1186. Maximum Subarray Sum with One Deletion

Medium Array Dynamic Programming

Leetcode Link

Problem Description

The task is to find the maximum sum of a contiguous subarray from a given array of integers with the option to delete at most one element from the subarray. The subarray must remain non-empty even after a deletion, if any. Thus, the final subarray can either be a contiguous array without deletions or one where a single element has been removed. It's important to optimize the sum even if that means including negative numbers, as long as they maximally contribute to the overall sum.

Intuition

To tackle this problem, we utilize dynamic programming to consider each subarray scenario and the effect of an element deletion. The intuition behind the solution is to calculate, for every index in the array, the maximum subarray sum ending at that index (`left`) and starting at that index (`right`). We construct two arrays to keep track of these sums. The `left` array is filled by traversing the array from left to right, and the `right` array is filled by traversing from right to left.

By calculating the `left` maximum sums, we have the maximum subarray sum possible up to every index, without any deletion. The `right` array provides us the same, but starting at each index and moving to the end. Then, for every index, assuming that index is the deleted element, we can sum the maximum totals from the `left` and `right` arrays—essentially the sums just before and just after the deleted element. This way, we consider the maximum sums possible with one deletion for every index.

We also take into account the possibility of no deletion being optimal by keeping the maximum sum found while calculating the `left` array. Finally, we simply return the largest sum found, which will either include no deletions or one deletion, whichever yields a larger sum.

Solution Approach

The solution uses dynamic programming to find the maximum sum of a subarray that can optionally have one element deleted. The approach involves constructing two auxiliary arrays: `left` and `right`.

The `left` array is used to store the maximum subarray sum ending at each index when no deletion occurs. We traverse the array from left to right, updating the current sum `s` by comparing it with 0 - we never want the sum to drop below 0 because a negative sum would decrease the total achievable sum. For each element `x` in the array at index `i`, we calculate `s = max(s, 0) + x` and then store that in `left[i]`.

Following that, we initialize the `right` array, which stores the maximum subarray sum starting at each index and again with no deletions allowed. The traversal this time is right to left. Similar to the `left` array calculation, we update `s` for each element in a reverse manner, i.e., `s = max(s, 0) + arr[i]`.

Now, these two arrays combined give us the maximum subarray sums before and after each index. The candidate solutions for the maximum sum with one deletion at each index `i` would be the sum of `left[i - 1] + right[i + 1]`, effectively skipping the `i`th element.

We then compute the maximum value from the `left` array, which represents the maximum subarray sum without any deletion. Also, we iterate through the array to find the maximum sum if one deletion occurs, using the method described above.

The returned result is the maximum sum found, `ans`, taking into account both scenarios - with and without a single deletion. This approach ensures that all possible subarrays are accounted for, and the optimal solution is determined accurately.

Here's code execution visualized step by step:

1. Initialize two arrays `left` and `right` of size `n` with all zeroes.
2. Set a temporary sum `s` to 0.
3. Iterate over the array `arr` while updating `left`:
    - For each element `v`, update `s` to `max(s, 0) + x` and assign `left[i]` to `s`.
4. Reset `s` to 0 and iterate over `arr` in reverse while updating `right`:
    - For each element `arr[i]`, update `s` to `max(s, 0) + arr[i]` and assign `right[i]` to `s`.
5. Find the maximum value in `left`, which represents the best case without deletion.
6. Iterate from the second to the second-last element of the array to check cases with one deletion:
    - Update `ans` to the maximum of `ans` and `left[i - 1] + right[i + 1]`.
7. Return `ans` which now contains the maximum subarray sum allowing for at most one deletion.

The algorithm has a linear time complexity `O(n)` due to the single pass made to fill both the `left` and `right` arrays.

Example Walkthrough

Let's use a simple example to demonstrate the solution approach. Consider the array `arr = [1, -2, 3, 4, -5, 6]`.

