

# Two Pointers

## 1. 3Sum

**Pattern:** Two Pointers

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### Problem Statement

Given an integer array `nums`, return all the triplets `[nums[i], nums[j], nums[k]]` such that `i != j`, `i != k`, `j != k`, and `nums[i] + nums[j] + nums[k] == 0`.

Notice that the solution set must not contain duplicate triplets.

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### Sample Input & Output

```
Input: nums = [-1,0,1,2,-1,-4]
Output: [[-1,-1,2],[-1,0,1]]
Explanation: Two valid triplets sum to zero.
Duplicates like [-1,0,1] appearing twice are removed.
```

```
Input: nums = [0,1,1]
Output: []
Explanation: No triplet sums to zero.
```

```
Input: nums = [0,0,0]
Output: [[0,0,0]]
Explanation: Only one triplet exists, and it sums to zero.
```

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## LeetCode Editorial Solution + Inline Tests

```
from typing import List

class Solution:
    def threeSum(self, nums: List[int]) -> List[List[int]]:
        # STEP 1: Initialize structures
        # - Sort to enable two pointers and skip duplicates
        # - Use list to collect valid triplets
        nums.sort()
        result = []
        n = len(nums)

        # STEP 2: Main loop / recursion
        # - Fix first number (i), then use two pointers for rest
        # - Skip duplicates for i to avoid repeated triplets
        for i in range(n - 2):
            if i > 0 and nums[i] == nums[i - 1]:
                continue # Skip duplicate i values

            left = i + 1
            right = n - 1

            # Two-pointer search for complement = -nums[i]
            while left < right:
                total = nums[i] + nums[left] + nums[right]

                if total == 0:
                    result.append([nums[i], nums[left], nums[right]])

                    # STEP 3: Update state / bookkeeping
                    # - Skip duplicates for left and right
                    while left < right and nums[left] == nums[left + 1]:
                        left += 1
                    while left < right and nums[right] == nums[right - 1]:
                        right -= 1

                    left += 1
                    right -= 1
                elif total < 0:
                    left += 1 # Need larger sum
                else:
                    right -= 1
```

```

        right -= 1 # Need smaller sum

# STEP 4: Return result
# - Already filtered duplicates; empty if none found
return result

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

    # Test 1: Normal case
    assert sol.threeSum([-1, 0, 1, 2, -1, -4]) == [[-1, -1, 2], [-1, 0, 1]]

    # Test 2: Edge case - no solution
    assert sol.threeSum([0, 1, 1]) == []

    # Test 3: Tricky/negative - all zeros
    assert sol.threeSum([0, 0, 0]) == [[0, 0, 0]]

    print(" All tests passed!")

```

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

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## Example Walkthrough

We'll trace `threeSum([-1, 0, 1, 2, -1, -4])` step by step.

### Initial State:

- Input: `nums = [-1, 0, 1, 2, -1, -4]`
- After sorting: `nums = [-4, -1, -1, 0, 1, 2]`
- `result = []`, `n = 6`

---

### Loop 1: `i = 0` → `nums[i] = -4`

- Not a duplicate (first element).

- Set `left = 1, right = 5` → values: -1 and 2
- **While `left < right`:**
  - `total = -4 + (-1) + 2 = -3` → too small → `left += 1` → `left = 2`
  - `total = -4 + (-1) + 2 = -3` → still too small → `left += 1` → `left = 3`
  - `total = -4 + 0 + 2 = -2` → too small → `left = 4`
  - `total = -4 + 1 + 2 = -1` → too small → `left = 5` → now `left == right` → exit

→ No triplet found with -4.

---

**Loop 2:** `i = 1` → `nums[i] = -1`

- Not duplicate (`i=1, nums[0] = -4` -1)
- `left = 2, right = 5` → values: -1 and 2
- **While `left < right`:**
  - `total = -1 + (-1) + 2 = 0` → Found triplet `[-1, -1, 2]`
    - \* Append to `result` → `result = [[-1, -1, 2]]`
  - \* Skip duplicates:
    - `nums[2] == nums[3]?` → `-1 != 0` → no skip
    - `nums[5] == nums[4]?` → `2 != 1` → no skip
  - \* Move pointers: `left = 3, right = 4`
  - Now `left=3, right=4` → values: 0 and 1
  - `total = -1 + 0 + 1 = 0` → Found `[-1, 0, 1]`
    - \* Append → `result = [[-1, -1, 2], [-1, 0, 1]]`
  - \* No duplicates next → move: `left=4, right=3` → exit loop

**Loop 3:**  $i = 2 \rightarrow \text{nums}[i] = -1$

- Duplicate!  $i > 0$  and  $\text{nums}[2] == \text{nums}[1] \rightarrow \text{continue}$

**Loop 4:**  $i = 3 \rightarrow \text{nums}[i] = 0$

- $\text{left} = 4, \text{right} = 5 \rightarrow 0 + 1 + 2 = 3 > 0 \rightarrow \text{right} -= 1 \rightarrow \text{right} = 4 \rightarrow \text{exit}$

Loops end. Return `result = [[-1, -1, 2], [-1, 0, 1]]`.

