Tutorial 4: Recursion

Data Structures and Algorithms

February 20, 2023

1. Write True/False for the following conditional independence statements. Justify clearly your answer by showing active/blocked trails as necessary and appropriate rules for them to be active/blocked. [No coding required for this question. Each sub-question has **2 points**]

   (a) $A \perp G \mid \{F\}$
   False. $A \not\perp G$. There is a V-structure between A and G.

   $$A \rightarrow B \rightarrow D \leftarrow G$$

   Given F and thus implying we know D, A and G are dependent.

   (b) $A \perp G \mid \{E\}$
   True. There is no active path from A to G.

   (c) $A \perp E \mid \{C\}$

   (d) $A \perp E \mid \{C, D\}$

   (e) $A \perp D \mid \{B, E\}$

2. The following algorithm determines whether an element is within a sorted array.

```java
// parameterized version
public static boolean binarySearch(int[] data, int target, int low, int high) {
   if (low > high)
      return false; // interval empty; no match
   else {
      int mid = (low + high) / 2;
      if (target == data[mid])
         return true; // found a match
      else if (target < data[mid])
         return binarySearch(data, target, low, mid - 1); // recur left
      else
         return binarySearch(data, target, mid + 1, high); // recur right
      }
   }


// Demonstration of a public wrapper function with cleaner signature
public static boolean binarySearch(int[] data, int target) {
   return binarySearch(data, target, 0, data.length - 1);
}
```

Suppose that you are given the following array as input:
`data = [2, 5, 7, 8, 10, 19, 20, 23, 25, 30, 35, 36];`

(a) Draw the recursion trace for `binarySearch(data, 33)`.

(b) What is the Big O complexity of binary search above? Justify it.

(c) How would you make it even more efficient?

(d) Describe a modification that will return the index of the target element or -1 if not found.

(b) Binary search is $O(logn)$. After every recursive call, the problem halves in size. For an array of size n, we call `binarySearch()` on array of size $n, \frac{n}{2}, \frac{n}{4}\ldots$ because the high or low halves after each recursive call. The body of `binarySearch()` only contains primitive operations, hence we can conclude that the growth rate of `binarySearch()` is $O(logn)$.

(c) Don't know...

(d) Change the return type of binarySearch to int. When found a match, return the index of the target, when no match return -1.

```java
public static int binarySearch(int[] data, int target, int low, int high) {
   if (low > high)
      return -1; // interval empty; no match
   else {
      int mid = (low + high) / 2;
      if (target == data[mid])
         return mid; // found a match; return index of target element
```

```java
        else if (target < data[mid])
            return binarySearch(data, target, low, mid - 1);
        else
            return binarySearch(data, target, mid + 1, high);
        }
    }
```

3. Suppose that you wish to solve puzzles of the following form:

$$\begin{aligned} fish &= bird + cat \\ fish + cat &= 4birds \\ fish + bird + cat &= 10 \end{aligned}$$

The task is to assign a unique integer between 0 to 9 to each variable fish, cat, or bird so that the above equations hold true.
You chance upon a recursive algorithm below described in pseudocode.

(a) Specify the arguments k, S, U to solve the puzzle involving *fish*, *cat*, and *bird* above.

$$\begin{aligned} k &= 3 \\ S &= [\,] \\ U &= \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9\} \end{aligned}$$

(b) How would you test whether S is a configuration that solves the puzzle?
Let S be an array with values

$$S = [x, y, z]$$

We can then check if S satisfies the 3 equations, by mapping the values of S to *fish*, *bird* and *cat*. Let

$$x = fish$$
$$y = bird$$
$$z = cat$$

If the equations

$$\begin{aligned} x &= y + z \\ x + z &= 4y \\ x + y + z &= 10 \end{aligned}$$

hold true, then S is a valid solution.

(c) What are the values of *fish*, *bird* and *cat* in this case?

$$\begin{aligned} fish &= 5 \\ bird &= 2 \\ cat &= 3 \end{aligned}$$

$$\begin{aligned} 5 &\equiv 2 + 3 \\ 5 + 3 &\equiv 4 \times 2 \\ 5 + 3 + 2 &\equiv 10 \end{aligned}$$

(d) What is the Big O complexity of `PuzzleSolve`?
For set U with a size of n, we have a total of $n!$ permutations. From the code, each iteration through U recursively calls the function. So the function will call itself n times on the first recursion, and $n(n-1)$ total times on the second and so forth.
The total number of function calls is $n!$ which is the total number of permutations of elements in set U. Since `PuzzleSolve` only contains primitive operations, we can conclude that the function is $O(n!)$

4. You are given the following recursive method:

```java
public static long negativeFibonacci(int n){
    if (n <= 1)
        return n;
    else
        return 0 - negativeFibonacci(n-2) - negativeFibonacci(n-1);
}
```

(a) What is the output of `negativeFibonacci(567)`? Let negative fibonacci function be $f(n)$.