1. Initialize `left` and `right` arrays of size 6 (the size of `arr`) with all zeroes: `left = [0, 0, 0, 0, 0, 0]`, `right = [0, 0, 0, 0, 0, 0]`.
2. Set `s = 0`. Traverse `arr` from left to right to fill `left` array:
    - `i = 0`: `s = max(0, 0) + 1 = 1`, `left[0] = 1`
    - `i = 1`: `s = max(1, 0) - 2 = -1`, but since we can't have negative sums reset `s = 0`, then `left[1] = 0`
    - `i = 2`: `s = max(0, 0) + 3 = 3`, `left[2] = 3`
    - `i = 3`: `s = max(3, 0) + 4 = 7`, `left[3] = 7`
    - `i = 4`: `s = max(7, 0) - 5 = 2`, `left[4] = 2`
    - `i = 5`: `s = max(2, 0) + 6 = 8`, `left[5] = 8` Now, `left = [1, 0, 3, 7, 2, 8]`.
3. Reset `s = 0`. Traverse `arr` from right to left to fill `right` array:
    - `i = 5`: `s = max(0, 0) + 6 = 6`, `right[5] = 6`
    - `i = 4`: `s = max(6, 0) - 5 = 1`, `right[4] = 1`
    - `i = 3`: `s = max(1, 0) + 4 = 5`, `right[3] = 5`
    - `i = 2`: `s = max(5, 0) + 3 = 8`, `right[2] = 8`
    - `i = 1`: `s = max(8, 0) - 2 = 6`, `right[1] = 6`
    - `i = 0`: `s = max(6, 0) + 1 = 7`, `right[0] = 7` Now, `right = [7, 6, 8, 5, 1, 6]`.
4. Find the maximum value in `left`, which is `8`.
5. Iterate from the second to the second-last element of the array to check cases with one deletion. We need to consider `left[i - 1] + right[i + 1]`:
    - `i = 1`: `ans = max(0, 1 + 8) = 9` (deleting `-2`)
    - `i = 2`: `ans = max(9, 1 + 5) = 9` (no change, deletion of `3` not beneficial)
    - `i = 3`: `ans = max(9, 3 + 1) = 9` (no change, deletion of `4` not beneficial)
    - `i = 4`: `ans = max(9, 7 + 6) = 13` (deleting `-5`)
6. Return `ans` which is now `13`, the maximum subarray sum if at most one deletion is allowed.

The final result for this example is a sum of `13`, which is achieved by the subarray `[1, 3, 4, 6]` with the deletion of `-5`. This walkthrough illustrates how the dynamic programming solution accounts for all possible scenarios to find the maximum sum of a contiguous subarray with at most one deletion.

Python Solution

```python
from typing import List

class Solution:
    def maximumSum(self, arr: List[int]) -> int:
        # Calculate the length of the input array
        n = len(arr)

        # Initialize two lists to store the maximum subarray sum from left and right
        max_sum_left = [0] * n
        max_sum_right = [0] * n

        # Calculate the maximum subarray sum from the left
        current_sum = 0
        for i, value in enumerate(arr):
            current_sum = max(current_sum, 0) + value
            max_sum_left[i] = current_sum

        # Reset the current sum for the next loop
        current_sum = 0

        # Calculate the maximum subarray sum from the right
        for i in range(n - 1, -1, -1):
            current_sum = max(current_sum, 0) + arr[i]
            max_sum_right[i] = current_sum

        # Find the maximum sum of the non-empty subarray
        max_sum = max(max_sum_left)

        # Traverse the array and find the maximum sum by potentially removing one element
        for i in range(1, n - 1):
            max_sum = max(max_sum, max_sum_left[i - 1] + max_sum_right[i + 1])

        # Return the maximum sum found
        return max_sum

# Example usage:
# sol = Solution()
# print(sol.maximumSum([1, -2, 0, 3]))  # Output: 4
```

Java Solution

```java
class Solution {
    public int maximumSum(int[] arr) {
        int n = arr.length; // Store the length of the array.
        int[] leftMaxSum = new int[n]; // Maximum subarray sum ending at each index from the left.
        int[] rightMaxSum = new int[n]; // Maximum subarray sum starting at each index from the right.
        int maxSum = Integer.MIN_VALUE; // Initialize maxSum with the smallest possible integer value.

        // Calculate the maximum subarray sum from the left and find the max subarray sum without deletion.
        int currentSum = 0; // Initialize a variable to keep track of the current summation.
        for (int i = 0; i < n; ++i) {
            currentSum = Math.max(currentSum, 0) + arr[i]; // Calculate the sum while resetting if negative.
            leftMaxSum[i] = currentSum; // Store the maximum sum up to the current index from the left.
            maxSum = Math.max(maxSum, currentSum); // Update the maximum subarray sum seen so far.
        }

        // Calculate the maximum subarray sum from the right.
        currentSum = 0; // Reset the currentSum for the right max subarray calculation.
        for (int i = n - 1; i >= 0; --i) {
            currentSum = Math.max(currentSum, 0) + arr[i]; // Calculate the sum while resetting if negative.
            rightMaxSum[i] = currentSum; // Store the maximum sum up to the current index from the right.
        }

        // Check the maximum sum by considering deleting one element from the array.
        for (int i = 1; i < n - 1; ++i) {
            // Sum of subarrays left to i excluding arr[i] and right to i excluding arr[i] provides a sum
            // for the array with arr[i] deleted. Update maxSum if this sum is larger.
            maxSum = Math.max(maxSum, leftMaxSum[i - 1] + rightMaxSum[i + 1]);
        }

        return maxSum; // Return the maximum subarray sum with at most one element deletion.
    }
}
```

