Dynamic Memory & ADTs in C

Readings: CP:AMA 17.1, 17.2, 17.3, 17.4

The primary goal of this section is to be able to use dynamic memory.
The heap

The **heap** is the final section in the C memory model.

It can be thought of as a big “pile” (or “pool”) of memory that is available to your program.

Memory is **dynamically** “borrowed” from the heap. We call this **allocation**.

When the borrowed memory is no longer needed, it can be “returned” and possibly **reused**. We call this **deallocation**.

If too much memory has already been allocated, attempts to borrow additional memory fail.
low

Code

Read-Only Data

Global Data

Heap

↓

Stack

high
Unfortunately, there is also a *data structure* known as a heap, and the two are unrelated.

To avoid confusion, prominent computer scientist Donald Knuth campaigned to use the name “free store” or the “memory pool”, but the name “heap” has stuck.

A similar problem arises with “the stack” region of memory because there is also a Stack ADT. However, their behaviour is very similar so it is far less confusing.
malloc

The malloc (memory allocation) function obtains memory from the heap dynamically. It is provided in <stdlib.h>.

// malloc(s) requests s bytes of memory from the heap
// and returns a pointer to a block of s bytes, or
// NULL if not enough memory is available
// time: O(1) [close enough for this course]

For example, if you want enough space for an array of 100 ints:

```c
int *my_array = malloc(100 * sizeof(int));
```

or a single struct posn:

```c
struct posn *my_posn = malloc(sizeof(struct posn));
```

These two examples illustrate the most common use of dynamic memory: allocating space for arrays and structures.
You should always use `sizeof` with `malloc` to improve portability and to improve communication.

Seashell allows

```c
int *my_array = malloc(400);
```

instead of

```c
int *my_array = malloc(100 * sizeof(int));
```

but the latter is much better style and is more portable.
Strictly speaking, the type of the malloc parameter is `size_t`, which is a special type produced by the `sizeof` operator.

`size_t` and `int` are different types of integers.

Seashell is mostly forgiving, but in other C environments using an `int` when C expects a `size_t` may generate a warning.

The proper `printf` placeholder to print a `size_t` is `%zd`. 
The declaration for the malloc function is:

```c
void *malloc(size_t s);
```

The return type is a (void *) (void pointer), a special pointer that can point at any type.

```c
int *my_array = malloc(10 * sizeof(int));

struct posn *my_posn = malloc(sizeof(struct posn));
```
```c
int main(void) {
    int *arr1 = malloc(10 * sizeof(int));
    int *arr2 = malloc(5 * sizeof(int));
    //...
}
```
An unsuccessful call to \texttt{malloc} returns \texttt{NULL}.

In practice it’s good style to check every \texttt{malloc} return value and gracefully handle a \texttt{NULL} instead of crashing.

```c
int *my_array = malloc(n * sizeof(int));
if (my_array == NULL) {
    printf("Sorry, I'm out of memory! I'm exiting....\n");
    exit(EXIT_FAILURE);
}
```

In the “real world” you should always perform this check, but in this course, you do \textbf{not} have to check for a \texttt{NULL} return value unless instructed otherwise.

\textbf{In these notes, we omit this check to save space.}
The heap memory provided by `malloc` is **uninitialized**.

```c
int *a = malloc(10 * sizeof(int));
printf("the mystery value is: %d\n", a[0]);
```

Although `malloc` is very complicated, for the purposes of this course, you can assume that `malloc` is $O(1)$.

There is also a `calloc` function which essentially calls `malloc` and then “initializes” the memory by filling it with zeros. `calloc` is $O(n)$, where $n$ is the size of the block.
free

For every block of memory obtained through malloc, you must eventually free the memory (when the memory is no longer in use).

```c
// free(p) returns memory at p back to the heap
// requires: p must be from a previous malloc
// effects: the memory at p is invalid
// time: O(1)

int *my_array = malloc(n * sizeof(int));
// ...
// ...
free(my_array);
```

In the Seashell environment, you must free every block.
Invalid after free

Once a block of memory is freed, reading from or writing to that memory is invalid and may cause errors (or unpredictable results).

Similarly, it is invalid to free memory that was not returned by a malloc or that has already been freed.

```c
int *a = malloc(10 * sizeof(int));
free(a);
int k = a[0];   // INVALID
a[0] = 42;      // INVALID
free(a);        // INVALID
a = NULL;       // GOOD STYLE
```

Pointer variables may still contain the address of the memory that was freed, so it is often good style to assign NULL to a freed pointer variable.
Memory leaks

A memory leak occurs when allocated memory is not eventually freed.

