Missionaries and Cannibals Solution

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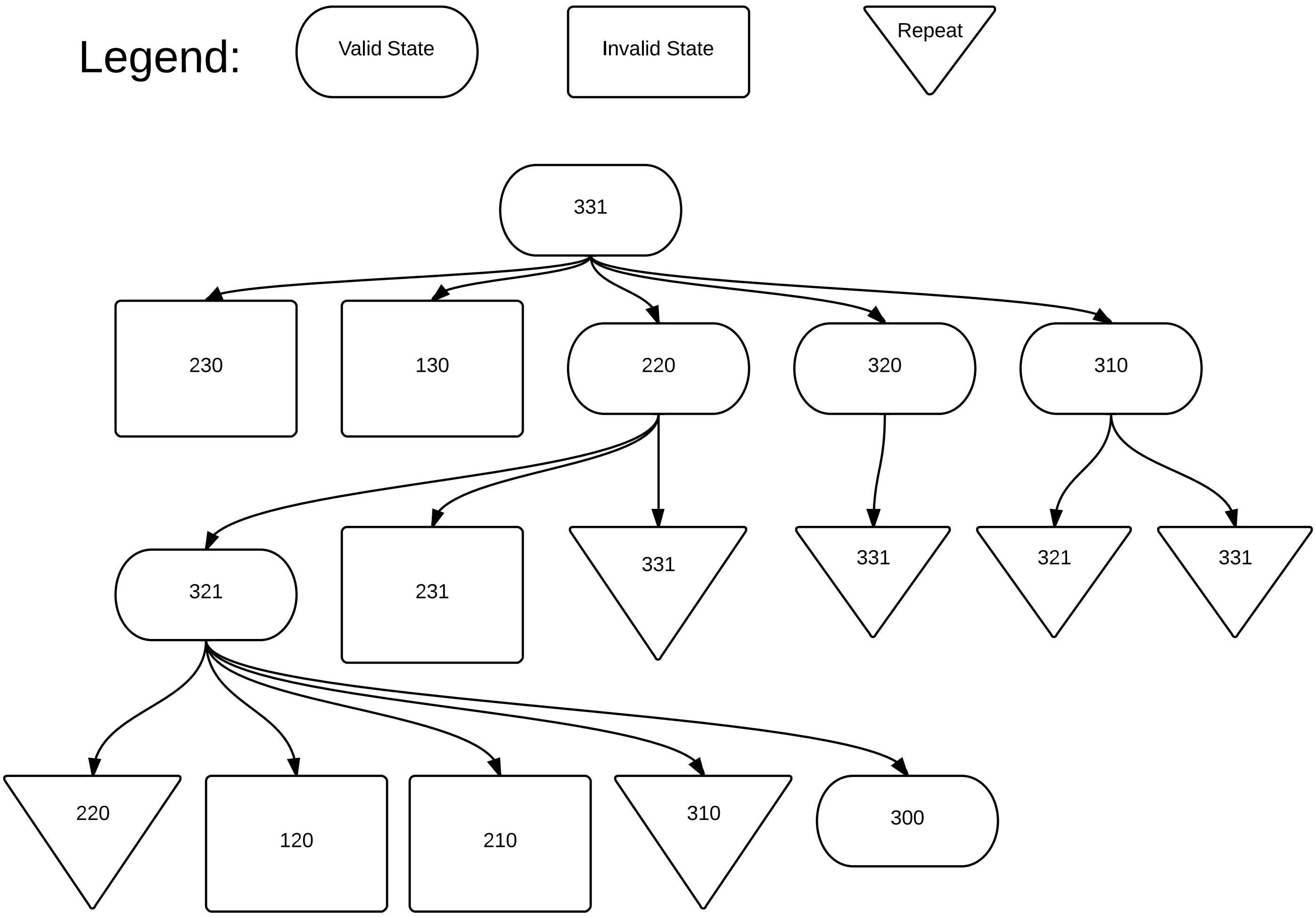
0.1 Introduction

In the Missionaries and Cannibals problem, we can represent the missionaries, cannibals and position of the boat using the notation (m, c, b). If boat has a value of 1, we assume it is on the starting side of the river. Thus, the initial problem state is represented as (3,3,1).

We can find an upper bound on the number of states by considering that for the number of missionaries and cannibals on the starting side of the river, this value must be between 0-4, inclusive. The boat must either be on the starting side or the other side (so only 2 options). We can multiply these options to arrive at $4 \cdot 4 \cdot 2 = 32$ total unique permutations of the number of states. This is the upper bound. More generally, give m missionaries and c cannibals, we can say the upper bound for the problem is $(m+1) \cdot (c+1) \cdot 2$ states.

