The primary goal of this section is to be able to use arrays.

C only has two built-in types of “compound” data storage:

- **structures**

- **arrays**

```c
int my_array[6] = {4, 8, 15, 16, 23, 42};
```

An array is a data structure that contains a **fixed number** of elements that all have the **same type**.

Because arrays are built-in to C, they are used for many tasks where lists are used in Racket, but arrays and lists are very different. In Section 11 we construct Racket-like lists in C.

To define an array we must know the **length** of the array **in advance** (we address this limitation in Section 10).

Each individual value in the array is known as an **element**. To access an element, its **index** is required.

The first element of `my_array` is at index 0, and it is written as `my_array[0].`

The second element is `my_array[1]` and the last is `my_array[5].`

In computer science we often start counting at 0.
example: accessing array elements

Each individual array element can be used in an expression as if it was a variable.

```c
int a[6] = {4, 8, 15, 16, 23, 42};

int j = a[0]; // j is 4
int * p = &a[j-1]; // p points at a[3]

a[2] = a[a[0]]; // a[2] is now 23
++a[1]; // a[1] is now 9
```

example: arrays & iteration

Arrays and iteration are a powerful combination.

```c
int a[6] = {4, 8, 15, 16, 23, 42};
int sum = 0;

for (int i = 0; i < 6; ++i) {
    printf("a[%d] = %d\n", i, a[i]);
    sum += a[i];
}
printf("sum = %d\n", sum);
```

Array initialization

Arrays can only be initialized with braces ({}).

```c
int a[6] = {4, 8, 15, 16, 23, 42};

a = {0, 0, 0, 0, 0, 0}; // INVALID
a = ??? ; // INVALID
```

Once defined, the entire array cannot be assigned to at once.

Each individual element must be mutated.

```c
for (int i=0; i < 6; ++i) {
    a[i] = 0;
}
Like variables, the value of an uninitialized array depends on the scope of the array:

```c
int a[5];
```

- uninitialized **global** arrays are zero-filled.
- uninitialized **local** arrays are filled with arbitrary ("garbage") values from the stack.

If there are not enough elements in the braces, the remaining values are initialized to zero (even with local arrays).

```c
int c[5] = {0};      // c[0]...c[4] = 0
```

If an array is initialized, the length of the array can be omitted from the declaration and **automatically** determined from the number of elements in the initialization.

```c
int a[] = {4, 8, 15, 16, 23, 42}; // int a[6] = ...
```

This syntax is only allowed if the array is initialized.

```c
int b[]; // INVALID
```

Similar to structures, C99 supports a partial initialization syntax.

```c
```

Omitted elements are initialized to zero.

C99 allows the length of an **uninitialized local array** to be determined while the program is running. The size of the stack frame is increased accordingly.

```c
printf("How many numbers? ");
int count = read_int();

int a[count];  // count determined at run-time
```

This approach has many disadvantages and in the most recent version of C (C11), this feature was made optional. In Section 10 we see a better approach.
Array size

The **length** of an array is the number of elements in the array.

The **size** of an array is the number of bytes it occupies in memory.

An array of $k$ elements, each of size $s$, requires exactly $k \times s$ bytes.

In the C memory model, array elements are adjacent to each other.
Each element of an array is placed in memory immediately after the previous element.

If `a` is an integer array with six elements (`int a[6]`) the size of `a` is:

\[(6 \times \text{sizeof(int)}) = 6 \times 4 = 24.\]

Not everyone uses the same terminology for length and size.

example: array in memory

