

CSC 211: Computer Programming

(Recursive) Backtracking

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Images and material from web.stanford.edu

Recursion Reminder

- Problem solving technique in which we solve a task by reducing it to smaller tasks (of the same kind)
 - then use same approach to solve the smaller tasks
- Technically, a recursive function is one that **calls itself**
- General form:
 - **base case**
 - solution for a **trivial case**
 - it can be used to stop the recursion (prevents "stack overflow")
 - every recursive algorithm needs at least one base case
 - **recursive call(s)**
 - divide problem into **smaller instance(s)** of the **same structure**

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Recursion Reminder

- Recursive Checklist:
 - **Find what information we need to keep track of.** What inputs/outputs are needed to solve the problem at each step?
 - **Find our base case(s).** What are the simplest (nonrecursive) instance(s) of this problem?
 - **Find our recursive step.** How can this problem be solved in terms of one or more simpler instances of the same problem that lead to a base case?
 - **Ensure every input is handled.** Do we cover all possible cases? Do we need to handle errors?

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 - **Ensure every input is handled.** Do we cover all possible cases? Do we need to handle errors?

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Backtracking

- Write a recursive function `printAllBinary` that accepts an integer number of digits and prints all binary numbers that have exactly that many digits, in ascending order, one per line

`printAllBinary(2);`

00
01
10
11

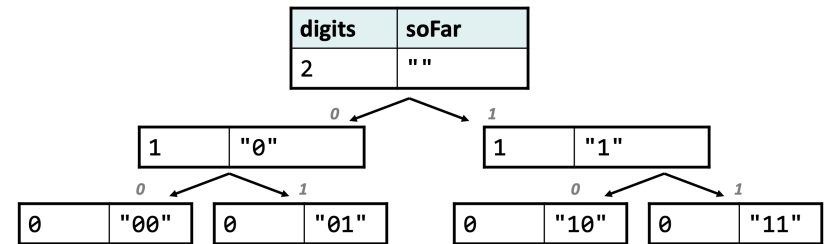
`printAllBinary(3);`

000
001
010
011
100
101
110
111

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Decision Trees

`printAllBinary(2);`

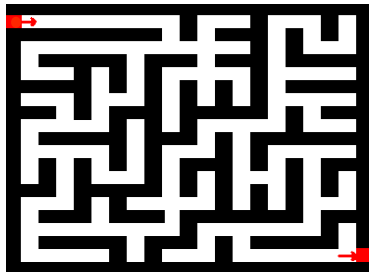


- This kind of diagram is called a **call tree** or **decision tree**
- Think of each call as a choice or decision made by the algorithm:
 - Should I choose 0 as the next digit?
 - Should I choose 1 as the next digit?
- The idea is to try every permutation. For every position, there are 2 options, either '0' or '1'. **Backtracking** can be used in this approach to try every possibility or permutation to generate the correct set of strings.

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Backtracking

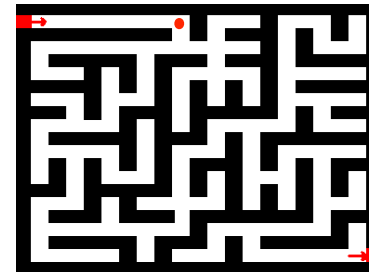
- Recursive Backtracking:** using recursion to explore solutions to a problem and abandoning them if they are not suitable



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Backtracking

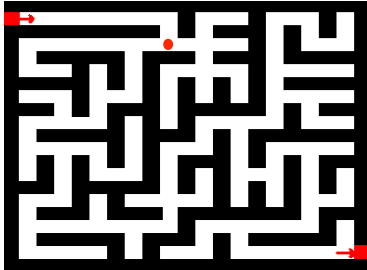
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Backtracking

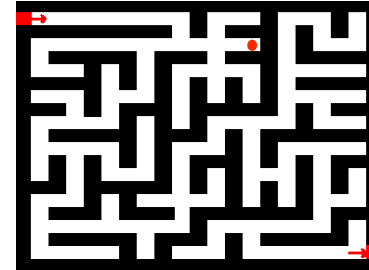
- › **Recursive Backtracking:** using recursion to explore solutions to a problem and abandoning them if they are not suitable



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Backtracking

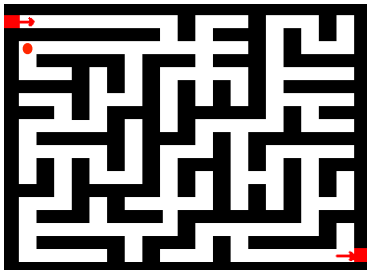
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Backtracking

