

Sliding Window

1. Longest Substring Without Repeating Characters

Pattern: Sliding Window

Problem Statement

Given a string `s`, find the length of the **longest substring** without repeating characters.

Sample Input & Output

```
Input: "abcabcbb"
Output: 3
Explanation: The answer is "abc", with length 3.
```

```
Input: "bbbbbb"
Output: 1
Explanation: All characters are the same; longest valid substring is "b".
```

```
Input: "pwwkew"
Output: 3
Explanation: "wke" is the longest substring without repeats
(not "pwke", which is a subsequence).
```

LeetCode Editorial Solution + Inline Tests

```
from typing import List

class Solution:
    def lengthOfLongestSubstring(self, s: str) -> int:
        # STEP 1: Initialize structures
        # - Use a set to track characters in current window
        # - Use two pointers (left, right) to define window
        char_set = set()
        left = 0
        max_len = 0

        # STEP 2: Main loop / recursion
        # - Expand window by moving right pointer
        # - If duplicate found, shrink from left until unique
        for right in range(len(s)):
            # STEP 3: Update state / bookkeeping
            # - Why here? Ensures window always has unique chars
            # - What breaks if not? Duplicates would stay in set
            while s[right] in char_set:
                char_set.remove(s[left])
                left += 1
            char_set.add(s[right])
            max_len = max(max_len, right - left + 1)

        # STEP 4: Return result
        # - Handles empty string (max_len stays 0)
        return max_len

# ----- INLINE TESTS -----
if __name__ == "__main__":
    sol = Solution()

    # Test 1: Normal case
    assert sol.lengthOfLongestSubstring("abcabcbb") == 3

    # Test 2: Edge case
    assert sol.lengthOfLongestSubstring("bbbb") == 1

    # Test 3: Tricky/negative
    assert sol.lengthOfLongestSubstring("pwwkew") == 3
```

```
# Extra: Empty string
assert sol.lengthOfLongestSubstring("") == 0

print(" All tests passed!")
```

How to use: Copy-paste this block into .py or Quarto cell → run directly → instant feedback.

Example Walkthrough

We'll trace `s = "pwwkew"` step by step.
Initial state: `char_set = {}`, `left = 0`, `max_len = 0`.

Step 1: `right = 0` → char 'p'
- 'p' not in `char_set` → skip while loop
- Add 'p' → `char_set = {'p'}`
- `max_len = max(0, 0-0+1) = 1`
State: `left=0, right=0, set={'p'}, max_len=1`

Step 2: `right = 1` → char 'w'
- 'w' not in set → skip while
- Add 'w' → `char_set = {'p', 'w'}`
- `max_len = max(1, 1-0+1) = 2`
State: `left=0, right=1, set={'p', 'w'}, max_len=2`

Step 3: $\text{right} = 2 \rightarrow \text{char 'w'}$

- 'w' is in set \rightarrow enter while loop
- Remove $s[\text{left}] = \text{'p'} \rightarrow \text{set} = \{\text{'w'}\}, \text{left} = 1$
- Check again: 'w' still in set \rightarrow remove $s[1] = \text{'w'} \rightarrow \text{set} = \{\}, \text{left} = 2$
- Now 'w' not in set \rightarrow exit while
- Add 'w' $\rightarrow \text{set} = \{\text{'w'}\}$
- $\text{max_len} = \max(2, 2-2+1) = 2$

State: $\text{left}=2, \text{right}=2, \text{set}=\{\text{'w'}\}, \text{max_len}=2$

Step 4: $\text{right} = 3 \rightarrow \text{char 'k'}$

- 'k' not in set \rightarrow skip while
- Add 'k' $\rightarrow \text{set} = \{\text{'w'}, \text{'k'}\}$
- $\text{max_len} = \max(2, 3-2+1) = 2 \rightarrow$ still 2

State: $\text{left}=2, \text{right}=3, \text{set}=\{\text{'w'}, \text{'k'}\}, \text{max_len}=2$

Step 5: $\text{right} = 4 \rightarrow \text{char 'e'}$

- 'e' not in set \rightarrow skip while
- Add 'e' $\rightarrow \text{set} = \{\text{'w'}, \text{'k'}, \text{'e'}\}$
- $\text{max_len} = \max(2, 4-2+1) = 3$