A graphical representation of the graph of first few level of states can be found below:


Legend:
Valid State
Invalid State
Repeat
331
230
130
220
320
310
321
231
331
331
321
331
220
120
210
310
300

0.2 Implementation of the model

The model is implemented in `CannibalProblem.java`. Here's my code for `getSuccessors`:

```
public ArrayList<UUSearchNode> getSuccessors() {
  // the final array to be returned
  ArrayList<UUSearchNode> retArr = new ArrayList<UUSearchNode>();

  int boatPlace = state[2];
  int candMissionaries = -1;
  int candCannibals = -1;
  int candBoat = -1;

  // Determine which missionaries and cannibals can travel
  if (boatPlace == 1){
    System.out.println("Boat @ starting side");
    // the candidate missionaries that can travel on the boat
    candMissionaries = state[0];
    candCannibals = state[1];
    candBoat = 0;
  } else if (boatPlace == 0){
    candMissionaries = totalMissionaries - state[0];
    candCannibals = totalCannibals - state[1];
    candBoat = 1;
  } else {
    // not valid input for boat
    System.out.println("Boat place not valid: " + boatPlace);
    System.exit(1);
  }

  for(int missCount=candMissionaries; missCount>=0; missCount--){
    for(int cannCount=candCannibals; cannCount>=0; cannCount--){
      System.out.println("Checking ("+missCount+","+cannCount+")");
      CannibalNode possNode;

      // Must fit in boat and have at least one missionary rowing
      if (missCount + cannCount <= BOAT_SIZE && (missCount > 0 || cannCount > 0
        // Must have something happen
        if (missCount == 0 && cannCount == 0){
          continue;
        }

        if (boatPlace == 1){
          // boat on starting side so starting side is subtracted
          possNode = new CannibalNode(candMissionaries - missCount,
              candCannibals - cannCount, candBoat, depth+1);
        } else {
          // boat on other side so starting side is added
          possNode = new CannibalNode( state[0] + missCount,
```

```
                state[1] + cannCount, candBoat, depth+1);
        }
        System.out.println("("+possNode.state[0]+","+possNode.state[1]+","+poss
      } else {
        continue;
      }

      boolean isSafe = isSafeState(possNode);
      if (isSafe){
        // State is valid, add to the array
        System.out.println("Adding " + possNode);
        retArr.add(possNode);
      } else {
        // Node was not a valid state
        System.out.println("Not a safe state!");
      }
    }
  }
  return retArr;
}
```

The basic idea of `getSuccessors` is that it returns an array of valid states based off of the node that was passed in. So, given the first start node: (331), it will run through each combination of missionaries and cannibals. So it checks 3 Missionaries and 3 Cannibals on the boat, then 3 Missionaries 2 Cannibals, then 3 Missionaries 1 Cannibal, 3 Missionaries 0 Cannibals, 2 Missionaries 1 Cannibal and so on. As per the drawing before, the valid states from a *getSuccessors* on (331) are: (220), (320), (310).

Then, it will check if that combination is valid for the boat size. Also check whether there is anybody on the boat itself to mark whether the edge is valid or not. If it is, it will add or subtract (depending on where the boat is) to create the new state. This new state is passed into the `isSafeState` to verify whether the missionaries are safe. If they are, return true. If not, return false.

```
// checks whether the humans get eaten :(
private boolean isSafeState(CannibalNode node){
  // miss + cannibals on starting side
  int startMissionaries = node.state[0];
  int startCannibals = node.state[1];
  // miss + cannibals on other side
  int otherMissionaries = totalMissionaries - startMissionaries;
  int otherCannibals = totalCannibals - startCannibals;

  if (startMissionaries != 0 && otherMissionaries != 0){
    // must have more missionaries than cannibals or else eaten :(
    if (startMissionaries >= startCannibals &&
        otherMissionaries >= otherCannibals){
      return true;
    }
  }
```

```java
  // If no missionaries are on one side, must mean missionaries are on other si
  // Therefore, we check if the missionaries are outnumbered on the other side
  // Also starting with 1 Cannibal and 0 Missionaries on starting side is NOT
  // a valid state
  if (otherMissionaries == 0){
    return startMissionaries >= startCannibals;
  }

  if (startMissionaries == 0){
    return otherMissionaries >= otherCannibals;
  }

  // not a safe state
  return false;
}
```

I used a method `isSafeState` that returns `true` if the missionaries do not get eaten by the cannibals. We can check this by first validating that there are missionaries on either side of the river. Then we MUST make sure that the cannibals cannot outnumber missionaries on either side.

If there are no missionaries on one side, that implies that all the missionaries are on the other side. Thus, we just need to check whether the missionaries are outnumbered on the other side. This will cover the edge case where there are no missionaries but more than 0 cannibals on the same side. Without this edge case, the algorithm would not correctly process a node like (031).