```c
int a[6] = {4, 8, 15, 16, 23, 42};
printf("&a[0] = %p ... &a[5] = %p\n", &a[0], &a[5]);
&a[0] = 0x5000 ... &a[5] = 0x5014
```

<table>
<thead>
<tr>
<th>addresses</th>
<th>contents (4 bytes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x5000 ... 0x5003</td>
<td>4</td>
</tr>
<tr>
<td>0x5004 ... 0x5007</td>
<td>8</td>
</tr>
<tr>
<td>0x5008 ... 0x500B</td>
<td>15</td>
</tr>
<tr>
<td>0x500C ... 0x500F</td>
<td>16</td>
</tr>
<tr>
<td>0x5010 ... 0x5013</td>
<td>23</td>
</tr>
<tr>
<td>0x5014 ... 0x5017</td>
<td>42</td>
</tr>
</tbody>
</table>

Array length

C does not explicitly keep track of the array **length** as part of the array data structure.

You must keep track of the array length separately.

Typically, the array length is stored in a separate variable.

```c
const int a.length = 6;
int a[6] = {4, 8, 15, 16, 23, 42};
```
const int a_length = 6;
int a[a_length];

The above definition is fine in Seashell, but some C environments do not allow the length of the array to be specified by a variable.

In those environments, the \texttt{#define} syntax is more often used. This is common in CP:AMA.

\texttt{#define A\_LENGTH 6}
int a[A\_LENGTH];

Theoretically, in some circumstances you could use \texttt{sizeof} to determine the length of an array.

\begin{verbatim}
int len = sizeof(a) / sizeof(a[0]);
\end{verbatim}

The CP:AMA textbook uses this on occasion. However, in practice, this should be avoided, as the \texttt{sizeof} operator only properly reports the array size in very specific circumstances.

\section*{The array identifier}

The value of an array (\texttt{a}) is the same as the address of the array (\&\texttt{a}), which is also the address of the first element (\&\texttt{a}[0]).

\begin{verbatim}
int a[] = \{4, 8, 15, 16, 23, 42\};
trace_ptr(a);
trace_ptr(&a);
trace_ptr(&a[0]);
\end{verbatim}

\begin{verbatim}
a => 0x5000
&a => 0x5000
&a[0] => 0x5000
\end{verbatim}
Dereferencing the array (*a) is equivalent to referencing the first element (a[0]).

```c
int a[] = {4, 8, 15, 16, 23, 42};

trace_int(a[0]);
trace_int(*a);
```

```
a[0] => 4
*a => 4
```

### Passing arrays to functions

When an array is passed to a function only the address of the array is copied into the stack frame.

This is more efficient than copying the entire array to the stack.

> Typically, the length of the array is unknown to the function, and is a separate parameter.

There is no method of “enforcing” that the length passed to a function is valid.

Functions should **require** that the length is valid, but there is no way for a function to **assert** that requirement.

#### example: array parameters

```c
int sum_array(int a[], int len) {
    int sum = 0;
    for (int i = 0; i < len; ++i) {
        sum += a[i];
    }
    return sum;
}

int main(void) {
    int my_array[6] = {4, 8, 15, 16, 23, 42};
    trace_int(sum_array(my_array, 6));
}
```

```
sum_array(my_array, 6) => 108
```

Note the parameter syntax: `int a[]`

and the calling syntax: `sum_array(my_array, 6).`
As we have seen before, passing an address to a function allows the function to change (mutate) the contents at that address.

```c
void array_add1(int a[], int len) {
    for (int i = 0; i < len; ++i) {
        ++a[i];
    }
}
```

It's good style to use the `const` keyword to both prevent mutation and communicate that no mutation occurs.

```c
int sum_array(const int a[], int len) {
    int sum = 0;
    for (int i = 0; i < len; ++i) {
        sum += a[i];
    }
    return sum;
}
```

Because a structure can contain an array:

```c
struct mystruct {
    int big[1000];
};
```

It is especially important to pass a pointer to such a structure, otherwise, the entire array is copied to the stack frame.