State: $\text{left}=2, \text{right}=4, \text{set}=\{\text{'w'}, \text{'k'}, \text{'e'}\}, \text{max_len}=3$

Step 6: $\text{right} = 5 \rightarrow \text{char 'w'}$

- 'w' is in set \rightarrow enter while
- Remove $s[2] = \text{'w'} \rightarrow \text{set} = \{\text{'k'}, \text{'e'}\}, \text{left} = 3$
- Now 'w' not in set \rightarrow exit while
- Add 'w' $\rightarrow \text{set} = \{\text{'k'}, \text{'e'}, \text{'w'}\}$
- $\text{max_len} = \max(3, 5-3+1) = 3$ (unchanged)

Final State: $\text{max_len} = 3 \rightarrow$ returned.

Complexity Analysis

- **Time Complexity:** $O(n)$

Each character is visited **at most twice** — once by **right** pointer, once by **left** pointer. The inner **while** loop may seem nested, but it's amortized constant per character.

- **Space Complexity:** $O(\min(m, n))$

m = size of charset (e.g., ASCII = 128). The set stores at most all unique characters in the string, which is bounded by alphabet size or string length n , whichever is smaller.

2. Longest Repeating Character Replacement

Pattern: Sliding Window

Problem Statement

You are given a string **s** and an integer **k**. You can choose **any character** in the string and change it to **any other uppercase English character** at most **k** times.

Return the length of the **longest substring** containing the same letter after performing the above operations.

Sample Input & Output

```
Input: s = "ABAB", k = 2
```

```
Output: 4
```

```
Explanation: Replace the two 'A's with 'B's or vice versa → "BBBB".
```

Input: s = "AABABBA", k = 1
Output: 4
Explanation: Replace one 'B' in "AABABB" → "AAAABB" → longest valid is "AABA" → "AAAA" (length 4).

Input: s = "AAAA", k = 0
Output: 4
Explanation: No replacements needed; entire string is already uniform.

LeetCode Editorial Solution + Inline Tests

```
from typing import List

class Solution:
    def characterReplacement(self, s: str, k: int) -> int:
        # STEP 1: Initialize structures
        # - freq: tracks count of each char in current window
        # - max_freq: highest freq of any char in window
        # - left: start of sliding window
        # - max_len: result to return
        freq = [0] * 26
        max_freq = 0
        left = 0
        max_len = 0

        # STEP 2: Main loop / recursion
        # - Expand window by moving right pointer
        # - Invariant: window is valid if (window_size - max_freq) <= k
        for right in range(len(s)):
            # Update frequency of current character
            idx = ord(s[right]) - ord('A')
            freq[idx] += 1
            max_freq = max(max_freq, freq[idx])

            # STEP 3: Update state / bookkeeping
            # - If window becomes invalid, shrink from left
            # - Why? We want largest valid window ending at 'right'
            window_size = right - left + 1
```

```

        if window_size - max_freq > k:
            left_idx = ord(s[left]) - ord('A')
            freq[left_idx] -= 1
            left += 1

        # Update max length after possible adjustment
        max_len = max(max_len, right - left + 1)

    # STEP 4: Return result
    # - max_len holds the answer; handles empty string via init
    return max_len

# ----- INLINE TESTS -----
if __name__ == "__main__":
    sol = Solution()

    # Test 1: Normal case
    assert sol.characterReplacement("ABAB", 2) == 4, \
        f"Expected 4, got {sol.characterReplacement('ABAB', 2)}"

    # Test 2: Edge case - no replacements needed
    assert sol.characterReplacement("AAAA", 0) == 4, \
        f"Expected 4, got {sol.characterReplacement('AAAA', 0)}"

    # Test 3: Tricky/negative - limited replacements
    assert sol.characterReplacement("AABABBA", 1) == 4, \
        f"Expected 4, got {sol.characterReplacement('AABABBA', 1)}"

    print(" All tests passed!")

```

How to use: Copy-paste this block into .py or Quarto cell → run directly → instant feedback.

Example Walkthrough

We'll trace `s = "AABABBA"`, `k = 1` step by step.

