Dynamic Memory & ADTs in C

Optional Textbook 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 a program.

Memory is ***allocated*** from the heap upon request.

This memory is *"borrowed"*, and can be *"returned"* (*"freed"*) back to the heap when it is no longer needed (deallocation).

Returned memory may be **reused** (*"recycled"*) for a future allocation.

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

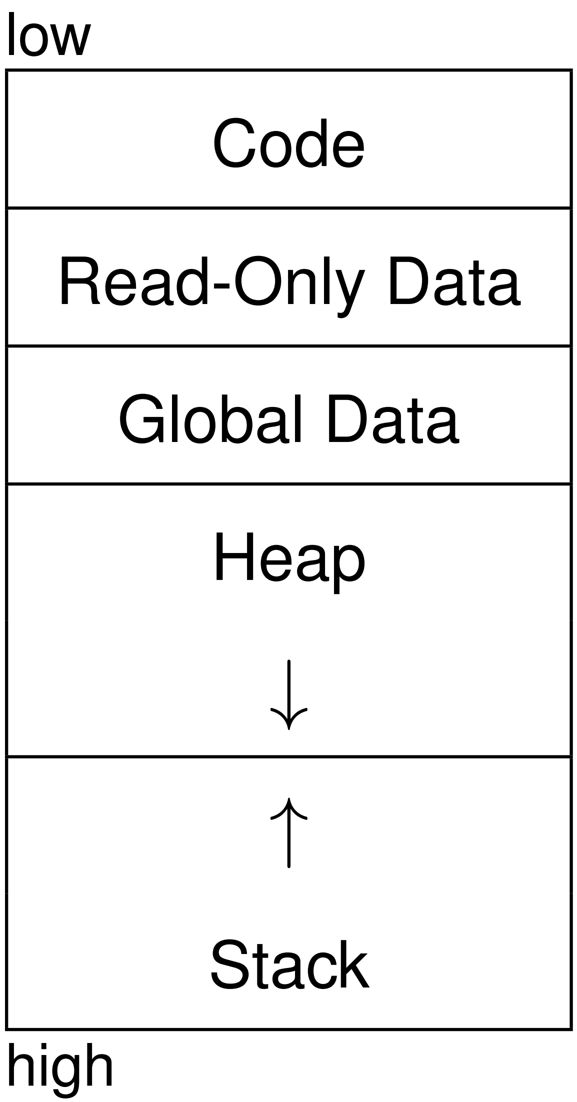
Advantages of heap-allocated memory

Dynamic: The allocation size can be determined at run time (while the program is running).

Resizable: A heap allocation can be “resized”.

Duration: Heap allocations *persist* until they are “freed”. A function can create a data structure (one or more allocations) that continues to exist after the function `return`s.

Safety: If memory runs out, it can be detected and handled properly (unlike stack overflows).


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` (**m**emory **alloc**ation) function obtains memory from the heap. It is provided in <`stdlib.h`>.

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

For example, for an array of 100 `int`s:

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

or a single `struct posn`:

```
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**.

Uninitialized

The heap memory provided by `malloc` is **uninitialized**.

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

printf("mystery values: (%d, %d)\n", my_posn->x,
                                     my_posn->y);
```

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.

Dynamic Arrays

With pointer notation, the syntax for accessing a heap array is nearly identical to the syntax for a stack (or global) array.

```
int *my_array = malloc(n * sizeof(int));

// initialize the array
for (int i = 0; i < n; ++i) {
  my_array[i] = 0;
}
```

We could use `malloc(n * 4)`, but `malloc(n * sizeof(int))` is clearer and better style.

Always use `sizeof` with `malloc` to improve communication.

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` format specifier to print a `size_t` is `%zd`.

The declaration for the `malloc` function is:

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

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

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

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

For this course, we assume `malloc` is $O(1)$.

In practice, the constant time may be quite large.