```c
int slower(struct mystruct s) {
...
}
int faster(struct mystruct *s) {
...
}
```

**Pointer arithmetic**

We have not yet discussed any pointer arithmetic.

C allows an integer to be added to a pointer, but the result may not be what you expect.

If `p` is a pointer, the value of `(p+1)` depends on the type of the pointer `p`.

`(p+1)` adds the `sizeof` whatever `p` points at.

According to the official C standard, pointer arithmetic is only valid within an array (or a structure) context. This becomes clearer later.
Pointer arithmetic rules

- When adding an integer $i$ to a pointer $p$, the address computed by $(p + i)$ in C is given in “normal” arithmetic by:
  \[ p + i \times \text{sizeof}(*p). \]
- Subtracting an integer from a pointer $(p - i)$ works in the same way.
- Mutable pointers can be incremented (or decremented). $++p$ is equivalent to $p = p + 1$.

You cannot add two pointers.

You can subtract a pointer $q$ from another pointer $p$ if the pointers are the same type (point to the same type). The value of $(p - q)$ in C is given in “normal” arithmetic by:

\[ (p - q)/\text{sizeof}(\ast p). \]

In other words, if $p = q + i$ then $i = p - q$.

Pointers (of the same type) can be compared with the comparison operators: $<$, $<=$, $==$, $!=$, $>=, >$

(e.g., if $(p < q)$ ...).

Pointer arithmetic and arrays

Pointer arithmetic is useful when working with arrays.

Recall that for an array $a$, the value of $a$ is the address of the first element ($\&a[0]$).

Using pointer arithmetic, the address of the second element $\&a[1]$ is $(a + 1)$, and it can be referenced as $\ast(a + 1)$.

The array indexing syntax ([]) is an operator that performs pointer arithmetic.

\[ a[i] \text{ is equivalent to } \ast(a + i). \]
C does not perform any array “bounds checking”.
For a given array $a$ of length $l$, C does not verify that $a[j]$ is valid ($0 \leq j < l$).
C simply “translates” $a[j]$ to $*(a + j)$, which may be outside the bounds of the array (e.g., $a[1000000]$ or $a[-1]$).
This is a common source of errors and bugs and a common criticism of C. Many modern languages have fixed this shortcoming and have “bounds checking” on arrays.

In array pointer notation, square brackets ([ ]) are not used, and all array elements are accessed through pointer arithmetic.

```c
int sum_array(const int * a, int len) {
    int sum = 0;
    for (const int *p = a; p < a + len; ++p) {
        sum += *p;
    }
    return sum;
}
```

Note that the above code behaves identically to the previously defined `sum_array`:

```c
int sum_array(const int a[], int len) {
    int sum = 0;
    for (int i = 0; i < len; ++i) {
        sum += a[i];
    }
    return sum;
}
```

another example: pointer notation

```c
// count_match(item, a, len) counts the number of occurrences of item in the array a
int count_match(int item, const int *a, int len) {
    int count = 0;
    const int *p = a;
    while (p < a + len) {
        if (*p == item) {
            ++count;
        }
        ++p;
    }
    return count;
}
```
The choice of notation (pointers or 
[ ]) is a matter of style and context. You are expected to be comfortable with both.

C makes no distinction between the following two function declarations:

```
int array_function(int a[], int len) {...} // a[
int array_function(int *a, int len) {...} // *a
```

In most contexts, there is no practical difference between an array identifier and an immutable pointer.

The subtle differences between an array and a pointer are discussed at the end of Section 09.

**Array map**

Aside from the awkward function pointer parameter syntax, the implementation of `array_map` is straightforward.