Initial state:

- `freq = [0]*26` → all zeros
- `max_freq = 0`

- left = 0
- max_len = 0

Step 1: right = 0 \rightarrow char 'A'

- idx = 0
- freq[0] = 1
- max_freq = max(0, 1) = 1
- window_size = 1, 1 - 1 = 0 \leq 1 \rightarrow valid
- max_len = max(0, 1) = 1

State: left=0, max_len=1, freq[A]=1

Step 2: right = 1 \rightarrow char 'A'

- freq[0] = 2
- max_freq = 2
- window_size = 2, 2 - 2 = 0 \leq 1 \rightarrow valid
- max_len = 2

State: left=0, max_len=2, freq[A]=2

Step 3: right = 2 \rightarrow char 'B'

- idx = 1, freq[1] = 1
- max_freq = max(2, 1) = 2
- window_size = 3, 3 - 2 = 1 \leq 1 \rightarrow valid
- max_len = 3

State: left=0, max_len=3, freq[A]=2, B=1

Step 4: right = 3 \rightarrow char 'A'

- freq[0] = 3
- max_freq = 3
- window_size = 4, 4 - 3 = 1 \leq 1 \rightarrow valid
- max_len = 4

State: left=0, max_len=4, freq[A]=3, B=1

Step 5: $\text{right} = 4 \rightarrow \text{char 'B'}$

- $\text{freq}[1] = 2$
- $\text{max_freq} = \max(3, 2) = 3$
- $\text{window_size} = 5, 5 - 3 = 2 > 1 \rightarrow \text{invalid!}$
- Shrink window:
- $\text{s}[\text{left}] = \text{'A'} \rightarrow \text{freq}[0] = 2$
- $\text{left} = 1$
- New window: indices 1-4 $\rightarrow \text{size} = 4$
- $\text{max_len} = \max(4, 4) = 4$

State: $\text{left}=1, \text{max_len}=4, \text{freq}[\text{A}]=2, \text{B}=2$

Step 6: $\text{right} = 5 \rightarrow \text{char 'B'}$

- $\text{freq}[1] = 3$
- $\text{max_freq} = \max(2, 3) = 3$
- $\text{window_size} = 5 (1-5), 5 - 3 = 2 > 1 \rightarrow \text{invalid}$
- Shrink:
- $\text{s}[1] = \text{'A'} \rightarrow \text{freq}[0] = 1$
- $\text{left} = 2$
- New window: 2-5 $\rightarrow \text{size} = 4$
- $\text{max_len} = 4$

State: $\text{left}=2, \text{freq}[\text{A}]=1, \text{B}=3$

Step 7: $\text{right} = 6 \rightarrow \text{char 'A'}$

- $\text{freq}[0] = 2$
- $\text{max_freq} = \max(3, 2) = 3$
- $\text{window_size} = 5 (2-6), 5 - 3 = 2 > 1 \rightarrow \text{invalid}$
- Shrink:
- $\text{s}[2] = \text{'B'} \rightarrow \text{freq}[1] = 2$
- $\text{left} = 3$
- New window: 3-6 $\rightarrow \text{size} = 4$
- $\text{max_len} = 4$

Final Output: 4

Key Insight:

We never reduce `max_freq` when shrinking — it may become stale, but that's okay!
Because we only care about **longer** windows, and a stale `max_freq` only makes the condition stricter (safe).

Complexity Analysis

- **Time Complexity:** $O(n)$

We traverse the string once with `right` pointer. Each character is visited at most twice (once by `right`, once by `left`). All operations inside loop are $O(1)$.

- **Space Complexity:** $O(1)$

The frequency array has fixed size 26 (uppercase English letters). No other space scales with input.

3. Minimum Window Substring

Pattern: Sliding Window + Hash Map (Two Pointers with Character Frequency Tracking)

Problem Statement

Given two strings `s` and `t` of lengths `m` and `n` respectively, return the **minimum substring** of `s` such that every character in `t` (including duplicates) is included in the window.

If there is no such substring, return the empty string `""`.

The testcases will be generated such that the answer is **unique**.

Sample Input & Output

Input: s = "ADOBECODEBANC", t = "ABC"

Output: "BANC"

Explanation: "BANC" is the smallest substring containing all chars of "ABC".

Input: s = "a", t = "a"

Output: "a"

Explanation: Single character match - edge case with minimal input.

Input: s = "a", t = "aa"

Output: ""

Explanation: t has two 'a's but s only has one → impossible.

