YEAH Assignment 3

Recursion!

Some Logistics

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    - Be aware that you should be working together on **all** parts of this assignment. If you don't implement parts of this assignment, you'll be at a significant **disadvantage** on the exams!

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- **Pair programming is allowed on this assignment!**
  - Be aware that you should be working together on **all** parts of this assignment. If you don't implement parts of this assignment, you'll be at a significant **disadvantage** on the exams!
- Small point: if you're on Windows and you're getting build errors right off the bat, you'll need to redownload the starter code!

Let’s begin!

Part 1: The Sierpinski Triangle

- Remember our beautiful Sierpinski Carpet?

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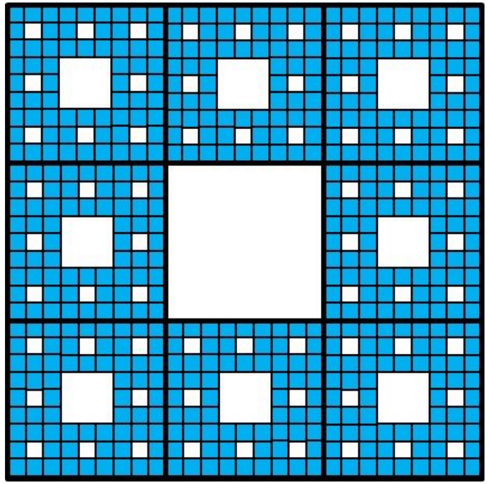

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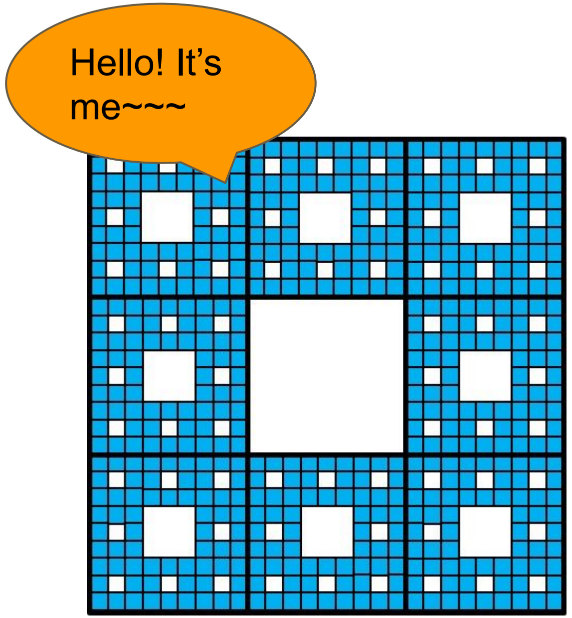

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Waclaw Sierpinski, trusted distributor of CS 106B material

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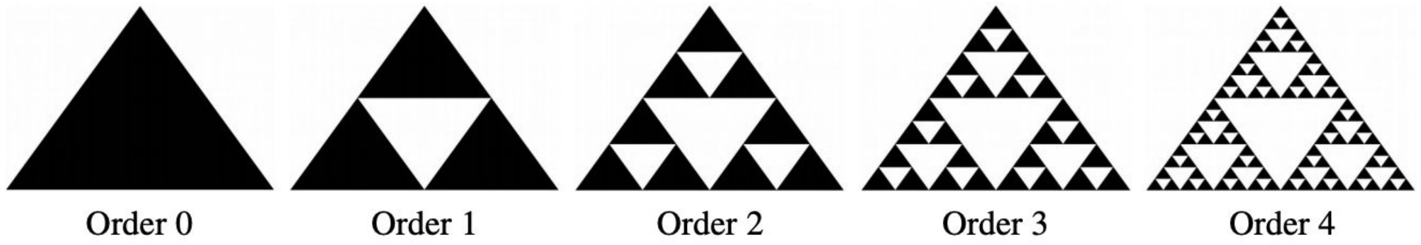
“I dedicate these shapes to Keith Schwarz” - Sierpinski, probably

Waclaw Sierpinski, trusted distributor of CS 106B material

Part 1: The Sierpinski Triangle



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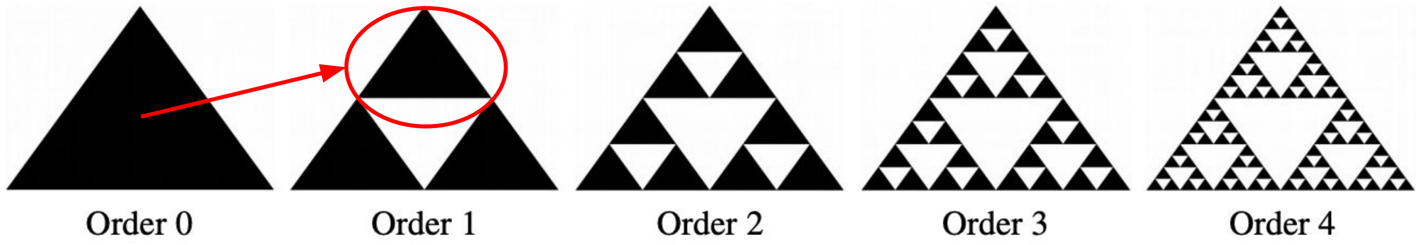

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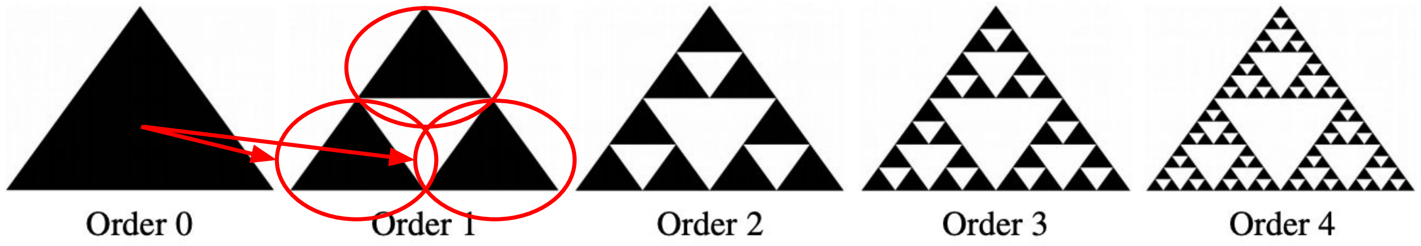

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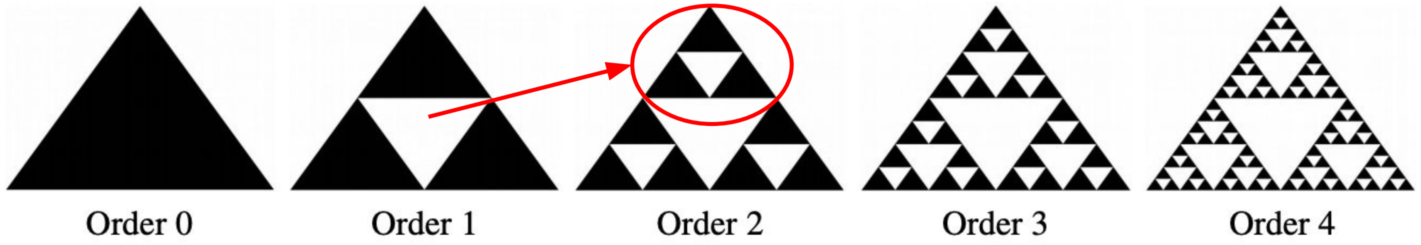
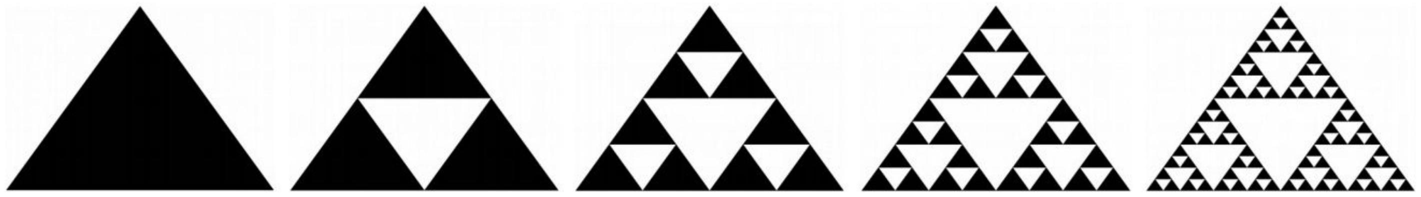


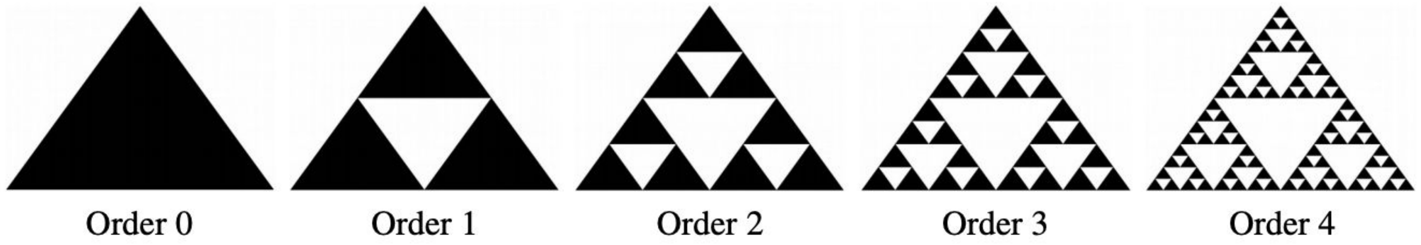
Part 1: The Sierpinski Triangle

- You are writing a program that draws *n-order* Sierpinski Triangles



Part 1: The Sierpinski Triangle

- You are writing a program that draws *n-order* Sierpinski Triangles
- The Sierpinski triangle is defined *recursively*, meaning:
    - An order-0 Sierpinski triangle is a plain filled triangle.
    - An order-*n* Sierpinski triangle, where *n > 0*, consists of three Sierpinski triangles of order *n – 1*, each half as large as the main triangle, arranged so that they meet corner-to-corner.



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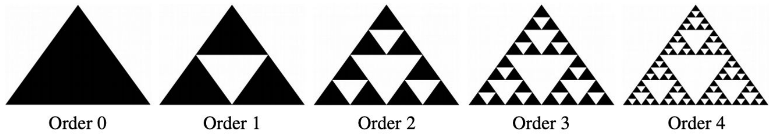

- You are responsible for handling two functions
- The first function draws a black triangle on the canvas given the 3 vertices

```
void drawTriangle(GWindow& window,
                  double x0, double y0,
                  double x1, double y1,
                  double x2, double y2);
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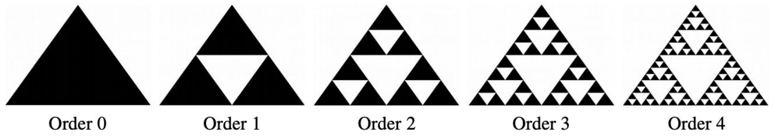

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I'm already implemented for you :)

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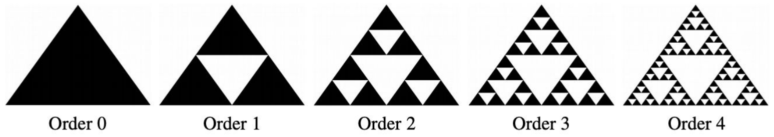

- You are responsible for handling two functions
- The first function draws a black triangle on the canvas given the 3 vertices
- The second function is the recursive function you need to implement