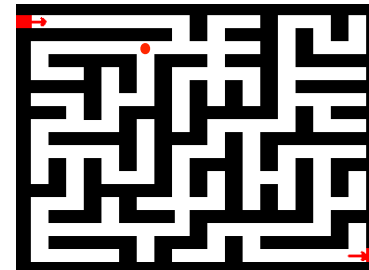
- › **Recursive Backtracking:** using recursion to explore solutions to a problem and abandoning them if they are not suitable



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Backtracking

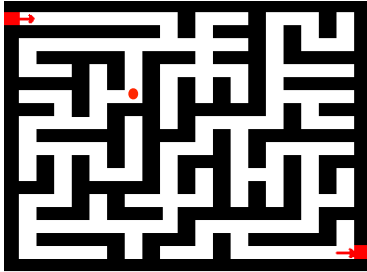
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Backtracking

- **Recursive Backtracking**: using recursion to explore solutions to a problem and abandoning them if they are not suitable



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Backtracking

- Let's take a look at a problem similar to the binarySequence problem.

	diceRoll(2)		
▸ Write a recursive function diceRoll that accepts an integer representing a number of 6-sided dice to roll, and output all possible permutations of values that could appear on the dice.	{1,1}	{3, 1}	{5, 1}
	{1, 2}	{3, 2}	{5, 2}
	{1, 3}	{3, 3}	{5, 3}
	{1, 4}	{3, 4}	{5, 4}
	{1, 5}	{3, 5}	{5, 5}
	{1, 6}	{3, 6}	{5, 6}
	{2, 1}	{4, 1}	{6, 1}
	{2, 2}	{4, 2}	{6, 2}
	{2, 3}	{4, 3}	{6, 3}
	{2, 4}	{4, 4}	{6, 4}
	{2, 5}	{4, 5}	{6, 5}
	{2, 6}	{4, 6}	{6, 6}

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Backtracking

- Backtracking Checklist:

- ✓ **Find what choice(s) we have at each step.** What different options are there for the next step?

For each valid choice:

- **Make it and explore recursively.** Pass the information for a choice to the next recursive call(s).
- **Undo it after exploring.** Restore everything to the way it was before making this choice.

- ✓ **Find our base case(s).** What should we do when we are out of decisions?

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Backtracking

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What die value should I choose next?

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Backtracking

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For each valid choice:

- **Make it and explore recursively.** Pass the information for a choice to the next recursive call(s).

- **Undo it after exploring.** Restore everything to the way it was before making this choice.

- ✓ Find our base case(s). What should we do when we are out of decisions?

We need to communicate the dice chosen so far to the next recursive call

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Backtracking

Backtracking Checklist:

- ✓ Find what choice(s) we have at each step. What different options are there for the next step?

We need to be able to remove the die we added to our first roll so far

For each valid choice:

- **Make it and explore recursively.** Pass the information for a choice to the next recursive call(s).

- **Undo it after exploring.** Restore everything to the way it was before making this choice.

- ✓ Find our base case(s). What should we do when we are out of decisions?

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Backtracking

Backtracking Checklist:

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For each valid choice:

- **Make it and explore recursively.** Pass the information for a choice to the next recursive call(s).

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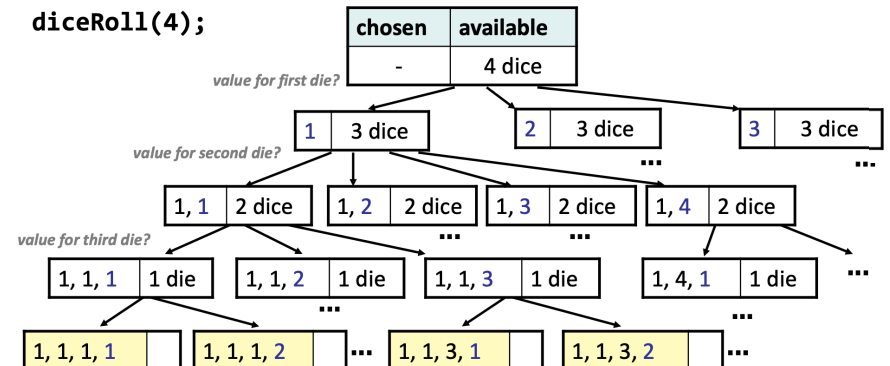
- ✓ Find our base case(s). What should we do when we are out of decisions?

We have no dice left to choose, print them out

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Backtracking

diceRoll(4);



• Observations?

• This is a really big search space.

• Depending on approach, we can make wasteful decisions. Can we optimize it? Yes. Will we right now? No.