---

### Complexity Analysis

- **Time Complexity:**  $O(n^2)$

Sorting takes  $O(n \log n)$ . The outer loop runs  $O(n)$  times. For each  $i$ , the two-pointer scan is  $O(n)$ . Total:  $O(n \log n + n^2) = O(n^2)$ .

- **Space Complexity:**  $O(1)$  (or  $O(n)$  if counting output)

We only use a few pointers and the result list. Sorting may use  $O(\log n)$  stack space (Timsort), but no extra DS scales with input beyond output.

## 2. 3Sum Closest

**Pattern:** Two Pointers

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### Problem Statement

Given an integer array `nums` of length `n` and an integer `target`, find three integers in `nums` such that the sum is closest to `target`. Return the sum of the three integers.

You may assume that each input would have exactly one solution.

## Sample Input & Output

```
Input: nums = [-1,2,1,-4], target = 1
Output: 2
Explanation: The sum that is closest to the target is 2
             (-1 + 2 + 1 = 2).
```

```
Input: nums = [0,0,0], target = 1
Output: 0
Explanation: Only possible sum is 0, which is closest to 1.
```

```
Input: nums = [1,1,1,0], target = -100
Output: 2
Explanation: Smallest possible sum is 1+1+0=2, which is still
             the closest to -100.
```

---

## LeetCode Editorial Solution + Inline Tests

```
from typing import List

class Solution:
    def threeSumClosest(
        self, nums: List[int], target: int
    ) -> int:
        # STEP 1: Initialize structures
        #   - Sort array to enable two pointers
        #   - Track closest sum and min diff from target
        nums.sort()
        n = len(nums)
        closest_sum = float('inf')
        min_diff = float('inf')

        # STEP 2: Main loop / recursion
        #   - Fix first number (i), then use two pointers
        #   - Invariant: for each i, we find best j,k > i
        for i in range(n - 2):
            left = i + 1
```

```

    right = n - 1

    # Two-pointer scan for best pair
    while left < right:
        curr_sum = nums[i] + nums[left] + nums[right]
        curr_diff = abs(curr_sum - target)

        # STEP 3: Update state / bookkeeping
        # - Update if we found a closer sum
        # - Why here? We must check every valid triplet
        if curr_diff < min_diff:
            min_diff = curr_diff
            closest_sum = curr_sum

        # Move pointers based on sum vs target
        if curr_sum < target:
            left += 1
        elif curr_sum > target:
            right -= 1
        else:
            # Exact match - can't get closer
            return curr_sum

    # STEP 4: Return result
    # - Guaranteed to have found at least one triplet
    return closest_sum

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

    # Test 1: Normal case
    assert sol.threeSumClosest([-1,2,1,-4], 1) == 2

    # Test 2: Edge case - all same
    assert sol.threeSumClosest([0,0,0], 1) == 0

    # Test 3: Tricky/negative - target far from all sums
    assert sol.threeSumClosest([1,1,1,0], -100) == 2

    print(" All tests passed!")

```

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

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### Example Walkthrough

We'll walk through **Test 1**: `nums = [-1, 2, 1, -4]`, `target = 1`.

**Initial Setup:** - Input: `nums = [-1, 2, 1, -4]`, `target = 1` - After sorting: `nums = [-4, -1, 1, 2]` - `n = 4` - `closest_sum = inf`, `min_diff = inf`

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**Step 1:** `i = 0` → `nums[i] = -4`  
- `left = 1`, `right = 3`  
- Enter while `left < right` (`1 < 3` → `True`)

**Step 1.1:**  
- `curr_sum = -4 + (-1) + 2 = -3`  
- `curr_diff = abs(-3 - 1) = 4`  
- Since `4 < inf` → update:  
- `min_diff = 4`  
- `closest_sum = -3`  
- Since `-3 < 1` → move left to 2

**State:** `closest_sum = -3`, `min_diff = 4`

---

**Step 1.2:** `left = 2`, `right = 3`  
- `curr_sum = -4 + 1 + 2 = -1`  
- `curr_diff = abs(-1 - 1) = 2`  
- `2 < 4` → update:  
- `min_diff = 2`  
- `closest_sum = -1`  
- `-1 < 1` → move left to 3

**State:** `closest_sum = -1`, `min_diff = 2`

---



**Step 1.3:** `left = 3, right = 3` → loop ends (`left < right` is False)

---

**Step 2:** `i = 1` → `nums[i] = -1`

- `left = 2, right = 3`

- Enter loop (`2 < 3` → True)

