Collaboration: In lab, we encourage collaboration and discussion as you work through the problems. These activities, like recitation, are meant to get you to review what we’ve learned, look at problems from a different perspective and allow you to ask questions about topics you don’t understand. We encourage discussing problems with other students in this lab!

Setup:
Download the lab handout and code from the course website [https://web2.qatar.cmu.edu/~mhhammou/15122-s23/schedule.html](https://web2.qatar.cmu.edu/~mhhammou/15122-s23/schedule.html) and move it to your private directory in your unix.qatar.cmu.edu machine. Following that create a directory, move the handout to it, and unzip the handout file by executing the following commands:

```
% mkdir lab_05
% mv 05-handout.tgz lab_05
% cd lab_05
% tar -xvf 05-handout.tgz
```

Lagged Fibonacci

The regular Fibonacci numbers are given by the function $F(i)$ where $F(i) = i$ for $i \in [0, 2)$ and where $F(i) = F(i-1) + F(i-2)$ for $i \geq 2$. More explicitly:

$$
\begin{align*}
F(0) &= 0 \\
F(1) &= 1 \\
F(i) &= F(i-1) + F(i-2) \quad \text{for} \quad i \geq 2
\end{align*}
$$

The lagged Fibonacci numbers make use of two additional parameters $j$ and $k$, where $0 < j < k$. They are defined by the function $LF(i)$ where $LF(i) = i$ for $i \in [0, k)$ and where $LF(i) = LF(i-j) + LF(i-k)$ otherwise. Here is a C0 function that implements this definition (note that $j$ and $k$ do not change during the computation):

```c
int LF(int i, int j, int k)
{
    //@requires 0 < j && j < k;
    //@requires i >= 0;
    {
        if (i < k) return i;

        int res = 0;
        res += LF(i-j, j, k);
        res += LF(i-k, j, k);
        return res;
    }
}
```

(1.a) The regular Fibonacci numbers can easily be computed on the basis of $LF$. Can you do so?

$$F(i) = LF(\text{_______________________})$$

While $LF$ computes the desired result accurately, it is quite slow for large inputs! This is because it repeats many of the sub-computations over and over again, which is slow, inefficient, and redundant. Can you see why?
**Memoization**

To avoid these redundant computations, we introduce a data structure known as a *memo table* — in our case it will be an array of integers. The idea is that, the first time we compute the lagged Fibonacci number for \(i\), we store it at index \(i\) in the memo table. Next time we need the \(i\)-th lagged Fibonacci number, we simply look it up in the table.

Saving the result of computations that we would do over and over is called *memoization*. This requires a bit of extra space in the form of the memo table, but it can save an enormous amount of time because it avoids recomputing these results over and over. This is known as a *space-time trade-off*, a really important concept in computer science.

(2.a) Using the slow \(LF\) function, write a specification function \(\text{is\_memo\_table}\) that checks that, for all \(i \in [0, \text{len}]\) (note the inclusive upper bound!), \(M[i]\) is either 0 or \(LF(i, j, k)\).

```c
bool is_memo_table(int[] M, int len, int j, int k)
//@ requires 0 <= len && len < \length(M);
```

(2.b) Write a new recursive function \(lf\_memo\), which returns the same results as \(LF\) but uses a memo table to avoid re-computing results by writing them into an array of integers.

Before the function does any work, it should check whether the result is already in the memo table, and if so just return that value. If you do have to compute the number, store it in the memo table before returning, so that future calls will not have to do the same work again.

**DANGER!** Do not use the function \(LF\) in your \(lf\_memo\) function outside of contracts! This will reintroduce the problem where we perform many redundant computations, which defeats the entire purpose of our memo table! At this point, \(LF\) has become a specification function for us.

```c
int lf_memo(int[] M, int i, int j, int k)
//@ requires 0 < j && j < k;
//@ requires 0 <= i && i < \length(M);
//@ requires is_memo_table(M, i, j, k);
//@ ensures is_memo_table(M, i, j, k);
//@ ensures result == LF(i, j, k);
```

(2.c) Using \(lf\_memo\) as a helper function, write the function \(fast\_lf(i, j, k)\) that initializes a new array and calls the helper to compute the lagged Fibonacci number.

```c
int fast_lf(int i, int j, int k)
//@ requires 0 < j && j < k;
//@ requires 0 <= i;
//@ ensures \result == LF(i, j, k);
```

(2.d) Check that your \(fast\_lf\) function works by running it in coin with \(-d\) for some small Fibonacci numbers. Then run it in coin without \(-d\) so that you actually notice a speedup. Running with \(-d\) is slow as \(LF\) is called in the postcondition.

(2.e) What is the 54,321\textsuperscript{st} Fibonacci number (mod 2\textsuperscript{32}, of course)? What is the 100,000\textsuperscript{th} lagged Fibonacci number with \(j = 1\) and \(k = 25\)?

How do their functions look the same? How do they look different?
(2.f) What is the worst-case asymptotic complexity of the call LF(n, 1, 2)? A way to approach this problem is to estimate the number of recursive calls during this computation: try drawing a diagram that visualizes this!

(2.g) What is the worst-case asymptotic complexity of the call fast_LF(n, 1, 2)? A way to approach this problem is to count how many times this call will write to the memo table. Can you see why?

Timing code

In Unix, there is a way to determine the actual running time of a program. You use the time command followed by the program name (and its arguments) that you want to time. For example, to time an executable a.out in your current directory, you would enter:

```
% time ./a.out
Testing with n = 1000... Done. 0
real 0m1.027s
user 0m0.952s
sys 0m0.074s
```

The second number (user time) is the best one to track for this activity. It is closer to what we want than the system time (the amount of time the program handed control over to the operating system) or the “real” time, which is the sum of the two.

(3.a) In the lab directory, run the following commands:

```
% cc0 -o LFtest lf.c0 LFtest.c0
% cc0 -o memotest lf.c0 memotest.c0
```

This will create the executables LFtest and memotest that take an argument n, and print the result of lagged fibonacci performed on the arguments (n, 1, 2) — these are actually just the regular Fibonacci numbers! You can use these to time both the specification function and your new function. For example, to time the LF specification function using input 10, you would enter:

```
% time ./LFtest 10
```

Timing LFtest and memotest with increasing values of n will allow you to confirm the big-O complexity of the functions LF and fast_LF you found earlier.

This is a common approach: You can first analyze the asymptotic complexity of a program by looking at its code. Then you can confirm your hypothesis by running the program for varying values of n and plotting your results.