CS107, Lecture 11
The Heap, Continued

Reading: K&R 5.6-5.9 or Essential C section 6 on the heap

CS107 Topic 3

How can we effectively manage all types of memory in our programs?

Why is answering this question important?

- Shows us how we can pass around data efficiently with pointers (last time)
- Introduces us to the heap and allocating memory that we manually manage (today)
- Helps us better understand use-after-free vulnerabilities, a common bug (today)

assign3: implement a function using resizable arrays to read lines of any length from a file and write 2 programs using that function to print the last N lines of a file and print just the unique lines of a file. These programs emulate the **tail** and **uniq** Unix commands!

Learning Goals

- Learn about the differences between the stack and the heap and when to use each one
- Become familiar with the **malloc**, **calloc**, **realloc** and **free** functions for managing memory on the heap
- Understand use-after-free vulnerabilities and vulnerability disclosure

Lecture Plan

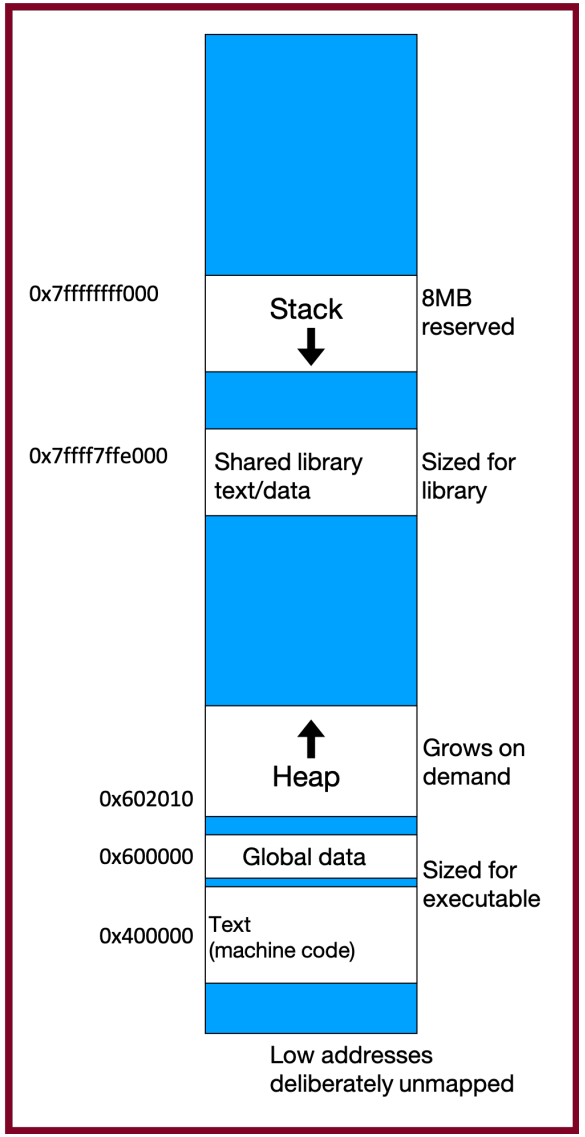
- **Recap:** The Heap So Far
- Freeing Memory
- **Practice:** Pig Latin + Valgrind
- Use-after-free bugs and vulnerability disclosure
- **realloc**

```
cp -r /afs/ir/class/cs107/lecture-code/lect11 .
```

The Heap

- The **heap** is a part of memory that you can manage yourself.
- The **heap** is a part of memory below the stack that you can manage yourself. Unlike the stack, the memory only goes away when you delete it yourself.
- Unlike the stack, the heap grows **upwards** as more memory is allocated.

The heap is **dynamic memory** – memory that can be allocated, resized, and freed during **program runtime**.



Working with the heap

Working with the heap consists of 3 core steps:

1. Allocate memory with malloc/realloc/strdup/calloc
2. Assert heap pointer is not NULL
3. Free when done

The heap is **dynamic memory**, so you may encounter many **runtime errors**, even if your code compiles!

malloc

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

To allocate memory on the heap, use the **`malloc`** function ("memory allocate") and specify the number of bytes you'd like.

- This function returns a pointer to *the **starting address** of the new memory*. It doesn't know or care whether it will be used as an array, a single block of memory, etc.
- **`void *`**means a pointer to generic memory. You can set another pointer equal to it without any casting.
- The memory is *not* cleared out before being allocated to you!
- If `malloc` returns `NULL`, then there wasn't enough memory for this request.