Overall, I tested both methods by manually expanding the states graph from the initial problem setup of (331) and then cross-checking with the results that the `getSuccessors` method yields. This verifies the method for the first level. We could test the second and third levels in the states graph via grabbing the array returned by the first `getSuccessors` method and calling `getSuccessors` again on one of the valid states.

Below is the code for a private method in *CannibalProblem.java* and some manual code executed in *CannibalDriver.java*.

```java
private void testSuccessors(){
  ArrayList<UUSearchNode> retArr = startNode.getSuccessors();
  System.out.println(retArr);
}
```

```java
// Test levels 2 and 3
ArrayList<UUSearchNode> retArr = mcProblem.startNode.getSuccessors();
System.out.println(retArr.get(0).getSuccessors().get(1).getSuccessors());
```

Since the code works for levels 1, 2 and 3 and matches the actual valid states drawn manually, it covers the the cases for the boat going from one side to another. In other words, given an arbitrary state at level x, we get the valid successor states for state x+1 level. Thus, by induction, we prove the correctness of the code. We cross-reference with the drawing above to verify the states returned are valid states.

Hence the *getSuccessors*() and *isSafeState*() methods are correct.

0.3 Breadth-first search

```
public List<UUSearchNode> breadthFirstSearch(){
  resetStats();

  // Goal node that completes the search
  UUSearchNode goalNode = null;
  UUSearchNode grandparent = null;

  // Initialize queue with start node
  Queue<UUSearchNode> queue = new LinkedList<UUSearchNode>();
  queue.add(startNode);
  HashMap<Integer, UUSearchNode> visited = new HashMap<Integer, UUSearchNode>(

  while(!queue.isEmpty()){
    updateMemory(queue.size() + visited.size());
    System.out.println("Queue: " + queue);
    UUSearchNode parentNode = (UUSearchNode) queue.remove();
    System.out.println("Using " + parentNode);

    incrementNodeCount();

    // check if the goal has been reached
    if (parentNode.goalTest()){
      goalNode = parentNode;
      int key = parentNode.hashCode();
      visited.put(key, grandparent);
      break;
    }

    ArrayList<UUSearchNode> children = parentNode.getSuccessors();
    for(int i=0; i < children.size(); i++){
      // if haven't seen before
      UUSearchNode childNode = children.get(i);
      int nodeKey = childNode.hashCode();
      System.out.println(nodeKey);
      if (!visited.containsKey(nodeKey)){
        // mark previous node
        if (!queue.contains(childNode)){
          queue.add(childNode);
        }
      } else {
        System.out.println("Already seen " + childNode);
      }
    }
    // visited 'key' will contain the hashCode of the node
    // visited 'value' will contain the node's predecessor node
    // startNode has no predecessor
    int key = parentNode.hashCode();
```

```java
      visited.put(key, grandparent);

      // once all children have been added, mark this node visited
      grandparent = parentNode;

    }


    System.out.println(goalNode);

    // Check if goalNode has been found
    if (goalNode == null){
      return null;
    } else {
      // return the backchain link
      return backchain(goalNode, visited);
    }
  }

// backchain should only be used by bfs, not the recursive dfs
private List<UUSearchNode> backchain(UUSearchNode goalNode,
    HashMap<Integer, UUSearchNode> visited) {
  List<UUSearchNode> retArr = new ArrayList<UUSearchNode>();
  while (goalNode != null){
    retArr.add(goalNode);
    goalNode = visited.get(goalNode.hashCode());
  }
  return retArr;
}
```

We implement BFS with a queue and a HashMap (instead of a linked list which is not as efficient). The queue is FIFO and allows us to dequeue the startNode and enqueue its successors, then dequeue the first level of the startNode's successors and enqueue *their* successors etc. By nature of BFS, we successively check each depth level from the startNode. We also avoid duplicates by checking if the queue already contains some node.

The HashMap visited will keep track of which nodes have already been visited by using the provided *hashCode* function. The key of the HashMap is the hashcode of the node. The value of the HashMap is the predecessor node that links to it in the graph. We track the memory by considering the size of the queue and the size of the *visited* HashMap at any point. We also increment the nodes count each time we dequeue a node from the queue.

Thus, when we find the goalnode, we can simply use a *while* loop to backchain from goalnode using the *visited* HashMap to find its predecessor.

If no path is found, we return *null*. Otherwise, return the path via backchaining.

