An Introduction to C

Readings: CP:AMA 2.2, 2.3, 2.7, 4.1, 5.1, 9.1

- the ordering of topics is different in the text
- some portions of the above sections have not been covered yet

The primary goal of this section is to be able to write and test simple functions in C.
C was developed by Dennis Ritchie in 1969–73 to make the Unix operating system more portable.

It was named “C” because it was a successor to “B”, which was a smaller version of the language BCPL.

C was specifically designed to give programmers “low-level” access to memory (discussed in Section 04 and Section 05).

It was also designed to be easily translatable into “machine code” (discussed in Section 13).
Today, thousands of popular programs, and portions of all of the popular operating systems (Linux, Windows, Mac OS X, iOS, Android) are written in C.

There are a few different versions of the C standard. In this course, the C99 standard is used.
From Racket to C

First, we learn to write simple functions in C.

This allows us to become familiar with the C syntax without introducing too many new concepts.

In Section 03 we introduce new programming concepts (imperative programming).

Read your assignments carefully: you may not be able to “jump ahead” and start programming with imperative style (e.g., with mutable variables or loops).
Comments

// C comment

/* C multi-line
cmment */

; Racket comment

#| Racket multi-line
cmment |

In C, any text on a line after // is a comment.

Any text between /* and */ is also a comment, and can extend over multiple lines. This is useful for commenting out a large section of code.

C’s multi-line comment cannot be “nested”:

/* this /* nested comment is an */ error */
Expressions

C uses the more familiar \textit{infix} algebraic notation \((3 + 3)\) instead of the \textit{prefix} notation used in Racket \((+ 3 3)\).

\begin{verbatim}
// C Expressions: 
3 + 3
1 + 3 * 2
(1 + 3) * 2

; Racket Expressions: 
(+ 3 3)
(+ 1 (* 3 2))
(* (+ 1 3) 2)
\end{verbatim}

With infix notation, parentheses are often necessary to control the order of operations.

\textbf{Use parentheses to clarify} the order of operations in an expression.
C operators

C distinguishes between operators (e.g., +, -, *, /) and functions. The C order of operations ("operator precedence rules") are consistent with mathematics: multiplicative operators (*, /) have higher precedence than additive operators (+, -).

In C there are also non-mathematical operators (e.g., for working with data) and almost 50 operators in total.

As the course progresses more operators are introduced.

The full order of operations is quite complicated (see CP:AMA Appendix A).
In C, each operator is either *left* or *right* associative to further clarify any ambiguity (see CP:AMA 4.1).

The multiplication operators are *left*-associative:

\[ 4 \times 5 \div 2 \] is equivalent to \[ (4 \times 5) \div 2 \].

The distinction in this particular example is important in C.
The / operator

When working with integers, the C division operator (/) truncates (rounds toward zero†) any intermediate values, and behaves the same as the Racket quotient function.

\[
\begin{align*}
(4 \times 5) / 2 & \Rightarrow 10 \\
4 \times (5 / 2) & \Rightarrow 8 \\
-5 / 2 & \Rightarrow -2
\end{align*}
\]

Remember, use parentheses to clarify the order of operations.

† C99 standardized the “(round toward zero)” behaviour.
The % operator

The C remainder operator (%) (also known as the modulo operator) behaves the same as the remainder function in Racket.

9 % 2 ⇒ 1
9 % 3 ⇒ 0
9 % 5 ⇒ 4

The value of \((a \% b)\) is equal to: \(a - (a / b) \times b\).

In this course, avoid using % with negative integers.

\((i \% j)\) has the same sign as \(i\) (see CP:AMA 4.1).
Function definitions

// C function:

```c
int my_sqr(int n) {
    return n * n;
}
```

; Racket function:

```racket
;; my-sqr: Int -> Int
(define (my-sqr n)
  (* n n))
```

There are many subtle and important differences between defining a function in Racket and in C.

We explore those differences over the next few slides.
Identifiers

C identifiers ("names") must start with a letter, and can only contain letters, underscores and numbers.

For example, use `my_sqr` instead of `my-sqr`.

Underscore style is the most popular style in C, and the style we use in this course.

In other languages, camelCaseStyle is popular alternative.

C identifiers can start with a leading underscore (`_name`) but they may interfere with reserved keywords. Avoid them in this course as they may interfere with marmoset tests.
Function block and return

```c
int my_sqr(int n) {
    return n * n;
}
```

Braces (`{}`). indicate the beginning and end of the function **body**, known in C as the function **block**.

The expression is preceded by the `return` keyword and followed by a semicolon (`;`).

```
(define (my-sqr n)
  (* n n))
```

Note the placement of the braces (`{}`) and the use of whitespace and indentation (more on this later).
Dynamic typing in Racket

Racket uses *dynamic typing*: types are determined *while* the program is running.

```scheme
;; dtype: (anyof Int Str) -> (anyof Bool Sym)

(define (dtype param)
  (cond [(integer? param) true]
       [(string? param) 'dynamic]))
```

The types of the parameter and the produced ("returned") value are both *dynamic*.