**Step 2.1:**

- `curr_sum = -1 + 1 + 2 = 2`

- `curr_diff = abs(2 - 1) = 1`

- `1 < 2` → update:

- `min_diff = 1`

- `closest_sum = 2`

- `2 > 1` → move `right` to 2

**State:** `closest_sum = 2, min_diff = 1`

---

**Step 2.2:** `left = 2, right = 2` → loop ends

---

**Step 3:** `i = 2` → loop stops (`range(n-2) = range(2)` → `i=0,1` only)

**Final Return:** `closest_sum = 2`

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## Complexity Analysis

- **Time Complexity:**  $O(n^2)$

Sorting takes  $O(n \log n)$ . The outer loop runs  $O(n)$  times, and the inner two-pointer scan is  $O(n)$  per outer iteration → total  $O(n^2)$ . Dominates sorting.

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

Only a few extra variables (`closest_sum`, `min_diff`, pointers). Sorting is in-place (Python's Timsort uses  $O(n)$  worst-case, but we consider auxiliary space →  $O(1)$  for algorithm logic).

### 3. Container With Most Water

**Pattern:** Two Pointers

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#### Problem Statement

You are given an integer array **height** of length **n**. There are **n** vertical lines drawn such that the two endpoints of the *i*th line are (*i*, 0) and (*i*, **height**[*i*]).

Find two lines that together with the x-axis form a container, such that the container contains the most water.

Return the maximum amount of water a container can store.

**Note:** You may not slant the container.

---

#### Sample Input & Output

Input: `height = [1,8,6,2,5,4,8,3,7]`

Output: 49

Explanation: The max area is between index 1 (height 8) and index 8 (height 7): width = 7, height =  $\min(8,7)=7 \rightarrow \text{area} = 7*7=49$ .

Input: `height = [1,1]`

Output: 1

Explanation: Only two lines; width=1, height=1  $\rightarrow$  area=1.

Input: `height = [4,3,2,1,4]`

Output: 16

Explanation: Leftmost (4) and rightmost (4)  $\rightarrow$  width=4, height=4  $\rightarrow$  area=16 (better than inner pairs).

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## LeetCode Editorial Solution + Inline Tests

```
from typing import List

class Solution:
    def maxArea(self, height: List[int]) -> int:
        # STEP 1: Initialize structures
        # - Use two pointers at ends to maximize width
        # - Track max_area seen so far
        left = 0
        right = len(height) - 1
        max_area = 0

        # STEP 2: Main loop / recursion
        # - While pointers haven't crossed
        # - Compute current area using min height * width
        while left < right:
            width = right - left
            h = min(height[left], height[right])
            current_area = width * h
            max_area = max(max_area, current_area)

            # STEP 3: Update state / bookkeeping
            # - Move pointer with smaller height inward
            # - Why? Larger height might yield bigger area
            if height[left] < height[right]:
                left += 1
            else:
                right -= 1

        # STEP 4: Return result
        # - max_area is updated throughout; safe for all cases
        return max_area

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

    # Test 1: Normal case
    assert sol.maxArea([1,8,6,2,5,4,8,3,7]) == 49, "Normal case failed"

    # Test 2: Edge case
```

```
assert sol.maxArea([1,1]) == 1, "Edge case (two elements) failed"

# Test 3: Tricky/negative
assert sol.maxArea([4,3,2,1,4]) == 16, "Tricky symmetric case failed"

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

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

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### Example Walkthrough

We'll trace `maxArea([1,8,6,2,5,4,8,3,7])` step by step.

**Initial state:**

- `height = [1,8,6,2,5,4,8,3,7]`
  - `left = 0, right = 8, max_area = 0`
- 

**Step 1:**

- Line: `while left < right` → `0 < 8` → enter loop
  - `width = 8 - 0 = 8`
  - `h = min(height[0], height[8]) = min(1, 7) = 1`
  - `current_area = 8 * 1 = 8`
  - `max_area = max(0, 8) = 8`
  - Since `height[0] (1) < height[8] (7)`, move left → `left = 1`
  - **State:** `left=1, right=8, max_area=8`
- 

**Step 2:**

- `1 < 8` → continue
- `width = 8 - 1 = 7`
- `h = min(8, 7) = 7`
- `current_area = 7 * 7 = 49`
- `max_area = max(8, 49) = 49`
- `height[1] (8) > height[8] (7)` → move right → `right = 7`
- **State:** `left=1, right=7, max_area=49`

---

**Step 3:**

- $1 < 7 \rightarrow$  continue
  - `width = 6`
  - `h = min(8, 3) = 3`
  - `current_area = 6 * 3 = 18`
  - `max_area` remains 49
  - $8 > 3 \rightarrow$  move `right`  $\rightarrow$  `right = 6`
  - **State:** `left=1, right=6, max_area=49`
- 

**Step 4:**

- $1 < 6 \rightarrow$  continue
  - `width = 5`
  - `h = min(8, 8) = 8`
  - `current_area = 5 * 8 = 40`
  - `max_area` still 49
  - Heights equal  $\rightarrow$  move either; code moves `right` (since `else` branch)  $\rightarrow$  `right = 5`
  - **State:** `left=1, right=5, max_area=49`
- 

**Step 5:**

- $1 < 5 \rightarrow$  continue
- `width = 4`
- `h = min(8, 4) = 4`
- `current_area = 16`  $\rightarrow$  no change
- Move `right`  $\rightarrow$  `right = 4`

Continue similarly... all subsequent areas are 40.

Eventually, `left` and `right` meet  $\rightarrow$  loop ends.

**Final return:** 49

**Key insight:** By always moving the shorter pointer, we never miss a better area — because keeping the shorter one limits height, and reducing width further can't help unless we find a taller line.

---

## Complexity Analysis

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

We traverse the array once with two pointers moving toward each other — exactly  $n-1$  iterations.

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

Only a few integer variables (`left`, `right`, `max_area`, etc.) are used — no extra space proportional to input size.

## 4. Valid Palindrome

**Pattern:** Two Pointers

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### Problem Statement

A phrase is a **palindrome** if, after converting all uppercase letters into lowercase letters and removing all non-alphanumeric characters, it reads the same forward and backward. Alphanumeric characters include letters and numbers.

Given a string `s`, return `true` if it is a **palindrome**, or `false` otherwise.

---

### Sample Input & Output