```
void drawSierpinskiTriangle(GWindow& window,
                            double x0, double y0,
                            double x1, double y1,
                            double x2, double y2,
                            int order)
```

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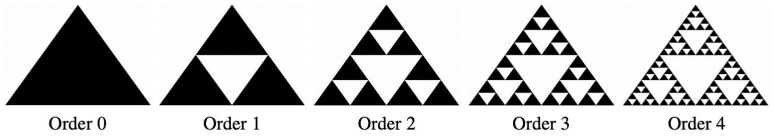

- A few implementation thoughts:
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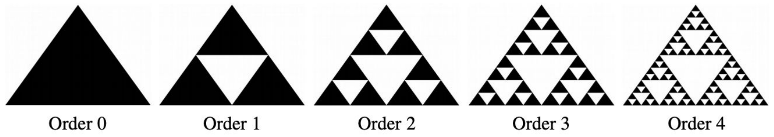

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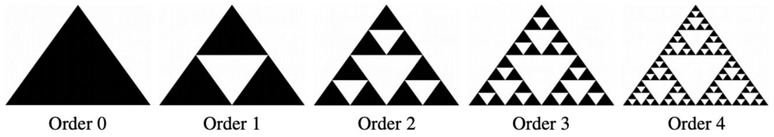

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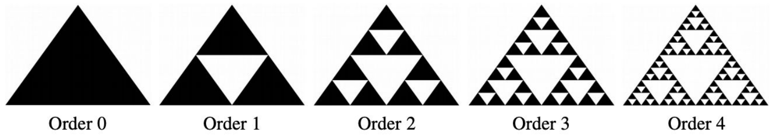

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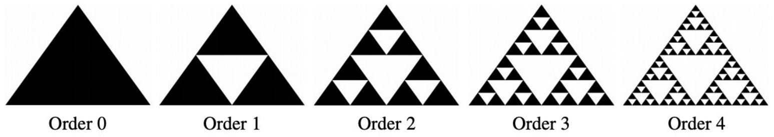

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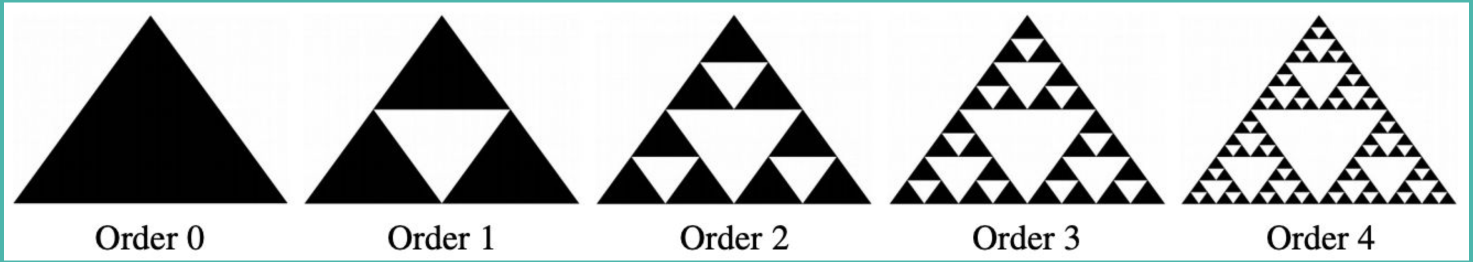
  - Highly recommend drawing this one out and planning exactly where your points are going to be before coding. Even if you understand this problem, it's still easy to make math errors (trust me! - Trip, who gets this wrong every time he tries it)

Questions about Part 1?



Part 2: Human Pyramids

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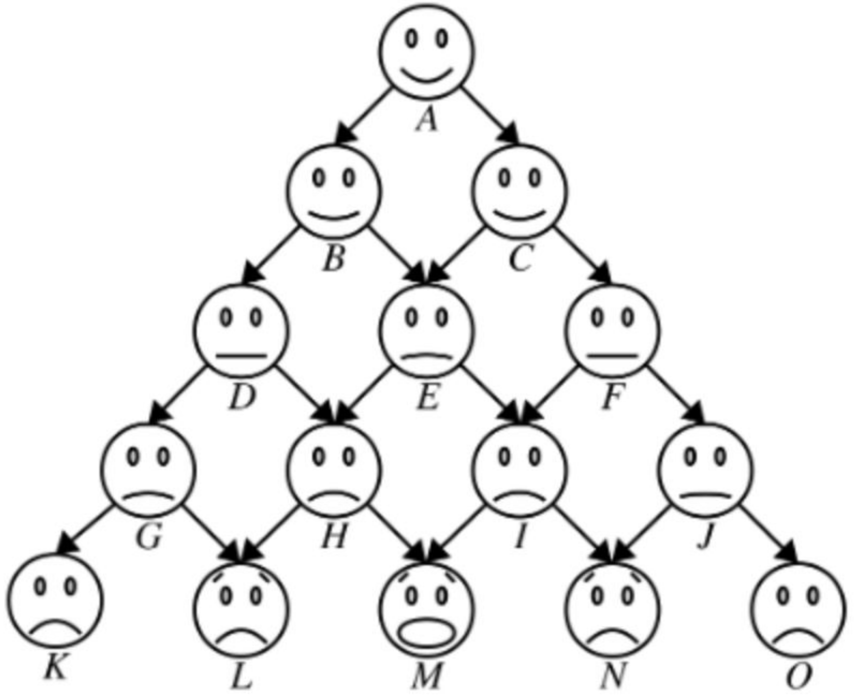
- …
- OUCH!

Part 2: Human Pyramids

- Here’s a human pyramid:



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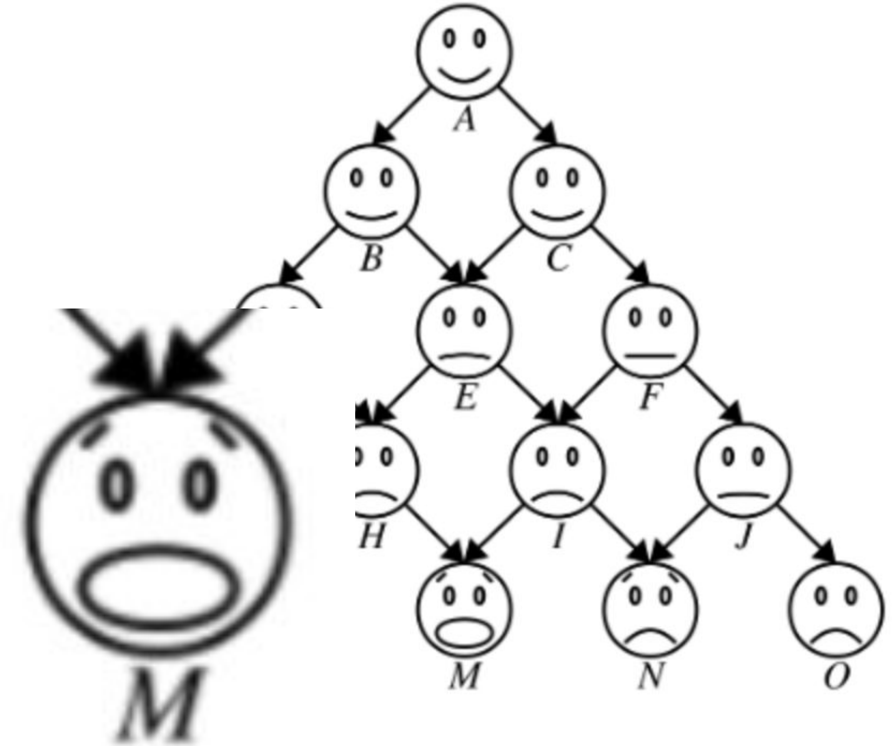

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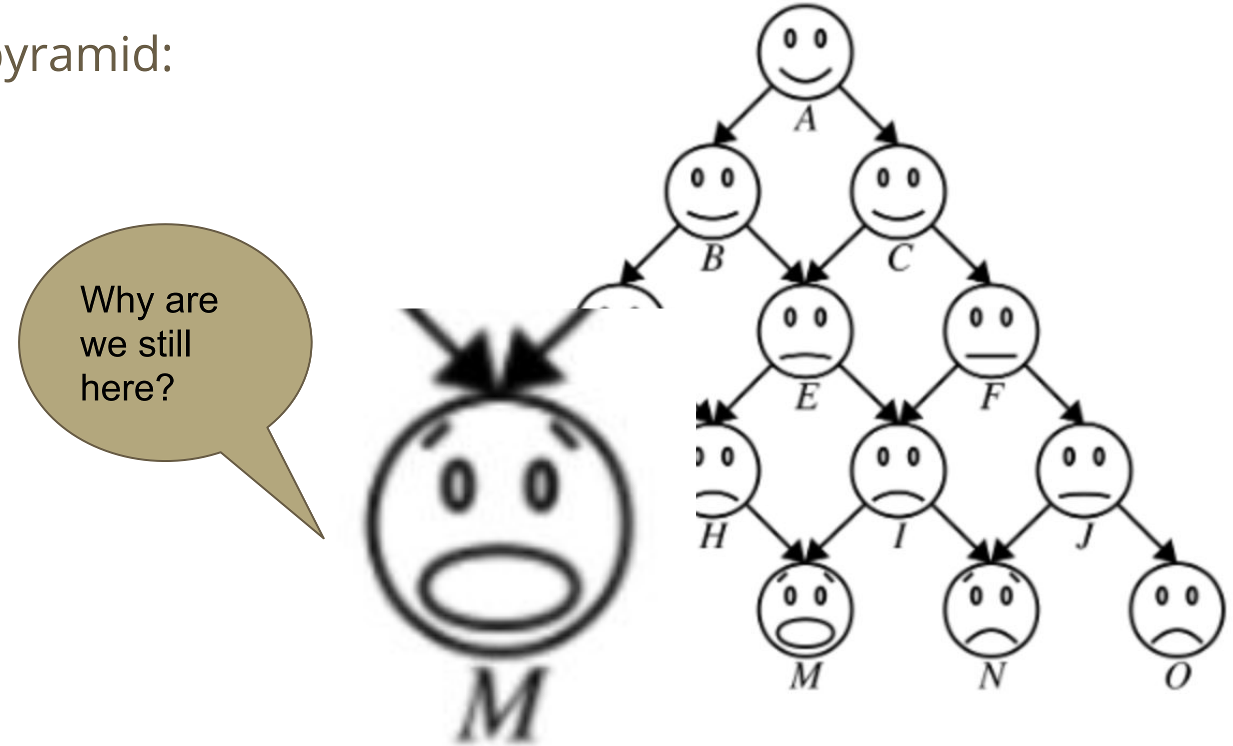

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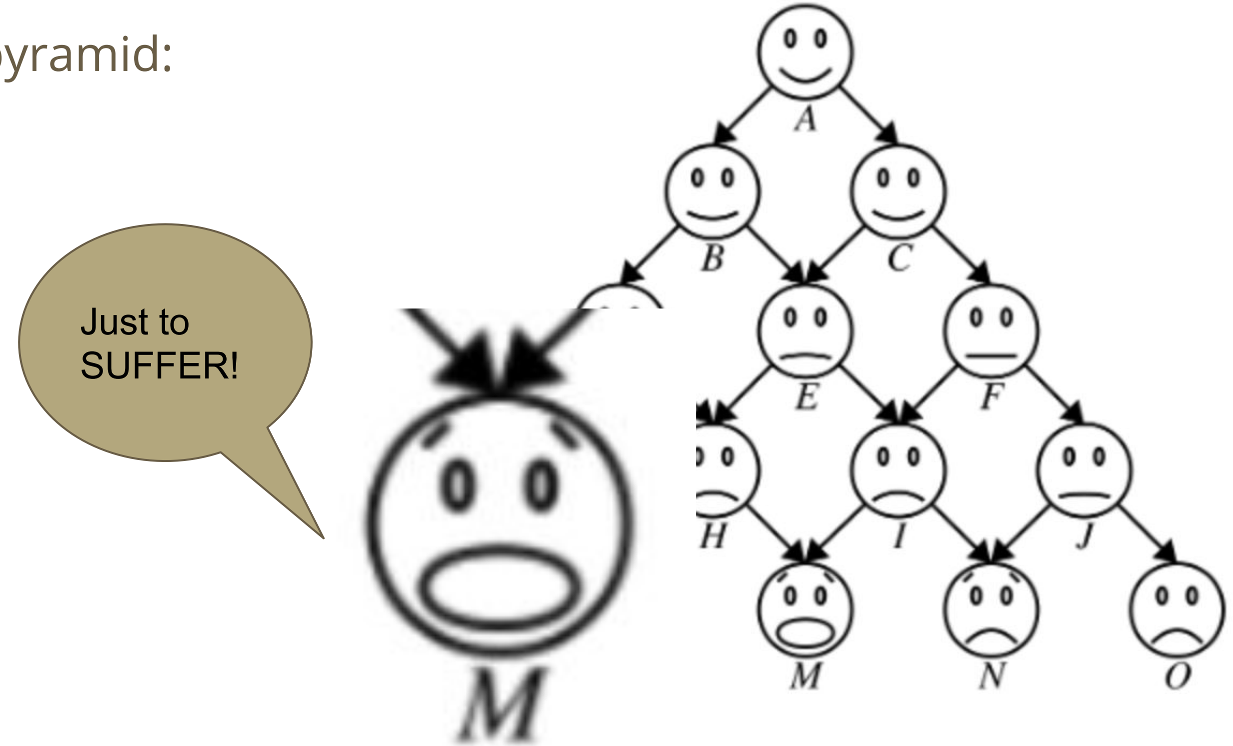
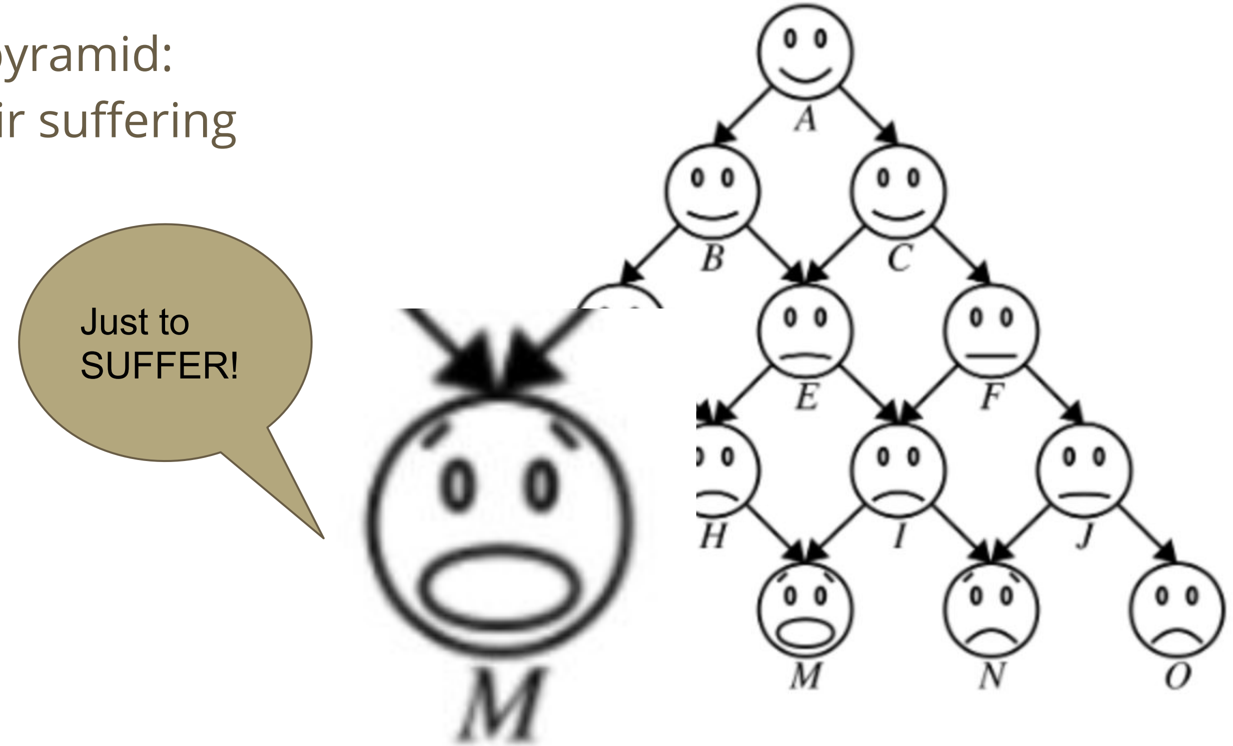


Part 2: Human Pyramids

- Here's a human pyramid:
- Let's quantify their suffering



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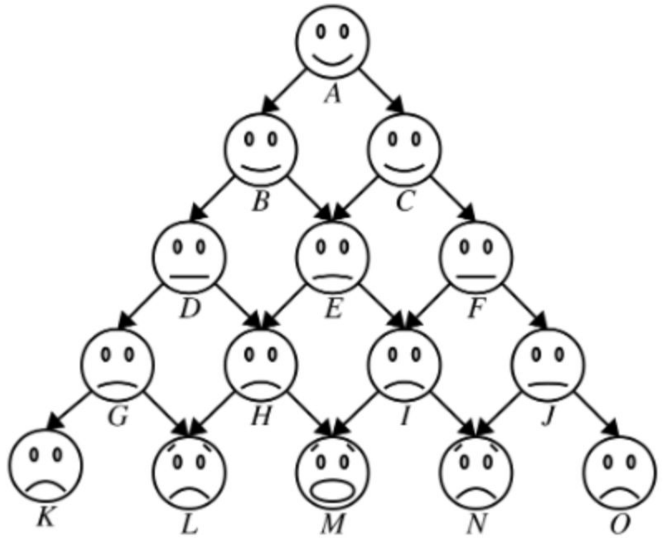
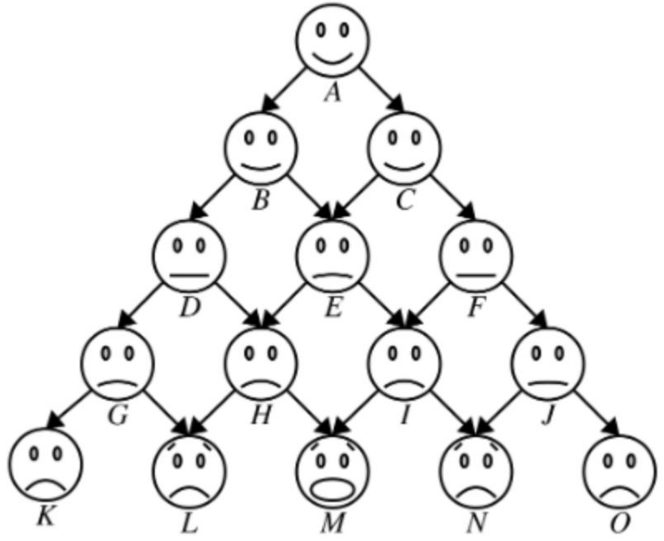
Part 2: Human Pyramids

- Problem set-up
  - Each person supports half the body weight of each of the people immediately above them, plus half of the weight that each of those people are supporting.
  - Each person weighs 160 pounds.



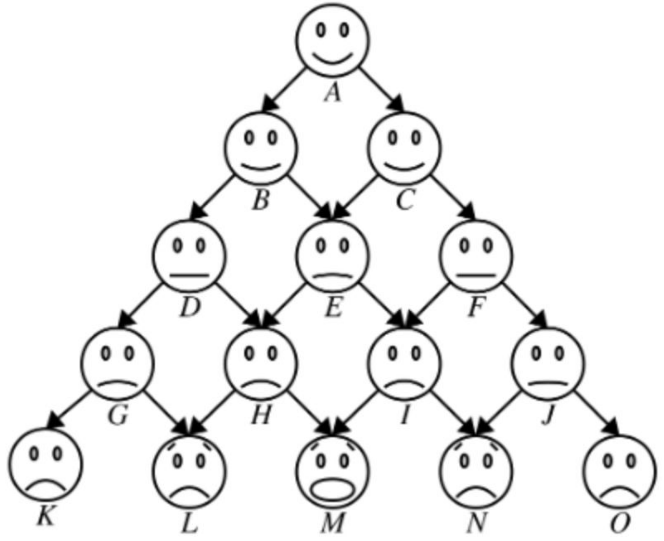
Part 2: Human Pyramids

- Let’s try a few examples!



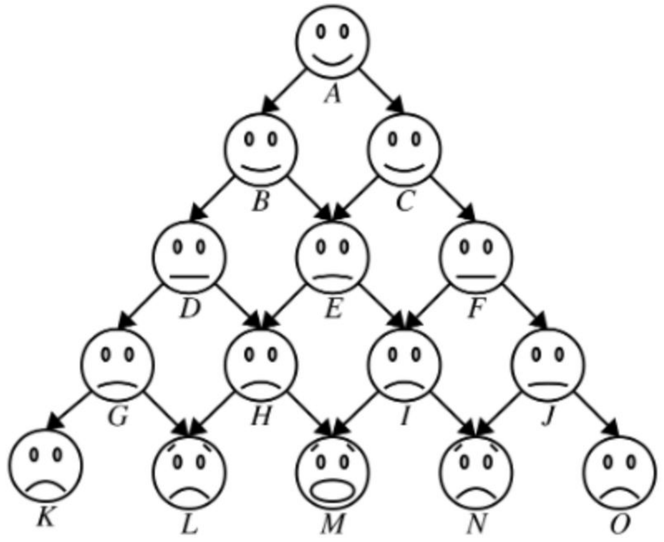
Part 2: Human Pyramids

- How much weight is **A** carrying?



Part 2: Human Pyramids

- How much weight is **A** carrying?
  - **0** lbs; no calculation needed, there are no one above them **A**.



Part 2: Human Pyramids

- How much weight is **A** carrying?
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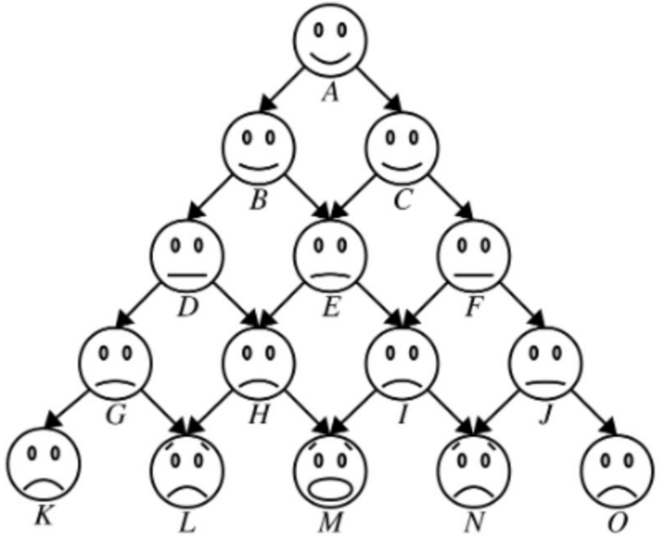
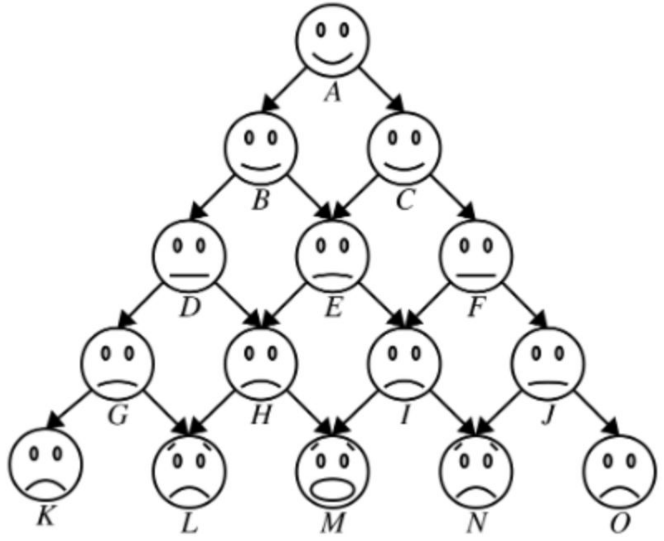
  - This problem almost… *trivial* ;)



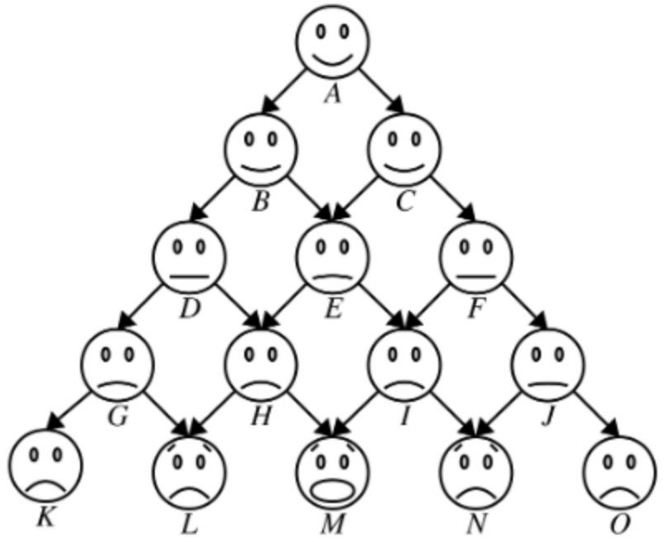
Part 2: Human Pyramids

- How much weight is **D** carrying?



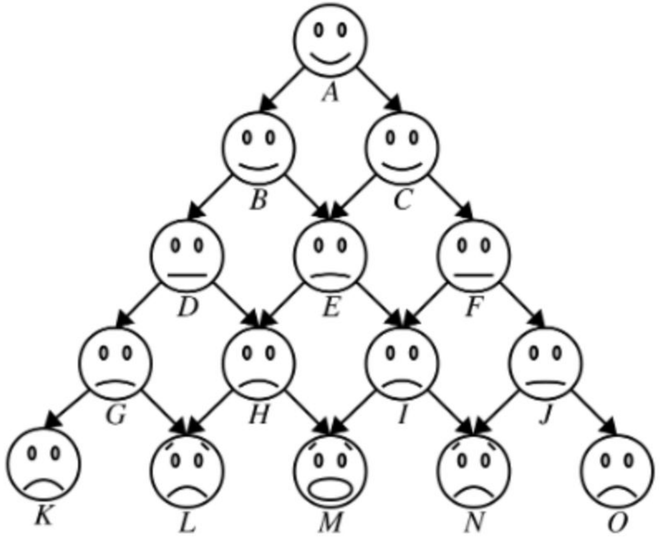
Part 2: Human Pyramids

- How much weight is **D** carrying?
  - **B** is above **D**, so **D** carries half of **B**'s weight.



Part 2: Human Pyramids

- How much weight is **D** carrying?
  - **B** is above **D**, so **D** carries half of **B**'s weight.
    - That is 80 lbs.
  - **D** also carries half of the weight **B** is carrying.



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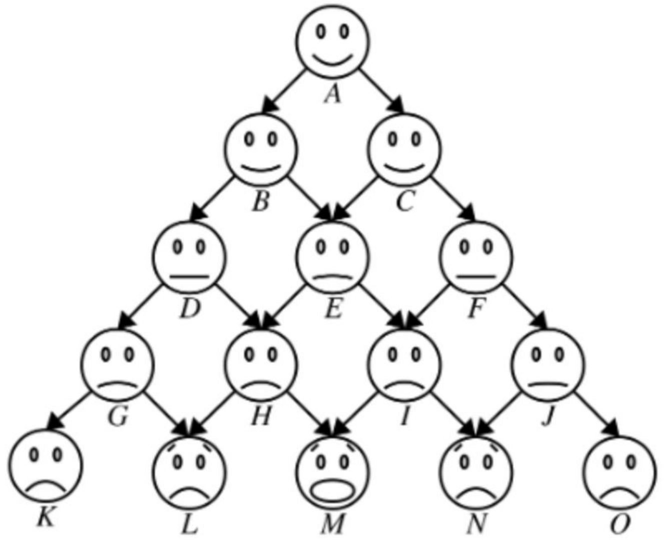

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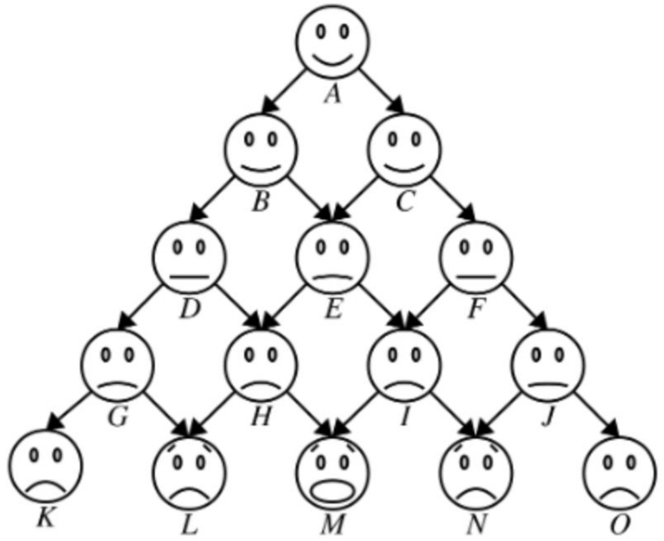

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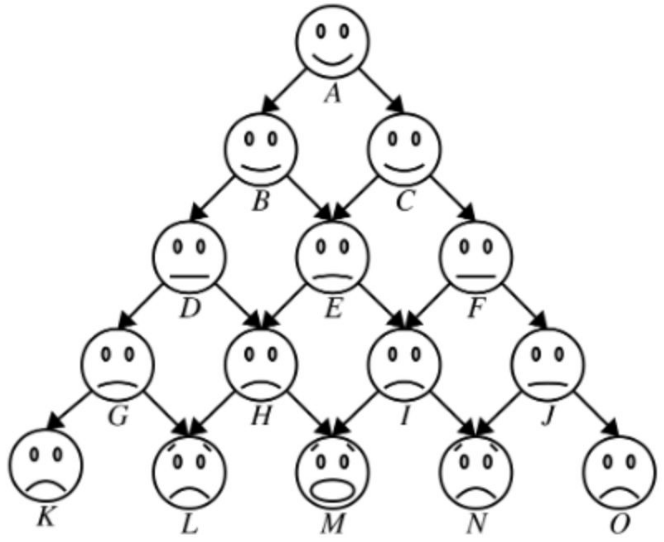
        - How much weight is **B** carrying?
            - **A** is above **B**, so **B** carries half of **A**'s weight.
                - That is 80 lbs. And half of that is 40 lbs.



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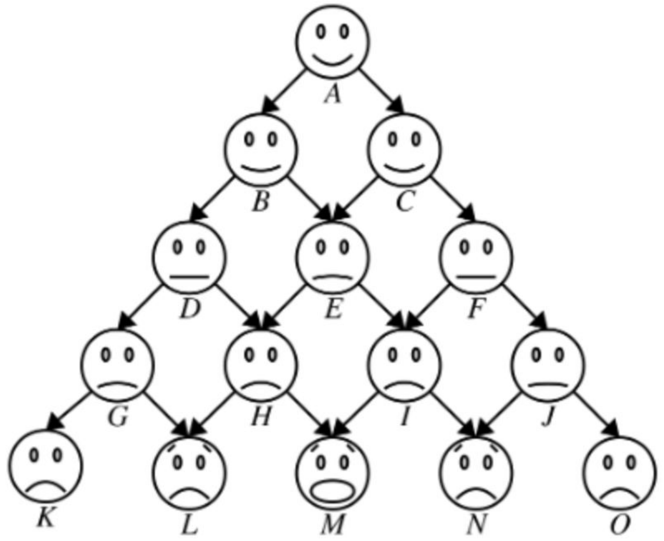
            - **A** is above **B**, so **B** carries half of **A**'s weight.
                - That is 80 lbs. And half of that is 40 lbs.
    - In total, **D** is carrying **120** lbs.



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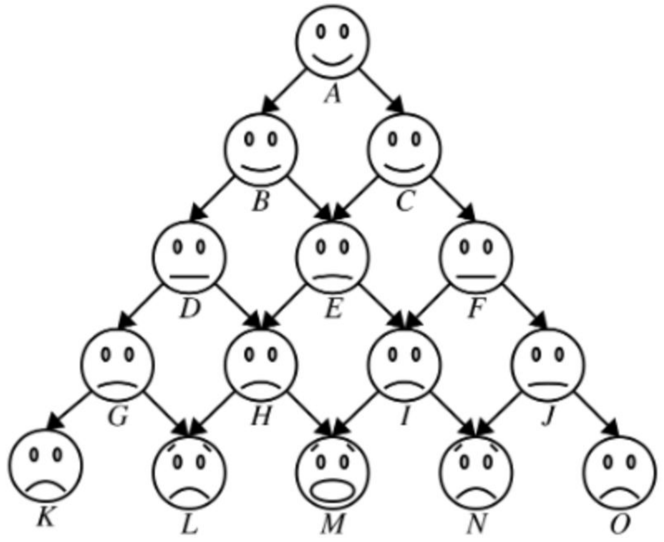

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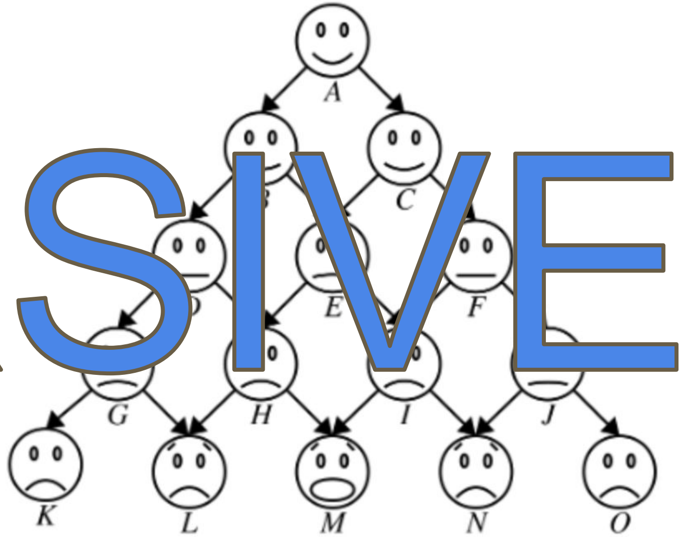
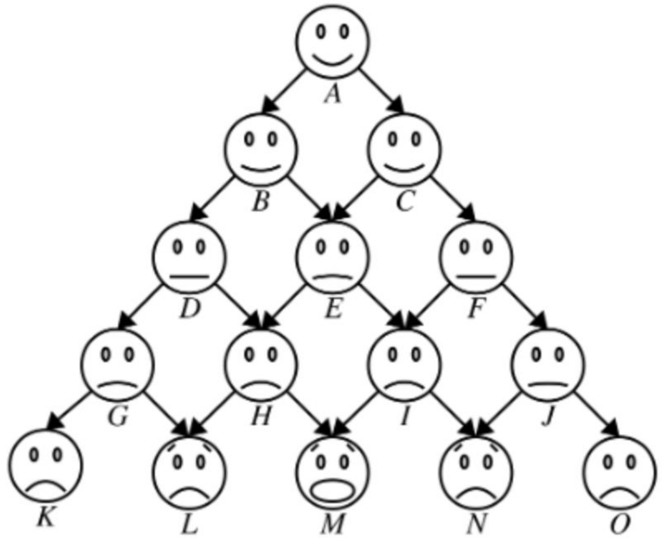
RECURSIVE



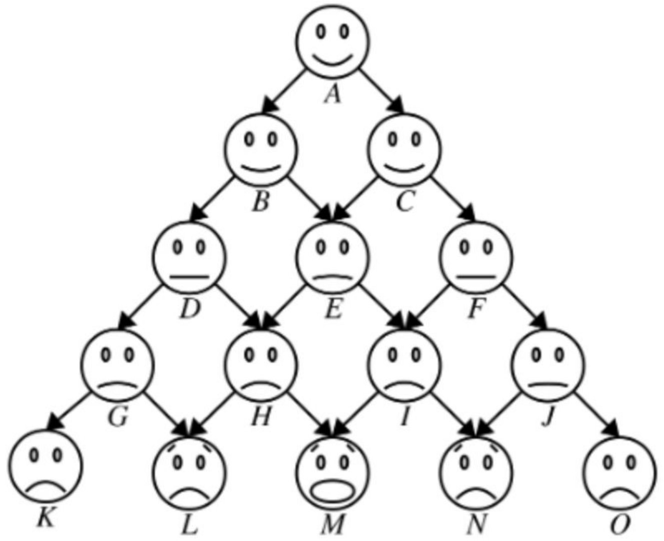
Part 2: Human Pyramids

- How much weight is **E** carrying?



Part 2: Human Pyramids

- How much weight is **E** carrying?
    - To save some work, we know from the previous example that **B** yields 80 lbs (half of **B**'s weight) + 40 lbs (half of the weight **B** is carrying) = 120 lbs.



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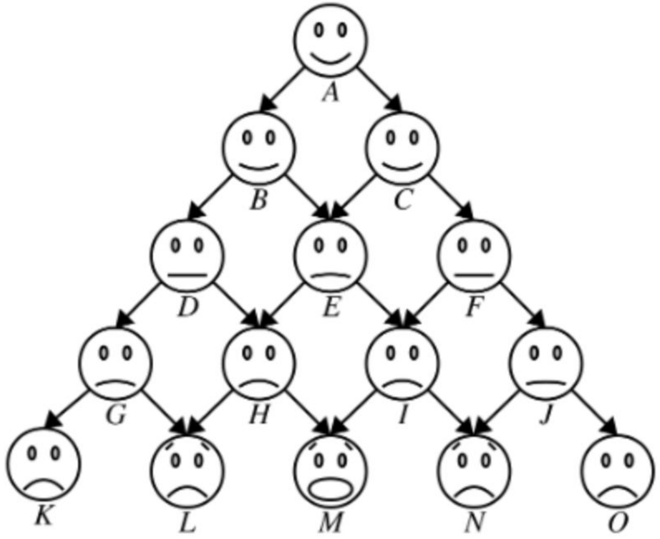

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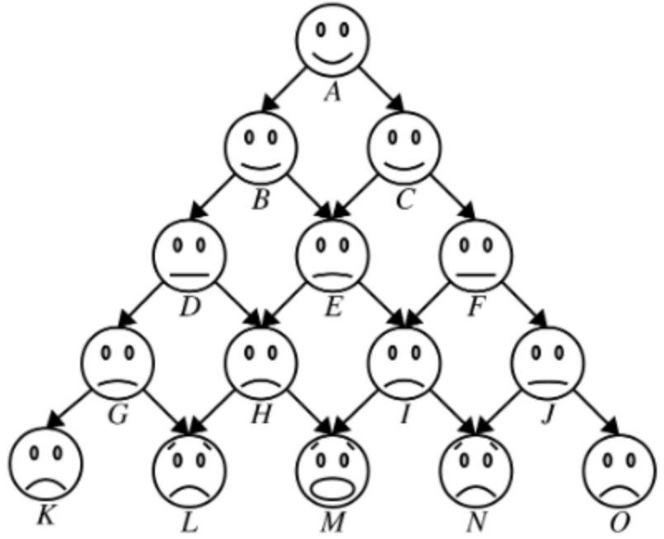

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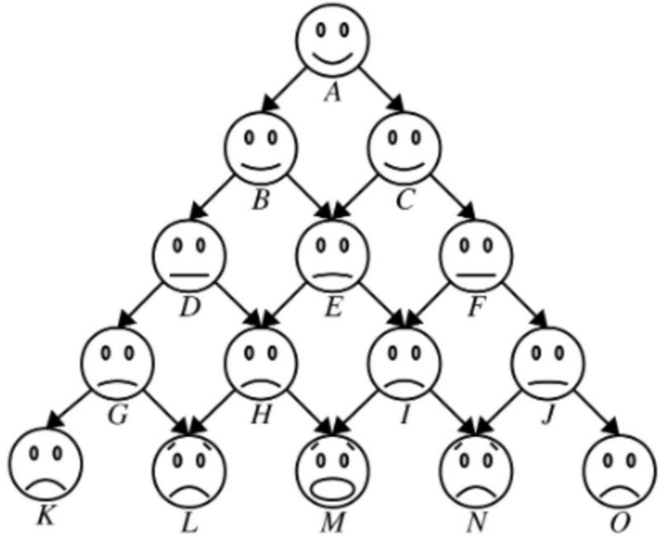

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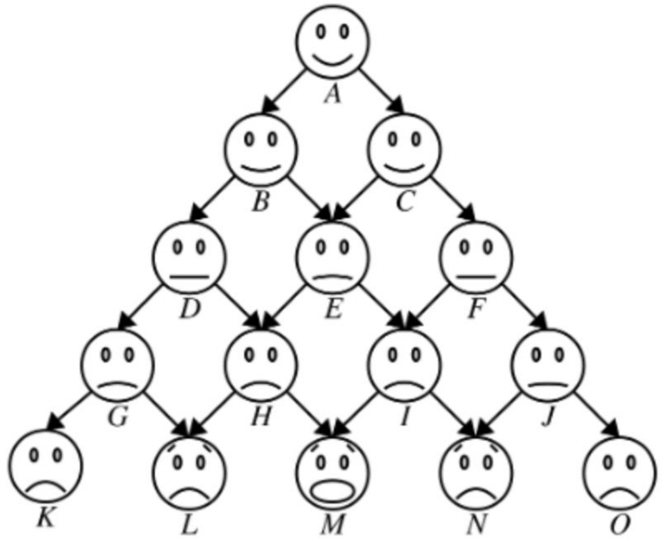

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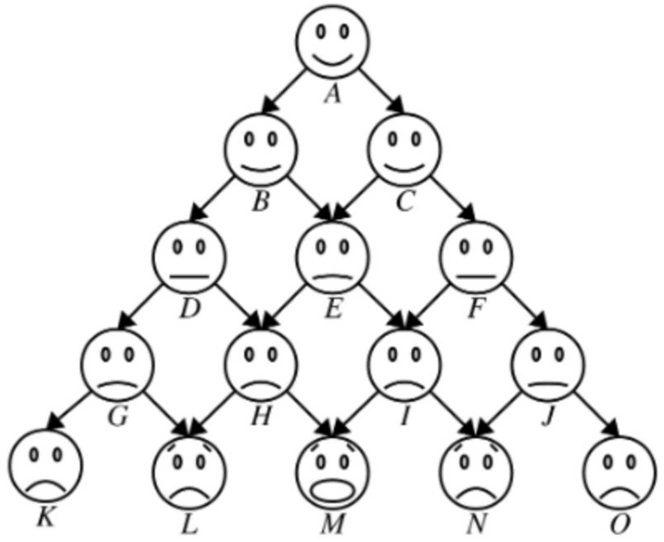
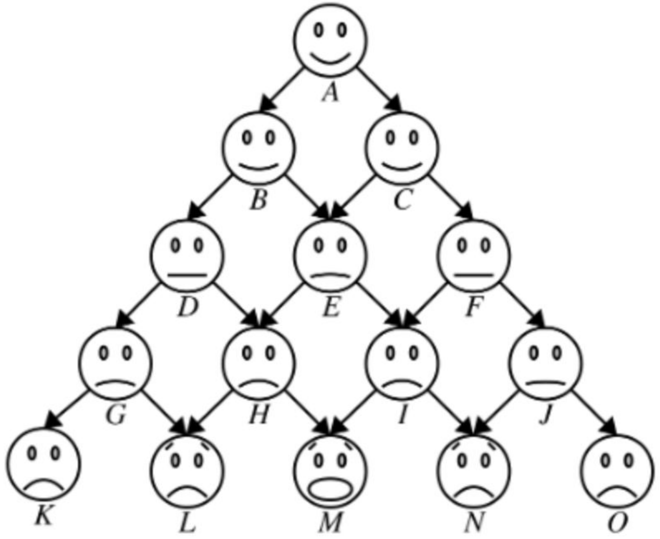
    - How much weight is **C** carrying?
      - **A** is above **C**, so **C** carries half of **A**'s weight.



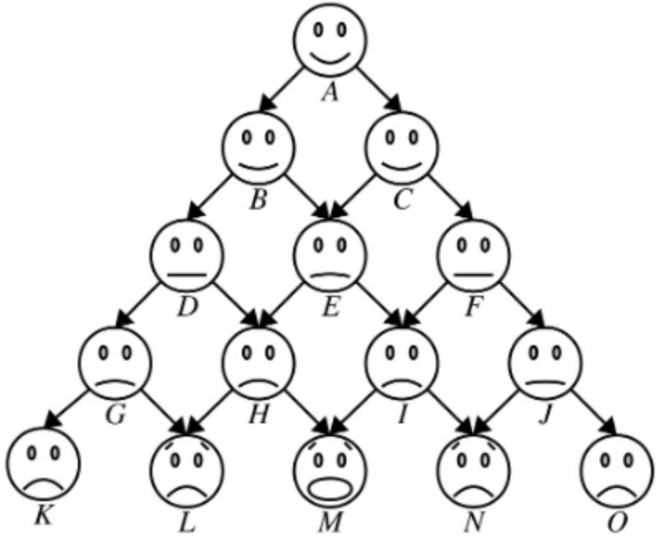
Part 2: Human Pyramids

- How much weight is **E** carrying?
  - To save some work, we know from the previous example that **B** yields 80 lbs (half of **B**'s weight) + 40 lbs (half of the weight **B** is carrying) = 120 lbs.
  - **C** is above **E**, so **E** carries half of **C**'s weight.
    - That is 80 lbs.
  - **E** also carries half of the weight **C** is carrying.
    - How much weight is **C** carrying?
      - **A** is above **C**, so **C** carries half of **A**'s weight.
        - That is 80 lbs. And half of that is 40 lbs.



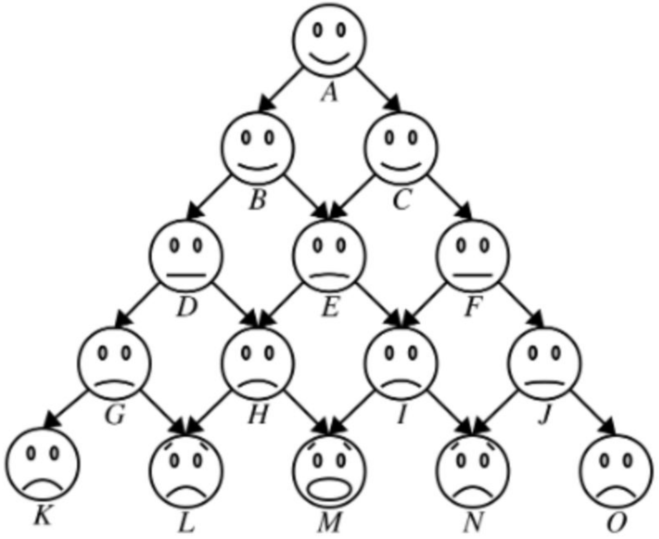
Part 2: Human Pyramids

- How much weight is **E** carrying?
  - To save some work, we know from the previous example that **B** yields 80 lbs (half of **B**'s weight) + 40 lbs (half of the weight **B** is carrying) = 120 lbs.
  - **C** is above **E**, so **E** carries half of **C**'s weight.
    - That is 80 lbs.
  - **E** also carries half of the weight **C** is carrying.
    - How much weight is **C** carrying?
      - **A** is above **C**, so **C** carries half of **A**'s weight.
        - That is 80 lbs. And half of that is 40 lbs.
  - In total, **E** is carrying **240** lbs.



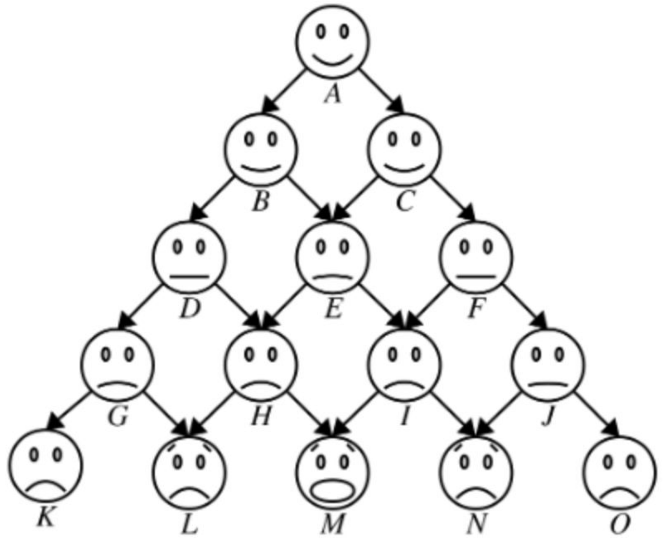
Part 2: Human Pyramids

- How much weight is **E** carrying?
    - To save some work, we know from the previous example that **B** yields 80 lbs (half of **B**'s weight) + 40 lbs (half of the weight **B** is carrying) = 120 lbs.
    - **C** is above **E**, so **E** carries half of **C**'s weight.
        - That is 80 lbs.
    - **E** also carries half of the weight **C** is carrying.
        - How much weight is **C** carrying?
            - **A** is above **C**, so **C** carries half of **A**'s weight.
                - That is 80 lbs. And half of that is 40 lbs.
    - In total, **E** is carrying **240** lbs.
- Despite the fact that **D** and **E** are on the same row, **E** is carrying double the weight **D** is carrying!



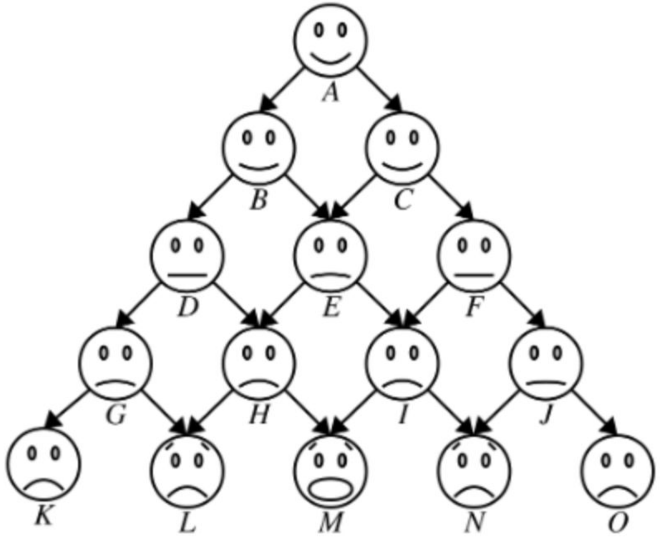
Part 2: Human Pyramids

- How much weight is **M** carrying?



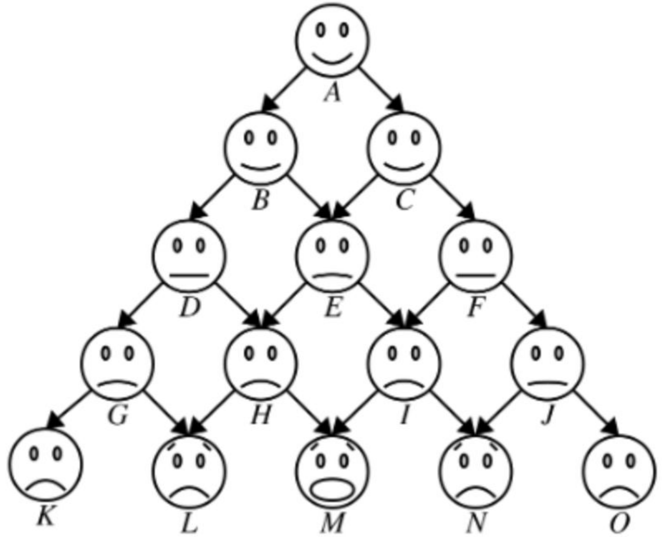
Part 2: Human Pyramids

- How much weight is **M** carrying?



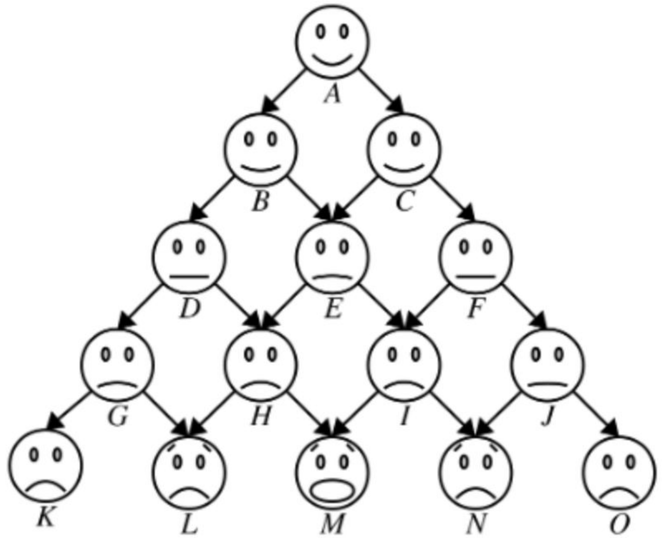
Part 2: Human Pyramids

- How much weight is **M** carrying?
- Sorry I'm just kidding, we are not doing this LOL...



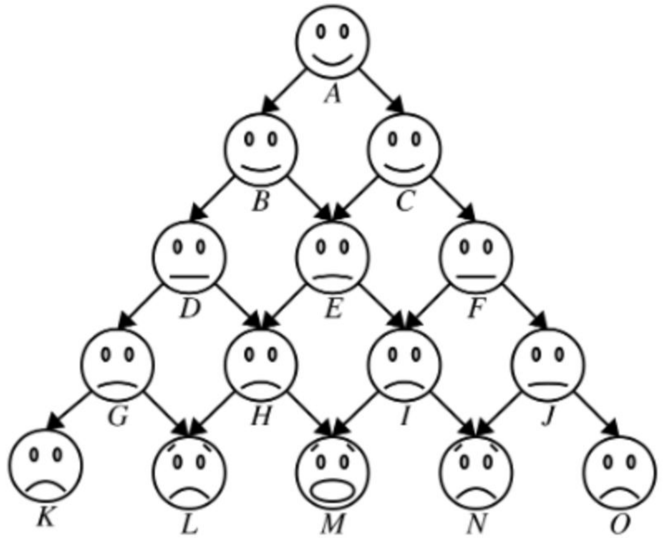
Part 2: Human Pyramids

- How much weight is **M** carrying?
- Sorry I'm just kidding, we are not doing this LOL...
- The point is, this problem fairly computationally heavy after just several rows.



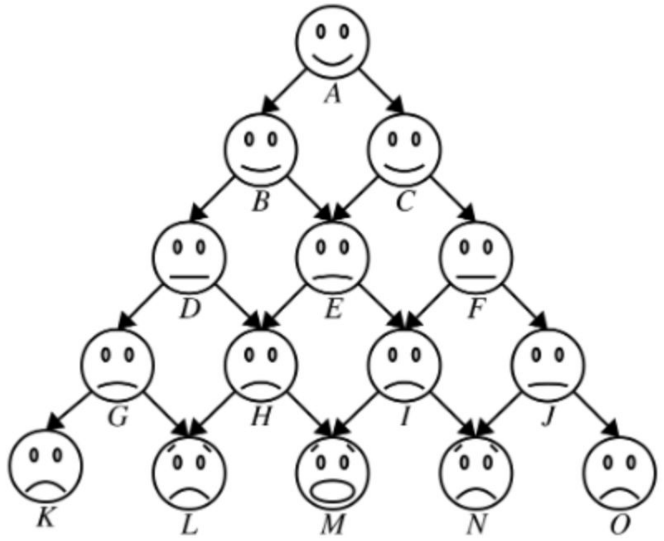
Part 2: Human Pyramids

- Let’s get into the code!



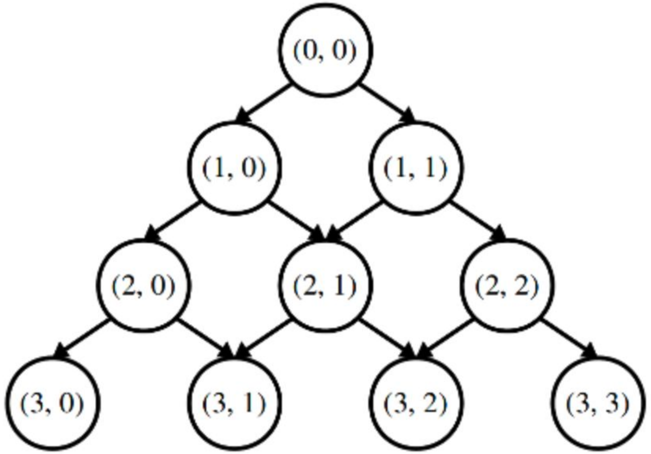
Part 2: Human Pyramids

- Let's get into the code!
- double weightOnBackOf(int row, int col, int pyramidHeight);



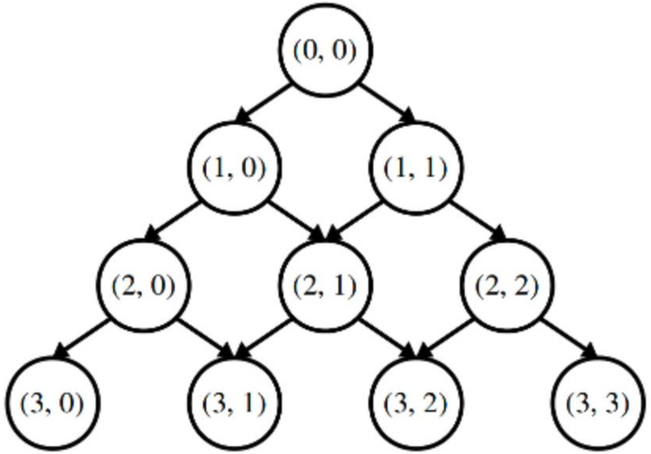
Part 2: Human Pyramids

- Let's get into the code!
- `double weightOnBackOf(int row, int col, int pyramidHeight);`
- Coordinate system (row, col) →


$$\begin{tikzcd}[column sep=tiny]
 & & & (0,0) \arrow[dl] \arrow[dr] & & & \\
 & & (1,0) \arrow[dl] \arrow[dr] & & (1,1) \arrow[dl] \arrow[dr] & & \\
 & (2,0) \arrow[dl] \arrow[dr] & & (2,1) \arrow[dl] \arrow[dr] & & (2,2) \arrow[dl] \arrow[dr] & \\
(3,0) & & (3,1) & & (3,2) & & (3,3)
\end{tikzcd}$$

Part 2: Human Pyramids

- Let’s get into the code!
- double weightOnBackOf(int row, int col, int pyramidHeight);
- Coordinate system (row, col) →
- “pyramidHeight” refers to the number of rows



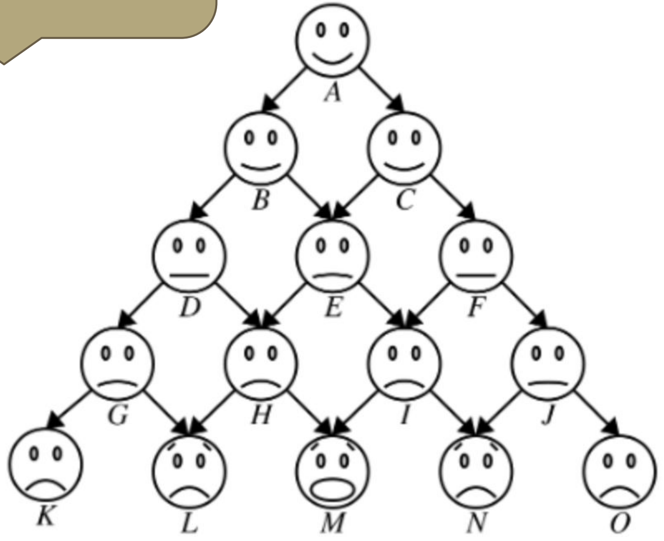
Part 2: Human Pyramids

- Quiz time!

Part 2: Human Pyramids

- Quiz time!

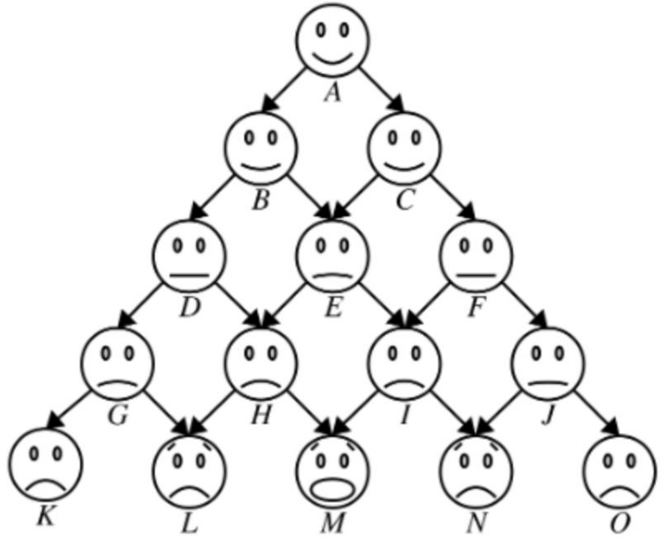
Hey I’m back!