LeetCode Editorial Solution + Inline Tests

```
from typing import List
from collections import Counter

class Solution:
    def minWindow(self, s: str, t: str) -> str:
        # STEP 1: Initialize structures
        # - t_count tracks required char frequencies from t
        # - window_count tracks current window char frequencies
        # - have = chars in window meeting required count
        # - need = total unique chars we must satisfy
        if not t or not s:
            return ""

        t_count = Counter(t)
        window_count = {}
        have = 0
        need = len(t_count)
        res = ""
        res_len = float('inf')
        left = 0
```

```

# STEP 2: Main loop / recursion
# - Expand right pointer to include new char
# - Update window_count and check if char requirement met
for right in range(len(s)):
    char = s[right]
    window_count[char] = (
        window_count.get(char, 0) + 1
    )

# STEP 3: Update state / bookkeeping
# - Only increment 'have' when count exactly matches need
if (
    char in t_count
    and window_count[char] == t_count[char]
):
    have += 1

# Contract window from left while valid
while have == need:
    # Update result if current window smaller
    current_length = right - left + 1
    if current_length < res_len:
        res = s[left:right + 1]
        res_len = current_length

    # Remove leftmost char and update counts
    left_char = s[left]
    window_count[left_char] -= 1
    if (
        left_char in t_count
        and window_count[left_char] < t_count[left_char]
    ):
        have -= 1
    left += 1

# STEP 4: Return result
# - Return empty string if no valid window found
if res_len == float('inf'):
    return ""
return res

```

```

# ----- INLINE TESTS -----

```

```

if __name__ == "__main__":
    sol = Solution()

    # Test 1: Normal case
    result1 = sol.minWindow("ADOBECODEBANC", "ABC")
    assert result1 == "BANC", f"Expected 'BANC', got '{result1}'"

    # Test 2: Edge case
    result2 = sol.minWindow("a", "a")
    assert result2 == "a", f"Expected 'a', got '{result2}'"

    # Test 3: Tricky/negative
    result3 = sol.minWindow("a", "aa")
    assert result3 == "", f"Expected '', got '{result3}'"

    print(" All tests passed!")

```

How to use: Copy-paste this block into .py or Quarto cell → run directly → instant feedback.

Example Walkthrough

We'll trace `s = "ADOBECODEBANC"`, `t = "ABC"` step by step.

Initial State:

- `t_count = {'A':1, 'B':1, 'C':1}`
- `window_count = {}`
- `have = 0, need = 3`
- `res = "", res_len = ∞`
- `left = 0`

Step 1: `right = 0` → char 'A'

- `window_count = {'A':1}`
- 'A' in `t_count` and count matches → `have = 1`
- `have (1) < need (3)` → skip while loop
- **State:** `left=0, have=1`

Step 2: `right = 1` \rightarrow `'D'`
- `window_count = {'A':1, 'D':1}`
- `'D'` not in `t_count` \rightarrow `have` unchanged
- **State:** `left=0, have=1`

Step 3: `right = 2` \rightarrow `'O'`
- Add `'O'` \rightarrow `window_count['O']=1`
- Not in `t` \rightarrow `have=1`

Step 4: `right = 3` \rightarrow `'B'`
- `window_count['B']=1`
- `'B'` in `t` and count matches \rightarrow `have = 2`
- Still < 3 \rightarrow continue

Step 5: `right = 4` \rightarrow `'E'`
- Add `'E'` \rightarrow no effect on `have`

Step 6: `right = 5` \rightarrow `'C'`
- `window_count['C']=1`
- `'C'` in `t` and count matches \rightarrow `have = 3`
- Now `have == need` \rightarrow enter while loop

Inside while loop (valid window: "ADOBEC")

- `Length = 6 < ∞` \rightarrow update `res = "ADOBEC", res_len = 6`
- Remove `s[0] = 'A':`
- `window_count['A'] = 0`
- `'A'` in `t` and now $0 < 1$ \rightarrow `have = 2`
- Exit while loop
- **State:** `left=1, have=2, res="ADOBEC"`

Continue expanding `right`...

Eventually, at `right = 12 ('C')`, window `"ODEBANC"` becomes valid again.