```
// effects: replaces each element a[i] with f(a[i])
void array_map(int (*f)(int), int a[], int len) {
    for (int i=0; i < len; ++i) {
        a[i] = f(a[i]);
    }
}
```
#include "array_map.h"

int add1(int i) {
    return i + 1;
}

int sqr(int i) {
    return i * i;
}

int main(void) {
    int a[] = {4, 8, 15, 16, 23, 42};
    print_array(a, 6);
    array_map(add1, a, 6);
    print_array(a, 6);
    array_map(sqr, a, 6);
    print_array(a, 6);
    4, 8, 15, 16, 23, 42.
    5, 9, 16, 17, 24, 43.
    25, 81, 256, 289, 576, 1849.

Selection sort

In selection sort, the smallest element is selected to be the first element in the new sorted sequence, and then the next smallest element is selected to be the second element, and so on.

First, we find the position of the smallest element...

8 6 7 5 3 0 9

and then we swap the first element with the smallest.

0 6 7 5 3 8 9

Then, we find the next smallest element...

0 6 7 5 3 8 9

and then we swap that element with the second one, and so forth...

0 3 7 5 6 8 9
void selection_sort(int a[], int len) {
        int pos = 0;
        for (int i=0; i < len - 1; ++i) {
            pos = i;
            for (int j = i + 1; j < len; ++j) {
                if (a[j] < a[pos]) {
                    pos = j;
                }
            }
            swap(&a[i], &a[pos]); // see Section 05
        }
    }

    // Notes:
    // i: loops from 0 ... len-2 and represents the
    //   "next" element to be replaced
    // j: loops from i+1 ... len-1 and is "searching"
    //   for the next smallest element
    // pos: position of the "next smallest"

Quicksort

Quicksort is an example of a "divide & conquer" algorithm.

First, an element is selected as a "pivot" element.

The list is then partitioned (divided) into two sub-groups: elements less than (or equal to) the pivot and those greater than the pivot.

Finally, each sub-group is then sorted (conquered).

Quick sort is also known as partition-exchange sort or Hoare's quicksort (named after the author).

We have already seen the implementation of quick sort in racket.

(define (quick-sort lon)
    (cond [(empty? lon) empty]
          [else (define pivot (first lon))
                (define less (filter (lambda (x)
                                      (<= x pivot)) (rest lon)))
                (define greater (filter (lambda (x)
                                          (> x pivot)) (rest lon)))
                (append (quick-sort less)
                        (list pivot)
                        (quick-sort greater))])))

For simplicity, we select the first element as the "pivot". A more in-depth discussion of pivot selection occurs in CS 240.
In our C implementation of quick sort, we:

- select the first element of the array as our “pivot”
- move all elements that are larger than the pivot to the back of the array
- move ("swap") the pivot into the correct position
- recursively sort the “smaller than” sub-array and the “larger than” sub-array

The core quick sort function `quick_sort_range` has parameters for the range of elements (first and last) to be sorted, so a wrapper function is required.

```c
void quick_sort_range(int a[], int first, int last) {
    if (last <= first) return; // length is <= 1

    int pivot = a[first]; // first element is the pivot
    int pos = last; // where to put next larger

    for (int i = last; i > first; --i) {
        if (a[i] > pivot) {
            swap(&a[pos], &a[i]);
            --pos;
        }
    }
    swap(&a[first], &a[pos]); // put pivot in correct place
    quick_sort_range(a, first, pos-1);
    quick_sort_range(a, pos+1, last);
}
```

```c
void quick_sort(int a[], int len) {
    quick_sort_range(a, 0, len-1);
}
```

### Binary search

In Racket, the built-in function `member` can be used to determine if a list contains an element.

We can write a similar function in C that finds the index of an element in an array:

```c
// find(item, a, len) finds the index of item in a,
// or returns -1 if it does not exist
int find(int item, const int a[], int len) {
    for (int i=0; i < len; ++i) {
        if (a[i] == item) {
            return i;
        }
    }
    return -1;
}
```
But what if the array was previously *sorted*?

We can use **binary search** to find the element faster:

```c
int find_sorted(int item, const int a[], int len) {
    int low = 0;
    int mid = 0;
    int high = len-1;
    while (low <= high) {
        mid = (low + high) / 2;
        if (a[mid] == item) {
            return mid;
        } else if (a[mid] < item) {
            low = mid + 1;
        } else {
            high = mid - 1;
        }
    }
    return -1;
}
```

---

**Multi-dimensional data**

All of the arrays seen so far have been one-dimensional (1D) arrays.

We can represent multi-dimensional data by “mapping” the higher dimensions down to one.

For example, consider a 2D array with 2 rows and 3 columns.