```
double weightOnBackOf(int row, int col, int pyramidHeight);
```

Part 2: Human Pyramids

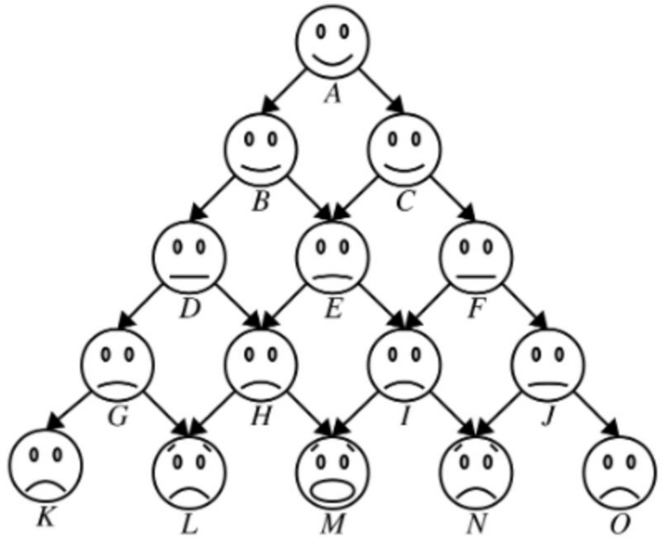
- What is the function call to get the weight on back of **H**?



