

5. Longest Palindromic Substring


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Summary

This article is for intermediate readers. It introduces the following ideas: Palindrome, Dynamic Programming and String Manipulation. Make sure you understand what a palindrome means. A palindrome is a string which reads the same in both directions. For example, $S = \text{"aba"}$ is a palindrome, $S = \text{"abc"}$ is not.

Solution

Approach 1: Longest Common Substring

Common mistake

Some people will be tempted to come up with a quick solution, which is unfortunately flawed (however can be corrected easily):

Reverse S and become S' . Find the longest common substring between S and S' , which must also be the longest palindromic substring.

This seemed to work, let's see some examples below.

For example, $S = \text{"caba"}$, $S' = \text{"abac"}$.

The longest common substring between S and S' is "aba", which is the answer.

Let's try another example: $S = \text{"abacdfgdcaba"}$, $S' = \text{"abacdghdcaba"}$.

The longest common substring between S and S' is "abacd". Clearly, this is not a valid palindrome.

Algorithm

We could see that the longest common substring method fails when there exists a reversed copy of a non-palindromic substring in some other part of S . To rectify this, each time we find a longest common substring candidate, we check if the substring's indices are the same as the reversed substring's original indices. If it is, then we attempt to update the longest palindrome found so far; if not, we skip this and find the next candidate.

This gives us an $O(n^2)$ Dynamic Programming solution which uses $O(n^2)$ space (could be improved to use $O(n)$ space). Please read more about Longest Common Substring here (http://en.wikipedia.org/wiki/Longest_common_substring).

Approach 2: Brute Force

The obvious brute force solution is to pick all possible starting and ending positions for a substring, and verify if it is a palindrome.

Complexity Analysis

- Time complexity : $O(n^3)$. Assume that n is the length of the input string, there are a total of $\binom{n}{2} = \frac{n(n-1)}{2}$ such substrings (excluding the trivial solution where a character itself is a palindrome). Since verifying each substring takes $O(n)$ time, the run time complexity is $O(n^3)$.
- Space complexity : $O(1)$.

Approach 3: Dynamic Programming

To improve over the brute force solution, we first observe how we can avoid unnecessary re-computation while validating palindromes. Consider the case "ababa". If we already knew that "bab" is a palindrome, it is obvious that "ababa" must be a palindrome since the two left and right end letters are the same.

We define $P(i, j)$ as following:

$$P(i, j) = \begin{cases} \text{true,} & \text{if the substring } S_i \dots S_j \text{ is a palindrome} \\ \text{false,} & \text{otherwise.} \end{cases}$$

Therefore,

$$P(i, j) = (P(i + 1, j - 1) \text{ and } S_i == S_j)$$

The base cases are:

$$P(i, i) = \text{true}$$

$$P(i, i + 1) = (S_i == S_{i+1})$$

This yields a straight forward DP solution, which we first initialize the one and two letters palindromes, and work our way up finding all three letters palindromes, and so on...

Complexity Analysis

- Time complexity : $O(n^2)$. This gives us a runtime complexity of $O(n^2)$.
- Space complexity : $O(n^2)$. It uses $O(n^2)$ space to store the table.

Additional Exercise

Could you improve the above space complexity further and how?

Approach 4: Expand Around Center

In fact, we could solve it in $O(n^2)$ time using only constant space.

We observe that a palindrome mirrors around its center. Therefore, a palindrome can be expanded from its center, and there are only $2n - 1$ such centers.

You might be asking why there are $2n - 1$ but not n centers? The reason is the center of a palindrome can be in between two letters. Such palindromes have even number of letters (such as "abba") and its center are between the two 'b's.

Java Copy

```

1 public String longestPalindrome(String s) {
2     if (s == null || s.length() < 1) return "";
3     int start = 0, end = 0;
4     for (int i = 0; i < s.length(); i++) {
5         int len1 = expandAroundCenter(s, i, i);
6         int len2 = expandAroundCenter(s, i, i + 1);
7         int len = Math.max(len1, len2);
8         if (len > end - start) {
9             start = i - (len - 1) / 2;
10            end = i + len / 2;
11        }
12    }
13    return s.substring(start, end + 1);
14 }
15
16 private int expandAroundCenter(String s, int left, int right) {
17     int L = left, R = right;
18     while (L >= 0 && R < s.length() && s.charAt(L) == s.charAt(R)) {
19         L--;
20         R++;
21     }
22     return R - L - 1;
23 }

```

Complexity Analysis

- Time complexity : $O(n^2)$. Since expanding a palindrome around its center could take $O(n)$ time, the overall complexity is $O(n^2)$.
- Space complexity : $O(1)$.

