An Introduction to C

Optional Textbook 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.

A brief history of 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) and be easily translatable into “machine code” (Section 13).

Thousands of popular programs and portions of **all** of the popular operating systems are written in C.

C versions

There are a few different versions of the C standard.

In this course, we use the C99 standard (from 1999).

The C11 standard (2011) added some new features to the language, but those features are not needed in this course.

The C18 standard (2018) only fixes a few bugs from C11.

The C2x standard (202?) is currently in development.

Introductory C

In this section we learn to write simple functions and programs 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 topics not yet covered (*e.g.,* loops).

Comments

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

Any text between `/* and */` is also a comment.

`/* ... */` can extend over multiple lines and can comment out large sections of code.

```
// C comment (one-line only)

/* This is a
   multi-line comment */
```

C's multi-line comment cannot be "nested":
`/* this /* nested comment is an */ error */`

Expressions

C expressions use traditional *infix* algebraic notation: (*e.g.,* `3 + 3`).

Use parentheses to specify the order of operations (normal arithmetic rules apply).

`1 + 3 * 2` ⇒ `7`

`(1 + 3) * 2` ⇒ `8`

`Racket` uses *prefix* notation: `(+ 3 3)`

Languages that use prefix (or postfix) notation do not require parenthesis to specify the order of operations.

Operators

In addition to the traditional mathematical ***operators*** (*e.g.,* `+`, `-`, `*`), C also has *non-mathematical* operators (*e.g.,* data operators).

With over 40 operators in total, the order of operations is complicated (see CP:AMA Appendix A).

C does not have an *exponentiation* operator (*e.g.,* x^n).

Confusingly, the *"bitwise exclusive or"* operator (^) looks like an exponentiation operator. Bitwise operators are beyond the scope of this course.

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 * 5 / 2` is equivalent to `(4 * 5) / 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.

```
(4 * 5) / 2   ⇒  10
4 * (5 / 2)   ⇒   8
   -5 / 2     ⇒  -2
```

Remember, use parentheses to clarify the order of operations.

C99 standardized the "(round toward zero)" behaviour.

The % operator

The C **modulo** operator (%) produces the **remainder** after integer division.

```
9 % 2   ⇒  1
9 % 3   ⇒  0
9 % 5   ⇒  4
```

The value of `(a % b)` is equal to: `a - (a / b) * b`.

It is often best to avoid using `%` with negative integers.

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

C identifiers

Every function, variable and structure requires an ***identifier*** (or "name").

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

In this course, use `underscore_style` (or *snake* case) for identifiers with compound words.

For example: `hst_rate`, `trace_int`, `quick_sort`

Use `underscore_style` in your code.

`underscore_style` is the most popular style for C projects.

In other languages (*e.g.,* Java) `camelCaseStyle` is popular.

In practice, it is important to use the recommended style for the language and/or follow the project (or corporate) style guide.

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.

Anatomy of a function definition

```
int my_add(int a, int b) {
  return a + b;
}
```

- braces ({}) indicate the beginning/end of a function ***block***
- `return` keyword, followed by an expression, followed by a semicolon (`;`)
- parameters (a, b) are separated by a comma
- the function and parameter **types** are specified (*i.e.,* `int`)

Note the placement of the braces ({}) and the use of whitespace and indentation (more on this later).

Static type system

C uses a ***static type system***: all types **must** be known **before** the program is run and the type of an identifier **cannot change**.

For now, we will only use C **`integers`** (more types in Section 04).

```
int my_add(int a, int b) {
  return a + b;
}
```

The `return` type of `my_add` is an `int` (appears *before* `my_add`).

The parameters a and b are also both `int`s.

Racket uses a **dynamic** type system.

If the type in a function definition is omitted:

```
int my_add(int a, int b) {   // properly typed
  return a + b;
}

bad_add(a, b) {              // missing types
  return a + b;
}
```

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

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

This is **very bad style**: specify *every* type.

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-add "hello" 3)    ; Racket runtime error
```

In C, it is impossible to violate the contract *type*.

“Type” *runtime* errors do not exist.

```
my_add("hello", 3)    // does not run in C
```


Function terminology

We ***call*** a function by ***passing*** it ***arguments***.

A function ***returns*** a value.

```
my_add(1, 2)   ⇒   3
```

We *call* `my_add` and *pass* it the *arguments* `1` and `2`.

`my_add(1, 2)` *returns* 3.

In “functional” language terminology (*e.g.,* `Racket`) we **apply** a function, which **consumes** arguments and it **produces** a value.

Functions without parameters

Use the `void` keyword to indicate a function has no parameters.

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

To call a parameterless function, put nothing between the parentheses (do not pass `void`).

