



500+ Live Coding Interview Problems for C/Embedded C

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General C Programming (80 Problems)

Problem 1: Reverse a Null-Terminated String In-Place

Issue Description

Reverse a null-terminated string in-place, e.g., "hello" becomes "olleh".

Handle edge cases like NULL or empty strings.

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** Reversed string in-place.
- **Approach:** Use two pointers to swap characters from ends.
- **Steps:** Validate input, find length, swap characters using pointers.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <string.h>

// Reverses a null-terminated string in-place.
void reverseString(char* str) {
    if (str == NULL || str[0] == '\0') return; // Handle NULL or empty
    int len = 0;
    while (str[len] != '\0') len++; // Find length
    for (int i = 0, j = len - 1; i < j; i++, j--) { // Swap characters
        char temp = str[i];
        str[i] = str[j];
        str[j] = temp;
    }
}

// Unit test helper
void assertStringEquals(const char* expected, char* actual, const char* testName) {
    printf("%s: %s\n", testName, strcmp(expected, actual) == 0 ? "PASSED" : "FAILED");
}

// Unit tests for reverseString
void testReverseString() {
    char test1[] = "hello";
    reverseString(test1);
    assertStringEquals("olleh", test1, "Test 1.1 - Normal string");
    char test2[] = "";
    reverseString(test2);
    assertStringEquals("", test2, "Test 1.2 - Empty string");
}
```

Best Practices & Expert Tips

- **Best Practices:** Validate inputs; use O(1) space.
- **Tips:** Explain two-pointer technique; test edge cases in interviews.

Problem 2: Find the First Non-Repeating Character in a String

Issue Description

Return the first character that appears once in a string, e.g., 'l' in "leetcode".

Return '\0' if none.

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string (lowercase).
- **Output:** First non-repeating character or '\0'.
- **Approach:** Count frequencies, then find first character with count 1.
- **Steps:** Validate input, use frequency array, scan for count 1.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
// Returns first non-repeating character (lowercase letters).
char firstNonRepeatingChar(const char* str) {
    if (str == NULL || str[0] == '\0') return '\0'; // Handle edge cases
    int freq[26] = {0}; // Frequency array
    for (int i = 0; str[i] != '\0'; i++) freq[str[i] - 'a']++;
    for (int i = 0; str[i] != '\0'; i++) {
        if (freq[str[i] - 'a'] == 1) return str[i]; // First with count 1
    }
    return '\0';
}

// Unit test helper
void assertCharEquals(char expected, char actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests for firstNonRepeatingChar
void testFirstNonRepeatingChar() {
    assertCharEquals('l', firstNonRepeatingChar("leetcode"), "Test 2.1 - Normal case");
    assertCharEquals('\0', firstNonRepeatingChar("aabb"), "Test 2.2 - No non-repeating");
}
```

Best Practices & Expert Tips

- **Best Practices:** Use fixed-size array; validate inputs.
- **Tips:** Discuss frequency array; mention hash table for general cases.

Problem 3: Check if Two Strings are Anagrams

Issue Description

Check if two strings are anagrams (same characters, same frequencies), e.g., "listen" and "silent".

Problem Decomposition & Solution Steps

- **Input:** Two null-terminated strings (lowercase).

- **Output:** Boolean (true if anagrams).
- **Approach:** Compare character frequencies.
- **Steps:** Check lengths, use frequency array, compare counts.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
#include <stdbool.h>

// Checks if two strings are anagrams (lowercase).
bool areAnagrams(const char* str1, const char* str2) {
    if (str1 == NULL || str2 == NULL || strlen(str1) != strlen(str2)) return false;
    int freq[26] = {0}; // Frequency array
    for (int i = 0; str1[i] != '\0'; i++) {
        freq[str1[i] - 'a']++;
        freq[str2[i] - 'a']--;
    }
    for (int i = 0; i < 26; i++) {
        if (freq[i] != 0) return false; // Non-zero means not anagrams
    }
    return true;
}

// Unit test helper
void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests for areAnagrams
void testAreAnagrams() {
    assertBoolEquals(true, areAnagrams("listen", "silent"), "Test 3.1 - Valid anagrams");
    assertBoolEquals(false, areAnagrams("hello", "world"), "Test 3.2 - Not anagrams");
}
```

Best Practices & Expert Tips

- **Best Practices:** Check lengths first; use O(1) space.
- **Tips:** Explain frequency array; discuss sorting alternative.

Problem 4: Implement strlen

Issue Description

Return the length of a null-terminated string, excluding '\0', e.g., "hello" returns 5.

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** Length as size_t.
- **Approach:** Count characters until '\0'.
- **Steps:** Validate input, iterate to count.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
// Returns length of null-terminated string.
size_t myStrlen(const char* str) {
    if (str == NULL) return 0; // Handle NULL
    size_t len = 0;
    while (str[len] != '\0') len++; // Count until '\0'
    return len;
}

// Unit test helper
void assertSizeTEquals(size_t expected, size_t actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests for myStrlen
void testMyStrlen() {
    assertSizeTEquals(5, myStrlen("hello"), "Test 4.1 - Normal string");
    assertSizeTEquals(0, myStrlen ""), "Test 4.2 - Empty string");
}
```

Best Practices & Expert Tips

- **Best Practices:** Use `size_t`; check `NULL`.
- **Tips:** Mention pointer arithmetic alternative; test edge cases.

Problem 5: Convert a String to an Integer (atoi)

Issue Description

Convert a string to a signed integer, handling spaces, signs, and overflow, e.g., "-123" returns -123.

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** Integer value.
- **Approach:** Parse string, handle signs, check overflow.
- **Steps:** Skip spaces, parse sign, convert digits, handle overflow.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
#include <limits.h>

// Converts string to integer with overflow handling.
int myAtoi(const char* str) {
    if (str == NULL) return 0; // Handle NULL
    int i = 0;
    while (str[i] == ' ') i++; // Skip spaces
    int sign = 1;
    if (str[i] == '-') { sign = -1; i++; } else if (str[i] == '+') i++;
    long result = 0;
    while (str[i] >= '0' && str[i] <= '9') { // Convert digits
        result = result * 10 + (str[i] - '0');
        if (result * sign > INT_MAX) return INT_MAX;
        if (result * sign < INT_MIN) return INT_MIN;
    }
    return (int)(result * sign); }
```

```

// Unit test helper
void assertEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests for myAtoi
void testMyAtoi() {
    assertEquals(123, myAtoi("123"), "Test 5.1 - Positive number");
    assertEquals(-123, myAtoi("-123"), "Test 5.2 - Negative number");
}

```

Best Practices & Expert Tips

- **Best Practices:** Handle overflow; skip whitespace.
- **Tips:** Discuss long for intermediate results; test overflow cases.

Problem 6: Merge Two Sorted Arrays

Issue Description

Merge two sorted arrays into the first array, which has enough space, e.g., [1,3,0,0] and [2,4] becomes [1,2,3,4].

Problem Decomposition & Solution Steps

- **Input:** Two sorted arrays, their sizes.
- **Output:** First array contains merged sorted elements.
- **Approach:** Merge from end to avoid shifting.
- **Steps:** Compare from end, place larger elements.
- **Complexity:** Time O(n+m), Space O(1).

Coding Part (with Unit Tests)

```

// Merges two sorted arrays into arr1.
void mergeSortedArrays(int* arr1, int m, int* arr2, int n) {
    int i = m - 1, j = n - 1, k = m + n - 1; // Indices
    while (i >= 0 && j >= 0) { // Merge from end
        arr1[k--] = (arr1[i] > arr2[j]) ? arr1[i--] : arr2[j--];
    }
    while (j >= 0) arr1[k--] = arr2[j--]; // Copy remaining
}

// Unit test helper
void assertEquals(int expected, int actual, const char* testName) {
    int pass = 1;
    for (int i = 0; i < size; i++) if (expected[i] != actual[i]) pass = 0;
    printf("%s: %s\n", testName, pass ? "PASSED" : "FAILED");
}

// Unit tests for mergeSortedArrays
void testMergeSortedArrays() {
    int arr1[6] = {1, 3, 5, 0, 0, 0}, arr2[] = {2, 4, 6};
    int expected[] = {1, 2, 3, 4, 5, 6};
    mergeSortedArrays(arr1, 3, arr2, 3);
    assertEquals(expected, arr1, 6, "Test 6.1 - Normal merge");
}

```

Best Practices & Expert Tips

- **Best Practices:** Merge from end; validate inputs.
- **Tips:** Explain why end-to-start saves space; test empty arrays.

Problem 7: Find the Maximum Element in an Array

Issue Description

Find the maximum element in an integer array, e.g., [1,5,3] returns 5.

Problem Decomposition & Solution Steps

- **Input:** Array and size.
- **Output:** Maximum integer.
- **Approach:** Track max while iterating.
- **Steps:** Validate input, scan array.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
// Returns maximum element in array.
int findMax(int* arr, int size) {
    if (arr == NULL || size <= 0) return INT_MIN; // Handle edge cases
    int max = arr[0];
    for (int i = 1; i < size; i++) {
        if (arr[i] > max) max = arr[i]; // Update max
    }
    return max;
}

// Unit tests for findMax
void testFindMax() {
    int arr1[] = {1, 5, 3, 8, 2};
    assertEquals(8, findMax(arr1, 5), "Test 7.1 - Normal array");
    int arr2[] = {1};
    assertEquals(1, findMax(arr2, 1), "Test 7.2 - Single element");
}
```

Best Practices & Expert Tips

- **Best Practices:** Use INT_MIN for invalid cases; validate inputs.
- **Tips:** Discuss linear scan; mention parallelization for large arrays.

Problem 8: Remove Duplicates from a Sorted Array In-Place

Issue Description

Remove duplicates from a sorted array in-place, returning new length, e.g., [1,1,2] becomes [1,2].

Problem Decomposition & Solution Steps

- **Input:** Sorted array and size.
- **Output:** New length; unique elements in array.
- **Approach:** Use two pointers for unique elements.
- **Steps:** Validate input, copy unique elements.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
// Removes duplicates in-place, returns new length.
int removeDuplicates(int* arr, int size) {
    if (arr == NULL || size <= 0) return 0;
    if (size == 1) return 1;
    int unique = 1; // Next unique position
    for (int i = 1; i < size; i++) {
        if (arr[i] != arr[unique - 1]) arr[unique++] = arr[i];
    }
    return unique;
}

// Unit tests for removeDuplicates
void testRemoveDuplicates() {
    int arr1[] = {1, 1, 2, 2, 3};
    int expected[] = {1, 2, 3};
    int len = removeDuplicates(arr1, 5);
    assertArrayEquals(expected, arr1, len, "Test 8.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:** Modify in-place; handle edge cases.
- **Tips:** Explain two-pointer technique; test single-element case.

Problem 9: Rotate an Array by k Positions

Issue Description

Rotate array right by k positions, e.g., [1,2,3,4,5] with k=2 becomes [4,5,1,2,3].

Problem Decomposition & Solution Steps

- **Input:** Array, size, k.
- **Output:** Rotated array in-place.
- **Approach:** Reverse entire array, then reverse segments.
- **Steps:** Normalize k, reverse array, reverse segments.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
// Helper to reverse array segment
void reverse(int* arr, int start, int end) {
    while (start < end) {
        int temp = arr[start];
        arr[start++] = arr[end--];
    }
}

// Rotates array right by k positions
void rotateArray(int* arr, int size, int k) {
    if (arr == NULL || size <= 1 || k == 0) return;
    k = k % size; // Normalize k
    reverse(arr, 0, size - 1); // Reverse all
    reverse(arr, 0, k - 1); // Reverse first k
    reverse(arr, k, size - 1); // Reverse rest
}

// Unit tests for rotateArray
void testRotateArray() {
    int arr1[] = {1, 2, 3, 4, 5};
    int expected[] = {4, 5, 1, 2, 3};
    rotateArray(arr1, 5, 2);
    assertArrayEquals(expected, arr1, 5, "Test 9.1 - Normal rotate");
}
```

Best Practices & Expert Tips

- **Best Practices:** Normalize k; use helper functions.
- **Tips:** Explain reversal method; test large k values.

Problem 10: Check if a String is a Palindrome

Issue Description

Check if a string is a palindrome (reads same forward and backward), e.g., "racecar" returns true.

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** Boolean (true if palindrome).
- **Approach:** Compare characters from ends.
- **Steps:** Validate input, use two pointers to compare.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
// Checks if string is a palindrome.
bool isPalindrome(const char* str) {
    if (str == NULL || str[0] == '\0') return true; // Handle edge cases
    int len = strlen(str);
    for (int i = 0, j = len - 1; i < j; i++, j--) { // Compare ends
        if (str[i] != str[j]) return false;
    }
    return true;
}
```

```

// Unit tests for isPalindrome
void testIsPalindrome() {
    assertBoolEquals(true, isPalindrome("racecar"), "Test 10.1 - Palindrome");
    assertBoolEquals(false, isPalindrome("hello"), "Test 10.2 - Not palindrome");
}

```

Best Practices & Expert Tips

- **Best Practices:** Validate inputs; compare from ends.
- **Tips:** Discuss two-pointer approach; test empty strings.

Main Function to Run All Tests

```

int main() {
    printf("Running tests for all problems:\n");
    testReverseString();
    testFirstNonRepeatingChar();
    testAreAnagrams();
    testMyStrlen();
    testMyAtoi();
    testMergeSortedArrays();
    testFindMax();
    testRemoveDuplicates();
    testRotateArray();
    testIsPalindrome();
    return 0;
}

```

Problem 11: Implement strstr to Find a Substring in a String

Issue Description

Find the first occurrence of a substring (needle) in a string (haystack), returning a pointer to the start or NULL if not found, e.g., strstr("hello", "ll") returns pointer to "ll".

Problem Decomposition & Solution Steps

- **Input:** Two null-terminated strings (haystack, needle).
- **Output:** Pointer to first occurrence or NULL.
- **Approach:** Check each position in haystack for needle match.
- **Steps:** Validate inputs, iterate haystack, compare substrings.
- **Complexity:** Time O(n*m), Space O(1).

Coding Part (with Unit Tests)

```

#include <stdio.h>
#include <string.h>
#include <stdbool.h>

// Returns pointer to first occurrence of needle in haystack or NULL.
char* mystrstr(const char* haystack, const char* needle) {
    if (haystack == NULL || needle == NULL || needle[0] == '\0') return (char*)haystack;
    for (int i = 0; haystack[i] != '\0'; i++) { // Iterate haystack
        if (haystack[i] == needle[0]) {
            int j = 1;
            while (needle[j] != '\0' && haystack[i + j] == needle[j]) j++;
            if (needle[j] == '\0') return (char*)(haystack + i);
        }
    }
    return NULL;
}

```

```

        int j = 0;
        while (needle[j] != '\0' && haystack[i + j] == needle[j]) j++; // Check match
        if (needle[j] == '\0') return (char*)&haystack[i]; // Full match found
    }
    return NULL;
}

// Unit test helper
void assertPtrEquals(const char* expected, const char* actual, const char* testName) {
    printf("%s: %s\n", testName, (expected == actual || (expected && actual && strcmp(expected,
actual) == 0)) ? "PASSED" : "FAILED");
}

// Unit tests for myStrstr
void testMyStrstr() {
    assertPtrEquals("llo", myStrstr("hello", "ll"), "Test 11.1 - Substring found");
    assertPtrEquals(NULL, myStrstr("hello", "xyz"), "Test 11.2 - Substring not found");
}

```

Best Practices & Expert Tips

- **Best Practices:** Handle empty needle; validate inputs.
- **Tips:** Discuss KMP algorithm for optimization; test edge cases like empty strings.

Problem 12: Count Occurrences of a Character in a String

Issue Description

Count how many times a character appears in a string, e.g., 'l' in "hello" returns 3.

Problem Decomposition & Solution Steps

- **Input:** String and character.
- **Output:** Integer count.
- **Approach:** Iterate string, count matches.
- **Steps:** Validate input, scan string.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```

// Counts occurrences of ch in str.
int countChar(const char* str, char ch) {
    if (str == NULL) return 0; // Handle NULL
    int count = 0;
    for (int i = 0; str[i] != '\0'; i++) { // Scan string
        if (str[i] == ch) count++;
    }
    return count;
}

// Unit test helper
void assertIntEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

```

```

// Unit tests for countChar
void testCountChar() {
    assertEquals(3, countChar("hello", 'l'), "Test 12.1 - Normal case");
    assertEquals(0, countChar("hello", 'x'), "Test 12.2 - Char not found");
}

```

Best Practices & Expert Tips

- **Best Practices:** Check NULL; simple iteration.
- **Tips:** Explain linear scan; test empty string and missing char.

Problem 13: Replace All Spaces in a String with '%20'

Issue Description

Replace all spaces in a string with "%20" in-place, assuming sufficient space, e.g., "hello world" becomes "hello%20world".

Problem Decomposition & Solution Steps

- **Input:** String with extra space at end.
- **Output:** Modified string.
- **Approach:** Count spaces, replace from end.
- **Steps:** Validate input, count spaces, replace backwards.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```

// Replaces spaces with "%20" in-place.
void replaceSpaces(char* str, int len) {
    if (str == NULL || len <= 0) return;
    int spaces = 0;
    for (int i = 0; i < len; i++) if (str[i] == ' ') spaces++;
    int newLen = len + 2 * spaces;
    for (int i = len - 1, j = newLen - 1; i >= 0; i--) { // Replace from end
        if (str[i] == ' ') {
            str[j--] = '0'; str[j--] = '2'; str[j--] = '%';
        } else {
            str[j--] = str[i];
        }
    }
}

// Unit test helper
void assertEquals(const char* expected, const char* actual, const char* testName) {
    printf("%s: %s\n", testName, strcmp(expected, actual) == 0 ? "PASSED" : "FAILED");
}

// Unit tests for replaceSpaces
void testReplaceSpaces() {
    char test1[20] = "hello world ";
    replaceSpaces(test1, 11);
    assertEquals("hello%20world", test1, "Test 13.1 - Normal case");
}

```

Best Practices & Expert Tips

- **Best Practices:** Work backwards to avoid shifting; validate inputs.
- **Tips:** Explain why backwards replacement saves space; test multiple spaces.

Problem 14: Find the Longest Common Prefix Among an Array of Strings

Issue Description

Find the longest common prefix among an array of strings, e.g., ["flower", "flow", "flight"] returns "fl".

Problem Decomposition & Solution Steps

- **Input:** Array of strings, size.
- **Output:** Longest common prefix.
- **Approach:** Compare characters of first string with others.
- **Steps:** Validate input, iterate characters, check matches.
- **Complexity:** Time O(n*m), Space O(1).

Coding Part (with Unit Tests)

```
// Returns longest common prefix; caller frees memory.
char* longestCommonPrefix(char** strs, int size) {
    if (strs == NULL || size == 0) return "";
    if (size == 1) return strs[0];
    int len = strlen(strs[0]);
    for (int i = 0; i < len; i++) { // Check each character
        for (int j = 1; j < size; j++) {
            if (strs[j][i] != strs[0][i] || strlen(strs[j]) <= i) {
                char* result = (char*)malloc(i + 1);
                strncpy(result, strs[0], i);
                result[i] = '\0';
                return result;
            }
        }
    }
    char* result = (char*)malloc(len + 1);
    strcpy(result, strs[0]);
    return result;
}

// Unit tests for longestCommonPrefix
void testLongestCommonPrefix() {
    char* strs[] = {"flower", "flow", "flight"};
    char* result = longestCommonPrefix(strs, 3);
    assertEquals("fl", result, "Test 14.1 - Normal case");
    free(result);
}
```

Best Practices & Expert Tips

- **Best Practices:** Handle memory allocation; check empty array.
- **Tips:** Discuss vertical scanning; test single string case.

Problem 15: Implement a Function to Copy a String

Issue Description

Copy a source string to a destination, including '\0', e.g., copy "hello" to new buffer.

Problem Decomposition & Solution Steps

- **Input:** Source and destination strings.
- **Output:** Copied string in destination.
- **Approach:** Copy characters until '\0'.
- **Steps:** Validate inputs, copy characters.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
// Copies src to dest, including '\0'.
void myStrcpy(char* dest, const char* src) {
    if (dest == NULL || src == NULL) return;
    int i = 0;
    while ((dest[i] = src[i]) != '\0') i++; // Copy until '\0'
}

// Unit tests for myStrcpy
void testMyStrcpy() {
    char dest[10];
    myStrcpy(dest, "hello");
    assertStringEquals("hello", dest, "Test 15.1 - Normal copy");
}
```

Best Practices & Expert Tips

- **Best Practices:** Check NULL; ensure dest has space.
- **Tips:** Discuss buffer overflow risks; test empty string.

Problem 16: Reverse Words in a String

Issue Description

Reverse the order of words in a string, e.g., "hello world" becomes "world hello".

Problem Decomposition & Solution Steps

- **Input:** String with words.
- **Output:** String with reversed words.
- **Approach:** Reverse entire string, then each word.
- **Steps:** Validate input, reverse string, reverse words.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
// Helper to reverse segment
void reverseSegment(char* str, int start, int end) {
    while (start < end) {
        char temp = str[start];
        str[start++] = str[end--];
    }
}

// Reverses words in string in-place
void reverseWords(char* str) {
    if (str == NULL || str[0] == '\0') return;
    int len = strlen(str);
    reverseSegment(str, 0, len - 1); // Reverse entire string
    int start = 0;
    for (int i = 0; i <= len; i++) { // Reverse each word
        if (str[i] == ' ' || str[i] == '\0') {
            reverseSegment(str, start, i - 1);
            start = i + 1;
        }
    }
}

// Unit tests for reverseWords
void testReverseWords() {
    char test1[] = "hello world";
    reverseWords(test1);
    assertEquals("world hello", test1, "Test 16.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:** Handle spaces; reverse in-place.
- **Tips:** Explain two-step reversal; test multiple words.

Problem 17: Check if a Number is Prime

Issue Description

Check if a number is prime (divisible only by 1 and itself), e.g., 7 returns true.

Problem Decomposition & Solution Steps

- **Input:** Integer.
- **Output:** Boolean (true if prime).
- **Approach:** Check divisibility up to square root.
- **Steps:** Validate input, test divisors.
- **Complexity:** Time $O(\sqrt{n})$, Space $O(1)$.

Coding Part (with Unit Tests)

```
// Checks if n is prime.
bool isPrime(int n) {
    if (n <= 1) return false; // Handle non-prime cases
    for (int i = 2; i * i <= n; i++) { // Check up to sqrt(n)
        if (n % i == 0) return false;
    }
    return true;
}
// Unit tests for isPrime
void testIsPrime() {
    assertEquals(true, isPrime(7), "Test 17.1 - Prime number");
    assertEquals(false, isPrime(4), "Test 17.2 - Non-prime");
}
```

Best Practices & Expert Tips

- **Best Practices:** Optimize with sqrt; handle negatives.
- **Tips:** Explain sqrt optimization; test small numbers.

Problem 18: Find the Factorial of a Number

Issue Description

Compute the factorial of a non-negative integer, e.g., $5! = 120$.

Problem Decomposition & Solution Steps

- **Input:** Non-negative integer.
- **Output:** Factorial as unsigned long.
- **Approach:** Iterative multiplication.
- **Steps:** Validate input, multiply numbers.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
// Computes factorial of n.
unsigned long factorial(int n) {
    if (n < 0) return 0; // Handle invalid input
    if (n == 0 || n == 1) return 1;
    unsigned long result = 1;
    for (int i = 2; i <= n; i++) result *= i; // Multiply
    return result;
}

// Unit tests for factorial
void testFactorial() {
    assertEquals(120, factorial(5), "Test 18.1 - Normal case");
    assertEquals(1, factorial(0), "Test 18.2 - Zero case");
}
```

Best Practices & Expert Tips

- **Best Practices:** Use unsigned long; check negative input.
- **Tips:** Discuss overflow; test edge cases like 0.

Problem 19: Compute the Power of a Number (x^n)

Issue Description

Compute x raised to power n , e.g., $2^3 = 8$.

Problem Decomposition & Solution Steps

- **Input:** Base x (double), exponent n (int).
- **Output:** x^n as double.
- **Approach:** Use binary exponentiation.
- **Steps:** Handle negative n , use bit manipulation.
- **Complexity:** Time $O(\log n)$, Space $O(1)$.

Coding Part (with Unit Tests)

```
// Computes x^n using binary exponentiation.
double myPow(double x, int n) {
    if (n == 0) return 1.0;
    long long m = n; // Handle INT_MIN
    if (m < 0) { x = 1 / x; m = -m; }
    double result = 1.0, curr = x;
    while (m > 0) { // Binary exponentiation
        if (m & 1) result *= curr;
        curr *= curr;
        m >>= 1;
    }
    return result;
}

// Unit test helper
void assertDoubleEquals(double expected, double actual, const char* testName) {
    printf("%s: %s\n", testName, (expected - actual < 0.0001 && actual - expected < 0.0001) ? "PASSED"
: "FAILED");
}

// Unit tests for myPow
void testMyPow() {
    assertDoubleEquals(8.0, myPow(2.0, 3), "Test 19.1 - Positive exponent");
    assertDoubleEquals(0.25, myPow(2.0, -2), "Test 19.2 - Negative exponent");
}
```

Best Practices & Expert Tips

- **Best Practices:** Handle negative exponents; use long long.
- **Tips:** Explain binary exponentiation; test zero and negative n .

Problem 20: Sort an Array Using Bubble Sort

Issue Description

Sort an integer array using bubble sort, e.g., [5,2,8] becomes [2,5,8].

Problem Decomposition & Solution Steps

- **Input:** Array and size.
- **Output:** Sorted array in-place.
- **Approach:** Repeatedly swap adjacent elements if out of order.
- **Steps:** Validate input, iterate and swap.
- **Complexity:** Time $O(n^2)$, Space $O(1)$.

Coding Part (with Unit Tests)

```
// Sorts array using bubble sort.
void bubbleSort(int* arr, int size) {
    if (arr == NULL || size <= 1) return;
    for (int i = 0; i < size - 1; i++) { // Pass through array
        for (int j = 0; j < size - i - 1; j++) {
            if (arr[j] > arr[j + 1]) { // Swap if out of order
                int temp = arr[j];
                arr[j] = arr[j + 1];
                arr[j + 1] = temp;
            }
        }
    }
}

// Unit tests for bubbleSort
void testBubbleSort() {
    int arr1[] = {5, 2, 8, 1, 9};
    int expected[] = {1, 2, 5, 8, 9};
    bubbleSort(arr1, 5);
    assertArrayEquals(expected, arr1, 5, "Test 20.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:** Optimize by checking swaps; validate inputs.
- **Tips:** Discuss bubble sort's simplicity; test sorted arrays.

Main Function to Run All Tests

```
int main() {
    printf("Running tests for problems 11 to 20:\n");
    testMyStrstr();
    testCountChar();
    testReplaceSpaces();
    testLongestCommonPrefix();
    testMyStrcpy();
    testReverseWords();
    testIsPrime();
    testFactorial();
    testMyPow();
    testBubbleSort();
    return 0;
}
```

Problem 21: Swap Two Integers Without a Temporary Variable

Issue Description

Swap two integers in-place without using a temporary variable, e.g., $a=5, b=3$ becomes $a=3, b=5$.

Problem Decomposition & Solution Steps

- **Input:** Two integer pointers.
- **Output:** Swapped values.
- **Approach:** Use XOR operations.
- **Steps:** Validate pointers, apply XOR swap.
- **Complexity:** Time O(1), Space O(1).

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <string.h>
#include <stdbool.h>
#include <stdlib.h>

// Swaps two integers using XOR.
void swapIntegers(int* a, int* b) {
    if (a == NULL || b == NULL) return; // Validate pointers
    *a ^= *b; // a = a XOR b
    *b ^= *a; // b = (a XOR b) XOR b = a
    *a ^= *b; // a = (a XOR b) XOR a = b
}

// Unit test helper
void assertEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests for swapIntegers
void testSwapIntegers() {
    int a = 5, b = 3;
    swapIntegers(&a, &b);
    assertEquals(3, a, "Test 21.1 - Swap a");
    assertEquals(5, b, "Test 21.2 - Swap b");
}
```

Best Practices & Expert Tips

- **Best Practices:** Validate pointers; use XOR for no temp variable.
- **Tips:** Explain XOR swap; mention arithmetic alternative ($a = a + b$, etc.).

Problem 22: Find the Second Largest Element in an Array

Issue Description

Find the second largest element in an integer array, e.g., [5,3,8,1] returns 5.

Problem Decomposition & Solution Steps

- **Input:** Array, size.
- **Output:** Second largest integer.
- **Approach:** Track largest and second largest in one pass.
- **Steps:** Validate input, scan array.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
#include <limits.h>

// Returns second largest element.
int secondLargest(int* arr, int size) {
    if (arr == NULL || size < 2) return INT_MIN; // Validate input
    int first = INT_MIN, second = INT_MIN;
    for (int i = 0; i < size; i++) { // Single pass
        if (arr[i] > first) {
            second = first;
            first = arr[i];
        } else if (arr[i] > second && arr[i] != first) {
            second = arr[i];
        }
    }
    return second;
}

// Unit tests for secondLargest
void testSecondLargest() {
    int arr[] = {5, 3, 8, 1};
    assertEquals(5, secondLargest(arr, 4), "Test 22.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:** Handle edge cases; single pass.
- **Tips:** Discuss handling duplicates; test small arrays.

Problem 23: Check if a String Contains Only Digits

Issue Description

Check if a string contains only digits, e.g., "123" returns true, "12a" returns false.

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** Boolean.
- **Approach:** Check each character.
- **Steps:** Validate input, verify digits.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
// Checks if string contains only digits.
bool isOnlyDigits(const char* str) {
    if (str == NULL || str[0] == '\0') return false; // Validate input
    for (int i = 0; str[i] != '\0'; i++) { // Check each character
        if (str[i] < '0' || str[i] > '9') return false;
    }
    return true;
}
```

```

// Unit test helper
void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests for isOnlyDigits
void testIsOnlyDigits() {
    assertBoolEquals(true, isOnlyDigits("123"), "Test 23.1 - Only digits");
    assertBoolEquals(false, isOnlyDigits("12a"), "Test 23.2 - Non-digit");
}

```

Best Practices & Expert Tips

- **Best Practices:** Check empty/NULL; simple iteration.
- **Tips:** Discuss character range check; test empty string.

Problem 24: Convert a Decimal Number to Binary (Return as String)

Issue Description

Convert a decimal number to its binary representation as a string, e.g., 10 returns "1010".

Problem Decomposition & Solution Steps

- **Input:** Non-negative integer.
- **Output:** Binary string (caller frees).
- **Approach:** Divide by 2, collect remainders.
- **Steps:** Validate input, build string backwards, reverse.
- **Complexity:** Time O(log n), Space O(log n).

Coding Part (with Unit Tests)

```

// Converts decimal to binary string.
char* decimalToBinary(int n) {
    if (n < 0) return NULL; // Handle invalid input
    if (n == 0) return strdup("0"); // Handle zero
    char* result = (char*)malloc(33); // Max 32 bits + '\0'
    int i = 0;
    while (n > 0) { // Collect remainders
        result[i++] = (n % 2) + '0';
        n /= 2;
    }
    result[i] = '\0';
    reverseSegment(result, 0, i - 1); // Reuse reverse from Problem 16
    return result;
}

// Unit tests for decimalToBinary
void testDecimalToBinary() {
    char* result = decimalToBinary(10);
    assertStringEquals("1010", result, "Test 24.1 - Normal case");
    free(result);
}

```

Best Practices & Expert Tips

- **Best Practices:** Allocate sufficient memory; free result.
- **Tips:** Explain reverse step; test zero and large numbers.

Problem 25: Implement a Function to Compare Two Strings

Issue Description

Compare two strings lexicographically, returning -1, 0, or 1 for less, equal, or greater, e.g., "abc" vs "abd" returns -1.

Problem Decomposition & Solution Steps

- **Input:** Two null-terminated strings.
- **Output:** Integer (-1, 0, 1).
- **Approach:** Compare characters until mismatch or end.
- **Steps:** Validate inputs, compare characters.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
// Compares two strings lexicographically.
int mystrcmp(const char* s1, const char* s2) {
    if (s1 == NULL || s2 == NULL) return (s1 == s2) ? 0 : (s1 ? 1 : -1);
    while (*s1 && (*s1 == *s2)) { s1++; s2++; } // Compare until mismatch
    return (*s1 == *s2) ? 0 : (*s1 > *s2 ? 1 : -1);
}

// Unit tests for mystrcmp
void testMystrcmp() {
    assertEquals(-1, mystrcmp("abc", "abd"), "Test 25.1 - Less than");
    assertEquals(0, mystrcmp("abc", "abc"), "Test 25.2 - Equal");
}
```

Best Practices & Expert Tips

- **Best Practices:** Handle NULL; compare efficiently.
- **Tips:** Discuss pointer vs index approach; test NULL cases.

Problem 26: Find the Most Frequent Element in an Array

Issue Description

Find the element with the highest frequency in an array, e.g., [1,2,2,3] returns 2.

Problem Decomposition & Solution Steps

- **Input:** Array, size.
- **Output:** Most frequent element.
- **Approach:** Use hash table (array for small range).
- **Steps:** Validate input, count frequencies, find max.
- **Complexity:** Time O(n), Space O(k) (k=range).

Coding Part (with Unit Tests)

```
// Returns most frequent element (assumes 0-99 range).
int mostFrequent(int* arr, int size) {
    if (arr == NULL || size <= 0) return -1;
    int freq[100] = {0}; // Frequency array
    for (int i = 0; i < size; i++) freq[arr[i]]++;
    int maxCount = 0, result = arr[0];
    for (int i = 0; i < 100; i++) {
        if (freq[i] > maxCount) {
            maxCount = freq[i];
            result = i;
        }
    }
    return result;
}

// Unit tests for mostFrequent
void testMostFrequent() {
    int arr[] = {1, 2, 2, 3};
    assertEquals(2, mostFrequent(arr, 4), "Test 26.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:** Validate input; assume range for array.
- **Tips:** Discuss hash table for large ranges; test ties.

Problem 27: Check if a String is a Valid Email Address

Issue Description

Check if a string is a valid email (basic validation: local@domain.tld), e.g., "user@domain.com" returns true.

Problem Decomposition & Solution Steps

- **Input:** String.
- **Output:** Boolean.
- **Approach:** Check for @, domain, and TLD.
- **Steps:** Validate structure, check characters.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
// Checks if string is a valid email (basic).
bool isValidEmail(const char* str) {
    if (str == NULL || str[0] == '\0') return false;
    int atCount = 0, dotCount = 0, i = 0;
    while (str[i] != '\0') {
        if (str[i] == '@') atCount++;
        else if (str[i] == '.' && atCount == 1) dotCount++;
        else if ((str[i] < 'a' || str[i] > 'z') && (str[i] < '0' || str[i] > '9') && str[i] != '_' && str[i] != '@' && str[i] != '.') return false;
        i++;
    }
    return atCount == 1 && dotCount >= 1;
}
```

```

// Unit tests for isValidEmail
void testIsValidEmail() {
    assertEquals(true, isValidEmail("user@domain.com"), "Test 27.1 - Valid email");
    assertEquals(false, isValidEmail("user@domain"), "Test 27.2 - Invalid email");
}

```

Best Practices & Expert Tips

- **Best Practices:** Simple rules for validation; check NULL.
- **Tips:** Discuss regex for complex validation; test edge cases.

Problem 28: Convert a Binary String to a Decimal Number

Issue Description

Convert a binary string to its decimal equivalent, e.g., "1010" returns 10.

Problem Decomposition & Solution Steps

- **Input:** Binary string.
- **Output:** Integer.
- **Approach:** Sum powers of 2 for '1' bits.
- **Steps:** Validate input, compute sum.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```

// Converts binary string to decimal.
int binaryToDecimal(const char* str) {
    if (str == NULL || str[0] == '\0') return 0;
    int result = 0;
    for (int i = 0; str[i] != '\0'; i++) { // Process each bit
        if (str[i] != '0' && str[i] != '1') return -1;
        result = result * 2 + (str[i] - '0');
    }
    return result;
}

// Unit tests for binaryToDecimal
void testBinaryToDecimal() {
    assertEquals(10, binaryToDecimal("1010"), "Test 28.1 - Normal case");
}

```

Best Practices & Expert Tips

- **Best Practices:** Validate binary digits; handle NULL.
- **Tips:** Explain bit shifting; test invalid inputs.

Problem 29: Merge Two Sorted Arrays Without Extra Space

Issue Description

Merge two sorted arrays into sorted order without extra space, e.g., [1,3], [2,4] into one array.

Problem Decomposition & Solution Steps

- **Input:** Two sorted arrays, sizes.
- **Output:** Merged sorted arrays.
- **Approach:** Use gap method (shell sort-inspired).
- **Steps:** Validate input, merge using gaps.
- **Complexity:** Time $O((n+m)\log(n+m))$, Space $O(1)$.

Coding Part (with Unit Tests)

```
// Helper to swap if out of order
void swapIfGreater(int* a, int* b) {
    if (*a > *b) {
        int temp = *a;
        *a = *b;
        *b = temp;
    }
}

// Merges two sorted arrays without extra space.
void mergeNoExtraSpace(int* arr1, int m, int* arr2, int n) {
    if (arr1 == NULL || arr2 == NULL) return;
    int gap = (m + n + 1) / 2;
    while (gap > 0) { // Reduce gap
        for (int i = 0; i + gap < m + n; i++) {
            if (i < m && i + gap < m) swapIfGreater(&arr1[i], &arr1[i + gap]);
            else if (i < m && i + gap >= m) swapIfGreater(&arr1[i], &arr2[i + gap - m]);
            else if (i >= m) swapIfGreater(&arr2[i - m], &arr2[i + gap - m]);
        }
        gap = (gap == 1) ? 0 : (gap + 1) / 2;
    }
}

// Unit tests for mergeNoExtraSpace
void testMergeNoExtraSpace() {
    int arr1[] = {1, 3}, arr2[] = {2, 4};
    int expected[] = {1, 2}, expected2[] = {3, 4};
    mergeNoExtraSpace(arr1, 2, arr2, 2);
    assertArrayEquals(expected, arr1, 2, "Test 29.1 - Array 1");
    assertArrayEquals(expected2, arr2, 2, "Test 29.2 - Array 2");
}
```

Best Practices & Expert Tips

- **Best Practices:** Minimize space; validate inputs.
- **Tips:** Explain gap method; test unequal sizes.

Problem 30: Find the Longest Palindromic Substring

Issue Description

Find the longest palindromic substring in a string, e.g., "babad" returns "bab" or "aba".

Problem Decomposition & Solution Steps

- **Input:** String.
- **Output:** Longest palindromic substring (caller frees).

- **Approach:** Expand around center for each position.
- **Steps:** Validate input, check odd/even palindromes.
- **Complexity:** Time O(n^2), Space O(1).

Coding Part (with Unit Tests)

```

// Helper to expand around center
int expandAroundCenter(const char* str, int left, int right) {
    while (left >= 0 && str[right] != '\0' && str[left] == str[right]) {
        left--;
        right++;
    }
    return right - left - 1; // Length of palindrome
}

// Returns longest palindromic substring.
char* longestPalindrome(const char* str) {
    if (str == NULL || str[0] == '\0') return "";
    int start = 0, maxLen = 0, len = strlen(str);
    for (int i = 0; i < len; i++) { // Check each center
        int len1 = expandAroundCenter(str, i, i); // Odd length
        int len2 = expandAroundCenter(str, i, i + 1); // Even length
        if (len1 > maxLen) { maxLen = len1; start = i - (len1 - 1) / 2; }
        if (len2 > maxLen) { maxLen = len2; start = i - len2 / 2 + 1; }
    }
    char* result = (char*)malloc(maxLen + 1);
    strncpy(result, str + start, maxLen);
    result[maxLen] = '\0';
    return result;
}

// Unit tests for longestPalindrome
void testLongestPalindrome() {
    char* result = longestPalindrome("babad");
    assertEquals("bab", result, "Test 30.1 - Normal case");
    free(result);
}

```

Best Practices & Expert Tips

- **Best Practices:** Free memory; handle edge cases.
- **Tips:** Explain expand-around-center; discuss Manacher's algorithm.

Main Function to Run All Tests

```

int main() {
    printf("Running tests for problems 21 to 30:\n");
    testSwapIntegers();
    testSecondLargest();
    testIsOnlyDigits();
    testDecimalToBinary();
    testMyStrcmp();
    testMostFrequent();
    testIsValidEmail();
    testBinaryToDecimal();
    testMergeNoExtraSpace();
    testLongestPalindrome();
    return 0;
}

```

Problem 31: Remove All Occurrences of a Value from an Array

Issue Description

Remove all instances of a given value from an array in-place and return the new length.

For example, given [3,2,2,3] and val=3, the array becomes [2,2] with length 2.

Problem Decomposition & Solution Steps

- **Input:** Integer array, size, value to remove.
- **Output:** New length; array with value removed.
- **Approach:** Use two pointers to copy non-matching elements to the front.
- **Steps:**
 1. Validate input (NULL, size <= 0).
 2. Iterate array, copy non-matching elements to a new position.
 3. Return new length.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <string.h>
#include <stdbool.h>
#include <stdlib.h>

// Removes all occurrences of val in-place, returns new length.
int removeElement(int* arr, int size, int val) {
    if (arr == NULL || size <= 0) return 0; // Validate input
    int k = 0; // Index for next non-val element
    for (int i = 0; i < size; i++) { // Copy non-matching elements
        if (arr[i] != val) arr[k++] = arr[i];
    }
    return k;
}

// Unit test helper
void assertArrayEquals(int* expected, int* actual, int size, const char* testName) {
    int pass = 1;
    for (int i = 0; i < size; i++) if (expected[i] != actual[i]) pass = 0;
    printf("%s: %s\n", testName, pass ? "PASSED" : "FAILED");
}

// Unit tests for removeElement
void testRemoveElement() {
    int arr[] = {3, 2, 2, 3};
    int expected[] = {2, 2};
    int len = removeElement(arr, 4, 3);
    assertArrayEquals(expected, arr, len, "Test 31.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:** Modify in-place; validate inputs; use two-pointer technique for efficiency.
- **Expert Tips:**
 - In interviews, explain the two-pointer approach: "One pointer tracks the position to place the next non-matching element, while another iterates through the array."

- Highlight why in-place modification is critical: "It ensures O(1) space, avoiding the need for a new array."
- Suggest testing edge cases like all elements matching val or an empty array.
- If asked to optimize, mention that this solution is already optimal for time and space, but discuss potential for parallel processing in large datasets.

Problem 32: Check if a String is a Subsequence of Another String

Issue Description

Determine if string s is a subsequence of string t, where s's characters appear in t in the same order, e.g., "abc" is a subsequence of "ahbgdc".

Problem Decomposition & Solution Steps

- **Input:** Two null-terminated strings.
- **Output:** Boolean (true if subsequence).
- **Approach:** Use two pointers to check if s's characters appear in order in t.
- **Steps:**
 1. Validate inputs.
 2. Iterate t, matching s's characters sequentially.
 3. Return true if all of s is matched.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
// Checks if s is a subsequence of t.
bool isSubsequence(const char* s, const char* t) {
    if (s == NULL || t == NULL) return false; // Validate inputs
    if (s[0] == '\0') return true; // Empty s is subsequence
    int i = 0, j = 0;
    while (t[j] != '\0') { // Iterate t
        if (s[i] == t[j]) i++; // Match found, advance s
        j++;
        if (s[i] == '\0') return true; // All of s matched
    }
    return false;
}

// Unit tests for isSubsequence
void testIsSubsequence() {
    assertBoolEquals(true, isSubsequence("abc", "ahbgdc"), "Test 32.1 - Valid subsequence");
    assertBoolEquals(false, isSubsequence("axc", "ahbgdc"), "Test 32.2 - Invalid subsequence");
}
```

Best Practices & Expert Tips

- **Best Practices:** Handle empty s; validate inputs; use two pointers.
- **Expert Tips:**
 - Explain the two-pointer method: "One pointer tracks s, another t, advancing s only on a match to ensure order."
 - In interviews, discuss edge cases like empty strings or s longer than t.

- Mention optimization for large t: "For multiple s queries, preprocessing t with an index map could improve performance."
- Emphasize clarity: "Write clean code first, then discuss optimizations like dynamic programming if asked."

Problem 33: Find the Sum of All Even Numbers in an Array

Issue Description

Compute the sum of all even numbers in an integer array, e.g., [1,2,3,4] returns 6 (2+4).

Problem Decomposition & Solution Steps

- **Input:** Array, size.
- **Output:** Sum of even numbers.
- **Approach:** Iterate array, sum even elements.
- **Steps:**
 1. Validate input.
 2. Sum numbers where num % 2 == 0.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
// Returns sum of even numbers in array.
int sumEvenNumbers(int* arr, int size) {
    if (arr == NULL || size <= 0) return 0; // Validate input
    int sum = 0;
    for (int i = 0; i < size; i++) { // Sum even numbers
        if (arr[i] % 2 == 0) sum += arr[i];
    }
    return sum;
}

// Unit tests for sumEvenNumbers
void testSumEvenNumbers() {
    int arr[] = {1, 2, 3, 4};
    assertEquals(6, sumEvenNumbers(arr, 4), "Test 33.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:** Validate inputs; use simple iteration.
- **Expert Tips:**
 - In interviews, clarify requirements: "Does the sum need to handle overflow? I'll use int for simplicity but can use long if needed."
 - Discuss edge cases: "Test arrays with no even numbers or negative numbers."
 - Suggest optimization: "For large arrays, parallel summation could be considered, but this solution is optimal for simplicity."
 - Emphasize readability: "Clear variable names like 'sum' make the code self-explanatory."

Problem 34: Reverse Only Vowels in a String

Issue Description

Reverse only the vowels in a string in-place, e.g., "hello" becomes "holle" (e,o swapped).

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** String with vowels reversed.
- **Approach:** Use two pointers to find and swap vowels.
- **Steps:**
 1. Validate input.
 2. Identify vowels, swap from ends.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
// Helper to check if a character is a vowel.
bool isVowel(char c) {
    c = tolower(c);
    return c == 'a' || c == 'e' || c == 'i' || c == 'o' || c == 'u';
}

// Reverses vowels in string in-place.
void reverseVowels(char* str) {
    if (str == NULL || str[0] == '\0') return; // Validate input
    int left = 0, right = strlen(str) - 1;
    while (left < right) { // Swap vowels
        while (left < right && !isVowel(str[left])) left++;
        while (left < right && !isVowel(str[right])) right--;
        char temp = str[left];
        str[left++] = str[right];
        str[right--] = temp;
    }
}

// Unit tests for reverseVowels
void testReverseVowels() {
    char str[] = "hello";
    reverseVowels(str);
    assertEquals("holle", str, "Test 34.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:** Handle case-insensitive vowels; validate inputs.
- **Expert Tips:**
 - Explain the two-pointer approach: "Move pointers inward until vowels are found, then swap."
 - In interviews, clarify vowel definition: "Should I include 'y'? I'll exclude it unless specified."
 - Suggest precomputing a vowel lookup table for speed if called frequently.
 - Discuss edge cases: "Test strings with no vowels or all vowels to ensure robustness."

Problem 35: Find the First Missing Positive Integer in an Array

Issue Description

Find the smallest missing positive integer in an array, e.g., [3,4,-1,1] returns 2.

Problem Decomposition & Solution Steps

- **Input:** Array, size.
- **Output:** Smallest missing positive integer.
- **Approach:** Use array as hash table by placing numbers in their index.
- **Steps:**
 1. Validate input.
 2. Place each number i in index $i-1$.
 3. Find first index where value \neq index+1.
- **Complexity:** Time $O(n)$, Space $O(1)$.

Coding Part (with Unit Tests)

```
// Finds first missing positive integer.
int firstMissingPositive(int* arr, int size) {
    if (arr == NULL || size <= 0) return 1; // Validate input
    for (int i = 0; i < size; i++) { // Ignore non-positive and large numbers
        while (arr[i] > 0 && arr[i] <= size && arr[arr[i] - 1] != arr[i]) {
            int temp = arr[arr[i] - 1];
            arr[arr[i] - 1] = arr[i];
            arr[i] = temp;
        }
    }
    for (int i = 0; i < size; i++) { // Find first mismatch
        if (arr[i] != i + 1) return i + 1;
    }
    return size + 1;
}

// Unit tests for firstMissingPositive
void testFirstMissingPositive() {
    int arr[] = {3, 4, -1, 1};
    assertEquals(2, firstMissingPositive(arr, 4), "Test 35.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:** Use in-place hashing; validate inputs.
- **Expert Tips:**
 - Explain in-place hashing: "Place number i at index $i-1$ to use the array as a hash table."
 - In interviews, walk through an example: "For [3,4,-1,1], place 1 at index 0, 3 at index 2, etc."
 - Discuss edge cases: "Test arrays with no missing positives or all negatives."
 - Highlight $O(1)$ space: "This avoids extra memory, which is critical for large arrays."

Problem 36: Perform Matrix Transposition

Issue Description

Transpose a square matrix by swapping elements across the main diagonal, e.g., $\begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix}$ becomes $\begin{bmatrix} 1 & 3 \\ 2 & 4 \end{bmatrix}$.

Problem Decomposition & Solution Steps

- **Input:** Square matrix (2D array), size.
- **Output:** Transposed matrix in-place.
- **Approach:** Swap elements where $i < j$.
- **Steps:**
 1. Validate input.
 2. Swap elements across diagonal.
- **Complexity:** Time $O(n^2)$, Space $O(1)$.

Coding Part (with Unit Tests)

```
// Transposes n x n matrix in-place.
void transposeMatrix(int** matrix, int n) {
    if (matrix == NULL || n <= 0) return; // Validate input
    for (int i = 0; i < n; i++) { // Swap across diagonal
        for (int j = i + 1; j < n; j++) {
            int temp = matrix[i][j];
            matrix[i][j] = matrix[j][i];
            matrix[j][i] = temp;
        }
    }
}

// Unit test helper
void assertMatrixEquals(int** expected, int** actual, int n, const char* testName) {
    int pass = 1;
    for (int i = 0; i < n; i++) for (int j = 0; j < n; j++) if (expected[i][j] != actual[i][j]) pass = 0;
    printf("%s: %s\n", testName, pass ? "PASSED" : "FAILED");
}

// Unit tests for transposeMatrix
void testTransposeMatrix() {
    int matrix[2][2] = {{1, 2}, {3, 4}};
    int* ptrs[2] = {matrix[0], matrix[1]};
    int expected[2][2] = {{1, 3}, {2, 4}};
    int* exp_ptrs[2] = {expected[0], expected[1]};
    transposeMatrix(ptrs, 2);
    assertMatrixEquals(exp_ptrs, ptrs, 2, "Test 36.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:** Validate inputs; swap only upper triangle.
- **Expert Tips:**
 - Explain swapping: "Only swap $i < j$ to avoid redundant swaps."
 - In interviews, clarify: "I assume a square matrix; discuss non-square cases if needed."
 - Suggest optimization: "For sparse matrices, consider storing only non-zero elements."
 - Test edge cases: "Single element or empty matrix to ensure robustness."

Problem 37: Check if a Number is a Perfect Square

Issue Description

Check if a number is a perfect square, e.g., 16 returns true (4^2), 14 returns false.

Problem Decomposition & Solution Steps

- **Input:** Non-negative integer.
- **Output:** Boolean.
- **Approach:** Use binary search to find square root.
- **Steps:**
 1. Validate input.
 2. Binary search for i where $i \cdot i == n$.
- **Complexity:** Time $O(\log n)$, Space $O(1)$.

Coding Part (with Unit Tests)

```
// Checks if n is a perfect square.
bool isPerfectSquare(int n) {
    if (n < 0) return false; // Validate input
    if (n == 0 || n == 1) return true;
    long left = 1, right = n / 2;
    while (left <= right) { // Binary search
        long mid = left + (right - left) / 2;
        long square = mid * mid;
        if (square == n) return true;
        if (square < n) left = mid + 1;
        else right = mid - 1;
    }
    return false;
}

// Unit tests for isPerfectSquare
void testIsPerfectSquare() {
    assertEquals(true, isPerfectSquare(16), "Test 37.1 - Perfect square");
    assertEquals(false, isPerfectSquare(14), "Test 37.2 - Not perfect square");
}
```

Best Practices & Expert Tips

- **Best Practices:** Use long to avoid overflow; validate inputs.
- **Expert Tips:**
 - Explain binary search: "Search for i where $i \cdot i$ equals n , reducing time to $O(\log n)$."
 - In interviews, discuss alternatives: "Linear search is $O(\sqrt{n})$, but binary is faster."
 - Test edge cases: "Check 0, 1, and large numbers."
 - Highlight efficiency: "Binary search is optimal; discuss Newton's method for floating-point."

Problem 38: Find the Longest Word in a String

Issue Description

Find the longest word in a space-separated string, e.g., "hello world" returns "hello".

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** Longest word (caller frees).
- **Approach:** Parse words, track longest.
- **Steps:**
 1. Validate input.
 2. Iterate string, extract words, compare lengths.
- **Complexity:** Time O(n), Space O(n).

Coding Part (with Unit Tests)

```
// Returns longest word in string.
char* longestWord(const char* str) {
    if (str == NULL || str[0] == '\0') return strdup("");
    // Validate input
    char* result = (char*)malloc(strlen(str) + 1);
    int maxLen = 0, currLen = 0, start = 0, maxStart = 0;
    for (int i = 0; ; i++) { // Parse words
        if (str[i] == ' ' || str[i] == '\0') {
            if (currLen > maxLen) {
                maxLen = currLen;
                maxStart = start;
            }
            start = i + 1;
            currLen = 0;
            if (str[i] == '\0') break;
        } else {
            currLen++;
        }
    }
    strncpy(result, str + maxStart, maxLen);
    result[maxLen] = '\0';
    return result;
}

// Unit tests for longestWord
void testLongestWord() {
    char* result = longestWord("hello world");
    assertEquals("hello", result, "Test 38.1 - Normal case");
    free(result);
}
```

Best Practices & Expert Tips

- **Best Practices:** Free memory; handle empty strings.
- **Expert Tips:**
 - Explain parsing: "Track word boundaries with spaces, updating max length."
 - In interviews, clarify: "If multiple words have max length, return first."
 - Suggest optimization: "For frequent calls, tokenize string into array."
 - Test edge cases: "Single word, all same length, or empty string."

Problem 39: Find the Maximum Sum Subarray (Kadane's Algorithm)

Issue Description

Find the subarray with the maximum sum, e.g., [-2,1,-3,4,-1,2,1,-5,4] returns 6 ([4,-1,2,1]).

Problem Decomposition & Solution Steps

- **Input:** Array, size.
- **Output:** Maximum subarray sum.
- **Approach:** Kadane's algorithm tracks max sum ending at each index.
- **Steps:**
 1. Validate input.
 2. Track current and global max sums.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
// Returns maximum subarray sum using Kadane's algorithm.
int maxSubArray(int* arr, int size) {
    if (arr == NULL || size <= 0) return 0; // Validate input
    int maxSoFar = arr[0], currMax = arr[0];
    for (int i = 1; i < size; i++) { // Track max sum
        currMax = currMax + arr[i] > arr[i] ? currMax + arr[i] : arr[i];
        maxSoFar = maxSoFar > currMax ? maxSoFar : currMax;
    }
    return maxSoFar;
}

// Unit tests for maxSubArray
void testMaxSubArray() {
    int arr[] = {-2, 1, -3, 4, -1, 2, 1, -5, 4};
    assertEquals(6, maxSubArray(arr, 9), "Test 39.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:** Handle single element; validate inputs.
- **Expert Tips:**
 - Explain Kadane's: "Track max sum ending at each index, resetting if negative."
 - In interviews, walk through: "For [-2,1,-3,4], currMax becomes 4 at index 3."
 - Discuss edge cases: "Test all negative numbers or single element."
 - Suggest extensions: "To return subarray indices, store start/end pointers."

Problem 40: Encode a String Using Run-Length Encoding

Issue Description

Encode a string using run-length encoding, e.g., "AAABBC" becomes "3A2B1C".

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** Encoded string (caller frees).
- **Approach:** Count consecutive characters.
- **Steps:**
 1. Validate input.
 2. Count runs, build string.
- **Complexity:** Time O(n), Space O(n).

Coding Part (with Unit Tests)

```
// Returns run-length encoded string.
char* runLengthEncode(const char* str) {
    if (str == NULL || str[0] == '\0') return strdup("");
    char* result = (char*)malloc(strlen(str) * 2 + 1);
    int k = 0, count = 1;
    for (int i = 1; ; i++) { // Count runs
        if (str[i] == str[i - 1] && str[i] != '\0') {
            count++;
        } else {
            k += sprintf(result + k, "%d%c", count, str[i - 1]);
            count = 1;
            if (str[i] == '\0') break;
        }
    }
    result[k] = '\0';
    return result;
}

// Unit tests for runLengthEncode
void testRunLengthEncode() {
    char* result = runLengthEncode("AAABBC");
    assertEquals("3A2B1C", result, "Test 40.1 - Normal case");
    free(result);
}
```

Best Practices & Expert Tips

- **Best Practices:** Allocate enough memory; free result.
- **Expert Tips:**
 - Explain encoding: "Count consecutive chars, append count and char."
 - In interviews, clarify: "Assume printable chars; discuss max count limits."
 - Suggest optimization: "Precompute result size for exact allocation."
 - Test edge cases: "Single char, repeated chars, or empty string."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for problems 31 to 40:\n");
    testRemoveElement();
    testIsSubsequence();
    testSumEvenNumbers();
    testReverseVowels();
    testFirstMissingPositive();
    testTransposeMatrix();
    testIsPerfectSquare();
    testLongestWord();
    testMaxSubArray();
    testRunLengthEncode();
    return 0;
}
```

Problem 41: Check if a String is a Valid IPv4 Address

Issue Description

Determine if a string represents a valid IPv4 address in dot-decimal format (e.g., "192.168.1.1").

A valid IPv4 address consists of four octets (0-255) separated by dots, with no leading zeros unless the number is 0, and no invalid characters.

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** Boolean (true if valid IPv4).
- **Approach:** Split string by dots, validate each octet.
- **Steps:**
 1. Check for NULL or empty string.
 2. Count dots to ensure exactly three.
 3. Parse each octet, verifying it's a number between 0-255 with no leading zeros.
 4. Ensure no invalid characters or format issues.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <string.h>
#include <stdbool.h>
#include <stdlib.h>
#include <ctype.h>

// Checks if str is a valid IPv4 address.
bool isValidIPv4(const char* str) {
    if (str == NULL || str[0] == '\0') return false; // Check NULL/empty
    int dotCount = 0, num = 0, len = strlen(str);
    for (int i = 0; i <= len; i++) { // Process each character
        if (str[i] == '.' || str[i] == '\0') { // End of octet
            if (dotCount > 3 || num > 255 || (i > 0 && str[i-1] == '.')) return false; // Invalid
format
            dotCount++;
            num = 0;
            if (str[i] == '\0' && dotCount != 4) return false; // Must have 4 octets
        }
        else if (isdigit(str[i])) { // Build number
            if (num == 0 && i > 0 && str[i-1] == '0' && str[i] != '.') return false; // No leading
zeros
            num = num * 10 + (str[i] - '0');
        } else {
            return false; // Invalid character
        }
    }
    return dotCount == 4;
}

// Unit test helper
void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests for isValidIPv4
void testIsValidIPv4() {
    assertBoolEquals(true, isValidIPv4("192.168.1.1"), "Test 41.1 - Valid IPv4");
    assertBoolEquals(false, isValidIPv4("256.1.2.3"), "Test 41.2 - Invalid octet");
    assertBoolEquals(false, isValidIPv4("1.2.3"), "Test 41.3 - Too few octets");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate input rigorously for NULL, empty strings, and correct dot count.
 - Check for leading zeros and ensure octets are within 0-255.
 - Use standard library functions like isdigit for character validation.
 - Handle edge cases like consecutive dots or trailing dots.
- **Expert Tips:**
 - Explain validation: "Each octet must be a number between 0-255, with no leading zeros unless 0 itself."
 - In interviews, clarify requirements: "Ask if spaces or negative numbers are allowed."
 - Suggest optimization: "For performance, consider pre-checking string length."
 - Test thoroughly: "Include cases like '01.1.2.3' (invalid) and '0.0.0.0' (valid)."

Problem 42: Find the kth Smallest Element in an Unsorted Array

Issue Description

Find the kth smallest element in an unsorted integer array, e.g., [7,10,4,3,20,15], k=3 returns 7 (third smallest).

Problem Decomposition & Solution Steps

- **Input:** Array, size, k (1-based).
- **Output:** kth smallest element.
- **Approach:** Use quickselect (partition-based).
- **Steps:**
 1. Validate input (NULL, k out of bounds).
 2. Partition array around a pivot.
 3. Recurse on appropriate partition until kth element found.
- **Complexity:** Average Time O(n), Worst O(n^2), Space O(1).

Coding Part (with Unit Tests)

```
// Helper to partition array
int partition(int* arr, int left, int right) {
    int pivot = arr[right], i = left - 1;
    for (int j = left; j < right; j++) { // Move smaller elements to left
        if (arr[j] <= pivot) {
            i++;
            int temp = arr[i];
            arr[i] = arr[j];
            arr[j] = temp;
        }
    }
    int temp = arr[i + 1];
    arr[i + 1] = arr[right];
    arr[right] = temp;
    return i + 1;
}

// Finds kth smallest element (1-based k).
int kthSmallest(int* arr, int size, int k) {
    if (arr == NULL || size <= 0 || k < 1 || k > size) return -1; // Validate input
    int left = 0, right = size - 1;
```

```

        while (left <= right)
        { // Quickselect
            int pivotIdx = partition(arr, left, right);
            if (pivotIdx == k - 1) return arr[pivotIdx];
            if (pivotIdx > k - 1) right = pivotIdx - 1;
            else left = pivotIdx + 1;
        }
        return -1;
    }

    // Unit test helper
    void assertEquals(int expected, int actual, const char* testName) {
        printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
    }

    // Unit tests for kthSmallest
    void testKthSmallest() {
        int arr[] = {7, 10, 4, 3, 20, 15};
        assertEquals(7, kthSmallest(arr, 6, 3), "Test 42.1 - k=3");
    }
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate k and array bounds to avoid errors.
 - Use quickselect for average-case $O(n)$ performance.
 - Choose a good pivot (e.g., last element or random) to reduce worst-case scenarios.
 - Avoid modifying original array unless required.
- **Expert Tips:**
 - Explain quickselect: "Partition like quicksort, but recurse only on the side containing k."
 - In interviews, discuss pivot choice: "Random pivots can reduce worst-case to $O(n)$ expected."
 - Suggest alternatives: "Sorting is $O(n \log n)$, but quickselect is faster on average."
 - Test edge cases: "k=1, k=size, or duplicate elements."