Approach 5: Manacher's Algorithm

There is even an $O(n)$ algorithm called Manacher's algorithm, explained here in detail (<http://articles.leetcode.com/longest-palindromic-substring-part-ii/>). However, it is a non-trivial algorithm, and no one expects you to come up with this algorithm in a 45 minutes coding session. But, please go ahead and understand it, I promise it will be a lot of fun.

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(/water1)

water1 (/water1) ★0 ⌚ August 22, 2018 10:20 PM

javascript实现

请帮我看 还可以怎么 优化? 谢谢

```
var longestPalindrome = function(s) {
    if (s === s.split('').reverse().join('')) {
```

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(/abhigenie92)

abhigenie92 (/abhigenie92) ★4 ⌚ August 14, 2018 7:20 PM

Can't you reverse and and then check it?

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Longest Palindromic Substring Part II

November 20, 2011 by 1337c0d3r [💬](#) 160 Replies

Given a string S, find the longest palindromic substring in S.

Note:

This is Part II of the article: [Longest Palindromic Substring](#). Here, we describe an algorithm (Manacher's algorithm) which finds the longest palindromic substring in linear time. Please read [Part I](#) for more background information.

In my [previous post](#) we discussed a total of four different methods, among them there's a pretty simple algorithm with $O(N^2)$ run time and constant space complexity. Here, we discuss an algorithm that runs in $O(N)$ time and $O(N)$ space, also known as Manacher's algorithm.

Hint:

Think how you would improve over the simpler $O(N^2)$ approach. Consider the worst case scenarios. The worst case scenarios are the inputs with multiple palindromes overlapping each other. For example, the inputs: "aaaaaaaa" and "cabcbabcbabcb". In fact, we could take advantage of the palindrome's symmetric property and avoid some of the unnecessary computations.

An $O(N)$ Solution (Manacher's Algorithm):

First, we transform the input string, S, to another string T by inserting a special character '#' in between letters. The reason for doing so will be immediately clear to you soon.

For example: S = "abaaba", T = "#a#b#a#a#b#a#".

To find the longest palindromic substring, we need to expand around each T_i such that $T_{i-d} \dots T_{i+d}$ forms a palindrome. You should immediately see that d is the length of the palindrome itself centered at T_i .

We store intermediate result in an array P , where $P[i]$ equals to the length of the palindrome centered at T_i . The longest palindromic substring would then be the maximum element in P .

Using the above example, we populate P as below (from left to right):

```
T = # a # b # a # a # b # a #
P = 0 1 0 3 0 1 6 1 0 3 0 1 0
```

Looking at P , we immediately see that the longest palindrome is “abaaba”, as indicated by $P_6 = 6$.

Did you notice by inserting special characters (#) in between letters, both palindromes of odd and even lengths are handled gracefully? (Please note: This is to demonstrate the idea more easily and is not necessarily needed to code the algorithm.)

Now, imagine that you draw an imaginary vertical line at the center of the palindrome “abaaba”. Did you notice the numbers in P are symmetric around this center? That’s not only it, try another palindrome “aba”, the numbers also reflect similar symmetric property. Is this a coincidence? The answer is yes and no. This is only true subjected to a condition, but anyway, we have great progress, since we can eliminate recomputing part of $P[i]$ ’s.

Let us move on to a slightly more sophisticated example with more some overlapping palindromes, where $S =$ “babcbabcbaccba”.