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Backtracking

- Let's us write flexible code, allowing us to make a decision and "backtrack" if we need to

5	3			7				
6			1	9	5			
	9	8					6	
8				6				3
4			8		3			1
7				2				6
	6					2	8	
			4	1	9			5
				8			7	9

5	3	4	6	7	8	9	1	2
6	7	2	1	9	5	3	4	8
1	9	8	3	4	2	5	6	7
8	5	9	7	6	1	4	2	3
4	2	6	8	5	3	7	9	1
7	1	3	9	2	4	8	5	6
9	6	1	5	3	7	2	8	4
2	8	7	4	1	9	6	3	5
3	4	5	2	8	6	1	7	9

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Backtracking

- Pseudocode**
- function diceRolls(dice, chosenArr):
 - if dice == 0:
 - Print current roll.
 - else:
 - // handle all roll values for a single die; let recursion do the rest.
 - for each die value i in range [1..6]:
 - choose that the current die will have value i
 - // explore the remaining dice
 - diceRolls(dice-1, chosenArr)
 - un-choose (*backtrack*) the value I

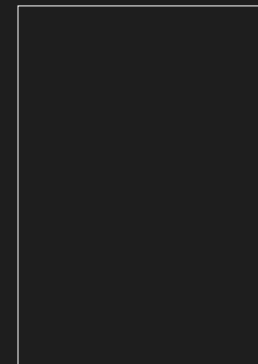
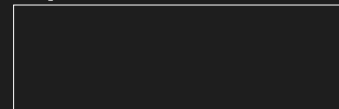
** Need to keep track of our choices somehow

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Code Demo

Recursive Backtracking Trace

Output for diceRolls (2):



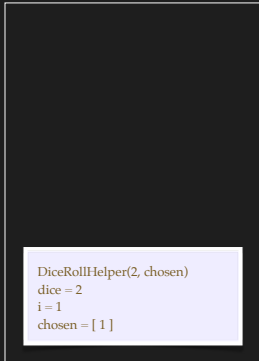
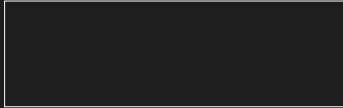
Stack

```
void diceRollHelper(int dice, std::vector<int>& chosen) {
    // Base Case
    if (dice == 0) {
        //Print out contents of vector {1,1}
        std::cout << "{";
        for(int i=0; i < chosen.size(); i++){
            std::cout << chosen.at(i);
            if(i < chosen.size() -1){
                std::cout << ",";
            }
        }
        std::cout << "}" << "\n";
    }
    //Recursive case
    else {
        for (int i = 1; i <= 6; i++) {
            chosen.push_back(i);
            diceRollHelper(dice - 1, chosen);
            chosen.pop_back();
        }
    }
}
```

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Recursive Backtracking Trace

Output for diceRolls (2):



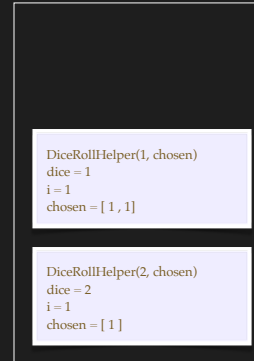
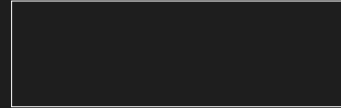
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Recursive Backtracking Trace

Output for diceRolls (2):



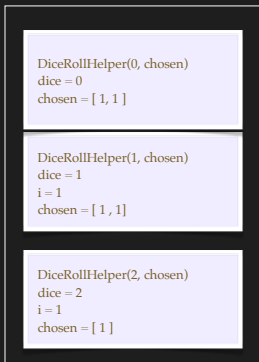
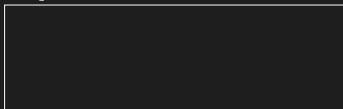
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Recursive Backtracking Trace

Output for diceRolls (2):



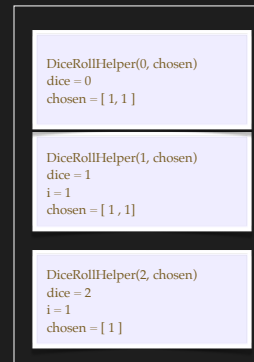
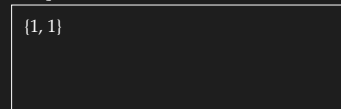
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    }  
}
```

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Recursive Backtracking Trace

Output for diceRolls (2):



Stack

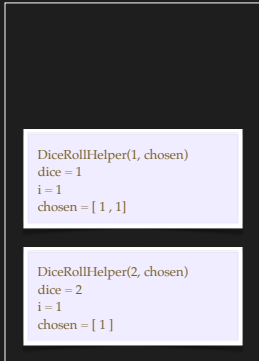
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    }  
}
```

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Recursive Backtracking Trace

Output for diceRolls (2):