Always assert with the heap

Let's write a function that returns an array of the first **len** multiples of **mult**.

```
1 int *array_of_multiples(int mult, int len) {
2     int *arr = malloc(sizeof(int) * len);
3     assert(arr != NULL);
4     for (int i = 0; i < len; i++) {
5         arr[i] = mult * (i + 1);
6     }
7     return arr;
8 }
```

- If an allocation error occurs (e.g. out of heap memory!), malloc will return NULL. This is an important case to check **for robustness**.
- **assert** will crash the program if the provided condition is false. A memory allocation error is significant, and we should terminate the program.

Other heap allocations: `calloc`

```
void *calloc(size_t nmemb, size_t size);
```

`calloc` is like `malloc` that **zeros out** the memory for you—thanks, `calloc`!

- You might notice its interface is also a little different—it takes two parameters, which are multiplied to calculate the number of bytes (`nmemb * size`).

```
// allocate and zero 20 ints
int *scores = calloc(20, sizeof(int));

// alternate (but slower)
int *scores = malloc(20 * sizeof(int));
for (int i = 0; i < 20; i++) scores[i] = 0;
```

- calloc is more expensive than malloc because it zeros out memory. Use only when necessary!

Other heap allocations: `strdup`

```
char *strdup(char *s);
```

`strdup` is a convenience function that returns a **null-terminated**, heap-allocated string with the provided text, instead of you having to **`malloc`** and copy in the string yourself.

```
char *str = strdup("Hello, world!");  // on heap
str[0] = 'h';
```

You could imagine **strdup** might be implemented in terms of **malloc** + **strcpy**.

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- **Freeing Memory**
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- Use-after-free bugs and vulnerability disclosure
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```
cp -r /afs/ir/class/cs107/lecture-code/lect11 .
```

Cleaning Up with `free`

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

- If we allocated memory on the heap and no longer need it, it is our responsibility to **free** it.
- To do this, use the **`free`** command and pass in the *starting address on the heap for the memory you no longer need.*
- Example:

```
char *bytes = malloc(4);
…
free(bytes);
```

Free

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

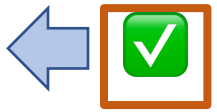
When you free an allocation, you are freeing up what it *points* to. You are not freeing the pointer itself. You can still use the pointer to point to something else.

```
char *str = strdup("hello");
...
free(str);
str = strdup("hi");
```

free details

Even if you have multiple pointers to the same block of memory, each memory block should only be freed **once**.

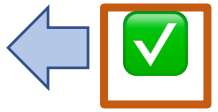
```
char *bytes = malloc(4);
char *ptr = bytes;
…
free(bytes);
…
free(ptr);
```

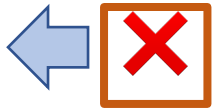


❌ Memory at this address was already freed!

You must free the address you received in the previous allocation call; you cannot free just part of a previous allocation.

```
char *bytes = malloc(4);
char *ptr   = malloc(10);
…
free(bytes);
…
free(ptr + 1);
```





Cleaning Up

You may need to free memory allocated by other functions if that function expects the caller to handle memory cleanup.

```
char *str = strdup("Hello!");
…
free(str);     // our responsibility to free!
```

Memory Leaks

A **memory leak** is when you do not free memory you previously allocated.

```
char *str = strdup("hello");
...
str = strdup("hi"); // memory leak!  Lost previous str
```

Memory Leaks

A **memory leak** is when you do not free memory you previously allocated.

- Your program should be responsible for cleaning up any memory it allocates but no longer needs.
- If you never free any memory and allocate an extremely large amount, you may run out of memory in the heap!
- However, memory leaks rarely (if ever) cause crashes.
- We recommend not to worry about freeing memory until your program is written. Then, go back and free memory as appropriate.
- Valgrind is a very helpful tool for finding memory leaks!

Lecture Plan

- **Recap:** The Heap So Far
- Freeing Memory
- **Practice: Pig Latin + Valgrind**
- Use-after-free bugs and vulnerability disclosure
- **realloc**