Programs that leak memory may suffer degraded performance or eventually crash.

```c
int *my_array;
my_array = malloc(10 * sizeof(int));
my_array = malloc(10 * sizeof(int)); // Memory Leak!
```

In this example, the address from the original `malloc` has been overwritten.

That memory is now “lost” (or leaked) and so it can never be freed.
Garbage collection

Many modern languages (including Racket) have a *garbage collector*.

A garbage collector *detects* when memory is no longer in use and *automatically* frees memory and returns it to the heap.

One disadvantage of a garbage collector is that it can be slow and affect performance, which is a concern in high performance computing.
Merge Sort

In *merge sort*, the array is split (in half) into two separate arrays. The two arrays are sorted and then they are merged back together into the original array.

This is another example of a *divide and conquer* algorithm.

The arrays are *divided* into two smaller problems, which are then sorted (*conquered*). The results are combined to solve the original problem.

To simplify our implementation, we use a merge helper function.
// merge(dest, src1, len1, src2, len2) modifies dest to contain
// the elements from both src1 and src2 in sorted order
// requires: length of dest is at least (len1 + len2)
// src1 and src2 are sorted
// effects: modifies dest
// time: \(O(n)\), where \(n\) is \(len1 + len2\)

void merge(int dest[], const int src1[], int len1,
           const int src2[], int len2) {
    int pos1 = 0;
    int pos2 = 0;
    for (int i = 0; i < len1 + len2; ++i) {
        if (pos1 == len1 || (pos2 < len2 && src2[pos2] < src1[pos1])) {
            dest[i] = src2[pos2];
            ++pos2;
        } else {
            dest[i] = src1[pos1];
            ++pos1;
        }
    }
}
void merge_sort(int a[], int len) {
    if (len <= 1) return;
    int llen = len / 2;
    int rlen = len - llen;

    int *left = malloc(llen * sizeof(int));
    int *right = malloc(rlen * sizeof(int));

    for (int i = 0; i < llen; ++i) left[i] = a[i];
    for (int i = 0; i < rlen; ++i) right[i] = a[i + llen];

    merge_sort(left, llen);
    merge_sort(right, rlen);

    merge(a, left, llen, right, rlen);

    free(left);
    free(right);
}

Merge sort is $O(n \log n)$, even in the worst case.
Duration

Using dynamic (heap) memory, a function can obtain memory that persists after the function has returned.

```c
// build_array(n) returns a new array initialized with
// values a[0] = 0, a[1] = 1, ... a[n-1] = n-1
// effects: allocates a heap array (caller must free)

int *build_array(int len) {
    assert(len > 0);
    int *a = malloc(len * sizeof(int));
    for (int i = 0; i < len; ++i) {
        a[i] = i;
    }
    return a;    // array exists beyond function return
}
```

The caller (client) is responsible for freeing the memory (the contract should communicate this).
The `<string.h>` function `strdup` makes a duplicate of a string.

```c
// my_strdup(s) makes a duplicate of s
// effects: allocates memory (caller must free)

char *my_strdup(const char *s) {
    char *newstr = malloc((strlen(s) + 1) * sizeof(char));
    strcpy(newstr, s);
    return newstr;
}
```

Recall that the `strcpy(dest, src)` copies the characters from `src` to `dest`, and that the `dest` array must be large enough.

When allocating memory for strings, don’t forget to include space for the null terminator.

`strdup` is not officially part of the C standard, but common.
Resizing arrays

Because malloc requires the size of the block of memory to be allocated, it does not seem to solve the problem:

“What if we do not know the length of an array in advance?”

To solve this problem, we can resize an array by:

- creating a new array
- copying the items from the old to the new array
- freeing the old array
example: resizing an array

As we will see shortly, this is not how it is done in practice, but this is an illustrative example.

```c
// my_array has a length of 100
int *my_array = malloc(100 * sizeof(int));

// stuff happens...

// oops, my_array now needs to have a length of 101
int *old = my_array;
my_array = malloc(101 * sizeof(int));
for (int i = 0; i < 100; ++i) {
    my_array[i] = old[i];
}
free(old);
```
 realloc

To make resizing arrays easier, there is a realloc function.

```c
// realloc(p, newsize) resizes the memory block at p
// to be newsize and returns a pointer to the
// new location, or NULL if unsuccessful
// requires: p must be from a previous malloc/realloc
// effects: the memory at p is invalid (freed)
// time: O(n), where n is min(newsize, oldsize)
```

Similar to our previous example, realloc preserves the contents from the old array location.

```c
int *my_array = malloc(100 * sizeof(int));
// stuff happens...
my_array = realloc(my_array, 101 * sizeof(int));
```
The pointer returned by `realloc` may actually be the original pointer, depending on the circumstances.