{1, 1}



Stack

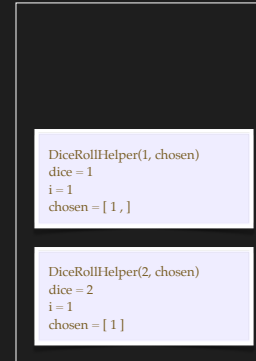
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    }  
}
```

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Recursive Backtracking Trace

Output for diceRolls (2):

{1, 1}



Stack

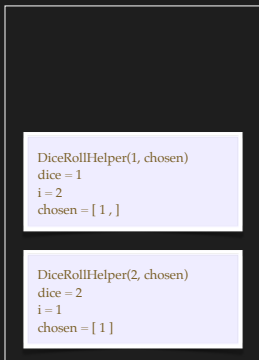
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        }  
    }  
}
```

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Recursive Backtracking Trace

Output for diceRolls (2):

{1, 1}



Stack

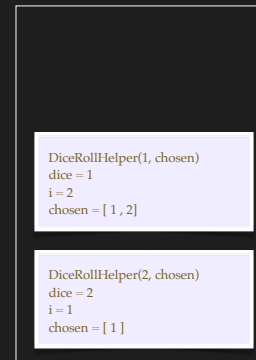
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}
```

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Recursive Backtracking Trace

Output for diceRolls (2):

{1, 1}



Stack

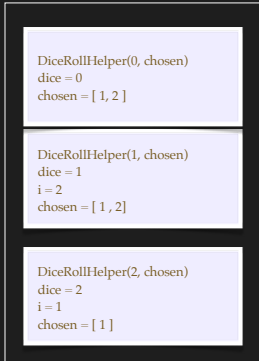
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Recursive Backtracking Trace

Output for diceRolls (2):

{1, 1}



Stack

```

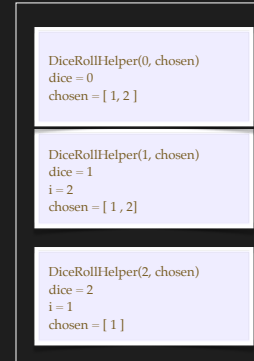
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            chosen.pop_back();
        }
    }
}
    
```

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Recursive Backtracking Trace

Output for diceRolls (2):

{1, 1}
{1, 2}



Stack

```

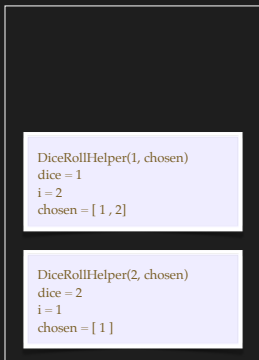
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    }
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```

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Recursive Backtracking Trace

Output for diceRolls (2):

{1, 1}
{1, 2}



Stack

```

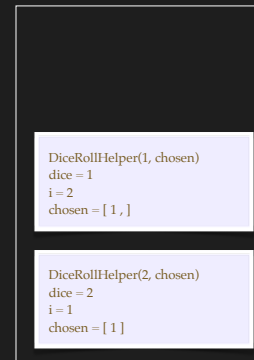
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Recursive Backtracking Trace

Output for diceRolls (2):

{1, 1}
{1, 2}



Stack

```

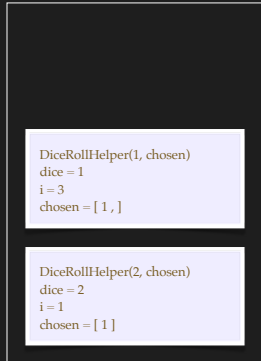
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```

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Recursive Backtracking Trace

Output for diceRolls (2):

```
{1, 1}
{1, 2}
```



Stack

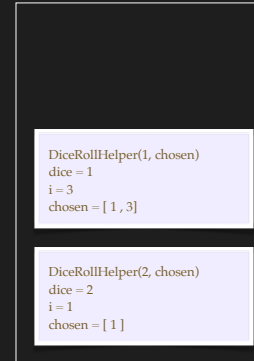
```
void diceRollHelper(int dice, std::vector<int>& chosen) {  
    // Base Case  
    if (dice == 0) {  
        //Print out contents of vector {1,1}  
        std::cout << "{";  
        for(int i=0; i < chosen.size(); i++){  
            std::cout << chosen.at(i);  
            if(i < chosen.size() -1){  
                std::cout << ",";  
            }  
        }  
        std::cout << "} \n";  
    }  
    //Recursive case  
    else {  
        for (int i = 1; i <= 6; i++) {  
            chosen.push_back(i);  
            diceRollHelper(dice - 1, chosen);  
            chosen.pop_back();  
        }  
    }  
}
```

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Recursive Backtracking Trace