```
Input: s = "A man, a plan, a canal: Panama"
```

```
Output: true
```

```
Explanation: After cleaning: "amanaplanacanalpanama" - reads  
same forwards/backwards.
```

```
Input: s = "race a car"
```

```
Output: false
```

```
Explanation: Cleaned string is "raceacar", which is not a palindrome.
```

Input: s = " "

Output: true

Explanation: Empty string (after cleaning) is considered a palindrome.

---

## LeetCode Editorial Solution + Inline Tests

```
from typing import List

class Solution:
    def isPalindrome(self, s: str) -> bool:
        # STEP 1: Initialize two pointers at start and end
        # - Left pointer starts at beginning
        # - Right pointer starts at end
        left, right = 0, len(s) - 1

        # STEP 2: Move pointers toward center while valid
        # - Skip non-alphanumeric chars from both ends
        # - Compare lowercase versions when both are valid
        while left < right:
            # Skip non-alphanumeric from left
            while left < right and not s[left].isalnum():
                left += 1
            # Skip non-alphanumeric from right
            while left < right and not s[right].isalnum():
                right -= 1

            # Compare characters (case-insensitive)
            if s[left].lower() != s[right].lower():
                return False

            # Move both pointers inward
            left += 1
            right -= 1

        # STEP 3: If loop completes, it's a palindrome
        # - All valid char pairs matched
        return True
```

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

    # Test 1: Normal case
    assert sol.isPalindrome("A man, a plan, a canal: Panama") == True

    # Test 2: Edge case - empty or whitespace
    assert sol.isPalindrome(" ") == True

    # Test 3: Tricky/negative - non-palindrome with mixed case/symbols
    assert sol.isPalindrome("race a car") == False

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

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

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## Example Walkthrough

Let's trace `s = "A man, a plan, a canal: Panama"` step by step:

### 1. Initialize pointers:

- `left = 0` (points to 'A')
- `right = 29` (points to 'a' — last char)

### 2. First outer loop (`left=0`, `right=29`):

- Both 'A' and 'a' are alphanumeric → no skipping.
- Compare `'A'.lower()` ('a') vs `'a'.lower()` ('a') → match.
- Update: `left = 1`, `right = 28`.

### 3. Now `left=1` (' '), `right=28` ('m'):

- ' ' is not alphanumeric → `left` increments to 2 ('m').
- 'm' and 'm' → match.



- Update: `left = 3, right = 27`.

4. **Continue this process:**

- Skip commas, spaces, colons as needed.
- Always compare only alphanumeric chars in lowercase.
- Pointers move inward symmetrically.

5. **Eventually:**

- Pointers cross (`left >= right`)  $\rightarrow$  loop ends.
- Return `True`.

**Key Insight:**

We never create a new cleaned string — we **simulate** it by skipping invalid chars on the fly. This saves space and aligns with the **Two Pointers** pattern: two indices converging while maintaining a palindrome invariant.

---

**Complexity Analysis**

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

We scan each character at most once (each pointer moves inward monotonically). `isalnum()` and `lower()` are  $O(1)$  per char.

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

Only two integer pointers used — no extra storage proportional to input size. In-place comparison.

**5. Move Zeroes**

**Pattern:** Two Pointers

## Problem Statement

Given an integer array `nums`, move all 0's to the end of it while maintaining the relative order of the non-zero elements.

You must do this **in-place** without making a copy of the array.

Minimize the total number of operations.

---

## Sample Input & Output

Input: `[0,1,0,3,12]`

Output: `[1,3,12,0,0]`

Explanation: All zeros are moved to the end; non-zeros retain order.

Input: `[0]`

Output: `[0]`

Explanation: Single zero remains in place.

Input: `[1,2,3]`

Output: `[1,2,3]`

Explanation: No zeros to move - array unchanged.

---

## LeetCode Editorial Solution + Inline Tests

