15-122: Principles of Imperative Computation — Spring 2023

Recitation 01: C0 Basics — Thursday January 12th

Checkpoint 0

Identify and correct the syntax errors in the following code to make it valid C0:

```
1  #use conio
2
3  def fib(i):
4    if ((i = 0 || i = 1) == true) {
5      return i;
6    }
7  return fib(i - 1) + fib(i - 2)
8
9  int main():
10   print('This is the fibonacci sequence starting from: 0\n');
11
12   for (int i=0, i < 10, i++) {
13     printf("fib(%d) = %d\n");
14   }
```

Printing The simplest way to print something in C0 is to use `printf`. For example,

```
printf("Today is %d %s %d!\n", day, month, year);
```

The first argument is the string that you wish to print, optionally containing *format specifiers* among `%d`, `%s` and `%c`. During printing these format specifiers will be replaced by the values of the subsequent arguments, in the order (here the variables `day`, `month` and `year`). You use `%d` to print an **`int`** value, `%s` for a **`string`**, and `%c` for a **`char`**. Printing is *buffered* in C0, which means that output will be displayed on the terminal only when a *new line character* (written `\n`) is encountered. See the documentation for the `<conio>` library for more on printing in C0.

Although `printf` is most commonly used, C0 provides other printing functions, `print` to print a string, `printint` to print an integer, etc. See the documentation for the `<conio>` library for a complete list.

Executing C0 Programs

There are two ways to execute a C0 program: run it through the interpreter or compile it. Using `coin` (the **C0 in**terpreter) allows you to execute individual functions with your chosen inputs interactively. The `cc0` **c**ompiler for **C0** first translates your C0 code into an executable file (the default name is `a.out`), which you can then run to execute the `main` function (and any function `main` calls). There must be exactly one `main` function when using `cc0`, but no `main` is needed for `coin`.

Consider the following example where our program has been split into three files. What it does isn't important: what matters is that `dotproduct.c0` calls a function in `multiply.c0`, which itself calls a function in `add.c0`.

File `add.c0`

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

File `multiply.c0`

```
int multiply(int x, int y)
//@requires y >= 0;
{
  int result = 0;
  while (y > 0) {
    result = add(result, x);
    y--;
  }
  return result;
}
```

File `dotproduct.c0`

```
// Dot product of <x, y> and <a, b>:
//   <x, y> * <a, b> = x * a + y * b
int dot_product(int x, int y, int a, int b) {
  int first = multiply(x, a);
  int second = multiply(y, b);
  return add(first, second);
}

int main() {
  return dot_product(150, 61, 100, 2);
}
```

How would we compile this program with contract checking enabled?

```
% _____
```

How would you run the resulting executable?

```
% _____
```

How would you compile this program without contract checking enabled so that the executable is called `dptest`? How would you then run it?

```
% _____

% _____
```

How would you use `coin` to check that `multiply(3,2)` evaluates to `6`? What about using `coin` to find out what `multiply(-3,-2)` produces? You may want to enable contracts.

```
% _____
C0 interpreter (coin) 1.0.0 'Quarter' ...

--> _____
_____

--> _____
_____
```

Contracts

There are 4 types of contract annotations in C0 (for convenience, we're using `exp` here to mean any Boolean expression):

Annotation	Checked
`//@requires exp;`	before function execution
`//@ensures exp;`	before function returns
`//@loop_invariant exp;`	before the loop condition is checked
`//@assert exp;`	wherever you put it in the code

There are certain special variables and functions you have access to only in annotations. One of these is `\result`. It can be used only in `@ensures` statements and it will give you the return value of the function. (There are other such variables/functions that we'll get to later in the semester.)

To help you develop an intuition about contracts, here are some explanations of the different kinds of annotations:

- `@requires`: For checking _____
- `@ensures`: For checking _____

  Allow use of the special expression _____
- `@loop_invariant`: We can only write these immediately after the beginning of a **`while`** loop or **`for`** loop.