Output for diceRolls (2):

```
{1, 1}
{1, 2}
```



Stack

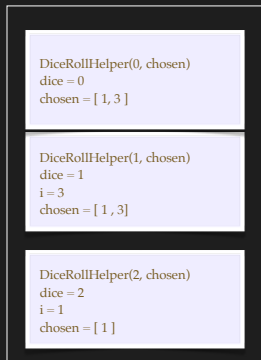
```
void diceRollHelper(int dice, std::vector<int>& chosen) {  
    // Base Case  
    if (dice == 0) {  
        //Print out contents of vector {1,1}  
        std::cout << "{";  
        for(int i=0; i < chosen.size(); i++){  
            std::cout << chosen.at(i);  
            if(i < chosen.size() -1){  
                std::cout << ",";  
            }  
        }  
        std::cout << "} \n";  
    }  
    //Recursive case  
    else {  
        for (int i = 1; i <= 6; i++) {  
            chosen.push_back(i);  
            diceRollHelper(dice - 1, chosen);  
            chosen.pop_back();  
        }  
    }  
}
```

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Recursive Backtracking Trace

Output for diceRolls (2):

```
{1, 1}
{1, 2}
```



Stack

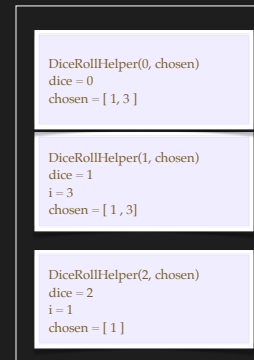
```
void diceRollHelper(int dice, std::vector<int>& chosen) {  
    // Base Case  
    if (dice == 0) {  
        //Print out contents of vector {1,1}  
        std::cout << "{";  
        for(int i=0; i < chosen.size(); i++){  
            std::cout << chosen.at(i);  
            if(i < chosen.size() -1){  
                std::cout << ",";  
            }  
        }  
        std::cout << "} \n";  
    }  
    //Recursive case  
    else {  
        for (int i = 1; i <= 6; i++) {  
            chosen.push_back(i);  
            diceRollHelper(dice - 1, chosen);  
            chosen.pop_back();  
        }  
    }  
}
```

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Recursive Backtracking Trace

Output for diceRolls (2):

```
{1, 1}
{1, 2}
{1, 3}
```



Stack

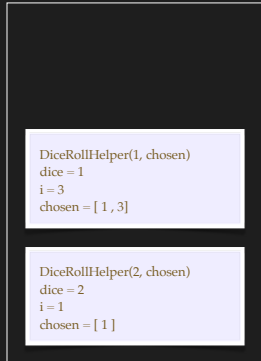
```
void diceRollHelper(int dice, std::vector<int>& chosen) {  
    // Base Case  
    if (dice == 0) {  
        //Print out contents of vector {1,1}  
        std::cout << "{";  
        for(int i=0; i < chosen.size(); i++){  
            std::cout << chosen.at(i);  
            if(i < chosen.size() -1){  
                std::cout << ",";  
            }  
        }  
        std::cout << "} \n";  
    }  
    //Recursive case  
    else {  
        for (int i = 1; i <= 6; i++) {  
            chosen.push_back(i);  
            diceRollHelper(dice - 1, chosen);  
            chosen.pop_back();  
        }  
    }  
}
```

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Recursive Backtracking Trace

Output for diceRolls (2):

```
{1, 1}
{1, 2}
{1, 3}
```



Stack

```
void diceRollHelper(int dice, std::vector<int>& chosen) {  
    // Base Case  
    if (dice == 0) {  
        //Print out contents of vector {1,1}  
        std::cout << "{";  
        for(int i=0; i < chosen.size(); i++){  
            std::cout << chosen.at(i);  
            if(i < chosen.size() -1){  
                std::cout << ",";  
            }  
        }  
        std::cout << "} \n";  
    }  
    //Recursive case  
    else {  
        for (int i = 1; i <= 6; i++) {  
            chosen.push_back(i);  
            diceRollHelper(dice - 1, chosen);  
            chosen.pop_back();  
        }  
    }  
}
```

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Recursive Backtracking Trace

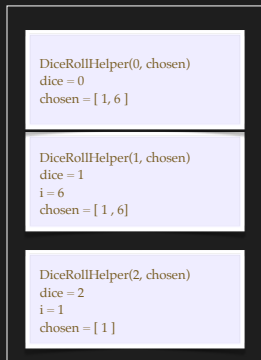
Fastforward...