```
double weightOnBackOf(int row, int col, int pyramidHeight);
```

Part 2: Human Pyramids

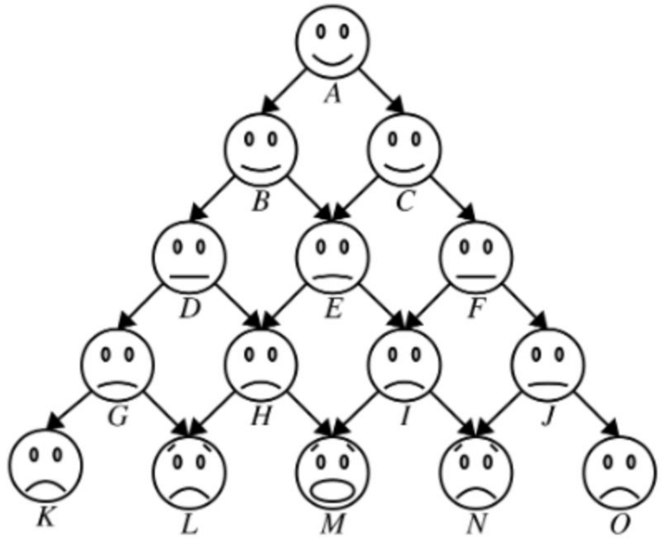
- What is the function call to get the weight on back of **H**?
    - weightOnBackOf(3, 1, 5)