Problem 43: Rotate a Matrix by 90 Degrees

Issue Description

Rotate an $n \times n$ matrix 90 degrees clockwise in-place, e.g., $\begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 9 \end{bmatrix}$ becomes $\begin{bmatrix} 7 & 4 & 1 \\ 8 & 5 & 2 \\ 9 & 6 & 3 \end{bmatrix}$.

Problem Decomposition & Solution Steps

- **Input:** Square matrix, size.
- **Output:** Rotated matrix in-place.
- **Approach:** Transpose (swap across diagonal), then reverse each row.
- **Steps:**
 1. Validate input.
 2. Swap elements across diagonal (i, j to j, i).
 3. Reverse each row.
- **Complexity:** Time $O(n^2)$, Space $O(1)$.

Coding Part (with Unit Tests)

```
// Rotates n x n matrix 90 degrees clockwise in-place.
void rotateMatrix(int** matrix, int n) {
    if (matrix == NULL || n <= 0) return; // Validate input
    for (int i = 0; i < n; i++) { // Transpose (swap across diagonal)
        for (int j = i + 1; j < n; j++) {
            int temp = matrix[i][j];
            matrix[i][j] = matrix[j][i];
            matrix[j][i] = temp;
        }
    }
    for (int i = 0; i < n; i++) { // Reverse each row
        for (int j = 0; j < n / 2; j++) {
            int temp = matrix[i][j];
            matrix[i][j] = matrix[i][n - 1 - j];
            matrix[i][n - 1 - j] = temp;
        }
    }
}

// Unit test helper
void assertMatrixEquals(int** expected, int** actual, int n, const char* testName) {
    int pass = 1;
    for (int i = 0; i < n; i++) for (int j = 0; j < n; j++) if (expected[i][j] != actual[i][j]) pass = 0;
    printf("%s: %s\n", testName, pass ? "PASSED" : "FAILED");
}

// Unit tests for rotateMatrix
void testRotateMatrix() {
    int matrix[3][3] = {{1, 2, 3}, {4, 5, 6}, {7, 8, 9}};
    int* ptrs[3] = {matrix[0], matrix[1], matrix[2]};
    int expected[3][3] = {{7, 4, 1}, {8, 5, 2}, {9, 6, 3}};
    int* exp_ptrs[3] = {expected[0], expected[1], expected[2]};
    rotateMatrix(ptrs, 3);
    assertMatrixEquals(exp_ptrs, ptrs, 3, "Test 43.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Perform rotation in-place to minimize space usage.
 - Validate input for NULL or invalid size.
 - Break rotation into two steps (transpose, reverse) for clarity.
 - Ensure matrix is square before processing.
- **Expert Tips:**
 - Explain approach: "Transpose swaps (i,j) with (j,i), then row reversal achieves 90-degree rotation."
 - In interviews, visualize: "Draw a 3x3 matrix to show how elements move."
 - Suggest alternatives: "For non-square matrices, extra space may be needed."
 - Test edge cases: "Single element or 2x2 matrices."

Problem 44: Check if Two Strings are One Edit Away

Issue Description

Check if two strings are one edit (insert, delete, or replace) away, e.g., "pale" and "ple" are one edit away (delete 'a').

Problem Decomposition & Solution Steps

- **Input:** Two null-terminated strings.
- **Output:** Boolean.
- **Approach:** Compare strings based on length differences.
- **Steps:**
 1. Validate inputs.
 2. Handle equal length (replace), length diff=1 (insert/delete).
 3. Check for at most one difference.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
// Checks if strings are one edit away.
bool oneEditAway(const char* s1, const char* s2) {
    if (s1 == NULL || s2 == NULL) return false; // Validate input
    int len1 = strlen(s1), len2 = strlen(s2);
    if (abs(len1 - len2) > 1) return false; // More than one edit
    if (len1 == len2) { // Check replace
        int diff = 0;
        for (int i = 0; i < len1; i++) if (s1[i] != s2[i]) diff++;
        return diff <= 1;
    }
    if (len1 > len2) { // Ensure s1 is shorter
        const char* temp = s1; s1 = s2; s2 = temp;
        int t = len1; len1 = len2; len2 = t;
    }
    int i = 0, j = 0, diff = 0; // Check insert/delete
    while (i < len1 && j < len2) {
        if (s1[i] != s2[j]) { if (++diff > 1) return false; j++; }
        else { i++; j++; }
    }
    return true;
}

// Unit tests for oneEditAway
void testOneEditAway() {
    assertBoolEquals(true, oneEditAway("pale", "ple"), "Test 44.1 - One delete");
    assertBoolEquals(false, oneEditAway("pale", "bake"), "Test 44.2 - Two edits");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle NULL and length differences explicitly.
 - Use two-pointer approach for insert/delete cases.
 - Optimize by checking length difference first.
 - Ensure symmetry by swapping strings if needed.
- **Expert Tips:**
 - Explain logic: "Equal lengths check for one replace; length diff=1 checks insert/delete."
 - In interviews, clarify: "Ask if case matters or spaces are allowed."
 - Suggest optimization: "Early exit on length difference > 1 saves time."
 - Test edge cases: "Empty strings, single char, or identical strings."

Problem 45: Find the Product of All Elements in an Array Except Self

Issue Description

Given an array, return an array where each element is the product of all other elements, e.g., [1,2,3,4] returns [24,12,8,6].

Problem Decomposition & Solution Steps

- **Input:** Array, size.
- **Output:** New array with products.
- **Approach:** Compute left and right products without division.
- **Steps:**
 1. Validate input.
 2. Compute left products, then multiply by right products.
- **Complexity:** Time O(n), Space O(1) (excluding output).

Coding Part (with Unit Tests)

```
// Returns array of products except self (caller frees).
int* productExceptSelf(int* arr, int size, int* returnSize) {
    if (arr == NULL || size <= 0) { *returnSize = 0; return NULL; } // Validate input
    int* result = (int*)malloc(size * sizeof(int));
    *returnSize = size;
    result[0] = 1; // Left products
    for (int i = 1; i < size; i++) result[i] = result[i - 1] * arr[i - 1];
    int right = 1; // Right products
    for (int i = size - 1; i >= 0; i--) {
        result[i] *= right;
        right *= arr[i];
    }
    return result;
}
// Unit tests for productExceptSelf
void testProductExceptSelf() {
    int arr[] = {1, 2, 3, 4};
    int expected[] = {24, 12, 8, 6};
    int size;
    int* result = productExceptSelf(arr, 4, &size);
    assertArrayEquals(expected, result, size, "Test 45.1 - Normal case");
    free(result);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Avoid division to handle zeros robustly.
 - Allocate result array dynamically; set returnSize.
 - Validate inputs to prevent crashes.
 - Free allocated memory in tests.
- **Expert Tips:**
 - Explain approach: "Left pass computes products before i, right pass multiplies products after i."
 - In interviews, discuss: "Division-based solution fails with zeros; this is O(1) space excluding output."
 - Test edge cases: "Arrays with zeros or length 2."

- Suggest optimization: "Single pass with two pointers is possible but less readable."

Problem 46: Find the Shortest Word in a String

Issue Description

Find the shortest word in a space-separated string, e.g., "hello world a" returns "a".

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** Shortest word (caller frees).
- **Approach:** Parse words, track shortest.
- **Steps:**
 1. Validate input.
 2. Extract words, update shortest length.
- **Complexity:** Time O(n), Space O(n).

Coding Part (with Unit Tests)

```
// Returns shortest word in string (caller frees).
char* shortestWord(const char* str) {
    if (str == NULL || str[0] == '\0') return strdup("");
    // Validate input
    char* result = (char*)malloc(strlen(str) + 1);
    int minLen = INT_MAX, currLen = 0, start = 0, minStart = 0;
    for (int i = 0; ; i++) { // Parse words
        if (str[i] == ' ' || str[i] == '\0') {
            if (currLen > 0 && currLen < minLen) {
                minLen = currLen;
                minStart = start;
            }
            start = i + 1;
            currLen = 0;
            if (str[i] == '\0') break;
        } else {
            currLen++;
        }
    }
    strncpy(result, str + minStart, minLen);
    result[minLen] = '\0';
    return result;
}

// Unit tests for shortestWord
void testShortestWord() {
    char* result = shortestWord("hello world a");
    assertEquals("a", result, "Test 46.1 - Normal case");
    free(result);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Allocate sufficient memory for result.
 - Handle empty strings and single-word cases.
 - Free allocated memory in tests.
 - Return first shortest word if multiple exist.

- **Expert Tips:**

- Explain parsing: "Track word boundaries, update min length as we go."
- In interviews, clarify: "Ask if spaces are trimmed or multiple shortest words matter."
- Suggest optimization: "Tokenizing into an array could help for repeated queries."
- Test edge cases: "Empty string, single char, or all same length."

Problem 47: Check if a Number is a Fibonacci Number

Issue Description

Check if a number is a Fibonacci number (in sequence 0,1,1,2,3,5,...), e.g., 8 returns true, 7 returns false.

Problem Decomposition & Solution Steps

- **Input:** Non-negative integer.
- **Output:** Boolean.
- **Approach:** Check if n is a perfect square of $5n^2 + 4$ or $5n^2 - 4$.
- **Steps:**
 1. Validate input.
 2. Use Fibonacci property to check squares.
- **Complexity:** Time O(1), Space O(1).

Coding Part (with Unit Tests)

```
// Helper to check perfect square (from Problem 37).
bool isPerfectSquare(long n) {
    if (n < 0) return false;
    long left = 0, right = n / 2 + 1;
    while (left <= right) {
        long mid = left + (right - left) / 2;
        long square = mid * mid;
        if (square == n) return true;
        if (square < n) left = mid + 1;
        else right = mid - 1;
    }
    return false;
}

// Checks if n is a Fibonacci number.
bool isFibonacci(int n) {
    if (n < 0) return false; // Validate input
    return isPerfectSquare(5L * n * n + 4) || isPerfectSquare(5L * n * n - 4);
}

// Unit tests for isFibonacci
void testIsFibonacci() {
    assertEquals(true, isFibonacci(8), "Test 47.1 - Fibonacci number");
    assertEquals(false, isFibonacci(7), "Test 47.2 - Non-Fibonacci");
}
```

Best Practices & Expert Tips

- **Best Practices:**

- Use long to avoid overflow in calculations.
- Validate negative inputs.

- Reuse perfect square function for modularity.
- Handle edge cases like 0 and 1.
- **Expert Tips:**
 - Explain property: "A number is Fibonacci if $5n^2 + 4$ or $5n^2 - 4$ is a perfect square."
 - In interviews, justify: "This is faster than generating Fibonacci numbers."
 - Suggest alternative: "Generate Fibonacci numbers up to n for small inputs."
 - Test edge cases: "0, 1, and large numbers like 144."

Problem 48: Find the Longest Consecutive Sequence in an Array

Issue Description

Find the length of the longest consecutive sequence in an array, e.g., [100,4,200,1,3,2] returns 4 ([1,2,3,4]).

Problem Decomposition & Solution Steps

- **Input:** Array, size.
- **Output:** Length of longest consecutive sequence.
- **Approach:** Use hash set to check sequences.
- **Steps:**
 1. Validate input.
 2. Build hash set.
 3. Check each potential sequence start.
- **Complexity:** Time O(n), Space O(n).

Coding Part (with Unit Tests)

```
// Returns length of longest consecutive sequence.
int longestConsecutive(int* arr, int size) {
    if (arr == NULL || size <= 0) return 0; // Validate input
    int* hash = (int*)calloc(100000, sizeof(int)); // Simple hash for range
    int offset = 50000; // Handle negative numbers
    for (int i = 0; i < size; i++) hash[arr[i] + offset] = 1; // Mark present
    int maxLen = 0;
    for (int i = 0; i < size; i++) { // Check sequence starting at arr[i]
        if (hash[arr[i] + offset - 1] == 0) { // Start of sequence
            int curr = arr[i], len = 0;
            while (hash[curr + offset]) { len++; curr++; }
            maxLen = len > maxLen ? len : maxLen;
        }
    }
    free(hash);
    return maxLen;
}

// Unit tests for longestConsecutive
void testLongestConsecutive() {
    int arr[] = {100, 4, 200, 1, 3, 2};
    assertEquals(4, longestConsecutive(arr, 6), "Test 48.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use hash set for O(1) lookups.

- Free allocated memory.
 - Handle negative numbers with offset.
 - Validate inputs thoroughly.
- **Expert Tips:**
 - Explain hash approach: "Check only sequence starts to avoid redundant work."
 - In interviews, discuss: "Sorting is $O(n \log n)$; hash set is $O(n)$."
 - Test edge cases: "Duplicates, single element, or no sequence."
 - Suggest optimization: "Use a dynamic hash table for arbitrary ranges."

Problem 49: Compress a String (e.g., "aabbb" → "a2b3")

Issue Description

Compress a string by replacing repeated characters with their count, e.g., "aabbb" becomes "a2b3".

Return original if compressed is longer.

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** Compressed string (caller frees).
- **Approach:** Count consecutive characters.
- **Steps:**
 1. Validate input.
 2. Count runs, build compressed string.
 3. Return original if compressed is longer.
- **Complexity:** Time $O(n)$, Space $O(n)$.

Coding Part (with Unit Tests)

```
// Compresses string with run-length encoding.
char* compressString(const char* str) {
    if (str == NULL || str[0] == '\0') return strdup("");
    int len = strlen(str);
    char* result = (char*)malloc(len * 2 + 1);
    int k = 0, count = 1;
    for (int i = 1; ; i++) { // Count runs
        if (str[i] == str[i - 1] && str[i] != '\0') {
            count++;
        } else {
            k += sprintf(result + k, "%c%d", str[i - 1], count);
            count = 1;
            if (str[i] == '\0') break;
        }
    }
    if (k >= len) { free(result); return strdup(str); } // Return original if longer
    result[k] = '\0';
    return result;
}

// Unit tests for compressString
void testCompressString() {
    char* result = compressString("aabbb");
    assertStringEquals("a2b3", result, "Test 49.1 - Normal case");
    free(result);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Return original string if compression doesn't save space.
 - Allocate sufficient memory for result.
 - Free memory in tests and handle NULL inputs.
 - Use sprintf for clean number-to-string conversion.
- **Expert Tips:**
 - Explain compression: "Count consecutive chars, append char and count."
 - In interviews, clarify: "Ask if single chars should be compressed (e.g., 'a' → 'a1')."
 - Suggest optimization: "Precompute compressed length to avoid extra allocation."
 - Test edge cases: "Single char, no repeats, or long runs."

Problem 50: Find the Majority Element in an Array

Issue Description

Find the element that appears more than $n/2$ times in an array (guaranteed to exist), e.g., [2,2,1,1,1,2,2] returns 2.

Problem Decomposition & Solution Steps

- **Input:** Array, size.
- **Output:** Majority element.
- **Approach:** Use Boyer-Moore voting algorithm.
- **Steps:**
 1. Validate input.
 2. Track candidate and count, reset count on mismatch.
 3. Return candidate (guaranteed majority).
- **Complexity:** Time $O(n)$, Space $O(1)$.

Coding Part (with Unit Tests)

```
// Finds majority element (>n/2 occurrences).
int majorityElement(int* arr, int size) {
    if (arr == NULL || size <= 0) return -1; // Validate input
    int candidate = arr[0], count = 1;
    for (int i = 1; i < size; i++) { // Boyer-Moore voting
        if (count == 0) candidate = arr[i];
        count += (arr[i] == candidate) ? 1 : -1;
    }
    return candidate;
}

// Unit tests for majorityElement
void testMajorityElement() {
    int arr[] = {2, 2, 1, 1, 1, 2, 2};
    assertEquals(2, majorityElement(arr, 7), "Test 50.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use Boyer-Moore for $O(1)$ space.

- Validate inputs to handle edge cases.
 - Leverage problem guarantee (majority exists).
 - Keep algorithm simple and efficient.
- **Expert Tips:**
 - Explain Boyer-Moore: "Majority element survives as candidate by canceling out others."
 - In interviews, walk through: "For [2,2,1], count becomes 1,0,1, selecting 2."
 - Discuss alternatives: "Hash table is O(n) space; sorting is O(n log n)."
 - Test edge cases: "Single element or minimal majority."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for problems 41 to 50:\n");
    testIsValidIPv4();
    testKthSmallest();
    testRotateMatrix();
    testOneEditAway();
    testProductExceptSelf();
    testShortestWord();
    testIsFibonacci();
    testLongestConsecutive();
    testCompressString();
    testMajorityElement();
    return 0;
}
```

Problem 51: Implement a Function to Convert a String to Lowercase

Issue Description

Convert all uppercase characters in a string to lowercase in-place, e.g., "Hello World" becomes "hello world".

The function should handle non-alphabetic characters (leave unchanged) and assume the input is a null-terminated string.

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** Modified string in-place.
- **Approach:** Iterate through the string, converting uppercase to lowercase.
- **Steps:**
 1. Validate input (NULL or empty string).
 2. Check each character; if uppercase, convert to lowercase using ASCII offset.
 3. Preserve non-alphabetic characters.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <string.h>
#include <stdbool.h>
#include <stdlib.h>
#include <ctype.h>
```

```

// Converts string to lowercase in-place.
void toLowerCase(char* str) {
    if (str == NULL || str[0] == '\0') return; // Validate input
    for (int i = 0; str[i] != '\0'; i++) { // Iterate and convert
        if (str[i] >= 'A' && str[i] <= 'Z') {
            str[i] = str[i] + 32; // ASCII offset for lowercase
        }
    }
}

// Unit test helper
void assertStringEquals(const char* expected, char* actual, const char* testName) {
    printf("%s: %s\n", testName, strcmp(expected, actual) == 0 ? "PASSED" : "FAILED");
}

// Unit tests for toLowerCase
void testtoLowerCase() {
    char str[] = "Hello World";
    toLowerCase(str);
    assertStringEquals("hello world", str, "Test 51.1 - Normal case");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate input to handle NULL or empty strings safely.
 - Use ASCII offset or tolower for reliable conversion.
 - Modify in-place to minimize space usage.
 - Ensure non-alphabetic characters remain unchanged.
- **Expert Tips:**
 - Explain ASCII conversion: "Uppercase to lowercase is a +32 offset in ASCII."
 - In interviews, clarify: "Ask if we should use tolower or assume ASCII."
 - Suggest optimization: "Use tolower for portability across character encodings."
 - Test edge cases: "Mixed case, no letters, or special characters."

Problem 52: Find the Sum of Digits in a Number

Issue Description

Compute the sum of all digits in a non-negative integer, e.g., 123 returns 6 (1+2+3).

Handle large numbers and ensure robustness for edge cases like 0.

Problem Decomposition & Solution Steps

- **Input:** Non-negative integer.
- **Output:** Sum of digits.
- **Approach:** Extract digits using division and modulo.
- **Steps:**
 1. Validate input (non-negative).
 2. Extract each digit using $n \% 10$ and divide n by 10.
 3. Sum digits until n becomes 0.
- **Complexity:** Time $O(\log n)$, Space $O(1)$.

Coding Part (with Unit Tests)

```
// Returns sum of digits in n.
int sumOfDigits(int n) {
    if (n < 0) return 0; // Validate input
    int sum = 0;
    while (n > 0) { // Extract and sum digits
        sum += n % 10;
        n /= 10;
    }
    return sum;
}
// Unit test helper
void assertEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests for sumOfDigits
void testSumOfDigits() {
    assertEquals(6, sumOfDigits(123), "Test 52.1 - Normal case");
    assertEquals(0, sumOfDigits(0), "Test 52.2 - Zero case");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle negative numbers (return 0 or clarify requirements).
 - Use integer division and modulo for digit extraction.
 - Avoid string conversion to keep space O(1).
 - Test edge cases like 0 and single-digit numbers.
- **Expert Tips:**
 - Explain modulo: "n % 10 gets the last digit; n /= 10 removes it."
 - In interviews, discuss: "Ask if negative numbers are allowed."
 - Suggest optimization: "For very large numbers, use long long."
 - Test edge cases: "Large numbers like 9999 or single digits."

Problem 53: Check if a String is a Valid Parentheses Sequence

Issue Description

Check if a string containing parentheses ('(', ')', '{', '}', '[', ']') is valid, i.e., all brackets match correctly in order, e.g., "({[]})" returns true, "({}" returns false.

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** Boolean.
- **Approach:** Use a stack to track opening brackets.
- **Steps:**
 1. Validate input.
 2. Push opening brackets; pop and match closing brackets.
 3. Ensure stack is empty at the end.
- **Complexity:** Time O(n), Space O(n).

Coding Part (with Unit Tests)

```
// Checks if string is a valid parentheses sequence.
bool isValidParentheses(const char* str) {
    if (str == NULL) return false; // Validate input
    char stack[1000];
    int top = -1;
    for (int i = 0; str[i] != '\0'; i++) { // Process each character
        if (str[i] == '(' || str[i] == '{' || str[i] == '[') {
            stack[++top] = str[i]; // Push opening
        } else if (str[i] == ')' && (top < 0 || stack[top--] != '(')) return false;
        else if (str[i] == '}' && (top < 0 || stack[top--] != '{')) return false;
        else if (str[i] == ']' && (top < 0 || stack[top--] != '[')) return false;
    }
    return top == -1; // Stack must be empty
}

// Unit test helper
void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests for isValidParentheses
void testIsValidParentheses() {
    assertBoolEquals(true, isValidParentheses("{}{}"), "Test 53.1 - Valid parentheses");
    assertBoolEquals(false, isValidParentheses("([)]"), "Test 53.2 - Invalid parentheses");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use a stack to track matching brackets.
 - Validate input for NULL.
 - Handle all bracket types explicitly.
 - Ensure stack underflow/overflow is managed.
- **Expert Tips:**
 - Explain stack usage: "Push opening brackets; pop and verify for closing."
 - In interviews, clarify: "Ask if other characters are allowed."
 - Suggest optimization: "Dynamic stack allocation for arbitrary sizes."
 - Test edge cases: "Empty string, single bracket, or mismatched pairs."

Problem 54: Implement a Function to Tokenize a String by Spaces

Issue Description

Split a string into words based on spaces, returning an array of strings, e.g., "hello world" returns ["hello", "world"].

The caller frees the memory.

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** Array of strings, size.
- **Approach:** Parse string, allocate tokens dynamically.
- **Steps:**

1. Validate input.
 2. Count words to allocate array.
 3. Extract and store each word.
- **Complexity:** Time O(n), Space O(n).

Coding Part (with Unit Tests)

```

// Tokenizes string by spaces; caller frees result.
char** tokenizeString(const char* str, int* size) {
    if (str == NULL || str[0] == '\0') { *size = 0; return NULL; } // Validate input
    char** result = (char**)malloc(100 * sizeof(char*)); // Max 100 tokens
    int wordCount = 0, start = 0, len = strlen(str);
    for (int i = 0; ; i++) { // Extract words
        if (str[i] == ' ' || str[i] == '\0') {
            if (i > start) {
                result[wordCount] = (char*)malloc(i - start + 1);
                strncpy(result[wordCount], str + start, i - start);
                result[wordCount][i - start] = '\0';
                wordCount++;
            }
            start = i + 1;
            if (str[i] == '\0') break;
        }
    }
    *size = wordCount;
    return result;
}

// Unit tests for tokenizeString
void testTokenizeString() {
    int size;
    char** result = tokenizeString("hello world", &size);
    assertEquals(2, size, "Test 54.1 - Token count");
    assertEquals("hello", result[0], "Test 54.2 - First token");
    for (int i = 0; i < size; i++) free(result[i]);
    free(result);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Allocate memory dynamically for tokens and array.
 - Set size for caller to know token count.
 - Free all allocated memory in tests.
 - Handle multiple spaces and empty strings.
- **Expert Tips:**
 - Explain parsing: "Track word boundaries with spaces, allocate each token."
 - In interviews, clarify: "Ask if multiple spaces or leading/trailing spaces matter."
 - Suggest optimization: "Count words first to allocate exact array size."
 - Test edge cases: "Multiple spaces, single word, or empty string."

Problem 55: Find the Minimum Window Substring Containing All Characters of Another String

Issue Description

Find the smallest substring of s that contains all characters of t (including duplicates), e.g., s="ADOBECODEBANC", t="ABC" returns "BANC".

Problem Decomposition & Solution Steps

- **Input:** Two strings (s, t).
- **Output:** Smallest substring (caller frees).
- **Approach:** Use sliding window with frequency map.
- **Steps:**
 1. Validate inputs.
 2. Build frequency map for t.
 3. Slide window in s, track valid windows.
- **Complexity:** Time O(n), Space O(k) (k=charset size).

Coding Part (with Unit Tests)

```
// Returns minimum window substring; caller frees.
char* minWindow(const char* s, const char* t) {
    if (s == NULL || t == NULL || s[0] == '\0' || t[0] == '\0') return strdup("");
    int map[128] = {0}, required = 0, formed = 0;
    for (int i = 0; t[i]; i++) { map[t[i]]++; required++; } // Build t's frequency map
    int minLen = INT_MAX, minStart = 0, left = 0;
    for (int right = 0; s[right]; right++) { // Slide window
        if (map[s[right]] > 0) formed++; // Add character
        map[s[right]]--;
        while (formed == required) { // Shrink window
            if (right - left + 1 < minLen) {
                minLen = right - left + 1;
                minStart = left;
            }
            map[s[left]]++;
            if (map[s[left]] > 0) formed--;
            left++;
        }
    }
    if (minLen == INT_MAX) return strdup("");
    char* result = (char*)malloc(minLen + 1);
    strncpy(result, s + minStart, minLen);
    result[minLen] = '\0';
    return result;
}

// Unit tests for minWindow
void testMinWindow() {
    char* result = minWindow("ADOBECODEBANC", "ABC");
    assertStringEquals("BANC", result, "Test 55.1 - Normal case");
    free(result);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use fixed-size array for frequency map (ASCII).
 - Handle edge cases (empty strings, no valid window).
 - Free allocated memory.
 - Optimize by shrinking window when valid.
- **Expert Tips:**
 - Explain sliding window: "Expand until all chars found, then shrink to minimize."
 - In interviews, walk through: "For 'ADOBEC', track ABC's frequencies."
 - Suggest optimization: "Use two-pointers with a counter for required chars."
 - Test edge cases: "t longer than s, or no valid window."

Problem 56: Implement a Function to Reverse a String Between Two Indices

Issue Description

Reverse a substring in-place between given indices (inclusive), e.g., "abcdef", left=1, right=4 becomes "aedcbf" (bcde reversed).

Problem Decomposition & Solution Steps

- **Input:** String, left and right indices.
- **Output:** Modified string in-place.
- **Approach:** Swap characters from left to right.
- **Steps:**
 1. Validate input and indices.
 2. Swap characters between left and right.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
// Reverses string between indices left and right (inclusive).
void reverseStringRange(char* str, int left, int right) {
    if (str == NULL || left < 0 || right >= (int)strlen(str) || left > right) return; // Validate
    input
    while (left < right) { // Swap characters
        char temp = str[left];
        str[left++] = str[right];
        str[right--] = temp;
    }
}

// Unit tests for reverseStringRange
void testReverseStringRange() {
    char str[] = "abcdef";
    reverseStringRange(str, 1, 4);
    assertEquals("aedcbf", str, "Test 56.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate indices to prevent out-of-bounds access.
 - Modify in-place to save space.
 - Handle edge cases like $\text{left} = \text{right}$.
 - Ensure input string is mutable.
- **Expert Tips:**
 - Explain swapping: "Two pointers converge, swapping chars until they meet."
 - In interviews, clarify: "Ask if indices are 0-based or inclusive."
 - Suggest optimization: "This is optimal; no further speedup possible."
 - Test edge cases: "Single char, full string, or invalid indices."

Problem 57: Check if a Number is a Perfect Number

Issue Description

Check if a number is perfect (sum of proper divisors equals the number), e.g., 6 ($1+2+3=6$) returns true, 12 returns false.

Problem Decomposition & Solution Steps

- **Input:** Positive integer.
- **Output:** Boolean.
- **Approach:** Sum divisors up to $\text{sqrt}(n)$.
- **Steps:**
 1. Validate input (positive).
 2. Find divisors and sum them.
 3. Check if sum equals number.
- **Complexity:** Time $O(\text{sqrt}(n))$, Space $O(1)$.

Coding Part (with Unit Tests)

```
// Checks if n is a perfect number.
bool isPerfectNumber(int n) {
    if (n <= 1) return false; // Validate input
    int sum = 1; // Include 1 as divisor
    for (int i = 2; i * i <= n; i++) { // Sum divisors
        if (n % i == 0) {
            sum += i;
            if (i * i != n) sum += n / i; // Add pair divisor
        }
    }
    return sum == n;
}

// Unit tests for isPerfectNumber
void testIsPerfectNumber() {
    assertEquals(true, isPerfectNumber(6), "Test 57.1 - Perfect number");
    assertEquals(false, isPerfectNumber(12), "Test 57.2 - Non-perfect");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Optimize by checking divisors up to \sqrt{n} .
 - Include 1 but exclude n itself in sum.
 - Validate input (non-positive numbers).
 - Handle edge cases like 1.
- **Expert Tips:**
 - Explain optimization: "Check up to \sqrt{n} to avoid redundant divisors."
 - In interviews, list examples: "6, 28, 496 are perfect numbers."
 - Suggest optimization: "For large n , precompute perfect numbers."
 - Test edge cases: "1, small numbers, or large perfect numbers."

Problem 58: Find the Longest Repeating Substring in a String

Issue Description

Find the longest substring that appears at least twice in a string, e.g., "banana" returns "ana".

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** Longest repeating substring (caller frees).
- **Approach:** Use suffix array or sliding window with hash set.
- **Steps:**
 1. Validate input.
 2. Check all substrings, store in hash set.
 3. Track longest repeating substring.
- **Complexity:** Time $O(n^2)$, Space $O(n)$.

Coding Part (with Unit Tests)

```
// Returns longest repeating substring; caller frees.
char* longestRepeatingSubstring(const char* str) {
    if (str == NULL || str[0] == '\0') return strdup("");
    int len = strlen(str), maxLen = 0, maxStart = 0;
    char* result = (char*)malloc(len + 1);
    char seen[1000][1000] = {0}; // Simple hash set for substrings
    for (int i = 0; i < len; i++) { // Check all substrings
        for (int j = 1; j <= len - i; j++) {
            char temp[1000];
            strncpy(temp, str + i, j);
            temp[j] = '\0';
            if (seen[i][j]) { // Found repeat
                if (j > maxLen) {
                    maxLen = j;
                    maxStart = i;
                }
            } else {
                seen[i][j] = 1;
            }
        }
    }
    strncpy(result, str + maxStart, maxLen);
    result[maxLen] = '\0';
}
```

```

        return result;
    }

// Unit tests for longestRepeatingSubstring
void testLongestRepeatingSubstring() {
    char* result = longestRepeatingSubstring("banana");
    assertEquals("ana", result, "Test 58.1 - Normal case");
    free(result);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate input for NULL or empty strings.
 - Free allocated memory.
 - Use efficient data structure for substring tracking.
 - Handle cases with no repeating substrings.
- **Expert Tips:**
 - Explain approach: "Check all substrings, mark seen ones to find repeats."
 - In interviews, suggest: "Suffix trees or Rabin-Karp for O(n log n)."
 - Discuss trade-offs: "Simple solution is O(n^2); advanced methods are complex."
 - Test edge cases: "No repeats, single char, or full string repeat."

Problem 59: Implement a Function to Convert a Hexadecimal String to Decimal

Issue Description

Convert a hexadecimal string (0-9, a-f, A-F) to its decimal equivalent, e.g., "1A" returns 26 (16+10).

Problem Decomposition & Solution Steps

- **Input:** Null-terminated hex string.
- **Output:** Decimal integer.
- **Approach:** Process each character, multiply by 16, and add.
- **Steps:**
 1. Validate input (valid hex chars).
 2. Convert each char to its decimal value.
 3. Accumulate result using base-16.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```

// Converts hex string to decimal.
int hexToDecimal(const char* str) {
    if (str == NULL || str[0] == '\0') return 0; // Validate input
    int result = 0;
    for (int i = 0; str[i] != '\0'; i++) { // Process each char
        result *= 16;
        if (str[i] >= '0' && str[i] <= '9') result += str[i] - '0';
        else if (str[i] >= 'a' && str[i] <= 'f') result += str[i] - 'a' + 10;
        else if (str[i] >= 'A' && str[i] <= 'F') result += str[i] - 'A' + 10;
        else return -1; // Invalid char
    }
    return result;
}

```

```

// Unit tests for hexToDecimal
void testHexToDecimal() {
    assertEquals(26, hexToDecimal("1A"), "Test 59.1 - Normal case");
    assertEquals(-1, hexToDecimal("GG"), "Test 59.2 - Invalid hex");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate all characters for valid hex digits.
 - Handle case-insensitive hex (a-f, A-F).
 - Return error code for invalid input.
 - Use efficient base-16 accumulation.
- **Expert Tips:**
 - Explain conversion: "Each char is multiplied by 16 and added to result."
 - In interviews, clarify: "Ask if negative hex values are allowed."
 - Suggest optimization: "Use lookup table for hex values."
 - Test edge cases: "Empty string, invalid chars, or large hex."

Problem 60: Find the Sum of All Odd Numbers in an Array

Issue Description

Compute the sum of all odd numbers in an integer array, e.g., [1,2,3,4] returns 4 (1+3).

Handle negative numbers and ensure robustness for edge cases.

Problem Decomposition & Solution Steps

- **Input:** Array, size.
- **Output:** Sum of odd numbers.
- **Approach:** Iterate array, sum odd numbers.
- **Steps:**
 1. Validate input (NULL, size <= 0).
 2. Add numbers where num % 2 != 0.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```

// Returns sum of odd numbers in array.
int sumOddNumbers(int* arr, int size) {
    if (arr == NULL || size <= 0) return 0; // Validate input
    int sum = 0;
    for (int i = 0; i < size; i++) { // Sum odd numbers
        if (arr[i] % 2 != 0) sum += arr[i];
    }
    return sum;
}

// Unit tests for sumOddNumbers
void testSumOddNumbers() {
    int arr[] = {1, 2, 3, 4};
    assertEquals(4, sumOddNumbers(arr, 4), "Test 60.1 - Normal case");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate input to prevent crashes.
 - Use simple modulo check for odd numbers.
 - Handle negative numbers correctly.
 - Test for arrays with no odd numbers.
- **Expert Tips:**
 - Explain logic: "Check num % 2 != 0 to identify odd numbers."
 - In interviews, clarify: "Ask if overflow handling is needed for large sums."
 - Suggest optimization: "Parallel summation for large arrays."
 - Test edge cases: "No odd numbers, negative numbers, or empty array."

Main Function to Run All Tests

```
int main() {  
    printf("Running tests for problems 51 to 60:\n");  
    testToLowercase();  
    testSumOfDigits();  
    testIsValidParentheses();  
    testTokenizeString();  
    testMinWindow();  
    testReverseStringRange();  
    testIsPerfectNumber();  
    testLongestRepeatingSubstring();  
    testHexToDecimal();  
    testSumOddNumbers();  
    return 0;  
}
```

Problem 61: Check if a String is a Valid Phone Number Format

Issue Description

Determine if a string represents a valid phone number in the format "(XXX) XXX-XXXX" or "XXX-XXX-XXXX", where X is a digit (e.g., "(123) 456-7890" or "123-456-7890" are valid).

The function should handle only these formats and reject invalid characters or structures.

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** Boolean (true if valid phone number).
- **Approach:** Check string length and format, validate digits, parentheses, spaces, and hyphens.
- **Algorithm:** Linear scan with pattern matching.
- **Steps:**
 1. Validate input for NULL or incorrect length.
 2. Check for two possible formats: with or without parentheses.
 3. Verify digits in positions for area code, exchange, and subscriber number.
 4. Ensure correct separators (parentheses, space, hyphen).
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <string.h>
#include <stdbool.h>
#include <ctype.h>

// Checks if str is a valid phone number in "(XXX) XXX-XXXX" or "XXX-XXX-XXXX" format.
bool isValidPhoneNumber(const char* str) {
    if (str == NULL || (strlen(str) != 12 && strlen(str) != 14)) return false; // Validate length
    bool hasParens = str[0] == '('; // Check if format includes parentheses
    if (hasParens && (str[4] != ')' || str[5] != ' ')) return false; // Check parens and space

    int digitPositions[] = {hasParens ? 1 : 0, hasParens ? 2 : 1, hasParens ? 3 : 2, // Area code
                           hasParens ? 6 : 4, hasParens ? 7 : 5, hasParens ? 8 : 6, // Exchange
                           hasParens ? 10 : 8, hasParens ? 11 : 9, hasParens ? 12 : 10, hasParens ? 13
                           : 11}; // Subscriber
    int hyphenPos = hasParens ? 9 : 7; // Hyphen position
    for (int i = 0; i < 10; i++) { // Verify digits
        if (!isdigit(str[digitPositions[i]])) return false;
    }
    if (str[hyphenPos] != '-') return false; // Verify hyphen
    return true;
}

// Unit test helper
void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests for isValidPhoneNumber
void testIsValidPhoneNumber() {
    assertBoolEquals(true, isValidPhoneNumber("(123) 456-7890"), "Test 61.1 - Valid with parens");
    assertBoolEquals(true, isValidPhoneNumber("123-456-7890"), "Test 61.2 - Valid without parens");
    assertBoolEquals(false, isValidPhoneNumber("123-456-789a"), "Test 61.3 - Invalid digit");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Strictly validate string length (12 or 14 characters).
 - Use isdigit for robust digit checking.
 - Check for exact format compliance (parentheses, space, hyphen).
 - Handle both formats explicitly to avoid ambiguity.
- **Expert Tips:**
 - Explain pattern matching: "We verify digits and separators at specific positions based on the format."
 - In interviews, clarify: "Ask if other formats (e.g., +1) are allowed."
 - Suggest optimization: "Regex could be used but is overkill for fixed formats."
 - Test edge cases: "Invalid chars, wrong separators, or incorrect lengths."

Problem 62: Implement a Function to Remove Leading Zeros from a String Number

Issue Description

Remove leading zeros from a string representing a number, e.g., "00123" becomes "123".

Return "0" for "0000" and handle invalid inputs gracefully.

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** New string without leading zeros (caller frees).
- **Approach:** Skip leading zeros, copy remaining digits.
- **Algorithm:** Linear scan to find first non-zero, then copy.
- **Steps:**
 1. Validate input for NULL or non-digit characters.
 2. Find first non-zero digit.
 3. Copy remaining characters or return "0" if all zeros.
- **Complexity:** Time O(n), Space O(n).

Coding Part (with Unit Tests)

```
#include <stdlib.h>

// Removes leading zeros from string number; caller frees result.
char* removeLeadingZeros(const char* str) {
    if (str == NULL || str[0] == '\0') return strdup("0"); // Handle NULL/empty
    int len = strlen(str), i = 0;
    while (str[i] == '0' && i < len - 1) i++; // Skip leading zeros
    for (int j = 0; j < len; j++) { // Validate digits
        if (!isdigit(str[j])) return strdup("0");
    }
    if (i == len - 1 && str[i] == '0') return strdup("0"); // All zeros
    char* result = (char*)malloc(len - i + 1);
    strcpy(result, str + i); // Copy from first non-zero
    return result;
}

// Unit test helper
void assertStringEquals(const char* expected, char* actual, const char* testName) {
    printf("%s: %s\n", testName, strcmp(expected, actual) == 0 ? "PASSED" : "FAILED");
}

// Unit tests for removeLeadingZeros
void testRemoveLeadingZeros() {
    char* result = removeLeadingZeros("00123");
    assertStringEquals("123", result, "Test 62.1 - Normal case");
    free(result);
    result = removeLeadingZeros("0000");
    assertStringEquals("0", result, "Test 62.2 - All zeros");
    free(result);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate input for non-digit characters.
 - Allocate exact memory for result.
 - Return "0" for all-zero inputs.
 - Free allocated memory in tests.
- **Expert Tips:**
 - Explain approach: "Scan to skip zeros, then copy the rest; handle edge case of all zeros."
 - In interviews, clarify: "Ask if negative numbers or decimals are allowed."
 - Suggest optimization: "In-place modification possible if mutable input."
 - Test edge cases: "All zeros, single digit, or invalid input."

Problem 63: Find the Maximum Difference Between Two Elements in an Array

Issue Description

Find the maximum difference between any two elements in an array where the larger element appears after the smaller, e.g., [7,1,5,3,6,4] returns 5 (6-1).

Problem Decomposition & Solution Steps

- **Input:** Array, size.
- **Output:** Maximum difference.
- **Approach:** Track minimum element seen so far and compute differences.
- **Algorithm:** Single-pass greedy.
- **Steps:**
 1. Validate input.
 2. Initialize min element and max difference.
 3. Update min and difference for each element.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
// Returns max difference where larger element appears after smaller.
int maxDifference(int* arr, int size) {
    if (arr == NULL || size < 2) return 0; // Validate input
    int minElement = arr[0], maxDiff = 0;
    for (int i = 1; i < size; i++) { // Track min and compute differences
        if (arr[i] < minElement) {
            minElement = arr[i]; // Update min
        } else {
            int diff = arr[i] - minElement;
            if (diff > maxDiff) maxDiff = diff; // Update max difference
        }
    }
    return maxDiff;
}

// Unit tests for maxDifference
void testMaxDifference() {
    int arr[] = {7, 1, 5, 3, 6, 4};
    assertEquals(5, maxDifference(arr, 6), "Test 63.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate input for size < 2.
 - Use single pass to minimize time complexity.
 - Track min element to avoid nested loops.
 - Handle cases where no valid difference exists.
- **Expert Tips:**
 - Explain greedy approach: "Track min element to compute max difference in one pass."
 - In interviews, clarify: "Ask if negative differences are allowed."
 - Suggest optimization: "This is optimal; parallel processing not practical."
 - Test edge cases: "Decreasing array, two elements, or duplicates."

Problem 64: Implement a Function to Split a String into an Array of Substrings

Issue Description

Split a string into substrings based on a delimiter (e.g., comma), e.g., "a,b,c" returns ["a", "b", "c"].

The caller frees the memory.

Problem Decomposition & Solution Steps

- **Input:** String, delimiter char.
- **Output:** Array of strings, size.
- **Approach:** Parse string, allocate tokens dynamically.
- **Algorithm:** Linear scan with delimiter detection.
- **Steps:**
 1. Validate input.
 2. Count tokens to allocate array.
 3. Extract and store substrings.
- **Complexity:** Time O(n), Space O(n).

Coding Part (with Unit Tests)

```
// Splits string by delimiter; caller frees result.
char** splitString(const char* str, char delim, int* size) {
    if (str == NULL || str[0] == '\0') { *size = 0; return NULL; } // Validate input
    char** result = (char**)malloc(100 * sizeof(char*)); // Max 100 tokens
    int wordCount = 0, start = 0, len = strlen(str);
    for (int i = 0; ; i++) { // Extract tokens
        if (str[i] == delim || str[i] == '\0') {
            if (i > start) {
                result[wordCount] = (char*)malloc(i - start + 1);
                strncpy(result[wordCount], str + start, i - start);
                result[wordCount][i - start] = '\0';
                wordCount++;
            }
            start = i + 1;
            if (str[i] == '\0') break;
        }
    }
    *size = wordCount;
    return result;
}

// Unit tests for splitString
void testSplitString() {
    int size;
    char** result = splitString("a,b,c", ',', &size);
    assertEquals(3, size, "Test 64.1 - Token count");
    assertEquals("a", result[0], "Test 64.2 - First token");
    for (int i = 0; i < size; i++) free(result[i]);
    free(result);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Allocate memory dynamically for tokens.

- Set size for caller to know token count.
 - Free all allocated memory in tests.
 - Handle consecutive delimiters and empty strings.
- **Expert Tips:**
 - Explain parsing: "Track substring boundaries with delimiter."
 - In interviews, clarify: "Ask if empty tokens are allowed."
 - Suggest optimization: "Count tokens first for exact allocation."
 - Test edge cases: "Consecutive delimiters, single token, or empty string."

Problem 65: Check if a String is a Rotation of Another String

Issue Description

Check if string s2 is a rotation of s1, e.g., "waterbottle" and "erbottlewat" returns true (s2 is s1 rotated).

Problem Decomposition & Solution Steps

- **Input:** Two strings.
- **Output:** Boolean.
- **Approach:** Concatenate s1 with itself, check if s2 is a substring.
- **Algorithm:** String concatenation + substring search.
- **Steps:**
 1. Validate inputs and lengths.
 2. Concatenate s1 with itself.
 3. Use strstr to check if s2 is in concatenated string.
- **Complexity:** Time O(n), Space O(n).

Coding Part (with Unit Tests)

```
// Checks if s2 is a rotation of s1.
bool isRotation(const char* s1, const char* s2) {
    if (s1 == NULL || s2 == NULL || strlen(s1) != strlen(s2)) return false; // Validate inputs
    if (s1[0] == '\0' && s2[0] == '\0') return true; // Handle empty strings
    int len = strlen(s1);
    char* concat = (char*)malloc(2 * len + 1); // Allocate for s1 + s1
    strcpy(concat, s1); strcat(concat, s1); // Concatenate s1 with itself
    bool result = strstr(concat, s2) != NULL; // Check if s2 is substring
    free(concat);
    return result;
}

// Unit tests for isRotation
void testIsRotation() {
    assertBoolEquals(true, isRotation("waterbottle", "erbottlewat"), "Test 65.1 - Valid rotation");
    assertBoolEquals(false, isRotation("hello", "world"), "Test 65.2 - Not rotation");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Check equal lengths first.
 - Use standard strstr for substring search.
 - Free allocated memory.

- Handle empty strings explicitly.
- **Expert Tips:**
 - Explain approach: "s2 is a rotation if it's a substring of s1+s1."
 - In interviews, clarify: "Ask if case sensitivity matters."
 - Suggest optimization: "KMP algorithm for substring search, but strstr is sufficient."
 - Test edge cases: "Empty strings, single char, or non-rotations."

Problem 66: Find the Smallest Positive Number Missing from an Array

Issue Description

Find the smallest positive integer missing from an array, e.g., [3,4,-1,1] returns 2.

Handle unsorted arrays with duplicates or negatives.

Problem Decomposition & Solution Steps

- **Input:** Array, size.
- **Output:** Smallest missing positive integer.
- **Approach:** Place numbers in their index (i at i-1).
- **Algorithm:** In-place hashing.
- **Steps:**
 1. Validate input.
 2. Rearrange array so arr[i] = i+1.
 3. Find first index where value != index+1.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```
// Finds smallest missing positive integer.
int smallestMissingPositive(int* arr, int size) {
    if (arr == NULL || size <= 0) return 1; // Validate input
    for (int i = 0; i < size; i++) { // Place numbers in correct index
        while (arr[i] > 0 && arr[i] <= size && arr[arr[i] - 1] != arr[i]) {
            int temp = arr[arr[i] - 1];
            arr[arr[i] - 1] = arr[i];
            arr[i] = temp;
        }
    }
    for (int i = 0; i < size; i++) { // Find first mismatch
        if (arr[i] != i + 1) return i + 1;
    }
    return size + 1; // All numbers 1 to size present
}

// Unit tests for smallestMissingPositive
void testSmallestMissingPositive() {
    int arr[] = {3, 4, -1, 1};
    assertEquals(2, smallestMissingPositive(arr, 4), "Test 66.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use in-place hashing to achieve O(1) space.
 - Ignore non-positive and out-of-range numbers.
 - Validate input for NULL or empty arrays.
 - Handle duplicates during rearrangement.
- **Expert Tips:**
 - Explain hashing: "Place number i at index i-1 to detect missing numbers."
 - In interviews, walk through: "For [3,4,-1,1], place 1 at index 0, 3 at 2."
 - Suggest alternative: "Hash set is O(n) space; this is optimal."
 - Test edge cases: "All negatives, consecutive numbers, or duplicates."

Problem 67: Implement a Function to Replace All Occurrences of a Substring

Issue Description

Replace all occurrences of a substring with another substring, e.g., "hello world", replace "ll" with "pp" returns "heppo world".

Problem Decomposition & Solution Steps

- **Input:** String, old substring, new substring.
- **Output:** New string with replacements (caller frees).
- **Approach:** Scan string, build result with replacements.
- **Algorithm:** Linear scan with substring matching.
- **Steps:**
 1. Validate inputs.
 2. Count occurrences to allocate result.
 3. Build new string, replacing matches.
- **Complexity:** Time O(n), Space O(n).

Coding Part (with Unit Tests)

```
// Replaces all occurrences of oldStr with newStr; caller frees result.
char* replaceSubstring(const char* str, const char* oldStr, const char* newStr) {
    if (str == NULL || oldStr == NULL || newStr == NULL || oldStr[0] == '\0') return strdup(str ? str : "");
    int len = strlen(str), oldLen = strlen(oldStr), newLen = strlen(newStr), count = 0;
    for (int i = 0; i <= len - oldLen; i++) { // Count occurrences
        if (strncmp(str + i, oldStr, oldLen) == 0) count++;
    }
    char* result = (char*)malloc(len + count * (newLen - oldLen) + 1);
    int k = 0;
    for (int i = 0; i < len; i++) { // Build result
        if (i <= len - oldLen && strncmp(str + i, oldStr, oldLen) == 0) {
            strcpy(result + k, newStr);
            k += newLen;
            i += oldLen - 1;
        } else {
            result[k++] = str[i];
        }
    }
    result[k] = '\0';
    return result;
}
```

```

// Unit tests for replaceSubstring
void testReplaceSubstring() {
    char* result = replaceSubstring("hello world", "ll", "pp");
    assertEquals("heppo world", result, "Test 67.1 - Normal case");
    free(result);
}

```

Best Practices & Expert Tips

- **Best Practices:**

- Validate all inputs, including empty oldStr.
- Allocate exact memory for result.
- Use strncmp for safe substring comparison.
- Free allocated memory in tests.

- **Expert Tips:**

- Explain approach: "Count matches first, then build result with replacements."
- In interviews, clarify: "Ask if overlapping matches are possible."
- Suggest optimization: "KMP for faster substring search in large strings."
- Test edge cases: "No matches, empty strings, or full string match."

Problem 68: Check if a String Contains Balanced Brackets

Issue Description

Check if a string with parentheses, braces, and brackets is balanced, e.g., "({[]})" returns true, "([)" returns false.

Only brackets are considered; other characters are ignored.

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** Boolean.
- **Approach:** Use stack to track opening brackets.
- **Algorithm:** Stack-based matching.
- **Steps:**
 1. Validate input.
 2. Push opening brackets; pop and match closing brackets.
 3. Ensure stack is empty at end.
- **Complexity:** Time O(n), Space O(n).

Coding Part (with Unit Tests)

```

// Checks if string has balanced brackets.
bool isBalancedBrackets(const char* str) {
    if (str == NULL) return false; // Validate input
    char stack[1000];
    int top = -1;
    for (int i = 0; str[i] != '\0'; i++) { // Process brackets
        if (str[i] == '(' || str[i] == '{' || str[i] == '[') {
            stack[++top] = str[i]; // Push opening bracket
        } else if (str[i] == ')' || str[i] == '}' || str[i] == ']') {
            if (top < 0) return false; // No matching opening
            char open = stack[top--];
            if ((str[i] == ')' && open != '(') ||
                (str[i] == '}' && open != '{') ||
                (str[i] == ']' && open != '['))
                return false;
        }
    }
    return top == -1; // Stack should be empty
}

```

```

        (str[i] == ')' && open != '[') return false; // Mismatch
    }
}
return top == -1; // Stack must be empty
}

// Unit tests for isBalancedBrackets
void testIsBalancedBrackets() {
    assertBoolEquals(true, isBalancedBrackets("{}{}"), "Test 68.1 - Balanced brackets");
    assertBoolEquals(false, isBalancedBrackets("([") ), "Test 68.2 - Unbalanced brackets");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use stack for matching brackets.
 - Ignore non-bracket characters.
 - Validate input for NULL.
 - Handle stack underflow/overflow.
- **Expert Tips:**
 - Explain stack usage: "Push opening brackets, pop and verify for closing."
 - In interviews, clarify: "Ask if non-bracket chars are allowed."
 - Suggest optimization: "Dynamic stack for large strings."
 - Test edge cases: "Empty string, single bracket, or mixed chars."

Problem 69: Find the Sum of Squares of All Numbers in an Array

Issue Description

Compute the sum of squares of all numbers in an integer array, e.g., [1,2,3] returns 14 ($1^2 + 2^2 + 3^2 = 1+4+9$).

Problem Decomposition & Solution Steps

- **Input:** Array, size.
- **Output:** Sum of squares.
- **Approach:** Iterate array, compute squares, and sum.
- **Algorithm:** Linear scan with arithmetic.
- **Steps:**
 1. Validate input.
 2. Square each number and add to sum.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```

// Returns sum of squares of array elements.
long sumOfSquares(int* arr, int size) {
    if (arr == NULL || size <= 0) return 0; // Validate input
    long sum = 0; // Use long to handle large squares
    for (int i = 0; i < size; i++) { // Compute squares and sum
        sum += (long)arr[i] * arr[i];
    }
    return sum;
}
// Unit tests for sumOfSquares

```

```

void testSumOfSquares() {
    int arr[] = {1, 2, 3};
    assertEquals(14, sumOfSquares(arr, 3), "Test 69.1 - Normal case");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use long to prevent overflow.
 - Validate input for NULL or empty arrays.
 - Keep arithmetic simple and precise.
 - Test for negative numbers and zeros.
- **Expert Tips:**
 - Explain arithmetic: "Square each number and accumulate in long to avoid overflow."
 - In interviews, clarify: "Ask if overflow handling is critical."
 - Suggest optimization: "Parallel summation for large arrays."
 - Test edge cases: "Zeros, negative numbers, or large values."

Problem 70: Implement a Function to Convert a String to Title Case

Issue Description

Convert a string to title case, capitalizing the first letter of each word, e.g., "hello world" becomes "Hello World".

Non-alphabetic characters remain unchanged.

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** Modified string in-place.
- **Approach:** Capitalize first letter of each word after spaces.
- **Algorithm:** Linear scan with state tracking.
- **Steps:**
 1. Validate input.
 2. Capitalize first char and chars after spaces.
 3. Convert others to lowercase.
- **Complexity:** Time O(n), Space O(1).

Coding Part (with Unit Tests)

```

// Converts string to title case in-place.
void toTitleCase(char* str) {
    if (str == NULL || str[0] == '\0') return; // Validate input
    bool newWord = true; // Track start of word
    for (int i = 0; str[i] != '\0'; i++) { // Process each char
        if (newWord && str[i] >= 'a' && str[i] <= 'z') {
            str[i] -= 32; // Capitalize
            newWord = false;
        } else if (!newWord && str[i] >= 'A' && str[i] <= 'Z') {
            str[i] += 32; // Lowercase non-first letters
        }
        newWord = str[i] == ' '; // Next char is new word
    }
}

```

```
// Unit tests for toTitleCase
void testToTitleCase() {
    char str[] = "hello world";
    toTitleCase(str);
    assertEquals("Hello World", str, "Test 70.1 - Normal case");}

```

Best Practices & Expert Tips

- **Best Practices:**

- Modify in-place to save space.
- Use ASCII offsets or toupper/tolower for portability.
- Handle non-alphabetic characters correctly.
- Validate input for NULL or empty strings.

- **Expert Tips:**

- Explain state tracking: "Use newWord flag to capitalize only first letters."
- In interviews, clarify: "Ask if non-alphabetic words need special handling."
- Suggest optimization: "Use standard library functions for non-ASCII."
- Test edge cases: "Multiple spaces, no letters, or mixed case."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for problems 61 to 70:\n");
    testIsValidPhoneNumber();
    testRemoveLeadingZeros();
    testMaxDifference();
    testSplitString();
    testIsRotation();
    testSmallestMissingPositive();
    testReplaceSubstring();
    testIsBalancedBrackets();
    testSumOfSquares();
    testToTitleCase();
    return 0;
}
```

Problem 71: Find the Longest Substring with at Most k Distinct Characters

Issue Description

Find the longest substring of a string that contains at most k distinct characters, e.g., for $s="eceba"$, $k=2$, return "ece" (length 3, contains 'e' and 'c').

Problem Decomposition & Solution Steps

- **Input:** String, integer k .
- **Output:** Longest substring (caller frees).
- **Approach:** Use a sliding window with a frequency map to track distinct characters.
- **Algorithm:** Sliding Window
 - **Explanation:** Maintain a window with at most k distinct characters using a frequency map.
 - Expand the window by adding characters, and shrink it when the number of distinct characters exceeds k .
 - Track the maximum window size and its starting position.

- **Steps:**
 1. Validate input (NULL, empty string, k <= 0).
 2. Use a frequency map to count characters in the window.
 3. Slide window: expand right, shrink left if > k distinct.
 4. Track longest substring.
- **Complexity:** Time O(n), Space O(m) (m = charset size).

Algorithm Explanation

The sliding window algorithm efficiently solves this by maintaining a dynamic substring with at most k distinct characters.

We use a frequency map (array for ASCII) to track character counts.

As we expand the window (move right pointer), we increment character counts.

If the number of distinct characters exceeds k, we shrink the window (move left pointer) until valid, updating the frequency map.

We track the maximum window length and start position to extract the substring.

This ensures O(n) time as each character is processed at most twice (added and removed once).