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Recursive Backtracking Trace

Output for diceRolls (2):

```
{1, 1} {1, 5}  
{1, 2} {1, 6}  
{1, 3}  
{1, 4}
```



Stack

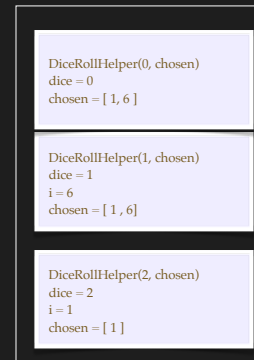
```
void diceRollHelper(int dice, std::vector<int>& chosen) {  
    // Base Case  
    if (dice == 0) {  
        //Print out contents of vector {1,1}  
        std::cout << "{";  
        for(int i=0; i < chosen.size(); i++){  
            std::cout << chosen.at(i);  
            if(i < chosen.size() -1){  
                std::cout << ",";  
            }  
        }  
        std::cout << "} \n";  
    }  
    //Recursive case  
    else {  
        for (int i = 1; i <= 6; i++) {  
            chosen.push_back(i);  
            diceRollHelper(dice - 1, chosen);  
            chosen.pop_back();  
        }  
    }  
}
```

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Recursive Backtracking Trace

Output for diceRolls (2):

```
{1, 1} {1, 5}  
{1, 2} {1, 6}  
{1, 3}  
{1, 4}
```



Stack

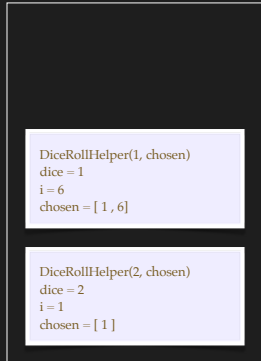
```
void diceRollHelper(int dice, std::vector<int>& chosen) {  
    // Base Case  
    if (dice == 0) {  
        //Print out contents of vector {1,1}  
        std::cout << "{";  
        for(int i=0; i < chosen.size(); i++){  
            std::cout << chosen.at(i);  
            if(i < chosen.size() -1){  
                std::cout << ",";  
            }  
        }  
        std::cout << "} \n";  
    }  
    //Recursive case  
    else {  
        for (int i = 1; i <= 6; i++) {  
            chosen.push_back(i);  
            diceRollHelper(dice - 1, chosen);  
            chosen.pop_back();  
        }  
    }  
}
```

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Recursive Backtracking Trace

Output for diceRolls (2):

```
{1, 1} {1, 5}
{1, 2} {1, 6}
{1, 3}
{1, 4}
```



Stack

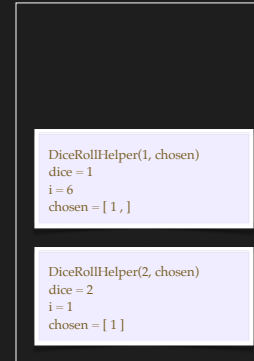
```
void diceRollHelper(int dice, std::vector<int>& chosen) {
    // Base Case
    if (dice == 0) {
        //Print out contents of vector {1,1}
        std::cout << "{";
        for(int i=0; i < chosen.size(); i++){
            std::cout << chosen.at(i);
            if(i < chosen.size() -1){
                std::cout << ",";
            }
        }
        std::cout << "} \n";
    }
    //Recursive case
    else {
        for (int i = 1; i <= 6; i++) {
            chosen.push_back(i);
            diceRollHelper(dice - 1, chosen);
            chosen.pop_back();
        }
    }
}
```

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Recursive Backtracking Trace

Output for diceRolls (2):

```
{1, 1} {1, 5}
{1, 2} {1, 6}
{1, 3}
{1, 4}
```



Stack

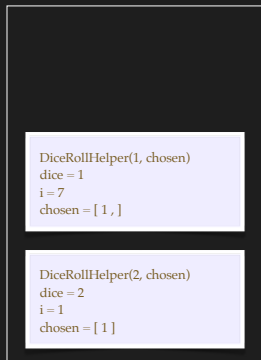
```
void diceRollHelper(int dice, std::vector<int>& chosen) {
    // Base Case
    if (dice == 0) {
        //Print out contents of vector {1,1}
        std::cout << "{";
        for(int i=0; i < chosen.size(); i++){
            std::cout << chosen.at(i);
            if(i < chosen.size() -1){
                std::cout << ",";
            }
        }
        std::cout << "} \n";
    }
    //Recursive case
    else {
        for (int i = 1; i <= 6; i++) {
            chosen.push_back(i);
            diceRollHelper(dice - 1, chosen);
            chosen.pop_back();
        }
    }
}
```

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Recursive Backtracking Trace

Output for diceRolls (2):

```
{1, 1} {1, 5}
{1, 2} {1, 6}
{1, 3}
{1, 4}
```



Stack

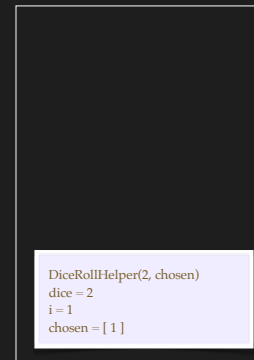
```
void diceRollHelper(int dice, std::vector<int>& chosen) {
    // Base Case
    if (dice == 0) {
        //Print out contents of vector {1,1}
        std::cout << "{";
        for(int i=0; i < chosen.size(); i++){
            std::cout << chosen.at(i);
            if(i < chosen.size() -1){
                std::cout << ",";
            }
        }
        std::cout << "} \n";
    }
    //Recursive case
    else {
        for (int i = 1; i <= 6; i++) {
            chosen.push_back(i);
            diceRollHelper(dice - 1, chosen);
            chosen.pop_back();
        }
    }
}
```