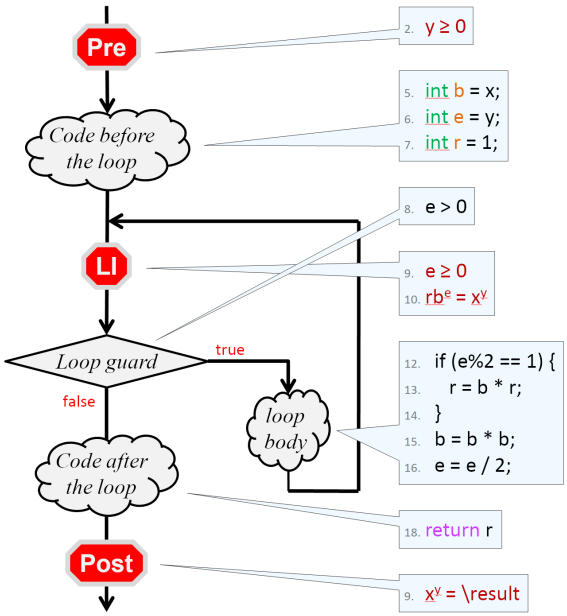
  When are these checked? _____.
- `@assert`: Assertion statements don't play the special role in reasoning that `@requires`, `@ensures`, and `@loop_invariant` statements do. They can be very helpful for debugging code and summarizing what you know, especially after a loop.

Proving the correctness of the mystery function

We use contracts to both test our code and to reason about code. With contracts, careful point-to reasoning and good testing both help us to be confident that our code is correct.

The code for the mystery function from lecture is reproduced on the left below. To its right is an annotated *control flow diagram* that highlights the different parts in in what sequence they are executed.

```
1  int f(int x, int y)
2  //@requires y >= 0;
3  //@ensures POW(x, y) == \result;
4  {
5    int b = x;
6    int e = y;
7    int r = 1;
8    while (e > 0)
9    //@loop_invariant e >= 0;
10   //@loop_invariant POW(b, e) * r == POW(x, y);
11   {
12     if (e % 2 == 1) {
13       r = b * r;
14     }
15     b = b * b;
16     e = e / 2;
17   }
18   return r;
19 }
```



Proving that this function is correct is divided into four steps. For each of them, give a brief intuitive explanation of what it achieves ("what"), determine the proof technique you are expected to use to prove it, write a precise statement of what you need to prove ("to show"), and list the lines of code you are allowed to use to prove this statement ("allowed lines").

INITialization:

What: *show that the loop invariants hold before the first iteration of the loop*

Proof technique: *point-to reasoning*

To show: _____

Allowed lines: _____

PREServation:

What: *show that each loop invariant is preserved by an arbitrary iteration of the loop*

Proof technique: *point-to reasoning*

To show: _____

Allowed lines: _____

EXIT:

What: *show that the postconditions follow from the loop invariants and the negation of the loop guard*

Proof technique: *point-to reasoning*

To show: _____

Allowed lines: _____

TERMination**:**

What: *show that the loop terminates*

Proof technique: *operational reasoning (although point-to reasoning is also possible)*

To show: _____

Allowed lines: _____

Having done this, express the allowed justification lines in terms of the parts of the control flow diagram — all proofs you will do in this class will follow this more general template.

We often think of INIT and PRES as part of a single larger step that shows that the loop invariants are valid.

Preservation of loop invariants

Showing that a loop invariant is preserved can be a bit confusing: we need to assume that the loop invariant, like `e >= 0` or `r * POW(b,e) == POW(x,y)`, is true just before we start executing the body of the loop (it is checked just before the loop guard), and use this information (together with the knowledge that the loop guard evaluated to `true`) to show that it is also true at the end of the loop (just before the loop guard is evaluated again). We do this relative to an *arbitrary* iteration of the loop. Here's a *different* loop body from what we saw in class.

```
1    while (e > 0)
2    //@loop_invariant e >= 0;
3    //@loop_invariant r * POW(b, e) == POW(x, y);
4    {
5      r = r * b;
6      e = e - 1;
7    }
```

Let's show that both loop invariants are preserved by an arbitrary iteration of this loop. We will express the various steps of these proofs using mathematical symbols (e.g., $e \geq 0$) but you are welcome to use code (e.g., `e >= 0`).

Recall that we use primed variables (e.g., e') to denote that value of this variable after the current iteration has been completed, while we omit the prime (e.g., e) for its value at the start of the current iteration.