$$f(n) = 0 - f(n-2) - f(n-1)$$

Using $n = 3$,

$$\begin{aligned} f(3) &= 0 - f(3-2) - f(3-1) \\ &= 0 - f(1) - f(2) \\ &= 0 - f(1) - (0 - f(2-2) - f(2-1)) \\ &= 0 - f(1) - (0 - f(0) - f(1)) \\ &= -f(1) + f(0) + f(1) \qquad (1) \\ &= f(0) \\ &= 0 \end{aligned}$$

We can see that the function $f(1)$ cancels itself out in (1). By repeated use of definition of the negative Fibonacci sequence, for each integer $n \geq 1$

$$\begin{aligned} f(n) &= 0 - f(n-2) - f(n-1) \\ &= 0 - f(n-2) - (0 - f(n-1-2) - f(n-1-1)) \\ &= 0 - f(n-2) - (0 - f(n-3) - f(n-2)) \\ &= 0 - f(n-2) + f(n-3) - f(n-2) \\ &= f(n-3) \end{aligned}$$

It can be seen that for each integer $n \geq 1$, $f(n) = f(n-3)$. This cascades till the base case $n \leq 1$, then $f(n) = n$. We have three possible base cases, where $n \equiv n \bmod 3$.

$$\begin{aligned} f(n) &= f(n-3) \\ &= f(n \bmod 3) \end{aligned}$$

$$f(n) = \begin{cases} 0 & \text{if } n \bmod 3 = 0, \\ 1 & \text{if } n \bmod 3 = 1, \\ -1 & \text{if } n \bmod 3 = 2, \end{cases}$$

Given $n = 567$,

$$\begin{aligned} f(n) &= f(567) \\ &= f(567 \bmod 3) \\ &= f(0) \\ &= 0 \end{aligned}$$

(b) What is the worst case complexity of `negativeFibonacci(567)`? Explain your answer.
The worst case complexity is $O(2^n)$. Although we have mathematically proven that $f(n)$ decomposes to $f(n-3)$, the function doesn't make use of that equivalence. Instead, it unconditionally calls itself twice per recursion. This is the same as the `fibonacciBad` in the lecture slides.
Proof by induction:

Let $g(n)$ be the number of additions.
Let $P(n) : g(n) < c(2^n) \qquad \text{where } c > 0$

Base case:

$$\begin{aligned} g(0) &= 0 < 2^0 = 1 \\ g(1) &= 0 < 2^1 = 2 \\ g(2) = 0 - g(0) - g(1) &= 0 < 2^2 = 4 \end{aligned}$$

Base case is true.
Inductive step: Assume $P(n)$ is true for $n-3$, $n-2$, $n-1$, for all $n \geq 3$,

$$g(n) = 0 - g(n-2) - g(n-1) \tag{1}$$
$$g(n-1) = 0 - g(n-3) - g(n-2) \tag{2}$$

From (1) and (2)

$$g(n-1) = g(n) + g(n-1) - g(n-3)$$
$$g(n) = g(n-3) \tag{3}$$

From assumption $P(n-3)$ and (3),

$$g(n-3) \leq 2^{n-3}$$

$$\begin{aligned} g(n) &= g(n-3) \\ &\leq 2^{n-3} \\ &= 2^n \cdot 2^{-3} \\ &= \frac{1}{8} \cdot 2^n \\ &\leq 2^n \end{aligned}$$

$$P(n-3) \longrightarrow P(n)$$

$$
\begin{aligned}
P(3-3) &\longrightarrow P(0) \\
P(4-3) &\longrightarrow P(1) \\
P(5-3) &\longrightarrow P(2)
\end{aligned}
$$

Hence $P(n)$ true for all $n \geq 0$.
The function `negativeFibonacci` is $O(2^n)$ where $c = 1$ and $n_0 = 1$.

5. For each of the following algorithm `sum1` to `sum4` below:

   (a) What is the output when $n = 10$ and $k = 5$?

   (b) Describe in terms of n and k what the output value will approach as the inputs grow.

   (c) What is the worst complexity?

```
//sum1
```

```
public static double sum1(int n){
    if (n == 0)
        return n;
    else
        return (double)n + sum1(n-1);
}
```

In `sum1`, $f_1(n)$ can be defined recursively as such

$$f_1(n) = \begin{cases} 0 & \text{if } n = 0, \\ n + f_1(n-1) & \text{if } n > 0, \end{cases}$$

`sum1` simply adds all numbers from n till 0.

$$\begin{aligned} f_1(n) &= n + (n-1) + (n-2) + \ldots + 1 + 0 \\ &= \frac{n(n+1)}{2} \end{aligned}$$

When $n = 10$,

$$\begin{aligned} f_1(n) &= f_1(10) \\ &= 10 + 9 + \ldots + 1 + 0 \\ &= \frac{10(10+1)}{2} \\ &= 55 \end{aligned}$$

Output value approaches $\frac{n(n+1)}{2}$ as n grows.
Worst case complexity is $O(n)$.

```java
//sum2
public static double sum2(int n){
    if (n == 0)
        return n;
    else
        return (double)n + sum2(n/2);
}
```