```
my_num()   ⇒   42
```

If the `void` is omitted in a parameterless function **definition**:

```
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).

Always use `void` to clearly communicate (and enforce) that there are no parameters.

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


No nested functions

In C, functions **cannot** be “nested” (defined) *inside* of another function (*a.k.a.* local functions).

```
int outer(int i) {
  int inner(int j) {    // INVALID
    // ...
  }
  // ...
}
```

The GNU C environment (`gcc`) has introduced a *language extension* for nested C functions, but it is not part of the C standard.

Function documentation

Provide a purpose for every function that shows an example of it being called, followed by a brief description of **what** the function does (not *how* it does it).

No contract *types* are necessary (they are part of the definition).

Add a **requires** comment if appropriate.

```
// my_divide(x, y) evaluates x/y using
//   integer division
// 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 a, int b) {              // GOOD
  return a + b;
}

int my_add(int a,int b){return a+b;}     // BAD

int my_add(int a, int                   // RIDICULOUSLY
b){return a+                            // BAD
b ; }
```

Follow the course style. The course staff and markers may not follow your code if it is poorly formatted.

CS 136 style

```
int my_add(int a, int b) {
  return a + b;
}
```

- 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 there are a large number of parameters, a large expression or a long purpose, continue (indented) on the following line.

```
// my_super_long_function(a, b, c, d, e, f, g) does some
//   amazing things with those parameters...

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

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

In many interpreted languages (including Racket), the entry point is simply the **top** of the file being "run".

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 `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) and zero is `return`ed *automatically* if it is not present.

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

Unless an assignment has special instructions, your `main` function should never `return` a non-zero value, as it causes your marmoset tests to fail.

There is no widespread consensus on whether having a `return` in `main` is "good style".

In these notes we do not show `return 0;` to save space.

On assignments and exams it is optional.

There is a constant `EXIT_SUCCESS` (defined as zero) which is also popular in practice.

```
int main(void) {
  //...
  return EXIT_SUCCESS;
}
```


Top-level expressions

In C, *top-level expressions* (code outside of a function) are not allowed.

Code only executes inside of a function.

```
1 + 1;             // INVALID

int my_add(int a, int b) {
  return a + b;
}

my_add(1, 2);      // INVALID
```

In `DrRacket`, the final values of *top-level expressions* are displayed in the "interactions window".

```
;; my racket program

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

(define (my-add a b)
  (+ a b))

(my-add 1 2)           ;; <-- top level
```

```
2
3
```


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):

```
int main(void) {
  trace_int(1 + 1);
  trace_int(my_add(1, 2));
}
```

```
1 + 1 => 2
my_add(1, 2) => 3
```


Leave your *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 (documentation omitted)

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

int my_add(int a, int b) {
  return a + b;
}

int main(void) {
  trace_int(1 + 1);
  trace_int(my_add(1, 2));
}
```

Note the necessary `#include` line at the top of the program.
For now, always add this line (it is explained in Section 06).

Function ordering

If the two functions are re-ordered:

```
int main(void) {
  trace_int(1 + 1);
  trace_int(my_add(1, 2));
}

int my_add(int a, int b) {    // now below main
  return a + b;
}
```

There is an error (such as):

```
implicit declaration of function 'my_add' is invalid
```

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

Program documentation

Document a program (state its purpose) at the **top** of the file (not necessarily where `main` is defined).

```
// This program informally tests the my_add function

#include "cs136.h"

// my_add(a, b) calculates the sum of a and b

int my_add(int a, int b) {
  return a + b;
}

int main(void) {
  trace_int(1 + 1);
  trace_int(my_add(1, 2));
}
```

There is no need to add additional documentation for `main` itself.

Testing

Our *tracing tools* are an excellent way for you to interact with your code and help you "see" what is happening.

They are helpful to *informally* test your code.

They are not a viable strategy to *thoroughly* test.

However, to facilitate more thorough testing, we will need Boolean expressions...

Boolean expressions

In C, Boolean expressions do not produce "true" or "false".

They produce either:

- zero (`0`) for "false", or
- one (`1`) for "true".

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

Comparison operators

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)
```

The operators <, <=, > and >= behave exactly as expected.