We test the BFS by running on state (331) and verifying that states are valid and that the path from start node to goal node make valid action edges.

```java
List<UUSearchProblem.UUSearchNode> path;
path = mcProblem.breadthFirstSearch();
```

```
if (path != null){
  System.out.println("bfs path length:  " + path.size() + " " + path);
  mcProblem.printStats();
  System.out.println("————————");
} else {
  System.out.println("————————");
  System.out.println("No path!");
}
```

The solution path, including the start node, is of length 15:

```
bfs path length: 15 [0, 0, 0, (11)|, 0, 2, 1, (10)|, 1, 1, 1, (10)|,
0, 1, 0, (9)|, 0, 3, 1, (8)|, 0, 2, 0, (7)|, 2, 2, 1, (6)|,
1, 1, 0, (5)|, 3, 1, 1, (4)|, 3, 0, 0, (3)|, 3, 2, 1, (2)|,
3, 2, 0, (1)|, 3, 1, 0, (1)|, 2, 2, 0, (1)|, 3, 3, 1, (0)|]
Nodes explored during last search: 15
Maximum memory usage during last search 15
```

We can manually verify that all the states are correctly reached through valid actions by actually tracing each iteration of the 2 for loops in the $getSuccessors()$ method. Then checking the path that BFS takes (it should explore each node in a depth first before continuing to the next depth).

```
Queue: [3, 3, 1, (0)|]
Using 3, 3, 1, (0)|
(1,3,0)
Not a safe state!
(2,2,0)
Adding 2, 2, 0, (1)|
(2,3,0)
Not a safe state!
(3,1,0)
Adding 3, 1, 0, (1)|
(3,2,0)
Adding 3, 2, 0, (1)|
Queue: [2, 2, 0, (1)|, 3, 1, 0, (1)|, 3, 2, 0, (1)|]
Using 2, 2, 0, (1)|
(3,3,1)
Adding 3, 3, 1, (2)|
(3,2,1)
Adding 3, 2, 1, (2)|
(2,3,1)
Not a safe state!
Already seen 3, 3, 1, (2)|
Queue: [3, 1, 0, (1)|, 3, 2, 0, (1)|, 3, 2, 1, (2)|]
Using 3, 1, 0, (1)|
(3,3,1)
Adding 3, 3, 1, (2)|
(3,2,1)
Adding 3, 2, 1, (2)|
Already seen 3, 3, 1, (2)|
```

```
Queue: [3, 2, 0, (1)|, 3, 2, 1, (2)|]
Using 3, 2, 0, (1)|
(3,3,1)
Adding 3, 3, 1, (2)|
Already seen 3, 3, 1, (2)|
Queue: [3, 2, 1, (2)|]
Using 3, 2, 1, (2)|
(1,2,0)
Not a safe state!
(2,1,0)
Not a safe state!
(2,2,0)
Adding 2, 2, 0, (3)|
(3,0,0)
Adding 3, 0, 0, (3)|
(3,1,0)
Adding 3, 1, 0, (3)|
Already seen 2, 2, 0, (3)|
Already seen 3, 1, 0, (3)|
Queue: [3, 0, 0, (3)|]
Using 3, 0, 0, (3)|
(3,2,1)
Adding 3, 2, 1, (4)|
(3,1,1)
Adding 3, 1, 1, (4)|
Already seen 3, 2, 1, (4)|
Queue: [3, 1, 1, (4)|]
Using 3, 1, 1, (4)|
(1,1,0)
Adding 1, 1, 0, (5)|
(2,0,0)
Not a safe state!
(2,1,0)
Not a safe state!
(3,0,0)
Adding 3, 0, 0, (5)|
Already seen 3, 0, 0, (5)|
Queue: [1, 1, 0, (5)|]
Using 1, 1, 0, (5)|
(3,1,1)
Adding 3, 1, 1, (6)|
(2,2,1)
Adding 2, 2, 1, (6)|
(2,1,1)
Not a safe state!
(1,3,1)
Not a safe state!
(1,2,1)
Not a safe state!
Already seen 3, 1, 1, (6)|
```

```
Queue: [2, 2, 1, (6)|]
Using 2, 2, 1, (6)|
(0,2,0)
Adding 0, 2, 0, (7)|
(1,1,0)
Adding 1, 1, 0, (7)|
(1,2,0)
Not a safe state!
(2,0,0)
Not a safe state!
(2,1,0)
Not a safe state!
Already seen 1, 1, 0, (7)|
Queue: [0, 2, 0, (7)|]
Using 0, 2, 0, (7)|
(2,2,1)
Adding 2, 2, 1, (8)|
(1,3,1)
Not a safe state!
(1,2,1)
Not a safe state!
(0,3,1)
Adding 0, 3, 1, (8)|
Already seen 2, 2, 1, (8)|
Queue: [0, 3, 1, (8)|]
Using 0, 3, 1, (8)|
(0,1,0)
Adding 0, 1, 0, (9)|
(0,2,0)
Adding 0, 2, 0, (9)|
Already seen 0, 2, 0, (9)|
Queue: [0, 1, 0, (9)|]
Using 0, 1, 0, (9)|
(2,1,1)
Not a safe state!
(1,2,1)
Not a safe state!
(1,1,1)
Adding 1, 1, 1, (10)|
(0,3,1)
Adding 0, 3, 1, (10)|
(0,2,1)
Adding 0, 2, 1, (10)|
Already seen 0, 3, 1, (10)|
Queue: [1, 1, 1, (10)|, 0, 2, 1, (10)|]
Using 1, 1, 1, (10)|
(0,0,0)
Adding 0, 0, 0, (11)|
(0,1,0)
Adding 0, 1, 0, (11)|
```

```
(1,0,0)
Not a safe state!
Already seen 0, 1, 0, (11)|
Queue: [0, 2, 1, (10)|, 0, 0, 0, (11)|]
Using 0, 2, 1, (10)|
(0,0,0)
Adding 0, 0, 0, (11)|
(0,1,0)
Adding 0, 1, 0, (11)|
Already seen 0, 1, 0, (11)|
Queue: [0, 0, 0, (11)|]
Using 0, 0, 0, (11)|
0, 0, 0, (11)|
```