Then we contract:

- Remove `'O'` \rightarrow still valid
- Remove `'D'` \rightarrow still valid
- Remove `'E'` \rightarrow still valid
- Remove `'B'` \rightarrow `window_count['B']=1` (still ok)
- Remove `'A'` \rightarrow `window_count['A']=0` \rightarrow **invalid!**
- Before removal: window = `"BANC"` \rightarrow length $4 < 6$ \rightarrow **update `res = "BANC"`**

Final `res = "BANC"`.

Complexity Analysis

- **Time Complexity:** $O(m + n)$

We traverse `s` with `right` pointer once ($O(m)$), and `left` moves forward at most `m` times total (each char visited at most twice). Building `t_count` is $O(n)$. Total linear.

- **Space Complexity:** $O(k)$

Where `k` is the number of unique characters in `t` (at most 52 for upper+lower letters). `window_count` and `t_count` store only chars from `t`, so space is bounded by alphabet size, **not** input length. Technically $O(1)$ for fixed alphabet, but $O(k)$ generally.

4. Find All Anagrams in a String

Pattern: Sliding Window + Hash Map (Fixed-Size Window)

Problem Statement

Given two strings `s` and `p`, return an array of all the start indices of `p`'s anagrams in `s`. You may return the answer in any order.

An **anagram** is a word or phrase formed by rearranging the letters of a different word or phrase, typically using all the original letters exactly once.

Sample Input & Output

```
Input: s = "cbaebabacd", p = "abc"
```

```
Output: [0, 6]
```

```
Explanation: The substring starting at index 0 ("cba")  
and index 6 ("bac") are anagrams of "abc".
```

```
Input: s = "abab", p = "ab"
```

```
Output: [0, 1, 2]
```

```
Explanation: Every consecutive 2-letter substring is an anagram of "ab".
```

Input: s = "a", p = "aa"
Output: []
Explanation: p is longer than s → no anagram possible.

LeetCode Editorial Solution + Inline Tests

```
from typing import List
from collections import Counter

class Solution:
    def findAnagrams(self, s: str, p: str) -> List[int]:
        # STEP 1: Initialize structures
        # - 'need' tracks required char frequencies from p
        # - 'window' tracks current sliding window frequencies
        need = Counter(p)
        window = Counter()
        res = []
        left = 0
        p_len = len(p)

        # Early exit if p longer than s
        if p_len > len(s):
            return []

        # STEP 2: Main loop - expand window with right pointer
        # - Add current char to window
        for right, char in enumerate(s):
            window[char] += 1

            # STEP 3: Shrink window if too large
            # - Maintain fixed size = len(p)
            if right - left + 1 > p_len:
                left_char = s[left]
                window[left_char] -= 1
                if window[left_char] == 0:
                    del window[left_char]
                left += 1
```



```

        # STEP 4: Check for anagram match
        # - Only when window is full size
        if right >= p_len - 1 and window == need:
            res.append(left)

    return res

# ----- INLINE TESTS -----
if __name__ == "__main__":
    sol = Solution()

    # Test 1: Normal case
    assert sol.findAnagrams("cbaebabacd", "abc") == [0, 6], \
        "Test 1 failed"

    # Test 2: Edge case - p longer than s
    assert sol.findAnagrams("a", "aa") == [], \
        "Test 2 failed"

    # Test 3: Tricky - overlapping anagrams
    assert sol.findAnagrams("abab", "ab") == [0, 1, 2], \
        "Test 3 failed"

    print(" All tests passed!")

```

How to use: Copy-paste this block into .py or Quarto cell → run directly → instant feedback.

Example Walkthrough

We'll walk through **two detailed examples** to reinforce understanding.

Example 1: `s = "cbaebabacd"`, `p = "abc"`

Goal: Find all start indices where a 3-letter substring is an anagram of "abc".

Initial Setup:

- `need = {'a':1, 'b':1, 'c':1}`

- window = {}
- left = 0, p_len = 3
- res = []

Now step through each right (0 to 9):

Step 1: right=0, char='c'

- window = {'c':1}
- Window size = 1 3 → no shrink
- right (0) < 2 → skip match
- State: left=0, res=[]

Step 2: right=1, char='b'

- window = {'c':1, 'b':1}
- Size = 2 3 → no shrink
- right (1) < 2 → skip match
- State: res=[]

Step 3: right=2, char='a'

- window = {'c':1, 'b':1, 'a':1}
- Size = 3 → no shrink
- right 2 → check: window == need → True
- Append left = 0 → res = [0]
- State: res=[0]