We communicate the types in the *contract* as a *comment*. 
C uses *static typing*: all types **must** be known before the program is run and they cannot change.

The return type of `my_sqr` is an `int` (for integer).

Parameter `n` is also an `int`. 
C Types

For now, we only use integers in C. More types are introduced soon.

Because C uses static typing, there are no functions equivalent to the Racket type-checking functions (e.g., integer? and string?). In Racket, a contract violation may cause a “type” runtime error.

(my-sqr "hello") ; Racket runtime error

In C, it is impossible to violate the contract type, and “type” runtime errors do not exist.

my_sqr("hello") // does not run in C
If you omit the type in a function definition:

```c
int my_sqr(int n) { // properly typed
    return n * n;
}

my_bad_sqr(n) { // missing types
    return n * n;
}
```

C assumes the type is an int and may display a warning such as:

```
type specifier missing, defaults to 'int'
```

This is **very bad style**: you should specify *every* type.
When working with integer values in C, do not add a leading (preceding) zero (0) to the value. For example, do not write 017 if you want to represent the number 17.

A leading zero may seem harmless, but it is not:

```
trace_int(17); 17 => 17
trace_int(017); 017 => 15
trace_int(my_sqr(010)); my_sqr(010) => 64
```

In C, integer values that start with a zero are evaluated in octal (base 8), so 010 is equivalent to 8.

Integer values that start with 0x are evaluated in hexadecimal, so 0x10 is equivalent to 16.
Function terminology

In this course, we use more common terminology:

We call a function by passing it arguments and it returns a value.

apply \Rightarrow call
consume \Rightarrow pass
produce \Rightarrow return

In “functional” CS 135 terminology, we apply a function, which consumes arguments and it produces a value.
More function syntax

Multiple arguments and parameters are separated by commas (,).

```c
int my_add(int x, int y) {
    return x + y;
}
```

```c
int my_num(void) {
    return my_add(40, 2);
}
```

Use `void` to define a function with no parameters.
Use () to call a parameterless function: e.g., `my_num()`.

Also, in C you cannot have `local` (or “nested”) functions defined inside of other functions.
If you omit the `void` in a parameterless function definition:

```c
int my_num() {
    // ...
}
```

C allows it. This is because `()` is used in an older C syntax to indicate an “unknown” or “arbitrary” number of parameters (beyond the scope of this course).

It is **much** better style to use `void` to clearly communicate and enforce that there are no parameters.

```c
int my_num(void) {
    // ...
}
```
Function documentation

Racket and C purpose statements are nearly identical:

// my_sqr(n) squares n
int my_sqr(int n) {
  return n * n;
}

;; (my-sqr n) squares n
;; my-sqr: Int -> Int
(define (my-sqr n)
  (* n n))

In C, the contract types are part of the function definition so no type contract documentation is necessary. However, you should still add a requires comment if appropriate.

// my_divide(x, y) ....
// requires: y is not 0

int my_divide(int x, int y) {
  return x / y;
}
Whitespace

C mostly ignores whitespace.

// The following three functions are equivalent

int my_add(int x, int y) {       // GOOD
    return x + y;
}

int my_add(int x, int y) { return x+y; }   // BAD

int my_add(int x, int y) { return x+y; }   // RIDICULOUSLY BAD

You should follow the course style. The course staff and markers may not understand your code if it is poorly formatted.
CS 136 Style

```c
int my_add(int x, int y) {
    return x + y;
}
```

- a block start (open brace `{`) appears at the end of a line
- a block end (close brace `}`) is aligned with the line that started it, and appears on a line by itself
- indent a block 2 (recommended), 3 or 4 spaces: be consistent
- add a space after commas and around arithmetic operators

Typing Ctrl-I in Seashell will auto-indent your code for you.
When you have a function with a large number of parameters, or a really large expression, place code on the following line.

```c
int my_super_long_function(int a, int b, int c, int d, int e, int f, int g) {
    return a * b + b * c + c * d + d * e + e * f + f * g + g * a;
}
```

The “best” way to style your code (e.g., block formatting) is a matter of taste and is often a topic of debate.

The style we have chosen is the most widely accepted style for C (and C++) projects (e.g., it conforms to the Google style guide).
Getting started

At this point you are probably eager to write your own functions in C. Unfortunately, we do not have an environment similar to DrRacket’s interactions window to evaluate expressions and informally test functions.

Next, we demonstrate how to run and test a simple C program.
Entry point

Typically, a program is “run” (or “launched”) by an Operating System (OS) through a shell or another program such as DrRacket.

