated heap space by dereferencing the pointer.
Example

```c
int *iptr = NULL;

iptr = malloc(sizeof(int));

*iptr = 5;

free(iptr);
```

Free up the heap memory we used.
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.
`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.
sizeof() example

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

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

I don’t ever want to see a number hard-coded in here!
A few notes on `sizeof()`

- `sizeof()` will not give you the number of elements in an array or allocated memory block
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- `sizeof()` should only be used on types in this course, it can give seemingly strange results when applied to variables
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.**”
Running out of Memory

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  $ 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.**”

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. */
}
```
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