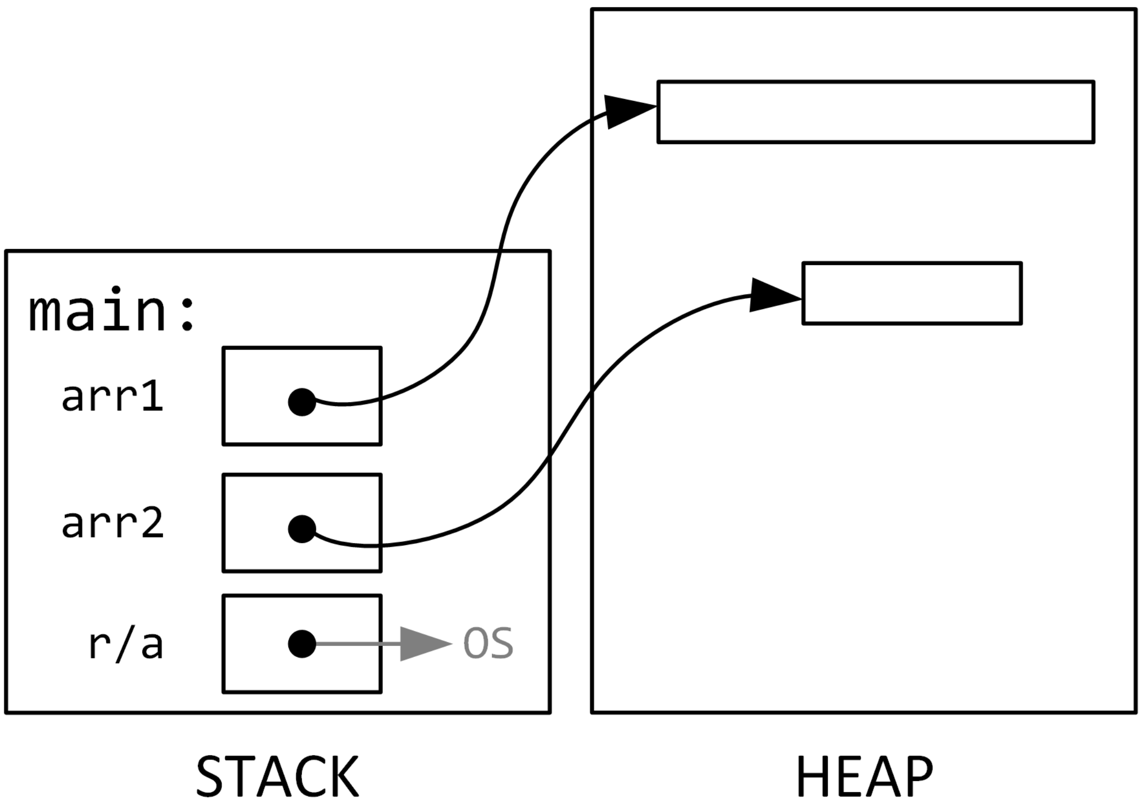
In addition, the running time for `malloc` depends on the state of the heap.

After multiple allocations and deallocations, the heap can become *fragmented*, which may affect the performace of `malloc`.

This is one of the disadvantages of heap memory.

example: visualizing the heap

```
int main(void) {
  int *arr1 = malloc(10 * sizeof(int));
  int *arr2 = malloc(5 * sizeof(int));
  //...
}
```



Out of memory

An unsuccessful call to `malloc` returns `NULL`.

In practice it's good style to check every `malloc` return value and gracefully handle a `NULL` instead of crashing.

```
int *my_array = malloc(n * sizeof(int));
if (my_array == NULL) {
  // handle out of memory
  // ...
}
```

In the "real world" you should **always** perform this check, but in this course, you do **not** have to check for a `NULL` return value unless instructed otherwise.

In these notes, we omit this check to save space.

free

Every block of memory obtained through `malloc` must eventually be `free`d (when the memory is no longer in use).

```
// 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)
```

> In the `Seashell` environment, every block **must** be `free`d.

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

Dangling pointers

Once a block of memory is `free`d, accessing that memory is invalid and may cause errors (or unpredictable results).

Consider this example:

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

The memory `my_array` is pointing at has been freed and is now invalid, but `my_array` is **still pointing at it**.

`free(my_array)` does **not** modify the pointer `my_array`.

A pointer to a freed allocation is known as a *“dangling pointer”*. It is often good style to assign `NULL` to a dangling pointer.

Invalid behaviour with free

It is invalid to `free` memory that was not returned by a `malloc` or that has already been `free`d. `free(NULL)` is okay and simply ignored.

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

free(my_array + 1);    // INVALID

free(my_array);        // VALID (my_array is now dangling)

int i = my_array[0];   // INVALID
my_array[0] = 42;      // INVALID

free(my_array);        // INVALID

my_array = NULL;       // GOOD STYLE (no longer dangling)
free(my_array);        // IGNORED
```

Memory leaks

A memory leak occurs when allocated memory is not eventually `free`d.

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

```
int *my_array = NULL;
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 `free`d.

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.

C does not have a garbage collector, so you will have to ensure your programs have no memory leaks.

Merge Sort

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

```c
// 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  [not asserted]
// 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;
    }
  }
}
```

```c
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

A significant advantage of dynamic memory is that a function can obtain memory that **persists after** the function has `return`ed.

