15-122: Principles of Imperative Computation

Recitation 4 Solutions

Josh Zimmerman

Bit manipulation

Let's look at some examples of masking so you can get a better idea of how it's used. First, let's write a function that, given a pixel in the ARGB format, returns the green and blue components of it. Your solution should use only `&`.

Solution:

```
typedef int pixel;
int greenAndBlue(pixel p)
//@ensures 0 <= \result && \result <= 0xffff;
{
  // We only want the lower 16 bits of p, so and the others with 0
  // to get rid of them
  return p & 0xffff;
}
```

Now, let's write a function that gets the alpha and red pixels of a pixel in the ARGB format. Your solution can use any of the bitwise operators, but will not need all of them.

Solution:

```
typedef int pixel;
int alphaAndRed(pixel p)
//@ensures 0 <= \result && \result <= 0xffff;
{
  // First, we want to put the top 16 bits in the bottom of the number.
  // Then, we want to get rid of any sign extension that the right shift
  // caused, so we use a mask to get rid of anything above the bottom 16
  // bits
  return (x >> 16) & 0xffff;
}
```

Arrays

Here's a slightly more complicated loop: it's a function that calculates the nth Fibonacci number more efficiently than the naive recursive implementation. Assume that we have a function:

```
int slow_fib(int n)
//@requires n >= 0;
;
```

that calculates Fibonacci recursively, and obeys all of the mathematical properties of the Fibonacci sequence. We don't worry about overflow for now – Fibonacci only uses addition, so we can think of it as being defined in terms of modular arithmetic.)

```
1 int fib(int n)
2 //@requires n >= 0;
3 //@ensures \result == slow_fib(n);
4 {
5   int[] F = alloc_array(int, n);
6   if (n > 0) {
7      F[0] = 0;
8   }
9   else {
10     return 0;
11  }
12  if (n > 1) {
13     F[1] = 1;
14  }
15  else {
16    return 1;
17  }
18  for (int i = 2; i < n; i++)
19    //@loop_invariant 2 <= i && i <= n;
20    //@loop_invariant F[i - 1] == slow_fib(i - 1) && F[i - 2] == slow_fib(i - 2);
21    {
22     F[i] = F[i - 1] + F[i - 2];
23    }
24  return F[n - 1] + F[n - 2];
25 }
```

Fill in the blanks in the code to show that there are no out of bounds array accesses.

Are the invariants strong enough to prove the postcondition?

Solution:

Array access

The conditions above are necessary and sufficient to show that there are no out of bounds array accesses. Before we reference `F[0]` or `F[1]`, we check with conditional statements (lines 7 and 13) to make sure the accesses are in bounds.

Then, in the loop, our loop invariant guarantees that `2 <= i`. Thus, when we access `F[i - 2]`, we can be sure that `i - 2 >= 0`, so we won't be attempting to access a negative array element. Further, we know that `i < n` by the loop exit condition and `n == \length (F)`, so accessing `F[i]` can't cause any problems. (Neither can accessing `F[i - 1]`—`i - 1` is between `i - 2` and `i`.)

Then, when we access `F[n - 1]` and `F[n - 2]` on line 25, we know that `n == \length (F)`, and that `n > 1`. Since `n > 1`, `n > n - 2 >= 0`, so accessing `n - 2` is fine. Accessing `F[n - 1]` is okay since `n == \length (F)` and `n - 1` must also be positive.

Showing that the postcondition holds.

For the first loop invariant: We know `i >= 2` initially since it was initialized to 2. We know `i <= n` since if `n` were less than 2, we would already have returned.

`i' == i + 1`. Since `2 <= i`, `2 <= i'` as well (assuming no overflow). Further, by the loop guard, `i < n`. Thus, `i' <= n`.

For the second loop invariant:

If we assume that `slow_fib` follows the mathematical definition of Fibonacci correctly, we can show that the loop invariant holds at the start of the loop: `slow_fib(1) == 1 == F[1]` by line 14 and `slow_fib(0) == 0 == F[0]` by line 8.

Then, we can show that it is preserved. `F[i] == F[i - 1] + F[i - 2]`. By the loop invariant, `F[i - 1] == slow_fib(i - 1)` and `F[i - 2] == slow_fib(i - 2)`, so `F[i] == slow_fib(i)`. Also, `i' = i + 1` (so `i' - 1 == i`). Thus, `slow_fib(i' - 1) == F[i' - 1]`

Further, by the loop invariant, `slow_fib(i - 1) == F[i - 1]`, so `slow_fib(i' - 2) == F[i' - 2]`.

Finally, at the end of the loop, we know `i == n` by the loop invariant and the negated loop exit condition. So, we know that `F[n - 1] + F[n - 2] == slow_fib(n)`. Then we return that quantity, so we know that our postcondition is correct.

Termination

The loop terminates since `i` starts out as a number less than `n` and is incremented by 1 each iteration until it reaches `n`, which must happen since `n` and `i` are finite.