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <string.h>
#include <stdlib.h>
#include <stdbool.h>
#include <ctype.h>

// Returns longest substring with at most k distinct characters; caller frees.
char* longestSubstringKDistinct(const char* s, int k) {
    if (s == NULL || s[0] == '\0' || k <= 0) return strdup("");
    int map[128] = {0}, distinct = 0, maxLen = 0, maxStart = 0, left = 0;
    int len = strlen(s);
    for (int right = 0; right < len; right++) { // Slide window
        if (map[s[right]] == 0) distinct++;
        map[s[right]]++;
        while (distinct > k) { // Shrink window if too many distinct
            map[s[left]]--;
            if (map[s[left]] == 0) distinct--;
            left++;
        }
        if (right - left + 1 > maxLen) { // Update max substring
            maxLen = right - left + 1;
            maxStart = left;
        }
    }
    char* result = (char*)malloc(maxLen + 1);
    strncpy(result, s + maxStart, maxLen);
    result[maxLen] = '\0';
    return result;
}

// Unit test helper
void assertStringEquals(const char* expected, const char* actual, const char* testName) {
    printf("%s: %s\n", testName, strcmp(expected, actual) == 0 ? "PASSED" : "FAILED");
}
```

```

// Unit tests
void testLongestSubstringKDistinct() {
    char* result = longestSubstringKDistinct("eceba", 2);
    assertEquals("e", result, "Test 71.1 - Normal case");
    free(result);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use fixed-size array for frequency map (ASCII chars).
 - Validate inputs for NULL, empty string, or invalid k.
 - Free allocated memory in tests.
 - Track distinct count to avoid recomputing.
- **Expert Tips:**
 - Explain window management: "Expand until k+1 distinct, then shrink."
 - In interviews, clarify: "Ask if k can exceed charset size."
 - Suggest optimization: "Hash map for larger charsets, but array is sufficient for ASCII."
 - Test edge cases: "k=1, no valid substring, or all same char."

Problem 72: Check if a Number is a Happy Number

Issue Description

Determine if a number is happy, i.e., the sum of squares of its digits eventually reaches 1 (e.g., 19 is happy because $1^2 + 9^2 = 82, 8^2 + 2^2 = 68, \dots, 1$).

Problem Decomposition & Solution Steps

- **Input:** Positive integer.
- **Output:** Boolean.
- **Approach:** Compute sum of digit squares, detect cycle using hash set or slow-fast pointers.
- **Algorithm:** Floyd's Cycle Detection (Tortoise and Hare)
 - **Explanation:** Repeatedly compute the sum of squares of digits.
 - If the result is 1, the number is happy.
 - If a cycle is detected (not reaching 1), it's not happy.
 - Use slow-fast pointers to detect cycles efficiently.
- **Steps:**
 1. Validate input.
 2. Use slow and fast pointers to detect cycle or 1.
 3. Return true if 1 is reached.
 - **Complexity:** Time O(log n), Space O(1).

Algorithm Explanation

Floyd's cycle detection algorithm treats the sequence of digit square sums as a linked list.

The slow pointer moves one step (one sum), and the fast pointer moves two steps.

If they meet, a cycle exists, indicating the number is not happy.

If the slow pointer reaches 1, the number is happy.

This avoids explicit storage ($O(1)$ space) and handles large numbers efficiently, as the number of digits reduces logarithmically.

Coding Part (with Unit Tests)

```
// Computes sum of squares of digits.
int sumDigitSquares(int n) {
    int sum = 0;
    while (n > 0) { // Extract digits and square
        int digit = n % 10;
        sum += digit * digit;
        n /= 10;
    }
    return sum;
}

// Checks if n is a happy number using Floyd's cycle detection.
bool isHappy(int n) {
    if (n <= 0) return false; // Validate input
    int slow = n, fast = n;
    do { // Slow moves one step, fast moves two
        slow = sumDigitSquares(slow);
        fast = sumDigitSquares(sumDigitSquares(fast));
        if (slow == 1 || fast == 1) return true; // Happy number
    } while (slow != fast); // Cycle detected
    return false;
}

// Unit test helper
void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testIsHappy() {
    assertBoolEquals(true, isHappy(19), "Test 72.1 - Happy number");
    assertBoolEquals(false, isHappy(2), "Test 72.2 - Unhappy number");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use Floyd's algorithm for $O(1)$ space.
 - Validate non-positive inputs.
 - Optimize digit extraction with modulo.
 - Handle edge cases like 1.
- **Expert Tips:**
 - Explain cycle detection: "Slow-fast pointers detect loops in digit sums."
 - In interviews, clarify: "Ask if hash set is allowed ($O(\log n)$ space)."
 - Suggest alternative: "Hash set to store seen sums, but Floyd's is optimal."
 - Test edge cases: "1, small unhappy numbers, or large inputs."

Problem 73: Implement a Function to Reverse a String Recursively

Issue Description

Reverse a string in-place using recursion, e.g., "hello" becomes "olleh".

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** Reversed string in-place.
- **Approach:** Recursively swap characters from ends.
- **Algorithm:** Recursive Two-Pointer
 - **Explanation:** Use recursion to swap characters from the start and end of the string, moving inward until pointers meet.
 - Base case is when left \geq right.
- **Steps:**
 1. Validate input.
 2. Recursively swap characters at left and right indices.
 3. Base case: stop when left \geq right.
- **Complexity:** Time $O(n)$, Space $O(n)$ (recursion stack).

Algorithm Explanation

The recursive two-pointer algorithm divides the problem into smaller subproblems.

For each recursive call, swap the characters at the left and right indices and recurse on the substring between $\text{left}+1$ and $\text{right}-1$.

The base case ($\text{left} \geq \text{right}$) stops recursion when the pointers cross or meet.

This in-place approach ensures $O(1)$ extra space beyond the recursion stack, and the recursion depth is $O(n/2)$.

Coding Part (with Unit Tests)

```
// Helper for recursive string reversal.
void reverseStringRecursiveHelper(char* str, int left, int right) {
    if (left >= right) return; // Base case: pointers meet or cross
    char temp = str[left]; // Swap characters
    str[left] = str[right];
    str[right] = temp;
    reverseStringRecursiveHelper(str, left + 1, right - 1); // Recurse on inner substring
}

// Reverses string in-place using recursion.
void reverseStringRecursive(char* str) {
    if (str == NULL || str[0] == '\0') return; // Validate input
    reverseStringRecursiveHelper(str, 0, strlen(str) - 1); // Start recursion
}

// Unit tests
void testReverseStringRecursive() {
    char str[] = "hello";
    reverseStringRecursive(str);
    assertEquals("olleh", str, "Test 73.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate input for NULL or empty strings.
 - Use helper function to manage indices.
 - Perform in-place swaps to save space.
 - Ensure string is mutable.
- **Expert Tips:**
 - Explain recursion: "Swap ends and recurse on inner substring until pointers meet."
 - In interviews, clarify: "Discuss iterative vs. recursive trade-offs."
 - Suggest optimization: "Iterative solution avoids $O(n)$ stack space."
 - Test edge cases: "Single char, empty string, or long strings."

Problem 74: Find the Maximum Sum of a Contiguous Subarray of Size k

Issue Description

Find the maximum sum of any contiguous subarray of size k, e.g., [1,4,2,10,2,3,1,0,20], k=4 returns 24 (10+2+3+1).

Problem Decomposition & Solution Steps

- **Input:** Array, size, k.
- **Output:** Maximum sum.
- **Approach:** Use sliding window to compute sums of size k.
- **Algorithm:** Sliding Window
 - **Explanation:** Compute the sum of the first k elements, then slide the window by subtracting the leftmost element and adding the next, updating the maximum sum.
- **Steps:**
 1. Validate input ($k \leq \text{size}$).
 2. Compute initial window sum.
 3. Slide window, update max sum.
- **Complexity:** Time $O(n)$, Space $O(1)$.

Algorithm Explanation

The sliding window algorithm maintains a fixed-size window of k elements.

Initially, sum the first k elements.

For each subsequent window, subtract the element exiting the window and add the new element entering it.

Track the maximum sum seen.

This ensures $O(n)$ time as each element is processed at most twice (added and subtracted once), and only the current sum is stored.

Coding Part (with Unit Tests)

```
// Returns max sum of contiguous subarray of size k.
int maxSumSubarrayK(int* arr, int size, int k) {
    if (arr == NULL || size < k || k <= 0) return 0; // Validate input
    int sum = 0;
    for (int i = 0; i < k; i++) sum += arr[i]; // Initial window sum
    int maxSum = sum;
    for (int i = k; i < size; i++) { // Slide window
        sum = sum - arr[i - k] + arr[i]; // Remove left, add right
        if (sum > maxSum) maxSum = sum; // Update max
    }
    return maxSum;
}

// Unit test helper
void assertEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testMaxSumSubarrayK() {
    int arr[] = {1, 4, 2, 10, 2, 3, 1, 0, 20};
    assertEquals(24, maxSumSubarrayK(arr, 9, 4), "Test 74.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate $k \leq size$ and non-negative.
 - Use sliding window to avoid recomputing sums.
 - Handle edge cases like $k = size$.
 - Use long for sum if overflow is a concern.
- **Expert Tips:**
 - Explain sliding window: "Maintain k -size window, update sum in $O(1)$ per step."
 - In interviews, clarify: "Ask if negative numbers are allowed."
 - Suggest optimization: "This is optimal; prefix sums are $O(n)$ space."
 - Test edge cases: " $k=1$, $k=size$, or all negative numbers."

Problem 75: Implement a Function to Check if a String is a Valid URL

Issue Description

Check if a string is a valid URL, supporting http/https protocols, e.g., "https://example.com" returns true, "ftp://example" returns false.

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** Boolean.
- **Approach:** Check protocol, domain, and optional path using character validation.
- **Algorithm:** Pattern Matching
 - **Explanation:** Validate the URL by checking for "http://" or "https://", followed by a valid domain (alphanumeric, dots, hyphens), and optional path.
 - Use linear scan to verify character rules.

- **Steps:**
 1. Validate input for NULL or empty.
 2. Check for valid protocol.
 3. Validate domain and optional path characters.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The pattern matching algorithm checks the URL structure sequentially.

First, verify the protocol ("http://" or "https://").

Then, ensure the domain contains valid characters (alphanumeric, dots, hyphens) and follows basic rules (e.g., no consecutive dots).

Finally, allow an optional path with broader character support.

The linear scan ensures each character is checked exactly once, making it efficient for typical URLs.

Coding Part (with Unit Tests)

```
// Checks if str is a valid URL (http or https).
bool isValidURL(const char* str) {
    if (str == NULL || str[0] == '\0') return false; // Validate input
    if (strncmp(str, "http://", 7) != 0 && strncmp(str, "https://", 8) != 0) return false; // Check protocol
    int i = str[5] == 's' ? 8 : 7; // Skip protocol
    bool hasDomain = false;
    while (str[i] && str[i] != '/') { // Validate domain
        if (!isalnum(str[i]) && str[i] != '-' && str[i] != '.') return false;
        if (str[i] == '.' && str[i+1] == '.') return false; // No consecutive dots
        hasDomain = true;
        i++;
    }
    while (str[i]) { // Validate optional path
        if (!isalnum(str[i]) && str[i] != '/' && str[i] != '-' && str[i] != '.') return false;
        i++;
    }
    return hasDomain; // Ensure domain exists
}
// Unit tests
void testIsValidURL() {
    assertEquals(true, isValidURL("https://example.com"), "Test 75.1 - Valid URL");
    assertEquals(false, isValidURL("ftp://example"), "Test 75.2 - Invalid protocol");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate protocol explicitly (http/https).
 - Check domain and path characters strictly.
 - Handle edge cases like missing domain.
 - Use standard library for character checks.
- **Expert Tips:**
 - Explain validation: "Check protocol, then domain and path with allowed chars."
 - In interviews, clarify: "Ask if other protocols or query params are allowed."

- Suggest optimization: "Regex for complex URLs, but linear scan is simpler."
- Test edge cases: "No protocol, invalid chars, or minimal URLs."

Problem 76: Find the First Repeating Character in a String

Issue Description

Find the first character that repeats in a string, e.g., "abca" returns 'a'.

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** First repeating character or '\0' if none.
- **Approach:** Use a hash set to track seen characters.
- **Algorithm:** Hash Set
 - **Explanation:** Iterate through the string, storing characters in a hash set.
 - The first character already in the set is the answer.
 - Use an array for ASCII characters for simplicity.
- **Steps:**
 1. Validate input.
 2. Track seen characters in array.
 3. Return first character seen twice.
- **Complexity:** Time O(n), Space O(m) (m = charset size).

Algorithm Explanation

The hash set algorithm uses a boolean array (for ASCII) to mark characters as seen.

As we iterate, if a character is already marked, it's the first repeat.

This ensures O(n) time since each character is checked once, and the fixed-size array (128 for ASCII) provides O(1) lookups.

The algorithm is efficient and straightforward, avoiding complex data structures.

Coding Part (with Unit Tests)

```
// Returns first repeating character or '\0' if none.
char firstRepeatingChar(const char* str) {
    if (str == NULL || str[0] == '\0') return '\0'; // Validate input
    bool seen[128] = {false}; // Hash set for ASCII chars
    for (int i = 0; str[i] != '\0'; i++) { // Check each char
        if (seen[str[i]]) return str[i]; // Found repeat
        seen[str[i]] = true; // Mark as seen
    }
    return '\0'; // No repeats
}
// Unit test helper
void assertCharEquals(char expected, char actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}
```

```

// Unit tests
void testFirstRepeatingChar() {
    assertEquals('a', firstRepeatingChar("abca"), "Test 76.1 - Normal case");
    assertEquals('\0', firstRepeatingChar("abc"), "Test 76.2 - No repeat");
}

```

Best Practices & Expert Tips

- **Best Practices:**

- Use fixed-size array for ASCII to save space.
- Validate input for NULL or empty strings.
- Return clear indicator ('\0') for no repeats.
- Keep algorithm simple for readability.

- **Expert Tips:**

- Explain hash set: "Mark chars in array; first seen twice is answer."
- In interviews, clarify: "Ask if case matters or non-ASCII chars are included."
- Suggest optimization: "Bit vector for smaller space if only lowercase."
- Test edge cases: "Empty string, no repeats, or single char."

Problem 77: Implement a Function to Convert a Decimal to Octal

Issue Description

Convert a decimal number to its octal representation as a string, e.g., 33 returns "41" ($38^1 + 18^0$).

Problem Decomposition & Solution Steps

- **Input:** Non-negative integer.
- **Output:** Octal string (caller frees).
- **Approach:** Repeatedly divide by 8, collect remainders.
- **Algorithm:** Base Conversion
 - **Explanation:** Divide the number by 8, collect remainders in reverse order, and build the string.
 - Each remainder (0-7) represents an octal digit.
- **Steps:**
 1. Validate input.
 2. Collect remainders by dividing by 8.
 3. Reverse digits to form octal string.
- **Complexity:** Time $O(\log n)$, Space $O(\log n)$.

Algorithm Explanation

The base conversion algorithm converts decimal to octal by repeatedly dividing by 8 and collecting remainders, which form the octal digits.

Since remainders are collected in reverse order, we store them in an array and reverse when building the string.

The number of digits is $O(\log n)$ (base 8), and each division is $O(1)$, making the algorithm efficient for typical integers.

Coding Part (with Unit Tests)

```
// Converts decimal to octal string; caller frees.
char* decimalToOctal(int n) {
    if (n < 0) return strdup("0"); // Validate input
    if (n == 0) return strdup("0");
    char temp[32]; // Max digits for int
    int i = 0;
    while (n > 0) { // Collect remainders
        temp[i++] = (n % 8) + '0'; // Convert to char
        n /= 8;
    }
    char* result = (char*)malloc(i + 1);
    for (int j = 0; j < i; j++) { // Reverse digits
        result[j] = temp[i - 1 - j];
    }
    result[i] = '\0';
    return result;
}

// Unit tests
void testDecimalToOctal() {
    char* result = decimalToOctal(33);
    assertStringEquals("41", result, "Test 77.1 - Normal case");
    free(result);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate non-negative input.
 - Allocate exact memory for result.
 - Handle edge case of 0 explicitly.
 - Free allocated memory in tests.
- **Expert Tips:**
 - Explain conversion: "Divide by 8, collect remainders, reverse for octal."
 - In interviews, clarify: "Ask if negative numbers are allowed."
 - Suggest optimization: "Use sprintf for simplicity, but manual is clearer."
 - Test edge cases: "0, single digit, or large numbers."

Problem 78: Check if a String is a Pangram

Issue Description

Check if a string is a pangram, i.e., contains all alphabet letters (a-z, case-insensitive), e.g., "The quick brown fox jumps" returns true.

Problem Decomposition & Solution Steps

- **Input:** Null-terminated string.
- **Output:** Boolean.
- **Approach:** Track unique letters using a set.
- **Algorithm:** Set-Based Counting
 - **Explanation:** Convert characters to lowercase, mark letters (a-z) in a boolean array, and check if all 26 are present.

- Ignore non-letters.
- **Steps:**
 1. Validate input.
 2. Mark lowercase letters in array.
 3. Check for 26 distinct letters.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The set-based counting algorithm uses a boolean array (size 26) to mark the presence of each letter (a-z).

We iterate through the string, converting each alphabetic character to lowercase and marking its index.

After processing, we check if all 26 letters are marked.

This is O(n) time as each character is processed once, and O(1) space since the array size is fixed (26).

Coding Part (with Unit Tests)

```
// Checks if str is a pangram (contains all a-z, case-insensitive).
bool isPangram(const char* str) {
    if (str == NULL || str[0] == '\0') return false; // Validate input
    bool seen[26] = {false};
    int count = 0;
    for (int i = 0; str[i] != '\0'; i++) { // Process each char
        if (isalpha(str[i])) {
            int index = tolower(str[i]) - 'a';
            if (!seen[index]) {
                seen[index] = true;
                count++;
            }
        }
    }
    return count == 26; // All letters present
}

// Unit tests
void testIsPangram() {
    assertBoolEquals(true, isPangram("The quick brown fox jumps"), "Test 78.1 - Pangram");
    assertBoolEquals(false, isPangram("hello"), "Test 78.2 - Not pangram");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use fixed-size array for letters (26).
 - Ignore non-alphabetic characters.
 - Handle case-insensitivity with tolower.
 - Validate input for NULL or empty.
- **Expert Tips:**
 - Explain counting: "Mark each letter's presence; check for 26."
 - In interviews, clarify: "Ask if spaces or special chars affect result."
 - Suggest optimization: "Bit vector for even less space."
 - Test edge cases: "Missing letters, all same letter, or empty string."

Problem 79: Find the Maximum Product Subarray

Issue Description

Find the maximum product of a contiguous subarray, e.g., [2,3,-2,4] returns 6 ([2,3]).

Problem Decomposition & Solution Steps

- **Input:** Array, size.
- **Output:** Maximum product.
- **Approach:** Track max and min products due to negative numbers.
- **Algorithm:** Kadane's Algorithm (Modified)
 - **Explanation:** Extend Kadane's algorithm to track both max and min products at each step, as negative numbers can flip results.
 - Update global max product.
- **Steps:**
 1. Validate input.
 2. Track max/min products for each position.
 3. Update global max product.

- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The modified Kadane's algorithm handles products by maintaining maximum and minimum products ending at each index, as a negative number can make a large negative product positive when multiplied by another negative.

For each element, compute new max/min by considering the current element alone or multiplying with previous max/min.

Update the global maximum product.

This handles cases like [-2,3,-4] where negatives create large positives.

Coding Part (with Unit Tests)

```
// Returns maximum product of contiguous subarray.
Long maxProductSubarray(int* arr, int size) {
    if (arr == NULL || size <= 0) return 0; // Validate input
    long maxSoFar = arr[0], maxEnding = arr[0], minEnding = arr[0];
    for (int i = 1; i < size; i++) { // Track max/min products
        long temp = maxEnding; // Store for min calculation
        maxEnding = arr[i] > arr[i] * maxEnding ? arr[i] : arr[i] * maxEnding;
        maxEnding = maxEnding > arr[i] * minEnding ? maxEnding : arr[i] * minEnding;
        minEnding = arr[i] < arr[i] * temp ? arr[i] : arr[i] * temp;
        minEnding = minEnding < arr[i] * minEnding ? minEnding : arr[i] * minEnding;
        maxSoFar = maxSoFar > maxEnding ? maxSoFar : maxEnding;
    }
    return maxSoFar;
}
// Unit tests
void testMaxProductSubarray() {
    int arr[] = {2, 3, -2, 4};
    assertEquals(6, maxProductSubarray(arr, 4), "Test 79.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use long to handle large products.
 - Track min product for negative numbers.
 - Validate input for NULL or empty.
 - Handle single-element arrays.
- **Expert Tips:**
 - Explain Kadane's: "Track max/min products to handle negative flips."
 - In interviews, clarify: "Ask if returning subarray indices is needed."
 - Suggest optimization: "This is optimal; dynamic programming not needed."
 - Test edge cases: "All negatives, zeros, or single element."

Problem 80: Implement a Function to Merge Two Strings Alternately

Issue Description

Merge two strings by alternating characters, starting with the first string, e.g., "abc", "pqr" returns "apbqcr".

If one string is longer, append remaining characters.

Problem Decomposition & Solution Steps

- **Input:** Two strings.
- **Output:** Merged string (caller frees).
- **Approach:** Alternate characters from both strings, append leftovers.
- **Algorithm:** Linear Merging
 - **Explanation:** Iterate through both strings, taking one character from each in turn until one is exhausted, then append the rest of the longer string.
- **Steps:**
 1. Validate inputs.
 2. Allocate result based on combined lengths.
 3. Merge characters alternately, append remaining.
- **Complexity:** Time $O(n+m)$, Space $O(n+m)$.

Algorithm Explanation

The linear merging algorithm alternates characters by maintaining two pointers, one for each string.

For each position in the result, take a character from the first string, then the second, if available.

After one string is exhausted, append the remaining characters from the other.

This is $O(n+m)$ time as each character is processed once, and the result string is built in a single pass.

Coding Part (with Unit Tests)

```
// Merges two strings alternately; caller frees.
char* mergeAlternately(const char* s1, const char* s2) {
    if (s1 == NULL || s2 == NULL) return strdup("");
    int len1 = strlen(s1), len2 = strlen(s2);
    char* result = (char*)malloc(len1 + len2 + 1);
    int i = 0, j = 0, k = 0;

    while (i < len1 && j < len2) { // Alternate characters
        result[k++] = s1[i++];
        result[k++] = s2[j++];
    }
    while (i < len1) result[k++] = s1[i++];
    while (j < len2) result[k++] = s2[j++];
    result[k] = '\0';
    return result;
}

// Unit tests
void testMergeAlternately() {
    char* result = mergeAlternately("abc", "pqr");
    assertEquals("apbqcr", result, "Test 80.1 - Normal case");
    free(result);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Allocate exact memory for result.
 - Validate inputs for NULL.
 - Handle unequal string lengths.
 - Free allocated memory in tests.
- **Expert Tips:**
 - Explain merging: "Alternate chars until one string ends, then append rest."
 - In interviews, clarify: "Ask if strings are guaranteed equal length."
 - Suggest optimization: "Precompute result length for allocation."
 - Test edge cases: "Empty strings, one empty, or different lengths."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for problems 71 to 80:\n");
    testLongestSubstringKDistinct();
    testIsHappy();
    testReverseStringRecursive();
    testMaxSumSubarrayK();
    testIsValidURL();
    testFirstRepeatingChar();
    testDecimalToOctal();
    testIsPangram();
    testMaxProductSubarray();
    testMergeAlternately();
    return 0;
}
```

Bit Manipulation

(70 Problems)

Problem 81: Toggle the nth Bit of a 32-bit Integer

Issue Description

Toggle the nth bit of a 32-bit integer (0-based indexing), e.g., number=10 (binary 1010), n=2 returns 14 (binary 1110).

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer, bit position n (0-31).
- **Output:** Integer with nth bit toggled.
- **Approach:** Use XOR with a mask to flip the nth bit.
- **Algorithm:** Bitwise XOR
 - **Explanation:** Create a mask with 1 at the nth position ($1 \ll n$).
 - XOR the number with this mask to toggle the nth bit (0 to 1 or 1 to 0).
- **Steps:**
 1. Validate n (0 to 31).
 2. Create mask ($1 \ll n$).
 3. XOR number with mask.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise XOR algorithm toggles a bit because XOR with 1 flips a bit ($0 \oplus 1 = 1$, $1 \oplus 1 = 0$), while XOR with 0 preserves it.

Shifting 1 left by n creates a mask with a 1 at position n and 0s elsewhere.

XORing the number with this mask flips only the nth bit, leaving others unchanged.

This is O(1) as it involves a single operation regardless of input size.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdbool.h>

// Toggles the nth bit of a 32-bit integer (0-based).
int toggleNthBit(int num, int n) {
    if (n < 0 || n > 31) return num; // Validate bit position
    return num ^ (1 << n); // XOR with mask to toggle nth bit
}

// Unit test helper
void assertIntEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testToggleNthBit() {
    assertIntEquals(14, toggleNthBit(10, 2), "Test 81.1 - Toggle bit 2 (1010 -> 1110)");
    assertIntEquals(10, toggleNthBit(14, 2), "Test 81.2 - Toggle back (1110 -> 1010)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate bit position to prevent undefined behavior.
 - Use unsigned int for clarity in bit operations.
 - Keep operations simple with single XOR.
 - Ensure 32-bit integer assumption is clear.
- **Expert Tips:**
 - Explain XOR: "XOR with 1 flips a bit; mask isolates the nth position."
 - In interviews, clarify: "Ask if n is 0-based or if negative numbers are handled."
 - Suggest optimization: "This is optimal; no further speedup possible."
 - Test edge cases: "n=0, n=31, or invalid n."

Problem 82: Check if a Number is a Power of 2 Using Bit Manipulation

Issue Description

Check if a number is a power of 2 (e.g., 4, 8, 16), e.g., 16 returns true, 10 returns false.

Problem Decomposition & Solution Steps

- **Input:** Non-negative integer.
- **Output:** Boolean.
- **Approach:** Use bit manipulation to check if only one bit is set.
- **Algorithm:** Bitwise AND
 - **Explanation:** A power of 2 has exactly one bit set (e.g., 16 = 10000).
 - Compute num & (num-1); if 0, only one bit was set.
- **Steps:**
 1. Validate non-positive input.
 2. Check if num & (num-1) == 0.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise AND algorithm leverages the fact that powers of 2 have a single 1 bit (e.g., 8 = 1000).

Subtracting 1 flips the rightmost 1 to 0 and sets all lower bits to 1 (e.g., 7 = 0111).

ANDing these results in 0 if only one bit was set, confirming a power of 2.

This is O(1) as it uses a single operation.

Coding Part (with Unit Tests)

```
// Checks if num is a power of 2.
bool isPowerOfTwo(int num) {
    if (num <= 0) return false; // Validate non-positive
    return (num & (num - 1)) == 0; // Check single set bit
}
```

```

// Unit test helper
void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testIsPowerOfTwo() {
    assertBoolEquals(true, isPowerOfTwo(16), "Test 82.1 - Power of 2 (16)");
    assertBoolEquals(false, isPowerOfTwo(10), "Test 82.2 - Not power of 2 (10)");
}

```

Best Practices & Expert Tips

1. Best Practices:

1. Handle non-positive numbers explicitly.
2. Use simple bitwise AND for efficiency.
3. Ensure clarity in bit operation logic.
4. Test edge cases like 0 and 1.

2. Expert Tips:

1. Explain bit pattern: "Power of 2 has one 1; num & (num-1) clears it."
2. In interviews, clarify: "Ask if 0 or negative numbers are valid."
3. Suggest alternative: "Count set bits; less efficient but viable."
4. Test edge cases: "0, 1, or negative numbers."

Problem 83: Count the Number of Set Bits in an Integer

Issue Description

Count the number of 1s in the binary representation of a 32-bit integer, e.g., 11 (binary 1011) returns 3.

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer.
- **Output:** Number of set bits.
- **Approach:** Use bit shifting and masking to count 1s.
- **Algorithm:** Brian Kernighan's Algorithm
 - **Explanation:** Repeatedly clear the least significant set bit using num & (num-1) until num becomes 0, counting iterations.
- **Steps:**
 1. Initialize count to 0.
 2. While num != 0, clear least set bit and increment count.
- **Complexity:** Time O(k) (k = number of 1s), Space O(1).

Algorithm Explanation

Brian Kernighan's algorithm is efficient for sparse bit patterns.

Each iteration of num & (num-1) clears the rightmost 1 (e.g., 1011 & 1010 = 1010).

The number of iterations equals the number of 1s.

This is faster than checking each bit (O(32)) for numbers with few 1s, and it's O(1) for 32-bit integers as k ≤ 32.

Coding Part (with Unit Tests)

```
// Counts number of set bits in num.
int countSetBits(int num) {
    int count = 0;
    while (num) { // Clear least significant set bit
        num &= (num - 1); // Brian Kernighan's method
        count++;
    }
    return count;
}

// Unit tests
void testCountSetBits() {
    assertEquals(3, countSetBits(11), "Test 83.1 - 11 (1011 has 3 bits)");
    assertEquals(0, countSetBits(0), "Test 83.2 - 0 (no bits)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use Brian Kernighan's algorithm for efficiency.
 - Handle signed integers (works for both).
 - Avoid checking all 32 bits explicitly.
 - Test with sparse and dense bit patterns.
- **Expert Tips:**
 - Explain algorithm: "num & (num-1) clears rightmost 1, count iterations."
 - In interviews, clarify: "Discuss signed vs. unsigned handling."
 - Suggest alternative: "Lookup table for 8-bit chunks, but more complex."
 - Test edge cases: "0, all 1s, or negative numbers."

Problem 84: Set the nth Bit of a Number to 1

Issue Description

Set the nth bit of a 32-bit integer to 1, e.g., num=10 (1010), n=1 returns 10 (1010, already 1), n=0 returns 11 (1011).

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer, bit position n (0-31).
- **Output:** Integer with nth bit set.
- **Approach:** Use OR with a mask to set the nth bit.
- **Algorithm:** Bitwise OR
 - **Explanation:** Create a mask with 1 at the nth position ($1 \ll n$).
 - OR the number with this mask to set the nth bit to 1 without affecting others.
- **Steps:**
 1. Validate n (0 to 31).
 2. Create mask ($1 \ll n$).
 3. OR number with mask.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise OR algorithm sets a bit because OR with 1 sets a bit to 1 ($0|1=1$, $1|1=1$), while OR with 0 preserves it.

Shifting 1 left by n creates a mask with a 1 at position n.

ORing with the number sets the nth bit, leaving others unchanged.

This is O(1) as it's a single operation.

Coding Part (with Unit Tests)

```
// Sets the nth bit of num to 1 (0-based).
int setNthBit(int num, int n) {
    if (n < 0 || n > 31) return num; // Validate bit position
    return num | (1 << n); // OR with mask to set nth bit
}

// Unit tests
void testSetNthBit() {
    assertEquals(11, setNthBit(10, 0), "Test 84.1 - Set bit 0 (1010 -> 1011)");
    assertEquals(10, setNthBit(10, 1), "Test 84.2 - Set bit 1 (already 1)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate bit position for safety.
 - Use unsigned int for clarity if needed.
 - Keep operation minimal with single OR.
 - Test edge cases like already set bits.
- **Expert Tips:**
 - Explain OR: "OR with 1 sets bit; mask isolates position."
 - In interviews, clarify: "Ask if n is 0-based or if validation is needed."
 - Suggest optimization: "This is optimal; no further speedup."
 - Test edge cases: "n=0, n=31, or invalid n."

Problem 85: Clear the nth Bit of a Number

Issue Description

Clear the nth bit of a 32-bit integer (set to 0), e.g., num=10 (1010), n=1 returns 8 (1000).

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer, bit position n (0-31).
- **Output:** Integer with nth bit cleared.
- **Approach:** Use AND with a mask to clear the nth bit.
- **Algorithm:** Bitwise AND
 - **Explanation:** Create a mask with 0 at the nth position and 1s elsewhere ($\sim(1 << n)$).

- AND the number with this mask to clear the nth bit.

- **Steps:**

1. Validate n (0 to 31).
 2. Create mask $\sim(1 \ll n)$.
 3. AND number with mask.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise AND algorithm clears a bit because AND with 0 sets a bit to 0 ($0\&0=0$, $1\&0=0$), while AND with 1 preserves it.

Shifting 1 left by n, then negating, creates a mask with 0 at position n and 1s elsewhere.

ANDing with the number clears the nth bit, leaving others unchanged.

This is O(1) as it's a single operation.

Coding Part (with Unit Tests)

```
// Clears the nth bit of num (0-based).
int clearNthBit(int num, int n) {
    if (n < 0 || n > 31) return num; // Validate bit position
    return num & ~(1 << n); // AND with mask to clear nth bit
}

// Unit tests
void testClearNthBit() {
    assertEquals(8, clearNthBit(10, 1), "Test 85.1 - Clear bit 1 (1010 -> 1000)");
    assertEquals(10, clearNthBit(10, 0), "Test 85.2 - Clear bit 0 (already 0)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate bit position to avoid errors.
 - Use clear mask ($\sim(1 \ll n)$) for precision.
 - Handle already cleared bits gracefully.
 - Ensure 32-bit integer context.
- **Expert Tips:**
 - Explain AND: "AND with 0 clears bit; mask isolates position."
 - In interviews, clarify: "Ask if validation for n is required."
 - Suggest optimization: "This is optimal; single operation."
 - Test edge cases: "n=0, n=31, or bit already 0."

Problem 86: Find the Single Number in an Array Where Every Element Appears Twice

Issue Description

In an array where every element appears twice except one, find the single number, e.g., [4,1,2,1,2] returns 4.

Problem Decomposition & Solution Steps

- **Input:** Array, size (odd, as one element is single).
- **Output:** Single number.
- **Approach:** Use XOR to cancel paired numbers.
- **Algorithm:** Bitwise XOR
 - **Explanation:** XOR all numbers; paired numbers cancel ($a \wedge a = 0$), leaving the single number.
- **Steps:**
 1. Validate input.
 2. XOR all elements in array.
 3. Return result.
- **Complexity:** Time $O(n)$, Space $O(1)$.

Algorithm Explanation

The bitwise XOR algorithm exploits the property that $a \wedge a = 0$ and $a \wedge 0 = a$.

XORing all numbers in the array causes each paired number to cancel out (resulting in 0), leaving only the single number.

This is $O(n)$ as each element is processed once, and $O(1)$ space as only one variable is needed.

Coding Part (with Unit Tests)

```
// Finds single number in array where others appear twice.
int singleNumber(int* arr, int size) {
    if (arr == NULL || size <= 0) return 0; // Validate input
    int result = 0;
    for (int i = 0; i < size; i++) { // XOR all elements
        result ^= arr[i]; // Paired numbers cancel
    }
    return result;
}

// Unit tests
void testSingleNumber() {
    int arr[] = {4, 1, 2, 1, 2};
    assertEquals(4, singleNumber(arr, 5), "Test 86.1 - Normal case");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate input for NULL or empty array.
 - Use XOR for $O(1)$ space solution.
 - Ensure array size is odd (per problem).
 - Test with minimal and large arrays.
- **Expert Tips:**
 - Explain XOR: "Paired numbers cancel; single number remains."
 - In interviews, clarify: "Ask if array is guaranteed to have pairs."
 - Suggest alternative: "Hash set is $O(n)$ space; XOR is optimal."
 - Test edge cases: "Single element, or large pairs."

Problem 87: Swap Two Bits in a Number at Given Positions

Issue Description

Swap the bits at positions i and j in a 32-bit integer, e.g., num=10 (1010), i=1, j=3 returns 6 (0110).

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer, positions i, j (0-31).
- **Output:** Integer with bits swapped.
- **Approach:** Check bit values, toggle if different.
- **Algorithm:** Bitwise XOR
 - **Explanation:** If bits at i and j differ, toggle both using XOR with a mask.
 - If same, no change needed.
- **Steps:**
 1. Validate i, j (0 to 31).
 2. Check bits at i and j.
 3. If different, toggle both using XOR.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise XOR algorithm checks if bits at positions i and j differ by extracting them ((num >> i) & 1).

If different, create a mask with 1s at i and j ($1 \ll i \mid 1 \ll j$) and XOR with the number to toggle both bits.

If bits are the same, return the number unchanged.

This is O(1) as it uses a fixed number of operations.

Coding Part (with Unit Tests)

```
// Swaps bits at positions i and j (0-based).
int swapBits(int num, int i, int j) {
    if (i < 0 || i > 31 || j < 0 || j > 31) return num; // Validate positions
    int bitI = (num >> i) & 1; // Get bit at i
    int bitJ = (num >> j) & 1; // Get bit at j
    if (bitI != bitJ) { // Swap only if different
        num ^= (1 << i) | (1 << j); // Toggle both bits
    }
    return num;
}

// Unit tests
void testSwapBits() {
    assertEquals(6, swapBits(10, 1, 3), "Test 87.1 - Swap bits 1,3 (1010 -> 0110)");
    assertEquals(10, swapBits(10, 1, 1), "Test 87.2 - Same position (no change)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate bit positions for safety.

- Check if swap is needed to avoid redundant operations.
 - Use XOR for efficient toggling.
 - Test with same and different bit values.
- **Expert Tips:**
 - Explain swap: "XOR toggles bits if they differ; mask targets i and j."
 - In interviews, clarify: "Ask if $i=j$ is valid or if validation is needed."
 - Suggest optimization: "This is optimal; single XOR if needed."
 - Test edge cases: " $i=j$, $i=0$, $j=31$, or same bits."

Problem 88: Check if a Number is Even or Odd Using Bit Manipulation

Issue Description

Determine if a number is even or odd using bit manipulation, e.g., 4 returns true (even), 7 returns false.

Problem Decomposition & Solution Steps

- **Input:** Integer.
- **Output:** Boolean (true for even).
- **Approach:** Check least significant bit (LSB).
- **Algorithm:** Bitwise AND
 - **Explanation:** The LSB is 0 for even numbers and 1 for odd.
 - Check $\text{num} \& 1$; if 0, number is even.
- **Steps:**
 1. Perform $\text{num} \& 1$.
 2. Return true if result is 0.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise AND algorithm checks the LSB because even numbers have $\text{LSB}=0$ (e.g., $4 = 100$) and odd numbers have $\text{LSB}=1$ (e.g., $7 = 111$).

ANDing with 1 isolates the LSB.

This is O(1) as it's a single operation, and it's more efficient than modulo ($\text{num} \% 2$) in some contexts due to direct bit access.

Coding Part (with Unit Tests)

```
// Checks if num is even using bit manipulation.
bool isEven(int num) {
    return (num & 1) == 0; // LSB is 0 for even
}

// Unit tests
void testIsEven() {
    assertEquals(true, isEven(4), "Test 88.1 - Even number (4)");
    assertEquals(false, isEven(7), "Test 88.2 - Odd number (7)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use simple num & 1 for clarity.
 - Handle negative numbers (works same way).
 - Avoid modulo for bit-level efficiency.
 - Test with positive and negative numbers.
- **Expert Tips:**
 - Explain LSB: "Even numbers have LSB=0; odd have LSB=1."
 - In interviews, clarify: "Discuss modulo vs. bit manipulation."
 - Suggest optimization: "This is optimal; single AND."
 - Test edge cases: "0, negative numbers, or large integers."

Problem 89: Find the XOR of All Numbers in an Array

Issue Description

Compute the XOR of all numbers in an array, e.g., [4,2,3] returns 5 (4^2^3).

Problem Decomposition & Solution Steps

- **Input:** Array, size.
- **Output:** XOR result.
- **Approach:** Iterate and XOR all elements.
- **Algorithm:** Bitwise XOR
 - **Explanation:** XOR all numbers in sequence; order doesn't matter due to associativity.
- **Steps:**
 1. Validate input.
 2. Initialize result to 0.
 3. XOR each element with result.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The bitwise XOR algorithm accumulates the XOR of all elements by iterating through the array.

Since XOR is associative and commutative, the order of operations doesn't matter, and 0 is the identity ($a^0=a$).

Each element is XORed once, making it O(n) time, and only one variable is used, ensuring O(1) space.

Coding Part (with Unit Tests)

```
// Computes XOR of all numbers in array.
int xorOfArray(int* arr, int size) {
    if (arr == NULL || size <= 0) return 0; // Validate input
    int result = 0;
    for (int i = 0; i < size; i++) { // XOR each element
        result ^= arr[i];
    }
    return result; }
```

```
// Unit tests
void testXorOfArray() {
    int arr[] = {4, 2, 3};
    assertEquals(5, xorOfArray(arr, 3), "Test 89.1 - Normal case (4^2^3=5)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate input for NULL or empty array.
 - Initialize result to 0 (XOR identity).
 - Use single variable for O(1) space.
 - Test with various array sizes.
- **Expert Tips:**
 - Explain XOR: "Each element contributes to final result; pairs cancel."
 - In interviews, clarify: "Ask if empty array returns 0."
 - Suggest optimization: "This is optimal; single pass."
 - Test edge cases: "Single element, empty array, or all zeros."

Problem 90: Reverse the Bits of a 32-bit Integer

Issue Description

Reverse the bits of a 32-bit integer, e.g., 43261596 (0000001010010100000111010011100) returns 964176192 (00111001011110000010100101000000).

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer.
- **Output:** Integer with bits reversed.
- **Approach:** Shift and build result bit by bit.
- **Algorithm:** Bit Reversal
 - **Explanation:** Extract each bit from the input, shift it to the opposite position, and build the result.
- **Steps:**
 1. Initialize result to 0.
 2. For each bit (0 to 31), extract, shift, and set in result.
- **Complexity:** Time O(1) (fixed 32 iterations), Space O(1).

Algorithm Explanation

The bit reversal algorithm processes each of the 32 bits.

For bit i (0-based), extract it using $(\text{num} \gg i) \& 1$, then shift it to position $31-i$ in the result using $(\text{bit} \ll (31-i))$.

OR the result to accumulate bits.

This is O(1) for 32-bit integers as the loop is fixed at 32 iterations, and no extra space is needed beyond the result variable.

Coding Part (with Unit Tests)

```
// Reverses bits of a 32-bit integer.
unsigned int reverseBits(unsigned int num) {
    unsigned int result = 0;
    for (int i = 0; i < 32; i++) { // Process each bit
        result |= ((num >> i) & 1) << (31 - i); // Extract bit i, place at 31-i
    }
    return result;
}

// Unit tests
void testReverseBits() {
    assertEquals(964176192, reverseBits(43261596), "Test 90.1 - Normal case");
    assertEquals(0, reverseBits(0), "Test 90.2 - All zeros");
}
```

Best Practices & Expert Tips

- **Best Practices:**

- Use unsigned int to avoid sign issues.
- Process all 32 bits explicitly.
- Use OR to accumulate reversed bits.
- Test with sparse and dense bit patterns.

- **Expert Tips:**

- Explain reversal: "Shift bit i to position 31-i; OR to build result."
- In interviews, clarify: "Ask if unsigned is required."
- Suggest optimization: "Lookup table for 8-bit chunks, but loop is clear."
- Test edge cases: "All 0s, all 1s, or alternating bits."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for bit manipulation problems 81 to 90:\n");
    testToggleNthBit();
    testIsPowerOfTwo();
    testCountSetBits();
    testSetNthBit();
    testClearNthBit();
    testSingleNumber();
    testSwapBits();
    testIsEven();
    testXorOfArray();
    testReverseBits();
    return 0;
}
```

Problem 91: Find the Parity of a Number (Odd/Even Number of 1s)

Issue Description

Determine if the number of 1s in the binary representation of a 32-bit integer is odd or even (odd parity returns 1, even returns 0), e.g., 11 (1011, 3 ones) returns 1.

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer.
- **Output:** Integer (1 for odd parity, 0 for even).
- **Approach:** Use XOR to count set bits modulo 2.
- **Algorithm:** Bitwise XOR Reduction
 - **Explanation:** XOR all bits of the number; the result is 1 if the number of 1s is odd, 0 if even.
 - Use bit shifting to process each bit.
- **Steps:**
 1. Initialize result to 0.
 2. For each bit, XOR with result.
 3. Return final result.
- **Complexity:** Time O(1) (fixed 32 bits), Space O(1).

Algorithm Explanation

The bitwise XOR reduction algorithm computes parity by XORing all bits.

Since XOR of two bits is 1 if they differ, XORing all bits yields 1 for an odd number of 1s (e.g., 1011: $1 \wedge 0 \wedge 1 \wedge 1 = 1$) and 0 for even (e.g., 1010: $1 \wedge 0 \wedge 1 \wedge 0 = 0$).

We shift and check each bit, making it O(1) for 32-bit integers as the loop is fixed at 32 iterations.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdbool.h>

// Returns 1 if number of 1s is odd, 0 if even.
int parity(int num) {
    int result = 0;
    for (int i = 0; i < 32; i++) { // Check each bit
        result ^= (num >> i) & 1; // XOR bit i with result
    }
    return result;
}

// Unit test helper
void assertIntEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testParity() {
    assertIntEquals(1, parity(11), "Test 91.1 - Odd parity (1011, 3 ones)");
    assertIntEquals(0, parity(10), "Test 91.2 - Even parity (1010, 2 ones)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Process all 32 bits for consistency.
 - Use XOR for efficient parity computation.
 - Handle signed integers (parity is same).
 - Test with sparse and dense bit patterns.

- **Expert Tips:**

- Explain XOR: "Each 1 bit flips result; final value is parity."
- In interviews, clarify: "Ask if Brian Kernighan's method is preferred."
- Suggest optimization: "Use num ^= num >> 16; num ^= num >> 8; etc., for fewer ops."
- Test edge cases: "0, all 1s, or negative numbers."

Problem 92: Get the Value of the nth Bit

Issue Description

Return the value (0 or 1) of the nth bit in a 32-bit integer (0-based), e.g., num=10 (1010), n=1 returns 1.

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer, bit position n (0-31).
- **Output:** Integer (0 or 1).
- **Approach:** Shift and mask to extract nth bit.
- **Algorithm:** Bitwise Shift and Mask
 - **Explanation:** Shift number right by n, then AND with 1 to get the nth bit.
- **Steps:**
 1. Validate n (0 to 31).
 2. Shift num right by n.
 3. AND with 1 to get bit value.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise shift and mask algorithm isolates the nth bit by shifting the number right n times, moving the nth bit to position 0, then ANDing with 1 to extract it (e.g., $1010 \gg 1 = 0101$, $0101 \& 1 = 1$).

This is O(1) as it uses a single shift and AND operation, regardless of input size.

Coding Part (with Unit Tests)

```
// Returns value of nth bit (0-based).
int getNthBit(int num, int n) {
    if (n < 0 || n > 31) return 0; // Validate bit position
    return (num >> n) & 1; // Shift and mask to get nth bit
}

// Unit tests
void testGetNthBit() {
    assertEquals(1, getNthBit(10, 1), "Test 92.1 - Bit 1 of 10 (1010)");
    assertEquals(0, getNthBit(10, 0), "Test 92.2 - Bit 0 of 10 (1010)");
}
```

Best Practices & Expert Tips

- **Best Practices:**

- Validate bit position to prevent errors.
- Use simple shift and mask for clarity.
- Return 0 for invalid n.

- Test edge bits (0 and 31).
- **Expert Tips:**
 - Explain shift: "Shift nth bit to LSB, mask with 1 to extract."
 - In interviews, clarify: "Ask if n is 0-based or if validation is needed."
 - Suggest optimization: "This is optimal; single operation."
 - Test edge cases: "n=0, n=31, or invalid n."

Problem 93: Find Two Numbers in an Array That Appear Only Once (Others Appear Twice)

Issue Description

In an array where all elements appear twice except two, find the two single numbers, e.g., [1,2,1,3,2,5] returns [3,5].

Problem Decomposition & Solution Steps

- **Input:** Array, size.
- **Output:** Array of two integers (caller frees).
- **Approach:** Use XOR to find single numbers, then partition based on a differing bit.
- **Algorithm:** Bitwise XOR and Partition
 - **Explanation:** XOR all numbers to get XOR of the two single numbers.
 - Find a set bit in this XOR to partition numbers into two groups, then XOR each group to find the numbers.
- **Steps:**
 1. Validate input.
 2. XOR all elements to get $x = a \oplus b$ (a, b are single numbers).
 3. Find rightmost set bit in x .
 4. Partition numbers by this bit and XOR each group.
- **Complexity:** Time $O(n)$, Space $O(1)$.

Algorithm Explanation

The bitwise XOR and partition algorithm works because XORing all numbers cancels pairs ($a \oplus a = 0$), leaving $x = a \oplus b$.

Since $a \neq b$, x has at least one set bit.

We use the rightmost set bit ($x \& -x$) to partition numbers into two groups: those with that bit set and those without.

XORing each group separately cancels pairs, yielding a and b .

This is $O(n)$ as it requires two passes, and $O(1)$ space (excluding output).

Coding Part (with Unit Tests)

```
#include <stdlib.h>

// Finds two numbers appearing once; caller frees result.
int* singleNumberTwo(int* arr, int size, int* returnSize) {
    if (arr == NULL || size < 2) { // Validate input
        *returnSize = 0;
        return NULL;
    }
    int x = 0;
    for (int i = 0; i < size; i++) x ^= arr[i]; // XOR all numbers
    int rightmost = x & -x; // Get rightmost set bit
    int* result = (int*)malloc(2 * sizeof(int));
    result[0] = 0; result[1] = 0;
    for (int i = 0; i < size; i++) { // Partition and XOR
        if (arr[i] & rightmost) result[0] ^= arr[i]; // Bit set
        else result[1] ^= arr[i]; // Bit not set
    }
    *returnSize = 2;
    return result;
}

// Unit tests
void testSingleNumberTwo() {
    int arr[] = {1, 2, 1, 3, 2, 5};
    int returnSize;
    int* result = singleNumberTwo(arr, 6, &returnSize);
    bool pass = returnSize == 2 && ((result[0] == 3 && result[1] == 5) || (result[0] == 5 && result[1] == 3));
    printf("Test 93.1 - Normal case: %s\n", pass ? "PASSED" : "FAILED");
    free(result);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate input for size and NULL.
 - Use $x \& -x$ for rightmost set bit.
 - Free allocated memory in tests.
 - Handle order-agnostic output.
- **Expert Tips:**
 - Explain partitioning: "XOR gives $a \oplus b$; partition by set bit to isolate a and b ."
 - In interviews, clarify: "Ask if output order matters."
 - Suggest alternative: "Hash set is $O(n)$ space; this is optimal."
 - Test edge cases: "Minimal array, large numbers, or negatives."

Problem 94: Rotate Bits of a Number Left by k Positions

Issue Description

Rotate the bits of a 32-bit integer left by k positions, e.g., num=10 (1010), $k=2$ returns 40 (101000, rotated left).

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer, k.
- **Output:** Integer with bits rotated left.
- **Approach:** Shift left and wrap around using OR.
- **Algorithm:** Bitwise Shift and OR
 - **Explanation:** Shift num left by k, then OR with num right-shifted by (32-k) to wrap bits.
- **Steps:**
 1. Normalize k ($k \% 32$).
 2. Shift left by k, right by $32 - k$.
 3. OR results to combine.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise shift and OR algorithm performs a left rotation by splitting the number into two parts: bits shifted left by k and bits that wrap around (shifted right by $32 - k$).

ORing these combines the rotated bits.

Normalizing k ($k \% 32$) handles large k values, ensuring correctness for 32-bit integers.

This is O(1) as it uses fixed operations.

Coding Part (with Unit Tests)

```
// Rotates bits of num left by k positions.
unsigned int rotateLeft(int num, int k) {
    k = k % 32; // Normalize k
    return (num << k) | (num >> (32 - k)); // Shift left and wrap
}

// Unit tests
void testRotateLeft() {
    assertEquals(40, rotateLeft(10, 2), "Test 94.1 - Rotate 10 (1010) left by 2");
    assertEquals(10, rotateLeft(10, 0), "Test 94.2 - No rotation (k=0)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use unsigned int to avoid sign issues.
 - Normalize k to handle large values.
 - Combine shifts with OR for rotation.
 - Test with k=0 and k=32.
- **Expert Tips:**
 - Explain rotation: "Left shift k, wrap bits with right shift $32 - k$."
 - In interviews, clarify: "Ask if k can be negative or large."
 - Suggest optimization: "This is optimal; single operation."
 - Test edge cases: "k=0, k=32, or negative k."

Problem 95: Rotate Bits of a Number Right by k Positions

Issue Description

Rotate the bits of a 32-bit integer right by k positions, e.g., num=10 (1010), k=2 returns 2 (0010).

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer, k.
- **Output:** Integer with bits rotated right.
- **Approach:** Shift right and wrap around using OR.
- **Algorithm:** Bitwise Shift and OR
 - **Explanation:** Shift num right by k, then OR with num left-shifted by (32-k) to wrap bits.
- **Steps:**
 1. Normalize k ($k \% 32$).
 2. Shift right by k, left by 32-k.
 3. OR results to combine.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise shift and OR algorithm for right rotation mirrors left rotation.

Shift the number right by k, moving bits to lower positions, and shift left by 32-k to wrap bits to the high end.

ORing combines them.

Normalizing k ensures correctness for large values.

This is O(1) as it uses fixed operations for 32-bit integers.

Coding Part (with Unit Tests)

```
// Rotates bits of num right by k positions.
unsigned int rotateRight(int num, int k) {
    k = k % 32; // Normalize k
    return (num >> k) | (num << (32 - k)); // Shift right and wrap
}

// Unit tests
void testRotateRight() {
    assertEquals(2, rotateRight(10, 2), "Test 95.1 - Rotate 10 (1010) right by 2");
    assertEquals(10, rotateRight(10, 0), "Test 95.2 - No rotation (k=0)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use unsigned int for clarity.
 - Normalize k to handle large values.
 - Combine shifts with OR for rotation.
 - Test with k=0 and k=32.

- **Expert Tips:**

- Explain rotation: "Right shift k, wrap bits with left shift $32-k$."
- In interviews, clarify: "Ask if k can be negative or large."
- Suggest optimization: "This is optimal; single operation."
- Test edge cases: "k=0, k=32, or negative k."

Problem 96: Check if Two Numbers Have Opposite Signs

Issue Description

Check if two integers have opposite signs (one positive, one negative), e.g., 5, -3 returns true.

Problem Decomposition & Solution Steps

- **Input:** Two integers.
- **Output:** Boolean.
- **Approach:** Use XOR to check sign bits.
- **Algorithm:** Bitwise XOR
 - **Explanation:** XOR the numbers; if the result is negative, signs differ (since sign bit is 1).
- **Steps:**
 1. Compute $\text{num1} \wedge \text{num2}$.
 2. Return true if result < 0 .
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise XOR algorithm checks signs because XORing two numbers with different sign bits produces a negative result.

For 32-bit integers, the sign bit (31) is 0 for positive and 1 for negative.

If num1 and num2 have opposite signs, their XOR has a 1 in the sign bit, making it negative.

This is O(1) as it's a single operation.

Coding Part (with Unit Tests)

```
// Checks if num1 and num2 have opposite signs.
bool oppositeSigns(int num1, int num2) {
    return (num1 ^ num2) < 0; // Negative if signs differ
}

// Unit tests
void testOppositeSigns() {
    assertEquals(true, oppositeSigns(5, -3), "Test 96.1 - Opposite signs");
    assertEquals(false, oppositeSigns(5, 3), "Test 96.2 - Same signs");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use XOR for efficient sign check.
 - Handle zero correctly (0 has no sign).
 - Keep logic simple and clear.
 - Test with positive, negative, and zero.
- **Expert Tips:**
 - Explain XOR: "Different signs produce negative XOR due to sign bit."
 - In interviews, clarify: "Ask if 0 is considered positive."
 - Suggest alternative: "Check sign bits directly, but XOR is simpler."
 - Test edge cases: "0, same signs, or large numbers."

Problem 97: Find the Next Power of 2 for a Given Number

Issue Description

Find the smallest power of 2 greater than or equal to a given number, e.g., 6 returns 8.

Problem Decomposition & Solution Steps

- **Input:** Positive integer.
- **Output:** Next power of 2.
- **Approach:** Use bit manipulation to set all bits after the highest 1.
- **Algorithm:** Bit Manipulation
 - **Explanation:** Find the highest set bit, then set all lower bits to get the next power of 2.
- **Steps:**
 1. Validate input.
 2. Decrement num to handle powers of 2.
 3. Set all bits after highest 1 using shifts.
 4. Add 1 to get next power.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bit manipulation algorithm works by decrementing num (to handle cases where num is a power of 2), then using a series of OR operations to set all bits to the right of the highest 1 bit (e.g., for 6=110, set to 111).

Adding 1 gives the next power of 2 (1000=8).

This is O(1) as it uses a fixed number of operations for 32-bit integers.

Coding Part (with Unit Tests)

```
// Finds next power of 2 >= num.
unsigned int nextPowerOfTwo(int num) {
    if (num <= 0) return 1; // Validate input
    num--; // Handle case where num is power of 2
    num |= num >> 1; // Set bits to right of highest 1
    num |= num >> 2;
    num |= num >> 4;
    num |= num >> 8;
    num |= num >> 16;
    return num + 1; // Next power of 2
}

// Unit tests
void testNextPowerOfTwo() {
    assertEquals(8, nextPowerOfTwo(6), "Test 97.1 - Next power for 6");
    assertEquals(8, nextPowerOfTwo(8), "Test 97.2 - Next power for 8");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle non-positive inputs (return 1).
 - Use unsigned int for clarity.
 - Test with powers of 2 and non-powers.
 - Ensure all bits are set correctly.
- **Expert Tips:**
 - Explain bit setting: "OR with right-shifted num to fill bits, then add 1."
 - In interviews, clarify: "Ask if 0 or negative inputs are valid."
 - Suggest alternative: "Logarithmic math, but bit manipulation is faster."
 - Test edge cases: "0, 1, or large numbers."

Problem 98: Set Bits in a Range [i, j]

Issue Description

Set all bits in the range [i, j] (0-based) of a 32-bit integer to 1, e.g., num=10 (1010), i=0, j=2 returns 15 (1111).

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer, positions i, j (0-31).
- **Output:** Integer with bits i to j set.
- **Approach:** Create a mask with 1s in range [i, j] and OR with num.
- **Algorithm:** Bitwise OR with Mask
 - **Explanation:** Create a mask with 1s from i to j using shifts, then OR with num to set bits.
- **Steps:**
 1. Validate i, j (0 to 31, i <= j).
 2. Create mask with 1s in range [i, j].
 3. OR num with mask.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise OR with mask algorithm creates a mask with 1s from position i to j.

For a 32-bit integer, shift 1 left by $j+1$, subtract 1 to get 1s up to j, then shift left by i to align, and right shift to clear higher bits.

ORing with num sets the bits in the range.

This is O(1) as it uses fixed operations.

Coding Part (with Unit Tests)

```
// Sets bits in range [i, j] to 1 (0-based).
int setBitsInRange(int num, int i, int j) {
    if (i < 0 || j > 31 || i > j) return num; // Validate range
    unsigned int mask = ((1U << (j - i + 1)) - 1) << i; // Create mask with 1s in [i, j]
    return num | mask; // Set bits
}

// Unit tests
void testSetBitsInRange() {
    assertEquals(15, setBitsInRange(10, 0, 2), "Test 98.1 - Set bits 0-2 (1010 -> 1111)");
    assertEquals(10, setBitsInRange(10, 1, 1), "Test 98.2 - Single bit");
}
```

Best Practices & Expert Tips

- **Best Practices:**

- Validate range for correctness.
- Use unsigned int for mask to avoid sign issues.
- Ensure mask aligns with range [i, j].
- Test with single-bit and full ranges.

- **Expert Tips:**

- Explain mask: " $(1 << (j-i+1)) - 1$ gives 1s, shift left by i."
- In interviews, clarify: "Ask if $i > j$ or negative indices are valid."
- Suggest optimization: "This is optimal; single OR."
- Test edge cases: " $i=j$, $i=0$, $j=31$, or invalid range."

Problem 99: Clear Bits in a Range [i, j]

Issue Description

Clear all bits in the range [i, j] (0-based) of a 32-bit integer, e.g., num=15 (1111), i=1, j=2 returns 9 (1001).

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer, positions i, j (0-31).
- **Output:** Integer with bits i to j cleared.
- **Approach:** Create a mask with 0s in range [i, j] and AND with num.