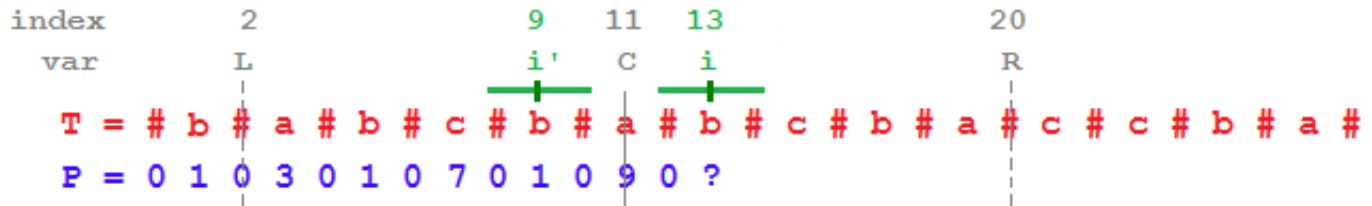
```

index          2          9    11    13          20
var           L          i'   C     i           R
T = # b # a # b # c # b # a # b # c # b # a # c # c # b # a #
P = 0 1 0 3 0 1 0 7 0 1 0 9 0 ?

```

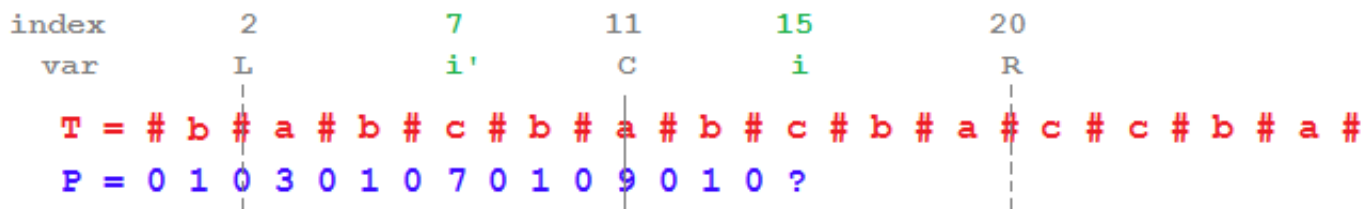
Above image shows T transformed from $S =$ “babcbabcbaccba”. Assumed that you reached a state where table P is partially completed. The solid vertical line indicates the center (C) of the palindrome “abcbabcb”. The two dotted vertical line indicate its left (L) and right (R) edges respectively. You are at index i and its mirrored index around C is i' . How would you calculate $P[i]$ efficiently?

Assume that we have arrived at index $i = 13$, and we need to calculate $P[13]$ (indicated by the question mark ?). We first look at its mirrored index i' around the palindrome’s center C , which is index $i' = 9$.



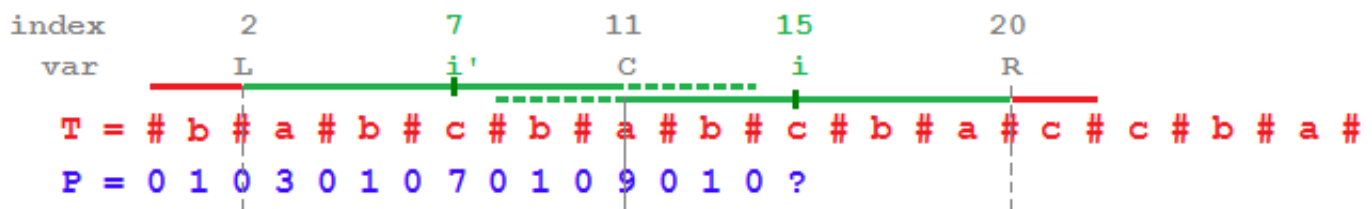
The two green solid lines above indicate the covered region by the two palindromes centered at i and i' . We look at the mirrored index of i around C , which is index i' . $P[i'] = P[9] = 1$. It is clear that $P[i]$ must also be 1, due to the symmetric property of a palindrome around its center.

As you can see above, it is very obvious that $P[i] = P[i'] = 1$, which must be true due to the symmetric property around a palindrome's center. In fact, all three elements after C follow the symmetric property (that is, $P[12] = P[10] = 0$, $P[13] = P[9] = 1$, $P[14] = P[8] = 0$).



Now we are at index $i = 15$, and its mirrored index around C is $i' = 7$. Is $P[15] = P[7] = 7$?

Now we are at index $i = 15$. What's the value of $P[i]$? If we follow the symmetric property, the value of $P[i]$ should be the same as $P[i'] = 7$. But this is wrong. If we expand around the center at T_{15} , it forms the palindrome "a#b#c#b#a", which is actually shorter than what is indicated by its symmetric counterpart. Why?