Step 4: right=3, char='e'

- window = {'c':1, 'b':1, 'a':1, 'e':1}
- Size = 4 > 3 → shrink: remove s[0]='c'
- window = {'b':1, 'a':1, 'e':1}, left=1
- Check: {'b','a','e'} != {'a','b','c'} → no match
- State: res=[0]

Step 5: right=4, char='b'

- window = {'b':2, 'a':1, 'e':1}
- Size = 4 > 3 → shrink: remove s[1]='b'
- window = {'b':1, 'a':1, 'e':1}, left=2
- No match
- State: res=[0]

Step 6: right=5, char='a'

- window = {'b':1, 'a':2, 'e':1}
- Shrink: remove s[2]='a' → window = {'b':1, 'a':1, 'e':1}, left=3

- No match
- **State:** res=[0]

Step 7: right=6, char='b'

- window = {'b':2, 'a':1, 'e':1}
- Shrink: remove s[3]='e' → window = {'b':2, 'a':1}, left=4
- No match
- **State:** res=[0]

Step 8: right=7, char='a'

- window = {'b':2, 'a':2}
- Shrink: remove s[4]='b' → window = {'b':1, 'a':2}, left=5
- No match
- **State:** res=[0]

Step 9: right=8, char='c'

- window = {'b':1, 'a':2, 'c':1}
- Shrink: remove s[5]='a' → window = {'b':1, 'a':1, 'c':1}, left=6
- Check: window == need → **True**
- Append left = 6 → res = [0, 6]
- **State:** res=[0,6]

Step 10: right=9, char='d'

- window = {'b':1, 'a':1, 'c':1, 'd':1}
- Shrink: remove s[6]='b' → window = {'a':1, 'c':1, 'd':1}, left=7
- No match
- **Final:** res = [0, 6]

Example 2: s = "a", p = "aa" (Edge Case)

- p_len = 2, len(s) = 1
 - Early exit: 2 > 1 → return [] immediately
 - **No loop runs** → efficient!
-

Complexity Analysis

- **Time Complexity:** $O(n)$

Single pass over `s` (`n = len(s)`). Each character is added once and removed once. Dictionary comparison (`window == need`) is $O(1)$ because the alphabet is bounded (26 lowercase letters).

- **Space Complexity:** $O(1)$

Both `need` and `window` store at most 26 key-value pairs. Space usage is constant, independent of input size.

5. Sliding Window Maximum

Pattern: Sliding Window

Problem Statement

You are given an array of integers `nums`, there is a sliding window of size `k` which is moving from the very left of the array to the very right. You can only see the `k` numbers in the window. Each time the sliding window moves right by one position.

Return the max sliding window.

Sample Input & Output

Input: `nums = [1,3,-1,-3,5,3,6,7]`, `k = 3`

Output: `[3,3,5,5,6,7]`

Explanation:

| Window position | Max |
|---------------------|-------|
| ----- | ----- |
| [1 3 -1] -3 5 3 6 7 | 3 |
| 1 [3 -1 -3] 5 3 6 7 | 3 |
| 1 3 [-1 -3 5] 3 6 7 | 5 |
| 1 3 -1 [-3 5 3] 6 7 | 5 |

```
1 3 -1 -3 [5 3 6] 7 6
1 3 -1 -3 5 [3 6 7] 7
```

Input: nums = [1], k = 1

Output: [1]

Explanation: Only one window possible.

Input: nums = [1,-1], k = 1

Output: [1, -1]

Explanation: Window size is 1, so each element is its own max.