Loop invariant on line 2 ($e \geq 0$):

Assume: _____

To show: _____

a. $e' =$ _____ by _____
b. _____ by _____
c. _____ by _____
d. _____ by _____

Loop invariant on line 3 ($rb^e = x^y$):

Assume: _____,

To show: _____.

a. $rb^e = x^y$ by assumption (or by line 3)
b. $r' =$ _____ by _____
c. $e' =$ _____ by _____
d. $b' =$ _____ by _____
e. _____ by _____
f. _____ by _____
g. _____ by _____

REFERENCE: Basic syntax for C0 programs

Semicolons: Statements are terminated by semicolons. At the end of most lines, you'll need a semicolon. (Exceptions are **`if`** statements, function definitions, **`#use`** statements, and loops.)

Types: Some of the types in C0 are:

- **`int`**: Integers x, where $-2^{31} \leq x < 2^{31}$.
- **`bool`**: Either `true` or `false`. Useful for conditionals, loops, and more.
  - `a || b` is true if either `a` or `b` are true
  - `a && b` is true if both `a` and `b` are true
  - `!a` is true if `a` is false
  - `x < y`, `x <= y`, `x > y`, `x >= y` all compare two integers `x` and `y` and return a **`bool`**
  - `x == y` and `x != y` compare most C0 types and return a **`bool`**. You can't compare strings this way, though, and it's usually bad style if you're writing code like `e == true`.
- **`string`**: An ordered sequence of characters enclosed in double quotes like `"Hello!"`
- **`char`**: A single character enclosed in single quotes, like `'c'`, `'z'`, `'F'`, or `'?'`.

Boolean operators: Both `&&` and `||` are *short-circuiting infix operators*.

They are *infix* (like other operators `+`, `-`, `%`, etc.) because they take two arguments and the operator is placed between the two arguments. The compiler mentions the word "infix operator" if you make a mistake with them, so it's good to be aware of this name for them.

They are *short-circuiting* because, if the expression to the left of `&&` evaluates to `false` or if the expression to the left of `||` evaluates to `true`, then the expression to the right will never get executed. This means that, even though evaluating the expression `y/x == 0` will cause an error if `x` is zero, evaluating the expression `x == 0 || y/x == 0` can never cause an error.

Locals: locals (also called "local variables," "assignable variables," "assignables," or "variables") are explicitly declared along with their type. Locals can never change type after they are declared.

```
1 int x = 5;                    // x is initialized to 5
2 int y;                        // We can't use y until we assign to it!
3 string str = "hello";
4 y = x + 4;                    // y is now equal to 9
5 x = x + 1;                    // x is now equal to 6
6 x = "world";                  // ERROR! string and int are different types!
```

Conditionals: These are one way we use **`bool`** values. Here's an example of **`if`** statements in C0:

```
if (condition) {
    //do something if condition == true
}
else if (condition2) {
    //do something if condition2 == true and condition == false
}
else {
    //do something if condition == false and condition2 == false
}
```

Loops: There are two kinds of loops in C0 — **`while`** loops and **`for`** loops.

- **`while`** loop: It takes a condition (something that evaluates to a Boolean). The loop executes until the condition is false.
- **`for`** loop: It takes three statements separated by semicolons. Execute the first statement once at the beginning of the loop, loop until the second statement (a condition) is false, and execute the third statement at the end of each iteration.

`while` loop

```
int x = 0;
while (x < 5) {
    printint(x);
    print("\n");
    x++;
}
```

`for` loop

```
for (int x = 0; x < 5; x++) {
    printint(x);
    print("\n");
}
```

These two examples do the same thing. Here, the **`for`** loop is preferred but there are cases (like binary search in an array, which we'll discuss later this semester) where **`while`** loops are cleaner.

Function definition: This example defines a function called `add` that takes two **`int`**s as arguments and returns an **`int`**.

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

Comments: Use `//` to start a single line comment and `/* ... */` for multi-line comments.

Indentation and braces: Your code will still work if it's not indented well, but it's really bad style to indent poorly. Python's indentation rules are good and you should generally follow them in C0 too. C0 uses curly braces (i.e., `{` and `}`) to denote the starts and ends of blocks, as seen above. For single-line blocks it's possible to omit the curly braces, but that can make debugging very difficult if you later add in another line to the block of code. For that reason, you may want to use braces, even for single-line statements.

Very Bad

```
if (x == 4)
println("x is 4");
```

Okay

```
if (x == 4)
    println("x is 4");
```

Good

```
if (x == 4) {
    println("x is 4");
}
```