```
double weightOnBackOf(int row, int col, int pyramidHeight);
```

Part 2: Human Pyramids

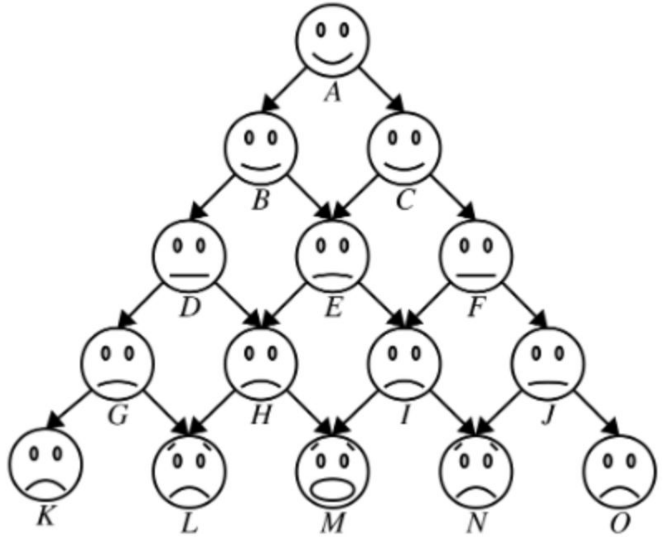
- What is the function call to get the weight on back of **H**?
    - weightOnBackOf(3, 1, 5)
- Which person is weightOnBackOf(4, 3, 5) referring to?



```
double weightOnBackOf(int row, int col, int pyramidHeight);
```

Part 2: Human Pyramids

- What is the function call to get the weight on back of **H**?
  - weightOnBackOf(3, 1, 5)
- Which person is weightOnBackOf(4, 3, 5) referring to?
  - Person **N**



```
double weightOnBackOf(int row, int col, int pyramidHeight);
```

Part 2: Human Pyramids

- What is the function call to get the weight on back of **H**?
    - weightOnBackOf(3, 1, 5)
- Which person is weightOnBackOf(4, 3, 5) referring to?
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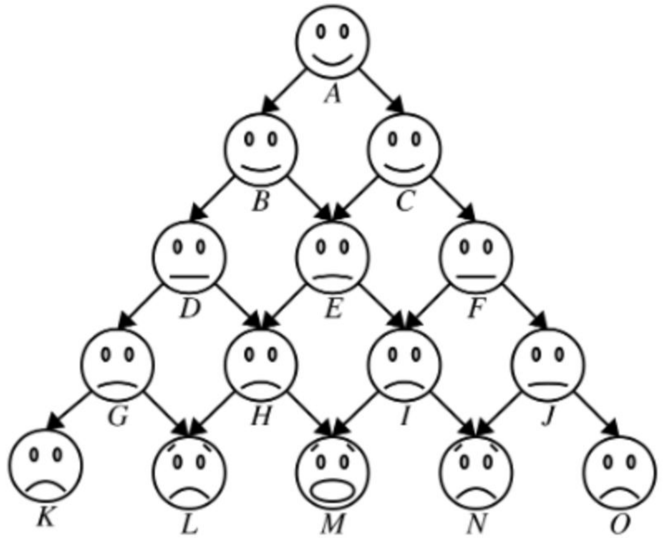
- Which person is weightOnBackOf(2, 4, 5) referring to?



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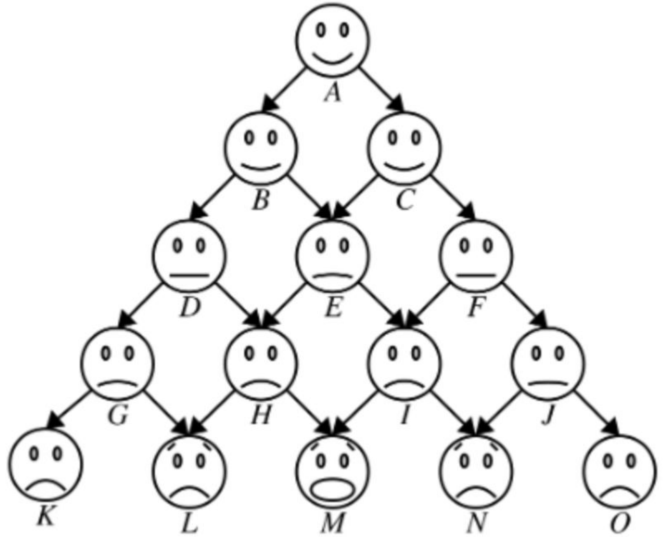
Part 2: Human Pyramids

- What is the function call to get the weight on back of **H**?
  - weightOnBackOf(3, 1, 5)
- Which person is weightOnBackOf(4, 3, 5) referring to?
  - Person **N**
- Which person is weightOnBackOf(2, 4, 5) referring to?
  - No one :(



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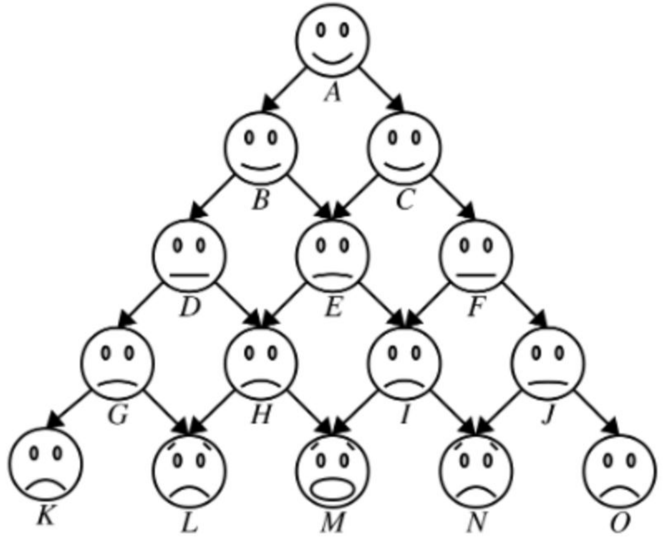
```

Part 2: Human Pyramids

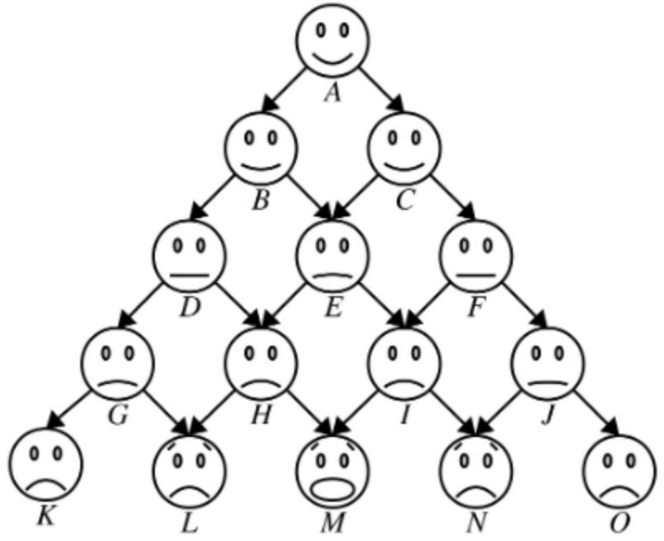
- What is the function call to get the weight on back of **H**?
  - weightOnBackOf(3, 1, 5)
- Which person is weightOnBackOf(4, 3, 5) referring to?
  - Person **N**
- Which person is weightOnBackOf(2, 4, 5) referring to?
  - No one :(
- weightOnBackOf(6, 1, 5)?



```
double weightOnBackOf(int row, int col, int pyramidHeight);
```

Part 2: Human Pyramids

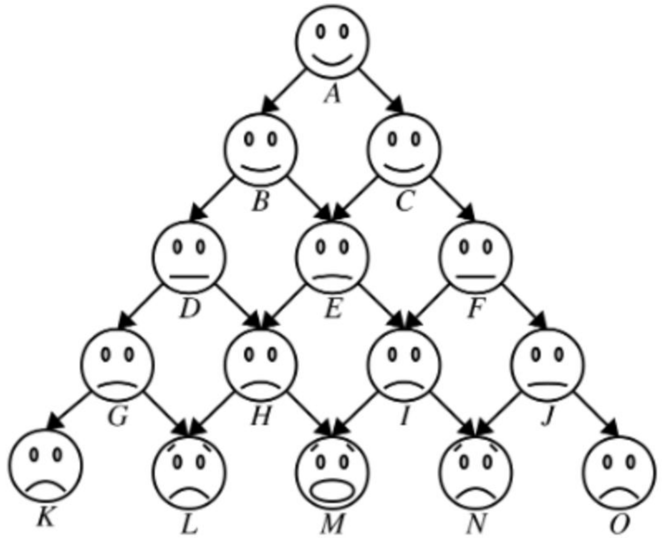
- What is the function call to get the weight on back of **H**?
    - weightOnBackOf(3, 1, 5)
- Which person is weightOnBackOf(4, 3, 5) referring to?
    - Person **N**
- Which person is weightOnBackOf(2, 4, 5) referring to?
    - No one :(
- weightOnBackOf(6, 1, 5)?
    - No one :(



```
double weightOnBackOf(int row, int col, int pyramidHeight);
```

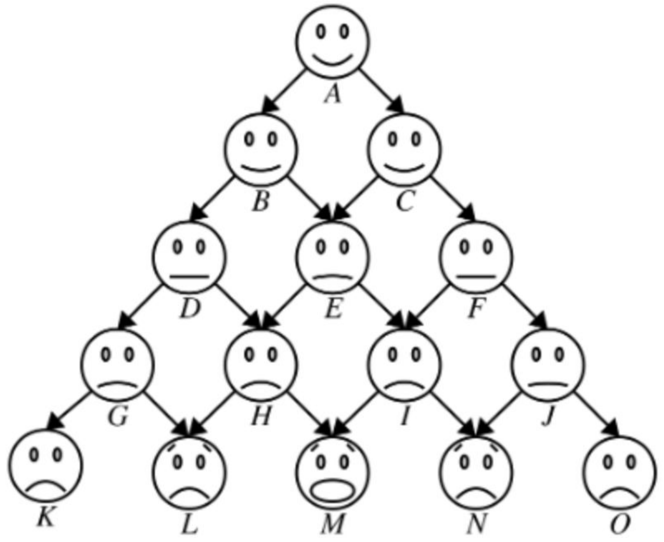
Part 2: Human Pyramids

- Some implementation thoughts:



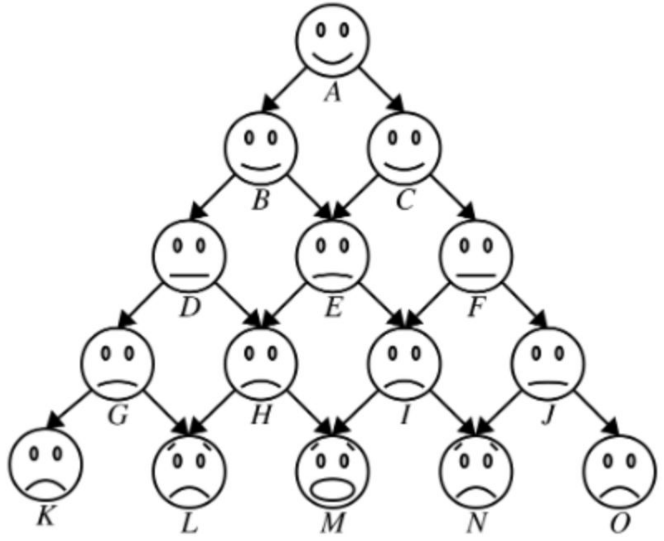
Part 2: Human Pyramids

- Some implementation thoughts:
  - Throw an error for invalid function calls (think through the possible cases thoroughly).



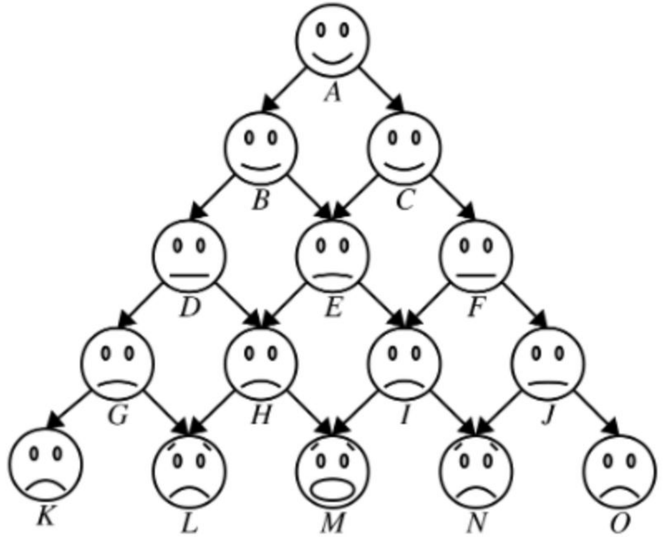
Part 2: Human Pyramids

- Some implementation thoughts:
  - Throw an error for invalid function calls (think through the possible cases thoroughly).
  - The top person carries no weight.



Part 2: Human Pyramids

- Some implementation thoughts:
  - Throw an error for invalid function calls (think through the possible cases thoroughly).
  - The top person carries no weight.
  - Some people are directly supporting two people, some people are directly supporting one person. How should you distinguish between the two cases?



Part 2: Human Pyramids

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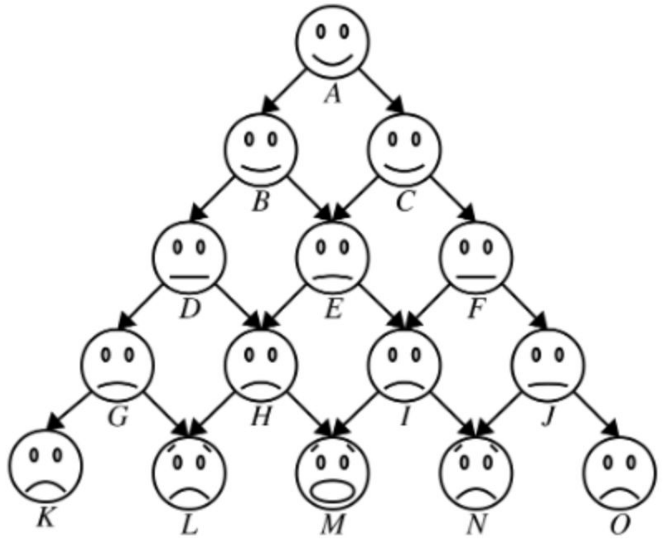
  - The top person carries no weight.
  - Some people are directly supporting two people, some people are directly supporting one person. How should you distinguish between the two cases?
  - Remember that the function returns a **double**!



Part 2: Human Pyramids

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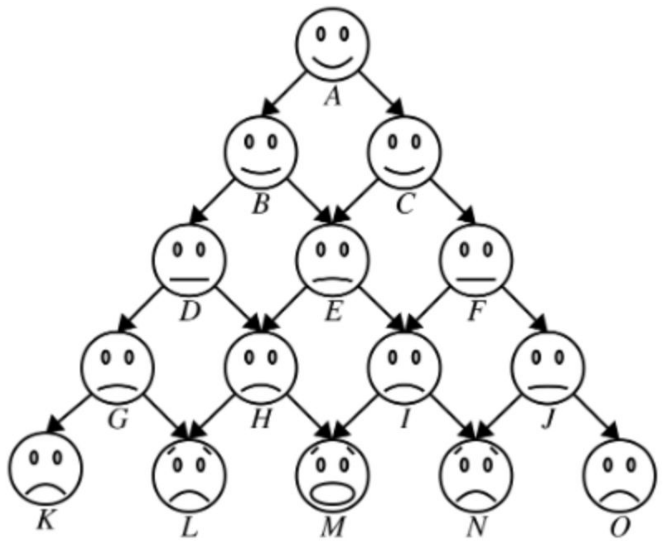
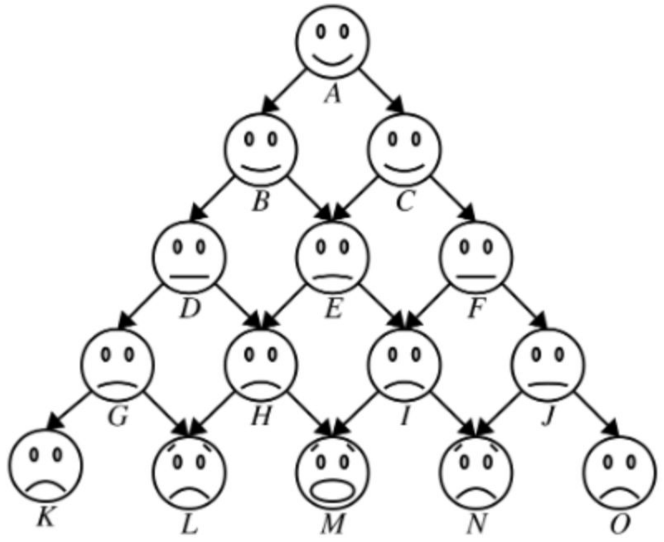
    - The top person carries no weight.
    - Some people are directly supporting two people, some people are directly supporting one person. How should you distinguish between the two cases?
    - Remember that the function returns a **double**!
    - Test your solution before moving on!