The above sequence validates BFS is working correctly and taking the correct paths for the problem of (331).

0.4 Memoizing depth-first search

```java
public List<UUSearchNode> depthFirstMemoizingSearch(int maxDepth) {
  resetStats();

  // You will write this method
  List<UUSearchNode> retArr = new ArrayList<UUSearchNode>();
  HashMap<UUSearchNode, Integer>visited = new HashMap<UUSearchNode, Integer>();

  List<UUSearchNode> startChildren = startNode.getSuccessors();

  // mark startNode as visited
  visited.put(startNode, startNode.getDepth());

  for(int i=0; i < startChildren.size(); i++){
    UUSearchNode child = startChildren.get(i);
    if (!visited.containsKey(child)){
      retArr = dfs(child, visited, child.getDepth(), CannibalDriver.MAXDEPTH);
      if (retArr != null){
        return retArr;
      }
    }

  }
  return null;
}

// recursive memoizing dfs. Private, because it has the extra
// parameters needed for recursion.
private List<UUSearchNode> dfs(UUSearchNode currentNode, HashMap<UUSearchNode,
    int depth, int maxDepth) {
  System.out.println("Following " + currentNode);

  // keep track of stats; these calls charge for the current node
```

```java
    updateMemory(visited.size());
    incrementNodeCount();
    List<UUSearchNode> retArr= new ArrayList<UUSearchNode>();

    // you write this method.  Comments *must* clearly show the
    //  "base case" and "recursive case" that any recursive function has.

    // BASE CASE: currentNode is the goal Node
    if (currentNode.goalTest()){
      retArr.add(currentNode);
      return retArr;
    } else {
      // RECURSIVE CASE: not the goalNode, continue recursing down successor line
      List<UUSearchNode> currentChildren = currentNode.getSuccessors();
      visited.put(currentNode, currentNode.getDepth());

      // stop if the depth is exceeded
      if (depth > maxDepth){
        System.out.println("Depth exceeded! Try a shorter route");
        return null;
      }

      for(int i=0; i < currentChildren.size(); i++){
        UUSearchNode child = currentChildren.get(i);

        // if it is depth limited, we need to make sure that the DFS doesn't stop
        // a duplicate (compare depths)
        if (!visited.containsKey(child) || visited.get(child) > depth){
          retArr = dfs(child, visited, child.getDepth(), maxDepth);
          if (retArr != null){
            retArr.add(child);
            return retArr;
          }
        }
      }
    System.out.println("No path found!");
      return null;
    }

}
```

We start by initializing the array which will be returned as the solution. We also initialize the HashMap which will mark whether the node has been visited and will have the key as the depth. We add the depth because, in some cases, if one sets a MAX DEPTH for DFS, DFS may explore one path and exceed this max depth. Then, when DFS checks shorter paths, it may run into a duplicate. We want DFS to continue if this duplicate's depth is smaller than the original node's depth. Hence, we add the *visited.get*(*child*) > *depth* method in the recursive DFS method.

The base case for memoizing DFS is if the node being examined is the goal node. In that case, we do not enter the recursive case and we can simply add this goal node into a list and return it.

The recursive case is if the node being examined is NOT the goal node. We also make checks so that the depth does not exceed $maxDepth$.

We loop through each one of the $startNode$'s successors and then run the recursive DFS method on them. In the recursive DFS function, if the node has already been seen, we return *null*. If the node has not been seen, we run recursive DFS again on each of the node's successors.

When the goal node is finally reached, as said before, we add it to a list and return that list. Then in the recursive DFS function, if the returned list is NOT *null*, then we add the currently examined node to that list and return the expanded list. In this way, we build the solution from the ground-up, starting with the goal node and then progressively adding nodes that link to one another.