Regardless, after `realloc` only the new returned pointer can be used. You should assume that the address passed to `realloc` was freed and is now invalid.

Typically, `realloc` is used to request a larger size and the additional memory is uninitialized.

If the size is smaller, the extraneous memory is discarded.
Although rare, in practice,

\[
\text{my\_array} = \text{realloc(my\_array, newsize)};
\]

could possibly cause a memory leak if an “out of memory” condition occurs.

In C99, an unsuccessful \text{realloc} returns \text{NULL} and the original memory block is not freed.

// safer use of \text{realloc}
int *tmp = realloc(my\_array, newsize);
if (tmp) {
    my\_array = tmp;
} else {
    // handle out of memory condition
}
String I/O: strings of unknown length

In Section 07 we saw how reading in strings can be susceptible to buffer overruns.

    char str[81];
    int retval = scanf("%s", str);

The target array is often oversized to ensure there is capacity to store the string. Unfortunately, regardless of the length of the array, a buffer overrun may occur.

To solve this problem we can continuously resize (realloc) an array while reading in only one character at a time.
// readstr() reads in a non-whitespace string from I/O
// or returns NULL if unsuccessful
// effects: allocates memory (caller must free)

char *readstr(void) {
    char c;
    if (scanf(" %c", &c) != 1) return NULL; // ignore initial WS
    int len = 1;
    char *str = malloc(len * sizeof(char));
    str[0] = c;
    while (1) {
        if (scanf("%c", &c) != 1) break;
        if (c == ' ' || c == '\n') break;
        ++len;
        str = realloc(str, len * sizeof(char));
        str[len - 1] = c;
    }
    str = realloc(str, (len + 1) * sizeof(char));
    str[len] = '\0';
    return str;
}
Improving readstr

Unfortunately, the running time of readstr is $O(n^2)$, where $n$ is the length of the string.

This is because realloc is $O(n)$ and occurs inside of the loop.

A better approach might be to allocate more memory than necessary and only call realloc when the array is “full”.

A popular strategy is to double the length of the array when it is full.

Similar to working with maximum-length arrays, we need to keep track of the “actual” length in addition to the allocated length.
char *readstr(void) {
    char c;
    if (scanf(" %c", &c) != 1) return NULL; // ignore initial WS
    int maxlen = 1;
    int len = 1;
    char *str = malloc(maxlen * sizeof(char));
    str[0] = c;
    while (1) {
        if (scanf("%c", &c) != 1) break;
        if (c == ' ' || c == '\n') break;
        if (len == maxlen) {
            maxlen *= 2;
            str = realloc(str, maxlen * sizeof(char));
        }
        ++len;
        str[len - 1] = c;
    }
    str = realloc(str, (len + 1) * sizeof(char));
    str[len] = '\0';
    return str;
}
With our “doubling” strategy, most iterations are $O(1)$, unless it is necessary to resize (realloc) the array.

The resizing time for the first 32 iterations would be:

$2, 4, 0, 8, 0, 0, 0, 16, 0, 0, 0, 0, 0, 0, 0, 0, 32, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 64$

For $n$ iterations, the total resizing time is at most:

$2 + 4 + 8 + \ldots + \frac{n}{4} + \frac{n}{2} + n + 2n = 4n - 2 = O(n)$.

By using this doubling strategy, the total run time for `readstr` is now only $O(n)$. 
ADTs in C

With dynamic memory, we now have the ability to implement an Abstract Data Type (ADT) in C.

In Section 06, the first ADT we saw was a simple stopwatch ADT. It demonstrated information hiding, which provides both security and flexibility.

It used an opaque structure, which meant that the client could not create a stopwatch.
example: stopwatch ADT

This is the **interface** we used in Section 06.

```c
// stopwatch.h [INTERFACE]

struct stopwatch;

// stopwatch_create() creates a new stopwatch at time 0:00
// effects: allocates memory (client must call stopwatch_destroy)
struct stopwatch *stopwatch_create(void);

// stopwatch_destroy(sw) frees memory for sw
// effects: sw is no longer valid
void stopwatch_destroy(struct stopwatch *sw);
```
We can now complete our implementation.