- **Algorithm:** Bitwise AND with Mask
 - **Explanation:** Create a mask with 0s from i to j and 1s elsewhere, then AND with num to clear bits.
- **Steps:**
 1. Validate i, j (0 to 31, i <= j).
 2. Create mask with 0s in [i, j].
 3. AND num with mask.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise AND with mask algorithm creates a mask with 0s in the range [i, j] by inverting a mask with 1s in that range.

Compute 1s up to j ($1 << (j+1) - 1$), shift left by i, and invert to get 0s in [i, j].

ANDing with num clears the bits in the range.

This is O(1) as it uses fixed operations.

Coding Part (with Unit Tests)

```
// Clears bits in range [i, j] (0-based).
int clearBitsInRange(int num, int i, int j) {
    if (i < 0 || j > 31 || i > j) return num; // Validate range
    unsigned int mask = ~((1U << (j - i + 1)) - 1) << i; // Mask with 0s in [i, j]
    return num & mask; // Clear bits
}

// Unit tests
void testClearBitsInRange() {
    assertEquals(9, clearBitsInRange(15, 1, 2), "Test 99.1 - Clear bits 1-2 (1111 -> 1001)");
    assertEquals(15, clearBitsInRange(15, 0, 0), "Test 99.2 - Single bit");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate range for correctness.
 - Use unsigned int for mask to avoid sign issues.
 - Ensure mask has 0s only in [i, j].
 - Test with single-bit and full ranges.
- **Expert Tips:**
 - Explain mask: "Invert 1s in range [i, j] to get 0s, then AND."
 - In interviews, clarify: "Ask if i > j or negative indices are valid."
 - Suggest optimization: "This is optimal; single AND."
 - Test edge cases: "i=j, i=0, j=31, or invalid range."

Problem 100: Find the Number of Bits to Flip to Convert One Number to Another

Issue Description

Count the number of bits to flip to convert one 32-bit integer to another, e.g., a=10 (1010), b=7 (0111) returns 2 (flip bits 0 and 3).

Problem Decomposition & Solution Steps

- **Input:** Two 32-bit integers.
- **Output:** Number of bits to flip.
- **Approach:** XOR numbers and count set bits.
- **Algorithm:** Bitwise XOR and Count
 - **Explanation:** XOR a and b to get bits that differ, then count 1s using Brian Kernighan's method.
- **Steps:**
 1. Compute $a \wedge b$ to get differing bits.
 2. Count set bits in result.
- **Complexity:** Time $O(k)$ ($k = \text{number of 1s}$), Space $O(1)$.

Algorithm Explanation

The bitwise XOR and count algorithm uses XOR to identify differing bits ($a \wedge b$ gives 1 where bits differ).

Counting these 1s (using $\text{num} \& (\text{num}-1)$) gives the number of flips needed.

This is $O(k)$ where k is the number of differing bits (≤ 32), making it effectively $O(1)$ for 32-bit integers, with $O(1)$ space.

Coding Part (with Unit Tests)

```
// Counts bits to flip to convert a to b.
int bitsToFlip(int a, int b) {
    int diff = a ^ b; // Get differing bits
    int count = 0;
    while (diff) { // Count set bits
        diff &= (diff - 1); // Brian Kernighan's method
        count++;
    }
    return count;
}

// Unit tests
void testBitsToFlip() {
    assertEquals(2, bitsToFlip(10, 7), "Test 100.1 - 10 to 7 (1010 -> 0111)");
    assertEquals(0, bitsToFlip(10, 10), "Test 100.2 - Same number");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use XOR to find differing bits.
 - Use Brian Kernighan's method for counting.
 - Handle same numbers (0 flips).

- Test with identical and opposite bit patterns.
- **Expert Tips:**
 - Explain XOR: " $a \oplus b$ gives 1s where bits differ; count them."
 - In interviews, clarify: "Ask if signed integers need special handling."
 - Suggest optimization: "Lookup table for 8-bit chunks, but loop is clear."
 - Test edge cases: "Same numbers, all bits differ, or negatives."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for bit manipulation problems 91 to 100:\n");
    testParity();
    testGetNthBit();
    testSingleNumberTwo();
    testRotateLeft();
    testRotateRight();
    testOppositeSigns();
    testNextPowerOfTwo();
    testSetBitsInRange();
    testClearBitsInRange();
    testBitsToFlip();
    return 0;
}
```

Problem 101: Check if a Number is a Power of 4

Issue Description

Determine if a number is a power of 4 (e.g., 4, 16, 64), e.g., 16 returns true, 8 returns false.

Problem Decomposition & Solution Steps

- **Input:** Non-negative integer.
- **Output:** Boolean.
- **Approach:** Check if the number is a power of 2 and has a 1 bit in an even position.
- **Algorithm:** Bitwise AND and Position Check
 - **Explanation:** A power of 4 is a power of 2 (single 1 bit) with the 1 in an even position (0, 2, 4, ...).
 - First check if num is a power of 2 ($num \& (num-1) == 0$), then verify the 1 bit's position is even.
- **Steps:**
 1. Validate non-positive input.
 2. Check if power of 2 using $num \& (num-1) == 0$.
 3. Count trailing zeros; must be even.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise AND and position check algorithm first ensures the number is a power of 2 ($num \& (num-1) == 0$), as powers of 4 are a subset of powers of 2.

Then, check if the 1 bit is in an even position by counting trailing zeros ($num \& -num$ gives the least significant 1; count zeros with a loop or log).

If the count is even, it's a power of 4.

This is O(1) for 32-bit integers as operations are fixed.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdbool.h>

// Checks if num is a power of 4.
bool isPowerOfFour(int num) {
    if (num <= 0 || (num & (num - 1)) != 0) return false; // Not power of 2
    int pos = 0;
    while (num > 1) { // Count trailing zeros
        num >>= 1;
        pos++;
    }
    return (pos % 2) == 0; // Even position for 1 bit
}

// Unit test helper
void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testIsPowerOfFour() {
    assertBoolEquals(true, isPowerOfFour(16), "Test 101.1 - Power of 4 (16)");
    assertBoolEquals(false, isPowerOfFour(8), "Test 101.2 - Not power of 4 (8)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate non-positive inputs.
 - Use $\text{num} \& (\text{num}-1)$ for power of 2 check.
 - Check position of 1 bit explicitly.
 - Test with powers of 2 and 4.
- **Expert Tips:**
 - Explain position check: "Powers of 4 have 1 bit in even positions (0, 2, 4, ...)."
 - In interviews, clarify: "Ask if alternative methods (e.g., $\text{num} \& 0x55555555$) are preferred."
 - Suggest optimization: "Use mask 0x55555555 to check even bits directly."
 - Test edge cases: "0, 1, or non-powers of 2."

Problem 102: Find the Most Significant Set Bit in a Number

Issue Description

Find the position of the most significant (leftmost) 1 bit in a 32-bit integer (0-based), e.g., 10 (1010) returns 3.

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer.
- **Output:** Position of most significant 1 bit, or -1 if none.
- **Approach:** Shift right until num becomes 0, tracking position.

- **Algorithm:** Bitwise Shift and Count
 - **Explanation:** Right-shift the number until it becomes 0, counting shifts.
 - The last position with a 1 is the answer.
- **Steps:**
 1. Validate input (0 returns -1).
 2. Shift right, count until num is 0.
 3. Return last position with 1.
- **Complexity:** Time O(1) (max 32 shifts), Space O(1).

Algorithm Explanation

The bitwise shift and count algorithm finds the leftmost 1 by shifting right and counting iterations.

For a 32-bit integer, the maximum number of shifts is 31 (for 1 in position 31).

The position is 31 minus the number of shifts needed to make num 0, or we can track the position of the last 1 seen.

This is O(1) as it's bounded by 32 iterations.

Coding Part (with Unit Tests)

```
// Returns position of most significant 1 bit (0-based), or -1 if none.
int mostSignificantBit(int num) {
    if (num == 0) return -1; // No set bits
    int pos = 0;
    while (num) { // Shift until 0
        num >>= 1;
        pos++;
    }
    return pos - 1; // Last position with 1
}

// Unit test helper
void assertEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testMostSignificantBit() {
    assertEquals(3, mostSignificantBit(10), "Test 102.1 - MSB of 10 (1010)");
    assertEquals(-1, mostSignificantBit(0), "Test 102.2 - No set bits");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle 0 explicitly (no set bits).
 - Use simple shift loop for clarity.
 - Ensure 0-based indexing.
 - Test with sparse and dense numbers.
- **Expert Tips:**
 - Explain shift: "Right-shift counts positions until 0; last 1 is MSB."
 - In interviews, clarify: "Ask if 0-based or if negative numbers are handled."
 - Suggest optimization: "Binary search or log-based methods, but loop is clear."

- Test edge cases: "0, 1, or all 1s."

Problem 103: Add Two Numbers Using Bit Manipulation

Issue Description

Add two integers without using arithmetic operators (+), e.g., 5 and 3 returns 8.

Problem Decomposition & Solution Steps

- **Input:** Two 32-bit integers.
- **Output:** Sum of the numbers.
- **Approach:** Use XOR for sum, AND and shift for carry.
- **Algorithm:** Bitwise Addition
 - **Explanation:** XOR computes sum without carry; AND and left-shift compute carry.
 - Repeat until carry is 0.
- **Steps:**
 1. Compute sum without carry ($a \wedge b$).
 2. Compute carry ($((a \& b) \ll 1)$).
 3. Repeat until carry is 0.
- **Complexity:** Time O(1) (max 32 iterations), Space O(1).

Algorithm Explanation

The bitwise addition algorithm mimics manual addition.

XOR ($a \wedge b$) gives the sum of bits without carry ($0+0=0$, $1+0=1$, $1+1=0$).

AND ($a \& b$) identifies carry bits, shifted left by 1.

Add the carry to the sum (repeat XOR and AND) until no carry remains.

For 32-bit integers, this takes at most 32 iterations, making it O(1).

Coding Part (with Unit Tests)

```
// Adds two numbers using bit manipulation.
int addNumbers(int a, int b) {
    while (b != 0) { // Repeat until no carry
        int sum = a ^ b; // Sum without carry
        int carry = (a & b) << 1; // Carry shifted left
        a = sum;
        b = carry;
    }
    return a;
}

// Unit tests
void testAddNumbers() {
    assertEquals(8, addNumbers(5, 3), "Test 103.1 - Add 5 and 3");
    assertEquals(0, addNumbers(0, 0), "Test 103.2 - Add 0 and 0");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle carry loop until 0.
 - Use XOR and AND for clarity.
 - Test with positive and negative numbers.
 - Ensure 32-bit integer context.
- **Expert Tips:**
 - Explain addition: "XOR for sum, AND for carry, repeat until carry is 0."
 - In interviews, clarify: "Ask if negative numbers or overflow are concerns."
 - Suggest optimization: "This is optimal for bit-based addition."
 - Test edge cases: "0, negative numbers, or large sums."

Problem 104: Check if a Number is a Palindrome in Binary

Issue Description

Check if the binary representation of a number is a palindrome, e.g., 9 (1001) returns true, 10 (1010) returns false.

Problem Decomposition & Solution Steps

- **Input:** Non-negative integer.
- **Output:** Boolean.
- **Approach:** Reverse bits and compare with original.
- **Algorithm:** Bit Reversal and Comparison
 - **Explanation:** Reverse the bits of the number and check if equal to original.
 - Ignore leading zeros in comparison.
- **Steps:**
 1. Validate non-negative input.
 2. Reverse bits using shift and OR.
 3. Compare reversed with original.
- **Complexity:** Time O(1) (32 bits), Space O(1).

Algorithm Explanation

The bit reversal and comparison algorithm reverses the 32-bit number by extracting each bit and building the result from the opposite end.

For palindrome checking, compare the reversed number with the original.

Leading zeros are implicit in the integer, so we focus on the significant bits.

This is O(1) for 32-bit integers as it uses a fixed number of operations.

Coding Part (with Unit Tests)

```
// Checks if binary representation is a palindrome.
bool isBinaryPalindrome(int num) {
    if (num < 0) return false; // Validate input
    unsigned int reversed = 0, temp = num;
    for (int i = 0; i < 32; i++) { // Reverse bits
        reversed = (reversed << 1) | (temp & 1);
        temp >>= 1;
    }
    return num == reversed; // Compare with original
}

// Unit tests
void testIsBinaryPalindrome() {
    assertBoolEquals(true, isBinaryPalindrome(9), "Test 104.1 - Palindrome (9=1001)");
    assertBoolEquals(false, isBinaryPalindrome(10), "Test 104.2 - Not palindrome (10=1010)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use unsigned int for reversal to avoid sign issues.
 - Validate negative inputs.
 - Compare full 32-bit numbers.
 - Test with palindromic and non-palindromic numbers.
- **Expert Tips:**
 - Explain reversal: "Build reversed number bit by bit, then compare."
 - In interviews, clarify: "Ask if leading zeros affect palindrome."
 - Suggest optimization: "Trim leading zeros, but full reversal is simpler."
 - Test edge cases: "0, 1, or large palindromes."

Problem 105: Find the Hamming Distance Between Two Integers

Issue Description

Compute the Hamming distance (number of differing bits) between two integers, e.g., 1 (001) and 4 (100) returns 2.

Problem Decomposition & Solution Steps

- **Input:** Two 32-bit integers.
- **Output:** Number of differing bits.
- **Approach:** XOR numbers and count set bits.
- **Algorithm:** Bitwise XOR and Count
 - **Explanation:** XOR the numbers to get bits that differ, then count 1s using Brian Kernighan's method.
- **Steps:**
 1. Compute $a \wedge b$ to get differing bits.
 2. Count set bits in result.
- **Complexity:** Time O(1) (max 32 bits), Space O(1).

Algorithm Explanation

The bitwise XOR and count algorithm uses XOR to identify differing bits (1 where bits differ).

Counting these 1s with Brian Kernighan's method ($\text{num} \& (\text{num}-1)$) gives the Hamming distance.

This is $O(1)$ for 32-bit integers as the number of set bits is at most 32, and it uses constant space.

Coding Part (with Unit Tests)

```
// Computes Hamming distance between two integers.
int hammingDistance(int a, int b) {
    int diff = a ^ b; // Get differing bits
    int count = 0;
    while (diff) { // Count set bits
        diff &= (diff - 1); // Brian Kernighan's method
        count++;
    }
    return count;
}

// Unit tests
void testHammingDistance() {
    assertEquals(2, hammingDistance(1, 4), "Test 105.1 - Distance between 1 (001) and 4 (100)");
    assertEquals(0, hammingDistance(3, 3), "Test 105.2 - Same number");
}
```

Best Practices & Expert Tips

- **Best Practices:**

- Use XOR to find differing bits.
- Use Brian Kernighan's method for counting.
- Handle same numbers (distance 0).
- Test with sparse and dense bit patterns.

- **Expert Tips:**

- Explain XOR: " a^b gives 1s where bits differ; count them."
- In interviews, clarify: "Ask if signed integers need special handling."
- Suggest optimization: "Lookup table for 8-bit chunks, but loop is clear."
- Test edge cases: "Same numbers, all bits differ, or negatives."

Problem 106: Multiply by 7 Using Bit Manipulation

Issue Description

Multiply a number by 7 without using multiplication operator, e.g., 5 returns 35.

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer.
- **Output:** Number multiplied by 7.
- **Approach:** Use bit shifts and addition ($\text{num} * 7 = \text{num} * (8 - 1) = (\text{num} \ll 3) - \text{num}$).

- **Algorithm:** Bitwise Shift and Subtract
 - **Explanation:** Compute $\text{num} * 8$ (left shift by 3) and subtract num to get $\text{num} * 7$.
- **Steps:**
 - Shift num left by 3 ($\text{num} * 8$).
 - Subtract num to get $\text{num} * 7$.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise shift and subtract algorithm uses the fact that $7 = 8 - 1$.

Left-shifting by 3 multiplies by 8 ($\text{num} \ll 3$), and subtracting num gives $\text{num} * 7$.

This avoids the multiplication operator and is O(1) as it uses a single shift and subtraction, with no extra space.

Coding Part (with Unit Tests)

```
// Multiplies num by 7 using bit manipulation.
int multiplyBySeven(int num) {
    return (num << 3) - num; // num * 8 - num = num * 7
}

// Unit tests
void testMultiplyBySeven() {
    assertEquals(35, multiplyBySeven(5), "Test 106.1 - 5 * 7 = 35");
    assertEquals(0, multiplyBySeven(0), "Test 106.2 - 0 * 7 = 0");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use shift and subtract for clarity.
 - Handle negative numbers (works same).
 - Test with zero and large numbers.
 - Ensure overflow awareness for large inputs.
- **Expert Tips:**
 - Explain formula: " $\text{num} * 7 = \text{num} * (8 - 1) = (\text{num} \ll 3) - \text{num}$."
 - In interviews, clarify: "Ask if overflow handling is needed."
 - Suggest optimization: "This is optimal; single shift and subtract."
 - Test edge cases: "0, negative numbers, or large values."

Problem 107: Find the Only Number Missing in an Array of 1 to n Using XOR

Issue Description

In an array of $n-1$ numbers from 1 to n , find the missing number, e.g., [1,2,4,5] ($n=5$) returns 3.

Problem Decomposition & Solution Steps

- **Input:** Array, size ($n-1$).
- **Output:** Missing number from 1 to n .

- **Approach:** XOR all numbers and 1 to n; result is the missing number.
- **Algorithm:** Bitwise XOR
 - **Explanation:** XOR all array elements and numbers 1 to n; paired numbers cancel, leaving the missing number.
- **Steps:**
 1. Validate input.
 2. XOR array elements.
 3. XOR with 1 to n.
 4. Return result.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The bitwise XOR algorithm uses the property that $a \wedge a = 0$ and $a \wedge 0 = a$.

XORing all array elements cancels paired numbers (present in both array and 1 to n).

XORing with 1 to n leaves the missing number.

This is O(n) as it requires one pass through the array and 1 to n, with O(1) space as only one variable is needed.

Coding Part (with Unit Tests)

```
// Finds missing number from 1 to n.
int missingNumber(int* arr, int size) {
    if (arr == NULL || size <= 0) return 1; // Validate input
    int result = 0;
    for (int i = 0; i < size; i++) result ^= arr[i]; // XOR array
    for (int i = 1; i <= size + 1; i++) result ^= i; // XOR 1 to n
    return result;
}

// Unit tests
void testMissingNumber() {
    int arr[] = {1, 2, 4, 5};
    assertEquals(3, missingNumber(arr, 4), "Test 107.1 - Missing 3");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate input for NULL or empty.
 - XOR array and 1 to n in separate loops for clarity.
 - Handle edge case of size=0.
 - Test with small and large n.
- **Expert Tips:**
 - Explain XOR: "Paired numbers cancel; missing number remains."
 - In interviews, clarify: "Ask if array is guaranteed in range 1 to n."
 - Suggest alternative: "Sum 1 to n and subtract array sum, but XOR avoids overflow."
 - Test edge cases: "n=1, missing first or last number."

Problem 108: Toggle Bits in a Range [i, j]

Issue Description

Toggle all bits in the range [i, j] (0-based) of a 32-bit integer, e.g., num=10 (1010), i=1, j=2 returns 12 (1100).

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer, positions i, j (0-31).
- **Output:** Integer with bits i to j toggled.
- **Approach:** Create a mask with 1s in range [i, j] and XOR with num.
- **Algorithm:** Bitwise XOR with Mask
 - **Explanation:** Create a mask with 1s from i to j, then XOR with num to toggle bits in the range.
- **Steps:**
 1. Validate i, j (0 to 31, i <= j).
 2. Create mask with 1s in [i, j].
 3. XOR num with mask.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise XOR with mask algorithm creates a mask with 1s in [i, j] by shifting 1 left by $j+1$, subtracting 1, and shifting left by i.

XORing with num toggles bits in the range ($0^1=1$, $1^1=0$).

This is O(1) as it uses fixed operations for 32-bit integers, with no extra space beyond the mask.

Coding Part (with Unit Tests)

```
// Toggles bits in range [i, j] (0-based).
int toggleBitsInRange(int num, int i, int j) {
    if (i < 0 || j > 31 || i > j) return num; // Validate range
    unsigned int mask = ((1U << (j - i + 1)) - 1) << i; // Mask with 1s in [i, j]
    return num ^ mask; // Toggle bits
}

// Unit tests
void testToggleBitsInRange() {
    assertEquals(12, toggleBitsInRange(10, 1, 2), "Test 108.1 - Toggle bits 1-2 (1010 -> 1100)");
    assertEquals(10, toggleBitsInRange(10, 0, 0), "Test 108.2 - Single bit");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate range for correctness.
 - Use unsigned int for mask to avoid sign issues.
 - Ensure mask has 1s only in [i, j].
 - Test with single-bit and full ranges.
- **Expert Tips:**
 - Explain XOR: "XOR with 1s toggles bits in range [i, j]."

- In interviews, clarify: "Ask if $i > j$ or negative indices are valid."
- Suggest optimization: "This is optimal; single XOR."
- Test edge cases: " $i=j$, $i=0$, $j=31$, or invalid range."

Problem 109: Check if a Number Has Alternating Bits

Issue Description

Check if the binary representation of a number has alternating bits (e.g., 10101), e.g., 5 (101) returns true, 7 (111) returns false.

Problem Decomposition & Solution Steps

- **Input:** Non-negative integer.
- **Output:** Boolean.
- **Approach:** Check if adjacent bits differ using XOR.
- **Algorithm:** Bitwise XOR and Check
 - **Explanation:** XOR num with $num \gg 1$ to compare adjacent bits; all 1s indicate alternating bits.
- **Steps:**
 1. Validate non-negative input.
 2. Compute $num \wedge (num \gg 1)$.
 3. Check if result is all 1s in significant bits.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise XOR and check algorithm compares adjacent bits by XORing num with $num \gg 1$ (e.g., $101 \wedge 010 = 111$).

If bits alternate, the XOR gives all 1s in the significant bits.

Check if the result is a power of 2 minus 1 (e.g., $111 = 2^3 - 1$).

This is O(1) as it uses fixed operations for 32-bit integers.

Coding Part (with Unit Tests)

```
// Checks if num has alternating bits.
bool hasAlternatingBits(int num) {
    if (num < 0) return false; // Validate input
    int xor = num ^ (num >> 1); // XOR with right-shifted num
    return (xor & (xor + 1)) == 0; // Check if all 1s (power of 2 minus 1)
}

// Unit tests
void testHasAlternatingBits() {
    assertEquals(true, hasAlternatingBits(5), "Test 109.1 - Alternating (101)");
    assertEquals(false, hasAlternatingBits(7), "Test 109.2 - Not alternating (111)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate non-negative input.
 - Use XOR to compare adjacent bits.
 - Check for all 1s with power of 2 trick.
 - Test with short and long alternating patterns.
- **Expert Tips:**
 - Explain XOR: "num ^ (num >> 1) gives 1s for alternating bits."
 - In interviews, clarify: "Ask if leading zeros affect result."
 - Suggest optimization: "Check bits directly, but XOR is elegant."
 - Test edge cases: "0, 1, or non-alternating patterns."

Problem 110: Find the Largest Power of 2 Less Than a Given Number

Issue Description

Find the largest power of 2 less than a given number, e.g., 10 returns 8.

Problem Decomposition & Solution Steps

- **Input:** Positive integer.
- **Output:** Largest power of 2 < num.
- **Approach:** Set all bits after the highest 1, then subtract 1.
- **Algorithm:** Bit Manipulation
 - **Explanation:** Find the highest 1 bit, set all lower bits, then subtract 1 to get the previous power of 2.
- **Steps:**
 1. Validate positive input.
 2. Set all bits after highest 1.
 3. Subtract 1 to get largest power of 2.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bit manipulation algorithm finds the highest 1 bit, sets all lower bits (e.g., for $10=1010$, set to 1111), and subtracts 1 to get the previous power of 2 ($1000=8$).

This is done by ORing num with right-shifted versions to fill lower bits, then subtracting 1.

It's O(1) as it uses a fixed number of operations for 32-bit integers.

Coding Part (with Unit Tests)

```
// Finds largest power of 2 < num.
unsigned int largestPowerOfTwoLessThan(int num) {
    if (num <= 1) return 0; // Validate input
    unsigned int x = num - 1; // Avoid power of 2 case
    x |= x >> 1; // Set bits to right of highest 1
    x |= x >> 2;
    x |= x >> 4;
    x |= x >> 8;
    x |= x >> 16;
    return x - (x >> 1); // Subtract half to get previous power
}

// Unit tests
void testLargestPowerOfTwoLessThan() {
    assertEquals(8, largestPowerOfTwoLessThan(10), "Test 110.1 - Largest power for 10");
    assertEquals(4, largestPowerOfTwoLessThan(7), "Test 110.2 - Largest power for 7");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle non-positive inputs (return 0).
 - Use unsigned int for clarity.
 - Test with powers of 2 and non-powers.
 - Ensure correct bit filling.
- **Expert Tips:**
 - Explain bit setting: "Fill bits after highest 1, subtract half for previous power."
 - In interviews, clarify: "Ask if num=1 or negative inputs are valid."
 - Suggest optimization: "Log-based method, but bit manipulation is faster."
 - Test edge cases: "1, 2, or large numbers."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for bit manipulation problems 101 to 110:\n");
    testIsPowerOfFour();
    testMostSignificantBit();
    testAddNumbers();
    testIsBinaryPalindrome();
    testHammingDistance();
    testMultiplyBySeven();
    testMissingNumber();
    testToggleBitsInRange();
    testHasAlternatingBits();
    testLargestPowerOfTwoLessThan();
    return 0;
}
```

Problem 111: Divide by 2 Using Bit Manipulation

Issue Description

Divide a number by 2 without using division or arithmetic operators, e.g., 10 returns 5.

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer.
- **Output:** Integer divided by 2 (floor).
- **Approach:** Use right shift to divide by 2.
- **Algorithm:** Bitwise Right Shift
 - **Explanation:** Right-shifting a number by 1 divides it by 2 (floor division), as it shifts all bits right, discarding the least significant bit.
- **Steps:**
 1. Validate input (handle negative numbers).
 2. Right shift by 1.
 3. Return result.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise right shift algorithm divides by 2 because shifting right moves all bits one position lower, effectively halving the value (e.g., $10 = 1010 \gg 1 = 0101 = 5$).

For negative numbers, right shift preserves the sign bit (arithmetic shift), ensuring floor division (e.g., $-10 \gg 1 = -5$).

This is O(1) as it's a single operation.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdbool.h>

// Divides num by 2 using bit manipulation.
int divideByTwo(int num) {
    return num >> 1; // Right shift by 1
}

// Unit test helper
void assertIntEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testDivideByTwo() {
    assertIntEquals(5, divideByTwo(10), "Test 111.1 - Divide 10 by 2");
    assertIntEquals(-5, divideByTwo(-10), "Test 111.2 - Divide -10 by 2");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use arithmetic right shift for signed integers.
 - Handle negative numbers correctly.
 - Keep operation simple with single shift.
 - Test with positive and negative inputs.
- **Expert Tips:**
 - Explain shift: "Right shift by 1 halves the number, preserving sign."

- In interviews, clarify: "Ask if negative numbers or overflow are concerns."
- Suggest optimization: "This is optimal; single shift."
- Test edge cases: "0, negative numbers, or large values."

Problem 112: Find the Complement of a Number (Flip All Bits)

Issue Description

Compute the complement of a 32-bit integer (flip all bits), e.g., 5 (000...0101) returns 4294967290 (111...1010).

Problem Decomposition & Solution Steps

- **Input:** 32-bit unsigned integer.
- **Output:** Integer with all bits flipped.
- **Approach:** Use bitwise NOT to flip all bits.
- **Algorithm:** Bitwise NOT
 - **Explanation:** Apply \sim num to flip all 32 bits (0 to 1, 1 to 0).
- **Steps:**
 1. Apply bitwise NOT to num.
 2. Return result.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise NOT algorithm flips all bits using the \sim operator (e.g., 5 = 000...0101 becomes 111...1010).

For a 32-bit unsigned integer, this directly gives the complement.

It's O(1) as it's a single operation, with no extra space needed.

Coding Part (with Unit Tests)

```
// Returns complement of num (flip all bits).
unsigned int findComplement(unsigned int num) {
    return ~num; // Flip all bits
}
// Unit tests
void testFindComplement() {
    assertEquals(4294967290U, findComplement(5), "Test 112.1 - Complement of 5");
    assertEquals(4294967295U, findComplement(0), "Test 112.2 - Complement of 0");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use unsigned int to avoid sign issues.
 - Apply NOT directly for simplicity.
 - Test with zero and non-zero inputs.
 - Ensure 32-bit context is clear.
- **Expert Tips:**
 - Explain NOT: "Flips all 32 bits in one operation."

- In interviews, clarify: "Ask if input is guaranteed unsigned."
- Suggest optimization: "This is optimal; single NOT."
- Test edge cases: "0, all 1s, or small numbers."

Problem 113: Check if a Number is a Multiple of 3 Using Bit Manipulation

Issue Description

Check if a number is a multiple of 3 using bit manipulation, e.g., 6 returns true, 7 returns false.

Problem Decomposition & Solution Steps

- **Input:** Non-negative integer.
- **Output:** Boolean.
- **Approach:** Count difference of 1s in even and odd bit positions.
- **Algorithm:** Bitwise Counting
 - **Explanation:** For a number to be divisible by 3, the difference between the count of 1s in even and odd bit positions must be a multiple of 3.
- **Steps:**
 1. Validate non-negative input.
 2. Count 1s in even and odd positions.
 3. Check if difference is divisible by 3.
- **Complexity:** Time O(1) (32 bits), Space O(1).

Algorithm Explanation

The bitwise counting algorithm uses the property that a number is divisible by 3 if the difference between 1s in odd and even bit positions (0-based) is divisible by 3.

We iterate through bits, counting 1s in even and odd positions separately, then compute the absolute difference.

If this difference is a multiple of 3, the number is divisible by 3.

This is O(1) for 32-bit integers.

Coding Part (with Unit Tests)

```
// Checks if num is a multiple of 3 using bit manipulation.
bool isMultipleOfThree(int num) {
    if (num < 0) return false; // Validate input
    int evenCount = 0, oddCount = 0;
    while (num) { // Count 1s in even/odd positions
        evenCount += num & 1; // Bit 0, 2, 4, ...
        num >>= 1;
        if (num) oddCount += num & 1; // Bit 1, 3, 5, ...
        num >>= 1;
    }
    return abs(evenCount - oddCount) % 3 == 0; // Difference divisible by 3
}
```

```

// Unit test helper
void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testIsMultipleOfThree() {
    assertBoolEquals(true, isMultipleOfThree(6), "Test 113.1 - Multiple of 3 (6)");
    assertBoolEquals(false, isMultipleOfThree(7), "Test 113.2 - Not multiple of 3 (7)");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate non-negative input.
 - Count even/odd bits separately.
 - Use abs for difference to handle cases.
 - Test with multiples and non-multiples.
- **Expert Tips:**
 - Explain counting: "Difference of even/odd 1s must be multiple of 3."
 - In interviews, clarify: "Ask if negative numbers are valid."
 - Suggest optimization: "Precompute for small numbers, but loop is general."
 - Test edge cases: "0, 3, or large numbers."

Problem 114: Swap Nibbles in a Byte

Issue Description

Swap the two nibbles (4-bit groups) in a byte, e.g., 100 (01100100) returns 70 (01000110).

Problem Decomposition & Solution Steps

- **Input:** 8-bit unsigned integer (byte).
- **Output:** Byte with nibbles swapped.
- **Approach:** Shift and combine nibbles.
- **Algorithm:** Bitwise Shift and OR
 - **Explanation:** Shift high nibble right by 4, low nibble left by 4, then OR to combine.
- **Steps:**
 1. Extract high nibble ($\text{num} \gg 4$).
 2. Extract low nibble ($\text{num} \& 0x0F$).
 3. Shift and combine with OR.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise shift and OR algorithm swaps nibbles by isolating the high nibble (bits 4-7) with right shift and the low nibble (bits 0-3) with masking, then shifting them to opposite positions and combining with OR.

For example, 100 (01100100) becomes $(0100 \ll 4) | (0110) = 01000110 = 70$.

This is O(1) as it uses fixed operations.

Coding Part (with Unit Tests)

```
// Swaps nibbles in a byte.  
unsigned char swapNibbles(unsigned char num) {  
    return ((num >> 4) & 0x0F) | ((num & 0x0F) << 4); // Swap high and low nibbles  
}  
  
// Unit tests  
void testSwapNibbles() {  
    assertEquals(70, swapNibbles(100), "Test 114.1 - Swap nibbles of 100 (01100100 -> 01000110)");  
    assertEquals(0, swapNibbles(0), "Test 114.2 - Swap nibbles of 0");  
}
```

Best Practices & Expert Tips

- **Best Practices:**

- Use unsigned char for 8-bit context.
- Mask to ensure 4-bit isolation.
- Combine with OR for clarity.
- Test with various byte values.

- **Expert Tips:**

- Explain swap: "Shift high nibble right, low nibble left, then OR."
- In interviews, clarify: "Ask if input is guaranteed 8-bit."
- Suggest optimization: "This is optimal; single operation."
- Test edge cases: "0, all 1s, or alternating bits."

Problem 115: Find the Position of the Rightmost Set Bit

Issue Description

Find the position of the rightmost 1 bit in a 32-bit integer (0-based), e.g., 10 (1010) returns 1.

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer.
- **Output:** Position of rightmost 1, or -1 if none.
- **Approach:** Use num & -num to isolate rightmost 1, then find position.
- **Algorithm:** Bitwise AND and Log
 - **Explanation:** Compute num & -num to get rightmost 1, then find its position using a loop or log.
- **Steps:**
 1. Validate input (0 returns -1).
 2. Compute rightmost 1 with num & -num.
 3. Count trailing zeros to get position.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise AND and log algorithm uses num & -num to isolate the rightmost 1 bit (e.g., 10 = 1010, -10 = ...11110110, 1010 & -10 = 0010).

The position is the number of trailing zeros, which can be found by shifting or using a log-based method.

This is O(1) for 32-bit integers as operations are fixed.

Coding Part (with Unit Tests)

```
// Returns position of rightmost 1 bit (0-based), or -1 if none.
int rightmostSetBit(int num) {
    if (num == 0) return -1; // No set bits
    int pos = 0;
    num = num & -num; // Isolate rightmost 1
    while (num > 1) { // Count trailing zeros
        num >>= 1;
        pos++;
    }
    return pos;
}

// Unit tests
void testRightmostSetBit() {
    assertEquals(1, rightmostSetBit(10), "Test 115.1 - Rightmost 1 in 10 (1010)");
    assertEquals(-1, rightmostSetBit(0), "Test 115.2 - No set bits");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle 0 explicitly (no set bits).
 - Use $\text{num} \& -\text{num}$ for rightmost 1.
 - Count position with shift for clarity.
 - Test with sparse and dense numbers.
- **Expert Tips:**
 - Explain AND: "num & -num isolates rightmost 1; count zeros for position."
 - In interviews, clarify: "Ask if 0-based or if negative numbers are handled."
 - Suggest optimization: "Use $\log_2(\text{num} \& -\text{num})$ if available."
 - Test edge cases: "0, 1, or high-position 1s."

Problem 116: Perform Bitwise AND Over a Range

Issue Description

Compute the bitwise AND of all numbers in the range $[m, n]$, e.g., $[5, 7]$ ($5=101$, $6=110$, $7=111$) returns 4 (100).

Problem Decomposition & Solution Steps

- **Input:** Two integers m, n ($m \leq n$).
- **Output:** Bitwise AND of numbers m to n .
- **Approach:** Find common prefix of m and n .
- **Algorithm:** Bitwise Shift and Compare
 - **Explanation:** The AND of a range is the common prefix of m and n , as differing bits will be 0 in some numbers.

- **Steps:**
 1. Validate $m \leq n$.
 2. Shift m and n right until equal.
 3. Shift result left by shift count.
- **Complexity:** Time $O(1)$ (max 32 shifts), Space $O(1)$.

Algorithm Explanation

The bitwise shift and compare algorithm finds the common prefix by right-shifting m and n until they are equal, counting shifts.

The result is the common value shifted left by the count.

For $[5,7]$, $5=101$, $7=111$; after one shift, $10=11$, so result is $10 \ll 1 = 100 = 4$.

This is $O(1)$ as shifts are bounded by 32.

Coding Part (with Unit Tests)

```
// Computes bitwise AND of numbers from m to n.
int rangeBitwiseAnd(int m, int n) {
    if (m < 0 || n < m) return 0; // Validate input
    int shift = 0;
    while (m != n) { // Shift until equal
        m >>= 1;
        n >>= 1;
        shift++;
    }
    return m << shift; // Shift back to get common prefix
}

// Unit tests
void testRangeBitwiseAnd() {
    assertEquals(4, rangeBitwiseAnd(5, 7), "Test 116.1 - AND of [5,7]");
    assertEquals(0, rangeBitwiseAnd(0, 1), "Test 116.2 - AND of [0,1]");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate $m \leq n$.
 - Shift until common prefix is found.
 - Handle edge cases like $m=n$.
 - Test with small and large ranges.
- **Expert Tips:**
 - Explain prefix: "AND keeps common prefix; differing bits become 0."
 - In interviews, clarify: "Ask if negative numbers are valid."
 - Suggest optimization: "This is optimal; shift-based is efficient."
 - Test edge cases: " $m=n$, $m=0$, or large n ."

Problem 117: Count the Number of 1s in a Binary Matrix

Issue Description

Count the total number of 1s in a binary matrix (2D array of 0s and 1s), e.g., `[[1,0],[1,1]]` returns 3.

Problem Decomposition & Solution Steps

- **Input:** 2D array, rows, columns.
- **Output:** Total count of 1s.
- **Approach:** Iterate through matrix, sum 1s.
- **Algorithm:** Linear Scan
 - **Explanation:** Iterate over each element, adding 1s to a counter.
 - No bit manipulation needed as elements are 0 or 1.
- **Steps:**
 1. Validate input (NULL, dimensions).
 2. Iterate over rows and columns.
 3. Sum elements equal to 1.
- **Complexity:** Time $O(r*c)$, Space $O(1)$.

Algorithm Explanation

The linear scan algorithm is straightforward: iterate through each cell of the matrix and increment a counter for each 1.

Since the matrix contains only 0s and 1s, no bit manipulation is needed per element.

This is $O(r*c)$ as each cell is visited once, with $O(1)$ space for the counter.

Coding Part (with Unit Tests)

```
// Counts 1s in binary matrix.
int countOnesInMatrix(int** matrix, int rows, int cols) {
    if (matrix == NULL || rows <= 0 || cols <= 0) return 0; // Validate input
    int count = 0;
    for (int i = 0; i < rows; i++) {
        for (int j = 0; j < cols; j++) {
            count += matrix[i][j]; // Add 1s
        }
    }
    return count;
}

// Unit tests
void testCountOnesInMatrix() {
    int rows = 2, cols = 2;
    int* matrix[] = {{(int[]){1, 0}}, {(int[]){1, 1}}};
    assertEquals(3, countOnesInMatrix(matrix, rows, cols), "Test 117.1 - Count 1s in
[[1,0],[1,1]]");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate matrix and dimensions.
 - Use simple iteration for clarity.
 - Assume elements are 0 or 1.
 - Test with empty and full matrices.
- **Expert Tips:**
 - Explain scan: "Sum 1s directly; no bit manipulation needed."
 - In interviews, clarify: "Ask if matrix elements are guaranteed 0/1."
 - Suggest optimization: "Bit-packed matrix could use bit counting, but not needed here."
 - Test edge cases: "Empty matrix, all 0s, or all 1s."

Problem 118: Check if a Number is a Gray Code Sequence

Issue Description

Check if a number's binary representation is a Gray code (adjacent bits differ by exactly one bit from its predecessor), e.g., 2 (10) returns true ($1^2=11$).

Problem Decomposition & Solution Steps

- **Input:** Non-negative integer.
- **Output:** Boolean.
- **Approach:** Check if num and num-1 differ by one bit.
- **Algorithm:** Bitwise XOR and Count
 - **Explanation:** A Gray code number differs from its predecessor by one bit.
 - Compute $\text{num} \wedge (\text{num}-1)$ and check if it has exactly one 1.
- **Steps:**
 1. Validate non-negative input.
 2. Compute $\text{num} \wedge (\text{num}-1)$.
 3. Check if result is a power of 2.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise XOR and count algorithm checks if num is a Gray code by XORing with num-1.

In a Gray code sequence, each number differs from the previous by one bit, so $\text{num} \wedge (\text{num}-1)$ should have exactly one 1 (a power of 2).

Use $\text{num} \& (\text{num}-1) == 0$ to verify.

This is O(1) as it uses fixed operations.

Coding Part (with Unit Tests)

```
// Checks if num is a Gray code sequence.
bool isGrayCode(int num) {
    if (num < 0) return false; // Validate input
    int xor = num ^ (num - 1); // XOR with predecessor
    return num == 0 || (xor & (xor - 1)) == 0; // Check single bit difference
}

// Unit tests
void testIsGrayCode() {
    assertEquals(true, isGrayCode(2), "Test 118.1 - Gray code (2=10)");
    assertEquals(false, isGrayCode(3), "Test 118.2 - Not Gray code (3=11)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle 0 explicitly (valid Gray code).
 - Use XOR to find bit difference.
 - Validate single bit with power of 2 check.
 - Test with Gray and non-Gray numbers.
- **Expert Tips:**
 - Explain Gray code: "num ^ (num-1) has one 1 for valid Gray code."
 - In interviews, clarify: "Ask if 0 is a valid Gray code."
 - Suggest optimization: "This is optimal; single XOR and check."
 - Test edge cases: "0, 1, or non-Gray sequences."

Problem 119: Find the XOR of Numbers from 1 to n

Issue Description

Compute the XOR of all numbers from 1 to n, e.g., n=4 returns 4 ($1^2^3^4$).

Problem Decomposition & Solution Steps

- **Input:** Positive integer n.
- **Output:** XOR of numbers 1 to n.
- **Approach:** Use pattern based on $n \% 4$.
- **Algorithm:** Pattern-Based XOR
 - **Explanation:** The XOR of 1 to n follows a pattern: $n \% 4 == 0$ returns n, $n \% 4 == 1$ returns 1, $n \% 4 == 2$ returns $n+1$, $n \% 4 == 3$ returns 0.
- **Steps:**
 1. Validate positive input.
 2. Compute $n \% 4$.
 3. Return result based on pattern.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The pattern-based XOR algorithm exploits the cyclic nature of XOR from 1 to n.

For n=4: $1 \oplus 2 \oplus 3 \oplus 4 = 4$; n=5: $1 \oplus 2 \oplus 3 \oplus 4 \oplus 5 = 1$; etc.

The pattern repeats every 4: $n \% 4 == 0$: n, $n \% 4 == 1$: 1, $n \% 4 == 2$: $n + 1$, $n \% 4 == 3$: 0.

This is O(1) as it uses a single modulo operation.

Coding Part (with Unit Tests)

```
// Computes XOR of numbers from 1 to n.
int xorFromOneToN(int n) {
    if (n <= 0) return 0; // Validate input
    switch (n % 4) { // Pattern based on n % 4
        case 0: return n;
        case 1: return 1;
        case 2: return n + 1;
        case 3: return 0;
    }
    return 0; // Unreachable
}

// Unit tests
void testXorFromOneToN() {
    assertEquals(4, xorFromOneToN(4), "Test 119.1 - XOR 1 to 4");
    assertEquals(1, xorFromOneToN(5), "Test 119.2 - XOR 1 to 5");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate positive input.
 - Use switch for clear pattern handling.
 - Test all cases of $n \% 4$.
 - Ensure O(1) with pattern.
- **Expert Tips:**
 - Explain pattern: "XOR from 1 to n cycles every 4; use modulo."
 - In interviews, clarify: "Ask if loop-based XOR is acceptable."
 - Suggest alternative: "Loop from 1 to n, but O(n) is slower."
 - Test edge cases: " $n=1$, $n=4$, or large n ."

Problem 120: Perform Bit Rotation with Carry

Issue Description

Rotate bits of a 32-bit integer left by k positions, carrying the overflow bits to the low end, e.g., num=10 (1010), k=2 returns 40 (101000).

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer, k.
- **Output:** Integer with bits rotated left, carrying overflow.
- **Approach:** Shift left and OR with overflow bits.
- **Algorithm:** Bitwise Shift and OR
 - **Explanation:** Shift num left by k, then OR with num right-shifted by (32-k) to carry overflow bits.
- **Steps:**
 1. Normalize k ($k \% 32$).
 2. Shift left by k, right by 32-k.
 3. OR results to combine.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise shift and OR algorithm performs a left rotation with carry by splitting the number into bits shifted left by k and overflow bits shifted right by 32-k, then ORing them.

Normalizing k ($k \% 32$) handles large values.

This is O(1) as it uses fixed operations for 32-bit integers, identical to standard left rotation (Problem 94).

Coding Part (with Unit Tests)

```
// Rotates bits left by k with carry.
unsigned int rotateLeftWithCarry(int num, int k) {
    k = k % 32; // Normalize k
    return (num << k) | (num >> (32 - k)); // Shift left and carry
}

// Unit tests
void testRotateLeftWithCarry() {
    assertEquals(40, rotateLeftWithCarry(10, 2), "Test 120.1 - Rotate 10 (1010) left by 2");
    assertEquals(10, rotateLeftWithCarry(10, 0), "Test 120.2 - No rotation (k=0)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use unsigned int to avoid sign issues.
 - Normalize k to handle large values.
 - Combine shifts with OR for rotation.
 - Test with k=0 and k=32.
- **Expert Tips:**
 - Explain rotation: "Left shift k, carry bits with right shift 32-k."
 - In interviews, clarify: "Ask if k can be negative or large."
 - Suggest optimization: "This is optimal; single operation."
 - Test edge cases: "k=0, k=32, or negative k."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for bit manipulation problems 111 to 120:\n");
    testDivideByTwo();
    testFindComplement();
    testIsMultipleOfThree();
    testSwapNibbles();
    testRightmostSetBit();
    testRangeBitwiseAnd();
    testCountOnesInMatrix();
    testIsGrayCode();
    testXorFromOneToN();
    testRotateLeftWithCarry();
    return 0;
}
```

Problem 121: Find the Number of Bits Required to Represent a Number

Issue Description

Determine the minimum number of bits needed to represent a non-negative integer in binary, e.g., 10 (1010) returns 4.

Problem Decomposition & Solution Steps

- **Input:** Non-negative 32-bit integer.
- **Output:** Number of bits required.
- **Approach:** Find the position of the most significant bit.
- **Algorithm:** Bitwise Shift and Count
 - **Explanation:** Shift right until the number becomes 0, counting shifts.
 - The number of bits is the position of the leftmost 1 plus 1.
- **Steps:**
 1. Validate input (0 returns 1).
 2. Shift right, counting until 0.
 3. Return count.
- **Complexity:** Time O(1) (max 32 shifts), Space O(1).

Algorithm Explanation

The bitwise shift and count algorithm finds the most significant bit by right-shifting until the number becomes 0.

Each shift reduces the number, and the count of shifts gives the position of the leftmost 1.

Add 1 to include that bit.

For 0, return 1 (single bit).

This is O(1) for 32-bit integers as shifts are bounded by 32.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdbool.h>

// Returns number of bits to represent num.
int bitsRequired(int num) {
    if (num == 0) return 1; // 0 needs 1 bit
    int count = 0;
    while (num) { // Shift until 0
        num >>= 1;
        count++;
    }
    return count;
}

// Unit test helper
void assertIntEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testBitsRequired() {
    assertIntEquals(4, bitsRequired(10), "Test 121.1 - Bits for 10 (1010)");
    assertIntEquals(1, bitsRequired(0), "Test 121.2 - Bits for 0");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle 0 explicitly (1 bit).
 - Use simple shift loop for clarity.
 - Test with small and large numbers.
 - Ensure non-negative input.
- **Expert Tips:**
 - Explain shift: "Count shifts to find leftmost 1; add 1 for bit count."
 - In interviews, clarify: "Ask if 0 or negative numbers need special handling."
 - Suggest optimization: "Use $\log_2(\text{num}) + 1$, but shift is clearer."
 - Test edge cases: "0, 1, or max 32-bit number."

Problem 122: Check if a Number is a Power of 8

Issue Description

Check if a number is a power of 8 (e.g., 8, 64, 512), e.g., 64 returns true, 16 returns false.

Problem Decomposition & Solution Steps

- **Input:** Non-negative integer.
- **Output:** Boolean.
- **Approach:** Check if power of 2 and 1 bit in position divisible by 3.
- **Algorithm:** Bitwise AND and Position Check

- **Explanation:** Powers of 8 are powers of 2 ($\text{num} \& (\text{num}-1) == 0$) with the 1 bit in positions 0, 3, 6, etc.
- Count trailing zeros; must be multiple of 3.
- **Steps:**
 1. Validate non-positive input.
 2. Check power of 2.
 3. Count trailing zeros; check if divisible by 3.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise AND and position check algorithm verifies if the number is a power of 2 (single 1 bit).

Powers of 8 have their 1 bit in positions 0, 3, 6, ...

(multiples of 3).

Count trailing zeros using $\text{num} \& -\text{num}$ and check if the position (log-based or shift) is divisible by 3.

This is O(1) for 32-bit integers.

Coding Part (with Unit Tests)

```
// Checks if num is a power of 8.
bool isPowerOfEight(int num) {
    if (num <= 0 || (num & (num - 1)) != 0) return false; // Not power of 2
    int pos = 0;
    while (num > 1) { // Count trailing zeros
        num >>= 1;
        pos++;
    }
    return pos % 3 == 0; // Position divisible by 3
}

// Unit test helper
void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testIsPowerOfEight() {
    assertBoolEquals(true, isPowerOfEight(64), "Test 122.1 - Power of 8 (64)");
    assertBoolEquals(false, isPowerOfEight(16), "Test 122.2 - Not power of 8 (16)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate non-positive and non-power of 2.
 - Check position divisibility by 3.
 - Test with powers of 8 and other powers.
 - Use shift for position count.
- **Expert Tips:**
 - Explain check: "Powers of 8 have 1 bit in positions 0, 3, 6, ..."
 - In interviews, clarify: "Ask if mask-based check (0x24924924) is preferred."

- Suggest optimization: "Use mask for even/odd bits, but shift is clear."
- Test edge cases: "0, 1, or non-powers of 2."

Problem 123: Swap Even and Odd Bits in a Number

Issue Description

Swap even and odd bits in a 32-bit integer (0-based), e.g., 10 (1010) returns 5 (0101).

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer.
- **Output:** Integer with even and odd bits swapped.
- **Approach:** Extract even/odd bits, shift, and combine.
- **Algorithm:** Bitwise AND, Shift, and OR
 - **Explanation:** Mask even bits (0xAAAA...), odd bits (0x5555...), shift them to swap positions, and OR to combine.
- **Steps:**
 1. Extract even bits ($\text{num} \& 0xAAAA...$).
 2. Extract odd bits ($\text{num} \& 0x5555...$).
 3. Shift even bits right, odd bits left.
 4. OR to combine.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise AND, shift, and OR algorithm uses masks to isolate even (0xAAAAAAA) and odd (0x55555555) bits.

Shift even bits right by 1 and odd bits left by 1 to swap positions, then OR to combine.

For 10 (1010), even bits (10) become 01, odd bits (01) become 10, resulting in 0101 = 5.

This is O(1) for 32-bit integers.

Coding Part (with Unit Tests)

```
// Swaps even and odd bits (0-based).
unsigned int swapEvenOddBits(int num) {
    return ((num & 0xAAAAAAA) >> 1) | ((num & 0x55555555) << 1); // Swap even/odd bits
}

// Unit tests
void testSwapEvenOddBits() {
    assertEquals(5, swapEvenOddBits(10), "Test 123.1 - Swap bits in 10 (1010 -> 0101)");
    assertEquals(0, swapEvenOddBits(0), "Test 123.2 - Swap bits in 0");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use standard masks (0xAAAA..., 0x5555...).
 - Use unsigned int for clarity.
 - Test with alternating and non-alternating bits.
 - Ensure 32-bit context.
- **Expert Tips:**
 - Explain masks: "0xAAAA..."
 - for even, 0x5555...
 - for odd; shift and OR."
 - In interviews, clarify: "Ask if 0-based indexing is assumed."
 - Suggest optimization: "This is optimal; single operation."
 - Test edge cases: "0, all 1s, or sparse bits."

Problem 124: Find the Single Number in an Array Where Others Appear Three Times

Issue Description

In an array where every element appears three times except one, find the single number, e.g., [2,2,2,3] returns 3.

Problem Decomposition & Solution Steps

- **Input:** Array, size.
- **Output:** Single number.
- **Approach:** Use bit counting modulo 3.
- **Algorithm:** Bitwise Count Modulo 3
 - **Explanation:** For each bit position, count 1s across all numbers.
 - Bits with count not divisible by 3 belong to the single number.
- **Steps:**
 1. Validate input.
 2. Count 1s for each bit position.
 3. Take count % 3 to build result.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The bitwise count modulo 3 algorithm counts 1s at each bit position across all numbers.

Since most numbers appear three times, their bits contribute counts divisible by 3.

The single number's bits contribute to counts not divisible by 3.

Taking count % 3 for each bit builds the single number.

This is O(n) for n elements, O(1) space (32-bit result).

Coding Part (with Unit Tests)

```
// Finds number appearing once, others three times.
int singleNumberThree(int* arr, int size) {
    if (arr == NULL || size <= 0) return 0; // Validate input
    int result = 0;
    for (int i = 0; i < 32; i++) { // Check each bit
        int bitCount = 0;
        for (int j = 0; j < size; j++) { // Count 1s at bit i
            bitCount += (arr[j] >> i) & 1;
        }
        if (bitCount % 3 != 0) { // Bit in single number
            result |= (1 << i);
        }
    }
    return result;
}

// Unit tests
void testSingleNumberThree() {
    int arr[] = {2, 2, 2, 3};
    assertEquals(3, singleNumberThree(arr, 4), "Test 124.1 - Single number 3");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate input for NULL or empty.
 - Process all 32 bits.
 - Use modulo 3 to identify single number's bits.
 - Test with small and large arrays.
- **Expert Tips:**
 - Explain modulo: "Counts divisible by 3 cancel; remainder gives single number."
 - In interviews, clarify: "Ask if negative numbers are valid."
 - Suggest optimization: "Bit manipulation with state machines, but this is clear."
 - Test edge cases: "Single element, negative numbers."

Problem 125: Perform Bitwise OR Over a Range

Issue Description

Compute the bitwise OR of all numbers in the range [m, n], e.g., [5, 7] (5=101, 6=110, 7=111) returns 7 (111).

Problem Decomposition & Solution Steps

- **Input:** Two integers m, n ($m \leq n$).
- **Output:** Bitwise OR of numbers m to n.
- **Approach:** Iterate over range or use bit manipulation (approximation).
- **Algorithm:** Linear OR (or Approximation)
 - **Explanation:** OR all numbers in [m, n].
 - Alternatively, approximate by ORing m and n for small ranges.
- **Steps:**
 1. Validate $m \leq n$.
 2. Iterate from m to n, ORing each number.

- 3. Return result.
- **Complexity:** Time $O(n-m)$, Space $O(1)$.

Algorithm Explanation

The linear OR algorithm computes the OR by iterating through $[m, n]$, ORing each number.

For small ranges, this is practical.

For large ranges, note that OR includes all bits set in any number, so $m \mid n$ is often close, but iteration ensures correctness.

This is $O(n-m)$ time, $O(1)$ space.

For 32-bit integers, an approximation could use bit patterns, but iteration is clearer.

Coding Part (with Unit Tests)

```
// Computes bitwise OR of numbers from m to n.
int rangeBitwiseOr(int m, int n) {
    if (m < 0 || n < m) return 0; // Validate input
    int result = m;
    for (int i = m + 1; i <= n; i++) { // OR all numbers
        result |= i;
    }
    return result;
}

// Unit tests
void testRangeBitwiseOr() {
    assertEquals(7, rangeBitwiseOr(5, 7), "Test 125.1 - OR of [5,7]");
    assertEquals(5, rangeBitwiseOr(5, 5), "Test 125.2 - OR of [5,5]");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate $m \leq n$.
 - Iterate for correctness.
 - Handle single-number range.
 - Test with small and large ranges.
- **Expert Tips:**
 - Explain OR: "All bits set in any number appear in result."
 - In interviews, clarify: "Ask if approximation ($m \mid n$) is acceptable."
 - Suggest optimization: "For large ranges, analyze bit patterns, but iteration is safe."
 - Test edge cases: " $m=n$, large ranges, or negative m ."

Problem 126: Check if a Number is a Power of 16

Issue Description

Check if a number is a power of 16 (e.g., 16, 256), e.g., 256 returns true, 64 returns false.

Problem Decomposition & Solution Steps

- **Input:** Non-negative integer.
- **Output:** Boolean.
- **Approach:** Check if power of 2 and 1 bit in position divisible by 4.
- **Algorithm:** Bitwise AND and Position Check
 - **Explanation:** Powers of 16 are powers of 2 with 1 bit in positions 0, 4, 8, etc.
 - Check power of 2, then verify position is divisible by 4.
- **Steps:**
 1. Validate non-positive input.
 2. Check power of 2.
 3. Count trailing zeros; check divisible by 4.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise AND and position check algorithm ensures the number is a power of 2 ($\text{num} \& (\text{num}-1) == 0$).

Powers of 16 have their 1 bit in positions 0, 4, 8, ...

(multiples of 4).

Count trailing zeros and check if divisible by 4.

This is O(1) for 32-bit integers as operations are fixed.

Coding Part (with Unit Tests)

```
// Checks if num is a power of 16.
bool isPowerOfSixteen(int num) {
    if (num <= 0 || (num & (num - 1)) != 0) return false; // Not power of 2
    int pos = 0;
    while (num > 1) { // Count trailing zeros
        num >>= 1;
        pos++;
    }
    return pos % 4 == 0; // Position divisible by 4
}

// Unit tests
void testIsPowerOfSixteen() {
    assertEquals(true, isPowerOfSixteen(256), "Test 126.1 - Power of 16 (256)");
    assertEquals(false, isPowerOfSixteen(64), "Test 126.2 - Not power of 16 (64)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate non-positive and non-power of 2.
 - Check position divisibility by 4.
 - Test with powers of 16 and others.
 - Use shift for position count.
- **Expert Tips:**
 - Explain check: "Powers of 16 have 1 bit in positions 0, 4, 8, ..."
 - In interviews, clarify: "Ask if mask-based check is preferred."
 - Suggest optimization: "Use mask 0x11111111, but shift is clear."
 - Test edge cases: "0, 1, or non-powers of 2."

Problem 127: Find the Position of the Leftmost Set Bit

Issue Description

Find the position of the leftmost 1 bit in a 32-bit integer (0-based), e.g., 10 (1010) returns 3.

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer.
- **Output:** Position of leftmost 1, or -1 if none.
- **Approach:** Shift right until 0, tracking position.
- **Algorithm:** Bitwise Shift and Count
 - **Explanation:** Right-shift until the number is 0, counting shifts.
 - The last position with a 1 is the answer.
- **Steps:**
 1. Validate input (0 returns -1).
 2. Shift right, count until 0.
 3. Return last position.
- **Complexity:** Time O(1) (max 32 shifts), Space O(1).

Algorithm Explanation

The bitwise shift and count algorithm finds the leftmost 1 by right-shifting until 0, tracking the position.

For a 32-bit integer, the maximum shifts are 31 (for 1 in position 31).

The position is the count minus 1.

This is O(1) as shifts are bounded by 32.

(Note: Identical to Problem 102, repeated for completeness.)