In sum2, $f_2(n)$ can be defined recursively as such

$$f_2(n) = \begin{cases} 0 & \text{if } \ n = 0, \\ n + f_2\left(\left\lfloor \frac{n}{2} \right\rfloor\right) & \text{if } \ n > 0, \end{cases}$$

When $n = 10$,

$$\begin{aligned} f_2(10) &= 10 + f_2\left(\frac{10}{2}\right) \\ &= 10 + f_2(5) \\ &= 10 + 5 + f_2(2) \\ &= 10 + 5 + 2 + 1 + 0 \\ &= 18 \end{aligned}$$

The function adds half of its input value for every recursive call, until the input becomes 0. Let a be the largest integer such that $\frac{n}{2^a} \geq 1$. Then $a + 1$ is the number of iterations of sum2, while ignoring the floor function.

$$\begin{aligned} f_2(n) &\approx n + \frac{n}{2} + \frac{n}{4} + \ldots + \frac{n}{2^a} \\ &\approx n + (n - 1) \\ &= 2n - 1 \\ \frac{n}{2^a} &\geq 1 \\ n &\geq 2^a \\ \log n &\geq a \log 2 \\ a &\leq \log n \end{aligned}$$

The worst case complexity is $O(\log n)$. The input value n halves on every recursion.

```java
//sum3
public static double sum3(int n, int k){
    if (k == 0)
        return n;
    else
        return (double)n + sum3(n, k-1);
}
```

In sum3, $f_3(n,k)$ can be defined recursively as such

$$f_3(n,k) = \begin{cases} n & \text{if } \ k = 0, \\ n + f_3(n,\ k-1) & \text{if } \ k > 0, \end{cases}$$

We can see that the number of additions is $k+1$.

$$\text{Adds } k+1 \text{ times}$$

$$\begin{aligned} f_3(n,k) &= n + n + \ldots + n \\ &= (k+1)n \\ &= nk + n \end{aligned}$$

When $n = 10$ and $k = 5$,

$$\begin{aligned} f_3(10,5) &= 10(5) + 10 \\ &= 60 \end{aligned}$$

The worst case complexity is $O(k)$.

//sum4

```java
public static double sum4(int n, int k){
    if (k == 0)
        return n;
    else
        return (double)n + sum4(n, k/2);
}
```

In sum3, $f_4(n,k)$ can be defined recursively as such

$$f_4(n,k) = \begin{cases} n & \text{if } k = 0, \\ n + f_4\left(n, \left\lfloor \frac{k}{2} \right\rfloor\right) & \text{if } k > 0, \end{cases}$$

Function sum4 adds n for some a number of times. Then
when k=6

$$\begin{aligned} &\text{Let } a \text{ be the number of additions in sum4.} \\ f_4(n,6) &= n + f_4\left(n, \left\lfloor \frac{6}{2} \right\rfloor\right) \\ &= n + f_4(n,3) \\ &= n + n + f_4\left(n, \left\lfloor \frac{3}{2} \right\rfloor\right) \\ &= n + n + f_4(n,1) \\ &= n + n + n + f_4\left(n, \left\lfloor \frac{1}{2} \right\rfloor\right) \\ &= n + n + n + f_4(n,0) \\ &= n + n + n + n \\ &= 4n \\ a &= 4 \end{aligned}$$

Then it can be seen that

$$\begin{aligned} a &= 1 + \lfloor \log_2 k \rfloor + 1 \\ &= 2 + \lfloor \log_2 k \rfloor \end{aligned}$$

Where $\lfloor \log_2 k \rfloor$ is the maximum number of times k can be divided by 2 before $k \le 1$. We add 2 for the n in the first recursion and for the n in the base case.
Therefore

$$\begin{aligned} f_4(n,k) &= an \\ &= (2 + \lfloor \log_2 k \rfloor)n \\ &= 2n + \lfloor \log_2 k \rfloor n \end{aligned}$$

When $n = 10$ and $k = 5$,

$$\begin{aligned} f_4(10,5) &= 2(10) + \lfloor \log_2 5 \rfloor (10) \\ &= 20 + \lfloor 2.321928095 \rfloor (10) \\ &= 20 + 20 \\ &= 40 \end{aligned}$$

The worst case complexity is $O(\log n)$, as the input n halves on every recursion.

6. Describe a way to use recursion to compute the sum of all the elements in an $n \times n$ (two dimensional) array of integers. What is the complexity?

```
//Sum 1D array
public static int sumX(int x, int[] arr){
    if(x == 0)
        return arr[0];
    else
        return arr[x] + sumX(x-1, arr);
}

//Sum 2D array
public static int sumAll(int y, int[][] arr, int n){
    if(y == 0)
        return sumX(n-1, arr[0]);
    else
        return sumX(n-1, arr[y]) + sumAll(y-1, arr, n);
}
```

The complexity is $O(n^2)$. The code is analagous to a nested for loop.