```
cp -r /afs/ir/class/cs107/lecture-code/lect11 .
```

Example: Pig Latin

Let's write a program that can convert text to Pig Latin! Simplified Pig Latin rules:

- If the word starts with a vowel, append "way": *apple* -> *appleway*
- Otherwise, move all starting consonants to the end and append "ay": *bridge* -> *idgebray*

We want to write a function **char *pig_latin(const char *in)** that returns the Pig Latin version of the given string.

- Good use case for heap allocation – array size is unknown until we convert it to Pig Latin! We'll create and return a heap-allocated string.
- The caller must free the string when it is done.

Example: Pig Latin

We will also see an example of how to uncover memory leaks using Valgrind.

valgrind --leak-check=full --show-leak-kinds=all [program info here]

Demo: Pig Latin + Valgrind

`pig_latin.c`

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- **Use-after-free bugs and vulnerability disclosure**
- **realloc**

```
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```

Use-After-Free

"Use-After-Free" is a bug where you continue to use heap memory after you have freed it.

```
char *bytes = malloc(4);
char *ptr = bytes;
…
free(bytes);
…
strncpy(ptr, argv[1], 3);
```

We freed bytes but did not set ptr to NULL

✗ Memory at this address was already freed, but now we are using it!

This is possible because **free()** doesn't change the pointer passed in, it just frees the memory it points to.

Use-After-Free

- What happens when we have a use-after-free bug? ***Undefined Behavior / a memory error!***
  - Maybe the memory still has its original contents?
  - Maybe the memory is used to store some other heap data now?
- Use-after-free is not just a functionality issue; it can cause a range of unintended behavior, including accessing/modifying memory you shouldn't be able to access

It's our job as programmers to find and fix use-after-free and other bugs not just for the functional correctness of our programs, but to protect people who use and interact with our code.

Use-After Free as a Vulnerability

- Use After Free Vulnerabilities in CVE database
- Use-after-free in Chrome (2020)
- Google's attempts to reduce Chrome use-after-free vulnerabilities (2021)
- Use-after-free in iOS (2020)
- Google 2023 Chrome fixes include use-after-free vulnerability and heap buffer overflow (2023)

What should someone do if they find a vulnerability? How can we incentivize responsible disclosure?

Disclosure

Various roles in this process: **users** (those at risk), **makers** (e.g., software company), **security researchers** (who found the vulnerability), **bad actors** (who wish to exploit the issue to harm users), etc.

- Users want to be protected with secure software
- Makers want to make their software secure and not have it exploited – they probably want to have time to fix vulnerabilities before they are made public
- Security researchers want their issues to be fixed and be rewarded for finding them
- Bad actors want to learn about vulnerabilities before they are patched

Full Disclosure

One approach is to make vulnerabilities public as soon as they are found.
Vulnerabilities unknown to the software maker before release are called “zero-day vulnerabilities” because they “have 0 days to fix the problem”.

- puts pressure on the maker to fix it quickly
- discloses the vulnerability to the public as soon as it’s found
- Leaves users vulnerable until the maker releases a patch

Few people now endorse this approach due to its drawbacks.

Responsible Disclosure

Another approach is to privately alert the software maker to the vulnerability to fix it in a reasonable amount of time before publicizing the vulnerability.
This is called “responsible disclosure”:

- Contacts the makers of the software
- Informs them about the vulnerability
- Negotiates a reasonable timeline for a patch or fix
- Considers a deadline extension if necessary

time passes while the developers fix the bug

- Works with the developers to add the vulnerability to CVE Details https://www.cvedetails.com/ , from which it is added to the National Vulnerability Database https://nvd.nist.gov/

Responsible Disclosure

Responsible disclosure is the most common approach, and it is recommended by the ACM code of ethics:

Responsible disclosure is the approach more consistent with the ACM Code of Ethics. By keeping the existence of the vulnerability secret for a longer amount of time, it reduces the chance of harm to others (Principle 1.2). It also supports more robust patching (Principles 2.1, 2.9, and 3.6), as the company can take more time to develop the patch and confirm that it will not induce unintended consequences. Full disclosure puts individuals at risk of harm sooner, and those harms may be irreversible and onerous (contravening Principles 1.2 and 3.1). As such, full disclosure should the exception and should only be used when attempts at responsible disclosure have failed. Furthermore, the individual committing to the full disclosure needs to consider carefully the risks that they are imposing on others and be willing to accept the moral and possibly legal consequences (Principles 2.3 and 2.5).

Vulnerability Commercialization

Various entities may want to financially reward people for finding and reporting vulnerabilities:

- Software makers want to know about vulnerabilities in their software
- Other entities want to know about unpatched vulnerabilities to exploit them

Bug Bounty Programs

Many companies now offer “Bug Bounties,” or rewards for responsible disclosure.