```
from typing import List

class Solution:
    def moveZeroes(self, nums: List[int]) -> None:
        # STEP 1: Initialize structures
        #   - `left` tracks the position to place the next non-zero
        #   - Starts at 0: first valid spot for non-zero element
        left = 0

        # STEP 2: Main loop / recursion
```

```

# - Iterate through every element with `right`
# - Invariant: all elements before `left` are non-zero
# - When we find a non-zero, swap it to `left`
for right in range(len(nums)):
    if nums[right] != 0:
        # STEP 3: Update state / bookkeeping
        # - Swap non-zero to front; increment `left`
        # - Ensures stable order and minimal writes
        nums[left], nums[right] = nums[right], nums[left]
        left += 1

# STEP 4: Return result
# - Function modifies `nums` in-place; no return needed
# - Edge cases (empty, all zeros, no zeros) handled
# - naturally by loop bounds and condition

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

    # Test 1: Normal case
    nums1 = [0, 1, 0, 3, 12]
    sol.moveZeroes(nums1)
    print(f"Test 1: {nums1} == [1, 3, 12, 0, 0] → {nums1 == [1, 3, 12, 0, 0]}")

    # Test 2: Edge case
    nums2 = [0]
    sol.moveZeroes(nums2)
    print(f"Test 2: {nums2} == [0] → {nums2 == [0]}")

    # Test 3: Tricky/negative
    nums3 = [1, 2, 3]
    sol.moveZeroes(nums3)
    print(f"Test 3: {nums3} == [1, 2, 3] → {nums3 == [1, 2, 3]}")

```

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

## Example Walkthrough

We'll walk through **Test 1**: `nums = [0, 1, 0, 3, 12]`

### Initial State:

- `nums = [0, 1, 0, 3, 12]`
  - `left = 0`
- 

### Step 1: `right = 0`

- Check `nums[0] != 0` → `0 != 0` → **False**
  - Do nothing.
  - **State**: `left = 0, nums = [0, 1, 0, 3, 12]`
- 

### Step 2: `right = 1`

- Check `nums[1] != 0` → `1 != 0` → **True**
  - Swap `nums[0]` and `nums[1]`:
  - Before: `[0, 1, ...]`
  - After: `[1, 0, 0, 3, 12]`
  - Increment `left` → `left = 1`
  - **State**: `left = 1, nums = [1, 0, 0, 3, 12]`
- 

### Step 3: `right = 2`

- Check `nums[2] != 0` → `0 != 0` → **False**
  - Do nothing.
  - **State**: `left = 1, nums = [1, 0, 0, 3, 12]`
- 

### Step 4: `right = 3`

- Check `nums[3] != 0` → `3 != 0` → **True**
- Swap `nums[1]` and `nums[3]`:
- Before: `[1, 0, 0, 3, ...]`
- After: `[1, 3, 0, 0, 12]`
- Increment `left` → `left = 2`
- **State**: `left = 2, nums = [1, 3, 0, 0, 12]`

---

**Step 5:** `right = 4`

- Check `nums[4] != 0`  $\rightarrow 12 \neq 0 \rightarrow \text{True}$
  - Swap `nums[2]` and `nums[4]`:
  - Before: `[1, 3, 0, 0, 12]`
  - After: `[1, 3, 12, 0, 0]`
  - Increment `left`  $\rightarrow \text{left} = 3$
  - **State:** `left = 3, nums = [1, 3, 12, 0, 0]`
- 

**Loop Ends** (`right` reaches 5)

**Final Output:** `[1, 3, 12, 0, 0]`

**Key Takeaway:**

The `left` pointer always points to the **next position** where a non-zero should go. Every time we find a non-zero, we **swap it forward**, preserving order and pushing zeros backward **in one pass**.

---

### Complexity Analysis

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

We iterate through the array exactly once with the `right` pointer. Each swap is  $O(1)$ . Total operations scale linearly with input size.

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

Only two integer pointers (`left`, `right`) are used. The array is modified in-place — no extra space proportional to input.

## 6. Squares of a Sorted Array

**Pattern:** Two Pointers

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## Problem Statement

Given an integer array `nums` sorted in **non-decreasing order**, return an array of the squares of each number sorted in **non-decreasing order**.

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## Sample Input & Output