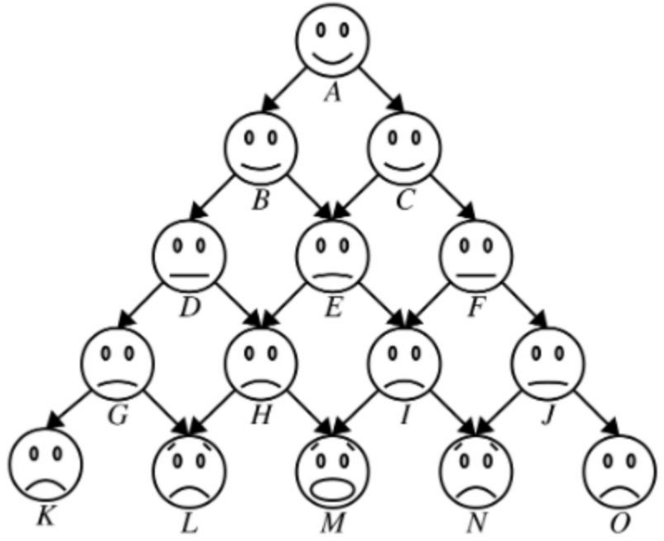
Part 2: Human Pyramids

- Questions before we move on to part 2 of part 2?



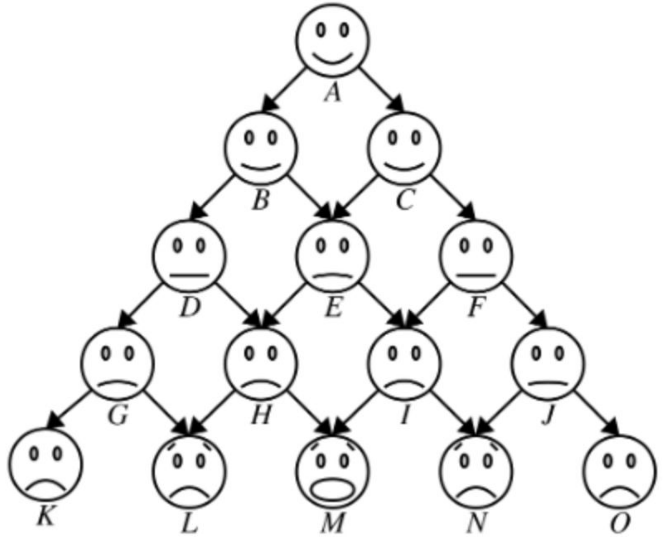
Part 2: Human Pyramids - Milestone 2

- Let's examine a ***HUGE*** efficiency flaw in our first implementation.



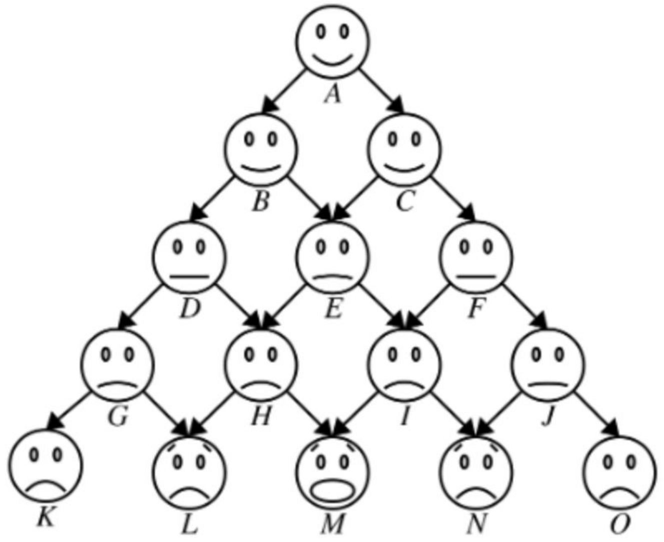
Part 2: Human Pyramids - Milestone 2

- Let’s examine a ***HUGE*** efficiency flaw in our first implementation.
- Say we’re interested in finding out how much weight **M** is carrying.



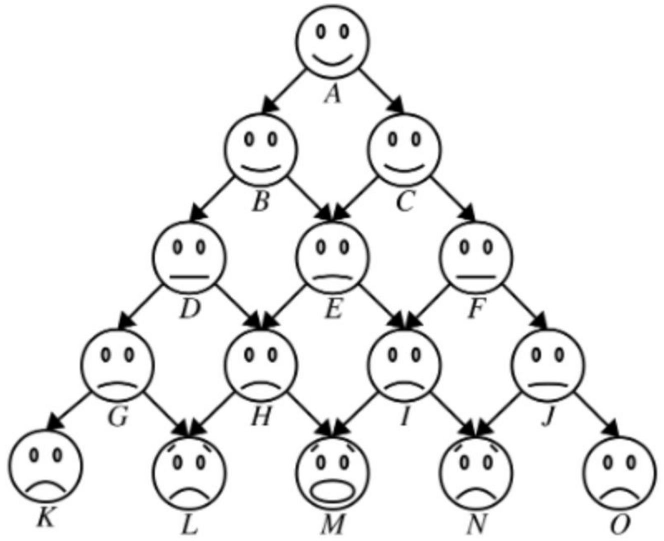
Part 2: Human Pyramids - Milestone 2

- Let's examine a ***HUGE*** efficiency flaw in our first implementation.
- Say we're interested in finding out how much weight **M** is carrying.
- How many times do we need to call the function with respect to **M**?



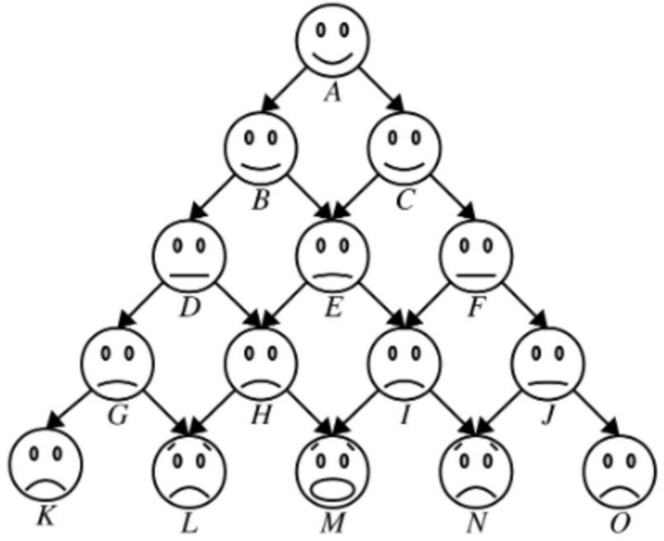
Part 2: Human Pyramids - Milestone 2

- Let's examine a ***HUGE*** efficiency flaw in our first implementation.
- Say we're interested in finding out how much weight **M** is carrying.
- How many times do we need to call the function with respect to **M**?
    - Just once



Part 2: Human Pyramids - Milestone 2

- Let's examine a ***HUGE*** efficiency flaw in our first implementation.
- Say we're interested in finding out how much weight **M** is carrying.
- How many times do we need to call the function with respect to **M**?
    - Just once
- What about **H**?



Part 2: Human Pyramids - Milestone 2

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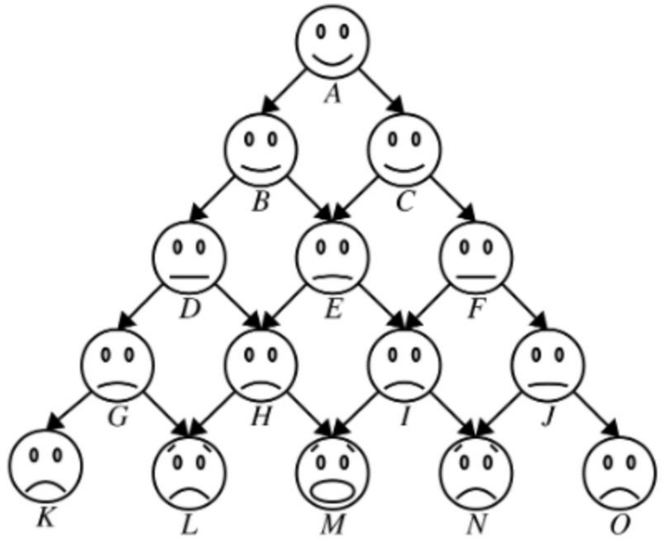
    - Just once
- What about **H**?
    - Once



Part 2: Human Pyramids - Milestone 2

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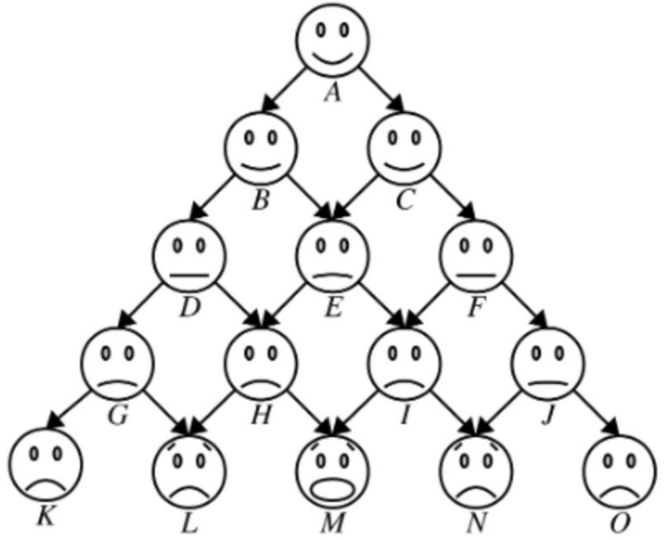
    - Just once
- What about **H**?
    - Once
- **E**?



Part 2: Human Pyramids - Milestone 2

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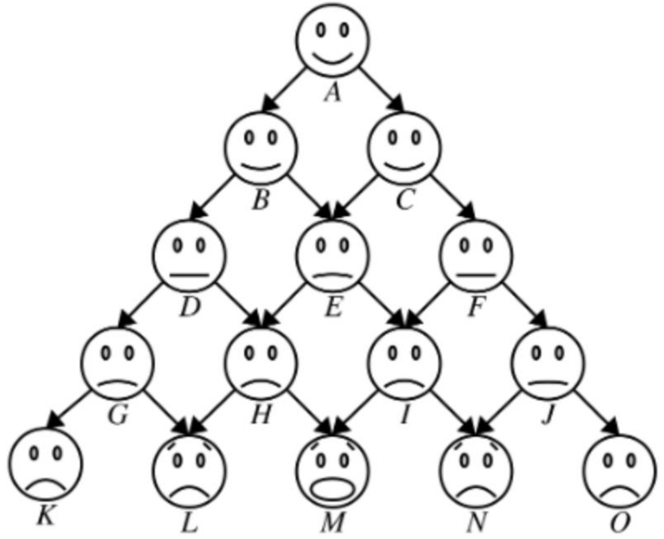
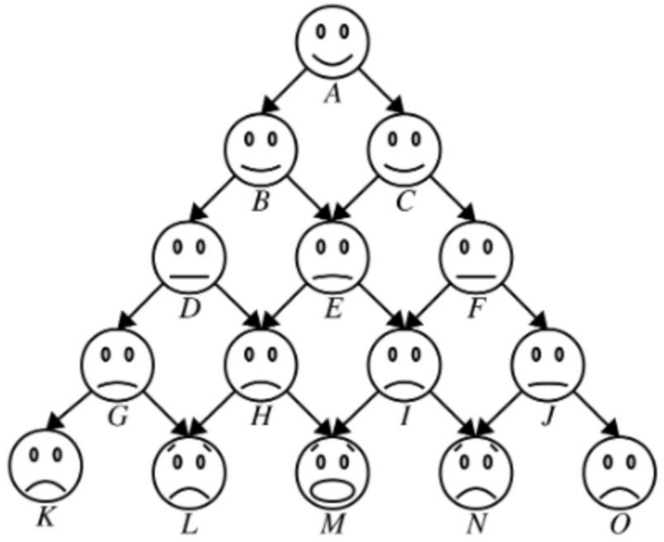
- Say we’re interested in finding out how much weight **M** is carrying.
- How many times do we need to call the function with respect to **M**?
  - Just once
- What about **H**?
  - Once
- **E**?
  - Twice



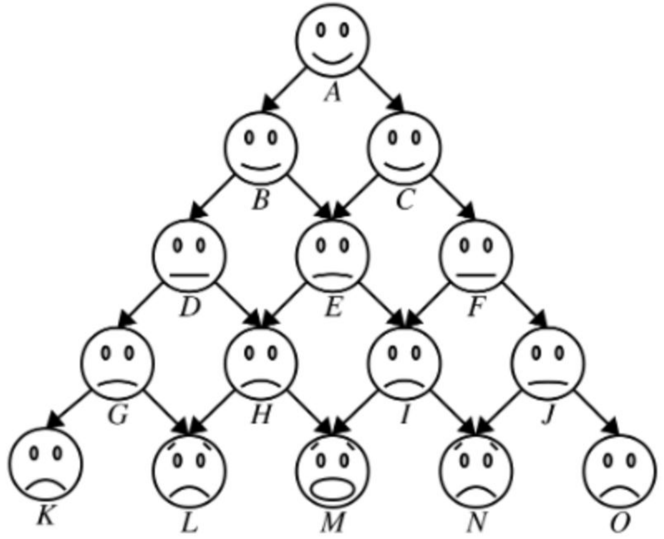
Part 2: Human Pyramids - Milestone 2

- Let's examine a ***HUGE*** efficiency flaw in our first implementation.
- Say we're interested in finding out how much weight **M** is carrying.
- How many times do we need to call the function with respect to **M**?
  - Just once
- What about **H**?
  - Once
- **E**?
  - Twice
- And **A** will be called 6 times!



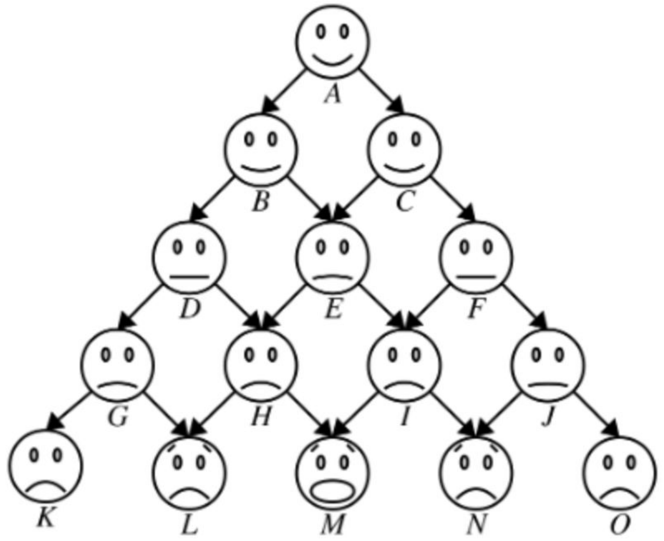
Part 2: Human Pyramids - Milestone 2

- This actually resembles a Pascal's Triangle (off topic, just slightly)



Part 2: Human Pyramids - Milestone 2

- This actually resembles a Pascal's Triangle (off topic, just slightly)
- Let the number on a person denote how many times this person needs to call **A**.