Good Version of a bug bounty process:

- Responsible disclosure process is followed
- Company is buying information & time to fix the bug

Bad version of a bug bounty process:

- Company does not fix the bug *or* notify the public.
- Not knowing what vulnerabilities exist makes it harder for users to calibrate trust
- Company is effectively buying silence

Vulnerabilities Equities Process

The US federal government is one of the largest discoverers and purchasers of 0-day vulnerabilities.

It follows a “Vulnerabilities Equities Process” (VEP) to determine which vulnerabilities to responsibly disclose and which to keep secret and use for espionage or intelligence gathering.

VEP claimed in 2017 that 90% of vulnerabilities are disclosed, but it is not clear what the impact or scope of the un-disclosed 10% of vulnerabilities are.

More reading here and here

Concerns with VEP

- Lack of transparency: little oversight as to whether the “bias towards responsible disclosure” is consistently upheld
- Harm of omission: withholding the opportunity to fix the vulnerability means that another actor could re-discover and use it
- Risk of stockpiling: Other people can hack into the stored 0-days and use them, as in the “Shadowbrokers” attack which led to serious ransomware attacks on hospitals and transportation systems
- Intended use: NSA’s intended use of vulnerabilities may be concerning, as in PRISM surveillance program.

Lecture Plan

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```
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```

realloc

```
void *realloc(void *ptr, size_t size);
```

- The **realloc** function takes an existing allocation pointer and enlarges to a new requested size. It returns the new pointer.
- If there is enough space after the existing memory block on the heap for the new size, **realloc** simply adds that space to the allocation.
- If there is not enough space, **realloc** *moves the memory to a larger location*, frees the old memory for you, and *returns a pointer to the new location*.

realloc

```
char *str = strdup("Hello");
assert(str != NULL);
…

// want to make str longer to hold "Hello world!"
char *addition = " world!";
str = realloc(str, strlen(str) + strlen(addition) + 1);
assert(str != NULL);

strcat(str, addition);
printf("%s", str);
free(str);
```

realloc

- realloc only accepts pointers that were previously returned by malloc/etc.
- Make sure to not pass pointers to the middle of heap-allocated memory.
- Make sure to not pass pointers to stack memory.

Cleaning Up with `free` and `realloc`

You only need to free the new memory coming out of `realloc`—the previous (smaller) one was already reclaimed by `realloc`.

```
char *str = strdup("Hello");
assert(str != NULL);
…
// want to make str longer to hold "Hello world!"
char *addition = " world!";
str = realloc(str, strlen(str) + strlen(addition) + 1);
assert(str != NULL);
strcat(str, addition);
printf("%s", str);
free(str);
```

Stack and Heap

- Generally, unless a situation requires dynamic allocation, stack allocation is preferred. Often both techniques are used together in a program.
- Heap allocation is a necessity when:
  - you have a very large allocation that could blow out the stack
  - you need to control the memory lifetime, or memory must persist outside of a function call
  - you need to resize memory after its initial allocation

assign3

assign3: implement a function using resizable arrays to read lines of any length from a file and write 2 programs using that function to print the last N lines of a file and print just the unique lines of a file. These programs emulate the **tail** and **uniq** Unix commands!

Structs

A *struct* is a way to define a new variable type that is a group of other variables.

```
struct date {           // declaring a struct type
    int month;
    int day;            // members of each date structure
};
…

struct date today;                      // construct structure instances
today.month = 1;
today.day = 28;

struct date new_years_eve = {12, 31};   // shorter initializer syntax
```

Structs

Wrap the struct definition in a **typedef** to avoid having to include the word **struct** every time you make a new variable of that type.

```
typedef struct date {
    int month;
    int day;
} date;
…

date today;
today.month = 1;
today.day = 28;

date new_years_eve = {12, 31};
```

Structs

If you pass a struct as a parameter, like for other parameters, C passes a **copy** of the entire struct.

```
void advance_day(date d) {
	d.day++;
}

int main(int argc, char *argv[]) {
	date my_date = {1, 28};
	advance_day(my_date);
	printf("%d", my_date.day); // 28
	return 0;
}
```

Structs

If you pass a struct as a parameter, like for other parameters, C passes a **copy** of the entire struct. **Use a pointer to modify a specific instance.**

```
void advance_day(date *d) {
      (*d).day++;
}

int main(int argc, char *argv[]) {
      date my_date = {1, 28};
      advance_day(&my_date);
      printf("%d", my_date.day); // 29
      return 0;
}
```