```
// build_array(len) returns a new array initialized with
//   values a[0] = 0, a[1] = 1, ... a[len-1] = len-1
// requires: len > 0
// effects: allocates memory (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
}
```

Dynamic memory side effect

Allocating (and deallocating) memory has a **side effect**: it modifies the "state" of the heap.

A function that allocates persistent memory (*i.e.*, not freed) has a side effect and must be documented.

The caller (client) is responsible for `free`ing the memory (communicate this).

```
// build_array(n) returns a new array...
// effects: allocates memory (caller must free)
```

A function could also free memory it did not allocate.

That would also be a side effect:

```
// process_and_destroy_array(a, len) ...
// requires: a is a heap-allocated array
// effects:  frees a (a is now invalid)
```

This behaviour is rare outside of ADTs.

example: strdup

The `strdup` function makes a duplicate (copy) of a string.

```
// 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.

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 at allocation time?"

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

- creating a new array
- copying the items from the old to the new array
- `free`ing 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.

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

// ...

// 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.

```
// 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
//           or NULL (then realloc behaves like malloc)
// 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.

```
int *my_array = malloc(100 * sizeof(int));
// ...
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**.

> Assume that the address passed to `realloc` was `free`d and is now **invalid**.
>
> Always think of `realloc` as a `malloc`, a “copy”, then a `free`.

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.

Be careful using `realloc` inside of a *helper* function.

```
// repeat(s) modifies s by repeating it ("abc" => "abcabc")
//   and returns the new s
// requires: s is a heap-allocated string
// effects:  re-allocates memory (s is invalid)

char *repeat(char *s) {
  int len = strlen(s);
  s = realloc(s, (len * 2 + 1) * sizeof(char));
  for (int i = 0; i < len; ++i) {
    s[i + len] = s[i];
  }
  s[len * 2] = '\0';
  return s;                     // this is ESSENTIAL
}
```

A common mistake is to make `repeat` a `void` function

(not return the new address for `s`).

This causes a **memory leak** if the address of `s` changes.

Although rare, in practice,

```
my_array = realloc(my_array, newsize);
```

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

In C99, an unsuccessful `realloc` returns `NULL` and the original memory block is not `free`d.

```
// safer use of 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 `char`acter at a time.

```c
// read_str_slow() reads in a non-whitespace string from I/O
//   or returns NULL if unsuccessful
// effects: allocates memory (caller must free)
// time: O(n^2)

char *read_str_slow(void) {
  char c = 0;
  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 the efficiency

Unfortunately, the running time of `read_str_slow` 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 *oversized arrays*, we need to keep track of the *"actual"* length in addition to the *allocated* length.

```c
// time: O(n) [see analysis on next slide]
char *read_str(void) {
  char c = 0;
  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:

1,2,0,4,0,0,0,8,0,0,0,0,0,0,0,16,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,32

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

$$1 + 2 + 4 + \ldots + \frac{n}{2} + n = 2n - 1 = O(n).$$

By using this doubling strategy, the **total** run time for `read_str` is now $O(n)$.

Reading in an array of strings

In Section 09, we discussed how an array of strings is often stored as an array of pointers (of type `char **`).

The following example repeatedly calls `read_str` to generate an array of strings.

```
// read_aos(len) reads in all non-whitespace strings from I/O
//   and returns an array of those strings
// notes: modifies *len to store the length of the array
//        returns NULL if there are no strings
// effects: allocates memory
//          (caller must free each string and the array itself)
//          modifies *len
//          reads input
// time: O(n) where n is the length of all strings (combined)

char **read_aos(int *len);
```

example: reading in an array of strings

```
char **read_aos(int *len) {
  char **aos = NULL;
  int maxlen = 0;
  *len = 0;
  while (1) {
    char *s = read_str();
    if (s == NULL) break;
    if (*len == maxlen) {
      if (maxlen == 0) maxlen = 1;
      maxlen *= 2;
      aos = realloc(aos, maxlen * sizeof(char *));
    }
    aos[*len] = s;
    *len += 1;
  }
  if (*len < maxlen) {
    aos = realloc(aos, *len * sizeof(char *));
  }
  return aos;
}
```

The `read_aos` function uses the array doubling strategy on the array of pointers.

Each element in the array (*e.g.*, `aos[i]`) is a pointer to a string.

To properly `free` the array of strings, each string must be freed in addition to the array itself.

```
int len = 0;
char **aos = read_aos(&len);

// ...

// free all the strings and the aos itself
for (int i = 0; i < len; ++i) {
  free(aos[i]);
}
free(aos);
```

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.

```
// 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 *oversized 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 oversized array implementation.

```
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;
  return s->data[s->len];
}
```

The doubling strategy is implemented in `push`.

```
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:

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

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 `push`es and `pop`s.

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