Part 2: Human Pyramids - Milestone 2

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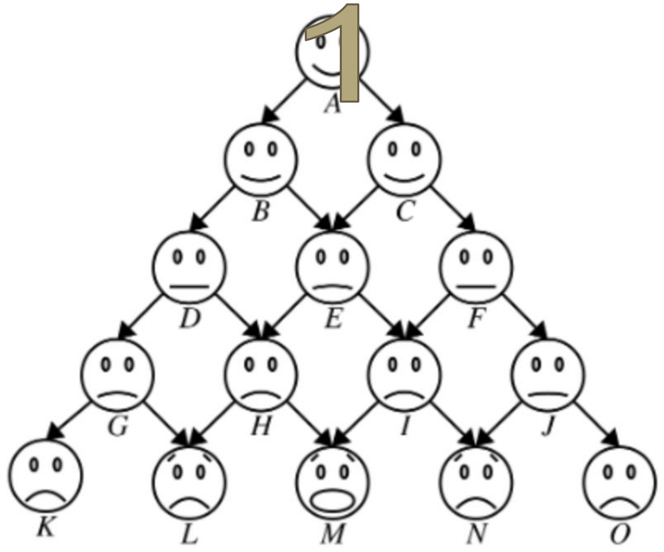

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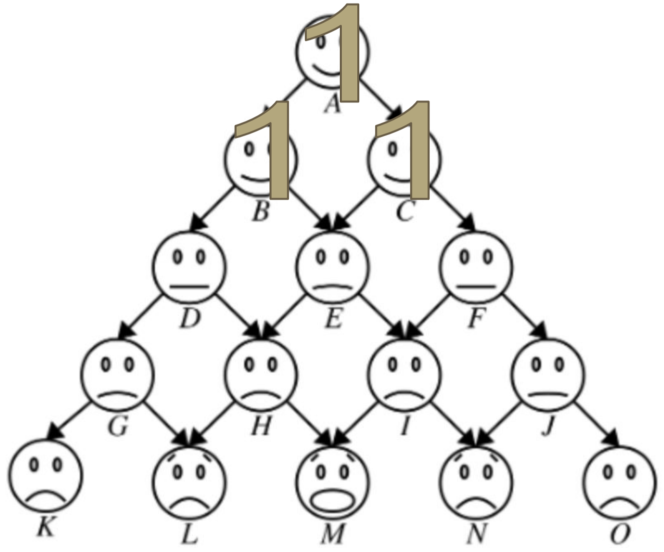

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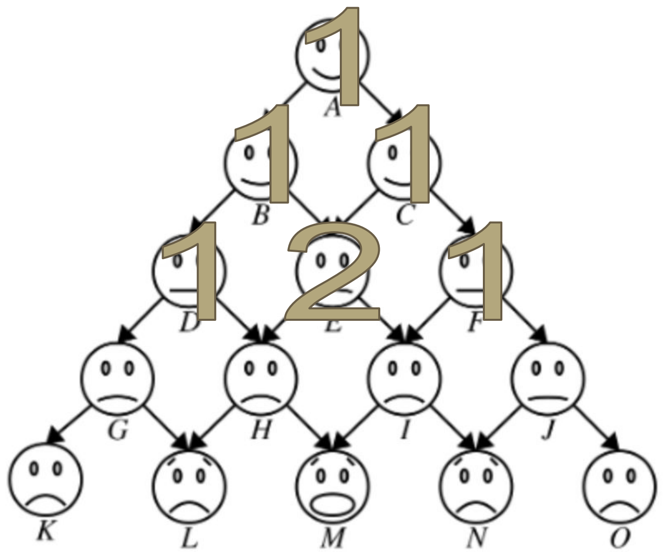

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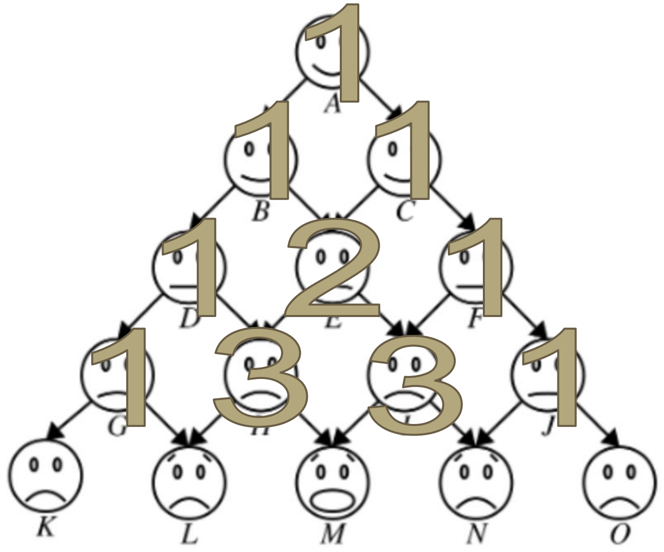
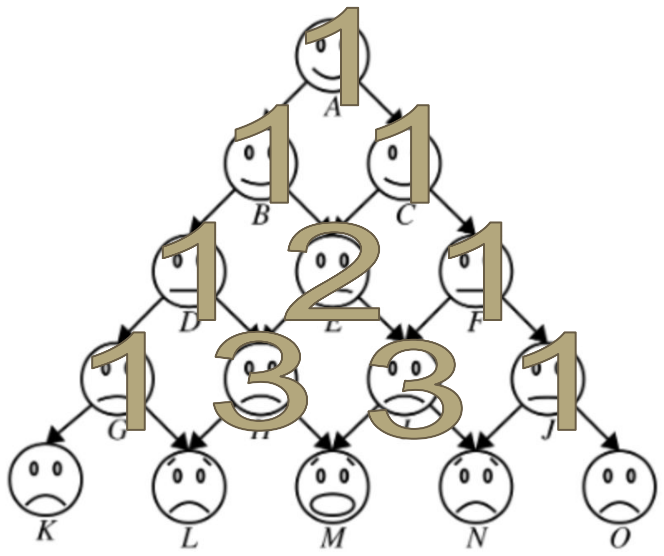


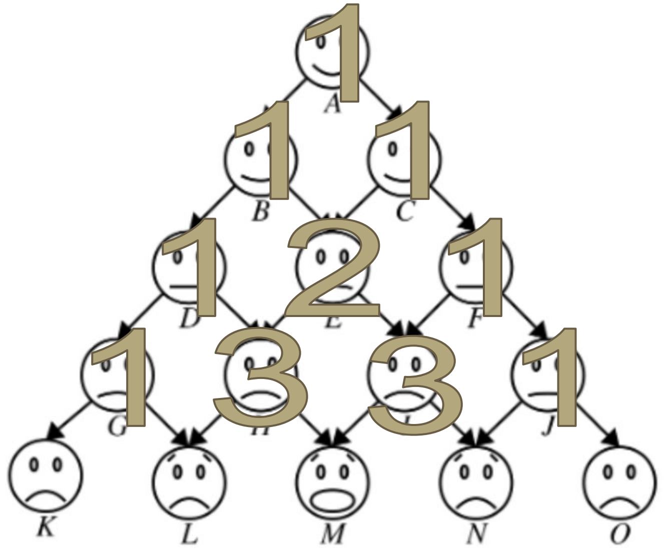
Part 2: Human Pyramids - Milestone 2

- This actually resembles a Pascal's Triangle (off topic, just slightly)
- Let the number on a person denote how many times this person needs to call **A**.
- You are expecting the last row filled out, but I'm out of animation budget :|



Part 2: Human Pyramids - Milestone 2

- Observation: As we get further into the recursive stack, the more copies of the **SAME** function calls we will be creating.



Part 2: Human Pyramids - Milestone 2

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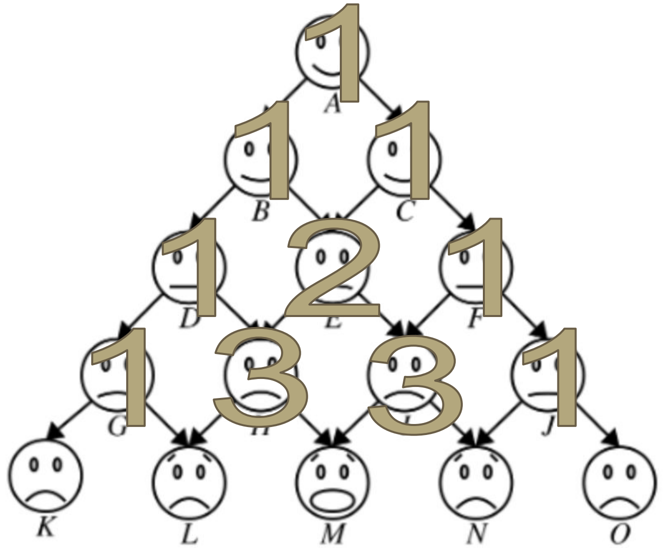
- Just the 10th row and we have surpassed 100 in the Pascal's Triangle.



Part 2: Human Pyramids - Milestone 2

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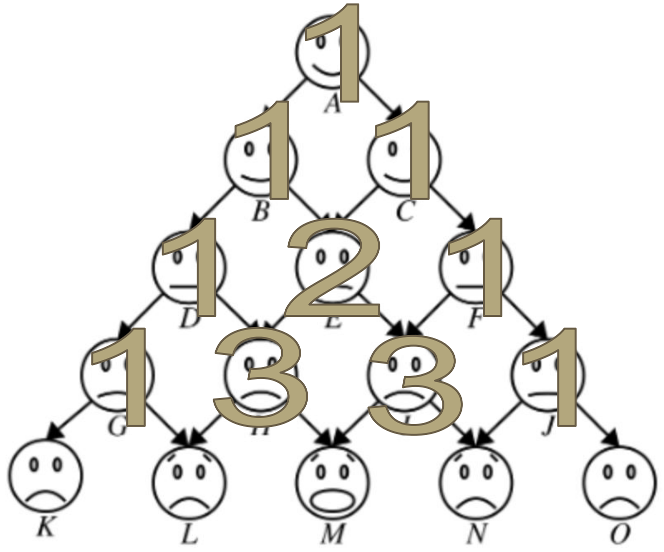

Part 2: Human Pyramids - Milestone 2

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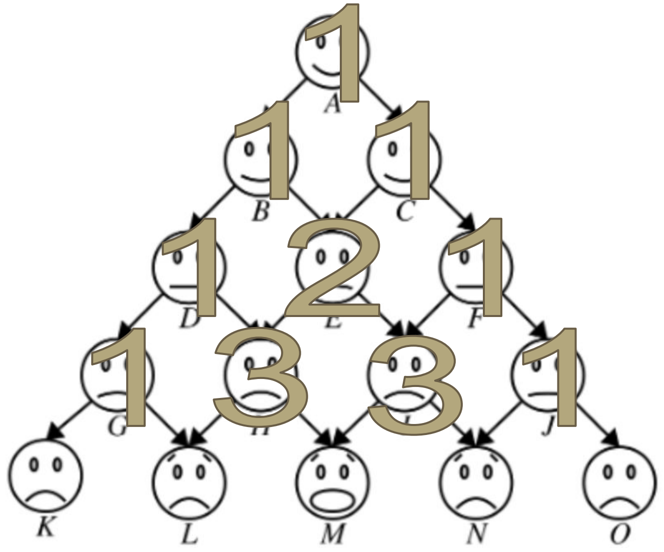

Part 2: Human Pyramids - Milestone 2

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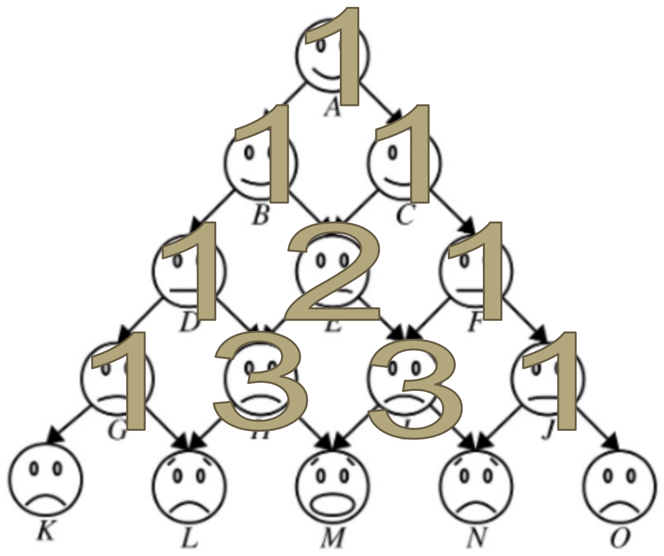
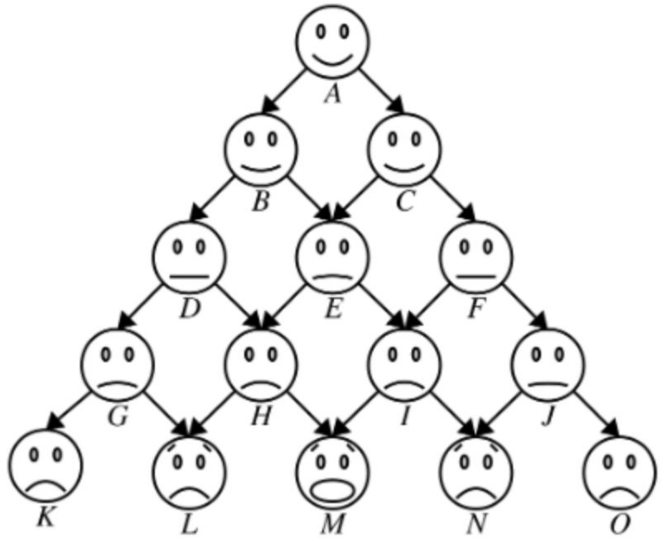
- 17th row > 10,000.
- Conclusion: This grows really really fast!



Part 2: Human Pyramids - Milestone 2

- We need a solution.



Part 2: Human Pyramids - Milestone 2

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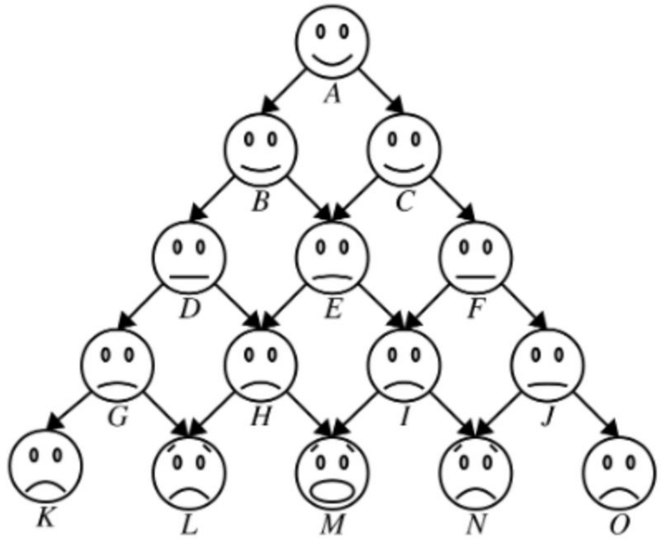
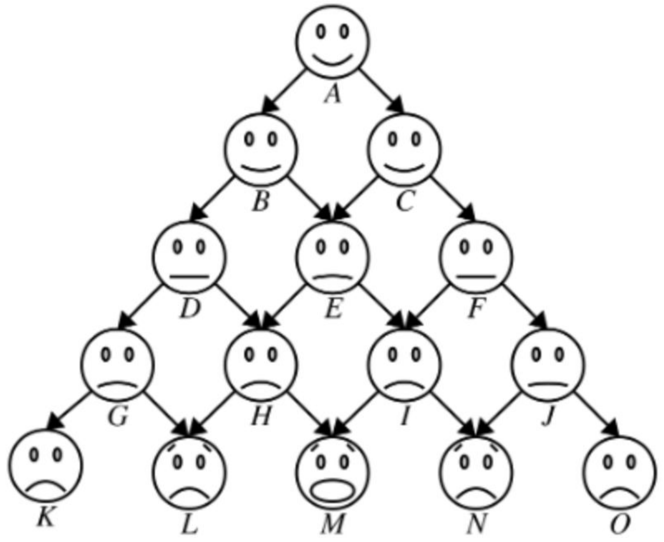


Part 2: Human Pyramids

- How much weight is **E** carrying?
  - To save some work, we know from the previous example that **B** yields 80 lbs (half of **B**'s weight) + 40 lbs (half of the weight **B** is carrying) = 120 lbs.



Part 2: Human Pyramids

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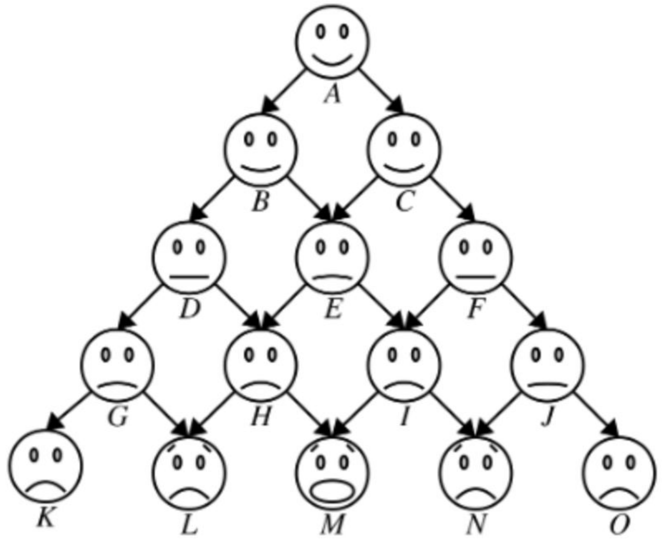
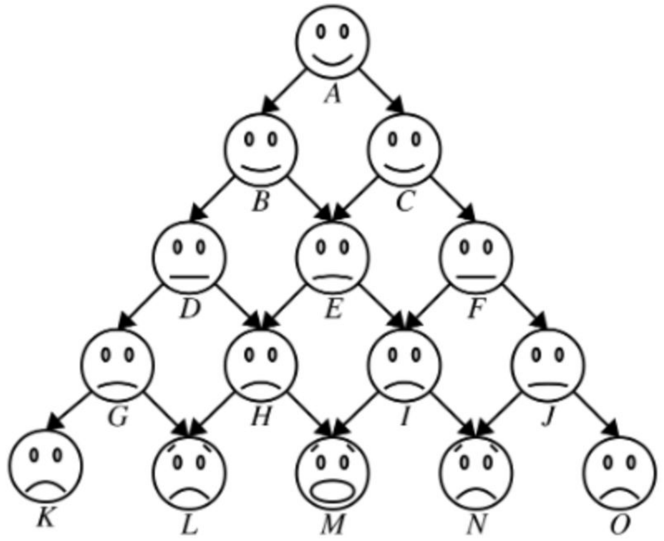


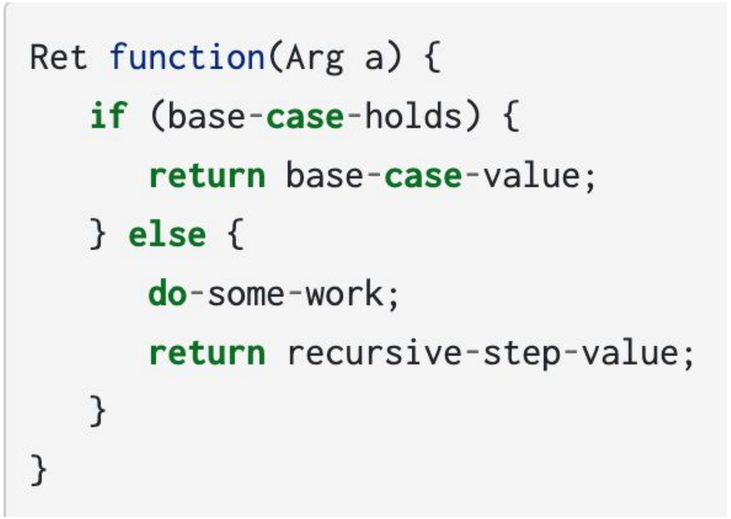
Part 2: Human Pyramids - Milestone 2

- ***Memoization***: using an auxiliary table to keep track of all the recursive calls that have been made before and what value was returned for each of them.