```
(2 < 3)   ⇒  1 (true)
(2 >= 3)  ⇒  0 (false)
```

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.

Logical Operators

The Logical operators are: `!` (not), && (and), `||` (or):

```
!(3 == 3)                ⇒  0
(3 == 3) && (2 == 3)     ⇒  0
(3 == 3) && !(2 == 3)    ⇒  1
(3 == 3) || (2 == 3)     ⇒  1
```

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

```
(a != 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 ||.

All non-zero values are true

Operators that *produce* a Boolean value (*e.g.,* ==) will always produce `0` or `1`.

Operators (or functions) that *expect* a Boolean value (*e.g.,* &&) will consider any non-zero value to be "true".

Only zero (`0`) is "false"[†].

```
(2 && 3)      ⇒  1
(0 || -2)     ⇒  1
!5            ⇒  0
```

[†] The value `NULL` (Section 05) is also considered false.

You are not expected to "memorize" the order of operations.

When in doubt (or to add clarity) **add parentheses**.

negation	!
multiplicative	* / %
additive	+ -
comparison	< <= >= >
equality	== !=
and	&&
or	||

bool type

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

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

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


Assertions

Use the `assert` function to test functions:

```
assert(my_add(1, 2) == 3);
```

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

If `exp` is true (non-zero), it does "nothing" and continues to the next line of code.

`assert` is very similar to Racket's `check-expect`:

```
(check-expect (my-add 1 2) 3)
```

```
// My second C program (now with better testing!)

#include "cs136.h"

int my_add(int a, int b) {
  return a + b;
}

int main(void) {
  assert(my_add(0, 0) == 0);
  assert(my_add(1, 1) == 2);
  assert(my_add(-2, 1) == -1);
}
```

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

Testing strategies

You are expected to test your own code.

Simply relying on the public marmoset tests is not a viable strategy to succeed in this course.

Function requirements

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

```
// 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;
}
```

In the slides, we often omit `asserts` to save space.

`assert` any feasible function requirements.

Infeasible requirements

Some requirements are infeasible to assert, or (as we will discuss in Section 08) they would be *inefficient* to assert.

It is good style to communicate (*i.e.,* document) that a requirement is not asserted:

```
// my_function(n) ....
// requires: n is a prime number [not asserted]
```


Multiple requirements

With multiple requirements, it is better to have several small `asserts`.

It makes it easier to determine which assertion failed (which requirement was not met).

```
// 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));    // OK

  assert(x > 0);                 // BETTER
  assert(y < z);
  //...
}
```


Statements

Blocks (`{}`) can contain multiple ***statements***:

```
int my_divide(int x, int y) {
  assert(y);                   // statement
  trace_int(y);                // statement
  return x / y;                // statement
  trace_int(x);                // unreachable statement
}
```

Statements are executed *in sequence* (one after the other).

The `return` statement **ends** the function.

In the above code, `trace_int(x);` will never execute.

> We define statements more precisely in Section 03.

Brief introduction to control flow

The `return` statement is a special kind of statement known as a ***control flow*** statement.

`return` "controls the flow" of the program by ending the function and `return`ing to the caller.

We explore control flow statements in Section 04, but first we will introduce one more control flow statement...

Conditionals

The `if` control flow statement allows us to have functions with conditional behaviour.

```
int my_abs(int n) {
  if (n < 0) {           // note: the () are required
    return -n;
  } else {
    return n;
  }
}
```

There can be more than one `return` in a function, but only one value is ever returned.

The function stops when the first `return` is executed.

example: recursion in C

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

int sum_first(int n) {
  assert(n >= 0);
  if (n == 0) {
    return 0;
  } else {
    return n + sum_first(n - 1);
  }
}
```

else if

If there are more than two possible results, use `else if`.

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

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


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 ...)
  (cond
    [q1   a1]
    [q2   a2]
    [else a3]))
```

```
int my_function(...) {
  if (q1) {
    return a1;
  } else if (q2) {
    return a2;
  } else {
    return a3;
  }
}
```


C's `if` *statement* does not produce a value: it only controls the "flow of execution" and cannot be used *inside* of an expression.

We revisit `if` in Section 04 after we understand how "statements" differ from expressions. For now, only use `if` as we have demonstrated.

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. Unlike `if`, `cond` does produces a value and can be used inside of an expression:

```
(+ y (cond [(< x 0) -x]
           [else     x]))
```

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 >= 0) ? v : -v    // abs(v)
(a > b) ? a : b      // 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.

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_add(010, 010));  my_add(010, 010) => 16
```

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`.

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
- Write a simple function in C
- 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