The OS needs to know where to start running the program. This is known as the entry point.

In many interpreted languages (including Racket), the entry point is simply the top of the file you are “running”.

In C, the entry point is a special function named main.

Every C program must have one (and only one) main function.
main

main has no parameters† and an int return type.

    int main(void) {
        //...
        return 0;       // success!
    }

The return value communicates to the OS the “error code” (also known as the “exit code”, “error number” or just errno).

A successful program returns zero (no error code).

† main has optional parameters (discussed in Section 13).
main is a special function and does not require an explicit return value. The default value is success (zero).

    // main() does not need a purpose statement

    int main(void) {
        //...
        return 0;       // this is optional
    }

In this course, main does not require a purpose statement, but in general it is good style to document the purpose of a program.

In this course, your main function should never return a non-zero value, as it causes your marmoset tests to fail.
Top-level expressions

In DrRacket, the final values of top-level expressions (code outside of a function) are displayed in the “interactions window”.

;; my racket program

(+ 1 1) ;; <-- top level

(define (my-sqr n)
    (* n n))

(my-sqr 7) ;; <-- top level

2
49
In C, *top-level expressions are not* allowed.

```c
// my C program

1 + 1;   // INVALID

int my_sqr(int n) {
    return n * n;
}

my_sqr(7);  // INVALID
```
Tracing expressions

We have provided *tracing tools* to help you “see” what your code is doing. Here, we use `trace_int` inside of `main` to *trace* several expressions and display them to the screen (console):

```c
int main(void) {
    trace_int(1 + 1);
    trace_int(my_sqr(7));
}

1 + 1 => 2
my_sqr(7) => 49
```

You can leave the *tracing* in your code. It is ignored in our tests and does not affect your results (no need to comment it out).
We’re now ready to run our first program.

    // My first C program

    #include "cs136.h"    // <-- more on this later

    int my_sqr(int n) {
        return n * n;
    }

    int main(void) {
        trace_int(1 + 1);
        trace_int(my_sqr(7));
    }

Note the necessary #include line at the top of the program.
For now, always add this line (it is explained later).
Function ordering

If you re-order the two functions in our program:

```c
int main(void) {
    trace_int(1 + 1);
    trace_int(my_sqr(7));
}

int my_sqr(int n) { // now below main
    return n * n;
}
```

You get an error such as:

implicit declaration of function 'my_sqr' is invalid

For now, always place function definitions **above** any other functions that reference them (so main is at the bottom).
Boolean expressions

To facilitate testing, we need Boolean expressions.

In C, a Boolean expression does not produce “true” or “false”.

An expression produces zero (0) for “false”, and one (1) for “true”.

In our environment, the constants true and false have been defined to be 1 and 0 (for convenience).

If used in a Boolean expression, any non-zero value is also considered “true”.

Only zero is “false”.
Equality operator

The equality operator in C is `==` (note the double equals).

(3 == 3) ⇒ 1 (true)
(2 == 3) ⇒ 0 (false)

The not equal operator is `!=`.

(2 != 3) ⇒ 1 (true)

Always use a double `==` for equality, not a single `=`.
The accidental use of a *single* `=` instead of a *double* `==` for equality is one of the most common programming mistakes in C. This can be a serious bug (we revisit this in Section 03). It is such a serious concern that it warrants an extra slide as a reminder.
The *not*, *and* and *or* operators are respectively `!`, `&&` and `||`.

\[
!(3 == 3) \quad \Rightarrow \quad 0 \\
(3 == 3) && (2 == 3) \quad \Rightarrow \quad 0 \\
(3 == 3) && !(2 == 3) \quad \Rightarrow \quad 1 \\
(3 == 3) || (2 == 3) \quad \Rightarrow \quad 1 \\
2 && 3 \quad \Rightarrow \quad 1 \quad (why?)
\]

Similar to Racket, C **short-circuits** and stops evaluating an expression when the value is known.

\[(a \neq 0) && (b / a == 2)\]

does not generate an error if `a` is 0.

A common mistake is to use a single `&` or `|` instead of `&&` or `||`. These operators have a different meaning.
Comparison operators

The operators \(<\), \(<=\), \(>\) and \(>=\) behave exactly as you would expect.

\[(2 < 3) \Rightarrow 1\]
\[(2 >= 3) \Rightarrow 0\]

\(! (a < b)\) is equivalent to \((a >= b)\).

It is always a good idea to add parentheses to make your expressions clear.

> has higher precedence than ==, so the expression

\[1 == 3 > 0\] is equivalent to \[1 == (3 > 0)\], but it could easily confuse some readers.
You are not expected to “memorize” the order of operations. When in doubt (or to add clarity) **add parentheses**.