Part 2: Human Pyramids - Milestone 2

Standard Recursion:



```
Ret function(Arg a) {
    if (base-case-holds) {
        return base-case-value;
    } else {
        do-some-work;
        return recursive-step-value;
    }
}
```

Part 2: Human Pyramids - Milestone 2

With Memoization:

```
Ret functionRec(Arg a, Table& table) {
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   } else if (table contains a) {
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   }
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Ret function(Arg a) {
    Table table;
    return functionRec(a, table);
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Part 2: Human Pyramids - Milestone 2

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Wrapper function

Part 2: Human Pyramids - Milestone 2

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Utilizing the table if possible

Wrapper function

Part 2: Human Pyramids - Milestone 2

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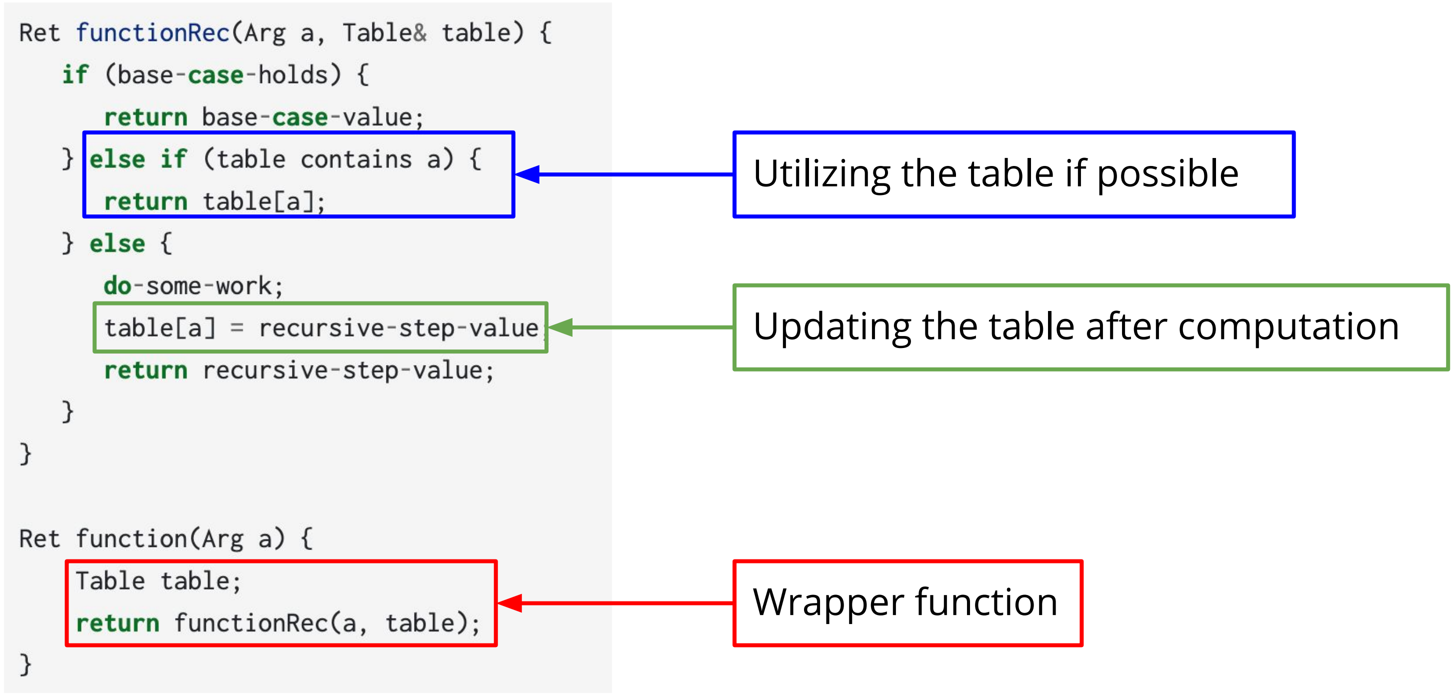

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Utilizing the table if possible
Updating the table after computation
Wrapper function

Part 2: Human Pyramids - Milestone 2

- Note that there isn't a variable of type **Table**

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Part 2: Human Pyramids - Milestone 2

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    - Can be updated during program execution.
    - Is efficient and elegant.

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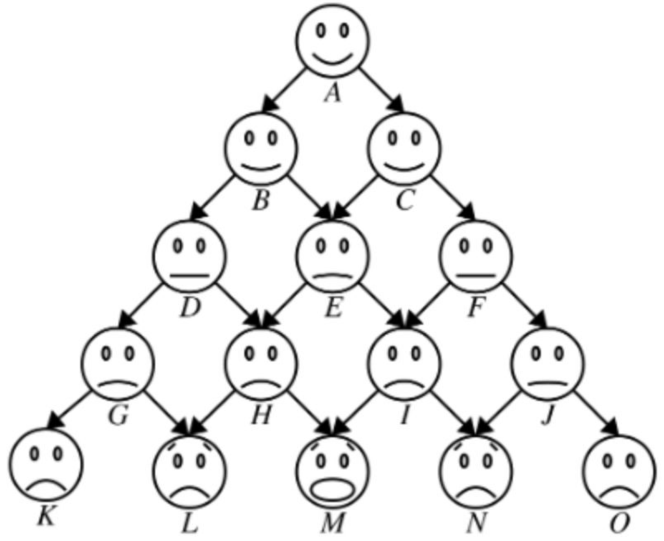
Questions about Part 2?



Context Switch Time!

Definition: A *context switch* occurs when a code routine is “switched off” the CPU so that another routine can begin / resume.

Part 3: What Are YOU Doing?

- Have you ever considered an iconic phrase like:

Part 3: What Are YOU Doing?

- Have you ever considered an iconic phrase like:

“To be or not to be”

Part 3: What Are YOU Doing?

- Have you ever considered an iconic phrase like:

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and wondered what it would be like to capitalize every possible subset of the words?

Part 3: What Are YOU Doing?

- Have you ever considered an iconic phrase like:

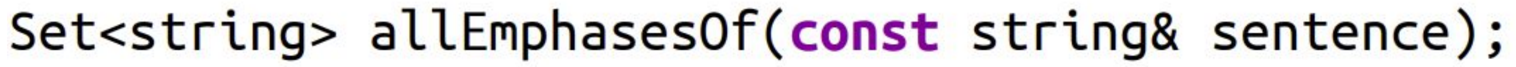
  “*To be or not to be*”

  and wondered what it would be like to capitalize every possible subset of the words?

  Me neither!

Part 3: What Are YOU Doing?

- Nonetheless, it's your job to implement the following function:



```
Set<string> allEmphasesOf(const string& sentence);
```

Part 3: What Are YOU Doing?

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- Given an arbitrary `sentence`, you'll need to return all possible combinations of emphases like so:

Part 3: What Are YOU Doing?

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what are you doing?
what are you DOING?
what are YOU doing?
what are YOU DOING?
what ARE you doing?
what ARE you DOING?
what ARE YOU doing?
what ARE YOU DOING?
```

What are you doing?

```
WHAT are you doing?
WHAT are you DOING?
WHAT are YOU doing?
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WHAT ARE you doing?
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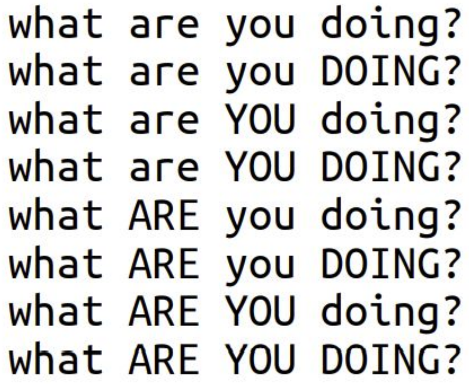
WHAT ARE YOU doing?
WHAT ARE YOU DOING?
```

Part 3: What Are YOU Doing?

- Let’s think about this critically for a second:



```
what are you doing?
what are you DOING?
what are YOU doing?
what are YOU DOING?
what ARE you doing?
what ARE you DOING?
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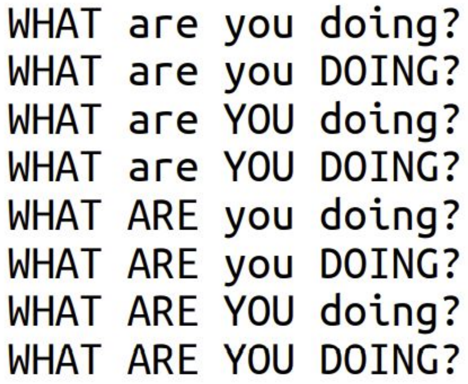
what ARE YOU DOING?
```



```
WHAT are you doing?
WHAT are you DOING?
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```

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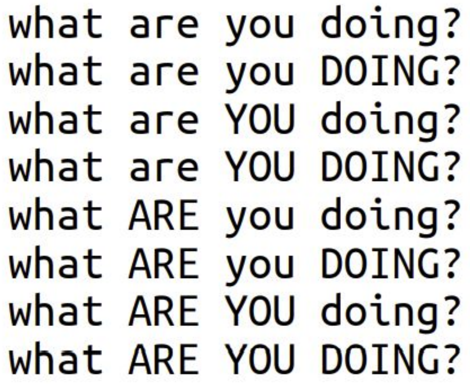

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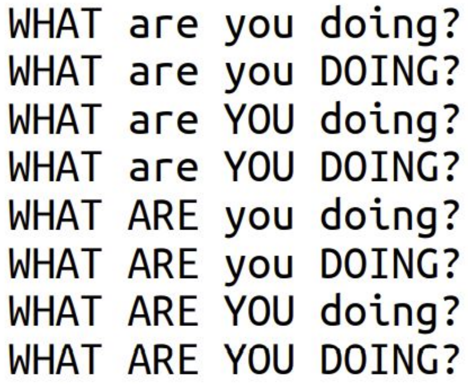

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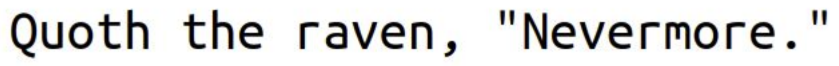
```

- It looks like at the upper left, *all tokens are lowercase,* and on the bottom right, all *tokens are uppercase*! Hmm, does this look like patterns you’ve seen before?

Part 3: What Are YOU Doing?

- Granted, you might sometimes have stranger-looking questions like this:



```
Quoth the raven, "Nevermore."
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- We've provided you with the following function to help **tokenize** the given sentence.

```
Vector<string> tokenize(const string& sentence);
```

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```
Quoth the raven, "Nevermore."
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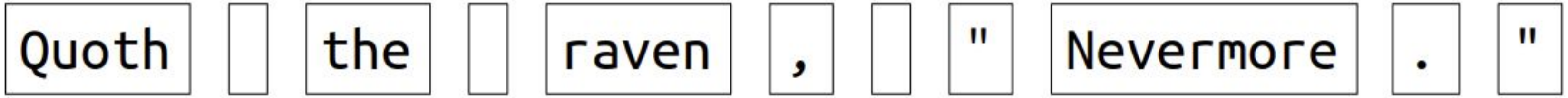
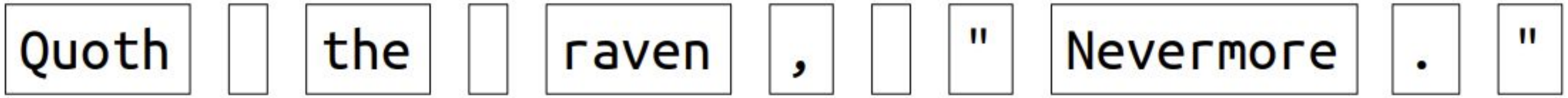
```
Vector<string> tokenize(const string& sentence);
```

  That can turn the above sentence into the following vector:

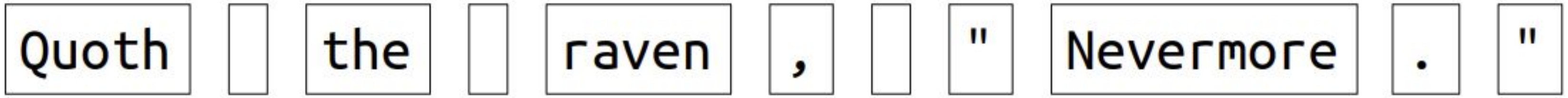


Part 3: What Are YOU Doing?



- The good news is, you can determine whether an individual token is a word or not by checking whether the first character is alphabetical!

Part 3: What Are YOU Doing?



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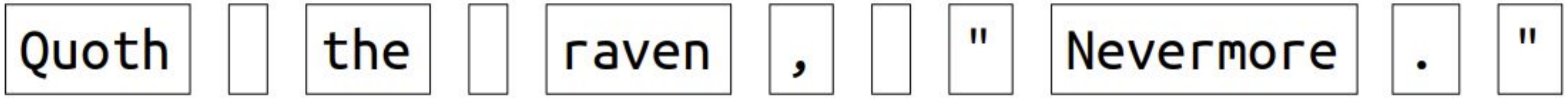
Part 3: What Are YOU Doing?



- The good news is, you can determine whether an individual token is a word or not by checking whether the first character is alphabetical!
    - That might look something like this: `isalpha(tokenizedString[someIndex][0])`
    - This way you can avoid trying to capitalize / lowercase strings that aren't words! To repeat, **you should ignore non-words!**

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    - Here's how to properly use `toUpperCase()`:

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string str = "hello there!"
str = toUpperCase(str);
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Any questions?

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Part 4: Shift Scheduling

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Part 4: Shift Scheduling

- Optimizing a shift schedule for profit is **absolutely not ethical!** Always be conscientious about *what* you're optimizing.
- Despite this… we're going to ask you to do just this in *Shift Scheduling*

Part 4: Shift Scheduling

- Here's what you'll be implementing:

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Set<Shift> highestValueScheduleFor(const Set<Shift>& shifts, int maxHours);
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```

- Your job is to return the collection of `shift`'s that maximizes profit given a full collection of `shifts` and a maximum number of hours an individual can work.
- Here are a few functions we've written for you that use `shift`:

```
int lengthOf(const Shift& shift);     // Returns the length of a shift.
int valueOf(const Shift& shift);      // Returns the value of this shift.
bool overlapsWith(const Shift& one,   // Returns whether two shifts overlap.
                  const Shift& two);
```

Part 4: Shift Scheduling

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```
int lengthOf(const Shift& shift);     // Returns the length of a shift.
int valueOf(const Shift& shift);      // Returns the value of this shift.
bool overlapsWith(const Shift& one,   // Returns whether two shifts overlap.
                  const Shift& two);
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  - Why is this such a bad idea?

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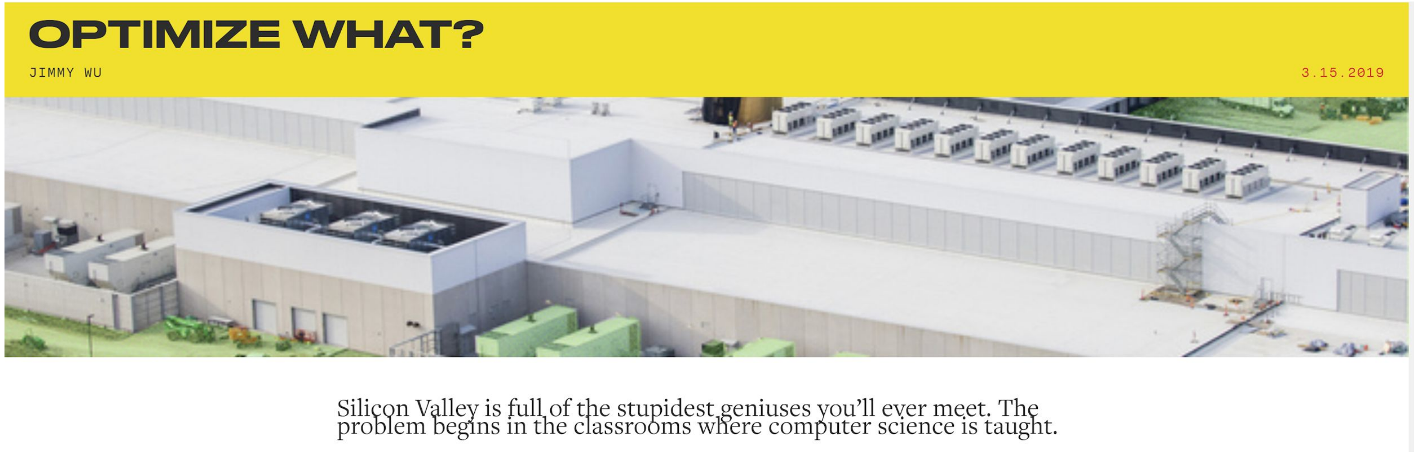
    - Remember to think long and hard about the implications of your work -- take a look at some of the schedules your algorithms produce -- you might be optimizing profit, but at what cost?
    - When making your recursive calls, ensure that **every** variable is being updated correctly! Ensure you can justify each modification you make to your parameters.

Any questions about part 4?

I'd recommend taking a look through Jimmy Wu's article *"Optimize What?"* It's an eye-opening piece about how a-seemingly innocuous CS education can be a *very* dangerous thing for society.



OPTIMIZE WHAT?

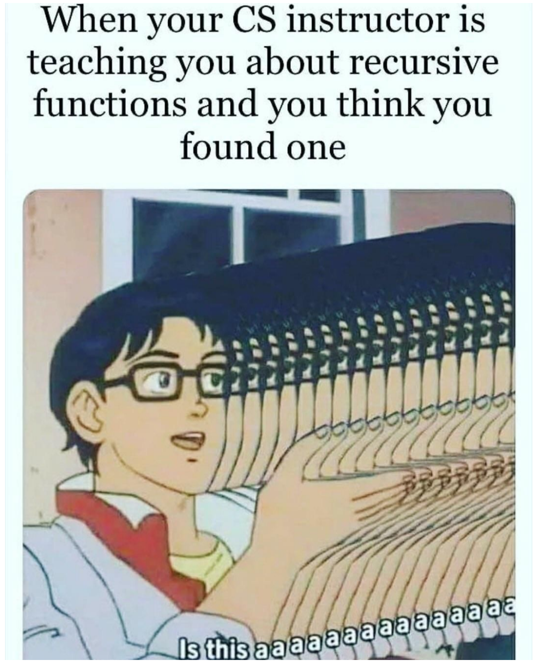
JIMMY WU

3.15.2019

Silicon Valley is full of the stupidest geniuses you'll ever meet. The problem begins in the classrooms where computer science is taught.

Congrats!

This was a **big** assignment, but we believe in you! Remember that you have lots of support!


When your CS instructor is teaching you about recursive functions and you think you found one
Is this aaaaaaaaaaaaaaaa