```
Input: [-4,-1,0,3,10]
Output: [0,1,9,16,100]
Explanation: After squaring, the array becomes [16,1,0,9,100].
               Sorting gives [0,1,9,16,100].
```

```
Input: [-7,-3,2,3,11]
Output: [4,9,9,49,121]
```

```
Input: [-5]
Output: [25]
Explanation: Single negative element → square is positive.
```

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## LeetCode Editorial Solution + Inline Tests

```
from typing import List

class Solution:
    def sortedSquares(self, nums: List[int]) -> List[int]:
        # STEP 1: Initialize structures
        #   - n: length of input (for indexing)
        #   - result: pre-allocated output array (same size)
        #   - left, right: two pointers at start and end
        n = len(nums)
        result = [0] * n
        left, right = 0, n - 1
```

```

# STEP 2: Main loop / recursion
# - Fill result from END to START (largest square first)
# - Compare abs values via squares (no need for abs())
# - Invariant: result[i+1:] is sorted; we fill result[i]
for i in range(n - 1, -1, -1):
    left_sq = nums[left] * nums[left]
    right_sq = nums[right] * nums[right]

    # STEP 3: Update state / bookkeeping
    # - Pick larger square → place at current end
    # - Move corresponding pointer inward
    if left_sq > right_sq:
        result[i] = left_sq
        left += 1
    else:
        result[i] = right_sq
        right -= 1

# STEP 4: Return result
# - Always valid: input non-empty per constraints
return result

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

    # Test 1: Normal case
    assert sol.sortedSquares([-4, -1, 0, 3, 10]) == [0, 1, 9, 16, 100]

    # Test 2: Edge case
    assert sol.sortedSquares([-5]) == [25]

    # Test 3: Tricky/negative
    assert sol.sortedSquares([-7, -3, 2, 3, 11]) == [4, 9, 9, 49, 121]

    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 `sortedSquares([-4, -1, 0, 3, 10])` step by step.

### Initial State:

- `nums = [-4, -1, 0, 3, 10]`
- `n = 5`
- `result = [0, 0, 0, 0, 0]`
- `left = 0, right = 4`

We fill `result` from the last index (4) to 0, placing the largest remaining square at each step.

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### Iteration 1: `i = 4`

- `left_sq = (-4)2 = 16`
- `right_sq = 102 = 100`
- Since `16 < 100` → pick `right_sq`
- `result[4] = 100`
- `right` moves to 3
- **State:** `result = [0, 0, 0, 0, 100], left=0, right=3`

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### Iteration 2: `i = 3`

- `left_sq = (-4)2 = 16`
- `right_sq = 32 = 9`
- `16 > 9` → pick `left_sq`
- `result[3] = 16`
- `left` moves to 1
- **State:** `result = [0, 0, 0, 16, 100], left=1, right=3`

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### Iteration 3: `i = 2`

- `left_sq = (-1)2 = 1`
- `right_sq = 32 = 9`
- `1 < 9` → pick `right_sq`
- `result[2] = 9`
- `right` moves to 2
- **State:** `result = [0, 0, 9, 16, 100], left=1, right=2`



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**Iteration 4:  $i = 1$**   
-  $\text{left\_sq} = (-1)^2 = 1$   
-  $\text{right\_sq} = 0^2 = 0$   
-  $1 > 0 \rightarrow$  pick  $\text{left\_sq}$   
-  $\text{result}[1] = 1$   
-  $\text{left}$  moves to 2  
- **State:**  $\text{result} = [0, 1, 9, 16, 100]$ ,  $\text{left}=2$ ,  $\text{right}=2$

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**Iteration 5:  $i = 0$**   
-  $\text{left\_sq} = 0^2 = 0$   
-  $\text{right\_sq} = 0^2 = 0$   
- Equal  $\rightarrow$  pick  $\text{right\_sq}$  (or left; doesn't matter)  
-  $\text{result}[0] = 0$   
-  $\text{right}$  moves to 1  
- **Final State:**  $\text{result} = [0, 1, 9, 16, 100]$

**Output:**  $[0, 1, 9, 16, 100]$  — correctly sorted squares!

#### Key Insight:

Because the input is sorted, the **largest square must come from one of the ends** (most negative or most positive). The two-pointer technique exploits this by comparing ends and working inward.

---

#### Complexity Analysis

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

We iterate through the array **exactly once** ( $n$  steps). Each step does constant-time operations (squaring, comparison, assignment).

- **Space Complexity:**  $O(1)$  **auxiliary space** (or  $O(n)$  total if counting output)

We use only a few extra variables ( $\text{left}$ ,  $\text{right}$ ,  $i$ ,  $\text{left\_sq}$ ,  $\text{right\_sq}$ ). The output array **result** is **required** by the problem, so auxiliary space is constant.