Coding Part (with Unit Tests)

```
// Returns position of leftmost 1 bit (0-based), or -1 if none.
int leftmostSetBit(int num) {
    if (num == 0) return -1; // No set bits
    int pos = 0;
    while (num) { // Shift until 0
        num >>= 1;
        pos++;
    }
    return pos - 1; // Last position with 1
}

// Unit tests
void testLeftmostSetBit() {
    assertEquals(3, leftmostSetBit(10), "Test 127.1 - Leftmost 1 in 10 (1010)");
    assertEquals(-1, leftmostSetBit(0), "Test 127.2 - No set bits");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle 0 explicitly (no set bits).
 - Use shift loop for clarity.
 - Ensure 0-based indexing.
 - Test with sparse and dense numbers.
- **Expert Tips:**
 - Explain shift: "Count shifts to find leftmost 1."
 - In interviews, clarify: "Ask if 0-based or negative numbers."
 - Suggest optimization: "Use $\log_2(\text{num})$, but loop is clearer."
 - Test edge cases: "0, 1, or all 1s."

Problem 128: Multiply by 3 Using Bit Manipulation

Issue Description

Multiply a number by 3 without using multiplication, e.g., 5 returns 15.

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer.
- **Output:** Number multiplied by 3.
- **Approach:** Use bit shifts and addition ($\text{num} * 3 = \text{num} * 2 + \text{num}$).
- **Algorithm:** Bitwise Shift and Add
 - **Explanation:** Left shift by 1 ($\text{num} * 2$), then add num to get $\text{num} * 3$.
- **Steps:**
 1. Shift num left by 1.
 2. Add num to result.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise shift and add algorithm uses $\text{num} * 3 = \text{num} * 2 + \text{num}$.

Left-shifting by 1 doubles the number ($\text{num} \ll 1$), and adding num gives the result.

This avoids multiplication and is O(1) as it uses a single shift and add, with no extra space.

Coding Part (with Unit Tests)

```
// Multiplies num by 3 using bit manipulation.
int multiplyByThree(int num) {
    return (num << 1) + num; // num * 2 + num = num * 3
}

// Unit tests
void testMultiplyByThree() {
    assertEquals(15, multiplyByThree(5), "Test 128.1 - 5 * 3 = 15");
    assertEquals(0, multiplyByThree(0), "Test 128.2 - 0 * 3 = 0");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use shift and add for clarity.
 - Handle negative numbers (works same).
 - Test with zero and large numbers.
 - Be aware of overflow for large inputs.
- **Expert Tips:**
 - Explain formula: " $\text{num} * 3 = (\text{num} \ll 1) + \text{num}$."
 - In interviews, clarify: "Ask if overflow handling is needed."
 - Suggest optimization: "This is optimal; single shift and add."
 - Test edge cases: "0, negative numbers, or large values."

Problem 129: Find the Number of Bits to Flip to Make Two Numbers Equal

Issue Description

Count the number of bits to flip to make two 32-bit integers equal, e.g., a=10 (1010), b=7 (0111) returns 2.

Problem Decomposition & Solution Steps

- **Input:** Two 32-bit integers.
- **Output:** Number of bits to flip.
- **Approach:** XOR numbers and count set bits.
- **Algorithm:** Bitwise XOR and Count
 - **Explanation:** XOR a and b to get differing bits, then count 1s.
 - (Note: Identical to Problem 100.)
- **Steps:**
 1. Compute $a \wedge b$.
 2. Count set bits using Brian Kernighan's method.

- **Complexity:** Time O(1) (max 32 bits), Space O(1).

Algorithm Explanation

The bitwise XOR and count algorithm identifies differing bits with $a \wedge b$ (1 where bits differ).

Counting these 1s with Brian Kernighan's method ($num \& (num-1)$) gives the number of flips needed.

This is O(1) for 32-bit integers as the number of set bits is at most 32.

Coding Part (with Unit Tests)

```
// Counts bits to flip to make a equal b.
int bitsToFlipEqual(int a, int b) {
    int diff = a ^ b; // Get differing bits
    int count = 0;
    while (diff) { // Count set bits
        diff &= (diff - 1); // Brian Kernighan's method
        count++;
    }
    return count;
}

// Unit tests
void testBitsToFlipEqual() {
    assertEquals(2, bitsToFlipEqual(10, 7), "Test 129.1 - 10 to 7 (1010 -> 0111)");
    assertEquals(0, bitsToFlipEqual(10, 10), "Test 129.2 - Same number");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use XOR to find differing bits.
 - Use Brian Kernighan's method for counting.
 - Handle same numbers (0 flips).
 - Test with identical and opposite bits.
- **Expert Tips:**
 - Explain XOR: " $a \wedge b$ gives 1s where bits differ; count them."
 - In interviews, clarify: "Ask if signed integers need handling."
 - Suggest optimization: "Lookup table for 8-bit chunks, but loop is clear."
 - Test edge cases: "Same numbers, all bits differ."

Problem 130: Perform Bit Reversal in a Byte

Issue Description

Reverse the bits in an 8-bit unsigned integer, e.g., 100 (01100100) returns 38 (00100110).

Problem Decomposition & Solution Steps

- **Input:** 8-bit unsigned integer.
- **Output:** Byte with bits reversed.
- **Approach:** Shift and build reversed byte.

- **Algorithm:** Bitwise Shift and OR
 - **Explanation:** Extract each bit and place it in the opposite position, building the result.
- **Steps:**
 1. Initialize result to 0.
 2. For each bit (0 to 7), extract and place in reverse position.
 3. Return result.
- **Complexity:** Time O(1) (8 bits), Space O(1).

Algorithm Explanation

The bitwise shift and OR algorithm reverses an 8-bit byte by extracting each bit (`num & 1`) and placing it in the opposite position (`result << 1 | bit`).

Iterate 8 times for an 8-bit byte.

For 100 (01100100), build 00100110 = 38.

This is O(1) as it's fixed at 8 iterations for a byte.

Coding Part (with Unit Tests)

```
// Reverses bits in a byte.
unsigned char reverseByte(unsigned char num) {
    unsigned char result = 0;
    for (int i = 0; i < 8; i++) { // Process 8 bits
        result = (result << 1) | (num & 1); // Place bit in reverse position
        num >>= 1;
    }
    return result;
}

// Unit tests
void testReverseByte() {
    assertEquals(38, reverseByte(100), "Test 130.1 - Reverse 100 (01100100 -> 00100110)");
    assertEquals(0, reverseByte(0), "Test 130.2 - Reverse 0");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use `unsigned char` for 8-bit context.
 - Process exactly 8 bits.
 - Test with sparse and dense bytes.
 - Use shift and OR for clarity.
- **Expert Tips:**
 - Explain reversal: "Extract bit, place in reverse position, shift result."
 - In interviews, clarify: "Ask if lookup table is preferred."
 - Suggest optimization: "Use 256-entry table for O(1), but loop is clear."
 - Test edge cases: "0, all 1s, or alternating bits."

Problem 131: Check if a Number Has Exactly One Set Bit

Issue Description

Check if a number has exactly one 1 bit (power of 2), e.g., 8 returns true, 10 returns false.

Problem Decomposition & Solution Steps

- **Input:** Non-negative integer.
- **Output:** Boolean.
- **Approach:** Check if power of 2.
- **Algorithm:** Bitwise AND
 - **Explanation:** A number with one 1 bit is a power of 2.
 - Check if $\text{num} \& (\text{num}-1) == 0$.
- **Steps:**
 1. Validate non-positive input.
 2. Check $\text{num} \& (\text{num}-1) == 0$.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise AND algorithm checks if a number is a power of 2, which has exactly one 1 bit (e.g., 8 = 1000).

Compute $\text{num} \& (\text{num}-1)$; if 0, only one bit is set, as $\text{num}-1$ flips the rightmost 1 to 0 and sets lower bits to 1.

This is O(1) as it's a single operation.

(Note: Similar to Problem 82, but focused on one bit.)

Coding Part (with Unit Tests)

```
// Checks if num has exactly one set bit.
bool hasOneSetBit(int num) {
    if (num <= 0) return false; // Validate input
    return (num & (num - 1)) == 0; // Check power of 2
}

// Unit tests
void testHasOneSetBit() {
    assertEquals(true, hasOneSetBit(8), "Test 131.1 - One set bit (8)");
    assertEquals(false, hasOneSetBit(10), "Test 131.2 - Multiple bits (10)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate non-positive inputs.
 - Use $\text{num} \& (\text{num}-1)$ for efficiency.
 - Test with powers of 2 and others.
 - Ensure clarity in single-bit check.
- **Expert Tips:**
 - Explain check: " $\text{num} \& (\text{num}-1)$ clears rightmost 1; 0 means one bit."

- In interviews, clarify: "Ask if 0 is valid."
- Suggest optimization: "This is optimal; single AND."
- Test edge cases: "0, 1, or non-powers."

Problem 132: Find the XOR of Numbers in a Range [a, b]

Issue Description

Compute the XOR of all numbers in the range [a, b], e.g., [3, 5] returns 6 ($3 \wedge 4 \wedge 5$).

Problem Decomposition & Solution Steps

- **Input:** Two integers a, b ($a \leq b$).
- **Output:** XOR of numbers a to b.
- **Approach:** Use XOR from 1 to n formula.
- **Algorithm:** Pattern-Based XOR
 - **Explanation:** $\text{XOR from } a \text{ to } b = \text{XOR}(1 \text{ to } b) \wedge \text{XOR}(1 \text{ to } a-1)$.
 - Use $n \% 4$ pattern for O(1).
- **Steps:**
 1. Validate $a \leq b$.
 2. Compute $\text{XOR}(1 \text{ to } b)$ and $\text{XOR}(1 \text{ to } a-1)$.
 3. XOR results to get range XOR.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The pattern-based XOR algorithm uses the XOR(1 to n) formula: $n \% 4 == 0: n$, $n \% 4 == 1: 1$, $n \% 4 == 2: n+1$, $n \% 4 == 3: 0$.

For range [a, b], compute $\text{XOR}(1 \text{ to } b) \wedge \text{XOR}(1 \text{ to } a-1)$ to cancel terms before a.

This is O(1) as it uses modulo and simple operations.

Coding Part (with Unit Tests)

```
// Computes XOR of numbers from 1 to n.
static int xorOneToN(int n) {
    if (n <= 0) return 0;
    switch (n % 4) {
        case 0: return n;
        case 1: return 1;
        case 2: return n + 1;
        case 3: return 0;
    }
    return 0;
}
// Computes XOR of numbers from a to b.
int rangeXor(int a, int b) {
    if (a < 0 || b < a) return 0; // Validate input
    return xorOneToN(b) ^ xorOneToN(a - 1); // XOR(1 to b) ^ XOR(1 to a-1)
}
// Unit tests
```

```

void testRangeXor() {
    assertEquals(6, rangeXor(3, 5), "Test 132.1 - XOR of [3,5]");
    assertEquals(3, rangeXor(3, 3), "Test 132.2 - XOR of [3,3]");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate $a \leq b$.
 - Use XOR pattern for $O(1)$.
 - Test single-number and multi-number ranges.
 - Handle edge cases like $a=0$.
- **Expert Tips:**
 - Explain formula: "Range XOR = $\text{XOR}(1 \text{ to } b) \wedge \text{XOR}(1 \text{ to } a-1)$."
 - In interviews, clarify: "Ask if negative inputs are valid."
 - Suggest optimization: "Loop is $O(b-a)$; pattern is $O(1)$."
 - Test edge cases: " $a=b$, $a=0$, or large ranges."

Problem 133: Clear the Least Significant Set Bit

Issue Description

Clear the least significant 1 bit in a 32-bit integer, e.g., 10 (1010) returns 8 (1000).

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer.
- **Output:** Integer with least significant 1 cleared.
- **Approach:** Use $\text{num} \& (\text{num}-1)$.
- **Algorithm:** Bitwise AND
 - **Explanation:** Compute $\text{num} \& (\text{num}-1)$ to clear the rightmost 1 bit.
- **Steps:**
 1. Validate input (0 returns 0).
 2. Compute $\text{num} \& (\text{num}-1)$.
 3. Return result.
- **Complexity:** Time $O(1)$, Space $O(1)$.

Algorithm Explanation

The bitwise AND algorithm clears the rightmost 1 bit because $\text{num}-1$ flips the rightmost 1 to 0 and sets all lower bits to 1.

ANDing with num clears the 1 bit (e.g., $1010 \& 1001 = 1000$).

This is $O(1)$ as it's a single operation, with no extra space.

Coding Part (with Unit Tests)

```
// Clears least significant 1 bit.
int clearLeastSignificantBit(int num) {
    return num & (num - 1); // Clear rightmost 1
}

// Unit tests
void testClearLeastSignificantBit() {
    assertEquals(8, clearLeastSignificantBit(10), "Test 133.1 - Clear LSB in 10 (1010 -> 1000)");
    assertEquals(0, clearLeastSignificantBit(0), "Test 133.2 - Clear LSB in 0");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle 0 correctly (returns 0).
 - Use single AND operation.
 - Test with sparse and dense numbers.
 - Ensure clarity in bit clearing.
- **Expert Tips:**
 - Explain AND: "num & (num-1) clears rightmost 1."
 - In interviews, clarify: "Ask if negative numbers are handled."
 - Suggest optimization: "This is optimal; single AND."
 - Test edge cases: "0, single 1, or all 1s."

Problem 134: Check if a Number is a Power of 10

Issue Description

Check if a number is a power of 10 (e.g., 10, 100, 1000), e.g., 100 returns true, 50 returns false.

Problem Decomposition & Solution Steps

- **Input:** Non-negative integer.
- **Output:** Boolean.
- **Approach:** Repeatedly divide by 10.
- **Algorithm:** Division-Based Check
 - **Explanation:** Divide by 10 until 1 or non-divisible.
 - Bit manipulation is impractical due to 10's non-power-of-2 nature.
- **Steps:**
 1. Validate non-positive input.
 2. Divide by 10 until 1 or non-divisible.
 3. Check if result is 1.
- **Complexity:** Time O(log n), Space O(1).

Algorithm Explanation

The division-based check algorithm repeatedly divides by 10 until the number is 1 (power of 10) or not divisible by 10 (not a power).

Bit manipulation is not suitable as 10 is not a power of 2.

This is O(log n) as it divides by 10 until reaching 1 or a non-divisible number, with O(1) space.

Coding Part (with Unit Tests)

```
// Checks if num is a power of 10.
bool isPowerOfTen(int num) {
    if (num <= 0) return false; // Validate input
    while (num > 1) { // Divide by 10
        if (num % 10 != 0) return false;
        num /= 10;
    }
    return num == 1;
}

// Unit tests
void testIsPowerOfTen() {
    assertEquals(true, isPowerOfTen(100), "Test 134.1 - Power of 10 (100)");
    assertEquals(false, isPowerOfTen(50), "Test 134.2 - Not power of 10 (50)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate non-positive inputs.
 - Use division for simplicity.
 - Test with powers of 10 and others.
 - Handle large numbers.
- **Expert Tips:**
 - Explain division: "Divide by 10 until 1; bit manipulation not viable."
 - In interviews, clarify: "Ask if bit-based solution is expected."
 - Suggest optimization: "Precompute powers of 10, but division is clear."
 - Test edge cases: "0, 1, or non-powers."

Problem 135: Find the Number of Bits Different in Two Numbers

Issue Description

Count the number of bits that differ between two 32-bit integers, e.g., 10 (1010) and 7 (0111) returns 2.

Problem Decomposition & Solution Steps

- **Input:** Two 32-bit integers.
- **Output:** Number of differing bits.
- **Approach:** XOR numbers and count set bits.

- **Algorithm:** Bitwise XOR and Count
 - **Explanation:** XOR to get differing bits, count 1s.
 - (Note: Identical to Problems 100, 129.)
- **Steps:**
 1. Compute $a \wedge b$.
 2. Count set bits using Brian Kernighan's method.
- **Complexity:** Time $O(1)$ (max 32 bits), Space $O(1)$.

Algorithm Explanation

The bitwise XOR and count algorithm uses $a \wedge b$ to get 1s where bits differ, then counts 1s with Brian Kernighan's method ($\text{num} \& (\text{num}-1)$).

This is $O(1)$ for 32-bit integers as the number of set bits is at most 32, with $O(1)$ space.

Coding Part (with Unit Tests)

```
// Counts differing bits between two numbers.
int bitsDifferent(int a, int b) {
    int diff = a ^ b; // Get differing bits
    int count = 0;
    while (diff) { // Count set bits
        diff &= (diff - 1); // Brian Kernighan's method
        count++;
    }
    return count;
}

// Unit tests
void testBitsDifferent() {
    assertEquals(2, bitsDifferent(10, 7), "Test 135.1 - Differing bits (1010, 0111)");
    assertEquals(0, bitsDifferent(10, 10), "Test 135.2 - Same number");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use XOR to find differing bits.
 - Use Brian Kernighan's method for counting.
 - Handle same numbers (0 differences).
 - Test with sparse and dense patterns.
- **Expert Tips:**
 - Explain XOR: " $a \wedge b$ gives 1s where bits differ; count them."
 - In interviews, clarify: "Ask if signed integers need handling."
 - Suggest optimization: "Lookup table for 8-bit chunks, but loop is clear."
 - Test edge cases: "Same numbers, all bits differ."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for bit manipulation problems 121 to 135:\n");
    testBitsRequired();
    testIsPowerOfEight();
    testSwapEvenOddBits();
    testSingleNumberThree();
```

```

    testRangeBitwiseOr();
    testIsPowerOfSixteen();
    testLeftmostSetBit();
    testMultiplyByThree();
    testBitsToFlipEqual();
    testReverseByte();
    testHasOneSetBit();
    testRangeXor();
    testClearLeastSignificantBit();
    testIsPowerOfTen();
    testBitsDifferent();
    return 0;
}

```

Problem 136: Set All Even Bits to 1

Issue Description

Set all even-positioned bits (0-based, positions 0, 2, 4, ...) in a 32-bit integer to 1, e.g., num=10 (1010) returns 1717986918 (0x66666666).

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer.
- **Output:** Integer with even bits set to 1.
- **Approach:** Use a mask to set even bits.
- **Algorithm:** Bitwise OR with Mask
 - **Explanation:** Create a mask with 1s in even positions (0xAAAAAAA), then OR with the number.
- **Steps:**
 1. Create mask 0xAAAAAAA (1010...1010).
 2. OR the number with the mask.
 3. Return result.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise OR with mask algorithm uses 0xAAAAAAA, which has 1s in even positions (0, 2, 4, ...).

ORing with the input sets these bits to 1 while preserving others.

For 10 (1010), OR with 1010...1010 sets even bits, resulting in a number with all even bits 1.

This is O(1) as it's a single operation.

Coding Part (with Unit Tests)

```

#include <stdio.h>
#include <stdbool.h>

// Sets all even bits (0-based) to 1.
unsigned int setEvenBits(int num) {
    return num | 0xAAAAAAA; // OR with mask for even bits
}
// Unit test helper

```

```

void assertIntEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testSetEvenBits() {
    assertIntEquals(0xAAAAAAAB, setEvenBits(10), "Test 136.1 - Set even bits in 10 (1010)");
    assertIntEquals(0xAAAAAAA, setEvenBits(0), "Test 136.2 - Set even bits in 0");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use unsigned int for clarity.
 - Use standard mask 0xAAAAAAAA.
 - Test with sparse and dense inputs.
 - Ensure 32-bit context.
- **Expert Tips:**
 - Explain mask: "0xAAAAAAAA has 1s in even positions; OR sets them."
 - In interviews, clarify: "Ask if 0-based indexing is assumed."
 - Suggest optimization: "This is optimal; single OR."
 - Test edge cases: "0, all 1s, or alternating bits."

Problem 137: Check if a Number is a Binary Palindrome

Issue Description

Check if the binary representation of a number is a palindrome, e.g., 9 (1001) returns true, 10 (1010) returns false.

Problem Decomposition & Solution Steps

- **Input:** Non-negative 32-bit integer.
- **Output:** Boolean.
- **Approach:** Reverse bits and compare with original.
- **Algorithm:** Bit Reversal and Comparison
 - **Explanation:** Reverse the bits of the number and check if equal to original.
 - (Note: Identical to Problem 104.)
- **Steps:**
 1. Validate non-negative input.
 2. Reverse bits using shift and OR.
 3. Compare reversed with original.
- **Complexity:** Time O(1) (32 bits), Space O(1).

Algorithm Explanation

The bit reversal and comparison algorithm reverses the 32-bit number by extracting each bit and building the result from the opposite end.

Compare with the original to check for palindrome.

Leading zeros are implicit, so focus on significant bits.

This is O(1) for 32-bit integers as it uses a fixed 32 iterations.

Coding Part (with Unit Tests)

```
// Checks if binary representation is a palindrome.
bool isBinaryPalindrome(int num) {
    if (num < 0) return false; // Validate input
    unsigned int reversed = 0, temp = num;
    for (int i = 0; i < 32; i++) { // Reverse bits
        reversed = (reversed << 1) | (temp & 1);
        temp >>= 1;
    }
    return num == reversed; // Compare with original
}

// Unit test helper
void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testIsBinaryPalindrome() {
    assertBoolEquals(true, isBinaryPalindrome(9), "Test 137.1 - Palindrome (9=1001)");
    assertBoolEquals(false, isBinaryPalindrome(10), "Test 137.2 - Not palindrome (10=1010)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use unsigned int for reversal.
 - Validate negative inputs.
 - Compare full 32-bit numbers.
 - Test with palindromic and non-palindromic numbers.
- **Expert Tips:**
 - Explain reversal: "Build reversed number bit by bit, then compare."
 - In interviews, clarify: "Ask if leading zeros affect palindrome."
 - Suggest optimization: "Trim leading zeros, but full reversal is simpler."
 - Test edge cases: "0, 1, or large palindromes."

Problem 138: Find the Number of Trailing Zeros in a Number's Binary Form

Issue Description

Count the number of trailing zeros in the binary representation of a number, e.g., 16 (10000) returns 4.

Problem Decomposition & Solution Steps

- **Input:** Non-negative 32-bit integer.
- **Output:** Number of trailing zeros.
- **Approach:** Count zeros after rightmost 1.
- **Algorithm:** Bitwise AND and Shift
 - **Explanation:** Use num & -num to find rightmost 1, then count trailing zeros.
- **Steps:**
 1. Validate input (0 returns 32).

2. Compute $\text{num} \& -\text{num}$ to isolate rightmost 1.
 3. Count shifts to reach 1.
- **Complexity:** Time O(1) (max 32 shifts), Space O(1).

Algorithm Explanation

The bitwise AND and shift algorithm isolates the rightmost 1 bit with $\text{num} \& -\text{num}$ (e.g., $16 = 10000$, $-16 = \dots 10000$, $10000 \& -10000 = 10000$).

Count shifts to reduce this to 1, giving the number of trailing zeros.

For 0, return 32 (all zeros).

This is O(1) as shifts are bounded by 32.

Coding Part (with Unit Tests)

```
// Counts trailing zeros in binary representation.
int trailingZeros(int num) {
    if (num == 0) return 32; // All zeros
    num = num & -num; // Isolate rightmost 1
    int count = 0;
    while (num > 1) { // Count shifts to 1
        num >>= 1;
        count++;
    }
    return count;
}

// Unit tests
void testTrailingZeros() {
    assertEquals(4, trailingZeros(16), "Test 138.1 - Trailing zeros in 16 (10000)");
    assertEquals(32, trailingZeros(0), "Test 138.2 - Trailing zeros in 0");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle 0 explicitly (32 zeros).
 - Use $\text{num} \& -\text{num}$ for rightmost 1.
 - Count shifts for clarity.
 - Test with powers of 2 and 0.
- **Expert Tips:**
 - Explain AND: " $\text{num} \& -\text{num}$ isolates rightmost 1; count zeros."
 - In interviews, clarify: "Ask if 0 returns 32 or other."
 - Suggest optimization: "Use $\log_2(\text{num} \& -\text{num})$, but shift is clear."
 - Test edge cases: "0, 1, or large numbers."

Problem 139: Perform Bitwise NOT in a Range

Issue Description

Invert all bits in the range $[i, j]$ (0-based) of a 32-bit integer, e.g., num=10 (1010), $i=1, j=2$ returns 12 (1100).

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer, positions i, j (0-31).
- **Output:** Integer with bits i to j inverted.
- **Approach:** Create a mask and XOR with num.
- **Algorithm:** Bitwise XOR with Mask
 - **Explanation:** Create a mask with 1s in $[i, j]$, then XOR to toggle bits.
 - (Note: Identical to Problem 108.)
- **Steps:**
 1. Validate i, j (0 to 31, $i \leq j$).
 2. Create mask with 1s in $[i, j]$.
 3. XOR num with mask.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise XOR with mask algorithm creates a mask with 1s in $[i, j]$ by shifting 1 left by $j+1$, subtracting 1, and shifting left by i .

XORing with num toggles bits in the range ($0^1=1, 1^1=0$).

This is O(1) as it uses fixed operations for 32-bit integers.

Coding Part (with Unit Tests)

```
// Inverts bits in range [i, j] (0-based).
int notInRange(int num, int i, int j) {
    if (i < 0 || j > 31 || i > j) return num; // Validate range
    unsigned int mask = ((1U << (j - i + 1)) - 1) << i; // Mask with 1s in [i, j]
    return num ^ mask; // Toggle bits
}
// Unit tests
void testNotInRange() {
    assertEquals(12, notInRange(10, 1, 2), "Test 139.1 - Invert bits 1-2 (1010 -> 1100)");
    assertEquals(10, notInRange(10, 0, 0), "Test 139.2 - Single bit");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate range for correctness.
 - Use unsigned int for mask.
 - Ensure mask has 1s only in $[i, j]$.
 - Test with single-bit and full ranges.
- **Expert Tips:**
 - Explain XOR: "XOR with 1s toggles bits in range."

- In interviews, clarify: "Ask if $i > j$ or negative indices."
- Suggest optimization: "This is optimal; single XOR."
- Test edge cases: " $i=j$, $i=0$, $j=31$."

Problem 140: Sum Bits in All Numbers from 1 to n

Issue Description

Sum the number of 1 bits in the binary representation of all numbers from 1 to n, e.g., n=3 returns 4 (1:1, 2:1, 3:2).

Problem Decomposition & Solution Steps

- **Input:** Non-negative integer n.
- **Output:** Total number of 1 bits from 1 to n.
- **Approach:** Use pattern for each bit position.
- **Algorithm:** Bit Position Counting
 - **Explanation:** For each bit position, count how many times it's 1 from 1 to n using a pattern.
- **Steps:**
 1. Validate non-negative input.
 2. For each bit (0 to 31), compute 1s.
 3. Sum counts across all bits.
- **Complexity:** Time O(1) (32 bits), Space O(1).

Algorithm Explanation

The bit position counting algorithm calculates 1s for each bit position.

For bit i, it's 1 in numbers where bit i is set, which occurs in blocks of 2^{i+1} .

Count full blocks ($n/(2^{i+1})$) and remaining bits.

Sum across all 32 bits.

This is O(1) as it's fixed at 32 iterations for 32-bit integers.

Coding Part (with Unit Tests)

```
// Sums 1 bits in all numbers from 1 to n.
int sumBits(int n) {
    if (n < 0) return 0; // Validate input
    int sum = 0;
    for (int i = 0; i < 32; i++) { // For each bit position
        int period = 1 << (i + 1); // Period for bit i
        sum += (n / period) * (1 << i); // Full blocks
        sum += n % period > (1 << i) - 1 ? n % period - (1 << i) + 1 : 0; // Partial block
    }
    return sum;
}
```

```

// Unit tests
void testSumBits() {
    assertEquals(4, sumBits(3), "Test 140.1 - Sum bits 1 to 3");
    assertEquals(1, sumBits(1), "Test 140.2 - Sum bits 1 to 1");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate non-negative input.
 - Process all 32 bits.
 - Use period-based counting.
 - Test with small and large n.
- **Expert Tips:**
 - Explain pattern: "Bit i is 1 in blocks of 2^{i+1} ; count full and partial blocks."
 - In interviews, clarify: "Ask if simpler loop-based counting is acceptable."
 - Suggest optimization: "Loop from 1 to n is O(n); this is O(1)."
 - Test edge cases: "0, 1, or large n."

Problem 141: Check if a Number is a Power of 3

Issue Description

Check if a number is a power of 3 (e.g., 9, 27), e.g., 27 returns true, 10 returns false.

Problem Decomposition & Solution Steps

- **Input:** Non-negative integer.
- **Output:** Boolean.
- **Approach:** Check divisibility by largest power of 3.
- **Algorithm:** Division-Based Check
 - **Explanation:** Use the largest power of 3 in 32-bit range (3^{19}).
 - If num divides it evenly, it's a power of 3.
- **Steps:**
 1. Validate non-positive input.
 2. Check if largest power of 3 divides num.
 3. Return true if divisible.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The division-based check algorithm uses the largest 32-bit power of 3 ($3^{19} = 1162261467$).

If num is a power of 3, it divides this number evenly (no remainder).

Bit manipulation is impractical as 3 is not a power of 2.

This is O(1) as it uses a single division.

Coding Part (with Unit Tests)

```
// Checks if num is a power of 3.  
bool isPowerOfThree(int num) {  
    if (num <= 0) return false; // Validate input  
    return 1162261467 % num == 0; // Largest 32-bit power of 3  
}  
  
// Unit tests  
void testIsPowerOfThree() {  
    assertEquals(true, isPowerOfThree(27), "Test 141.1 - Power of 3 (27)");  
    assertEquals(false, isPowerOfThree(10), "Test 141.2 - Not power of 3 (10)");  
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate non-positive inputs.
 - Use largest power of 3 (1162261467).
 - Test with powers of 3 and others.
 - Avoid bit manipulation for non-power-of-2.
- **Expert Tips:**
 - Explain check: "Num must divide largest power of 3."
 - In interviews, clarify: "Ask if bit-based solution is expected."
 - Suggest optimization: "Division is optimal; bit methods don't apply."
 - Test edge cases: "0, 1, or non-powers."

Problem 142: Find the Number of Leading Zeros in a Number

Issue Description

Count the number of leading zeros in the binary representation of a 32-bit integer, e.g., 10 (000...1010) returns 28.

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer.
- **Output:** Number of leading zeros.
- **Approach:** Find leftmost 1, subtract position from 31.
- **Algorithm:** Bitwise Shift and Count
 - **Explanation:** Shift right until 0, count shifts, and compute 31 - position.
- **Steps:**
 1. Validate input (0 returns 32).
 2. Shift right, count until 0.
 3. Return 31 - count.
- **Complexity:** Time O(1) (max 32 shifts), Space O(1).

Algorithm Explanation

The bitwise shift and count algorithm finds the leftmost 1 by right-shifting until 0, counting shifts.

The number of leading zeros is 31 minus the position of the leftmost 1.

For 0, return 32 (all zeros).

This is O(1) as shifts are bounded by 32 for 32-bit integers.

Coding Part (with Unit Tests)

```
// Counts leading zeros in 32-bit integer.
int leadingZeros(int num) {
    if (num == 0) return 32; // All zeros
    int count = 0;
    while (num) { // Shift until 0
        num >>= 1;
        count++;
    }
    return 31 - (count - 1); // 31 - position of leftmost 1
}

// Unit tests
void testLeadingZeros() {
    assertEquals(28, leadingZeros(10), "Test 142.1 - Leading zeros in 10 (1010)");
    assertEquals(32, leadingZeros(0), "Test 142.2 - Leading zeros in 0");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle 0 explicitly (32 zeros).
 - Use shift for clarity.
 - Compute zeros as 31 - position.
 - Test with sparse and dense numbers.
- **Expert Tips:**
 - Explain count: "31 minus leftmost 1 position gives leading zeros."
 - In interviews, clarify: "Ask if 32-bit context or negative numbers."
 - Suggest optimization: "Use `clz` intrinsic if available."
 - Test edge cases: "0, 1, or high-position 1s."

Problem 143: Implement a Function to Multiply by 9 Using Bit Manipulation

Issue Description

Multiply a number by 9 without using multiplication, e.g., 5 returns 45.

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer.
- **Output:** Number multiplied by 9.
- **Approach:** Use bit shifts and addition ($\text{num} * 9 = \text{num} * 8 + \text{num}$).
- **Algorithm:** Bitwise Shift and Add
 - **Explanation:** Left shift by 3 ($\text{num} * 8$), add num to get $\text{num} * 9$.
- **Steps:**
 1. Shift num left by 3.

- 2. Add num to result.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise shift and add algorithm uses $\text{num} * 9 = \text{num} * 8 + \text{num}$.

Left-shifting by 3 multiplies by 8 ($\text{num} \ll 3$), and adding num gives $\text{num} * 9$.

This avoids multiplication and is O(1) as it uses a single shift and add, with no extra space.

Coding Part (with Unit Tests)

```
// Multiplies num by 9 using bit manipulation.
int multiplyByNine(int num) {
    return (num << 3) + num; // num * 8 + num = num * 9
}

// Unit tests
void testMultiplyByNine() {
    assertEquals(45, multiplyByNine(5), "Test 143.1 - 5 * 9 = 45");
    assertEquals(0, multiplyByNine(0), "Test 143.2 - 0 * 9 = 0");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use shift and add for clarity.
 - Handle negative numbers (works same).
 - Test with zero and large numbers.
 - Be aware of overflow for large inputs.
- **Expert Tips:**
 - Explain formula: " $\text{num} * 9 = (\text{num} \ll 3) + \text{num}$."
 - In interviews, clarify: "Ask if overflow handling is needed."
 - Suggest optimization: "This is optimal; single shift and add."
 - Test edge cases: "0, negative numbers, or large values."

Problem 144: Check if Two Numbers Have the Same Number of Set Bits

Issue Description

Check if two numbers have the same number of 1 bits, e.g., 10 (1010, 2 1s) and 5 (0101, 2 1s) returns true.

Problem Decomposition & Solution Steps

- **Input:** Two 32-bit integers.
- **Output:** Boolean.
- **Approach:** Count set bits in each number.
- **Algorithm:** Bitwise Count
 - **Explanation:** Count 1s in both numbers using Brian Kernighan's method and compare.

- **Steps:**
 1. Count set bits in num1 using $\text{num} \& (\text{num}-1)$.
 2. Count set bits in num2.
 3. Compare counts.
- **Complexity:** Time O(1) (max 32 bits), Space O(1).

Algorithm Explanation

The bitwise count algorithm uses Brian Kernighan's method ($\text{num} \& (\text{num}-1)$) to count 1s in each number.

Compare the counts to check if equal.

This is O(1) as each number has at most 32 bits, and it uses constant space.

Coding Part (with Unit Tests)

```
// Checks if two numbers have same number of set bits.
bool sameSetBits(int num1, int num2) {
    int count1 = 0, count2 = 0;
    while (num1) { // Count bits in num1
        num1 &= (num1 - 1);
        count1++;
    }
    while (num2) { // Count bits in num2
        num2 &= (num2 - 1);
        count2++;
    }
    return count1 == count2;
}

// Unit tests
void testSameSetBits() {
    assertEquals(true, sameSetBits(10, 5), "Test 144.1 - Same set bits (10=1010, 5=0101)");
    assertEquals(false, sameSetBits(10, 7), "Test 144.2 - Different set bits (10=1010, 7=0111)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use Brian Kernighan's method for counting.
 - Handle negative numbers consistently.
 - Test with equal and unequal bit counts.
 - Ensure 32-bit context.
- **Expert Tips:**
 - Explain counting: "num & (num-1) counts 1s efficiently."
 - In interviews, clarify: "Ask if negative numbers affect bit count."
 - Suggest optimization: "Lookup table for 8-bit chunks, but loop is clear."
 - Test edge cases: "0, same numbers, or all 1s."

Problem 145: Find the Number of Bits to Flip to Make a Number a Palindrome

Issue Description

Count the number of bits to flip to make a number's binary representation a palindrome, e.g., 10 (1010) returns 2 (to 1001).

Problem Decomposition & Solution Steps

- **Input:** Non-negative 32-bit integer.
- **Output:** Number of bits to flip.
- **Approach:** Reverse bits, XOR with original, count 1s.
- **Algorithm:** Bit Reversal and XOR Count
 - **Explanation:** Reverse the number's bits, XOR with original to find differing bits, count 1s.
- **Steps:**
 1. Validate non-negative input.
 2. Reverse bits of num.
 3. XOR reversed with original.
 4. Count set bits.
- **Complexity:** Time O(1) (32 bits), Space O(1).

Algorithm Explanation

The bit reversal and XOR count algorithm reverses the 32-bit number, XORs it with the original to identify differing bits (1 where they differ), and counts these 1s using Brian Kernighan's method.

For 10 (1010), reverse to 0101, XOR gives 1111 (4 bits to flip, but 1001 needs 2 flips; adjust for minimal palindrome).

This is O(1) for 32 bits.

Coding Part (with Unit Tests)

```
// Counts bits to flip to make binary palindrome.
int bitsToMakePalindrome(int num) {
    if (num < 0) return 0; // Validate input
    unsigned int reversed = 0, temp = num;
    for (int i = 0; i < 32; i++) { // Reverse bits
        reversed = (reversed << 1) | (temp & 1);
        temp >>= 1;
    }
    int diff = num ^ reversed; // Differing bits
    int count = 0;
    while (diff) { // Count 1s
        diff &= (diff - 1);
        count++;
    }
    return count / 2; // Half the differing bits (symmetric flips)
}

// Unit tests
void testBitsToMakePalindrome() {
    assertEquals(2, bitsToMakePalindrome(10), "Test 145.1 - Bits to palindrome (10=1010 -> 1001)");
    assertEquals(0, bitsToMakePalindrome(9), "Test 145.2 - Already palindrome (9=1001)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate negative inputs.
 - Use reversal and XOR for differences.
 - Divide count by 2 for symmetric flips.
 - Test with palindromes and non-palindromes.
- **Expert Tips:**
 - Explain symmetry: "Half the differing bits needed due to palindrome symmetry."
 - In interviews, clarify: "Ask if leading zeros affect result."
 - Suggest optimization: "Consider significant bits only, but 32-bit is robust."
 - Test edge cases: "0, 1, or large numbers."

Problem 146: Set All Odd Bits to 0

Issue Description

Set all odd-positioned bits (0-based, positions 1, 3, 5, ...) in a 32-bit integer to 0, e.g., num=10 (1010) returns 8 (1000).

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer.
- **Output:** Integer with odd bits set to 0.
- **Approach:** Use a mask to clear odd bits.
- **Algorithm:** Bitwise AND with Mask
 - **Explanation:** Create a mask with 0s in odd positions (0xAAAAAAA), then AND with the number.
- **Steps:**
 1. Create mask 0xAAAAAAA (1010...1010).
 2. AND the number with the mask.
 3. Return result.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bitwise AND with mask algorithm uses 0xAAAAAAA (1s in even positions, 0s in odd).

ANDing with the input clears odd bits while preserving even bits.

For 10 (1010), AND with 1010...1010 gives 1000 = 8.

This is O(1) as it's a single operation.

Coding Part (with Unit Tests)

```
// Sets all odd bits (0-based) to 0.
unsigned int clearOddBits(int num) {
    return num & 0xAAAAAAAA; // AND with mask for even bits
}
```

```

// Unit tests
void testClearOddBits() {
    assertEquals(8, clearOddBits(10), "Test 146.1 - Clear odd bits in 10 (1010 -> 1000)");
    assertEquals(0, clearOddBits(0), "Test 146.2 - Clear odd bits in 0");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use unsigned int for clarity.
 - Use standard mask 0xAAAAAAA.
 - Test with sparse and dense inputs.
 - Ensure 32-bit context.
- **Expert Tips:**
 - Explain mask: "0xAAAAAAA has 0s in odd positions; AND clears them."
 - In interviews, clarify: "Ask if 0-based indexing is assumed."
 - Suggest optimization: "This is optimal; single AND."
 - Test edge cases: "0, all 1s, or alternating bits."

Problem 147: Find the Position of the Rightmost Unset Bit

Issue Description

Find the position of the rightmost 0 bit in a 32-bit integer (0-based), e.g., 10 (1010) returns 0.

Problem Decomposition & Solution Steps

- **Input:** 32-bit integer.
- **Output:** Position of rightmost 0, or -1 if none.
- **Approach:** Invert and find rightmost 1.
- **Algorithm:** Bitwise NOT and AND
 - **Explanation:** Invert num ($\sim\text{num}$), use $\sim\text{num} \& \sim\text{num}$ to find rightmost 1 (original 0), count position.
- **Steps:**
 1. Validate input (all 1s returns -1).
 2. Compute $\sim\text{num} \& \sim\text{num}$.
 3. Count shifts to find position.
- **Complexity:** Time O(1) (max 32 shifts), Space O(1).

Algorithm Explanation

The bitwise NOT and AND algorithm inverts the number ($\sim\text{num}$ turns 0s to 1s), then uses $\sim\text{num} \& \sim\text{num}$ to isolate the rightmost 1 (original 0).

Count shifts to find its position.

For 10 (1010), $\sim 10 = \dots 0101, 0101 \& 1011 = 0001$, position 0.

If all 1s, return -1.

This is O(1) as shifts are bounded by 32.

Coding Part (with Unit Tests)

```
// Returns position of rightmost 0 bit (0-based), or -1 if none.
int rightmostUnsetBit(int num) {
    if (num == -1) return -1; // All 1s
    num = ~num; // Invert to find 0s as 1s
    num = num & -num; // Isolate rightmost 1 (original 0)
    int pos = 0;
    while (num > 1) { // Count shifts
        num >>= 1;
        pos++;
    }
    return pos;
}

// Unit tests
void testRightmostUnsetBit() {
    assertEquals(0, rightmostUnsetBit(10), "Test 147.1 - Rightmost 0 in 10 (1010)");
    assertEquals(-1, rightmostUnsetBit(-1), "Test 147.2 - No unset bits");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle all 1s case (-1).
 - Use $\sim\text{num} \& \sim\text{num}$ for rightmost 0.
 - Count position with shifts.
 - Test with sparse and all-1s inputs.
- **Expert Tips:**
 - Explain NOT: " $\sim\text{num}$ turns 0s to 1s; find rightmost 1."
 - In interviews, clarify: "Ask if 0-based or all-1s case."
 - Suggest optimization: "Use $\log_2(\sim\text{num} \& \sim\text{num})$, but shift is clear."
 - Test edge cases: "0, all 1s, or sparse 0s."

Problem 148: Perform Bitwise XOR Over a Range

Issue Description

Compute the bitwise XOR of all numbers in the range $[m, n]$, e.g., $[3, 5]$ returns 6 ($3 \wedge 4 \wedge 5$).

Problem Decomposition & Solution Steps

- **Input:** Two integers m, n ($m \leq n$).
- **Output:** XOR of numbers m to n .
- **Approach:** Use XOR from 1 to n formula.
- **Algorithm:** Pattern-Based XOR
 - **Explanation:** $\text{XOR from } m \text{ to } n = \text{XOR}(1 \text{ to } n) \wedge \text{XOR}(1 \text{ to } m-1)$.
 - Use $n \% 4$ pattern.
 - (Note: Identical to Problem 132.)
- **Steps:**
 1. Validate $m \leq n$.
 2. Compute $\text{XOR}(1 \text{ to } n)$ and $\text{XOR}(1 \text{ to } m-1)$.

- 3. XOR results.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The pattern-based XOR algorithm uses $\text{XOR}(1 \text{ to } n) = n \% 4$:
 $n \% 4 == 0: n$, $n \% 4 == 1: 1$, $n \% 4 == 2: n+1$, $n \% 4 == 3: 0$.

Compute $\text{XOR}(1 \text{ to } n) ^ \text{XOR}(1 \text{ to } m-1)$ to get range XOR.

This is O(1) as it uses modulo and simple operations.

Coding Part (with Unit Tests)

```
// Computes XOR of numbers from 1 to n.
static int xorOneToN(int n) {
    if (n <= 0) return 0;
    switch (n % 4) {
        case 0: return n;
        case 1: return 1;
        case 2: return n + 1;
        case 3: return 0;
    }
    return 0;
}

// Computes XOR of numbers from m to n.
int rangeXor(int m, int n) {
    if (m < 0 || n < m) return 0; // Validate input
    return xorOneToN(n) ^ xorOneToN(m - 1); // XOR(1 to n) ^ XOR(1 to m-1)
}

// Unit tests
void testRangeXor() {
    assertEquals(6, rangeXor(3, 5), "Test 148.1 - XOR of [3,5]");
    assertEquals(3, rangeXor(3, 3), "Test 148.2 - XOR of [3,3]");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate $m \leq n$.
 - Use XOR pattern for O(1).
 - Test single-number and multi-number ranges.
 - Handle edge cases like $m=0$.
- **Expert Tips:**
 - Explain formula: "Range XOR = $\text{XOR}(1 \text{ to } n) ^ \text{XOR}(1 \text{ to } m-1)$."
 - In interviews, clarify: "Ask if negative inputs are valid."
 - Suggest optimization: "Loop is O($n-m$); pattern is O(1)."
 - Test edge cases: " $m=n$, $m=0$, or large ranges."

Problem 149: Check if a Number is a Power of 5

Issue Description

Check if a number is a power of 5 (e.g., 5, 25, 125), e.g., 125 returns true, 10 returns false.

Problem Decomposition & Solution Steps

- **Input:** Non-negative integer.
- **Output:** Boolean.
- **Approach:** Check divisibility by largest power of 5.
- **Algorithm:** Division-Based Check
 - **Explanation:** Use largest 32-bit power of 5 ($5^{13} = 1220703125$).
 - If num divides it evenly, it's a power of 5.
- **Steps:**
 1. Validate non-positive input.
 2. Check if largest power of 5 divides num.
 3. Return true if divisible.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The division-based check algorithm uses the largest 32-bit power of 5 ($5^{13} = 1220703125$).

If num is a power of 5, it divides this number evenly.

Bit manipulation is impractical as 5 is not a power of 2.

This is O(1) as it uses a single division.

Coding Part (with Unit Tests)

```
// Checks if num is a power of 5.
bool isPowerOfFive(int num) {
    if (num <= 0) return false; // Validate input
    return 1220703125 % num == 0; // Largest 32-bit power of 5
}
// Unit tests
void testIsPowerOfFive() {
    assertEquals(true, isPowerOfFive(125), "Test 149.1 - Power of 5 (125)");
    assertEquals(false, isPowerOfFive(10), "Test 149.2 - Not power of 5 (10)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate non-positive inputs.
 - Use largest power of 5 (1220703125).
 - Test with powers of 5 and others.
 - Avoid bit manipulation for non-power-of-2.
- **Expert Tips:**
 - Explain check: "Num must divide largest power of 5."

- In interviews, clarify: "Ask if bit-based solution is expected."
- Suggest optimization: "Division is optimal; bit methods don't apply."
- Test edge cases: "0, 1, or non-powers."

Problem 150: Find the Number of 1s in the Binary Representation of a Factorial

Issue Description

Count the number of 1 bits in the binary representation of $n!$, e.g., $4! = 24$ (11000) returns 2.

Problem Decomposition & Solution Steps

- **Input:** Non-negative integer n .
- **Output:** Number of 1s in $n!$.
- **Approach:** Compute factorial, count 1s.
- **Algorithm:** Factorial and Bit Count
 - **Explanation:** Compute $n!$ (handle overflow), then count 1s using Brian Kernighan's method.
- **Steps:**
 1. Validate non-negative input.
 2. Compute factorial (use long long for range).
 3. Count 1s in result.
- **Complexity:** Time $O(n + \log(n!))$, Space $O(1)$.

Algorithm Explanation

The factorial and bit count algorithm computes $n!$ by multiplying 1 to n , then counts 1s using $\text{num} \& (\text{num}-1)$.

Due to factorial size, use long long to handle larger n , but overflow limits practical n (up to ~ 20 for 64-bit).

Bit counting is $O(\log(n!))$ as it depends on the number's size, and factorial computation is $O(n)$.

Coding Part (with Unit Tests)

```
// Counts 1s in binary representation of n!
int bitsInFactorial(int n) {
    if (n < 0) return 0; // Validate input
    unsigned long long fact = 1;
    for (int i = 1; i <= n; i++) { // Compute factorial
        fact *= i;
    }
    int count = 0;
    while (fact) { // Count 1s
        fact &= (fact - 1);
        count++;
    }
    return count;
}

// Unit tests
void testBitsInFactorial() {
    assertEquals(2, bitsInFactorial(4), "Test 150.1 - Bits in 4! (24=11000)");
    assertEquals(1, bitsInFactorial(1), "Test 150.2 - Bits in 1! (1)");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use unsigned long long for factorial.
 - Validate non-negative input.
 - Test with small and large n (within limits).
 - Use Brian Kernighan's method for counting.
- **Expert Tips:**
 - Explain overflow: "Factorial grows fast; long long limits n to ~20."
 - In interviews, clarify: "Ask if overflow handling or modulo is needed."
 - Suggest optimization: "Precompute factorials or use bit patterns, but loop is clear."
 - Test edge cases: "0, 1, or large n."

Main Function to Run All Tests

```
int main() {  
    printf("Running tests for bit manipulation problems 136 to 150:\n");  
    testSetEvenBits();  
    testIsBinaryPalindrome();  
    testTrailingZeros();  
    testNotInRange();  
    testSumBits();  
    testIsPowerOfThree();  
    testLeadingZeros();  
    testMultiplyByNine();  
    testSameSetBits();  
    testBitsToMakePalindrome();  
    testClearOddBits();  
    testRightmostUnsetBit();  
    testRangeXor();  
    testIsPowerOfFive();  
    testBitsInFactorial();  
    return 0;  
}
```

Memory Management

(70 Problems)

Problem 151: Implement a Custom Malloc Wrapper to Track Memory Usage

Issue Description

Create a wrapper around malloc to track total allocated memory and number of allocations.

Problem Decomposition & Solution Steps

- **Input:** Size to allocate.
- **Output:** Pointer to allocated memory; track total size and count.
- **Approach:** Wrap malloc, maintain global counters.
- **Algorithm:** Wrapper with Tracking
 - **Explanation:** Call malloc, store size and increment allocation count, return pointer.
- **Steps:**
 1. Define global variables for total size and count.
 2. In wrapper, call malloc and update trackers.
 3. Return allocated pointer.
- **Complexity:** Time O(1), Space O(1) for tracking.

Algorithm Explanation

The wrapper algorithm calls malloc and updates global variables for total allocated bytes and number of allocations.

Thread safety is not required unless specified.

The wrapper preserves malloc's functionality while adding tracking, making it O(1) as it performs constant-time operations.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdlib.h>

// Global trackers
static size_t totalAllocated = 0;
static size_t allocationCount = 0;

// Custom malloc wrapper
void* myMalloc(size_t size) {
    void* ptr = malloc(size);
    if (ptr) {
        totalAllocated += size;
        allocationCount++;
    }
    return ptr;
}
// Get total allocated bytes
size_t getTotalAllocated() {
    return totalAllocated;
}
// Get allocation count
size_t getAllocationCount() {
    return allocationCount;
}
// Unit test helper
```

```

void assertSizeTEquals(size_t expected, size_t actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testMyMalloc() {
    totalAllocated = 0; // Reset
    allocationCount = 0;
    void* ptr = myMalloc(100);
    assertSizeTEquals(100, getTotalAllocated(), "Test 151.1 - Total allocated");
    assertSizeTEquals(1, getAllocationCount(), "Test 151.2 - Allocation count");
    free(ptr);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Check malloc return for NULL.
 - Use global variables for simplicity.
 - Reset trackers in tests.
 - Ensure thread safety if required.
- **Expert Tips:**
 - Explain tracking: "Global counters for size and count; update in wrapper."
 - In interviews, clarify: "Ask if thread safety or error logging is needed."
 - Suggest optimization: "Use a linked list for detailed tracking if needed."
 - Test edge cases: "Zero size, multiple allocations."

Problem 152: Detect a Memory Leak in a Given Program

Issue Description

Identify a memory leak in a sample program (conceptual, with code example).

Problem Decomposition & Solution Steps

- **Input:** Sample C code with allocations.
- **Output:** Identify unfreed memory.
- **Approach:** Analyze allocations and frees.
- **Algorithm:** Manual Inspection
 - **Explanation:** Check if each malloc has a corresponding free.
 - Provide a tool-like approach conceptually.
- **Steps:**
 1. Review code for malloc calls.
 2. Check for matching free calls.
 3. Report missing frees.
- **Complexity:** Time O(n) for code lines, Space O(1).

Algorithm Explanation

The manual inspection algorithm simulates a memory leak detector by tracking allocations and ensuring each has a free.

For a sample program, we identify allocations without corresponding frees.

In practice, tools like Valgrind automate this, but here we demonstrate manual analysis.

This is O(n) for code lines reviewed.

Coding Part (with Unit Tests)

```
// Sample program with a memory leak
void leakyFunction() {
    int* ptr1 = malloc(100 * sizeof(int)); // Allocated
    int* ptr2 = malloc(200 * sizeof(int)); // Allocated
    free(ptr1); // Freed
    // ptr2 not freed: LEAK
}

// Conceptual check (manual analysis)
void detectMemoryLeak() {
    printf("Test 152.1 - Leaky function analysis: ptr2 not freed, LEAK DETECTED\n");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Ensure every malloc has a free.
 - Use tools like Valgrind for automation.
 - Document allocations in complex code.
 - Test with various allocation patterns.
- **Expert Tips:**
 - Explain detection: "Match each malloc with a free; unmatched is a leak."
 - In interviews, clarify: "Ask if automated tool use is allowed."
 - Suggest optimization: "Wrap malloc/free to track automatically."
 - Test edge cases: "No frees, conditional frees."

Problem 153: Free a Linked List

Issue Description

Free all nodes in a singly linked list to prevent memory leaks.

Problem Decomposition & Solution Steps

- **Input:** Pointer to head of linked list.
- **Output:** None (memory freed).
- **Approach:** Traverse and free each node.
- **Algorithm:** Iterative Free
 - **Explanation:** Traverse list, free each node, update pointers.
- **Steps:**
 1. Validate head pointer.
 2. Save next pointer, free current node.

- 3. Move to next node until NULL.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The iterative free algorithm traverses the linked list, freeing each node after saving the next pointer to avoid losing the list.

It handles NULL or empty lists correctly.

This is O(n) for n nodes, using O(1) space as only temporary pointers are used.

Coding Part (with Unit Tests)

```
// Linked list node
typedef struct Node {
    int data;
    struct Node* next;
} Node;

// Frees entire linked list
void freeLinkedList(Node* head) {
    Node* current = head;
    while (current) {
        Node* next = current->next; // Save next
        free(current); // Free current
        current = next; // Move to next
    }
}

// Unit test (conceptual, checks no crashes)
void testFreeLinkedList() {
    Node* head = malloc(sizeof(Node));
    head->data = 1;
    head->next = malloc(sizeof(Node));
    head->next->data = 2;
    head->next->next = NULL;
    freeLinkedList(head);
    printf("Test 153.1 - Free linked list: PASSED (no crash)\n");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Save next pointer before freeing.
 - Handle NULL head.
 - Test with single and multi-node lists.
 - Avoid dangling pointers.
- **Expert Tips:**
 - Explain traversal: "Save next, free current, move forward."
 - In interviews, clarify: "Ask if recursive free is acceptable."
 - Suggest optimization: "Iterative is better than recursive for large lists."
 - Test edge cases: "NULL, single node, long list."

Problem 154: Write a Memory Pool Allocator for Fixed-Size Blocks

Issue Description

Implement a memory pool allocator for fixed-size blocks to reduce fragmentation.

Problem Decomposition & Solution Steps

- **Input:** Block size, number of blocks.
- **Output:** Allocate/free fixed-size blocks.
- **Approach:** Use a free list in pre-allocated memory.
- **Algorithm:** Free List Allocator
 - **Explanation:** Pre-allocate memory, maintain a free list of blocks, allocate/free by managing list.
- **Steps:**
 1. Initialize pool with pre-allocated memory.
 2. Link blocks in a free list.
 3. Allocate by returning head of free list.
 4. Free by adding block back to list.
- **Complexity:** Time O(1) for alloc/free, Space O($n * \text{block_size}$).

Algorithm Explanation

The free list allocator pre-allocates a contiguous memory block and divides it into fixed-size blocks, linked as a free list.

Allocation removes and returns the head block; freeing adds the block back to the list.

This is O(1) for both operations, with space proportional to the pool size.

Coding Part (with Unit Tests)

```
typedef struct MemoryPool {
    void* memory; // Pre-allocated memory
    void* freeList; // Head of free list
    size_t blockSize; // Size of each block
    size_t numBlocks; // Number of blocks
} MemoryPool;

// Initialize memory pool
MemoryPool* createMemoryPool(size_t blockSize, size_t numBlocks) {
    MemoryPool* pool = malloc(sizeof(MemoryPool));
    pool->blockSize = blockSize;
    pool->numBlocks = numBlocks;
    pool->memory = malloc(blockSize * numBlocks);
    pool->freeList = pool->memory;
    // Link blocks
    for (size_t i = 0; i < numBlocks - 1; i++) {
        *(void**)((char*)pool->memory + i * blockSize) = (char*)pool->memory + (i + 1) * blockSize;
    }
    *(void**)((char*)pool->memory + (numBlocks - 1) * blockSize) = NULL;
    return pool;
}
```

```

// Allocate block
void* poolAlloc(MemoryPool* pool) {
    if (!pool->freeList) return NULL;
    void* block = pool->freeList;
    pool->freeList = *(void**)block; // Update free list
    return block;
}

// Free block
void poolFree(MemoryPool* pool, void* block) {
    if (!block) return;
    *(void**)block = pool->freeList; // Add to free list
    pool->freeList = block;
}

// Destroy pool
void destroyMemoryPool(MemoryPool* pool) {
    if (pool) {
        free(pool->memory);
        free(pool);
    }
}

// Unit tests
void testMemoryPool() {
    MemoryPool* pool = createMemoryPool(16, 3);
    void* block1 = poolAlloc(pool);
    void* block2 = poolAlloc(pool);
    poolFree(pool, block1);
    void* block3 = poolAlloc(pool);
    assertEquals(1, block1 == block3, "Test 154.1 - Reuse freed block");
    destroyMemoryPool(pool);
    printf("Test 154.2 - Pool alloc/free: PASSED (no crash)\n");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate pool and block pointers.
 - Ensure block size accommodates pointers.
 - Test allocation and freeing cycles.
 - Free pool memory on destroy.
- **Expert Tips:**
 - Explain free list: "Link blocks in pre-allocated memory; alloc/free O(1)."
 - In interviews, clarify: "Ask if thread safety or alignment is needed."
 - Suggest optimization: "Use bitmaps for small blocks, but list is simple."
 - Test edge cases: "Empty pool, full allocation, multiple frees."

Problem 155: Check if a Pointer Points to Valid Memory (Conceptual)

Issue Description

Determine if a pointer points to valid, allocated memory (conceptual discussion).

Problem Decomposition & Solution Steps

- **Input:** Pointer.
- **Output:** Boolean (conceptual).

- **Approach:** Discuss validation techniques.
- **Algorithm:** Conceptual Validation
 - **Explanation:** No standard C function checks validity; discuss tracking allocations or OS-specific methods.
- **Steps:**
 1. Track allocations in a custom structure.
 2. Check if pointer falls within tracked ranges.
 3. Discuss OS-specific checks (e.g., msync).
- **Complexity:** Time O(n) for tracked allocations, Space O(n).

Algorithm Explanation

Validating a pointer's memory is non-trivial in standard C, as no built-in function checks if a pointer is valid.

A custom allocator can track allocated ranges (start, size) and check if the pointer lies within.

OS-specific methods (e.g., msync on POSIX) may help but are non-portable.

This is O(n) for n tracked allocations.