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Recursive Backtracking Trace

Output for diceRolls (2):

```
{1, 1} {1, 5}
{1, 2} {1, 6}
{1, 3}
{1, 4}
```



Stack

```
void diceRollHelper(int dice, std::vector<int>& chosen) {
    // Base Case
    if (dice == 0) {
        //Print out contents of vector {1,1}
        std::cout << "{";
        for(int i=0; i < chosen.size(); i++){
            std::cout << chosen.at(i);
            if(i < chosen.size() -1){
                std::cout << ",";
            }
        }
        std::cout << "} \n";
    }
    //Recursive case
    else {
        for (int i = 1; i <= 6; i++) {
            chosen.push_back(i);
            diceRollHelper(dice - 1, chosen);
            chosen.pop_back();
        }
    }
}
```

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Recursive Backtracking Trace

Output for diceRolls (2):

```
{1, 1} {1, 5}
{1, 2} {1, 6}
{1, 3}
{1, 4}
```

```
void diceRollHelper(int dice, std::vector<int>& chosen) {
    // Base Case
    if (dice == 0) {
        //Print out contents of vector {1,1}
        std::cout << "{";
        for(int i=0; i < chosen.size(); i++){
            std::cout << chosen.at(i);
            if(i < chosen.size() -1){
                std::cout << ",";
            }
        }
        std::cout << "} \n";
    }
    //Recursive case
    else {
        for (int i = 1; i <= 6; i++) {
            chosen.push_back(i);
            diceRollHelper(dice - 1, chosen);
            chosen.pop_back();
        }
    }
}
```

```
DiceRollHelper(2, chosen)
dice = 2
i = 1
chosen = []
```

Stack

49

Recursive Backtracking Trace

Output for diceRolls (2):

```
{1, 1} {1, 5}
{1, 2} {1, 6}
{1, 3}
{1, 4}
```

```
void diceRollHelper(int dice, std::vector<int>& chosen) {
    // Base Case
    if (dice == 0) {
        //Print out contents of vector {1,1}
        std::cout << "{";
        for(int i=0; i < chosen.size(); i++){
            std::cout << chosen.at(i);
            if(i < chosen.size() -1){
                std::cout << ",";
            }
        }
        std::cout << "} \n";
    }
    //Recursive case
    else {
        for (int i = 1; i <= 6; i++) {
            chosen.push_back(i);
            diceRollHelper(dice - 1, chosen);
            chosen.pop_back();
        }
    }
}
```

```
DiceRollHelper(2, chosen)
dice = 2
i = 2
chosen = []
```

Stack

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Recursive Backtracking Trace

Output for diceRolls (2):

```
{1, 1} {1, 5}
{1, 2} {1, 6}
{1, 3}
{1, 4}
```

```
void diceRollHelper(int dice, std::vector<int>& chosen) {
    // Base Case
    if (dice == 0) {
        //Print out contents of vector {1,1}
        std::cout << "{";
        for(int i=0; i < chosen.size(); i++){
            std::cout << chosen.at(i);
            if(i < chosen.size() -1){
                std::cout << ",";
            }
        }
        std::cout << "} \n";
    }
    //Recursive case
    else {
        for (int i = 1; i <= 6; i++) {
            chosen.push_back(i);
            diceRollHelper(dice - 1, chosen);
            chosen.pop_back();
        }
    }
}
```

```
DiceRollHelper(2, chosen)
dice = 2
i = 2
chosen = [2]
```

Stack

51

Recursive Backtracking Trace

Output for diceRolls (2):

```
{1, 1} {1, 5}
{1, 2} {1, 6}
{1, 3}
{1, 4}
```

```
void diceRollHelper(int dice, std::vector<int>& chosen) {
    // Base Case
    if (dice == 0) {
        //Print out contents of vector {1,1}
        std::cout << "{";
        for(int i=0; i < chosen.size(); i++){
            std::cout << chosen.at(i);
            if(i < chosen.size() -1){
                std::cout << ",";
            }
        }
        std::cout << "} \n";
    }
    //Recursive case
    else {
        for (int i = 1; i <= 6; i++) {
            chosen.push_back(i);
            diceRollHelper(dice - 1, chosen);
            chosen.pop_back();
        }
    }
}
```

```
DiceRollHelper(1, chosen)
dice = 1
i = 1
chosen = [2, ]
```

```
DiceRollHelper(2, chosen)
dice = 2
i = 2
chosen = [2]
```