However, memoizing dfs does NOT save significant memory compared to BFS. First, we consider whether the state space is finite or infinite. Given a finite state space of size n, the HashMap implemented in both DFS and BFS cannot exceed n nodes at any given time. Thus, both BFS and DFS implementations in the finite search space have $O(n)$ memory usage. Thus, they have the same $O(n)$ memory usage although DFS may have *slightly* lower memory usage compared to BFS if we find the goal soon and the *visited* set is small. But if one finds the goal late, memory usage will be higher. In contrast, BFS goes through each depth successively.

However, by nature of BFS, because it ripples out from the start node and checks each successive depth from the start node, in an infinite state space, BFS will terminate with time complexity $O(b^d)$, where d is the depth of the goal from start node and b is the upper bound of the graph's branching factor.

Conversely, in an infinite search space, DFS may not even terminate (without a MAXDEPTH limit)! Hence, in some cases, DFS may have substantially more exhaustive memory usage. However, as in the case of (331), it is possible for DFS to find the optimal path in the first "go" without backchaining. Thus, in these rare scenarios, could save some memory.

However, this is not consistent. Furthermore, DFS does not guarantee an optimal path if the goal is close. Thus, one should not use memoizing DFS over BFS unless one has a very good reason to do so:

```
List<UUSearchProblem.UUSearchNode> path;
path = mcProblem.depthFirstMemoizingSearch(MAXDEPTH);
if (path != null){
  System.out.println("dfs memoizing path length:" + path.size());
  mcProblem.printStats();
  System.out.println("--------");
}
```

```
dfs memoizing path length:11
Nodes explored during last search:  11
Maximum memory usage during last search 11

(1,3,0)
Not a safe state!
```

```
(2,2,0)
Adding 2, 2, 0, (1)|
(2,3,0)
Not a safe state!
(3,1,0)
Adding 3, 1, 0, (1)|
(3,2,0)
Adding 3, 2, 0, (1)|
Following 2, 2, 0, (1)|
(3,3,1)
Adding 3, 3, 1, (2)|
(3,2,1)
Adding 3, 2, 1, (2)|
(2,3,1)
Not a safe state!
Following 3, 2, 1, (2)|
(1,2,0)
Not a safe state!
(2,1,0)
Not a safe state!
(2,2,0)
Adding 2, 2, 0, (3)|
(3,0,0)
Adding 3, 0, 0, (3)|
(3,1,0)
Adding 3, 1, 0, (3)|
Following 3, 0, 0, (3)|
(3,2,1)
Adding 3, 2, 1, (4)|
(3,1,1)
Adding 3, 1, 1, (4)|
Following 3, 1, 1, (4)|
(1,1,0)
Adding 1, 1, 0, (5)|
(2,0,0)
Not a safe state!
(2,1,0)
Not a safe state!
(3,0,0)
Adding 3, 0, 0, (5)|
Following 1, 1, 0, (5)|
(3,1,1)
Adding 3, 1, 1, (6)|
(2,2,1)
Adding 2, 2, 1, (6)|
(2,1,1)
Not a safe state!
(1,3,1)
Not a safe state!
(1,2,1)
```

```
Not a safe state!
Following 2, 2, 1, (6)|
(0,2,0)
Adding 0, 2, 0, (7)|
(1,1,0)
Adding 1, 1, 0, (7)|
(1,2,0)
Not a safe state!
(2,0,0)
Not a safe state!
(2,1,0)
Not a safe state!
Following 0, 2, 0, (7)|
(2,2,1)
Adding 2, 2, 1, (8)|
(1,3,1)
Not a safe state!
(1,2,1)
Not a safe state!
(0,3,1)
Adding 0, 3, 1, (8)|
Following 0, 3, 1, (8)|
(0,1,0)
Adding 0, 1, 0, (9)|
(0,2,0)
Adding 0, 2, 0, (9)|
Following 0, 1, 0, (9)|
(2,1,1)
Not a safe state!
(1,2,1)
Not a safe state!
(1,1,1)
Adding 1, 1, 1, (10)|
(0,3,1)
Adding 0, 3, 1, (10)|
(0,2,1)
Adding 0, 2, 1, (10)|
Following 1, 1, 1, (10)|
(0,0,0)
Adding 0, 0, 0, (11)|
(0,1,0)
Adding 0, 1, 0, (11)|
(1,0,0)
Not a safe state!
Following 0, 0, 0, (11)|
```

0.5 Path-checking depth-first search

In Path-checking DFS, we ensure that the current path does not contain duplicates by using a set, currentPath. As a result, we avoid infinite loops. Each time we're about to call *getSuccessors*() on a child node, we check the set to ensure that it has not already been added. Thus, we don't track all states once, just the ones on the current path.