Coding Part (with Unit Tests)

```
// Conceptual: Track allocations
typedef struct Allocation {
    void* start;
    size_t size;
} Allocation;

#define MAX_ALLOCS 100
static Allocation allocs[MAX_ALLOCS];
static int allocCount = 0;

// Track allocation
void trackAllocation(void* ptr, size_t size) {
    if (allocCount < MAX_ALLOCS) {
        allocs[allocCount].start = ptr;
        allocs[allocCount].size = size;
        allocCount++;
    }
}

// Check if pointer is valid
bool isValidPointer(void* ptr) {
    for (int i = 0; i < allocCount; i++) {
        if (ptr >= allocs[i].start && ptr < (char*)allocs[i].start + allocs[i].size) {
            return true;
        }
    }
    return false;
}

// Unit tests
void testIsValidPointer() {
    void* ptr = malloc(100);
    trackAllocation(ptr, 100);
    assertBoolEquals(true, isValidPointer(ptr), "Test 155.1 - Valid pointer");
    assertBoolEquals(false, isValidPointer((void*)0x123), "Test 155.2 - Invalid pointer");
    free(ptr);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Track allocations explicitly.
 - Avoid dereferencing unverified pointers.
 - Use OS-specific checks cautiously.
 - Test with valid and invalid pointers.
- **Expert Tips:**
 - Explain limitation: "C can't check validity; need custom tracking."
 - In interviews, clarify: "Ask if OS-specific methods are allowed."
 - Suggest optimization: "Use hash tables for faster lookup."
 - Test edge cases: "NULL, unallocated, or boundary pointers."

Problem 156: Copy a Block of Memory Safely

Issue Description

Copy a block of memory from source to destination safely, e.g., copy 100 bytes.

Problem Decomposition & Solution Steps

- **Input:** Source pointer, destination pointer, size.
- **Output:** None (memory copied).
- **Approach:** Validate and use memcpy.
- **Algorithm:** Safe Memory Copy
 - **Explanation:** Check pointers and size, then use memcpy for copying.
- **Steps:**
 1. Validate non-NULL pointers and size.
 2. Use memcpy to copy memory.
 3. Handle errors if invalid.
- **Complexity:** Time $O(n)$, Space $O(1)$.

Algorithm Explanation

The safe memory copy algorithm validates pointers and size to prevent crashes or undefined behavior, then uses memcpy for efficient copying.

Validation ensures source and destination are non-NULL and size is non-negative.

This is $O(n)$ for n bytes copied, with $O(1)$ extra space.

Coding Part (with Unit Tests)

```
// Copies memory safely
bool safeMemcpy(void* dest, const void* src, size_t size) {
    if (!dest || !src || size == 0) return false;
    memcpy(dest, src, size);
    return true;
}
```

```

// Unit tests
void testSafeMemcpy() {
    int src[] = {1, 2, 3};
    int dest[3];
    bool result = safeMemcpy(dest, src, 3 * sizeof(int));
    assertBoolEquals(true, result && dest[0] == 1 && dest[1] == 2 && dest[2] == 3, "Test 156.1 - Copy array");
    assertBoolEquals(false, safeMemcpy(NULL, src, 3 * sizeof(int)), "Test 156.2 - NULL dest");
}

```

Best Practices & Expert Tips

- **Best Practices:**

- Validate pointers and size.
- Use memcpy for efficiency.
- Return success/failure status.
- Test with valid and invalid inputs.

- **Expert Tips:**

- Explain safety: "Check pointers to avoid crashes; use standard memcpy."
- In interviews, clarify: "Ask if overlap handling (memmove) is needed."
- Suggest optimization: "Custom copy loop for small sizes, but memcpy is optimized."
- Test edge cases: "NULL, zero size, or large blocks."

Problem 157: Find the Size of a Dynamically Allocated Array

Issue Description

Determine the size of a dynamically allocated array (conceptual, as C doesn't store size).

Problem Decomposition & Solution Steps

- **Input:** Pointer to dynamic array.
- **Output:** Size in bytes (conceptual).
- **Approach:** Track size during allocation.
- **Algorithm:** Size Tracking
 - **Explanation:** Since C doesn't store array sizes, track size in a wrapper structure.
- **Steps:**
 1. Wrap allocation with size tracking.
 2. Store size in structure.
 3. Return size when queried.
- **Complexity:** Time O(1), Space O(1) per allocation.

Algorithm Explanation

The size tracking algorithm requires wrapping allocations in a structure that stores the size alongside the pointer.

Standard C provides no way to query dynamic array size, so explicit tracking is needed.

Retrieving the size is O(1) after storing during allocation.

Coding Part (with Unit Tests)

```
typedef struct DynamicArray {
    void* data;
    size_t size;
} DynamicArray;

// Allocate with size tracking
DynamicArray* createDynamicArray(size_t size) {
    DynamicArray* arr = malloc(sizeof(DynamicArray));
    arr->data = malloc(size);
    arr->size = size;
    return arr;
}

// Get array size
size_t getArraySize(DynamicArray* arr) {
    return arr ? arr->size : 0;
}

// Free array
void freeDynamicArray(DynamicArray* arr) {
    if (arr) {
        free(arr->data);
        free(arr);
    }
}

// Unit tests
void testGetArraySize() {
    DynamicArray* arr = createDynamicArray(100);
    assertSizeTEquals(100, getArraySize(arr), "Test 157.1 - Array size");
    freeDynamicArray(arr);
    assertSizeTEquals(0, getArraySize(NULL), "Test 157.2 - NULL array");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Store size explicitly in structure.
 - Validate pointers before access.
 - Free both data and structure.
 - Test with various sizes.
- **Expert Tips:**
 - Explain limitation: "C doesn't store sizes; need custom tracking."
 - In interviews, clarify: "Ask if size in elements or bytes."
 - Suggest optimization: "Store size before array, but structure is safer."
 - Test edge cases: "NULL, zero size, or large arrays."

Problem 158: Resize a Dynamic Array

Issue Description

Resize a dynamically allocated array to a new size, preserving data.

Problem Decomposition & Solution Steps

- **Input:** Pointer, old size, new size.
- **Output:** Pointer to resized array.
- **Approach:** Use realloc with size tracking.
- **Algorithm:** Realloc with Copy
 - **Explanation:** Use realloc to resize, copy data if necessary, update size.
- **Steps:**
 1. Validate input and pointers.
 2. Use realloc to resize.
 3. Handle truncation or zero-initialization.
- **Complexity:** Time O(n) for copy, Space O(n).

Algorithm Explanation

The realloc with copy algorithm uses realloc to resize the array, which may copy data to a new location.

If size increases, new memory is zeroed or left uninitialized; if it decreases, data is truncated.

This is O(n) for n bytes copied, with space proportional to the new size.

Coding Part (with Unit Tests)

```
// Resize dynamic array
void* resizeArray(void* arr, size_t oldSize, size_t newSize) {
    if (!arr || newSize == 0) return NULL;
    void* newArr = realloc(arr, newSize);
    if (newArr && newSize > oldSize) {
        memset((char*)newArr + oldSize, 0, newSize - oldSize); // Zero new memory
    }
    return newArr;
}

// Unit tests
void testResizeArray() {
    int* arr = malloc(2 * sizeof(int));
    arr[0] = 1; arr[1] = 2;
    arr = resizeArray(arr, 2 * sizeof(int), 4 * sizeof(int));
    assertEquals(1, arr[0] && arr[1] == 2, "Test 158.1 - Resize and preserve data");
    free(arr);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Check realloc return for NULL.
 - Zero new memory if needed.
 - Validate input sizes.
 - Test with shrinking and expanding.
- **Expert Tips:**
 - Explain realloc: "May copy data; preserves existing content."
 - In interviews, clarify: "Ask if new memory should be initialized."
 - Suggest optimization: "Custom realloc for specific patterns."
 - Test edge cases: "NULL, zero size, or large resize."

Problem 159: Handle Stack Overflow Detection

Issue Description

Detect stack overflow in a C program (conceptual, with example).

Problem Decomposition & Solution Steps

- **Input:** Running program.
- **Output:** Detect stack overflow.
- **Approach:** Use guard pages or recursion depth.
- **Algorithm:** Conceptual Stack Check
 - **Explanation:** Monitor stack usage via guard pages or recursion limits (platform-specific).
- **Steps:**
 1. Set stack size limit (if possible).
 2. Use recursion depth counter or guard page.
 3. Signal overflow if exceeded.
- **Complexity:** Time O(1) per check, Space O(1).

Algorithm Explanation

Stack overflow detection in C is platform-dependent.

One approach uses a guard page (OS-level) that triggers a signal on access.

Another tracks recursion depth in recursive functions.

Here, we show a simple depth-based check.

This is O(1) per check, with minimal space.

Coding Part (with Unit Tests)

```
// Example recursive function with stack overflow check
bool stackOverflowDetected(int depth, int maxDepth) {
    if (depth > maxDepth) return true; // Overflow
    // Simulate recursion
    return false;
}

// Unit tests
void testStackOverflow() {
    assertEquals(false, stackOverflowDetected(10, 100), "Test 159.1 - No overflow");
    assertEquals(true, stackOverflowDetected(101, 100), "Test 159.2 - Overflow detected");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Set reasonable depth limits.
 - Use platform-specific signals if available.
 - Avoid infinite recursion.

- Test with deep and shallow calls.
- **Expert Tips:**
 - Explain detection: "Track depth or use guard pages for overflow."
 - In interviews, clarify: "Ask if platform-specific methods are allowed."
 - Suggest optimization: "Use OS signals for robust detection."
 - Test edge cases: "Max depth, shallow calls."

Problem 160: Implement a Custom Free Wrapper with Error Checking

Issue Description

Create a wrapper around free to check for invalid pointers and track deallocations.

Problem Decomposition & Solution Steps

- **Input:** Pointer to free.
- **Output:** None (memory freed, errors checked).
- **Approach:** Wrap free, validate pointer.
- **Algorithm:** Wrapper with Validation
 - **Explanation:** Check for NULL or invalid pointers, call free, track deallocations.
- **Steps:**
 1. Validate pointer (NULL check).
 2. Call free if valid.
 3. Update deallocation counter.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The wrapper algorithm validates the pointer (NULL is safe to free in C) and calls free.

A global counter tracks deallocations.

Invalid pointer detection requires tracking allocations (not implemented here for simplicity).

This is O(1) as it performs constant-time checks and free.

Coding Part (with Unit Tests)

```
// Global deallocation tracker
static size_t deallocationCount = 0;

// Custom free wrapper
void myFree(void* ptr) {
    if (ptr) { // Basic validation
        free(ptr);
        deallocationCount++;
    }
}
```

```

// Get deallocation count
size_t getDeallocationCount() {
    return deallocationCount;
}

// Unit tests
void testMyFree() {
    deallocationCount = 0; // Reset
    void* ptr = malloc(100);
    myFree(ptr);
    assertSizeTEquals(1, getDeallocationCount(), "Test 160.1 - Deallocation count");
    myFree(NULL);
    assertSizeTEquals(1, getDeallocationCount(), "Test 160.2 - NULL free");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Check for NULL before freeing.
 - Track deallocations for debugging.
 - Avoid double-free (requires tracking).
 - Test with valid and NULL pointers.
- **Expert Tips:**
 - Explain wrapper: "Validate and free; track for debugging."
 - In interviews, clarify: "Ask if double-free detection is needed."
 - Suggest optimization: "Track pointers to detect invalid frees."
 - Test edge cases: "NULL, already freed pointers."

Problem 161: Merge Two Dynamic Arrays into One

Issue Description

Merge two dynamically allocated arrays into a single array.

Problem Decomposition & Solution Steps

- **Input:** Two arrays, their sizes.
- **Output:** Pointer to merged array.
- **Approach:** Allocate new array, copy both.
- **Algorithm:** Allocate and Copy
 - **Explanation:** Allocate memory for total size, copy first array, then second.
- **Steps:**
 1. Validate inputs and sizes.
 2. Allocate new array for total size.
 3. Copy both arrays using memcpy.
 4. Return new array.
- **Complexity:** Time $O(n_1 + n_2)$, Space $O(n_1 + n_2)$.

Algorithm Explanation

The allocate and copy algorithm allocates a new array of size $n_1 + n_2$, then uses `memcpy` to copy the first array followed by the second.

Validation ensures non-NULL pointers and valid sizes.

This is $O(n_1 + n_2)$ for copying, with space for the new array.

Coding Part (with Unit Tests)

```
// Merge two dynamic arrays
void* mergeArrays(void* arr1, size_t size1, void* arr2, size_t size2) {
    if (!arr1 || !arr2 || size1 == 0 || size2 == 0) return NULL;
    void* result = malloc(size1 + size2);
    if (!result) return NULL;
    memcpy(result, arr1, size1);
    memcpy((char*)result + size1, arr2, size2);
    return result;
}

// Unit tests
void testMergeArrays() {
    int arr1[] = {1, 2};
    int arr2[] = {3, 4};
    int* result = mergeArrays(arr1, 2 * sizeof(int), arr2, 2 * sizeof(int));
    assertIntEquals(1, result && result[0] == 1 && result[1] == 2 && result[2] == 3 && result[3] == 4,
    "Test 161.1 - Merge arrays");
    free(result);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate pointers and sizes.
 - Use `memcpy` for efficiency.
 - Free result after use.
 - Test with different-sized arrays.
- **Expert Tips:**
 - Explain merge: "Allocate total size, copy arrays sequentially."
 - In interviews, clarify: "Ask if overlap or type safety is needed."
 - Suggest optimization: "Use `realloc` for in-place merge if applicable."
 - Test edge cases: "NULL, zero size, or large arrays."

Problem 162: Check for Memory Alignment in a Structure

Issue Description

Check if a structure's members are properly aligned in memory.

Problem Decomposition & Solution Steps

- **Input:** Structure definition.
- **Output:** Alignment status (conceptual).

- **Approach:** Calculate offsets and check alignment.
- **Algorithm:** Offset and Alignment Check
 - **Explanation:** Use `offsetof` to check member offsets, ensure they meet alignment requirements.
- **Steps:**
 1. Define structure with various types.
 2. Use `offsetof` to get member offsets.
 3. Check if offsets are multiples of type alignments.
- **Complexity:** Time O(1) for fixed struct, Space O(1).

Algorithm Explanation

The offset and alignment check algorithm uses `offsetof` to get byte offsets of structure members.

Each type (e.g., int, double) has an alignment requirement (typically size of type).

Check if each member's offset is a multiple of its alignment.

This is O(1) for a fixed structure.

Coding Part (with Unit Tests)

```
#include <stddef.h>

// Sample structure
typedef struct {
    char c; // 1 byte
    int i; // 4 bytes
    double d; // 8 bytes
} AlignedStruct;

// Check alignment
bool checkAlignment() {
    bool cAlign = offsetof(AlignedStruct, c) % 1 == 0; // char: 1-byte align
    bool iAlign = offsetof(AlignedStruct, i) % 4 == 0; // int: 4-byte align
    bool dAlign = offsetof(AlignedStruct, d) % 8 == 0; // double: 8-byte align
    return cAlign && iAlign && dAlign;
}

// Unit tests
void testCheckAlignment() {
    assertBoolEquals(true, checkAlignment(), "Test 162.1 - Structure alignment");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use `offsetof` for accuracy.
 - Check alignment per type.
 - Consider padding in structs.
 - Test with different member types.
- **Expert Tips:**
 - Explain alignment: "Offsets must be multiples of type alignment."
 - In interviews, clarify: "Ask if specific platform alignment rules apply."
 - Suggest optimization: "Use `#pragma pack` for control if needed."

- Test edge cases: "Packed structs, large types."

Problem 163: Detect Double-Free Errors

Issue Description

Detect if a pointer is freed multiple times (conceptual with tracking).

Problem Decomposition & Solution Steps

- **Input:** Pointer to free.
- **Output:** Detect double-free attempts.
- **Approach:** Track freed pointers.
- **Algorithm:** Freed Pointer Tracking
 - **Explanation:** Maintain a list of freed pointers, check before freeing.
- **Steps:**
 1. Track pointers in a freed list.
 2. Before freeing, check if already freed.
 3. Free and add to list if valid.
- **Complexity:** Time $O(n)$ for list check, Space $O(n)$.

Algorithm Explanation

The freed pointer tracking algorithm stores freed pointers in a list.

Before calling free, check if the pointer is in the list to detect double-free.

This is $O(n)$ for n freed pointers due to list search, with space for the list.

In practice, tools like Valgrind detect this automatically.

Coding Part (with Unit Tests)

```
#define MAX_FREED 100
static void* freedPointers[MAX_FREED];
static int freedCount = 0;

// Check and free pointer
bool safeFree(void* ptr) {
    if (!ptr) return false;
    for (int i = 0; i < freedCount; i++) {
        if (freedPointers[i] == ptr) return false; // Double-free
    }
    free(ptr);
    if (freedCount < MAX_FREED) {
        freedPointers[freedCount++] = ptr;
    }
    return true;
}
// Unit tests
void testSafeFree() {
    freedCount = 0;
    void* ptr = malloc(100);
    bool result1 = safeFree(ptr);
    bool result2 = safeFree(ptr);
```

```
    assertBoolEquals(true, result1, "Test 163.1 - First free");
    assertBoolEquals(false, result2, "Test 163.2 - Double-free detected");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Track freed pointers explicitly.
 - Validate pointer before freeing.
 - Limit list size to avoid overflow.
 - Test with single and double frees.
- **Expert Tips:**
 - Explain detection: "Check freed list to catch double-free."
 - In interviews, clarify: "Ask if hash table for O(1) is needed."
 - Suggest optimization: "Use hash table for faster checks."
 - Test edge cases: "NULL, multiple frees, or large lists."

Problem 164: Simulate Garbage Collection for C

Issue Description

Simulate a simple garbage collector for C by freeing unreachable memory.

Problem Decomposition & Solution Steps

- **Input:** Set of allocated pointers, reachable pointers.
- **Output:** Free unreachable memory.
- **Approach:** Mark and sweep simulation.
- **Algorithm:** Mark and Sweep
 - **Explanation:** Mark reachable pointers, sweep (free) unmarked ones.
- **Steps:**
 1. Track all allocations in a list.
 2. Mark reachable pointers.
 3. Free unmarked pointers.
- **Complexity:** Time $O(n)$, Space $O(n)$ for n allocations.

Algorithm Explanation

The mark and sweep algorithm tracks all allocations in a list.

Mark reachable pointers (e.g., in a root set), then sweep through the list, freeing unmarked pointers.

This simulates basic garbage collection, assuming a simple reachability model.

It's $O(n)$ for n pointers, with space for the allocation list.

Coding Part (with Unit Tests)

```
typedef struct AllocNode {
    void* ptr;
    bool marked;
} AllocNode;

static AllocNode allocations[MAX_ALLOCS];
static int allocIndex = 0;

// Track allocation
void trackAlloc(void* ptr) {
    if (allocIndex < MAX_ALLOCS) {
        allocations[allocIndex].ptr = ptr;
        allocations[allocIndex].marked = false;
        allocIndex++;
    }
}

// Mark reachable
void markReachable(void* ptr) {
    for (int i = 0; i < allocIndex; i++) {
        if (allocations[i].ptr == ptr) {
            allocations[i].marked = true;
        }
    }
}

// Sweep unmarked
void sweepUnmarked() {
    for (int i = 0; i < allocIndex; i++) {
        if (!allocations[i].marked && allocations[i].ptr) {
            free(allocations[i].ptr);
            allocations[i].ptr = NULL;
        }
    }
}

// Unit tests
void testGarbageCollection() {
    allocIndex = 0;
    void* ptr1 = malloc(100);
    void* ptr2 = malloc(200);
    trackAlloc(ptr1);
    trackAlloc(ptr2);
    markReachable(ptr1);
    sweepUnmarked();
    assertEquals(1, ptr1 != NULL, "Test 164.1 - ptr1 marked, not freed");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Track all allocations.
 - Mark only reachable pointers.
 - Free unmarked pointers safely.
 - Test with reachable/unreachable pointers.
- **Expert Tips:**
 - Explain mark-sweep: "Mark reachable, free unmarked memory."
 - In interviews, clarify: "Ask if complex reachability analysis is needed."
 - Suggest optimization: "Use reference counting for simpler cases."

- Test edge cases: "No allocations, all unreachable."

Problem 165: Defragment a Memory Pool

Issue Description

Defragment a memory pool by moving allocated blocks to contiguous memory.

Problem Decomposition & Solution Steps

- **Input:** Memory pool with allocated/free blocks.
- **Output:** Contiguous allocated blocks.
- **Approach:** Move allocated blocks to start.
- **Algorithm:** Compaction
 - **Explanation:** Track allocated blocks, move them to the start, update pointers.
- **Steps:**
 1. Track allocated blocks in pool.
 2. Move blocks to contiguous memory.
 3. Update pointers and free list.
- **Complexity:** Time $O(n)$, Space $O(n)$ for tracking.

Algorithm Explanation

The compaction algorithm iterates through the memory pool, moving allocated blocks to the start and updating their pointers.

Free blocks are linked at the end.

This reduces fragmentation by ensuring allocated blocks are contiguous.

It's $O(n)$ for n blocks, with space for tracking allocations.

Coding Part (with Unit Tests)

```

typedef struct Block {
    void* ptr;
    bool allocated;
    size_t size;
} Block;

typedef struct DefragPool {
    void* memory;
    Block* blocks;
    size_t blockSize;
    size_t numBlocks;
} DefragPool;

// Initialize pool
DefragPool* createDefragPool(size_t blockSize, size_t numBlocks) {
    DefragPool* pool = malloc(sizeof(DefragPool));
    pool->blockSize = blockSize;
    pool->numBlocks = numBlocks;
    pool->memory = malloc(blockSize * numBlocks);
    pool->blocks = malloc(numBlocks * sizeof(Block));
    for (size_t i = 0; i < numBlocks; i++) {
        pool->blocks[i].ptr = pool->memory + (i * blockSize);
        pool->blocks[i].size = blockSize;
        pool->blocks[i].allocated = false;
    }
    return pool;
}

```

```

        pool->blocks[i].ptr = (char*)pool->memory + i * blockSize;
        pool->blocks[i].allocated = false;
        pool->blocks[i].size = blockSize;
    }
    return pool;
}

// Allocate block
void* defragPoolAlloc(DefragPool* pool) {
    for (size_t i = 0; i < pool->numBlocks; i++) {
        if (!pool->blocks[i].allocated) {
            pool->blocks[i].allocated = true;
            return pool->blocks[i].ptr;
        }
    }
    return NULL;
}

// Defragment pool
void defragmentPool(DefragPool* pool) {
    size_t newPos = 0;
    for (size_t i = 0; i < pool->numBlocks; i++) {
        if (pool->blocks[i].allocated) {
            if (i != newPos) {
                memmove((char*)pool->memory + newPos * pool->blockSize, pool->blocks[i].ptr, pool-
>blockSize);
                pool->blocks[i].ptr = (char*)pool->memory + newPos * pool->blockSize;
            }
            newPos++;
        }
    }
}

// Free pool
void destroyDefragPool(DefragPool* pool) {
    if (pool) {
        free(pool->memory);
        free(pool->blocks);
        free(pool);
    }
}
// Unit tests
void testDefragmentPool() {
    DefragPool* pool = createDefragPool(16, 3);
    void* block1 = defragPoolAlloc(pool);
    void* block2 = defragPoolAlloc(pool);
    pool->blocks[0].allocated = false; // Free first block
    defragmentPool(pool);
    assertEquals(1, pool->blocks[1].ptr == pool->memory, "Test 165.1 - Block moved to start");
    destroyDefragPool(pool);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track allocated blocks explicitly.
 - Use memmove for safe copying.
 - Update pointers after moving.
 - Test with fragmented and contiguous pools.
- **Expert Tips:**
 - Explain defragmentation: "Move allocated blocks to start, update pointers."
 - In interviews, clarify: "Ask if pointer updates are external."
 - Suggest optimization: "Use bitmaps for allocation status."

- Test edge cases: "Empty pool, all allocated, or sparse allocations."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for memory management problems 151 to 165:\n");
    testMyMalloc();
    detectMemoryLeak();
    testFreeLinkedList();
    testMemoryPool();
    testIsValidPointer();
    testSafeMemcpy();
    testGetArraySize();
    testResizeArray();
    testStackOverflow();
    testMyFree();
    testMergeArrays();
    testCheckAlignment();
    testSafeFree();
    testGarbageCollection();
    testDefragmentPool();
    return 0;
}
```

Problem 166: Check if a Pointer is Within a Given Memory Range

Issue Description

Check if a pointer lies within a specified memory range [start, end).

Problem Decomposition & Solution Steps

- **Input:** Pointer, start address, size of range.
- **Output:** Boolean indicating if pointer is in range.
- **Approach:** Compare pointer against range boundaries.
- **Algorithm:** Range Check
 - **Explanation:** Check if $\text{pointer} \geq \text{start}$ and $\text{pointer} < \text{start} + \text{size}$.
- **Steps:**
 1. Validate pointers (non-NULL).
 2. Perform boundary comparison.
 3. Return true if within range.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The range check algorithm compares the pointer's address to the range [start, start + size).

If the pointer is greater than or equal to start and less than start + size, it's within the range.

This is O(1) as it involves simple comparisons, with no extra space.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>

// Check if pointer is within [start, start + size)
bool isPointerInRange(void* ptr, void* start, size_t size) {
    if (!ptr || !start || size == 0) return false;
    return (char*)ptr >= (char*)start && (char*)ptr < (char*)start + size;
}

// Unit test helper
void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testIsPointerInRange() {
    char* block = malloc(100);
    assertBoolEquals(true, isPointerInRange(block + 50, block, 100), "Test 166.1 - Pointer in range");
    assertBoolEquals(false, isPointerInRange(block + 100, block, 100), "Test 166.2 - Pointer out of
range");
    free(block);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate pointers and size.
 - Use `char*` for byte-level arithmetic.
 - Handle edge cases like zero size.
 - Test with boundary and out-of-range pointers.
- **Expert Tips:**
 - Explain check: "Compare `ptr` to `[start, start + size]`."
 - In interviews, clarify: "Ask if inclusive end is needed."
 - Suggest optimization: "This is optimal; simple comparisons."
 - Test edge cases: "NULL, boundary pointers, or empty range."

Problem 167: Align Memory to a Boundary

Issue Description

Allocate memory aligned to a specified boundary (e.g., 16-byte boundary).

Problem Decomposition & Solution Steps

- **Input:** Size, alignment boundary (power of 2).
- **Output:** Aligned memory pointer.
- **Approach:** Allocate extra space, adjust to boundary.
- **Algorithm:** Aligned Allocation
 - **Explanation:** Allocate `size + alignment`, adjust pointer to nearest boundary, store original for freeing.
- **Steps:**
 1. Validate alignment (power of 2).

2. Allocate size + alignment - 1.
 3. Adjust pointer to next aligned address.
 4. Store original pointer for freeing.
- **Complexity:** Time O(1), Space O(size + alignment).

Algorithm Explanation

The aligned allocation algorithm allocates extra space to ensure an aligned address exists.

Adjust the pointer by rounding up to the next multiple of the alignment (using bitwise operations for power-of-2 alignments).

Store the original pointer before the aligned one for proper freeing.

This is O(1) for allocation, with space for the requested size plus alignment overhead.

Coding Part (with Unit Tests)

```
// Allocate aligned memory
void* alignedMalloc(size_t size, size_t alignment) {
    if (size == 0 || (alignment & (alignment - 1)) != 0) return NULL; // Validate alignment
    void* raw = malloc(size + alignment - 1 + sizeof(void*));
    if (!raw) return NULL;
    void* aligned = (void*)((size_t)((char*)raw + sizeof(void*) + alignment - 1) / alignment) * alignment;
    ((void**)aligned)[-1] = raw; // Store original pointer
    return aligned;
}

// Free aligned memory
void alignedFree(void* ptr) {
    if (ptr) free(((void**)ptr)[-1]);
}

// Unit tests
void testAlignedMalloc() {
    void* ptr = alignedMalloc(100, 16);
    assertBoolEquals(true, ptr && ((size_t)ptr % 16) == 0, "Test 167.1 - 16-byte aligned");
    alignedFree(ptr);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate alignment as power of 2.
 - Store original pointer for freeing.
 - Use bitwise math for alignment.
 - Test with different alignments.
- **Expert Tips:**
 - Explain alignment: "Round up to next boundary; store raw pointer."
 - In interviews, clarify: "Ask if POSIX aligned_alloc is allowed."
 - Suggest optimization: "Use aligned_alloc for standard compliance."
 - Test edge cases: "Invalid alignment, zero size."

Problem 168: Track Memory Allocations

Issue Description

Track all memory allocations and their sizes for debugging or analysis.

Problem Decomposition & Solution Steps

- **Input:** Memory allocations via custom malloc.
- **Output:** Track allocated pointers and sizes.
- **Approach:** Use a list to store allocation metadata.
- **Algorithm:** Allocation Tracking
 - **Explanation:** Wrap malloc, store pointer and size in a list.
- **Steps:**
 1. Initialize a list for allocations.
 2. On malloc, add pointer and size.
 3. On free, remove from list.
- **Complexity:** Time $O(1)$ for tracking, $O(n)$ for querying, Space $O(n)$.

Algorithm Explanation

The allocation tracking algorithm wraps malloc and free, storing each allocation's pointer and size in a list.

Allocation adds to the list, freeing removes it.

This allows querying all active allocations.

Tracking is $O(1)$ per operation, querying is $O(n)$ for n allocations, with space for the list.

Coding Part (with Unit Tests)

```
#define MAX_ALLOCS 100
typedef struct AllocRecord {
    void* ptr;
    size_t size;
} AllocRecord;

static AllocRecord allocs[MAX_ALLOCS];
static int allocCount = 0;

// Custom malloc with tracking
void* trackMalloc(size_t size) {
    void* ptr = malloc(size);
    if (ptr && allocCount < MAX_ALLOCS) {
        allocs[allocCount].ptr = ptr;
        allocs[allocCount].size = size;
        allocCount++;
    }
    return ptr;
}
```

```

// Custom free with tracking
void trackFree(void* ptr) {
    if (!ptr) return;
    for (int i = 0; i < allocCount; i++) {
        if (allocs[i].ptr == ptr) {
            allocs[i] = allocs[--allocCount]; // Remove
            break;
        }
    }
    free(ptr);
}

// Unit tests
void testTrackMalloc() {
    allocCount = 0;
    void* ptr = trackMalloc(100);
    assertBoolEquals(true, allocCount == 1 && allocs[0].size == 100, "Test 168.1 - Track allocation");
    trackFree(ptr);
    assertBoolEquals(true, allocCount == 0, "Test 168.2 - Track free");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate pointers and list capacity.
 - Remove freed pointers from list.
 - Test with multiple allocations.
 - Handle list overflow.
- **Expert Tips:**
 - Explain tracking: "Store pointer and size; remove on free."
 - In interviews, clarify: "Ask if hash table for O(1) is needed."
 - Suggest optimization: "Use dynamic list or hash table for scalability."
 - Test edge cases: "No allocations, full list."

Problem 169: Handle Out-of-Memory Conditions

Issue Description

Handle cases where malloc returns NULL due to insufficient memory.

Problem Decomposition & Solution Steps

- **Input:** Allocation request.
- **Output:** Safe handling of NULL return.
- **Approach:** Check malloc return, provide fallback.
- **Algorithm:** Null Check with Fallback
 - **Explanation:** Wrap malloc, check for NULL, log error or retry.
- **Steps:**
 1. Call malloc and check return.
 2. If NULL, log error or retry.
 3. Return pointer or NULL.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The null check with fallback algorithm wraps malloc to detect NULL returns, indicating out-of-memory.

Log the error or implement a fallback (e.g., retry with smaller size).

This is O(1) per allocation attempt, with minimal space for logging.

Coding Part (with Unit Tests)

```
// Custom malloc with out-of-memory handling
void* safeMalloc(size_t size) {
    void* ptr = malloc(size);
    if (!ptr) {
        fprintf(stderr, "Out of memory for size %zu\n", size);
        // Fallback: Retry with smaller size (example)
        if (size > 1) return safeMalloc(size / 2);
    }
    return ptr;
}

// Unit tests (conceptual, assumes success)
void testSafeMalloc() {
    void* ptr = safeMalloc(100);
    assertBoolEquals(true, ptr != NULL, "Test 169.1 - Successful allocation");
    free(ptr);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Always check malloc return.
 - Log errors for debugging.
 - Implement fallback if appropriate.
 - Test with large allocations.
- **Expert Tips:**
 - Explain handling: "Check NULL; log or retry with smaller size."
 - In interviews, clarify: "Ask if specific fallback is required."
 - Suggest optimization: "Use memory pools for fallback."
 - Test edge cases: "Large sizes, repeated failures."

Problem 170: Merge Two Memory Blocks Without Overlap

Issue Description

Merge two non-overlapping memory blocks into a single block.

Problem Decomposition & Solution Steps

- **Input:** Two pointers, their sizes.
- **Output:** Pointer to merged block.

- **Approach:** Check for overlap, allocate and copy.
- **Algorithm:** Overlap Check and Merge
 - **Explanation:** Verify no overlap, allocate new block, copy both.
- **Steps:**
 1. Check if blocks overlap.
 2. Allocate new block for total size.
 3. Copy both blocks using memcpy.
- **Complexity:** Time $O(n_1 + n_2)$, Space $O(n_1 + n_2)$.

Algorithm Explanation

The overlap check and merge algorithm verifies that the blocks don't overlap by comparing their address ranges.

If non-overlapping, allocate a new block of size $n_1 + n_2$ and copy both blocks using memcpy.

This is $O(n_1 + n_2)$ for copying, with space for the new block.

Coding Part (with Unit Tests)

```
// Check if blocks overlap
bool isOverlapping(void* p1, size_t s1, void* p2, size_t s2) {
    return (char*)p1 < (char*)p2 + s2 && (char*)p2 < (char*)p1 + s1;
}

// Merge two non-overlapping blocks
void* mergeNonOverlapping(void* block1, size_t size1, void* block2, size_t size2) {
    if (!block1 || !block2 || isOverlapping(block1, size1, block2, size2)) return NULL;
    void* result = malloc(size1 + size2);
    if (!result) return NULL;
    memcpy(result, block1, size1);
    memcpy((char*)result + size1, block2, size2);
    return result;
}

// Unit tests
void testMergeNonOverlapping() {
    int arr1[] = {1, 2};
    int arr2[] = {3, 4};
    int* result = mergeNonOverlapping(arr1, 2 * sizeof(int), arr2, 2 * sizeof(int));
    assertBoolEquals(true, result && result[0] == 1 && result[3] == 4, "Test 170.1 - Merge blocks");
    free(result);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Check for overlap before merging.
 - Validate pointers and sizes.
 - Use memcpy for efficiency.
 - Test with non-overlapping blocks.
- **Expert Tips:**
 - Explain overlap: "Check if ranges intersect before merging."
 - In interviews, clarify: "Ask if overlap check is mandatory."
 - Suggest optimization: "Use realloc for in-place if applicable."
 - Test edge cases: "Overlapping blocks, zero size."

Problem 171: Implement a Custom Calloc Function

Issue Description

Implement a custom calloc that allocates and zeros memory for n items of size s.

Problem Decomposition & Solution Steps

- **Input:** Number of items, size per item.
- **Output:** Zero-initialized memory pointer.
- **Approach:** Allocate and zero memory.
- **Algorithm:** Allocate and Zero
 - **Explanation:** Use malloc for $n * s$ bytes, zero with memset.
- **Steps:**
 1. Validate inputs (n, s).
 2. Allocate $n * s$ bytes.
 3. Zero memory with memset.
- **Complexity:** Time $O(n * s)$, Space $O(n * s)$.

Algorithm Explanation

The allocate and zero algorithm computes total size ($n * s$), allocates using malloc, and zeros the memory with memset.

Validation prevents overflow in size calculation.

This is $O(n * s)$ for zeroing, with space for the allocated block.

Coding Part (with Unit Tests)

```
// Custom calloc
void* myCalloc(size_t num, size_t size) {
    if (num == 0 || size == 0 || num > SIZE_MAX / size) return NULL; // Avoid overflow
    size_t total = num * size;
    void* ptr = malloc(total);
    if (ptr) memset(ptr, 0, total);
    return ptr;
}

// Unit tests
void testMyCalloc() {
    int* arr = myCalloc(5, sizeof(int));
    assertBoolEquals(true, arr && arr[0] == 0 && arr[4] == 0, "Test 171.1 - Zeroed array");
    free(arr);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Check for size overflow.
 - Use memset for zeroing.
 - Validate inputs.
 - Test with various sizes.

- **Expert Tips:**

- Explain calloc: "Allocate and zero n * s bytes."
- In interviews, clarify: "Ask if standard malloc behavior is expected."
- Suggest optimization: "Use system malloc if available."
- Test edge cases: "Zero items, large sizes."

Problem 172: Check for Memory Corruption in a Linked List

Issue Description

Detect memory corruption in a linked list (e.g., invalid pointers or cycles).

Problem Decomposition & Solution Steps

- **Input:** Head of linked list.
- **Output:** Boolean indicating no corruption.
- **Approach:** Use slow and fast pointers for cycle detection.
- **Algorithm:** Floyd's Cycle Detection
 - **Explanation:** Detect cycles as a sign of corruption; validate pointers conceptually.
- **Steps:**
 1. Validate head pointer.
 2. Use slow/fast pointers to detect cycles.
 3. Return false if cycle found.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

Floyd's cycle detection algorithm uses two pointers moving at different speeds to detect cycles, indicating potential corruption (e.g., overwritten next pointers).

If slow and fast pointers meet, a cycle exists.

Additional checks (e.g., valid pointers) are platform-specific.

This is O(n) for n nodes, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct Node {  
    int data;  
    struct Node* next;  
} Node;  
  
// Check for linked list corruption (cycle detection)  
bool checkListCorruption(Node* head) {  
    if (!head) return true;  
    Node *slow = head, *fast = head;  
    while (fast && fast->next) {  
        slow = slow->next;  
        fast = fast->next->next;  
        if (slow == fast) return false; // Cycle detected  
    }  
    return true; }
```

```

// Unit tests
void testCheckListCorruption() {
    Node* head = malloc(sizeof(Node));
    head->next = malloc(sizeof(Node));
    head->next->next = NULL;
    assertBoolEquals(true, checkListCorruption(head), "Test 172.1 - No corruption");
    head->next->next = head; // Create cycle
    assertBoolEquals(false, checkListCorruption(head), "Test 172.2 - Cycle detected");
    free(head->next);
    free(head);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use Floyd's algorithm for cycles.
 - Validate head pointer.
 - Free test structures carefully.
 - Test with cyclic and acyclic lists.
- **Expert Tips:**
 - Explain cycle detection: "Slow/fast pointers meet if cycle exists."
 - In interviews, clarify: "Ask if other corruption types (e.g., invalid pointers) need checking."
 - Suggest optimization: "Use memory validation tools for deeper checks."
 - Test edge cases: "NULL, single node, cycles."

Problem 173: Swap Two Memory Blocks

Issue Description

Swap the contents of two equal-sized memory blocks.

Problem Decomposition & Solution Steps

- **Input:** Two pointers, size.
- **Output:** None (contents swapped).
- **Approach:** Use temporary buffer or XOR swap.
- **Algorithm:** Temporary Buffer Swap
 - **Explanation:** Allocate temp buffer, copy block1 to temp, block2 to block1, temp to block2.
- **Steps:**
 1. Validate pointers and size.
 2. Allocate temp buffer.
 3. Perform three-way copy.
- **Complexity:** Time O(n), Space O(n).

Algorithm Explanation

The temporary buffer swap algorithm allocates a temporary buffer to hold one block's contents, then copies block2 to block1 and temp to block2.

This avoids overlap issues and is simpler than XOR swap.

It's O(n) for n bytes, with O(n) space for the temp buffer.

Coding Part (with Unit Tests)

```
// Swap two memory blocks
bool swapMemoryBlocks(void* block1, void* block2, size_t size) {
    if (!block1 || !block2 || size == 0) return false;
    void* temp = malloc(size);
    if (!temp) return false;
    memcpy(temp, block1, size);
    memcpy(block1, block2, size);
    memcpy(block2, temp, size);
    free(temp);
    return true;
}

// Unit tests
void testSwapMemoryBlocks() {
    int arr1[] = {1, 2};
    int arr2[] = {3, 4};
    swapMemoryBlocks(arr1, arr2, 2 * sizeof(int));
    assertBoolEquals(true, arr1[0] == 3 && arr1[1] == 4 && arr2[0] == 1 && arr2[1] == 2, "Test 173.1 - Swap blocks");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate pointers and size.
 - Use temp buffer for safety.
 - Check temp allocation.
 - Test with equal-sized blocks.
- **Expert Tips:**
 - Explain swap: "Use temp to avoid overlap; copy three times."
 - In interviews, clarify: "Ask if XOR swap is preferred."
 - Suggest optimization: "XOR swap saves space but is slower."
 - Test edge cases: "NULL, zero size."

Problem 174: Implement a Memory-Efficient String Storage

Issue Description

Store multiple strings efficiently, minimizing memory usage.

Problem Decomposition & Solution Steps

- **Input:** Array of strings.
- **Output:** Structure storing strings compactly.
- **Approach:** Use a single buffer with offsets.
- **Algorithm:** Compact String Storage
 - **Explanation:** Store all strings in one buffer, use offsets to track starts.
- **Steps:**
 1. Calculate total string length.
 2. Allocate single buffer.

- 3. Copy strings and store offsets.
- **Complexity:** Time O(n) for n chars, Space O(n).

Algorithm Explanation

The compact string storage algorithm allocates a single buffer for all strings, copying them contiguously with null terminators.

An array of offsets tracks each string's start.

This reduces overhead compared to separate allocations.

It's O(n) for n characters copied, with O(n) space for the buffer and offsets.

Coding Part (with Unit Tests)

```

typedef struct StringStore {
    char* buffer;
    size_t* offsets;
    size_t count;
} StringStore;

// Create string store
StringStore* createStringStore(const char* strings[], size_t count) {
    StringStore* store = malloc(sizeof(StringStore));
    store->count = count;
    store->offsets = malloc(count * sizeof(size_t));
    size_t totalLen = 0;
    for (size_t i = 0; i < count; i++) totalLen += strlen(strings[i]) + 1;
    store->buffer = malloc(totalLen);
    size_t offset = 0;
    for (size_t i = 0; i < count; i++) {
        store->offsets[i] = offset;
        strcpy(store->buffer + offset, strings[i]);
        offset += strlen(strings[i]) + 1;
    }
    return store;
}

// Get string by index
const char* getString(StringStore* store, size_t index) {
    return index < store->count ? store->buffer + store->offsets[index] : NULL;
}

// Free store
void freeStringStore(StringStore* store) {
    if (store) {
        free(store->buffer);
        free(store->offsets);
        free(store);
    }
}

// Unit tests
void testStringStore() {
    const char* strings[] = {"hello", "world"};
    StringStore* store = createStringStore(strings, 2);
    assertBoolEquals(true, strcmp(getString(store, 0), "hello") == 0, "Test 174.1 - First string");
    freeStringStore(store);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use single buffer for efficiency.
 - Store offsets for access.
 - Include null terminators.
 - Test with multiple strings.
- **Expert Tips:**
 - Explain storage: "Single buffer with offsets reduces fragmentation."
 - In interviews, clarify: "Ask if dynamic resizing is needed."
 - Suggest optimization: "Use compression for very large strings."
 - Test edge cases: "Empty strings, single string."

Problem 175: Detect Buffer Overflow in a Program

Issue Description

Detect buffer overflow in a program (conceptual with example).

Problem Decomposition & Solution Steps

- **Input:** Program with buffer operations.
- **Output:** Identify overflow risks.
- **Approach:** Analyze bounds checking.
- **Algorithm:** Manual Inspection
 - **Explanation:** Check for missing bounds checks in array or buffer operations.
- **Steps:**
 1. Review code for buffer writes.
 2. Check for bounds validation.
 3. Report missing checks as overflow risks.
- **Complexity:** Time $O(n)$ for code lines, Space $O(1)$.

Algorithm Explanation

The manual inspection algorithm examines buffer operations (e.g., array writes, strcpy) for missing bounds checks.

A sample program demonstrates an overflow risk.

In practice, tools like AddressSanitizer detect overflows automatically.

This is $O(n)$ for n lines of code reviewed.

Coding Part (with Unit Tests)

```
// Sample program with buffer overflow
void riskyFunction(char* dest, const char* src) {
    strcpy(dest, src); // No bounds check: OVERFLOW RISK
}

// Conceptual check
void detectBufferOverflow() {
    printf("Test 175.1 - Risky function: strcpy without bounds check, OVERFLOW DETECTED\n");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Always check buffer bounds.
 - Use safe functions (e.g., strncpy).
 - Test with large inputs.
 - Use tools like AddressSanitizer.
- **Expert Tips:**
 - Explain detection: "Look for missing bounds checks in buffer operations."
 - In interviews, clarify: "Ask if automated tools are allowed."
 - Suggest optimization: "Wrap buffer operations with bounds checks."
 - Test edge cases: "Large inputs, no bounds checks."

Problem 176: Zero Out a Memory Block

Issue Description

Zero out a block of memory safely.

Problem Decomposition & Solution Steps

- **Input:** Pointer, size.
- **Output:** None (memory zeroed).
- **Approach:** Use memset with validation.
- **Algorithm:** Safe Zeroing
 - **Explanation:** Validate pointer and size, then use memset to zero.
- **Steps:**
 1. Check for valid pointer and size.
 2. Call memset with 0.
 3. Return success status.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The safe zeroing algorithm validates the pointer and size to prevent crashes, then uses memset to set all bytes to 0.

This is O(n) for n bytes, with no extra space beyond input.

Coding Part (with Unit Tests)

```
// Zero out memory block
bool zeroMemory(void* block, size_t size) {
    if (!block || size == 0) return false;
    memset(block, 0, size);
    return true;
}

// Unit tests
void testZeroMemory() {
    int arr[3] = {1, 2, 3};
    zeroMemory(arr, 3 * sizeof(int));
    assertBoolEquals(true, arr[0] == 0 && arr[2] == 0, "Test 176.1 - Zeroed array");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate pointer and size.
 - Use memset for efficiency.
 - Test with various block sizes.
 - Return success status.
- **Expert Tips:**
 - Explain zeroing: "Use memset for fast zeroing after validation."
 - In interviews, clarify: "Ask if secure zeroing is needed."
 - Suggest optimization: "Custom loop for small blocks, but memset is optimized."
 - Test edge cases: "NULL, zero size."

Problem 177: Compare Two Memory Blocks

Issue Description

Compare two memory blocks for equality.

Problem Decomposition & Solution Steps

- **Input:** Two pointers, size.
- **Output:** Boolean indicating equality.
- **Approach:** Use memcmp with validation.
- **Algorithm:** Safe Comparison
 - **Explanation:** Validate pointers and size, then use memcmp.
- **Steps:**
 1. Check for valid pointers and size.
 2. Call memcmp to compare.
 3. Return true if equal.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The safe comparison algorithm validates pointers and size, then uses memcmp to compare byte-by-byte.

If memcmp returns 0, the blocks are equal.

This is O(n) for n bytes, with no extra space.

Coding Part (with Unit Tests)

```
// Compare two memory blocks
bool compareMemory(const void* block1, const void* block2, size_t size) {
    if (!block1 || !block2 || size == 0) return false;
    return memcmp(block1, block2, size) == 0;
}

// Unit tests
void testCompareMemory() {
    int arr1[] = {1, 2};
    int arr2[] = {1, 2};
    int arr3[] = {1, 3};
    assertBoolEquals(true, compareMemory(arr1, arr2, 2 * sizeof(int)), "Test 177.1 - Equal blocks");
    assertBoolEquals(false, compareMemory(arr1, arr3, 2 * sizeof(int)), "Test 177.2 - Unequal
blocks");
}
```

Best Practices & Expert Tips

- **Best Practices:**

- Validate pointers and size.
- Use memcmp for efficiency.
- Test with equal and unequal blocks.
- Handle zero size.

- **Expert Tips:**

- Explain comparison: "Use memcmp for byte-by-byte check."
- In interviews, clarify: "Ask if specific comparison order is needed."
- Suggest optimization: "Custom loop for small blocks, but memcmp is optimized."
- Test edge cases: "NULL, zero size, identical blocks."

Problem 178: Check for Uninitialized Memory Access (Conceptual)

Issue Description

Detect access to uninitialized memory in a program (conceptual).

Problem Decomposition & Solution Steps

- **Input:** Program with memory operations.
- **Output:** Identify uninitialized accesses.
- **Approach:** Track initialization status.
- **Algorithm:** Conceptual Tracking

- **Explanation:** Track memory initialization; flag reads before writes.
- **Steps:**
 1. Track allocated memory and initialization.
 2. Check reads against initialized state.
 3. Report uninitialized accesses.
- **Complexity:** Time O(n) for tracking, Space O(n).

Algorithm Explanation

The conceptual tracking algorithm simulates tools like Valgrind by tracking allocated memory and marking it uninitialized until written.

Reading uninitialized memory triggers a warning.

This is O(n) for n tracked allocations, with space for tracking metadata.

Coding Part (with Unit Tests)

```
// Conceptual: Track initialization
typedef struct MemoryTracker {
    void* ptr;
    bool initialized;
} MemoryTracker;

static MemoryTracker trackers[MAX_ALLOCS];
static int trackCount = 0;

// Track allocation
void trackUninit(void* ptr) {
    if (trackCount < MAX_ALLOCS) {
        trackers[trackCount].ptr = ptr;
        trackers[trackCount].initialized = false;
        trackCount++;
    }
}

// Mark as initialized
void markInitialized(void* ptr) {
    for (int i = 0; i < trackCount; i++) {
        if (trackers[i].ptr == ptr) trackers[i].initialized = true;
    }
}

// Check if initialized
bool isInitialized(void* ptr) {
    for (int i = 0; i < trackCount; i++) {
        if (trackers[i].ptr == ptr) return trackers[i].initialized;
    }
    return false;
}

// Unit tests
void testUninitAccess() {
    void* ptr = malloc(100);
    trackUninit(ptr);
    assertBoolEquals(false, isInitialized(ptr), "Test 178.1 - Uninitialized");
    markInitialized(ptr);
    assertBoolEquals(true, isInitialized(ptr), "Test 178.2 - Initialized");
    free(ptr);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Track initialization explicitly.
 - Use tools like Valgrind in practice.
 - Test with initialized/uninitialized memory.
 - Avoid reading uninitialized memory.
- **Expert Tips:**
 - Explain tracking: "Flag memory as uninitialized until written."
 - In interviews, clarify: "Ask if tools are allowed."
 - Suggest optimization: "Use bitmaps for initialization status."
 - Test edge cases: "No allocations, multiple reads."

Problem 179: Detect Memory Leaks in a Tree Structure

Issue Description

Detect memory leaks in a binary tree by ensuring all nodes are freed.

Problem Decomposition & Solution Steps

- **Input:** Root of binary tree.
- **Output:** Free tree, report leaks (conceptual).
- **Approach:** Recursive free with tracking.
- **Algorithm:** Post-Order Free
 - **Explanation:** Recursively free left and right subtrees, then root; track allocations.
- **Steps:**
 1. Track all node allocations.
 2. Free tree recursively.
 3. Check if all nodes are freed.
- **Complexity:** Time $O(n)$, Space $O(n)$ for recursion.

Algorithm Explanation

The post-order free algorithm traverses the tree in post-order (left, right, root), freeing each node.

A tracker ensures all allocations are freed.

If any remain, a leak is detected.

This is $O(n)$ for n nodes, with $O(n)$ space for recursion stack and tracking.

Coding Part (with Unit Tests)

```
typedef struct TreeNode {  
    int data;  
    struct TreeNode *left, *right;  
} TreeNode;
```

```

static TreeNode* trackedNodes[MAX_ALLOCS];
static int nodeCount = 0;

// Track node allocation
void trackTreeNode(TreeNode* node) {
    if (nodeCount < MAX_ALLOCS) trackedNodes[nodeCount++] = node;
}

// Free tree and check for leaks
void freeTree(TreeNode* root) {
    if (!root) return;
    freeTree(root->left);
    freeTree(root->right);
    for (int i = 0; i < nodeCount; i++) {
        if (trackedNodes[i] == root) {
            trackedNodes[i] = trackedNodes[--nodeCount];
            break;
        }
    }
    free(root);
}

// Unit tests
void testFreeTree() {
    nodeCount = 0;
    TreeNode* root = malloc(sizeof(TreeNode));
    trackTreeNode(root);
    root->left = malloc(sizeof(TreeNode));
    trackTreeNode(root->left);
    root->right = NULL;
    root->left->left = root->left->right = NULL;
    freeTree(root);
    assertBoolEquals(true, nodeCount == 0, "Test 179.1 - No leaks");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use post-order traversal for freeing.
 - Track all node allocations.
 - Validate tree pointers.
 - Test with complex trees.
- **Expert Tips:**
 - Explain free: "Post-order ensures children freed before parent."
 - In interviews, clarify: "Ask if leak detection is automated."
 - Suggest optimization: "Use reference counting for complex graphs."
 - Test edge cases: "Empty tree, single node."

Problem 180: Reallocate Memory with Bounds Checking

Issue Description

Reallocate memory with bounds checking to prevent buffer overflows.

Problem Decomposition & Solution Steps

- **Input:** Pointer, old size, new size, max size.
- **Output:** Reallocated pointer or NULL.
- **Approach:** Use realloc with bounds check.
- **Algorithm:** Bounded Realloc
 - **Explanation:** Check new size against max, then realloc.
- **Steps:**
 1. Validate pointer and sizes.
 2. Check new size against max.
 3. Use realloc and initialize new memory.
- **Complexity:** Time O(n), Space O(n).

Algorithm Explanation

The bounded realloc algorithm validates the new size against a maximum to prevent excessive allocations.

It uses realloc to resize, initializing new memory if expanded.

This is O(n) for n bytes copied, with O(n) space for the new block.

Coding Part (with Unit Tests)

```
// Reallocate with bounds checking
void* boundedRealloc(void* ptr, size_t oldSize, size_t newSize, size_t maxSize) {
    if (!ptr || newSize > maxSize || newSize == 0) return NULL;
    void* newPtr = realloc(ptr, newSize);
    if (newPtr && newSize > oldSize) {
        memset((char*)newPtr + oldSize, 0, newSize - oldSize); // Zero new memory
    }
    return newPtr;
}

// Unit tests
void testBoundedRealloc() {
    int* arr = malloc(2 * sizeof(int));
    arr[0] = 1; arr[1] = 2;
    arr = boundedRealloc(arr, 2 * sizeof(int), 4 * sizeof(int), 5 * sizeof(int));
    assertBoolEquals(true, arr && arr[0] == 1 && arr[2] == 0, "Test 180.1 - Realloc with bounds");
    free(arr);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Check new size against max.
 - Initialize new memory.
 - Validate pointers and sizes.
 - Test with valid and invalid sizes.
- **Expert Tips:**
 - Explain bounds: "Cap size to prevent overflow; realloc as usual."
 - In interviews, clarify: "Ask if initialization is required."
 - Suggest optimization: "Custom realloc for specific patterns."
 - Test edge cases: "Exceed max, zero size."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for memory management problems 166 to 180:\n");
    testIsPointerInRange();
    testAlignedMalloc();
    testTrackMalloc();
    testSafeMalloc();
    testMergeNonOverlapping();
    testMyCalloc();
    testCheckListCorruption();
    testSwapMemoryBlocks();
    testStringStore();
    testBufferOverflow();
    testZeroMemory();
    testCompareMemory();
    testUninitAccess();
    testFreeTree();
    testBoundedRealloc();
    return 0;
}
```

Problem 181: Implement a Stack-Based Memory Allocator

Issue Description

Implement a stack-based memory allocator that allocates memory sequentially from a pre-allocated buffer and supports freeing in LIFO order.

Problem Decomposition & Solution Steps

- **Input:** Total buffer size, allocation requests.
- **Output:** Pointers to allocated memory; free in LIFO order.
- **Approach:** Use a single buffer with a top pointer.
- **Algorithm:** Stack Allocator
 - **Explanation:** Allocate memory by incrementing a top pointer; free by decrementing it in LIFO order.
- **Steps:**
 1. Initialize buffer and top pointer.
 2. Allocate by returning top and incrementing.
 3. Free by decrementing top if last allocation.
- **Complexity:** Time $O(1)$ for alloc/free, Space $O(n)$ for buffer.

Algorithm Explanation

The stack allocator uses a pre-allocated buffer and a top pointer to track the next free address.

Allocation returns the current top and increments it by the requested size.

Freeing only works for the last allocation, decrementing the top.

This is $O(1)$ for both operations, with $O(n)$ space for the buffer.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>

typedef struct StackAllocator {
    char* buffer;      // Pre-allocated memory
    size_t size;        // Total buffer size
    size_t top;         // Current top position
} StackAllocator;

// Initialize stack allocator
StackAllocator* createStackAllocator(size_t size) {
    StackAllocator* alloc = malloc(sizeof(StackAllocator));
    alloc->buffer = malloc(size);
    alloc->size = size;
    alloc->top = 0;
    return alloc;
}

// Allocate memory
void* stackAlloc(StackAllocator* alloc, size_t size) {
    if (!alloc || alloc->top + size > alloc->size) return NULL;
    void* ptr = alloc->buffer + alloc->top;
    alloc->top += size;
    return ptr;
}

// Free last allocation
bool stackFree(StackAllocator* alloc, void* ptr, size_t size) {
    if (!ptr || ptr != alloc->buffer + alloc->top - size) return false;
    alloc->top -= size;
    return true;
}

// Destroy allocator
void destroyStackAllocator(StackAllocator* alloc) {
    if (alloc) {
        free(alloc->buffer);
        free(alloc);
    }
}

// Unit test helper
void assertPtrEquals(void* expected, void* actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testStackAllocator() {
    StackAllocator* alloc = createStackAllocator(100);
    void* ptr1 = stackAlloc(alloc, 50);
    void* ptr2 = stackAlloc(alloc, 30);
    assertPtrEquals(alloc->buffer, ptr1, "Test 181.1 - First allocation");
    assertBoolEquals(true, stackFree(alloc, ptr2, 30), "Test 181.2 - Free last allocation");
    destroyStackAllocator(alloc);
}
```

Best Practices & Expert Tips

- **Best Practices:**

- Validate allocation size against buffer.
- Ensure LIFO freeing order.

- Initialize top to 0.
- Test with sequential alloc/free.
- **Expert Tips:**
 - Explain LIFO: "Free only last allocation to maintain stack."
 - In interviews, clarify: "Ask if alignment or non-LIFO freeing is needed."
 - Suggest optimization: "Align allocations for performance."
 - Test edge cases: "Full buffer, invalid free."

Problem 182: Check for Pointer Arithmetic Errors

Issue Description

Detect errors in pointer arithmetic, such as out-of-bounds access.

Problem Decomposition & Solution Steps

- **Input:** Pointer, base address, size, arithmetic offset.
- **Output:** Boolean indicating valid arithmetic.
- **Approach:** Check if result stays within bounds.
- **Algorithm:** Bounds Check
 - **Explanation:** Validate that pointer + offset stays within [base, base + size).
- **Steps:**
 1. Validate base, pointer, and size.
 2. Compute new pointer after offset.
 3. Check if new pointer is in bounds.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bounds check algorithm ensures that pointer arithmetic (e.g., `ptr + offset`) results in a pointer within the valid range [base, base + size).

This prevents out-of-bounds errors.

It's O(1) as it uses simple comparisons, with no extra space.

Coding Part (with Unit Tests)

```
// Check for pointer arithmetic errors
bool checkPointerArithmetic(void* ptr, void* base, size_t size, ptrdiff_t offset) {
    if (!ptr || !base || size == 0) return false;
    char* newPtr = (char*)ptr + offset;
    return newPtr >= (char*)base && newPtr < (char*)base + size;
}

// Unit tests
void testCheckPointerArithmetic() {
    char* base = malloc(100);
    char* ptr = base + 50;
```

```

        assertEquals(true, checkPointerArithmetic(ptr, base, 100, 10), "Test 182.1 - Valid
arithmetic");
        assertEquals(false, checkPointerArithmetic(ptr, base, 100, 60), "Test 182.2 - Out of bounds");
        free(base);
    }
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use `char*` for byte-level arithmetic.
 - Validate pointers and size.
 - Check both lower and upper bounds.
 - Test with boundary offsets.
- **Expert Tips:**
 - Explain bounds: "Ensure new pointer stays within [base, base + size]."
 - In interviews, clarify: "Ask if negative offsets are allowed."
 - Suggest optimization: "Use compiler sanitizers for runtime checks."
 - Test edge cases: "NULL, zero offset, boundary values."

Problem 183: Handle Memory Fragmentation

Issue Description

Reduce fragmentation in a memory pool by compacting allocated blocks.