Structs

The **arrow** operator lets you access the field of a struct pointed to by a pointer.

```
void advance_day(date *d) {
      d->day++;          // equivalent to (*d).day++;
}

int main(int argc, char *argv[]) {
      date my_date = {1, 28};
      advance_day(&my_date);
      printf("%d", my_date.day); // 29
      return 0;
}
```

Structs

C allows you to return structs from functions as well. It returns whatever is contained within the struct.

```
date create_new_years_date() {
      date d = {1, 1};
      return d;          // or return (date){1, 1};
}

int main(int argc, char *argv[]) {
      date my_date = create_new_years_date();
      printf("%d", my_date.day); // 1
      return 0;
}
```

Structs

sizeof gives you the entire size of a struct, which is the sum of the sizes of all its contents.

```
typedef struct date {
      int month;
      int day;
  } date;

int main(int argc, char *argv[]) {
      int size = sizeof(date);    // 8
      return 0;
}
```

Arrays of Structs

You can create arrays of structs just like any other variable type.

```
typedef struct my_struct {
     int x;
     char c;
} my_struct;

…

my_struct array_of_structs[5];
```

Arrays of Structs

To initialize an entry of the array, you must use this special syntax to confirm the type to C.

```
typedef struct my_struct {
     int x;
     char c;
} my_struct;

…

my_struct array_of_structs[5];
array_of_structs[0] = (my_struct){0, 'A'};
```

Arrays of Structs

You can also set each field individually.

```
typedef struct my_struct {
     int x;
     char c;
} my_struct;


…
my_struct array_of_structs[5];
array_of_structs[0].x = 2;
array_of_structs[0].c = 'A';
```

Recap

- **Recap:** The Heap So Far
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- Use-after-free bugs and vulnerability disclosure
- realloc

Next time: C Generics

Lecture 11 takeaway: We can allocate memory on the heap to manage it ourselves. We manipulate heap memory via pointers. There are many opportunities for errors, some of which can lead to vulnerabilities! (that should be properly disclosed).

Extra Practice

Goodbye, Free Memory

Where/how should we free memory below so that all memory is freed properly?

```
1 char *str = strdup("Hello");
2 assert(str != NULL);
3 char *ptr = str + 1;
4 for (int i = 0; i < 5; i++) {
5   int *num = malloc(sizeof(int));
6   *num = i;
7   printf("%s %d\n", ptr, *num);
8 }
9 printf("%s\n", str);
```

Recommendation: Don't worry about putting in frees until **after** you're finished with functionality.

Memory leaks will rarely crash your CS107 programs.

Goodbye, Free Memory

Where/how should we free memory below so that all memory is freed properly?

```
1  char *str = strdup("Hello");
2  assert(str != NULL);
3  char *ptr = str + 1;
4  for (int i = 0; i < 5; i++) {
5    int *num = malloc(sizeof(int));
6    *num = i;
7    printf("%s %d\n", ptr, *num);
8    free(num);
9  }
10 printf("%s\n", str);
11 free(str);
```

Recommendation: Don't worry about putting in frees until **after** you're finished with functionality.

Memory leaks will rarely crash your CS107 programs.

strcat_extend

Write a function that takes in a heap-allocated **str1,** enlarges it, and concatenates **str2** onto it.

```
1 char *strcat_extend(char *heap_str, const char *concat_str) {
2     (_____________________(1)_____________________);
3     heap_str = realloc(___(2A)___,___(2B)___);
4     (_____________________(3)_____________________);
5     strcat(___(3A)___, ___(3B)___);
6     return heapstr;
7 }
```

Example usage:

```
char *str = strdup("Hello ");
str = strcat_extend(str, "world!");
printf("%s\n", str);
free(str);
```

strcat_extend

Write a function that takes in a heap-allocated **str1,** enlarges it, and concatenates **str2** onto it.

```
1 char *strcat_extend(char *heap_str, const char *concat_str) {
2     int new_length = strlen(heap_str) + strlen(concat_str) + 1;
3     heap_str = realloc(heap_str, new_length);
4     assert(heap_str != NULL);
5     strcat(heap_str, concat_str);
6     return heapstr;
7 }
```

Example usage:

```
char *str = strdup("Hello ");
str = strcat_extend(str, "world!");
printf("%s\n", str);
free(str);
```