Colored lines are overlaid around the center at index i and i' . Solid green lines show the region that must match for both sides due to symmetric property around C .

Solid red lines show the region that might not match for both sides. Dotted green lines show the region that crosses over the center.

It is clear that the two substrings in the region indicated by the two solid green lines must match exactly. Areas across the center (indicated by dotted green lines) must also be symmetric. Notice carefully that $P[i']$ is 7 and it expands all the way across the left edge (L) of the palindrome (indicated by the solid red lines), which does not fall under the symmetric property of the palindrome anymore. All we know is $P[i] \geq 5$, and to find the real value of $P[i]$ we have to do character matching by expanding past the right edge (R). In this case, since $P[21] \neq P[1]$, we conclude that $P[i] = 5$.

Let's summarize the key part of this algorithm as below:

```

if  $P[i'] \leq R - i$ ,
then  $P[i] \leftarrow P[i']$ 
else  $P[i] \geq P[i']$ . (Which we have to expand past the right edge (R) to find  $P[i]$ ).

```

See how elegant it is? If you are able to grasp the above summary fully, you already obtained the essence of this algorithm, which is also the hardest part.

The final part is to determine when should we move the position of C together with R to the right, which is easy:

If the palindrome centered at i does expand past R , we update C to i , (the center of this new palindrome), and extend R to the new palindrome's right edge.

In each step, there are two possibilities. If $P[i] \leq R - i$, we set $P[i]$ to $P[i']$ which takes exactly one step. Otherwise we attempt to change the palindrome's center to i by expanding it starting at the right edge, R . Extending R (the inner while loop) takes at most a total of N steps, and positioning and testing each centers take a total of N steps too. Therefore, this algorithm guarantees to finish in at most $2*N$ steps, giving a linear time solution.

```

// Transform S into T.
// For example, S = "abba", T = "^#a#b#b#a#$".
// ^ and $ signs are sentinels appended to each end to avoid bounds checking
string preProcess(string s) {
    int n = s.length();
    if (n == 0) return "^$";
    string ret = "^";
    for (int i = 0; i < n; i++)
        ret += "#" + s.substr(i, 1);

    ret += "$";
    return ret;
}

string longestPalindrome(string s) {
    string T = preProcess(s);
    int n = T.length();
    int *P = new int[n];
    int C = 0, R = 0;
    for (int i = 1; i < n-1; i++) {
        int i_mirror = 2*C-i; // equals to i' = C - (i-C)

        P[i] = (R > i) ? min(R-i, P[i_mirror]) : 0;

        // Attempt to expand palindrome centered at i
        while (T[i + 1 + P[i]] == T[i - 1 - P[i]])
            P[i]++;
    }
}

```

```

// If palindrome centered at i expand past R,
// adjust center based on expanded palindrome.
if (i + P[i] > R) {
    C = i;
    R = i + P[i];
}
}

// Find the maximum element in P.
int maxLen = 0;
int centerIndex = 0;
for (int i = 1; i < n-1; i++) {
    if (P[i] > maxLen) {
        maxLen = P[i];
        centerIndex = i;
    }
}
delete[] P;

return s.substr((centerIndex - 1 - maxLen)/2, maxLen);
}

```

Note:

This algorithm is definitely non-trivial and you won't be expected to come up with such algorithm during an interview setting. However, I do hope that you enjoy reading this article and hopefully it helps you in understanding this interesting algorithm. You deserve a pat if you have gone this far! 😊

Further Thoughts:

- In fact, there exists a sixth solution to this problem — Using suffix trees. However, it is not as efficient as this one (run time $O(N \log N)$ and more overhead for building suffix trees) and is more complicated to implement. If you are interested, read Wikipedia's article about [Longest Palindromic Substring](#).
- What if you are required to find the longest palindromic subsequence? (Do you know the difference between substring and subsequence?)

Useful Links:

- » [Manacher's Algorithm \$O\(N\)\$ 时间求字符串的最长回文子串](#) (Best explanation if you can read Chinese)
- » [A simple linear time algorithm for finding longest palindrome sub-string](#)
- » [Finding Palindromes](#)
- » [Finding the Longest Palindromic Substring in Linear Time](#)
- » [Wikipedia: Longest Palindromic Substring](#)