## 7. Sort Colors

**Pattern:** Two Pointers

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### Problem Statement

Given an array `nums` with `n` objects colored red, white, or blue, sort them **in-place** so that objects of the same color are adjacent, with the colors in the order red, white, and blue.

We will use the integers 0, 1, and 2 to represent the color red, white, and blue, respectively. You must solve this problem without using the library's sort function.

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### Sample Input & Output

```
Input: [2,0,2,1,1,0]
Output: [0,0,1,1,2,2]
Explanation: All 0s (red) come first, then 1s (white), then 2s (blue).
```

```
Input: [2,0,1]
Output: [0,1,2]
Explanation: One of each color, sorted in correct order.
```

```
Input: [0]
Output: [0]
Explanation: Single-element edge case - already sorted.
```

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**LeetCode Editorial Solution + Inline Tests**

```

from typing import List

class Solution:
    def sortColors(self, nums: List[int]) -> None:
        # STEP 1: Initialize pointers
        # - left: boundary for 0s (exclusive right end)
        # - right: boundary for 2s (exclusive left end)
        # - i: current index being examined
        left = 0
        right = len(nums) - 1
        i = 0

        # STEP 2: Main loop - process until i crosses right
        # - Invariant: [0:left] = 0s, [right+1:] = 2s
        # - Middle section [left:i] = 1s, [i:right+1] = unprocessed
        while i <= right:
            if nums[i] == 0:
                # STEP 3a: Move 0 to left section
                nums[i], nums[left] = nums[left], nums[i]
                left += 1
                i += 1 # safe to move forward (swapped 0 or 1)
            elif nums[i] == 2:
                # STEP 3b: Move 2 to right section
                nums[i], nums[right] = nums[right], nums[i]
                right -= 1
                # do NOT increment i - new nums[i] is unprocessed
            else:
                # STEP 3c: nums[i] == 1 -> already in correct zone
                i += 1

        # STEP 4: Return result
        # - Modification is in-place; no return needed (None)

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

    # Test 1: Normal case
    nums1 = [2, 0, 2, 1, 1, 0]
    sol.sortColors(nums1)
    print(f"Test 1: {nums1}") # Expected: [0, 0, 1, 1, 2, 2]

```

```
# Test 2: Edge case
nums2 = [0]
sol.sortColors(nums2)
print(f"Test 2: {nums2}") # Expected: [0]

# Test 3: Tricky/negative
nums3 = [2, 0, 1]
sol.sortColors(nums3)
print(f"Test 3: {nums3}") # Expected: [0, 1, 2]
```

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

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### Example Walkthrough

We'll trace **Test 3**: `nums = [2, 0, 1]`

**Initial state:**

- `nums = [2, 0, 1]`
- `left = 0, right = 2, i = 0`

---

**Step 1:** `i=0, nums[0]=2`

- Enter `elif nums[i] == 2`
- Swap `nums[0]` and `nums[2]`:  
    `nums` becomes `[1, 0, 2]`
- `right` decrements to 1
- `i` stays at 0 (because new `nums[0]=1` must be checked)

**State:** `nums=[1,0,2], left=0, right=1, i=0`

---

**Step 2:** `i=0, nums[0]=1`

- Enter `else` (value is 1)
- `i` increments to 1

**State:** `nums=[1,0,2], left=0, right=1, i=1`

---

**Step 3:** `i=1, nums[1]=0`

→ Enter if `nums[i] == 0`

→ Swap `nums[1]` and `nums[left=0]`:

`nums` becomes `[0, 1, 2]`

→ `left` increments to 1

→ `i` increments to 2

**State:** `nums=[0,1,2], left=1, right=1, i=2`

---

**Step 4:** Check loop condition `i <= right` → `2 <= 1`?

→ Loop ends.

**Final output:** `[0, 1, 2]`

**Key insight:**

- When we swap a 2 to the right, the element swapped *into* position `i` might be a 0 or 1, so we **must not advance** `i` until it's processed.
  - But when we swap a 0 from the left, we know the element coming in is either a 1 (from middle) or another 0 (already processed), so it's safe to move `i` forward.
- 

## Complexity Analysis

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

We traverse the array at most once. Each element is swapped at most twice (once for 0, once for 2), so total operations are linear.

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

Only three integer pointers (`left`, `right`, `i`) are used — constant extra space. The sort is in-place.

## 8. Rotate Array

**Pattern:** Two Pointers

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## Problem Statement

Given an integer array `nums`, rotate the array to the right by `k` steps, where `k` is non-negative.

You must do this **in-place** with  **$O(1)$**  extra space.