This only ensures that there are no duplicates in the *current* path, but we could run into redundant nodes in other paths. The benefit, however, is that we use less memory than simply memoizing everything as in the previous memoizing DFS.

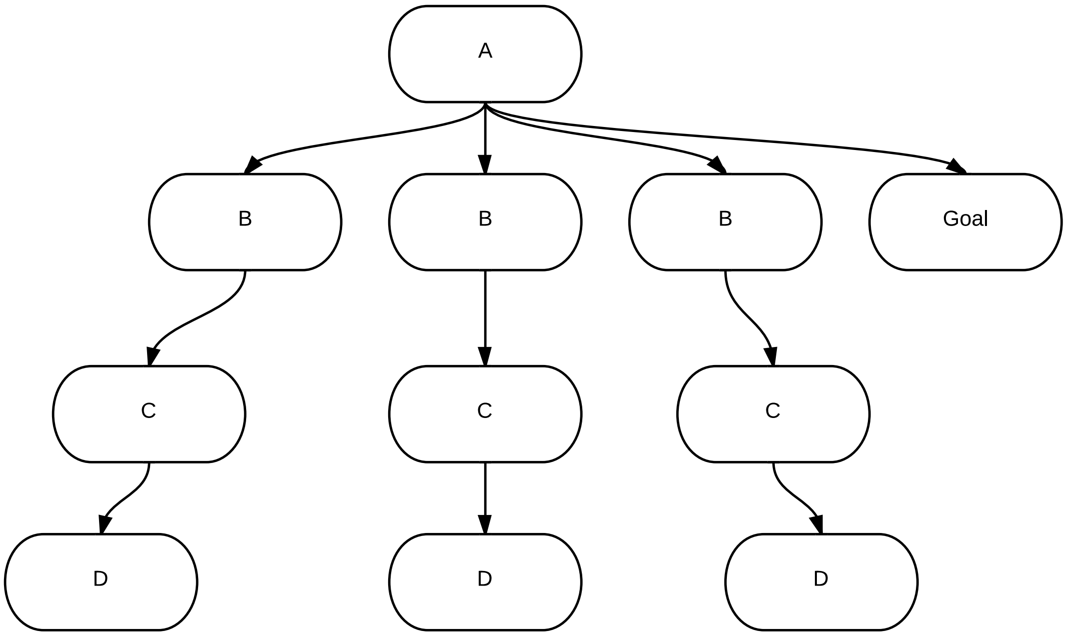
```
// set up the depth-first-search (path-checking version),
//  but call dfspc to do the real work
public List<UUSearchNode> depthFirstPathCheckingSearch(int maxDepth) {
  resetStats();

  // I wrote this method for you.  Nothing to do.
  HashSet<UUSearchNode> currentPath = new HashSet<UUSearchNode>();

  return dfsrpc(startNode, currentPath, 0, maxDepth);
}

// recursive path-checking dfs. Private, because it has the extra
// parameters needed for recursion.
private List<UUSearchNode> dfsrpc(UUSearchNode currentNode, HashSet<UUSearchNoc
    int depth, int maxDepth) {

  // you write this method
  System.out.println("Following " + currentNode);
  currentPath.add(currentNode);

  // keep track of stats; these calls charge for the current node
  updateMemory(currentPath.size());
  incrementNodeCount();
  List<UUSearchNode> retArr= new ArrayList<UUSearchNode>();

  // you write this method.  Comments *must* clearly show the
  //  "base case" and "recursive case" that any recursive function has.

  // BASE CASE: currentNode is the goal Node
  if (currentNode.goalTest()){
    retArr.add(currentNode);
    return retArr;
  } else {
    // RECURSIVE CASE: not the goalNode, continue recursing down successor line
    List<UUSearchNode> currentChildren = currentNode.getSuccessors();

    // stop if the depth is exceeded
    if (depth > maxDepth){
      System.out.println("Depth exceeded! Try a shorter route");
      return null;
    }
```

```
    for(int i=0; i < currentChildren.size(); i++){
      UUSearchNode child = currentChildren.get(i);

      // if it is depth limited, we need to make sure that the DFS doesn't stop
      // a duplicate (compare depths)
      if (!currentPath.contains(child)){
        retArr = dfsrpc(child, currentPath, child.getDepth(), maxDepth);
        if (retArr != null){
          retArr.add(child);
          return retArr;
        }
      }
    }
    return null;
  }

}
```

It depends on the graph that path-checking DFS and BFS are run, but generally path-checking does save a lot of memory given a looping graph. BFS could store all the nodes on the graph in its *visited* set so that its memory cost is n nodes. In this situation, path-checking's *currentPath* only stores the nodes found in the current path. The current path to the goalNode could only contain a small fraction of such nodes and save significant amounts of memory. While the memory allocated still needs to accomodate n nodes because hypothetically the *currentPath* set could contain n nodes, on average, depending on the graph, significant memory could be saved via path-checking.

