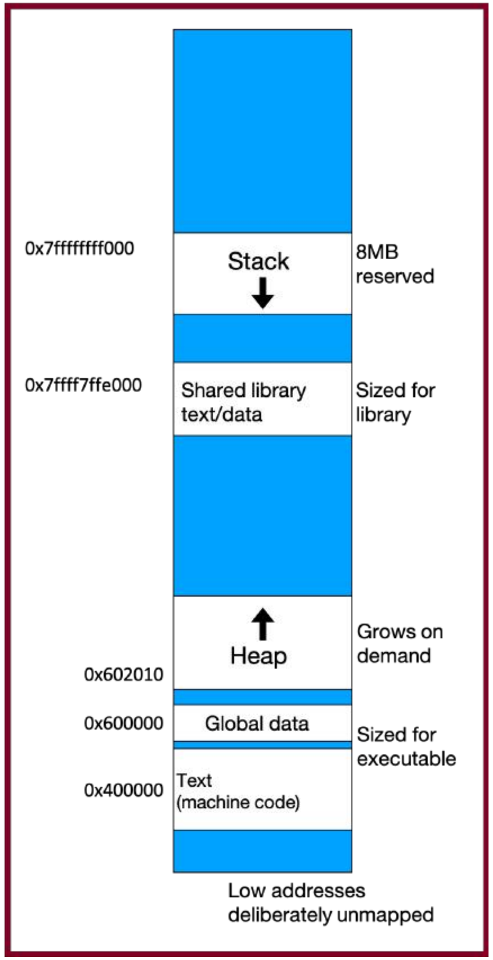
Memory Layout

- We are going to dive deeper into different areas of memory used by our programs.
- The **stack** is the place where all local variables and parameters live for each function. A function's stack "frame" goes away when the function returns.
- The stack grows **downwards** when a new function is called and shrinks **upwards** when the function is finished.



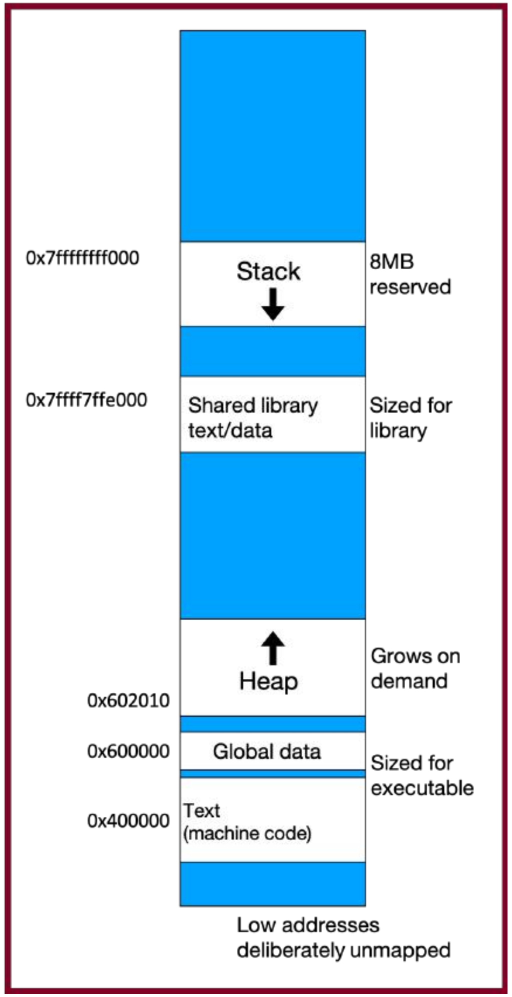
The Stack

- The stack behaves like a…well…stack! A new function call **pushes** on a new frame. A completed function call **pops** off the most recent frame.
- *Interesting fact:* C does not clear out memory when a function's frame is removed. Instead, it just marks that memory as usable for the next function call. This is more efficient!
- A *stack overflow* is when you use up all stack memory. E.g. a recursive call with too many function calls.
- What are the limitations of the stack?

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**.



`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.

Exercise: `malloc` multiples

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     /* TODO: arr declaration here */
3
4     for (int i = 0; i < len; i++) {
5         arr[i] = mult * (i + 1);
6     }
7     return arr;
8 }
```

Line 2: How should we declare `arr`?

A. `int arr[len];`
B. `int arr[] = malloc(sizeof(int));`
C. `int *arr = malloc(sizeof(int) * len);`
D. `int *arr = malloc(sizeof(int) * (len + 1));`
E. Something else

- Use a pointer to store the address returned by malloc.
- Malloc's argument is **the number of bytes** to allocate.

⚠️ **This code is missing an assertion.**

Always `assert` with the heap

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

```c
int *array_of_multiples(int mult, int len) {
    int *arr = malloc(sizeof(int) * len);
    assert(arr != NULL);
    for (int i = 0; i < len; i++) {
        arr[i] = mult * (i + 1);
    }
    return arr;
}
```

- 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';
```

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 **delete** 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` details

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

```
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);      ❌
```

Memory Leaks

- A memory leak is when you allocate memory on the heap, but do not free it.
- 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!

More on Valgrind in Lab 3!

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`

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

Heap allocation interface: A summary

```
void *malloc(size_t size);
void *calloc(size_t nmemb, size_t size);
void *realloc(void *ptr, size_t size);
char *strdup(char *s);
void free(void *ptr);
```

Heap **memory allocation** guarantee:

- `NULL` on failure, so check with `assert`
- Memory is contiguous; it is not recycled unless you call free
- `realloc` preserves existing data
- `calloc` zero-initializes bytes, `malloc` and `realloc` do not

Undefined behavior occurs:

- If you overflow (i.e., you access beyond bytes allocated)
- If you use after `free`, or if `free` is called twice on a location.
- If you `realloc/free` non-heap address

Engineering principles: stack vs heap

Stack ("local variables")

- **Fast**
  Fast to allocate/deallocate; okay to oversize
- **Convenient**.
  Automatic allocation/ deallocation; declare/initialize in one step
- **Reasonable type safety**
  Thanks to the compiler

⚠️ **Not especially plentiful**
Total stack size fixed, default 8MB

⚠️ **Somewhat inflexible**
Cannot add/resize at runtime, scope dictated by control flow in/out of functions

Heap (dynamic memory)

- **Plentiful**.
  Can provide more memory on demand!
- **Very flexible.**
  Runtime decisions about how much/when to allocate, can resize easily with realloc
- **Scope under programmer control**
  Can precisely determine lifetime

⚠️ **Lots of opportunity for error**
Low type safety, forget to allocate/free before done, allocate wrong size, etc., Memory leaks (much less critical)

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