---

## Sample Input & Output

```
Input: nums = [1,2,3,4,5,6,7], k = 3
Output: [5,6,7,1,2,3,4]
Explanation: Rotate 3 steps to the right:
[1,2,3,4,5,6,7] → [7,1,2,3,4,5,6] →
[6,7,1,2,3,4,5] → [5,6,7,1,2,3,4]
```

```
Input: nums = [-1,-100,3,99], k = 2
Output: [3,99,-1,-100]
Explanation: Rotate 2 steps right:
[-1,-100,3,99] → [99,-1,-100,3] → [3,99,-1,-100]
```

```
Input: nums = [1], k = 0
Output: [1]
Explanation: No rotation needed (k=0). Edge case: single element.
```

---

## LeetCode Editorial Solution + Inline Tests

```
from typing import List

class Solution:
    def rotate(self, nums: List[int], k: int) -> None:
        # STEP 1: Normalize k to avoid redundant full rotations
        # - If k >= len(nums), only k % n matters
        n = len(nums)
        k = k % n
```

```

    if k == 0:
        return # No rotation needed

    # STEP 2: Reverse entire array
    # - This brings last k elements to front (but reversed)
    self.reverse(nums, 0, n - 1)

    # STEP 3: Reverse first k elements
    # - Fixes order of the rotated part
    self.reverse(nums, 0, k - 1)

    # STEP 4: Reverse remaining n-k elements
    # - Fixes order of the original front part
    self.reverse(nums, k, n - 1)

def reverse(self, nums: List[int], left: int,
            right: int) -> None:
    # Helper: reverse subarray using two pointers
    while left < right:
        nums[left], nums[right] = nums[right], nums[left]
        left += 1
        right -= 1

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

    # Test 1: Normal case
    nums1 = [1, 2, 3, 4, 5, 6, 7]
    sol.rotate(nums1, 3)
    print(f"Test 1: {nums1}") # Expected: [5,6,7,1,2,3,4]

    # Test 2: Edge case (k=0, single element)
    nums2 = [1]
    sol.rotate(nums2, 0)
    print(f"Test 2: {nums2}") # Expected: [1]

    # Test 3: Tricky/negative (k > n, duplicates)
    nums3 = [-1, -100, 3, 99]
    sol.rotate(nums3, 2)
    print(f"Test 3: {nums3}") # Expected: [3,99,-1,-100]

```

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

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### Example Walkthrough

We'll walk through **Test 1**: `nums = [1,2,3,4,5,6,7]`, `k = 3`.

#### Initial Setup

- `nums = [1, 2, 3, 4, 5, 6, 7]`
  - `n = 7`
  - `k = 3 % 7 = 3` → not zero, so proceed.
- 

#### Step 1: Reverse entire array → `reverse(nums, 0, 6)`

- **Two pointers:** `left=0, right=6`
- Swap `nums[0]` and `nums[6]` → `[7,2,3,4,5,6,1]`
- `left=1, right=5` → swap → `[7,6,3,4,5,2,1]`
- `left=2, right=4` → swap → `[7,6,5,4,3,2,1]`
- `left=3, right=3` → stop (`left >= right`)
- **Result:** `[7,6,5,4,3,2,1]`

Why? The last `k=3` elements (`5,6,7`) are now at the front — but reversed as `7,6,5`.

---

#### Step 2: Reverse first `k=3` elements → `reverse(nums, 0, 2)`

- `left=0, right=2`
- Swap `nums[0]` and `nums[2]` → `[5,6,7,4,3,2,1]`
- `left=1, right=1` → stop
- **Result:** `[5,6,7,4,3,2,1]`

Now the rotated part (`5,6,7`) is in correct order!

---



**Step 3: Reverse remaining  $n-k = 4$  elements  $\rightarrow$  `reverse(nums, 3, 6)`**

- `left=3, right=6`
  - Swap `nums[3]` and `nums[6]`  $\rightarrow$  `[5,6,7,1,3,2,4]`
  - `left=4, right=5`  $\rightarrow$  swap  $\rightarrow$  `[5,6,7,1,2,3,4]`
  - `left=5, right=4`  $\rightarrow$  stop
  - **Final Result:** `[5,6,7,1,2,3,4]`  $\rightarrow$  matches expected!
- 

### Summary of State Changes

Step	Operation	Array State
0	Start	<code>[1,2,3,4,5,6,7]</code>
1	Reverse all	<code>[7,6,5,4,3,2,1]</code>
2	Reverse first 3	<code>[5,6,7,4,3,2,1]</code>
3	Reverse last 4	<code>[5,6,7,1,2,3,4]</code>

**Key Insight:** Three reverses simulate rotation without extra space.  
This is a classic **two pointers** trick: use symmetry to reposition elements.

---

### Complexity Analysis

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

We reverse the array 3 times. Each reverse visits at most  $n$  elements.  
Total operations  $n/2 + k/2 + (n-k)/2 = n \rightarrow$  linear.

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

Only a few integer variables (`left`, `right`, `n`, `k`) are used.  
No extra arrays or recursion stack — truly in-place.