However, the trade-off, as said before, is that one may run into redundant paths and increase the runtime of the path-checking DFS. This is a potential cost of nodes being visited twice.

Path-checking DFS may face a graph with many non-looping paths. Then it will check redundant paths over and over. Consider the following example where path-checking DFS takes much more run-time than BFS:


A
B
B
B
Goal
C
C
C
D
D
D

In this graph, path-checking BFS will separately check 3 branches of B-C-D in the runtime. In contrast, BFS will check the B node first, then skip the other 2 B nodes and arrive at G. Thus, path-checking BFS faces a graph with many non-loops and traverses many redundant paths. Hence, it takes much more runtime than BFS, especially if the branching factor of such non-loop paths is high.

0.6 Iterative deepening search

```
public List<UUSearchNode> IDSearch(int maxDepth) {
  resetStats();
  for(int i=0; i <= maxDepth; i++){
    HashMap<UUSearchNode, Integer> visited = new HashMap<UUSearchNode, Integer >
    List<UUSearchNode> retArr = dfs(startNode, visited, 0, maxDepth);
    if (retArr != null){
      return retArr;
    }
  }
  System.out.println("No path found!");
  return null;
}
```

BFS finds the shortest path because it goes from smallest depth to longest. Iterative deepening search mimics this by restricting the DFS to depth 0 at first and then slowly incrementing the depth when it doesn't find the goal. So if the goal is at layer 3, IDS will do DFS on all paths at level depth 0, then depth 1, then depth 2, and finally at depth 3 where it finds the goal. If IDS does find the goal, then that goal is optimal because we do not check any nodes deeper than the goal depth.

IDS does not take huge amounts of memory as its requisite memory is bound by maxdepth. To see why, consider the longest paths. The longest path in layer 1 is 1. The longest path in layer 2 is 2. Thus, the longest path is bounded by the maximum depth provided in IDS. Thus, we can check layer 1, then dump the memory information if goal is not found. And continue doing the same for the next layers.

IDS's runtime is not worse than BFS as the max depth is limited as well. The IDS's most expensive DFS will be about the same as BFS's worst case. Thus, it is very efficient. One scenario where IDS could be slow is if the graph has many branches at each depth.

Whether I would prefer memoizing DFS or path-checking DFS would depend on the graph I am searching. If the graph has many branches in each of its depths and many redundant nodes in such paths, memoizing may be a good idea. It would prevent duplication of effort at the expense of more memory. However, IDS with memoizing would not be better than BFS, so I would simply revert to BFS.

If the graph has many loops in its current paths at each depth, path-checking DFS would be a good idea as it would use less memory and have roughly the same runtime because there is little duplication of effort given that we assume few redundant paths. In this situation, path-checking with IDS would save on memory compared to BFS as BFS memoizes all states that have been visited.

0.7 Lossy missionaries and cannibals

We can still define the state of the lossy missionaries and cannibals problem with (m, c, b) where m is the number of missionaries, c is the number of cannibals and b is the side that the boat is on. Hence, given the original problem with E missionaries willing to be eaten, we can still define the problem as (3, 3, 1).

To implement the concept of "lossy" missionaries, we can define the static constant E in the CannibalDriver.java, as we did with the MAX DEPTH constant. Then, we would simply modify $isSafeState()$ function.

We can modify the if statement in $isSafeState()$ where in the original problem, checks whether there are more cannibals than missionaries. With E missionaries now willing to die, we can check whether the side opposite of the boat has E or less missionaries.

If so, it will be safe to send any number of cannibals to that side (with 0 missionaries). Or send any number of missionaries with cannibals to that side such that the total number of resultant missionaries (when the boat arrives) is still less than E.

An if statement like this would work:

```
if (startMissionaries + missionariesSent <= E && boatPlace == 0){
  return true;
}
```

Or conversely, for the other side:

```
if (otherMissionaries + missionariesSent <= E && boatPlace == 1){
  return true;
}
```

We would also need to keep track of how many missionaries have been eaten already, perhaps through a variable called *eatenCount*. We use this variable in order to calculate the missionaries on the other side. For instance if *eatenCount* $== 2$, then if the current state is at $(1, 1, 0)$. Given the original problem, then we know that are 0 missionaries on the other side and 2 cannibals on the other side.

The total upper bound for valid and invalid states is the same. For the given 3 missionaries, 3 cannibals and boat on starting side, the total number of valid/invalid states is still $4 \cdot 4 \cdot 2$.