C++ Solution

```cpp
#include <vector>
#include <algorithm> // Include algorithm for max_element

using namespace std;

class Solution {
public:
    int maximumSum(vector<int>& arr) {
        int size = arr.size();

        // Initialize vectors to keep track of maximum subarray sums
        // from the left and from the right.
        vector<int> maxLeft(size);
        vector<int> maxRight(size);

        // Calculate maximum subarray sums from the left.
        for (int i = 0, currentSum = 0; i < size; ++i) {
            currentSum = max(currentSum, 0) + arr[i];
            maxLeft[i] = currentSum;
        }

        // Calculate maximum subarray sums from the right.
        for (int i = size - 1, currentSum = 0; i >= 0; --i) {
            currentSum = max(currentSum, 0) + arr[i];
            maxRight[i] = currentSum;
        }

        // Initialize the answer with the maximum subarray sum that contains no deletion.
        int answer = *max_element(maxLeft.begin(), maxLeft.end());

        // Iterate through the array to find the maximum sum obtainable by deleting one element.
        for (int i = 1; i < size - 1; ++i) {
            // The maximum sum with one deletion can be found by
            // adding the maximum subarray sum to the left of the deleted element
            // and the maximum subarray sum to the right of the deleted element.
            answer = max(answer, maxLeft[i - 1] + maxRight[i + 1]);
        }

        return answer;
    }
};
```

Typescript Solution

```typescript
function maximumSum(arr: number[]): number {
    const arrLength = arr.length; // Number of elements in the array
    const dpLeft: number[] = new Array(arrLength); // Dynamic programming array storing max sum from the left
    const dpRight: number[] = new Array(arrLength); // Dynamic programming array storing max sum from the right

    // Calculate maximum subarray sum from the left for each element
    for (let i = 0, currentSum = 0; i < arrLength; ++i) {
        currentSum = Math.max(currentSum, 0) + arr[i];
        dpLeft[i] = currentSum;
    }

    // Calculate maximum subarray sum from the right for each element
    for (let i = arrLength - 1, currentSum = 0; i >= 0; --i) {
        currentSum = Math.max(currentSum, 0) + arr[i];
        dpRight[i] = currentSum;
    }

    // Find the maximum subarray sum already calculated from the left side
    let maxSum = Math.max(...dpLeft);
    // Check if any sum can be maximized by removing one element
    for (let i = 1; i < arrLength - 1; ++i) {
        maxSum = Math.max(maxSum, dpLeft[i - 1] + dpRight[i + 1]);
    }

    // Return the maximum sum found
    return maxSum;
}
```

Time and Space Complexity

Time Complexity

The given Python code has a time complexity of `O(n)`, where `n` is the length of the input array `arr`.

Here's the breakdown of the time complexity:

- The first `for` loop iterates through the array to compute the maximum subarray sums ending at each index (`left[]`). This loop runs for `n` iterations exactly.
- The second `for` loop calculates the maximum subarray sums starting at each index (`right[]`), iterating backward through the array. It also executes `n` iterations.
- Computing the maximum value of `left[]` is done in `O(n)` time.
- Another loop runs through the indices from 1 to `n - 2` to find the maximum sum obtained by possibly removing one element. This again is a single pass through the array, which accounts for `n` operations.
- Each operation within the loops is done in constant time `O(1)`.

Regarding time complexity, we perform a constant amount of work `n` times, leading to the overall time complexity of `O(n)`.

Space Complexity

The space complexity of the code is `O(n)` due to the additional space used for the `left[]` and `right[]` arrays, each of size `n`.

Here is the breakdown of the space complexity:

- Two arrays of size `n` (`left[]` and `right[]`) are created to store the cumulative sums.
- A few variables like `n`, `i`, `x`, and `ans` are also used which take up constant space.

Since the size of the two arrays scales with the input, the total additional space required by the algorithm is linear with respect to the input size, thus the space complexity is `O(n)`.