```
1 2 3
7 8 9
```

We can represent the data in a simple one-dimensional array.

```
int data[6] = {1, 2, 3, 7, 8, 9};
```

To access the entry in row *r* and column *c*, we simply access the element at `data[r*3 + c]`.

In general, it would be `data[row * NUMCOLS + col]`.

---

C supports multiple-dimension arrays, but they are not covered in this course.

```c
int two_d_array[2][3];
int three_d_array[10][10][10];
```

When multi-dimensional arrays passed as parameters, the second (and higher) dimensions must be fixed.

*(e.g., int function_2d(int a[][10], int numrows)).*

Internally, C represents a multi-dimensional array as a 1D array and performs “mapping” similar to the method described in the previous slide.

See CP-AMA sections 8.2 & 12.4 for more details.
Fixed-Length Arrays

A significant limitation of an array is that you need to know the length of the array in advance.

In Section 10 we introduce dynamic memory which can be used to circumvent this limitation, but first we explore a less sophisticated approach.

In some applications, it may be “appropriate” (or “easier”) to have a maximum length for an array.

In general, maximums should only be used when appropriate:

- They are wasteful if the maximum is excessively large.
- They are restrictive if the maximum is too small.

When working with maximum-length arrays, we need to keep track of

- the “actual” length of the array, and
- the maximum possible length.

To illustrate fixed-length arrays, we implement an integer stack structure with a maximum length of 100 elements.

The len field keeps track of the actual length of the stack.

```c
struct stack {
    int len;
    int maxlen;
    int data[100];
};
```

We need to provide a stack_init function to initialize the structure:

```c
void stack_init(struct stack *s) {
    assert(s);
    s->len = 0;
    s->maxlen = 100;
}
```
Ignoring the **push** operation for now, we can write the rest of the stack 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 > 0);
    return s->data[s->len - 1];
}

// note: stack_pop returns the element popped
int stack_pop(struct stack *s) {
    assert(s);
    assert(s->len > 0);
    s->len -= 1;
    return s->data[s->len];
}
```

What happens if we exceed the maximum length when we try to **push** an element?

There are a few possibilities:

- the stack is not modified and an error message is displayed
- a special return value can be used
- an **assertion** fails (terminating the program)
- the program explicitly **terminates** with an error message

Any approach may be appropriate as long as the contract properly documents the behaviour.

The **exit** function (part of `<stdlib.h>`) stops program execution. It is useful for “fatal” errors.

The argument passed to **exit** is equivalent to the **return** value of **main**.

For convenience, `<stdlib.h>` defines **EXIT_SUCCESS** which is 0 and **EXIT_FAILURE** which is non-zero.

```c
if (something_bad) {
    printf("FATAL ERROR: Something bad happened!\n");
    exit(EXIT_FAILURE);
}
```
// stack_push(item, s) pushes item onto stack s
// requires: s is a valid stack
// effects: modifies s
// if max stack size is exceeded,
// prints a message and exits

void stack_push(int item, struct stack *s) {
    assert(s);
    if (s->len == s->maxlen) {
        printf("FATAL ERROR: max stack size (%d) exceeded\n", s->maxlen);
        exit(EXIT_FAILURE);
    }
    s->data[s->len] = item;
    s->len += 1;
}

Goals of this Section

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

- define and initialize arrays
- use iteration to loop through arrays
- use pointer arithmetic
- explain how arrays are represented in the memory model, and how the array index operator ([ ]) uses pointer arithmetic to access array elements in constant time
- use both array index notation ([ ]) and array pointer notation and convert between the two
- use fixed-length arrays
- describe insertion sort, quicksort and binary search on a sorted array
- represent multi-dimensional data in a single-dimensional array