LeetCode Editorial Solution + Inline Tests

```
from typing import List
from collections import deque

class Solution:
    def maxSlidingWindow(
        self, nums: List[int], k: int
    ) -> List[int]:
        # STEP 1: Initialize structures
        # - Use deque to store indices of potential max values
        # - Maintain decreasing order: front = current max
        dq = deque()
        result = []

        for i in range(len(nums)):
            # STEP 2: Remove indices outside current window
            # - Window is [i - k + 1, i]
            # - If front index <= i - k, it's out of bounds
            if dq and dq[0] <= i - k:
                dq.popleft()

            # STEP 3: Maintain decreasing order in deque
            # - Remove from back while current num >= back val
            # - Ensures front always holds max for current win
            while dq and nums[dq[-1]] <= nums[i]:
```

```

        dq.pop()

        # STEP 4: Add current index to deque
        dq.append(i)

        # STEP 5: Record max once first window is complete
        # - First valid window ends at index k - 1
        if i >= k - 1:
            result.append(nums[dq[0]])

    return result

# ----- INLINE TESTS -----
if __name__ == "__main__":
    sol = Solution()

    # Test 1: Normal case
    assert sol.maxSlidingWindow(
        [1,3,-1,-3,5,3,6,7], 3
    ) == [3,3,5,5,6,7], "Normal case failed"

    # Test 2: Edge case - single element
    assert sol.maxSlidingWindow([1], 1) == [1], \
        "Single element failed"

    # Test 3: Tricky case - window size 1
    assert sol.maxSlidingWindow([1,-1], 1) == [1, -1], \
        "Window size 1 failed"

    print(" All tests passed!")

```

How to use: Copy-paste this block into .py or Quarto cell → run directly → instant feedback.

Example Walkthrough

We'll trace `nums = [1,3,-1,-3,5,3,6,7]`, `k = 3`.

Initial state:

`dq = deque()` (empty), `result = []`

i = 0 (num = 1)
- dq empty → skip popleft
- dq empty → skip while loop
- Append 0 → dq = [0]
- i=0 < 2 (k-1) → skip append to result
→ **State:** dq=[0], result=[]

i = 1 (num = 3)
- dq[0]=0 > 1-3=-2 → no popleft
- While: nums[0]=1 <= 3 → pop 0 → dq=[]
- Append 1 → dq = [1]
- i=1 < 2 → skip result
→ **State:** dq=[1], result=[]

i = 2 (num = -1)
- dq[0]=1 > 2-3=-1 → no popleft
- While: nums[1]=3 > -1 → don't pop
- Append 2 → dq = [1,2]
- i=2 >= 2 → add nums[1]=3 to result
→ **State:** dq=[1,2], result=[3]

i = 3 (num = -3)
- dq[0]=1 <= 3-3=0? No (1>0) → keep
- While: nums[2]=-1 > -3 → don't pop
- Append 3 → dq = [1,2,3]
- Add nums[1]=3 → result=[3,3]
→ **State:** dq=[1,2,3], result=[3,3]

i = 4 (num = 5)
 - dq[0]=1 <= 4-3=1 → **yes!** → popleft → dq=[2,3]
 - While:
 - nums[3]=-3 <= 5 → pop → dq=[2]
 - nums[2]=-1 <= 5 → pop → dq=[]
 - Append 4 → dq=[4]
 - Add nums[4]=5 → result=[3,3,5]
 → **State:** dq=[4], result=[3,3,5]

i = 5 (num = 3)
 - dq[0]=4 > 5-3=2 → keep
 - While: nums[4]=5 > 3 → don't pop
 - Append 5 → dq=[4,5]
 - Add nums[4]=5 → result=[3,3,5,5]
 → **State:** dq=[4,5], result=[3,3,5,5]

i = 6 (num = 6)
 - dq[0]=4 <= 6-3=3? No (4>3) → keep
 - While:
 - nums[5]=3 <= 6 → pop → dq=[4]
 - nums[4]=5 <= 6 → pop → dq=[]
 - Append 6 → dq=[6]
 - Add nums[6]=6 → result=[3,3,5,5,6]
 → **State:** dq=[6], result=[3,3,5,5,6]

i = 7 (num = 7)
 - dq[0]=6 > 7-3=4 → keep
 - While: nums[6]=6 <= 7 → pop → dq=[]
 - Append 7 → dq=[7]
 - Add nums[7]=7 → result=[3,3,5,5,6,7]
 → **Final result:** [3,3,5,5,6,7]

Key insight: The deque always keeps indices of elements in **decreasing order**, so the front is always the max of the current window. Out-of-window indices are removed from the front; smaller-or-equal elements are removed from the back before adding the new one.

Complexity Analysis

- **Time Complexity:** $O(n)$

Each element is pushed and popped from the deque **at most once**. The outer loop runs n times, and inner while loop operations are amortized constant time.

- **Space Complexity:** $O(k)$

The deque stores at most k indices (one per window position). The output list is $O(n - k + 1)$, but auxiliary space is dominated by the deque, which is $O(k)$.