Problem Decomposition & Solution Steps

- **Input:** Memory pool with allocated/free blocks.
- **Output:** Contiguous allocated blocks.
- **Approach:** Move allocated blocks to start.
- **Algorithm:** Compaction (Similar to Problem 165)
 - **Explanation:** Relocate allocated blocks to eliminate gaps, update pointers.
- **Steps:**
 1. Track allocated blocks.
 2. Move blocks to start of pool.
 3. Update pointers and free list.
- **Complexity:** Time $O(n)$, Space $O(n)$ for tracking.

Algorithm Explanation

The compaction algorithm moves allocated blocks to the start of the pool, eliminating gaps.

It updates pointers to reflect new locations and rebuilds the free list.

This is $O(n)$ for n blocks, with $O(n)$ space for tracking allocations.

(Note: Similar to Problem 165 but with simpler tracking.)

Coding Part (with Unit Tests)

```
typedef struct Block {
    void* ptr;
    bool allocated;
} Block;

typedef struct FragPool {
    void* memory;
    Block* blocks;
    size_t blockSize;
    size_t numBlocks;
} FragPool;

// Initialize pool
FragPool* createFragPool(size_t blockSize, size_t numBlocks) {
    FragPool* pool = malloc(sizeof(FragPool));
    pool->blockSize = blockSize;
    pool->numBlocks = numBlocks;
    pool->memory = malloc(blockSize * numBlocks);
    pool->blocks = malloc(numBlocks * sizeof(Block));
    for (size_t i = 0; i < numBlocks; i++) {
        pool->blocks[i].ptr = (char*)pool->memory + i * blockSize;
        pool->blocks[i].allocated = false;
    }
    return pool;
}

// Allocate block
void* fragPoolAlloc(FragPool* pool) {
    for (size_t i = 0; i < pool->numBlocks; i++) {
        if (!pool->blocks[i].allocated) {
            pool->blocks[i].allocated = true;
            return pool->blocks[i].ptr;
        }
    }
    return NULL;
}

// Defragment pool
void defragmentFragPool(FragPool* pool) {
    size_t newPos = 0;
    for (size_t i = 0; i < pool->numBlocks; i++) {
        if (pool->blocks[i].allocated) {
            if (i != newPos) {
                memmove((char*)pool->memory + newPos * pool->blockSize, pool->blocks[i].ptr, pool->blockSize);
                pool->blocks[i].ptr = (char*)pool->memory + newPos * pool->blockSize;
            }
            newPos++;
        }
    }
}

// Destroy pool
void destroyFragPool(FragPool* pool) {
    if (pool) {
        free(pool->memory);
        free(pool->blocks);
        free(pool);
    }
}
```

```

// Unit tests
void testDefragmentFragPool() {
    FragPool* pool = createFragPool(16, 3);
    void* block1 = fragPoolAlloc(pool);
    pool->blocks[1].allocated = true;
    defragmentFragPool(pool);
    assertBoolEquals(true, pool->blocks[1].ptr == pool->memory + 16, "Test 183.1 - Defragmented
block");
    destroyFragPool(pool);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track allocated blocks.
 - Use memmove for safe copying.
 - Update pointers post-compaction.
 - Test with fragmented pools.
- **Expert Tips:**
 - Explain compaction: "Move blocks to start, update pointers."
 - In interviews, clarify: "Ask if external pointer updates are needed."
 - Suggest optimization: "Use bitmaps for allocation status."
 - Test edge cases: "All free, all allocated."

Problem 184: Deep Copy a Structure

Issue Description

Create a deep copy of a structure containing pointers (e.g., string and nested struct).

Problem Decomposition & Solution Steps

- **Input:** Pointer to structure with pointers.
- **Output:** Deep copy of structure.
- **Approach:** Recursively copy pointers.
- **Algorithm:** Deep Copy
 - **Explanation:** Allocate new structure, copy non-pointers, recursively copy pointers.
- **Steps:**
 1. Allocate new structure.
 2. Copy non-pointer members.
 3. Duplicate pointer members (e.g., strings).
- **Complexity:** Time O(n), Space O(n) for n bytes.

Algorithm Explanation

The deep copy algorithm allocates a new structure and copies all members.

For pointers (e.g., strings), it allocates new memory and copies the contents.

This ensures the copy is independent.

It's O(n) for n bytes of data, with O(n) space for the new structure and its pointers.

Coding Part (with Unit Tests)

```
typedef struct Nested {
    char* str;
    int val;
} Nested;

typedef struct DeepStruct {
    int data;
    char* name;
    Nested* nested;
} DeepStruct;

// Deep copy structure
DeepStruct* deepCopy(DeepStruct* src) {
    if (!src) return NULL;
    DeepStruct* dst = malloc(sizeof(DeepStruct));
    dst->data = src->data;
    dst->name = src->name ? strdup(src->name) : NULL;
    dst->nested = src->nested ? malloc(sizeof(Nested)) : NULL;
    if (dst->nested) {
        dst->nested->str = src->nested->str ? strdup(src->nested->str) : NULL;
        dst->nested->val = src->nested->val;
    }
    return dst;
}

// Free structure
void freeDeepStruct(DeepStruct* s) {
    if (s) {
        free(s->name);
        if (s->nested) {
            free(s->nested->str);
            free(s->nested);
        }
        free(s);
    }
}

// Unit tests
void testDeepCopy() {
    DeepStruct s = {42, strdup("test"), malloc(sizeof(Nested))};
    s.nested->str = strdup("nested");
    s.nested->val = 100;
    DeepStruct* copy = deepCopy(&s);
    assertBoolEquals(true, copy && copy->data == 42 && strcmp(copy->name, "test") == 0 && copy->nested->val == 100, "Test 184.1 - Deep copy");
    freeDeepStruct(&s);
    freeDeepStruct(copy);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Copy all pointer members.
 - Allocate new memory for pointers.
 - Free original and copy separately.
 - Test with nested structures.
- **Expert Tips:**
 - Explain deep copy: "Duplicate all pointers to avoid sharing."

- In interviews, clarify: "Ask if specific pointer types are involved."
- Suggest optimization: "Use custom allocators for efficiency."
- Test edge cases: "NULL pointers, empty strings."

Problem 185: Check for Memory Alignment Issues in an Array

Issue Description

Check if elements in a dynamically allocated array are properly aligned.

Problem Decomposition & Solution Steps

- **Input:** Array pointer, element size, alignment.
- **Output:** Boolean indicating proper alignment.
- **Approach:** Check each element's address.
- **Algorithm:** Alignment Check
 - **Explanation:** Verify that each element's address is a multiple of the alignment.
- **Steps:**
 1. Validate array pointer and size.
 2. Check alignment of each element.
 3. Return true if all aligned.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The alignment check algorithm iterates through the array, checking if each element's address is a multiple of the specified alignment (e.g., 4 for int).

For a properly allocated array, elements are contiguous, so the base alignment often suffices.

This is O(n) for n elements, with O(1) space.

Coding Part (with Unit Tests)

```
// Check array alignment
bool checkArrayAlignment(void* arr, size_t num, size_t elemSize, size_t alignment) {
    if (!arr || num == 0 || (alignment & (alignment - 1)) != 0) return false;
    for (size_t i = 0; i < num; i++) {
        if (((size_t)((char*)arr + i * elemSize)) % alignment != 0) return false;
    }
    return true;
}

// Unit tests
void testCheckArrayAlignment() {
    int* arr = alignedMalloc(4 * sizeof(int), 4);
    assertBoolEquals(true, checkArrayAlignment(arr, 4, sizeof(int), 4), "Test 185.1 - Aligned array");
    alignedFree(arr);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate alignment as power of 2.
 - Check all element addresses.
 - Use aligned allocation for testing.
 - Test with different alignments.
- **Expert Tips:**
 - Explain alignment: "Each element must align to boundary."
 - In interviews, clarify: "Ask if base alignment is enough."
 - Suggest optimization: "Check base only for contiguous arrays."
 - Test edge cases: "Misaligned arrays, single element."

Problem 186: Simulate a Memory Manager

Issue Description

Simulate a memory manager with allocate, free, and status tracking.

Problem Decomposition & Solution Steps

- **Input:** Allocation/free requests.
- **Output:** Manage memory with tracking.
- **Approach:** Use a block list to track allocations.
- **Algorithm:** Block List Manager
 - **Explanation:** Maintain a list of blocks, allocate from free space, track status.
- **Steps:**
 1. Initialize pool with block list.
 2. Allocate by finding free block.
 3. Free by marking block as free.
- **Complexity:** Time $O(n)$ for alloc/free, Space $O(n)$.

Algorithm Explanation

The block list manager maintains a list of memory blocks with allocation status.

Allocation searches for a free block; freeing marks a block as free.

This simulates a simple memory manager.

It's $O(n)$ for n blocks due to linear search, with $O(n)$ space for the block list.

Coding Part (with Unit Tests)

```
typedef struct MemBlock {  
    void* ptr;  
    size_t size;  
    bool allocated;  
} MemBlock;  
  
typedef struct MemoryManager {
```

```

    void* pool;
    MemBlock* blocks;
    size_t numBlocks;
} MemoryManager;

// Initialize memory manager
MemoryManager* createMemoryManager(size_t size, size_t blockSize) {
    MemoryManager* mgr = malloc(sizeof(MemoryManager));
    mgr->numBlocks = size / blockSize;
    mgr->pool = malloc(size);
    mgr->blocks = malloc(mgr->numBlocks * sizeof(MemBlock));
    for (size_t i = 0; i < mgr->numBlocks; i++) {
        mgr->blocks[i].ptr = (char*)mgr->pool + i * blockSize;
        mgr->blocks[i].size = blockSize;
        mgr->blocks[i].allocated = false;
    }
    return mgr;
}

// Allocate block
void* memMgrAlloc(MemoryManager* mgr) {
    for (size_t i = 0; i < mgr->numBlocks; i++) {
        if (!mgr->blocks[i].allocated) {
            mgr->blocks[i].allocated = true;
            return mgr->blocks[i].ptr;
        }
    }
    return NULL;
}

// Free block
void memMgrFree(MemoryManager* mgr, void* ptr) {
    for (size_t i = 0; i < mgr->numBlocks; i++) {
        if (mgr->blocks[i].ptr == ptr) {
            mgr->blocks[i].allocated = false;
            break;
        }
    }
}

// Destroy manager
void destroyMemoryManager(MemoryManager* mgr) {
    if (mgr) {
        free(mgr->pool);
        free(mgr->blocks);
        free(mgr);
    }
}

// Unit tests
void testMemoryManager() {
    MemoryManager* mgr = createMemoryManager(100, 25);
    void* ptr = memMgrAlloc(mgr);
    assertBoolEquals(true, ptr != NULL, "Test 186.1 - Allocate block");
    memMgrFree(mgr, ptr);
    assertBoolEquals(true, memMgrAlloc(mgr) == ptr, "Test 186.2 - Reuse freed block");
    destroyMemoryManager(mgr);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track block status.
 - Validate pointers on free.

- Use fixed-size blocks for simplicity.
- Test with alloc/free cycles.
- **Expert Tips:**
 - Explain manager: "Track blocks; allocate from free list."
 - In interviews, clarify: "Ask if best-fit or first-fit allocation."
 - Suggest optimization: "Use free list for O(1) allocation."
 - Test edge cases: "Full pool, invalid free."

Problem 187: Free a 2D Array

Issue Description

Free a dynamically allocated 2D array (rows allocated separately).

Problem Decomposition & Solution Steps

- **Input:** 2D array pointer, number of rows.
- **Output:** None (memory freed).
- **Approach:** Free each row, then the array of pointers.
- **Algorithm:** Iterative Free
 - **Explanation:** Loop through rows, free each, then free the pointer array.
- **Steps:**
 1. Validate array and row count.
 2. Free each row pointer.
 3. Free the array of pointers.
- **Complexity:** Time O(n), Space O(1) for n rows.

Algorithm Explanation

The iterative free algorithm frees each row's memory, then the array of row pointers.

This handles jagged arrays (rows of different sizes) or uniform arrays.

It's O(n) for n rows, with O(1) space as no additional memory is needed.

Coding Part (with Unit Tests)

```
// Free 2D array
void free2DArray(int** arr, size_t rows) {
    if (!arr) return;
    for (size_t i = 0; i < rows; i++) {
        free(arr[i]);
    }
    free(arr);
}

// Unit tests
void testFree2DArray() {
    int** arr = malloc(2 * sizeof(int*));
    arr[0] = malloc(3 * sizeof(int));
    arr[1] = malloc(2 * sizeof(int));
    free2DArray(arr, 2);
    printf("Test 187.1 - Free 2D array: PASSED (no crash)\n");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate array pointer.
 - Free rows before pointer array.
 - Handle NULL rows safely.
 - Test with jagged arrays.
- **Expert Tips:**
 - Explain free: "Free each row, then the pointer array."
 - In interviews, clarify: "Ask if rows are uniform."
 - Suggest optimization: "Single block for uniform arrays."
 - Test edge cases: "NULL array, zero rows."

Problem 188: Check for Dangling Pointers

Issue Description

Detect dangling pointers after freeing memory.

Problem Decomposition & Solution Steps

- **Input:** Pointers and allocation status.
- **Output:** Boolean indicating no dangling pointers.
- **Approach:** Track freed pointers.
- **Algorithm:** Freed Pointer Check
 - **Explanation:** Maintain a list of freed pointers, check if a pointer is in it.
- **Steps:**
 1. Track allocations and frees.
 2. Check if pointer is in freed list.
 3. Report dangling pointers.
- **Complexity:** Time $O(n)$, Space $O(n)$ for n pointers.

Algorithm Explanation

The freed pointer check algorithm tracks allocated and freed pointers.

After freeing, add the pointer to a freed list.

Check if a pointer is in this list to detect dangling references.

This is $O(n)$ for n pointers in the list, with $O(n)$ space for storage.

Coding Part (with Unit Tests)

```
#define MAX_FREED 100
static void* freedPointers[MAX_FREED];
static int freedCount = 0;
```

```

// Track free
void trackDanglingFree(void* ptr) {
    if (ptr && freedCount < MAX_FREED) {
        freedPointers[freedCount++] = ptr;
    }
    free(ptr);
}

// Check for dangling pointer
bool isDangling(void* ptr) {
    for (int i = 0; i < freedCount; i++) {
        if (freedPointers[i] == ptr) return true;
    }
    return false;
}

// Unit tests
void testDanglingPointer() {
    freedCount = 0;
    void* ptr = malloc(100);
    trackDanglingFree(ptr);
    assertBoolEquals(true, isDangling(ptr), "Test 188.1 - Dangling pointer detected");
    assertBoolEquals(false, isDangling(malloc(50)), "Test 188.2 - Non-dangling pointer");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track freed pointers.
 - Validate pointers before checking.
 - Limit freed list size.
 - Test with freed and active pointers.
- **Expert Tips:**
 - Explain dangling: "Check if pointer was previously freed."
 - In interviews, clarify: "Ask if automated tools are allowed."
 - Suggest optimization: "Use hash table for O(1) checks."
 - Test edge cases: "NULL, multiple frees."

Problem 189: Initialize a Memory Block

Issue Description

Initialize a memory block with a specified value.

Problem Decomposition & Solution Steps

- **Input:** Pointer, size, value.
- **Output:** None (memory initialized).
- **Approach:** Use memset with validation.
- **Algorithm:** Safe Initialization
 - **Explanation:** Validate inputs, use memset to set bytes to value.
- **Steps:**
 1. Check pointer and size.

- 2. Call memset with value.
- 3. Return success status.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The safe initialization algorithm validates the pointer and size, then uses memset to set all bytes to the specified value.

This is O(n) for n bytes, with O(1) space as no additional memory is needed.

Coding Part (with Unit Tests)

```
// Initialize memory block
bool initMemory(void* block, size_t size, int value) {
    if (!block || size == 0) return false;
    memset(block, value, size);
    return true;
}

// Unit tests
void testInitMemory() {
    char arr[3] = {1, 2, 3};
    initMemory(arr, 3, 0xFF);
    assertBoolEquals(true, arr[0] == (char)0xFF && arr[2] == (char)0xFF, "Test 189.1 - Initialized block");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate pointer and size.
 - Use memset for efficiency.
 - Test with different values.
 - Return success status.
- **Expert Tips:**
 - Explain init: "Set all bytes to value using memset."
 - In interviews, clarify: "Ask if specific value range is needed."
 - Suggest optimization: "Custom loop for small blocks."
 - Test edge cases: "NULL, zero size."

Problem 190: Manage a Fixed-Size Memory Allocator

Issue Description

Implement a fixed-size block allocator (similar to Problem 154).

Problem Decomposition & Solution Steps

- **Input:** Block size, number of blocks.
- **Output:** Allocate/free fixed-size blocks.

- **Approach:** Use free list in pre-allocated pool.
- **Algorithm:** Free List Allocator
 - **Explanation:** Pre-allocate memory, manage blocks with a free list.
- **Steps:**
 1. Initialize pool and free list.
 2. Allocate from free list head.
 3. Free by adding to free list.
- **Complexity:** Time O(1) for alloc/free, Space O(n).

Algorithm Explanation

The free list allocator pre-allocates a pool and links blocks in a free list.

Allocation returns the head block; freeing adds it back.

This is O(1) for both operations, with O(n) space for the pool.

(Note: Similar to Problem 154 but with simpler free list.)

Coding Part (with Unit Tests)

```

typedef struct FixedAllocator {
    void* memory;
    void* freeList;
    size_t blockSize;
    size_t numBlocks;
} FixedAllocator;

// Initialize allocator
FixedAllocator* createFixedAllocator(size_t blockSize, size_t numBlocks) {
    FixedAllocator* alloc = malloc(sizeof(FixedAllocator));
    alloc->blockSize = blockSize;
    alloc->numBlocks = numBlocks;
    alloc->memory = malloc(blockSize * numBlocks);
    alloc->freeList = alloc->memory;
    for (size_t i = 0; i < numBlocks - 1; i++) {
        *(void**)((char*)alloc->memory + i * blockSize) = (char*)alloc->memory + (i + 1) * blockSize;
    }
    *(void**)((char*)alloc->memory + (numBlocks - 1) * blockSize) = NULL;
    return alloc;
}

// Allocate block
void* fixedAlloc(FixedAllocator* alloc) {
    if (!alloc->freeList) return NULL;
    void* block = alloc->freeList;
    alloc->freeList = *(void**)block;
    return block;
}

// Free block
void fixedFree(FixedAllocator* alloc, void* block) {
    if (block) {
        *(void**)block = alloc->freeList;
        alloc->freeList = block;
    }
}

```

```

// Destroy allocator
void destroyFixedAllocator(FixedAllocator* alloc) {
    if (alloc) {
        free(alloc->memory);
        free(alloc);
    }
}

// Unit tests
void testFixedAllocator() {
    FixedAllocator* alloc = createFixedAllocator(16, 3);
    void* block1 = fixedAlloc(alloc);
    fixedFree(alloc, block1);
    void* block2 = fixedAlloc(alloc);
    assertPtrEquals(block1, block2, "Test 190.1 - Reuse freed block");
    destroyFixedAllocator(alloc);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use free list for O(1) operations.
 - Validate block pointers.
 - Test alloc/free cycles.
 - Free pool on destroy.
- **Expert Tips:**
 - Explain free list: "Link blocks for fast alloc/free."
 - In interviews, clarify: "Ask if alignment is needed."
 - Suggest optimization: "Use bitmaps for small blocks."
 - Test edge cases: "Empty pool, multiple frees."

Problem 191: Handle Memory Alignment for a Structure

Issue Description

Ensure a structure's members are aligned properly in memory.

Problem Decomposition & Solution Steps

- **Input:** Structure definition.
- **Output:** Aligned structure allocation.
- **Approach:** Use aligned allocation and check offsets.
- **Algorithm:** Aligned Structure Allocation
 - **Explanation:** Allocate structure with aligned memory, verify member alignments.
- **Steps:**
 1. Allocate structure with alignment.
 2. Check member offsets for alignment.
 3. Return aligned pointer.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The aligned structure allocation algorithm uses a custom aligned allocator (from Problem 167) to ensure the structure's base address is aligned.

It verifies that each member's offset (via `offsetof`) is a multiple of its type's alignment.

This is O(1) for a fixed structure, with O(1) space.

Coding Part (with Unit Tests)

```
#include <stddef.h>

typedef struct AlignedStruct {
    char c;
    int i;
    double d;
} AlignedStruct;

// Allocate aligned structure
AlignedStruct* allocAlignedStruct(size_t alignment) {
    AlignedStruct* s = alignedMalloc(sizeof(AlignedStruct), alignment);
    if (!s) return NULL;
    if (offsetof(AlignedStruct, c) % 1 != 0 ||
        offsetof(AlignedStruct, i) % 4 != 0 ||
        offsetof(AlignedStruct, d) % 8 != 0) {
        alignedFree(s);
        return NULL;
    }
    return s;
}

// Unit tests
void testAllocAlignedStruct() {
    AlignedStruct* s = allocAlignedStruct(8);
    assertBoolEquals(true, s && ((size_t)s % 8) == 0, "Test 191.1 - Aligned structure");
    alignedFree(s);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use `offsetof` for alignment checks.
 - Validate type alignments.
 - Use aligned allocation.
 - Test with different alignments.
- **Expert Tips:**
 - Explain alignment: "Ensure member offsets match type requirements."
 - In interviews, clarify: "Ask if specific alignment is required."
 - Suggest optimization: "Use `#pragma pack` for control."
 - Test edge cases: "Misaligned structs, large types."

Problem 192: Merge Multiple Dynamic Arrays

Issue Description

Merge multiple dynamically allocated arrays into one.

Problem Decomposition & Solution Steps

- **Input:** Array of pointers, sizes, count.
- **Output:** Single merged array.
- **Approach:** Allocate total size, copy arrays.
- **Algorithm:** Multi-Array Merge
 - **Explanation:** Sum sizes, allocate new array, copy each array.
- **Steps:**
 1. Validate inputs and sizes.
 2. Calculate total size.
 3. Allocate and copy arrays.
- **Complexity:** Time $O(n)$, Space $O(n)$ for n total bytes.

Algorithm Explanation

The multi-array merge algorithm calculates the total size of all arrays, allocates a new array, and copies each array sequentially using `memcpy`.

Validation ensures non-NULL pointers and valid sizes.

This is $O(n)$ for n bytes copied, with $O(n)$ space for the new array.

Coding Part (with Unit Tests)

```
// Merge multiple arrays
void* mergeMultipleArrays(void** arrays, size_t* sizes, size_t count) {
    if (!arrays || !sizes || count == 0) return NULL;
    size_t total = 0;
    for (size_t i = 0; i < count; i++) {
        if (!arrays[i]) return NULL;
        total += sizes[i];
    }
    void* result = malloc(total);
    if (!result) return NULL;
    size_t offset = 0;
    for (size_t i = 0; i < count; i++) {
        memcpy((char*)result + offset, arrays[i], sizes[i]);
        offset += sizes[i];
    }
    return result;
}
// Unit tests
void testMergeMultipleArrays() {
    int arr1[] = {1, 2};
    int arr2[] = {3, 4};
    void* arrays[] = {arr1, arr2};
    size_t sizes[] = {2 * sizeof(int), 2 * sizeof(int)};
    int* result = mergeMultipleArrays(arrays, sizes, 2);
    assertBoolEquals(true, result && result[0] == 1 && result[3] == 4, "Test 192.1 - Merge multiple arrays");
}
```

```
    free(result);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate all pointers and sizes.
 - Use memcpy for efficiency.
 - Calculate total size carefully.
 - Test with multiple arrays.
- **Expert Tips:**
 - Explain merge: "Sum sizes, copy arrays sequentially."
 - In interviews, clarify: "Ask if overlap checks are needed."
 - Suggest optimization: "Use realloc for dynamic growth."
 - Test edge cases: "Empty arrays, single array."

Problem 193: Check for Memory Leaks in a Tree Structure

Issue Description

Detect memory leaks in a binary tree (similar to Problem 179).

Problem Decomposition & Solution Steps

- **Input:** Root of binary tree.
- **Output:** Free tree, report leaks.
- **Approach:** Recursive free with tracking.
- **Algorithm:** Post-Order Free with Tracking
 - **Explanation:** Free tree in post-order, track nodes to detect leaks.
- **Steps:**
 1. Track all node allocations.
 2. Free tree recursively.
 3. Check remaining tracked nodes.
- **Complexity:** Time $O(n)$, Space $O(n)$ for n nodes.

Algorithm Explanation

The post-order free with tracking algorithm frees the tree in post-order and removes each node from a tracked list.

After freeing, any remaining tracked nodes indicate leaks.

This is $O(n)$ for n nodes, with $O(n)$ space for tracking and recursion.

Coding Part (with Unit Tests)

```
static TreeNode* leakNodes[MAX_ALLOCS];
static int leakNodeCount = 0;
```

```

// Track node
void trackLeakNode(TreeNode* node) {
    if (leakNodeCount < MAX_ALLOCS) leakNodes[leakNodeCount] = node;
}

// Free tree and check leaks
bool freeTreeWithLeakCheck(TreeNode* root) {
    if (!root) return leakNodeCount == 0;
    freeTreeWithLeakCheck(root->left);
    freeTreeWithLeakCheck(root->right);
    for (int i = 0; i < leakNodeCount; i++) {
        if (leakNodes[i] == root) {
            leakNodes[i] = leakNodes[--leakNodeCount];
            break;
        }
    }
    free(root);
    return leakNodeCount == 0;
}

// Unit tests
void testFreeTreeWithLeakCheck() {
    leakNodeCount = 0;
    TreeNode* root = malloc(sizeof(TreeNode));
    trackLeakNode(root);
    root->left = NULL;
    root->right = NULL;
    assertBoolEquals(true, freeTreeWithLeakCheck(root), "Test 193.1 - No leaks");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track all nodes.
 - Use post-order free.
 - Check for remaining nodes.
 - Test with complex trees.
- **Expert Tips:**
 - Explain leak check: "Track nodes, ensure all are freed."
 - In interviews, clarify: "Ask if partial freeing is tested."
 - Suggest optimization: "Use hash table for tracking."
 - Test edge cases: "Empty tree, leaked nodes."

Problem 194: Allocate Memory for a 2D Array

Issue Description

Allocate a dynamic 2D array with specified rows and columns.

Problem Decomposition & Solution Steps

- **Input:** Number of rows, columns, element size.
- **Output:** Pointer to 2D array.
- **Approach:** Allocate pointer array and rows.
- **Algorithm:** 2D Array Allocation

- **Explanation:** Allocate array of pointers, then each row.
- **Steps:**
 1. Validate rows and columns.
 2. Allocate pointer array.
 3. Allocate each row.
- **Complexity:** Time O(rows), Space O(rows * cols).

Algorithm Explanation

The 2D array allocation algorithm allocates an array of pointers for rows, then allocates memory for each row.

This supports jagged arrays or uniform sizes.

It's O(rows) for allocation loops, with O(rows * cols) space for the array.

Coding Part (with Unit Tests)

```
// Allocate 2D array
int** alloc2DArray(size_t rows, size_t cols) {
    if (rows == 0 || cols == 0) return NULL;
    int** arr = malloc(rows * sizeof(int*));
    if (!arr) return NULL;
    for (size_t i = 0; i < rows; i++) {
        arr[i] = malloc(cols * sizeof(int));
        if (!arr[i]) {
            free2DArray(arr, i);
            return NULL;
        }
    }
    return arr;
}

// Unit tests
void testAlloc2DArray() {
    int** arr = alloc2DArray(2, 3);
    assertBoolEquals(true, arr && arr[0] && arr[1], "Test 194.1 - Allocate 2x3 array");
    free2DArray(arr, 2);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate rows and columns.
 - Handle allocation failures.
 - Free partially allocated arrays.
 - Test with various sizes.
- **Expert Tips:**
 - Explain allocation: "Array of pointers, each pointing to a row."
 - In interviews, clarify: "Ask if single-block allocation is preferred."
 - Suggest optimization: "Use single block for better locality."
 - Test edge cases: "Zero rows/cols, allocation failure."

Problem 195: Handle Memory Compaction

Issue Description

Compact memory in a pool to reduce fragmentation (similar to Problem 183).

Problem Decomposition & Solution Steps

- **Input:** Memory pool with allocated/free blocks.
- **Output:** Contiguous allocated blocks.
- **Approach:** Move allocated blocks to start.
- **Algorithm:** Compaction
 - **Explanation:** Relocate allocated blocks, update pointers.
- **Steps:**
 1. Track allocated blocks.
 2. Move blocks to start.
 3. Update pointers and free list.
- **Complexity:** Time $O(n)$, Space $O(n)$.

Algorithm Explanation

The compaction algorithm moves allocated blocks to the start of the pool, updating their pointers.

Free blocks are linked at the end.

This reduces fragmentation and is $O(n)$ for n blocks, with $O(n)$ space for tracking.

(Note: Similar to Problem 183 but with minimal tracking.)

Coding Part (with Unit Tests)

```
typedef struct CompactPool {
    void* memory;
    Block* blocks;
    size_t blockSize;
    size_t numBlocks;
} CompactPool;

// Initialize pool
CompactPool* createCompactPool(size_t blockSize, size_t numBlocks) {
    CompactPool* pool = malloc(sizeof(CompactPool));
    pool->blockSize = blockSize;
    pool->numBlocks = numBlocks;
    pool->memory = malloc(blockSize * numBlocks);
    pool->blocks = malloc(numBlocks * sizeof(Block));
    for (size_t i = 0; i < numBlocks; i++) {
        pool->blocks[i].ptr = (char*)pool->memory + i * blockSize;
        pool->blocks[i].allocated = false;
    }
    return pool;
}
```

```

// Allocate block
void* compactPoolAlloc(CompactPool* pool) {
    for (size_t i = 0; i < pool->numBlocks; i++) {
        if (!pool->blocks[i].allocated) {
            pool->blocks[i].allocated = true;
            return pool->blocks[i].ptr;
        }
    }
    return NULL;
}

// Compact pool
void compactPool(CompactPool* pool) {
    size_t newPos = 0;
    for (size_t i = 0; i < pool->numBlocks; i++) {
        if (pool->blocks[i].allocated) {
            if (i != newPos) {
                memmove((char*)pool->memory + newPos * pool->blockSize, pool->blocks[i].ptr, pool->blockSize);
                pool->blocks[i].ptr = (char*)pool->memory + newPos * pool->blockSize;
            }
            newPos++;
        }
    }
}

// Destroy pool
void destroyCompactPool(CompactPool* pool) {
    if (pool) {
        free(pool->memory);
        free(pool->blocks);
        free(pool);
    }
}

// Unit tests
void testCompactPool() {
    CompactPool* pool = createCompactPool(16, 3);
    void* block1 = compactPoolAlloc(pool);
    pool->blocks[1].allocated = true;
    compactPool(pool);
    assertBoolEquals(true, pool->blocks[1].ptr == pool->memory + 16, "Test 195.1 - Compacted block");
    destroyCompactPool(pool);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track allocated blocks.
 - Use memmove for safety.
 - Update pointers after compaction.
 - Test with fragmented pools.
- **Expert Tips:**
 - Explain compaction: "Move blocks to eliminate gaps."
 - In interviews, clarify: "Ask if external pointer updates are needed."
 - Suggest optimization: "Use free list for faster allocation."
 - Test edge cases: "All free, all allocated."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for memory management problems 181 to 195:\n");
    testStackAllocator();
    testCheckPointerArithmetic();
    testDefragmentFragPool();
    testDeepCopy();
    testCheckArrayAlignment();
    testMemoryManager();
    testFree2DArray();
    testDanglingPointer();
    testInitMemory();
    testFixedAllocator();
    testAllocAlignedStruct();
    testMergeMultipleArrays();
    testFreeTreeWithLeakCheck();
    testAlloc2DArray();
    testCompactPool();
    return 0;
}
```

Problem 196: Track Peak Memory Usage

Issue Description

Track the peak memory usage across all allocations in a program.

Problem Decomposition & Solution Steps

- **Input:** Memory allocation/free requests.
- **Output:** Peak memory usage in bytes.
- **Approach:** Wrap malloc and free to update current and peak memory.
- **Algorithm:** Peak Tracking
 - **Explanation:** Maintain current and peak memory counters, update on alloc/free.
- **Steps:**
 1. Initialize current and peak memory counters.
 2. On allocation, add size to current, update peak if higher.
 3. On free, subtract size from current.
- **Complexity:** Time O(1) per alloc/free, Space O(1).

Algorithm Explanation

The peak tracking algorithm wraps malloc and free, maintaining a current memory counter and a peak counter.

On allocation, add the size to current and update peak if current exceeds it.

On free, subtract the size.

This is O(1) per operation, with O(1) space for counters.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>

static size_t currentMemory = 0;
static size_t peakMemory = 0;

// Custom malloc with peak tracking
void* peakMalloc(size_t size) {
    void* ptr = malloc(size);
    if (ptr) {
        currentMemory += size;
        if (currentMemory > peakMemory) peakMemory = currentMemory;
    }
    return ptr;
}

// Custom free with peak tracking
void peakFree(void* ptr, size_t size) {
    if (ptr) {
        currentMemory -= size;
        free(ptr);
    }
}

// Get peak memory usage
size_t getPeakMemory() {
    return peakMemory;
}

// Unit test helper
void assertSizeTEquals(size_t expected, size_t actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testPeakMemory() {
    currentMemory = peakMemory = 0;
    void* ptr1 = peakMalloc(100);
    void* ptr2 = peakMalloc(200);
    assertSizeTEquals(300, getPeakMemory(), "Test 196.1 - Peak after allocations");
    peakFree(ptr1, 100);
    assertSizeTEquals(200, getPeakMemory(), "Test 196.2 - Peak persists after free");
    peakFree(ptr2, 200);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Update peak only when current exceeds it.
 - Validate sizes on free.
 - Reset counters for testing.
 - Test with multiple alloc/free cycles.
- **Expert Tips:**
 - Explain tracking: "Update current and peak on alloc; reduce current on free."
 - In interviews, clarify: "Ask if thread safety is needed."
 - Suggest optimization: "Use a linked list for per-allocation tracking."
 - Test edge cases: "Zero size, large allocations."

Problem 197: Check for Invalid Memory Access

Issue Description

Detect invalid memory access (e.g., out-of-bounds reads/writes) conceptually.

Problem Decomposition & Solution Steps

- **Input:** Pointer, base address, size, access offset.
- **Output:** Boolean indicating valid access.
- **Approach:** Check if access address is within bounds.
- **Algorithm:** Bounds Check
 - **Explanation:** Validate that pointer + offset is within [base, base + size).
- **Steps:**
 1. Validate pointer, base, and size.
 2. Compute access address.
 3. Check if address is in bounds.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bounds check algorithm ensures the access address (pointer + offset) lies within the valid range [base, base + size).

This detects invalid accesses like out-of-bounds reads/writes.

It's O(1) with simple comparisons, using O(1) space.

Coding Part (with Unit Tests)

```
// Check for invalid memory access
bool checkMemoryAccess(void* ptr, void* base, size_t size, ptrdiff_t offset) {
    if (!ptr || !base || size == 0) return false;
    char* accessPtr = (char*)ptr + offset;
    return accessPtr >= (char*)base && accessPtr < (char*)base + size;
}

// Unit tests
void testCheckMemoryAccess() {
    char* base = malloc(100);
    char* ptr = base + 50;
    assertBoolEquals(true, checkMemoryAccess(ptr, base, 100, 10), "Test 197.1 - Valid access");
    assertBoolEquals(false, checkMemoryAccess(ptr, base, 100, 60), "Test 197.2 - Invalid access");
    free(base);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use `char*` for byte-level arithmetic.
 - Validate all inputs.
 - Check both bounds.
 - Test with boundary accesses.

- **Expert Tips:**

- Explain check: "Ensure access address is within valid range."
- In interviews, clarify: "Ask if runtime tools like AddressSanitizer are allowed."
- Suggest optimization: "Use compiler sanitizers for automation."
- Test edge cases: "NULL, zero size, boundary offsets."

Problem 198: Safely Free a Nested Structure

Issue Description

Free a nested structure with pointers to avoid memory leaks.

Problem Decomposition & Solution Steps

- **Input:** Pointer to nested structure.
- **Output:** None (memory freed).
- **Approach:** Recursively free all pointers.
- **Algorithm:** Recursive Free
 - **Explanation:** Free nested pointers, then the structure itself.
- **Steps:**
 1. Validate structure pointer.
 2. Free nested pointers recursively.
 3. Free the structure.
- **Complexity:** Time $O(n)$, Space $O(n)$ for n pointers (recursion).

Algorithm Explanation

The recursive free algorithm traverses the structure, freeing all nested pointers (e.g., strings, nested structs) before freeing the structure itself.

This ensures no leaks in nested data.

It's $O(n)$ for n pointers, with $O(n)$ space for the recursion stack.

Coding Part (with Unit Tests)

```
typedef struct Nested {
    char* str;
    int val;
} Nested;

typedef struct DeepStruct {
    char* name;
    Nested* nested;
} DeepStruct;

// Safely free nested structure
void safeFreeDeepStruct(DeepStruct* s) {
    if (!s) return;
    free(s->name);
    if (s->nested) {
        free(s->nested->str);
        free(s->nested);
    }
}
```

```

        free(s);
    }

// Unit tests
void testSafeFreeDeepStruct() {
    DeepStruct* s = malloc(sizeof(DeepStruct));
    s->name = strdup("test");
    s->nested = malloc(sizeof(Nested));
    s->nested->str = strdup("nested");
    s->nested->val = 100;
    safeFreeDeepStruct(s);
    printf("Test 198.1 - Free nested struct: PASSED (no crash)\n");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Check for NULL before freeing.
 - Free nested pointers first.
 - Handle nested structures recursively.
 - Test with complex structures.
- **Expert Tips:**
 - Explain free: "Free pointers bottom-up to avoid leaks."
 - In interviews, clarify: "Ask if specific pointer types are involved."
 - Suggest optimization: "Use custom allocators for tracking."
 - Test edge cases: "NULL pointers, empty strings."

Problem 199: Handle Memory Allocation Failures

Issue Description

Handle cases where memory allocation fails gracefully.

Problem Decomposition & Solution Steps

- **Input:** Allocation request.
- **Output:** Pointer or NULL with error handling.
- **Approach:** Wrap malloc, handle NULL returns.
- **Algorithm:** Safe Allocation
 - **Explanation:** Check malloc return, log error or retry with smaller size.
- **Steps:**
 1. Call malloc and check for NULL.
 2. Log error or retry if NULL.
 3. Return pointer or NULL.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The safe allocation algorithm wraps malloc, checking for NULL to indicate failure.

It logs the error or retries with a smaller size as a fallback.

This is O(1) per attempt, with O(1) space for logging.

Coding Part (with Unit Tests)

```
// Safe malloc with failure handling
void* safeMalloc(size_t size) {
    void* ptr = malloc(size);
    if (!ptr) {
        fprintf(stderr, "Allocation failed for size %zu\n", size);
        if (size > 1) return safeMalloc(size / 2); // Fallback
    }
    return ptr;
}

// Unit tests
void testSafeMalloc() {
    void* ptr = safeMalloc(100);
    assertBoolEquals(true, ptr != NULL, "Test 199.1 - Successful allocation");
    free(ptr);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Always check malloc return.
 - Log failures for debugging.
 - Implement fallback strategies.
 - Test with large allocations.
- **Expert Tips:**
 - Explain handling: "Check NULL, retry or fail gracefully."
 - In interviews, clarify: "Ask if specific fallback is required."
 - Suggest optimization: "Use memory pools for reliability."
 - Test edge cases: "Repeated failures, large sizes."

Problem 200: Check for Memory Alignment in a Dynamic Buffer

Issue Description

Verify that a dynamically allocated buffer is aligned to a specified boundary.

Problem Decomposition & Solution Steps

- **Input:** Buffer pointer, alignment requirement.
- **Output:** Boolean indicating alignment.
- **Approach:** Check if buffer address is aligned.
- **Algorithm:** Alignment Check
 - **Explanation:** Verify buffer address is a multiple of alignment.
- **Steps:**
 1. Validate buffer and alignment.
 2. Check if address modulo alignment is 0.
 3. Return true if aligned.

- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The alignment check algorithm ensures the buffer's address is a multiple of the alignment (e.g., 16 for DMA).

It uses modulo to check alignment.

This is O(1) with simple arithmetic, using O(1) space.

Coding Part (with Unit Tests)

```
// Check buffer alignment
bool checkBufferAlignment(void* buffer, size_t alignment) {
    if (!buffer || (alignment & (alignment - 1)) != 0) return false;
    return (size_t)buffer % alignment == 0;
}

// Unit tests
void testCheckBufferAlignment() {
    void* buffer = alignedMalloc(100, 16);
    assertBoolEquals(true, checkBufferAlignment(buffer, 16), "Test 200.1 - Aligned buffer");
    alignedFree(buffer);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate alignment as power of 2.
 - Use aligned allocation for testing.
 - Check address directly.
 - Test with different alignments.
- **Expert Tips:**
 - Explain check: "Address must be multiple of alignment."
 - In interviews, clarify: "Ask if specific alignment is needed."
 - Suggest optimization: "Use aligned_alloc for standard compliance."
 - Test edge cases: "NULL, invalid alignment."

Problem 201: Split a Memory Block into Two

Issue Description

Split a memory block into two smaller blocks.

Problem Decomposition & Solution Steps

- **Input:** Pointer, original size, split size.
- **Output:** Two pointers to split blocks.
- **Approach:** Use realloc for first block, allocate second.
- **Algorithm:** Split Allocation

- **Explanation:** Shrink first block with realloc, allocate second block.
- **Steps:**
 1. Validate inputs and sizes.
 2. Realloc first block to split size.
 3. Allocate second block for remaining size.
- **Complexity:** Time O(n), Space O(n).

Algorithm Explanation

The split allocation algorithm uses realloc to resize the original block to the split size, then allocates a new block for the remaining size.

Data is copied by realloc if needed.

This is O(n) for n bytes, with O(n) space for the two blocks.

Coding Part (with Unit Tests)

```

typedef struct SplitResult {
    void* first;
    void* second;
} SplitResult;

// Split memory block
SplitResult splitMemoryBlock(void* block, size_t totalSize, size_t firstSize) {
    SplitResult result = {NULL, NULL};
    if (!block || firstSize >= totalSize) return result;
    result.first = realloc(block, firstSize);
    if (!result.first) return result;
    result.second = malloc(totalSize - firstSize);
    if (result.second) {
        memcpy(result.second, (char*)block + firstSize, totalSize - firstSize);
    }
    return result;
}

// Unit tests
void testSplitMemoryBlock() {
    int* block = malloc(4 * sizeof(int));
    for (int i = 0; i < 4; i++) block[i] = i + 1;
    SplitResult result = splitMemoryBlock(block, 4 * sizeof(int), 2 * sizeof(int));
    assertBoolEquals(true, result.first && result.second && ((int*)result.first)[0] == 1 &&
    ((int*)result.second)[0] == 3, "Test 201.1 - Split block");
    free(result.first);
    free(result.second);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate split size.
 - Handle realloc failure.
 - Copy data to second block.
 - Test with various split sizes.
- **Expert Tips:**
 - Explain split: "Realloc first, allocate second with copied data."

- In interviews, clarify: "Ask if data copying is needed."
- Suggest optimization: "Use single block with offsets if possible."
- Test edge cases: "Zero split size, full size."

Problem 202: Handle Memory Reuse in a Pool

Issue Description

Reuse freed memory in a fixed-size block pool.

Problem Decomposition & Solution Steps

- **Input:** Pool with fixed-size blocks.
- **Output:** Allocate/free with reuse.
- **Approach:** Use free list for reuse.
- **Algorithm:** Free List Reuse
 - **Explanation:** Maintain free list, reuse freed blocks for allocations.
- **Steps:**
 1. Initialize pool with free list.
 2. Allocate from free list.
 3. Free by adding to free list.
- **Complexity:** Time O(1) for alloc/free, Space O(n).

Algorithm Explanation

The free list reuse algorithm maintains a linked list of free blocks within the pool.

Allocation returns the head of the free list; freeing adds the block back.

This ensures reuse of freed memory.

It's O(1) for alloc/free, with O(n) space for the pool.

Coding Part (with Unit Tests)

```

typedef struct ReusePool {
    void* memory;
    void* freeList;
    size_t blockSize;
    size_t numBlocks;
} ReusePool;

// Initialize pool
ReusePool* createReusePool(size_t blockSize, size_t numBlocks) {
    ReusePool* pool = malloc(sizeof(ReusePool));
    pool->blockSize = blockSize;
    pool->numBlocks = numBlocks;
    pool->memory = malloc(blockSize * numBlocks);
    pool->freeList = pool->memory;
    for (size_t i = 0; i < numBlocks - 1; i++) {
        *(void**)((char*)pool->memory + i * blockSize) = (char*)pool->memory + (i + 1) * blockSize;
    }
}

```

```

        *(void**)&((char*)pool->memory + (numBlocks - 1) * blockSize) = NULL;
    return pool;
}

// Allocate block
void* reusePoolAlloc(ReusePool* pool) {
    if (!pool->freeList) return NULL;
    void* block = pool->freeList;
    pool->freeList = *(void**)&block;
    return block;
}

// Free block
void reusePoolFree(ReusePool* pool, void* block) {
    if (block) {
        *(void**)&block = pool->freeList;
        pool->freeList = block;
    }
}

// Destroy pool
void destroyReusePool(ReusePool* pool) {
    if (pool) {
        free(pool->memory);
        free(pool);
    }
}

// Unit tests
void testReusePool() {
    ReusePool* pool = createReusePool(16, 3);
    void* block1 = reusePoolAlloc(pool);
    reusePoolFree(pool, block1);
    void* block2 = reusePoolAlloc(pool);
    assertPtrEquals(block1, block2, "Test 202.1 - Reuse freed block");
    destroyReusePool(pool);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use free list for reuse.
 - Validate block pointers.
 - Test alloc/free cycles.
 - Free pool on destroy.
- **Expert Tips:**
 - Explain reuse: "Free list ensures freed blocks are reused."
 - In interviews, clarify: "Ask if alignment is needed."
 - Suggest optimization: "Use bitmaps for small blocks."
 - Test edge cases: "Empty pool, multiple frees."

Problem 203: Check for Unaligned Memory Access

Issue Description

Detect unaligned memory access in a program (conceptual).

Problem Decomposition & Solution Steps

- **Input:** Pointer, expected alignment.
- **Output:** Boolean indicating aligned access.
- **Approach:** Check pointer alignment.
- **Algorithm:** Alignment Check
 - **Explanation:** Verify pointer address is a multiple of alignment.
- **Steps:**
 1. Validate pointer and alignment.
 2. Check if address modulo alignment is 0.
 3. Return true if aligned.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The alignment check algorithm verifies that a pointer's address is a multiple of the required alignment.

Unaligned access can cause performance issues or crashes on some architectures.

This is O(1) with a modulo operation, using O(1) space.

Coding Part (with Unit Tests)

```
// Check for unaligned access
bool checkUnalignedAccess(void* ptr, size_t alignment) {
    if (!ptr || (alignment & (alignment - 1)) != 0) return false;
    return (size_t)ptr % alignment == 0;
}

// Unit tests
void testCheckUnalignedAccess() {
    void* ptr = alignedMalloc(100, 16);
    assertBoolEquals(true, checkUnalignedAccess(ptr, 16), "Test 203.1 - Aligned access");
    alignedFree(ptr);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate alignment as power of 2.
 - Check pointer directly.
 - Use aligned allocations for testing.
 - Test with different alignments.
- **Expert Tips:**
 - Explain unaligned: "Address must be multiple of alignment."
 - In interviews, clarify: "Ask if platform-specific checks are needed."
 - Suggest optimization: "Use compiler warnings for unaligned access."
 - Test edge cases: "NULL, invalid alignment."

Problem 204: Initialize a Dynamic Array with Zeros

Issue Description

Initialize a dynamically allocated array with zeros.

Problem Decomposition & Solution Steps

- **Input:** Size of array.
- **Output:** Zero-initialized array pointer.
- **Approach:** Use calloc or malloc + memset.
- **Algorithm:** Zero Initialization
 - **Explanation:** Allocate array, zero with memset.
- **Steps:**
 1. Validate size.
 2. Allocate with malloc.
 3. Zero with memset.
- **Complexity:** Time $O(n)$, Space $O(n)$.

Algorithm Explanation

The zero initialization algorithm allocates memory with malloc and uses memset to set all bytes to 0.

Alternatively, calloc could be used for direct zero-initialization.

This is $O(n)$ for n bytes, with $O(n)$ space for the array.

Coding Part (with Unit Tests)

```
// Initialize dynamic array with zeros
int* initZeroArray(size_t size) {
    if (size == 0) return NULL;
    int* arr = malloc(size * sizeof(int));
    if (arr) memset(arr, 0, size * sizeof(int));
    return arr;
}

// Unit tests
void testInitZeroArray() {
    int* arr = initZeroArray(5);
    assertBoolEquals(true, arr && arr[0] == 0 && arr[4] == 0, "Test 204.1 - Zeroed array");
    free(arr);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate size.
 - Use memset or calloc.
 - Check allocation success.
 - Test with various sizes.
- **Expert Tips:**
 - Explain init: "Use memset for zeroing after malloc."

- In interviews, clarify: "Ask if calloc is preferred."
- Suggest optimization: "Use calloc for system-optimized zeroing."
- Test edge cases: "Zero size, large arrays."

Problem 205: Handle Memory Defragmentation

Issue Description

Defragment a memory pool to reduce fragmentation (similar to Problems 165, 183).

Problem Decomposition & Solution Steps

- **Input:** Memory pool with allocated/free blocks.
- **Output:** Contiguous allocated blocks.
- **Approach:** Move allocated blocks to start.
- **Algorithm:** Compaction
 - **Explanation:** Relocate allocated blocks, update pointers.
- **Steps:**
 1. Track allocated blocks.
 2. Move blocks to start.
 3. Update pointers and free list.
- **Complexity:** Time O(n), Space O(n).

Algorithm Explanation

The compaction algorithm moves allocated blocks to the start of the pool, updating their pointers.

Free blocks are linked at the end.

This reduces fragmentation and is O(n) for n blocks, with O(n) space for tracking.

(Note: Similar to Problem 183 but with minimal implementation.)

Coding Part (with Unit Tests)

```
typedef struct DefragPool {
    void* memory;
    struct { void* ptr; bool allocated; } *blocks;
    size_t blockSize;
    size_t numBlocks;
} DefragPool;

// Initialize pool
DefragPool* createDefragPool(size_t blockSize, size_t numBlocks) {
    DefragPool* pool = malloc(sizeof(DefragPool));
    pool->blockSize = blockSize;
    pool->numBlocks = numBlocks;
    pool->memory = malloc(blockSize * numBlocks);
    pool->blocks = malloc(numBlocks * sizeof(*pool->blocks));
    for (size_t i = 0; i < numBlocks; i++) {
        pool->blocks[i].ptr = (char*)pool->memory + i * blockSize;
        pool->blocks[i].allocated = false;
    }
    return pool; }
```

```

// Allocate block
void* defragPoolAlloc(DefragPool* pool) {
    for (size_t i = 0; i < pool->numBlocks; i++) {
        if (!pool->blocks[i].allocated) {
            pool->blocks[i].allocated = true;
            return pool->blocks[i].ptr;
        }
    }
    return NULL;
}

// Defragment pool
void defragPool(DefragPool* pool) {
    size_t newPos = 0;
    for (size_t i = 0; i < pool->numBlocks; i++) {
        if (pool->blocks[i].allocated) {
            if (i != newPos) {
                memmove((char*)pool->memory + newPos * pool->blockSize, pool->blocks[i].ptr, pool->blockSize);
                pool->blocks[i].ptr = (char*)pool->memory + newPos * pool->blockSize;
            }
            newPos++;
        }
    }
}

// Destroy pool
void destroyDefragPool(DefragPool* pool) {
    if (pool) {
        free(pool->memory);
        free(pool->blocks);
        free(pool);
    }
}

// Unit tests
void testDefragPool() {
    DefragPool* pool = createDefragPool(16, 3);
    void* block1 = defragPoolAlloc(pool);
    pool->blocks[1].allocated = true;
    defragPool(pool);
    assertBoolEquals(true, pool->blocks[1].ptr == pool->memory + 16, "Test 205.1 - Defragmented block");
    destroyDefragPool(pool);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track allocated blocks.
 - Use memmove for safety.
 - Update pointers post-compaction.
 - Test with fragmented pools.
- **Expert Tips:**
 - Explain defrag: "Move blocks to start, update pointers."
 - In interviews, clarify: "Ask if external pointer updates are needed."
 - Suggest optimization: "Use free list for allocation."
 - Test edge cases: "All free, all allocated."

Problem 206: Check for Memory Corruption in a Dynamic Array

Issue Description

Detect memory corruption in a dynamic array (e.g., overwritten bounds).

Problem Decomposition & Solution Steps

- **Input:** Array pointer, size.
- **Output:** Boolean indicating no corruption.
- **Approach:** Use canary values at boundaries.
- **Algorithm:** Canary Check
 - **Explanation:** Place known values before/after array, check for changes.
- **Steps:**
 1. Allocate array with extra space for canaries.
 2. Set canary values at boundaries.
 3. Check canaries for corruption.
- **Complexity:** Time O(1), Space O(n + constant).

Algorithm Explanation

The canary check algorithm allocates extra space for canary values (e.g., magic numbers) before and after the array.

Before use, check if canaries are intact.

Corruption (e.g., buffer overflow) alters canaries.

This is O(1) for checks, with O(n) space for the array plus canaries.

Coding Part (with Unit Tests)

```
#define CANARY_VALUE 0xDEADBEEF

typedef struct SafeArray {
    size_t canaryStart;
    int* data;
    size_t size;
    size_t canaryEnd;
} SafeArray;

// Allocate array with canaries
SafeArray* createSafeArray(size_t size) {
    SafeArray* arr = malloc(sizeof(SafeArray));
    arr->data = malloc(size * sizeof(int) + 2 * sizeof(size_t));
    arr->canaryStart = CANARY_VALUE;
    arr->size = size;
    arr->canaryEnd = CANARY_VALUE;
    arr->data = (int*)((char*)arr->data + sizeof(size_t));
    return arr;
}

// Check for corruption
bool checkArrayCorruption(SafeArray* arr) {
    return arr && arr->canaryStart == CANARY_VALUE && arr->canaryEnd == CANARY_VALUE; }
```

```

// Free array
void freeSafeArray(SafeArray* arr) {
    if (arr) {
        free((char*)arr->data - sizeof(size_t));
        free(arr);
    }
}

// Unit tests
void testCheckArrayCorruption() {
    SafeArray* arr = createSafeArray(5);
    assertBoolEquals(true, checkArrayCorruption(arr), "Test 206.1 - No corruption");
    arr->canaryEnd = 0; // Simulate corruption
    assertBoolEquals(false, checkArrayCorruption(arr), "Test 206.2 - Corruption detected");
    freeSafeArray(arr);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use unique canary values.
 - Place canaries at both ends.
 - Check canaries before access.
 - Test with corrupted and clean arrays.
- **Expert Tips:**
 - Explain canaries: "Detect overwrites with boundary markers."
 - In interviews, clarify: "Ask if runtime tools are allowed."
 - Suggest optimization: "Use AddressSanitizer for robust checks."
 - Test edge cases: "NULL, corrupted canaries."

Problem 207: Merge Two Memory Pools

Issue Description

Merge two memory pools into a single pool, preserving allocated blocks.

Problem Decomposition & Solution Steps

- **Input:** Two pools with allocated/free blocks.
- **Output:** Single pool with all allocated blocks.
- **Approach:** Copy allocated blocks to new pool.
- **Algorithm:** Pool Merge
 - **Explanation:** Allocate new pool, copy allocated blocks, update pointers.
- **Steps:**
 1. Calculate total size and allocated blocks.
 2. Allocate new pool.
 3. Copy allocated blocks from both pools.
- **Complexity:** Time O(n), Space O(n) for n blocks.

Algorithm Explanation

The pool merge algorithm creates a new pool large enough for all blocks from both pools.

It copies allocated blocks to the new pool, updating pointers.

Free blocks are discarded or reused.

This is $O(n)$ for n blocks, with $O(n)$ space for the new pool.

Coding Part (with Unit Tests)

```
typedef struct MergePool {
    void* memory;
    struct { void* ptr; bool allocated; } *blocks;
    size_t blockSize;
    size_t numBlocks;
} MergePool;

// Initialize pool
MergePool* createMergePool(size_t blockSize, size_t numBlocks) {
    MergePool* pool = malloc(sizeof(MergePool));
    pool->blockSize = blockSize;
    pool->numBlocks = numBlocks;
    pool->memory = malloc(blockSize * numBlocks);
    pool->blocks = malloc(numBlocks * sizeof(*pool->blocks));
    for (size_t i = 0; i < numBlocks; i++) {
        pool->blocks[i].ptr = (char*)pool->memory + i * blockSize;
        pool->blocks[i].allocated = false;
    }
    return pool;
}

// Allocate block
void* mergePoolAlloc(MergePool* pool) {
    for (size_t i = 0; i < pool->numBlocks; i++) {
        if (!pool->blocks[i].allocated) {
            pool->blocks[i].allocated = true;
            return pool->blocks[i].ptr;
        }
    }
    return NULL;
}

// Merge two pools
MergePool* mergePools(MergePool* pool1, MergePool* pool2) {
    size_t totalBlocks = pool1->numBlocks + pool2->numBlocks;
    MergePool* newPool = createMergePool(pool1->blockSize, totalBlocks);
    size_t newPos = 0;
    for (size_t i = 0; i < pool1->numBlocks; i++) {
        if (pool1->blocks[i].allocated) {
            memcpy((char*)newPool->memory + newPos * pool1->blockSize, pool1->blocks[i].ptr, pool1->blockSize);
            newPool->blocks[newPos].ptr = (char*)newPool->memory + newPos * pool1->blockSize;
            newPool->blocks[newPos++].allocated = true;
        }
    }
    for (size_t i = 0; i < pool2->numBlocks; i++) {
        if (pool2->blocks[i].allocated) {
            memcpy((char*)newPool->memory + newPos * pool2->blockSize, pool2->blocks[i].ptr, pool2->blockSize);
            newPool->blocks[newPos].ptr = (char*)newPool->memory + newPos * pool2->blockSize;
            newPool->blocks[newPos++].allocated = true;
        }
    }
}
```

```

        }
    }
    return newPool;
}

// Destroy pool
void destroyMergePool(MergePool* pool) {
    if (pool) {
        free(pool->memory);
        free(pool->blocks);
        free(pool);
    }
}

// Unit tests
void testMergePools() {
    MergePool* pool1 = createMergePool(16, 2);
    MergePool* pool2 = createMergePool(16, 2);
    void* block1 = mergePoolAlloc(pool1);
    void* block2 = mergePoolAlloc(pool2);
    MergePool* merged = mergePools(pool1, pool2);
    assertBoolEquals(true, merged->blocks[0].allocated && merged->blocks[1].allocated, "Test 207.1 - Merged allocated blocks");
    destroyMergePool(pool1);
    destroyMergePool(pool2);
    destroyMergePool(merged);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track allocated blocks.
 - Copy only allocated blocks.
 - Update pointers in new pool.
 - Test with multiple pools.
- **Expert Tips:**
 - Explain merge: "Copy allocated blocks to new pool."
 - In interviews, clarify: "Ask if free blocks should be preserved."
 - Suggest optimization: "Use single pool with offsets."
 - Test edge cases: "Empty pools, all allocated."

Problem 208: Handle Memory Alignment for DMA

Issue Description

Allocate memory aligned for Direct Memory Access (DMA).

Problem Decomposition & Solution Steps

- **Input:** Size, DMA alignment (e.g., 64 bytes).
- **Output:** Aligned memory pointer.
- **Approach:** Use aligned allocation.
- **Algorithm:** DMA Aligned Allocation
 - **Explanation:** Allocate with extra space, align to DMA boundary, store original pointer.

- **Steps:**
 1. Validate size and alignment.
 2. Allocate size + alignment + pointer storage.
 3. Adjust to aligned address.
 4. Store original pointer for freeing.
- **Complexity:** Time O(1), Space O(n + alignment).

Algorithm Explanation

The DMA aligned allocation algorithm allocates extra space to ensure an aligned address for DMA (e.g., 64-byte boundary).

It adjusts the pointer to the next aligned address and stores the original for freeing.

This is O(1) for allocation, with O(n) space for the block plus overhead.

Coding Part (with Unit Tests)

```
// Allocate DMA-aligned memory
void* dmaMalloc(size_t size, size_t alignment) {
    if (size == 0 || (alignment & (alignment - 1)) != 0) return NULL;
    void* raw = malloc(size + alignment - 1 + sizeof(void*));
    if (!raw) return NULL;
    void* aligned = (void*)(((size_t)((char*)raw + sizeof(void*) + alignment - 1) / alignment) *
                           alignment);
    ((void**)aligned)[-1] = raw;
    return aligned;
}

// Free DMA-aligned memory
void dmaFree(void* ptr) {
    if (ptr) free(((void**)ptr)[-1]);
}

// Unit tests
void testDmaMalloc() {
    void* ptr = dmaMalloc(100, 64);
    assertBoolEquals(true, ptr && ((size_t)ptr % 64) == 0, "Test 208.1 - DMA aligned");
    dmaFree(ptr);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate alignment as power of 2.
 - Store original pointer for freeing.
 - Ensure DMA-compatible alignment.
 - Test with DMA alignments (e.g., 64, 128).
- **Expert Tips:**
 - Explain DMA: "Align for hardware requirements."
 - In interviews, clarify: "Ask if specific DMA alignment is needed."
 - Suggest optimization: "Use aligned_alloc for standard compliance."
 - Test edge cases: "Invalid alignment, zero size."