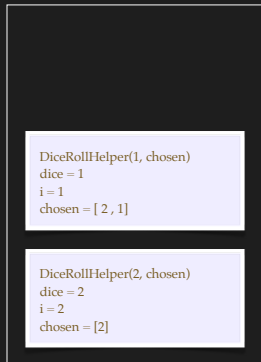
Stack

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Recursive Backtracking Trace

Output for diceRolls (2):

```
{1, 1} {1, 5}
{1, 2} {1, 6}
{1, 3}
{1, 4}
```



Stack

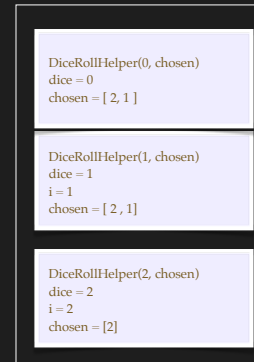
```
void diceRollHelper(int dice, std::vector<int>& chosen) {
    // Base Case
    if (dice == 0) {
        //Print out contents of vector {1,1}
        std::cout << "{";
        for(int i=0; i < chosen.size(); i++){
            std::cout << chosen.at(i);
            if(i < chosen.size() -1){
                std::cout << ",";
            }
        }
        std::cout << "} \n";
    }
    //Recursive case
    else {
        for (int i = 1; i <= 6; i++) {
            chosen.push_back(i);
            diceRollHelper(dice - 1, chosen);
            chosen.pop_back();
        }
    }
}
```

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Recursive Backtracking Trace

Output for diceRolls (2):

```
{1, 1} {1, 5}
{1, 2} {1, 6}
{1, 3}
{1, 4}
```



Stack

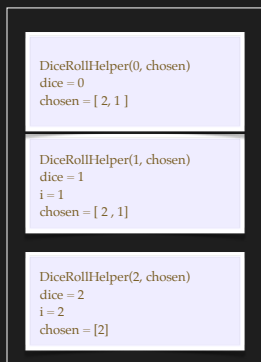
```
void diceRollHelper(int dice, std::vector<int>& chosen) {
    // Base Case
    if (dice == 0) {
        //Print out contents of vector {1,1}
        std::cout << "{";
        for(int i=0; i < chosen.size(); i++){
            std::cout << chosen.at(i);
            if(i < chosen.size() -1){
                std::cout << ",";
            }
        }
        std::cout << "} \n";
    }
    //Recursive case
    else {
        for (int i = 1; i <= 6; i++) {
            chosen.push_back(i);
            diceRollHelper(dice - 1, chosen);
            chosen.pop_back();
        }
    }
}
```

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Recursive Backtracking Trace

Output for diceRolls (2):

```
{1, 1} {1, 5}
{1, 2} {1, 6}
{1, 3} {2, 1}
{1, 4}
```



Stack

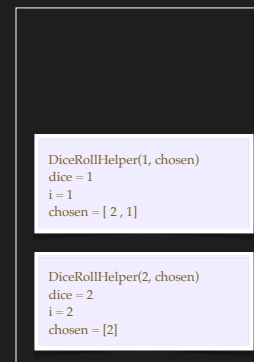
```
void diceRollHelper(int dice, std::vector<int>& chosen) {
    // Base Case
    if (dice == 0) {
        //Print out contents of vector {1,1}
        std::cout << "{";
        for(int i=0; i < chosen.size(); i++){
            std::cout << chosen.at(i);
            if(i < chosen.size() -1){
                std::cout << ",";
            }
        }
        std::cout << "} \n";
    }
    //Recursive case
    else {
        for (int i = 1; i <= 6; i++) {
            chosen.push_back(i);
            diceRollHelper(dice - 1, chosen);
            chosen.pop_back();
        }
    }
}
```

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Recursive Backtracking Trace

Output for diceRolls (2):

```
{1, 1} {1, 5}
{1, 2} {1, 6}
{1, 3} {2, 1}
{1, 4}
```



Stack

```
void diceRollHelper(int dice, std::vector<int>& chosen) {
    // Base Case
    if (dice == 0) {
        //Print out contents of vector {1,1}
        std::cout << "{";
        for(int i=0; i < chosen.size(); i++){
            std::cout << chosen.at(i);
            if(i < chosen.size() -1){
                std::cout << ",";
            }
        }
        std::cout << "} \n";
    }
    //Recursive case
    else {
        for (int i = 1; i <= 6; i++) {
            chosen.push_back(i);
            diceRollHelper(dice - 1, chosen);
            chosen.pop_back();
        }
    }
}
```

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