<table>
<thead>
<tr>
<th>Type</th>
<th>Operator(s)</th>
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<tbody>
<tr>
<td>negation</td>
<td>!</td>
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<tr>
<td>multiplicative</td>
<td>* / %</td>
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<tr>
<td>additive</td>
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<td>comparison</td>
<td>&lt; &lt;= &gt;= &gt;</td>
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<td>equality</td>
<td>== !=</td>
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<tr>
<td>and</td>
<td>&amp;&amp;</td>
</tr>
<tr>
<td>or</td>
<td></td>
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</table>
Assertions

The assert function can be used in place of Racket’s check-expect. The equivalent of:

(check-expect (my-sqr 7) 49)

is:

assert(my_sqr(7) == 49);

assert(exp) stops the program and displays a message if the expression exp is false (zero).

If exp is true (non-zero), it just continues to the next line of code.
// My second C program (now with testing!)

#include "cs136.h"

int my_sqr(int n) {
    return n * n;
}

int main(void) {
    assert(my_sqr(0) == 0);
    assert(my_sqr(1) == 1);
    assert(my_sqr(2) == 4);
    assert(my_sqr(32) == 1024);
    assert(my_sqr(-1) == 1);
    assert(my_sqr(-32) == 1024);
}

We discuss additional testing methods later. For now, test your code with asserts in your main function as above.
Function requirements

The assert function is also very useful for verifying function requirements.

At the start of each function, you can add asserts.

```c
// my_divide(x, y) ....
// requires: y is not 0

int my_divide(int x, int y) {
    assert(y != 0); // assert(y) also works
    return x / y;
}
```

Whenever it is feasible, assert any function requirements.
If you have a function with more than one requirement:

```c
// my_function(x, y, z) ....
// requires: x is positive
// y < z

int my_function(int x, int y, int z) {
  assert((x > 0) && (y < z)); // POOR
  assert(x > 0); // GOOD
  assert(y < z);
  //...
}
```

It is better to have several small `assert` statements. That way it is easier to determine which assertion failed (and which requirement was not met).
bool type

The bool type is an integer that can only have a value of 0 or 1.

```c
bool is_even(int n) {
    return (n % 2) == 0;
}

bool my_negate(bool v) {
    return !v;
}
```
Conditionals

C’s if statement allows us to have functions with conditional behaviour.

```c
int my_abs(int n) {
    if (n < 0) {
        return -n;
    } else {
        return n;
    }
}
```

There can be more than one return in a function, but only one value is returned. The function “exits” when the first return is reached.
**Emulating simple cond behaviour**

Racket’s cond special form consumes a sequence of question and answer pairs (where questions are Boolean expressions).

Racket functions that have the following cond behaviour can be re-written in C using if, else if and else:

```
(define (my-function ...)  // int my_function(...) {
  (cond              if (q1) {
    [q1  a1]          return a1;
    [q2  a2]          } else if (q2) {
    [else a3]])        return a2;
                        } else {
}
                      return a3;
}
```
example: using if, else and else if

// in_between(x, lo, hi) determines if lo < x < hi
// requires: lo <= hi

bool in_between(int x, int lo, int hi) {
    if (x < lo) {
        return false;
    } else if (x > hi) {
        return false;
    } else {
        return true;
    }
}

Recursion in C behaves the same as in Racket.

```c
// sum_first(n) sums the natural numbers 0..n
// requires: n >= 0

int sum_first(int n) {
    if (n <= 0) {
        return 0;
    } else {
        return n + sum_first(n - 1);
    }
}
```
if vs. cond

Given the examples we have seen so far, it might appear that Racket’s cond and C’s if are “the same”.

Fundamentally, they are quite different.

cond produces a value and can be used inside of an expression:

\[
(+ \ y \ (\text{cond} \ [(< \ x \ 0) \ -x] \\
\text{[else} \ \ x\])
\]

C’s if statement does not produce a value: it only controls the “flow of execution” and cannot be similarly used within an expression.

We revisit if in Section 04 after we understand how “statements” differ from expressions. For now, only use if as demonstrated.
Unlike C’s if statement, the C ternary conditional operator (?) does produce a value.

The value of the expression:

$$q ? a : b$$

is a if q is true (non-zero), and b otherwise.

For example:

$$(v \geq 0) ? v : -v \quad // \quad \text{abs}(v)$$

$$(a > b) ? a : b \quad // \quad \text{max}(a, b)$$

You may use the ?: operator in this course, but use it sparingly. Overuse of the ?: operator can make your code hard to follow.
Goals of this Section

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

- demonstrate the use of the C syntax and terminology introduced
- re-write a simple Racket function in C (and vice-versa)
- use the C operators introduced in this module
  (including \% == != >= && ||)
- explain the significance of the main function in C
- perform basic tracing in C using trace_int
- use assert for testing and to verify requirements
- provide the required documentation for C functions