// stopwatch.c [IMPLEMENTATION]

struct stopwatch {
    int seconds;
};
// requires: 0 <= seconds

struct stopwatch *stopwatch_create(void) {
    struct stopwatch *sw = malloc(sizeof(struct stopwatch));
    sw->seconds = 0;
    return sw;
}

void stopwatch_destroy(struct stopwatch *sw) {
    assert(sw);
    free(sw);
}
Implementing a Stack ADT

As discussed in Section 06, the stopwatch ADT illustrates the principles of an ADT, but it is not a typical ADT.

The **Stack ADT** (one of the *Collection ADTs*) is more representative.

The interface is nearly identical to the stack implementation from Section 07 that demonstrated *maximum-length arrays*.

The only differences are: it uses an opaque structure, it provides create and destroy functions, and there is no maximum: it can store an arbitrary number of integers.
// stack.h (INTERFACE)

struct stack;

struct stack *stack_create(void);

bool stack_is_empty(const struct stack *s);

int stack_top(const struct stack *s);

int stack_pop(struct stack *s);

void stack_push(int item, struct stack *s);

void stack_destroy(struct stack *s);
The Stack ADT uses the “doubling” strategy.

// stack.c (IMPLEMENTATION)

struct stack {
    int len;
    int maxlen;
    int *data;
};

struct stack *stack_create(void) {
    struct stack *s = malloc(sizeof(struct stack));
    s->len = 0;
    s->maxlen = 1;
    s->data = malloc(s->maxlen * sizeof(int));
    return s;
}

void stack_destroy(struct stack *s) {
    free(s->data);
    free(s);
}
Most of the operations are identical to the maximum-length implementation.

```c
bool stack_is_empty(const struct stack *s) {
    assert(s);
    return s->len == 0;
}

int stack_top(const struct stack *s) {
    assert(s);
    assert(s->len);
    return s->data[s->len - 1];
}

int stack_pop(struct stack *s) {
    assert(s);
    assert(s->len);
    s->len -= 1;
    s->len -= 1;
    return s->data[s->len];
}
```
The doubling strategy is implemented in push.

```c
void stack_push(int item, struct stack *s) {
    assert(s);
    if (s->len == s->maxlen) {
        s->maxlen *= 2;
        s->data = realloc(s->data, s->maxlen * sizeof(int));
    }
    s->data[s->len] = item;
    s->len += 1;
}
```

What is the running time of a single call to `stack_push`?

- \(O(n)\) when doubling occurs
- \(O(1)\) otherwise (most of the time)
Amortized analysis

To understand amortized analysis, we first consider a more abstract example than stack\_push.

Homer wants to do some “push-ups” to get some exercise.

His strategy is that on day $k$, when $k$ is a power of 2, he will do $k$ push-ups. He will then skip $(k - 1)$ days until it is another power of 2.

So the number of push-ups Homer does on the first 31 days is:

$$1, 2, 0, 4, 0, 0, 0, 8, 0, 0, 0, 0, 0, 0, 16, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0$$

After 31 days, he has done exactly 31 push-ups. So, on average, he is doing one push-up per day.
The analysis for stack.push is very similar.

Ignoring any pop operations, the total time for \( n \) calls to stack.push is \( O(n) \).

The amortized (“average”) time for each call is:

\[
O(n)/n = O(1).
\]

In other words, we can say that the amortized running time of stack.push is \( O(1) \).

// stack.push(item, s) pushes item onto stack s
// requires: s is a valid stack
// effects: modifies s
// time: \( O(1) \) [amortized]
You will use *amortized* analysis in CS 240 and in CS 341.

In this implementation, we never “shrink” the array when items are popped.

A popular strategy is to shrink when the length reaches \( \frac{1}{4} \) of the maximum capacity. Although more complicated, this also has an *amortized* run-time of \( O(1) \) for an arbitrary sequence of pushes and pops.

Languages that have a built-in resizable array (e.g., C++’s `vector`) often use a similar “doubling” strategy.
Goals of this Section

At the end of this section, you should be able to:

- describe the heap
- use the functions malloc, realloc and free to interact with the heap
- explain that the heap is finite, and demonstrate how to check malloc for success
- describe memory leaks, how they occur, and how to prevent them
- describe the doubling strategy, and how it can be used to manage dynamic arrays to achieve an amortized $O(1)$ run-time for additions
- create dynamic resizable arrays in the heap
- write functions that create and return a new struct
- document dynamic memory side-effects in contracts