Problem 209: Check for Memory Leaks in a Circular Buffer

Issue Description

Detect memory leaks in a circular buffer implementation.

Problem Decomposition & Solution Steps

- **Input:** Circular buffer with dynamic allocations.
- **Output:** Boolean indicating no leaks.
- **Approach:** Track allocations and frees.
- **Algorithm:** Allocation Tracking
 - **Explanation:** Track buffer and data allocations, ensure all are freed.
- **Steps:**
 1. Track buffer allocation.
 2. Free buffer and check tracker.
 3. Report leaks if tracker non-empty.
- **Complexity:** Time $O(n)$, Space $O(n)$ for n allocations.

Algorithm Explanation

The allocation tracking algorithm tracks the circular buffer's memory and any dynamic data.

On destruction, free all allocations and check if the tracker is empty.

Non-empty tracker indicates leaks.

This is $O(n)$ for n tracked allocations, with $O(n)$ space for tracking.

Coding Part (with Unit Tests)

```
typedef struct CircularBuffer {
    int* data;
    size_t size;
} CircularBuffer;

static void* trackedAllocs[MAX_ALLOCS];
static int allocCount = 0;

// Track allocation
void trackAlloc(void* ptr) {
    if (allocCount < MAX_ALLOCS) trackedAllocs[allocCount++] = ptr;
}

// Create circular buffer
CircularBuffer* createCircularBuffer(size_t size) {
    CircularBuffer* cb = malloc(sizeof(CircularBuffer));
    trackAlloc(cb);
    cb->data = malloc(size * sizeof(int));
    trackAlloc(cb->data);
    cb->size = size;
    return cb;
}
```

```

// Free circular buffer
bool freeCircularBuffer(CircularBuffer* cb) {
    if (!cb) return allocCount == 0;
    for (int i = 0; i < allocCount; i++) {
        if (trackedAllocs[i] == cb->data) {
            trackedAllocs[i] = trackedAllocs[--allocCount];
            free(cb->data);
            break;
        }
    }
    for (int i = 0; i < allocCount; i++) {
        if (trackedAllocs[i] == cb) {
            trackedAllocs[i] = trackedAllocs[--allocCount];
            free(cb);
            break;
        }
    }
    return allocCount == 0;
}

// Unit tests
void testCircularBufferLeaks() {
    allocCount = 0;
    CircularBuffer* cb = createCircularBuffer(5);
    assertBoolEquals(true, freeCircularBuffer(cb), "Test 209.1 - No leaks");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track all allocations.
 - Free buffer and data.
 - Check tracker for leaks.
 - Test with allocated buffers.
- **Expert Tips:**
 - Explain leak check: "Track and ensure all allocations freed."
 - In interviews, clarify: "Ask if dynamic data is stored."
 - Suggest optimization: "Use Valgrind for robust leak detection."
 - Test edge cases: "Empty buffer, partial frees."

Problem 210: Manage a Memory-Efficient Hash Table

Issue Description

Implement a memory-efficient hash table with dynamic resizing.

Problem Decomposition & Solution Steps

- **Input:** Key-value pairs, operations (insert, lookup).
- **Output:** Hash table with efficient memory use.
- **Approach:** Use open addressing with linear probing.
- **Algorithm:** Open Addressing Hash Table
 - **Explanation:** Store key-value pairs in a single array, resize when load factor is high.
- **Steps:**
 1. Initialize array with slots.
 2. Insert with linear probing.

- 3. Resize when load factor exceeds threshold.
- **Complexity:** Time O(1) average for insert/lookup, Space O(n).

Algorithm Explanation

The open addressing hash table uses a single array with linear probing to resolve collisions.

Keys and values are stored in slots, with a load factor (e.g., 0.75) triggering resizing.

This minimizes memory overhead compared to chained hash tables.

Average time is O(1), with O(n) space for n entries.

Coding Part (with Unit Tests)

```

typedef struct HashEntry {
    int key;
    int value;
    bool occupied;
} HashEntry;

typedef struct HashTable {
    HashEntry* entries;
    size_t size;
    size_t count;
} HashTable;

// Simple hash function
size_t hash(int key, size_t size) {
    return (size_t)key % size;
}

// Initialize hash table
HashTable* createHashTable(size_t size) {
    HashTable* ht = malloc(sizeof(HashTable));
    ht->entries = malloc(size * sizeof(HashEntry));
    ht->size = size;
    ht->count = 0;
    for (size_t i = 0; i < size; i++) ht->entries[i].occupied = false;
    return ht;
}

// Insert key-value pair
bool hashInsert(HashTable* ht, int key, int value) {
    if (ht->count >= ht->size * 0.75) return false; // Need resize
    size_t index = hash(key, ht->size);
    while (ht->entries[index].occupied) {
        if (ht->entries[index].key == key) {
            ht->entries[index].value = value;
            return true;
        }
        index = (index + 1) % ht->size;
    }
    ht->entries[index].key = key;
    ht->entries[index].value = value;
    ht->entries[index].occupied = true;
    ht->count++;
    return true;
}

```

```

// Lookup value by key
bool hashLookup(HashTable* ht, int key, int* value) {
    size_t index = hash(key, ht->size);
    size_t start = index;
    do {
        if (ht->entries[index].occupied && ht->entries[index].key == key) {
            *value = ht->entries[index].value;
            return true;
        }
        index = (index + 1) % ht->size;
    } while (index != start && ht->entries[index].occupied);
    return false;
}

// Free hash table
void freeHashTable(HashTable* ht) {
    if (ht) {
        free(ht->entries);
        free(ht);
    }
}

// Unit tests
void testHashTable() {
    HashTable* ht = createHashTable(10);
    hashInsert(ht, 1, 100);
    int value;
    assertBoolEquals(true, hashLookup(ht, 1, &value) && value == 100, "Test 210.1 - Insert and Lookup");
    freeHashTable(ht);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use open addressing for memory efficiency.
 - Resize at high load factor.
 - Handle collisions with probing.
 - Test with multiple insertions.
- **Expert Tips:**
 - Explain efficiency: "Open addressing saves memory vs. chaining."
 - In interviews, clarify: "Ask if resizing or specific hash is needed."
 - Suggest optimization: "Use double hashing for better distribution."
 - Test edge cases: "Full table, duplicate keys."

Main Function to Run All Tests

```

int main() {
    printf("Running tests for memory management problems 196 to 210:\n");
    testPeakMemory();
    testCheckMemoryAccess();
    testSafeFreeDeepStruct();
    testSafeMalloc();
    testCheckBufferAlignment();
    testSplitMemoryBlock();
    testReusePool();
    testCheckUnalignedAccess();
}

```

```

    testInitZeroArray();
    testDefragPool();
    testCheckArrayCorruption();
    testMergePools();
    testDmaMalloc();
    testCircularBufferLeaks();
    testHashTable();
    return 0;
}

```

Problem 211: Implement a Buddy Memory Allocator

Issue Description

Implement a buddy memory allocator that allocates memory in power-of-2 blocks, splitting and merging to reduce fragmentation.

Problem Decomposition & Solution Steps

- **Input:** Total memory size, allocation requests.
- **Output:** Allocated memory pointers.
- **Approach:** Use a binary buddy system with free lists for each power-of-2 size.
- **Algorithm:** Buddy Allocation
 - **Explanation:** Divide memory into power-of-2 blocks, split larger blocks for allocation, merge on free.
- **Steps:**
 1. Initialize memory with free lists for each power-of-2 size.
 2. Allocate by finding smallest suitable block, splitting if needed.
 3. Free by merging with buddy if free.
- **Complexity:** Time $O(\log n)$ for alloc/free, Space $O(n)$.

Algorithm Explanation

The buddy allocation algorithm divides memory into blocks of sizes 2^k .

Free lists track available blocks for each size.

Allocation finds the smallest sufficient block, splitting larger ones if needed.

Freeing checks if the buddy block is free, merging them to form a larger block.

This is $O(\log n)$ for operations (due to list traversal), with $O(n)$ space for memory and lists.

Coding Part (with Unit Tests)

```

#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>
#include <math.h>

#define MAX_ORDER 10

```

```

typedef struct BuddyBlock {
    struct BuddyBlock* next;
    size_t order; // 2^order size
} BuddyBlock;

typedef struct BuddyAllocator {
    void* memory;
    BuddyBlock* freeLists[MAX_ORDER + 1];
    size_t totalSize;
} BuddyAllocator;

// Initialize buddy allocator
BuddyAllocator* createBuddyAllocator(size_t size) {
    BuddyAllocator* alloc = malloc(sizeof(BuddyAllocator));
    alloc->totalSize = size;
    alloc->memory = malloc(size);
    for (int i = 0; i <= MAX_ORDER; i++) alloc->freeLists[i] = NULL;
    size_t order = (size_t)ceil(log2(size));
    BuddyBlock* block = (BuddyBlock*)alloc->memory;
    block->order = order > MAX_ORDER ? MAX_ORDER : order;
    block->next = NULL;
    alloc->freeLists[block->order] = block;
    return alloc;
}

// Allocate memory
void* buddyAlloc(BuddyAllocator* alloc, size_t size) {
    if (size == 0) return NULL;
    size_t order = (size_t)ceil(log2(size));
    if (order > MAX_ORDER) return NULL;
    for (size_t i = order; i <= MAX_ORDER; i++) {
        if (alloc->freeLists[i]) {
            BuddyBlock* block = alloc->freeLists[i];
            alloc->freeLists[i] = block->next;
            while (i > order) {
                i--;
                BuddyBlock* buddy = (BuddyBlock*)((char*)block + (1 << i));
                buddy->order = i;
                buddy->next = alloc->freeLists[i];
                alloc->freeLists[i] = buddy;
                block->order = i;
            }
            return block;
        }
    }
    return NULL;
}

// Free memory
void buddyFree(BuddyAllocator* alloc, void* ptr) {
    if (!ptr) return;
    BuddyBlock* block = (BuddyBlock*)ptr;
    size_t order = block->order;
    size_t blockSize = 1 << order;
    while (order < MAX_ORDER) {
        size_t buddyAddr = ((char*)ptr - (char*)alloc->memory) ^ blockSize;
        BuddyBlock* buddy = (BuddyBlock*)((char*)alloc->memory + buddyAddr);
        BuddyBlock** curr = &alloc->freeLists[order];
        while (*curr && *curr != buddy) curr = &(*curr)->next;
        if (!*curr) break;
        *curr = buddy->next; // Remove buddy
        ptr = (char*)ptr < (char*)buddy ? ptr : buddy;
        order++;
        blockSize <= 1;
        block = (BuddyBlock*)ptr;
        block->order = order;
    }
}

```

```

        block->next = alloc->freeLists[order];
        alloc->freeLists[order] = block;
    }

    // Destroy allocator
    void destroyBuddyAllocator(BuddyAllocator* alloc) {
        if (alloc) {
            free(alloc->memory);
            free(alloc);
        }
    }

    // Unit test helper
    void assertPtrNotNull(void* ptr, const char* testName) {
        printf("%s: %s\n", testName, ptr ? "PASSED" : "FAILED");
    }

    // Unit tests
    void testBuddyAllocator() {
        BuddyAllocator* alloc = createBuddyAllocator(1024);
        void* ptr1 = buddyAlloc(alloc, 128);
        assertPtrNotNull(ptr1, "Test 211.1 - Allocate 128 bytes");
        buddyFree(alloc, ptr1);
        void* ptr2 = buddyAlloc(alloc, 128);
        assertPtrNotNull(ptr2, "Test 211.2 - Reuse freed block");
        destroyBuddyAllocator(alloc);
    }
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use power-of-2 block sizes.
 - Maintain free lists for efficiency.
 - Validate size and order.
 - Test with split and merge scenarios.
- **Expert Tips:**
 - Explain buddy system: "Split blocks for alloc, merge on free."
 - In interviews, clarify: "Ask if alignment or minimum block size is needed."
 - Suggest optimization: "Use bitmaps for free block tracking."
 - Test edge cases: "Large allocations, multiple frees."

Problem 212: Check for Memory Leaks in a Graph Structure

Issue Description

Detect memory leaks in a directed graph by ensuring all nodes are freed.

Problem Decomposition & Solution Steps

- **Input:** Graph with nodes and edges.
- **Output:** Boolean indicating no leaks.
- **Approach:** Track allocations, free with DFS, check tracker.
- **Algorithm:** DFS Free with Tracking
 - **Explanation:** Use DFS to free nodes, track allocations to detect leaks.

- **Steps:**
 1. Track all node allocations.
 2. Free graph using DFS to avoid cycles.
 3. Check if tracker is empty.
- **Complexity:** Time $O(V + E)$, Space $O(V)$ for V nodes, E edges.

Algorithm Explanation

The DFS free with tracking algorithm uses depth-first search to free graph nodes, marking visited nodes to handle cycles.

Allocations are tracked in a list, and after freeing, any remaining tracked nodes indicate leaks.

This is $O(V + E)$ for traversal, with $O(V)$ space for tracking and recursion.

Coding Part (with Unit Tests)

```
#define MAX_NODES 100

typedef struct GraphNode {
    int data;
    struct GraphNode** neighbors;
    size_t neighborCount;
} GraphNode;

static GraphNode* trackedNodes[MAX_NODES];
static int nodeCount = 0;

// Track node
void trackGraphNode(GraphNode* node) {
    if (nodeCount < MAX_NODES) trackedNodes[nodeCount++] = node;
}

// Free graph with DFS
void freeGraphDFS(GraphNode* node, bool* visited) {
    if (!node || visited[(size_t)node % MAX_NODES]) return;
    visited[(size_t)node % MAX_NODES] = true;
    for (size_t i = 0; i < node->neighborCount; i++) {
        freeGraphDFS(node->neighbors[i], visited);
    }
    for (int i = 0; i < nodeCount; i++) {
        if (trackedNodes[i] == node) {
            trackedNodes[i] = trackedNodes[--nodeCount];
            break;
        }
    }
    free(node->neighbors);
    free(node);
}

// Check for leaks
bool checkGraphLeaks(GraphNode* root) {
    bool visited[MAX_NODES] = {false};
    freeGraphDFS(root, visited);
    return nodeCount == 0;
}
```

```

// Unit tests
void testGraphLeaks() {
    nodeCount = 0;
    GraphNode* root = malloc(sizeof(GraphNode));
    trackGraphNode(root);
    root->data = 1;
    root->neighborCount = 0;
    root->neighbors = NULL;
    assertBoolEquals(true, checkGraphLeaks(root), "Test 212.1 - No leaks");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track all node allocations.
 - Use DFS to handle cycles.
 - Check tracker for leaks.
 - Test with cyclic graphs.
- **Expert Tips:**
 - Explain DFS: "Free nodes while avoiding cycles."
 - In interviews, clarify: "Ask if garbage collection is needed."
 - Suggest optimization: "Use reference counting for complex graphs."
 - Test edge cases: "Cycles, disconnected nodes."

Problem 213: Allocate Memory for a 3D Array

Issue Description

Allocate a dynamic 3D array with specified dimensions.

Problem Decomposition & Solution Steps

- **Input:** Dimensions (depth, rows, cols), element size.
- **Output:** Pointer to 3D array.
- **Approach:** Allocate nested pointer arrays.
- **Algorithm:** 3D Array Allocation
 - **Explanation:** Allocate array of pointers to 2D arrays, then rows, then columns.
- **Steps:**
 1. Validate dimensions.
 2. Allocate depth pointers.
 3. Allocate row pointers for each depth.
 4. Allocate columns for each row.
- **Complexity:** Time $O(d * r)$, Space $O(d * r * c)$.

Algorithm Explanation

The 3D array allocation algorithm creates a triple-pointer structure: one array for depth, pointing to arrays of row pointers, each pointing to column arrays.

This supports jagged arrays.

It's $O(d * r)$ for allocation loops, with $O(d * r * c)$ space for the array.

Coding Part (with Unit Tests)

```
// Allocate 3D array
int*** alloc3DArray(size_t depth, size_t rows, size_t cols) {
    if (depth == 0 || rows == 0 || cols == 0) return NULL;
    int*** arr = malloc(depth * sizeof(int**));
    if (!arr) return NULL;
    for (size_t i = 0; i < depth; i++) {
        arr[i] = malloc(rows * sizeof(int*));
        if (!arr[i]) {
            for (size_t j = 0; j < i; j++) free2DArray(arr[j], rows);
            free(arr);
            return NULL;
        }
        for (size_t j = 0; j < rows; j++) {
            arr[i][j] = malloc(cols * sizeof(int));
            if (!arr[i][j]) {
                for (size_t k = 0; k < j; k++) free(arr[i][k]);
                for (size_t k = 0; k < i; k++) free2DArray(arr[k], rows);
                free(arr[i]);
                free(arr);
                return NULL;
            }
        }
    }
    return arr;
}

// Free 3D array
void free3DArray(int*** arr, size_t depth, size_t rows) {
    if (!arr) return;
    for (size_t i = 0; i < depth; i++) {
        free2DArray(arr[i], rows);
    }
    free(arr);
}

// Unit tests
void testAlloc3DArray() {
    int*** arr = alloc3DArray(2, 3, 4);
    assertBoolEquals(true, arr && arr[0] && arr[0][0], "Test 213.1 - Allocate 2x3x4 array");
    free3DArray(arr, 2, 3);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate all dimensions.
 - Handle allocation failures.
 - Free partially allocated arrays.
 - Test with various dimensions.
- **Expert Tips:**
 - Explain allocation: "Triple-pointer for depth, rows, cols."
 - In interviews, clarify: "Ask if single-block allocation is preferred."
 - Suggest optimization: "Use contiguous block for locality."
 - Test edge cases: "Zero dimensions, allocation failure."

Problem 214: Handle Memory Alignment for a Union

Issue Description

Ensure a union's members are properly aligned in memory.

Problem Decomposition & Solution Steps

- **Input:** Union definition, alignment requirement.
- **Output:** Aligned union pointer.
- **Approach:** Use aligned allocation, check member alignments.
- **Algorithm:** Aligned Union Allocation
 - **Explanation:** Allocate union with aligned memory, verify member offsets.
- **Steps:**
 1. Allocate union with alignment.
 2. Check member offsets for alignment.
 3. Return aligned pointer.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The aligned union allocation algorithm uses a custom aligned allocator to ensure the union's base address is aligned.

It checks that each member's offset (via `offsetof`) aligns with its type's requirement.

This is O(1) for a fixed union, with O(1) space.

Coding Part (with Unit Tests)

```
#include <stddef.h>

typedef union AlignedUnion {
    char c;
    int i;
    double d;
} AlignedUnion;

// Allocate aligned union
AlignedUnion* allocAlignedUnion(size_t alignment) {
    AlignedUnion* u = alignedMalloc(sizeof(AlignedUnion), alignment);
    if (!u) return NULL;
    if (offsetof(AlignedUnion, c) % 1 != 0 ||
        offsetof(AlignedUnion, i) % 4 != 0 ||
        offsetof(AlignedUnion, d) % 8 != 0) {
        alignedFree(u);
        return NULL;
    }
    return u;
}

// Unit tests
void testAllocAlignedUnion() {
    AlignedUnion* u = allocAlignedUnion(8);
    assertBoolEquals(true, u && ((size_t)u % 8) == 0, "Test 214.1 - Aligned union");
    alignedFree(u); }
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use offsetof for alignment checks.
 - Validate type alignments.
 - Use aligned allocation.
 - Test with different alignments.
- **Expert Tips:**
 - Explain alignment: "Ensure member offsets match type requirements."
 - In interviews, clarify: "Ask if specific alignment is needed."
 - Suggest optimization: "Use #pragma pack for control."
 - Test edge cases: "Misaligned unions, large types."

Problem 215: Track Memory Usage in a Real-Time System

Issue Description

Track memory usage in a real-time system with minimal overhead.

Problem Decomposition & Solution Steps

- **Input:** Allocation/free requests.
- **Output:** Current memory usage.
- **Approach:** Wrap malloc and free with lightweight counter.
- **Algorithm:** Lightweight Usage Tracking
 - **Explanation:** Maintain a single counter for current memory usage.
- **Steps:**
 1. Initialize usage counter.
 2. Increment on allocation.
 3. Decrement on free.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The lightweight usage tracking algorithm maintains a single counter for total allocated memory.

On malloc, increment by size; on free, decrement.

This is O(1) per operation, with O(1) space, suitable for real-time systems due to minimal overhead.

Coding Part (with Unit Tests)

```
static size_t rtMemoryUsage = 0;

// Real-time malloc
void* rtMalloc(size_t size) {
    void* ptr = malloc(size);
    if (ptr) rtMemoryUsage += size;
    return ptr; }
```

```

// Real-time free
void rtFree(void* ptr, size_t size) {
    if (ptr) {
        rtMemoryUsage -= size;
        free(ptr);
    }
}

// Get current usage
size_t getRTMemoryUsage() {
    return rtMemoryUsage;
}

// Unit tests
void testRTMemoryUsage() {
    rtMemoryUsage = 0;
    void* ptr = rtMalloc(100);
    assertSizeTEquals(100, getRTMemoryUsage(), "Test 215.1 - Track allocation");
    rtFree(ptr, 100);
    assertSizeTEquals(0, getRTMemoryUsage(), "Test 215.2 - Track free");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use single counter for low overhead.
 - Validate sizes on free.
 - Test with alloc/free cycles.
 - Keep real-time constraints in mind.
- **Expert Tips:**
 - Explain tracking: "Single counter for minimal overhead."
 - In interviews, clarify: "Ask if thread safety is needed."
 - Suggest optimization: "Use atomic operations for concurrency."
 - Test edge cases: "Zero size, multiple allocations."

Problem 216: Check for Memory Corruption in a Queue

Issue Description

Detect memory corruption in a dynamic queue (e.g., overwritten data).

Problem Decomposition & Solution Steps

- **Input:** Queue with dynamic array.
- **Output:** Boolean indicating no corruption.
- **Approach:** Use canary values around queue buffer.
- **Algorithm:** Canary Check
 - **Explanation:** Place canaries before/after queue buffer, check for changes.
- **Steps:**
 1. Allocate queue with extra space for canaries.
 2. Set canary values.
 3. Check canaries before operations.

- **Complexity:** Time O(1), Space O(n + constant).

Algorithm Explanation

The canary check algorithm allocates extra space for canary values around the queue's buffer.

Before queue operations, check if canaries are intact.

Corruption (e.g., overflow) alters canaries.

This is O(1) for checks, with O(n) space for the queue plus canaries.

Coding Part (with Unit Tests)

```

typedef struct SafeQueue {
    size_t canaryStart;
    int* data;
    size_t size;
    size_t canaryEnd;
} SafeQueue;

// Create safe queue
SafeQueue* createSafeQueue(size_t size) {
    SafeQueue* q = malloc(sizeof(SafeQueue));
    q->data = malloc(size * sizeof(int) + 2 * sizeof(size_t));
    q->canaryStart = CANARY_VALUE;
    q->size = size;
    q->canaryEnd = CANARY_VALUE;
    q->data = (int*)((char*)q->data + sizeof(size_t));
    return q;
}

// Check for corruption
bool checkQueueCorruption(SafeQueue* q) {
    return q && q->canaryStart == CANARY_VALUE && q->canaryEnd == CANARY_VALUE;
}

// Free queue
void freeSafeQueue(SafeQueue* q) {
    if (q) {
        free((char*)q->data - sizeof(size_t));
        free(q);
    }
}

// Unit tests
void testCheckQueueCorruption() {
    SafeQueue* q = createSafeQueue(5);
    assertBoolEquals(true, checkQueueCorruption(q), "Test 216.1 - No corruption");
    q->canaryEnd = 0; // Simulate corruption
    assertBoolEquals(false, checkQueueCorruption(q), "Test 216.2 - Corruption detected");
    freeSafeQueue(q);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use unique canary values.
 - Place canaries at both ends.

- Check before queue operations.
- Test with corrupted and clean queues.
- **Expert Tips:**
 - Explain canaries: "Detect overwrites with boundary markers."
 - In interviews, clarify: "Ask if runtime tools are allowed."
 - Suggest optimization: "Use AddressSanitizer for robust checks."
 - Test edge cases: "NULL, corrupted canaries."

Problem 217: Implement a Memory-Efficient Trie

Issue Description

Implement a trie for storing strings with minimal memory usage.

Problem Decomposition & Solution Steps

- **Input:** Strings to store.
- **Output:** Trie with lookup functionality.
- **Approach:** Use array-based nodes with only necessary children.
- **Algorithm:** Compact Trie
 - **Explanation:** Store children in fixed-size array, allocate only used slots.
- **Steps:**
 1. Define trie node with children array.
 2. Insert strings by creating nodes as needed.
 3. Lookup strings by traversing nodes.
- **Complexity:** Time $O(m)$ for insert/lookup ($m = \text{string length}$), Space $O(n)$.

Algorithm Explanation

The compact trie algorithm uses nodes with a fixed-size array for children (e.g., 26 for lowercase letters).

Only necessary nodes are allocated, reducing memory.

Insertion creates nodes for each character; lookup follows the path.

This is $O(m)$ per operation, with $O(n)$ space for n characters.

Coding Part (with Unit Tests)

```
#define ALPHABET_SIZE 26

typedef struct TrieNode {
    struct TrieNode* children[ALPHABET_SIZE];
    bool isEnd;
} TrieNode;

typedef struct Trie {
    TrieNode* root;
} Trie;
```

```

// Create trie
Trie* createTrie() {
    Trie* trie = malloc(sizeof(Trie));
    trie->root = malloc(sizeof(TrieNode));
    for (int i = 0; i < ALPHABET_SIZE; i++) trie->root->children[i] = NULL;
    trie->root->isEnd = false;
    return trie;
}

// Insert string
void trieInsert(Trie* trie, const char* str) {
    TrieNode* node = trie->root;
    for (int i = 0; str[i]; i++) {
        int idx = str[i] - 'a';
        if (!node->children[idx]) {
            node->children[idx] = malloc(sizeof(TrieNode));
            for (int j = 0; j < ALPHABET_SIZE; j++) node->children[idx]->children[j] = NULL;
            node->children[idx]->isEnd = false;
        }
        node = node->children[idx];
    }
    node->isEnd = true;
}

// Lookup string
bool trieLookup(Trie* trie, const char* str) {
    TrieNode* node = trie->root;
    for (int i = 0; str[i]; i++) {
        int idx = str[i] - 'a';
        if (!node->children[idx]) return false;
        node = node->children[idx];
    }
    return node->isEnd;
}

// Free trie
void freeTrieNode(TrieNode* node) {
    if (!node) return;
    for (int i = 0; i < ALPHABET_SIZE; i++) {
        freeTrieNode(node->children[i]);
    }
    free(node);
}

void freeTrie(Trie* trie) {
    if (trie) {
        freeTrieNode(trie->root);
        free(trie);
    }
}

// Unit tests
void testTrie() {
    Trie* trie = createTrie();
    trieInsert(trie, "hello");
    assertBoolEquals(true, trieLookup(trie, "hello"), "Test 217.1 - Insert and lookup");
    assertBoolEquals(false, trieLookup(trie, "hell"), "Test 217.2 - Prefix not found");
    freeTrie(trie);
}

```

Best Practices & Expert Tips

- **Best Practices:**

- Allocate children only as needed.
- Use fixed-size array for simplicity.

- Free nodes recursively.
- Test with multiple strings.
- **Expert Tips:**
 - Explain trie: "Store strings with shared prefixes."
 - In interviews, clarify: "Ask if case sensitivity or charset size matters."
 - Suggest optimization: "Use compressed tries for more efficiency."
 - Test edge cases: "Empty strings, long strings."

Problem 218: Handle Memory Allocation for a Sparse Matrix

Issue Description

Allocate memory for a sparse matrix using a compact representation.

Problem Decomposition & Solution Steps

- **Input:** Matrix dimensions, non-zero elements.
- **Output:** Sparse matrix structure.
- **Approach:** Use coordinate list (COO) format.
- **Algorithm:** COO Sparse Matrix
 - **Explanation:** Store non-zero elements with row, column, value.
- **Steps:**
 1. Define structure for non-zero elements.
 2. Allocate dynamic array for elements.
 3. Store row, column, value for non-zeros.
- **Complexity:** Time $O(k)$ for k non-zeros, Space $O(k)$.

Algorithm Explanation

The COO sparse matrix algorithm stores only non-zero elements in a dynamic array, with each entry containing row, column, and value.

This is memory-efficient for sparse matrices.

Operations like insertion are $O(1)$ per element, with $O(k)$ space for k non-zeros.

Coding Part (with Unit Tests)

```
typedef struct SparseElement {
    size_t row, col;
    int value;
} SparseElement;

typedef struct SparseMatrix {
    SparseElement* elements;
    size_t count;
    size_t rows, cols;
} SparseMatrix;
```

```

// Create sparse matrix
SparseMatrix* createSparseMatrix(size_t rows, size_t cols, size_t maxElements) {
    SparseMatrix* mat = malloc(sizeof(SparseMatrix));
    mat->elements = malloc(maxElements * sizeof(SparseElement));
    mat->count = 0;
    mat->rows = rows;
    mat->cols = cols;
    return mat;
}

// Add element
bool addSparseElement(SparseMatrix* mat, size_t row, size_t col, int value) {
    if (row >= mat->rows || col >= mat->cols || mat->count >= mat->rows * mat->cols) return false;
    mat->elements[mat->count].row = row;
    mat->elements[mat->count].col = col;
    mat->elements[mat->count].value = value;
    mat->count++;
    return true;
}

// Free sparse matrix
void freeSparseMatrix(SparseMatrix* mat) {
    if (mat) {
        free(mat->elements);
        free(mat);
    }
}

// Unit tests
void testSparseMatrix() {
    SparseMatrix* mat = createSparseMatrix(3, 3, 5);
    addSparseElement(mat, 1, 1, 42);
    assertBoolEquals(true, mat->count == 1 && mat->elements[0].value == 42, "Test 218.1 - Add element");
    freeSparseMatrix(mat);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use COO for simplicity.
 - Validate row/column indices.
 - Allocate enough space for elements.
 - Test with sparse and dense matrices.
- **Expert Tips:**
 - Explain COO: "Store only non-zero elements with coordinates."
 - In interviews, clarify: "Ask if CSR or other format is preferred."
 - Suggest optimization: "Use CSR for faster row access."
 - Test edge cases: "Empty matrix, full matrix."

Problem 219: Check for Memory Leaks in a Stack

Issue Description

Detect memory leaks in a dynamic stack implementation.

Problem Decomposition & Solution Steps

- **Input:** Stack with dynamic array.
- **Output:** Boolean indicating no leaks.
- **Approach:** Track allocations, ensure all freed.
- **Algorithm:** Allocation Tracking
 - **Explanation:** Track stack and array allocations, check on destruction.
- **Steps:**
 1. Track stack and array allocations.
 2. Free stack and array.
 3. Check if tracker is empty.
- **Complexity:** Time $O(n)$, Space $O(n)$ for n allocations.

Algorithm Explanation

The allocation tracking algorithm tracks the stack structure and its dynamic array.

On destruction, free both and check the tracker.

Non-empty tracker indicates leaks.

This is $O(n)$ for n tracked allocations, with $O(n)$ space for tracking.

Coding Part (with Unit Tests)

```
typedef struct Stack {
    int* data;
    size_t size;
} Stack;

// Create stack
Stack* createStack(size_t size) {
    Stack* stack = malloc(sizeof(Stack));
    trackAlloc(stack);
    stack->data = malloc(size * sizeof(int));
    trackAlloc(stack->data);
    stack->size = size;
    return stack;
}

// Free stack and check leaks
bool freeStack(Stack* stack) {
    if (!stack) return allocCount == 0;
    for (int i = 0; i < allocCount; i++) {
        if (trackedAllocs[i] == stack->data) {
            trackedAllocs[i] = trackedAllocs[--allocCount];
            free(stack->data);
            break;
        }
    }
    for (int i = 0; i < allocCount; i++) {
        if (trackedAllocs[i] == stack) {
            trackedAllocs[i] = trackedAllocs[--allocCount];
            free(stack);
            break;
        }
    }
    return allocCount == 0; }
```

```

// Unit tests
void testStackLeaks() {
    allocCount = 0;
    Stack* stack = createStack(5);
    assertBoolEquals(true, freeStack(stack), "Test 219.1 - No leaks");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track all allocations.
 - Free array and stack structure.
 - Check tracker for leaks.
 - Test with allocated stacks.
- **Expert Tips:**
 - Explain leak check: "Track and ensure all allocations freed."
 - In interviews, clarify: "Ask if dynamic data is stored."
 - Suggest optimization: "Use Valgrind for robust detection."
 - Test edge cases: "Empty stack, partial frees."

Problem 220: Optimize Memory Usage in a Circular Queue

Issue Description

Implement a memory-efficient circular queue with minimal overhead.

Problem Decomposition & Solution Steps

- **Input:** Queue capacity.
- **Output:** Circular queue with enqueue/dequeue.
- **Approach:** Use fixed-size array with head/tail pointers.
- **Algorithm:** Circular Queue
 - **Explanation:** Use single array, track head/tail, wrap indices.
- **Steps:**
 1. Allocate fixed-size array.
 2. Track head, tail, and count.
 3. Enqueue/dequeue with modulo for wrapping.
- **Complexity:** Time O(1), Space O(n).

Algorithm Explanation

The circular queue algorithm uses a fixed-size array with head and tail pointers.

Enqueue adds at tail, dequeue removes from head, with indices wrapping via modulo.

This minimizes memory by reusing the array.

Operations are O(1), with O(n) space for the array.

Coding Part (with Unit Tests)

```
typedef struct CircularQueue {
    int* data;
    size_t head, tail, size, count;
} CircularQueue;

// Create circular queue
CircularQueue* createCircularQueue(size_t size) {
    CircularQueue* q = malloc(sizeof(CircularQueue));
    q->data = malloc(size * sizeof(int));
    q->head = q->tail = q->count = 0;
    q->size = size;
    return q;
}

// Enqueue
bool enqueue(CircularQueue* q, int value) {
    if (q->count == q->size) return false;
    q->data[q->tail] = value;
    q->tail = (q->tail + 1) % q->size;
    q->count++;
    return true;
}

// Dequeue
bool dequeue(CircularQueue* q, int* value) {
    if (q->count == 0) return false;
    *value = q->data[q->head];
    q->head = (q->head + 1) % q->size;
    q->count--;
    return true;
}

// Free queue
void freeCircularQueue(CircularQueue* q) {
    if (q) {
        free(q->data);
        free(q);
    }
}

// Unit tests
void testCircularQueue() {
    CircularQueue* q = createCircularQueue(3);
    enqueue(q, 1);
    enqueue(q, 2);
    int value;
    assertBoolEquals(true, dequeue(q, &value) && value == 1, "Test 220.1 - Enqueue and dequeue");
    enqueue(q, 3);
    assertBoolEquals(true, q->count == 2, "Test 220.2 - Reuse after dequeue");
    freeCircularQueue(q);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use fixed-size array for efficiency.
 - Track count to detect full/empty.
 - Use modulo for wrapping.
 - Test with full and empty queues.
- **Expert Tips:**

- Explain circular queue: "Reuse array with wrapping indices."
- In interviews, clarify: "Ask if resizing is needed."
- Suggest optimization: "Use power-of-2 size for faster modulo."
- Test edge cases: "Full queue, wraparound."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for memory management problems 211 to 220:\n");
    testBuddyAllocator();
    testGraphLeaks();
    testAlloc3DArray();
    testAllocAlignedUnion();
    testRTMemoryUsage();
    testCheckQueueCorruption();
    testTrie();
    testSparseMatrix();
    testStackLeaks();
    testCircularQueue();
    return 0;
}
```


Embedded Systems

(80 Problems)

Problem 221: Implement a Circular Buffer for Sensor Data

Issue Description

Implement a circular buffer to store sensor data in an embedded system with efficient memory usage.

Problem Decomposition & Solution Steps

- **Input:** Sensor data values, buffer capacity.
- **Output:** Circular buffer with push/pop operations.
- **Approach:** Use a fixed-size array with head/tail pointers.
- **Algorithm:** Circular Buffer
 - **Explanation:** Store data in a fixed array, use head/tail indices with modulo wrapping.
- **Steps:**
 1. Initialize buffer with fixed size.
 2. Push data at tail, increment with modulo.
 3. Pop data from head, increment with modulo.
 4. Track count for full/empty checks.
- **Complexity:** Time O(1) for push/pop, Space O(n).

Algorithm Explanation

The circular buffer uses a fixed-size array with head and tail pointers.

Push adds data at tail, pop retrieves from head, with indices wrapping via modulo.

A count tracks the number of elements to detect full/empty states.

This is O(1) per operation, with O(n) space for the buffer.

Coding Part (with Unit Tests)

```
#include <stdint.h>
#include <stdbool.h>

#define SENSOR_BUFFER_SIZE 16

typedef struct SensorBuffer {
    int16_t data[SENSOR_BUFFER_SIZE];
    uint32_t head, tail, count;
} SensorBuffer;

// Initialize circular buffer
void initSensorBuffer(SensorBuffer* buffer) {
    buffer->head = buffer->tail = buffer->count = 0;
}

// Push sensor data
bool pushSensorData(SensorBuffer* buffer, int16_t value) {
    if (buffer->count >= SENSOR_BUFFER_SIZE) return false;
    buffer->data[buffer->tail] = value;
    buffer->tail = (buffer->tail + 1) % SENSOR_BUFFER_SIZE;
    buffer->count++;
    return true;
}
```

```

// Pop sensor data
bool popSensorData(SensorBuffer* buffer, int16_t* value) {
    if (buffer->count == 0) return false;
    *value = buffer->data[buffer->head];
    buffer->head = (buffer->head + 1) % SENSOR_BUFFER_SIZE;
    buffer->count--;
    return true;
}

// Unit test helper
void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

void assertInt16Equals(int16_t expected, int16_t actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testSensorBuffer() {
    SensorBuffer buffer;
    initSensorBuffer(&buffer);
    pushSensorData(&buffer, 42);
    int16_t value;
    assertBoolEquals(true, popSensorData(&buffer, &value), "Test 221.1 - Push and pop");
    assertInt16Equals(42, value, "Test 221.2 - Correct value");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use power-of-2 size for efficient modulo.
 - Track count for full/empty checks.
 - Use fixed-size array for memory efficiency.
 - Test with full buffer and wraparound.
- **Expert Tips:**
 - Explain circular buffer: "Fixed array with wrapping indices."
 - In interviews, clarify: "Ask if thread safety or interrupts are involved."
 - Suggest optimization: "Use bit-masking for modulo with power-of-2 sizes."
 - Test edge cases: "Full buffer, empty buffer, rapid push/pop."

Problem 222: Toggle an LED State (Bit Manipulation)

Issue Description

Toggle the state of an LED connected to a GPIO pin using bit manipulation.

Problem Decomposition & Solution Steps

- **Input:** GPIO port register, pin number.
- **Output:** Toggled pin state.
- **Approach:** Use XOR to toggle a specific bit in the register.
- **Algorithm:** Bit Toggle
 - **Explanation:** XOR the pin's bit with 1 to toggle its state.
- **Steps:**
 1. Validate pin number.

2. Create mask for the pin.
 3. XOR register with mask.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bit toggle algorithm uses XOR to flip the specified bit in the GPIO register (e.g., `reg ^= (1 << pin)`).

This toggles the LED (0 to 1 or 1 to 0) without affecting other pins.

It's O(1) with a single operation, using O(1) space.

Coding Part (with Unit Tests)

```
// Mock GPIO register
typedef struct {
    uint32_t value;
} GPIORegister;

// Toggle LED
void toggleLED(GPIORegister* port, uint8_t pin) {
    if (pin >= 32) return; // Validate pin
    port->value ^= (1U << pin);
}

// Unit tests
void testToggleLED() {
    GPIORegister port = {0};
    toggleLED(&port, 2);
    assertEquals(1U << 2, port.value, "Test 222.1 - Toggle ON");
    toggleLED(&port, 2);
    assertEquals(0, port.value, "Test 222.2 - Toggle OFF");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate pin number.
 - Use bitwise XOR for toggling.
 - Ensure register access is atomic.
 - Test with multiple toggles.
- **Expert Tips:**
 - Explain XOR: "Flips bit without affecting others."
 - In interviews, clarify: "Ask if hardware-specific register layout is needed."
 - Suggest optimization: "Use hardware-specific toggle registers if available."
 - Test edge cases: "Invalid pin, multiple pins."

Problem 223: Read and Parse Data from a UART Buffer

Issue Description

Read and parse a fixed-format packet from a UART buffer (e.g., <start><data><checksum>).

Problem Decomposition & Solution Steps

- **Input:** UART buffer with packet data.
- **Output:** Parsed data if valid.
- **Approach:** Read buffer, validate start byte and checksum.
- **Algorithm:** Packet Parsing
 - **Explanation:** Check start byte, extract data, verify checksum.
- **Steps:**
 1. Read start byte and validate.
 2. Extract data bytes.
 3. Compute and verify checksum.
 4. Return data if valid.
- **Complexity:** Time O(n), Space O(n) for n data bytes.

Algorithm Explanation

The packet parsing algorithm assumes a packet format: start byte (e.g., 0xAA), data bytes, and checksum (e.g., sum of data bytes).

It validates the start byte, extracts data, and checks the checksum.

This is O(n) for n data bytes, with O(n) space for storing data.

Coding Part (with Unit Tests)

```
#define START_BYTE 0xAA

typedef struct UARTPacket {
    uint8_t data[8];
    uint8_t length;
} UARTPacket;

// Mock UART read
uint8_t mockUARTBuffer[] = {0xAA, 0x01, 0x02, 0x03, 0x06}; // start, data, checksum
int mockUARTIndex = 0;

uint8_t readUARTByte() {
    return mockUARTBuffer[mockUARTIndex++];
}

// Parse UART packet
bool parseUARTPacket(UARTPacket* packet) {
    if (readUARTByte() != START_BYTE) return false;
    packet->length = 0;
    uint8_t checksum = 0;
    for (int i = 0; i < 8; i++) {
        uint8_t byte = readUARTByte();
        if (i < 7) {
            packet->data[i] = byte;
            checksum += byte;
            packet->length++;
        } else {
            return byte == checksum;
        }
    }
    return false;
}
```

```

// Unit tests
void testParseUARTPacket() {
    mockUARTIndex = 0;
    UARTPacket packet;
    assertBoolEquals(true, parseUARTPacket(&packet) && packet.data[0] == 0x01 && packet.data[2] == 0x03, "Test 223.1 - Valid packet");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate start byte and checksum.
 - Handle buffer overruns.
 - Use fixed-size data for predictability.
 - Test with valid/invalid packets.
- **Expert Tips:**
 - Explain parsing: "Validate format, compute checksum."
 - In interviews, clarify: "Ask about packet format or UART settings."
 - Suggest optimization: "Use DMA for UART data transfer."
 - Test edge cases: "Wrong start byte, incorrect checksum."

Problem 224: Implement a Simple State Machine for a Button Press

Issue Description

Implement a state machine to handle button press events (e.g., idle, pressed, released).

Problem Decomposition & Solution Steps

- **Input:** Button state (pressed/released).
- **Output:** Current state and actions (e.g., toggle LED).
- **Approach:** Use enum for states, switch for transitions.
- **Algorithm:** Finite State Machine
 - **Explanation:** Define states (idle, pressed, released), transition based on input.
- **Steps:**
 1. Define state enum and current state.
 2. Read button input.
 3. Transition states and perform actions.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The finite state machine defines states (idle, pressed, released).

On button input, it transitions: idle to pressed on press, pressed to released on release, released to idle.

Actions (e.g., toggle LED) occur on transitions.

This is O(1) per transition, with O(1) space.

Coding Part (with Unit Tests)

```
typedef enum { IDLE, PRESSED, RELEASED } ButtonState;

// Mock button read
bool mockButtonPressed = false;
bool readButton() { return mockButtonPressed; }

// State machine
void buttonStateMachine(ButtonState* state, GPIORegister* ledPort, uint8_t ledPin) {
    switch (*state) {
        case IDLE:
            if (readButton()) *state = PRESSED;
            break;
        case PRESSED:
            if (!readButton()) {
                *state = RELEASED;
                toggleLED(ledPort, ledPin);
            }
            break;
        case RELEASED:
            if (!readButton()) *state = IDLE;
            break;
    }
}

// Unit tests
void testButtonStateMachine() {
    ButtonState state = IDLE;
    GPIORegister ledPort = {0};
    mockButtonPressed = true;
    buttonStateMachine(&state, &ledPort, 2);
    assertIntEquals(PRESSED, state, "Test 224.1 - Transition to PRESSED");
    mockButtonPressed = false;
    buttonStateMachine(&state, &ledPort, 2);
    assertIntEquals(1U << 2, ledPort.value, "Test 224.2 - LED toggled on release");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use enum for clear state definitions.
 - Handle all state transitions.
 - Keep actions simple and atomic.
 - Test all state transitions.
- **Expert Tips:**
 - Explain FSM: "States transition based on button input."
 - In interviews, clarify: "Ask if debouncing or actions are needed."
 - Suggest optimization: "Use state tables for complex FSMs."
 - Test edge cases: "Rapid transitions, stuck button."

Problem 225: Debounce a Button Input

Issue Description

Debounce a button input to filter noise in an embedded system.

Problem Decomposition & Solution Steps

- **Input:** Raw button state, time ticks.
- **Output:** Stable button state.
- **Approach:** Use a counter to confirm stable state over time.
- **Algorithm:** Debounce Counter
 - **Explanation:** Count consecutive stable readings to confirm state.
- **Steps:**
 1. Read raw button state.
 2. Increment counter if state matches previous.
 3. Reset counter on state change.
 4. Confirm state after threshold.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The debounce counter algorithm reads the button state periodically.

If the state matches the previous reading, increment a counter; otherwise, reset it.

After a threshold (e.g., 10 ticks), confirm the state as stable.

This is O(1) per update, with O(1) space for state and counter.

Coding Part (with Unit Tests)

```
#define DEBOUNCE_THRESHOLD 10

typedef struct Debouncer {
    bool lastState;
    uint8_t counter;
    bool stableState;
} Debouncer;

// Initialize debouncer
void initDebouncer(Debouncer* deb) {
    deb->lastState = false;
    deb->counter = 0;
    deb->stableState = false;
}

// Debounce button
bool debounceButton(Debouncer* deb, bool rawState) {
    if (rawState == deb->lastState) {
        if (deb->counter < DEBOUNCE_THRESHOLD) deb->counter++;
        if (deb->counter >= DEBOUNCE_THRESHOLD) deb->stableState = rawState;
    } else {
        deb->counter = 0;
        deb->lastState = rawState;
    }
    return deb->stableState;
}

// Unit tests
void testDebounceButton() {
    Debouncer deb;
    initDebouncer(&deb);
```

```

        for (int i = 0; i < DEBOUNCE_THRESHOLD; i++) {
            debounceButton(&deb, true);
        }
        assertBoolEquals(true, debounceButton(&deb, true), "Test 225.1 - Stable high after threshold");
    }
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use a reasonable debounce threshold.
 - Update periodically (e.g., 10ms).
 - Track last and stable states.
 - Test with noisy inputs.
- **Expert Tips:**
 - Explain debouncing: "Filter noise with stable state counter."
 - In interviews, clarify: "Ask about polling frequency or hardware debouncing."
 - Suggest optimization: "Use hardware timers for sampling."
 - Test edge cases: "Rapid toggles, long presses."

Problem 226: Implement a PWM Signal Generator for a Motor

Issue Description

Generate a PWM signal for motor control with a specified duty cycle.

Problem Decomposition & Solution Steps

- **Input:** Duty cycle (0-100%), period ticks.
- **Output:** PWM signal on GPIO pin.
- **Approach:** Use timer to toggle pin based on duty cycle.
- **Algorithm:** PWM Generator
 - **Explanation:** Set pin high for duty cycle duration, low for remainder.
- **Steps:**
 1. Initialize timer and GPIO.
 2. Calculate on/off ticks from duty cycle.
 3. Toggle pin in timer interrupt.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The PWM generator algorithm uses a timer to count ticks within a period.

The GPIO pin is set high for duty cycle * period ticks and low for the rest.

The timer interrupt updates the pin state.

This is O(1) per interrupt, with O(1) space for configuration.

Coding Part (with Unit Tests)

```
typedef struct PWM {
    GPIORegister* port;
    uint8_t pin;
    uint32_t periodTicks;
    uint32_t onTicks;
    uint32_t counter;
} PWM;

// Initialize PWM
void initPWM(PWM* pwm, GPIORegister* port, uint8_t pin, uint32_t periodTicks, uint8_t dutyPercent) {
    pwm->port = port;
    pwm->pin = pin;
    pwm->periodTicks = periodTicks;
    pwm->onTicks = (periodTicks * dutyPercent) / 100;
    pwm->counter = 0;
    port->value |= (1U << pin); // Start high
}

// Timer interrupt handler
void pwmTimerHandler(PWM* pwm) {
    pwm->counter = (pwm->counter + 1) % pwm->periodTicks;
    if (pwm->counter < pwm->onTicks) {
        pwm->port->value |= (1U << pwm->pin);
    } else {
        pwm->port->value &= ~(1U << pwm->pin);
    }
}

// Unit tests
void testPWM() {
    GPIORegister port = {0};
    PWM pwm;
    initPWM(&pwm, &port, 3, 100, 50); // 50% duty
    pwmTimerHandler(&pwm);
    assertIntEquals(1U << 3, port.value, "Test 226.1 - PWM high at start");
    pwm.counter = 50;
    pwmTimerHandler(&pwm);
    assertIntEquals(0, port.value & (1U << 3), "Test 226.2 - PWM low after onTicks");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate duty cycle (0-100%).
 - Use hardware timers for accuracy.
 - Ensure atomic pin updates.
 - Test with different duty cycles.
- **Expert Tips:**
 - Explain PWM: "Toggle pin based on duty cycle ratio."
 - In interviews, clarify: "Ask if hardware PWM peripheral is available."
 - Suggest optimization: "Use dedicated PWM hardware for efficiency."
 - Test edge cases: "0% or 100% duty, short periods."

Problem 227: Read Analog Sensor Data Using ADC (Mock Interface)

Issue Description

Read analog sensor data using a mock ADC interface in an embedded system.

Problem Decomposition & Solution Steps

- **Input:** ADC channel.
- **Output:** Sensor value (e.g., 10-bit).
- **Approach:** Mock ADC read, return scaled value.
- **Algorithm:** ADC Read
 - **Explanation:** Call mock ADC function, scale to meaningful units.
- **Steps:**
 1. Validate channel.
 2. Read raw ADC value.
 3. Scale to physical units (e.g., voltage).
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The ADC read algorithm calls a mock ADC function to get a raw value (e.g., 0-1023 for 10-bit ADC).

It scales the value to a physical unit (e.g., 0-5V) based on reference voltage.

This is O(1) per read, with O(1) space for the result.

Coding Part (with Unit Tests)

```
// Mock ADC read
uint16_t mockADCRead(uint8_t channel) {
    return channel == 0 ? 512 : 0; // Simulate 2.5V for channel 0
}

// Read and scale ADC
float readADCSensor(uint8_t channel, float vref) {
    if (channel >= 8) return 0.0f; // Validate channel
    uint16_t raw = mockADCRead(channel);
    return (raw * vref) / 1023.0f; // Scale to voltage
}

// Unit tests
void testADCSensor() {
    float value = readADCSensor(0, 5.0f);
    assertFloatEquals(2.5f, value, 0.01f, "Test 227.1 - Read 2.5V from channel 0");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate ADC channel.
 - Scale raw values correctly.
 - Use reference voltage for accuracy.

- Test with different channels.
- **Expert Tips:**
 - Explain ADC: "Convert analog signal to digital, scale to units."
 - In interviews, clarify: "Ask about ADC resolution or reference voltage."
 - Suggest optimization: "Use DMA for continuous ADC reads."
 - Test edge cases: "Invalid channel, max/min values."

Problem 228: Control a GPIO Pin

Issue Description

Set or clear a GPIO pin to control an external device (e.g., LED).

Problem Decomposition & Solution Steps

- **Input:** GPIO port, pin number, state (high/low).
- **Output:** Updated pin state.
- **Approach:** Use bit manipulation to set/clear pin.
- **Algorithm:** Bit Set/Clear
 - **Explanation:** Set or clear specific bit in GPIO register.
- **Steps:**
 1. Validate pin number.
 2. Create mask for pin.
 3. Set or clear bit in register.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bit set/clear algorithm uses a mask to set (`reg |= mask`) or clear (`reg &= ~mask`) the specified pin in the GPIO register.

This controls the pin state without affecting others.

It's O(1) per operation, with O(1) space.

Coding Part (with Unit Tests)

```
// Set GPIO pin
void setGPIOPin(GPIORegister* port, uint8_t pin, bool state) {
    if (pin >= 32) return;
    if (state) {
        port->value |= (1U << pin);
    } else {
        port->value &= ~(1U << pin);
    }
}

// Unit tests
void testGPIOPin() {
    GPIORegister port = {0};
    setGPIOPin(&port, 4, true);
```

```
    assertEquals(1U << 4, port.value, "Test 228.1 - Set pin high");
    setGPIOPin(&port, 4, false);
    assertEquals(0, port.value, "Test 228.2 - Clear pin");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate pin number.
 - Use bitwise operations for efficiency.
 - Ensure atomic updates.
 - Test with both states.
- **Expert Tips:**
 - Explain bit manipulation: "Set or clear specific bit."
 - In interviews, clarify: "Ask if pin direction setup is needed."
 - Suggest optimization: "Use hardware-specific registers for speed."
 - Test edge cases: "Invalid pin, multiple pins."

Problem 229: Implement a Timer Interrupt Handler

Issue Description

Implement a timer interrupt handler for periodic tasks (e.g., LED blink).

Problem Decomposition & Solution Steps

- **Input:** Timer ticks, period.
- **Output:** Periodic action (e.g., toggle LED).
- **Approach:** Use counter to track ticks, perform action on period.
- **Algorithm:** Timer Interrupt
 - **Explanation:** Increment counter, trigger action when period reached.
- **Steps:**
 1. Initialize counter and period.
 2. Increment counter in interrupt.
 3. Perform action when counter hits period.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The timer interrupt algorithm increments a counter on each timer tick.

When the counter reaches the period, it performs an action (e.g., toggle LED) and resets the counter.

This is O(1) per interrupt, with O(1) space for counter and period.

Coding Part (with Unit Tests)

```
typedef struct Timer {
    uint32_t counter;
    uint32_t period;
    GPIORegister* port;
    uint8_t pin;
} Timer;

// Initialize timer
void initTimer(Timer* timer, GPIORegister* port, uint8_t pin, uint32_t period) {
    timer->counter = 0;
    timer->period = period;
    timer->port = port;
    timer->pin = pin;
}

// Timer interrupt handler
void timerInterruptHandler(Timer* timer) {
    if (++timer->counter >= timer->period) {
        toggleLED(timer->port, timer->pin);
        timer->counter = 0;
    }
}

// Unit tests
void testTimerInterrupt() {
    GPIORegister port = {0};
    Timer timer;
    initTimer(&timer, &port, 5, 2);
    timerInterruptHandler(&timer);
    timerInterruptHandler(&timer);
    assertEquals(1U << 5, port.value, "Test 229.1 - Toggle after period");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Keep interrupt handler short.
 - Use volatile for shared variables.
 - Reset counter on period.
 - Test with different periods.
- **Expert Tips:**
 - Explain ISR: "Perform minimal work in interrupt."
 - In interviews, clarify: "Ask if priority or nesting is considered."
 - Suggest optimization: "Offload tasks to main loop."
 - Test edge cases: "Zero period, frequent interrupts."

Problem 230: Read from an I2C Device

Issue Description

Read data from an I2C device using a mock interface.

Problem Decomposition & Solution Steps

- **Input:** Device address, register address.
- **Output:** Data read from device.
- **Approach:** Mock I2C read sequence.
- **Algorithm:** I2C Read
 - **Explanation:** Send device/register address, read data bytes.
- **Steps:**
 1. Validate addresses.
 2. Send start, device address, register address.
 3. Read data with ACK/NACK.
- **Complexity:** Time O(n), Space O(n) for n bytes.

Algorithm Explanation

The I2C read algorithm sends the device and register addresses, then reads data bytes, sending ACK for each except the last (NACK).

The mock interface simulates this sequence.

This is O(n) for n bytes, with O(n) space for the data buffer.

Coding Part (with Unit Tests)

```
// Mock I2C interface
uint8_t mockI2CRead(uint8_t deviceAddr, uint8_t regAddr, uint8_t* data, uint8_t len) {
    if (deviceAddr == 0x50 && regAddr == 0x10) {
        for (uint8_t i = 0; i < len; i++) data[i] = i + 1;
        return len;
    }
    return 0;
}

// Read I2C device
bool readI2CDevice(uint8_t deviceAddr, uint8_t regAddr, uint8_t* data, uint8_t len) {
    if (len == 0) return false;
    return mockI2CRead(deviceAddr, regAddr, data, len) == len;
}

// Unit tests
void testI2CRead() {
    uint8_t data[3];
    assertBoolEquals(true, readI2CDevice(0x50, 0x10, data, 3) && data[0] == 1 && data[2] == 3, "Test 230.1 - Read I2C data");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate addresses and length.
 - Handle ACK/NACK correctly.
 - Check for read success.
 - Test with valid/invalid devices.
- **Expert Tips:**
 - Explain I2C: "Send address, read data with ACK."

- In interviews, clarify: "Ask about I2C clock speed or interrupts."
- Suggest optimization: "Use DMA for large reads."
- Test edge cases: "Invalid address, zero length."

Problem 231: Write to an SPI Device

Issue Description

Write data to an SPI device using a mock interface.

Problem Decomposition & Solution Steps

- **Input:** Device chip select, data buffer.
- **Output:** Success/failure of write.
- **Approach:** Mock SPI write sequence.
- **Algorithm:** SPI Write
 - **Explanation:** Select device, send data bytes.
- **Steps:**
 1. Validate data and length.
 2. Assert chip select.
 3. Send data bytes.
 4. Deassert chip select.
- **Complexity:** Time $O(n)$, Space $O(n)$ for n bytes.

Algorithm Explanation

The SPI write algorithm asserts the chip select, sends data bytes via a mock SPI interface, and deasserts the chip select.

It ensures reliable data transfer.

This is $O(n)$ for n bytes, with $O(n)$ space for the data buffer.

Coding Part (with Unit Tests)

```
// Mock SPI interface
bool mockSPIWrite(uint8_t* data, uint8_t len) {
    return len > 0;
}

// Write to SPI device
bool writeSPIDevice(uint8_t* data, uint8_t len) {
    if (len == 0) return false;
    // Mock chip select assert/deassert
    return mockSPIWrite(data, len);
}

// Unit tests
void testSPIWrite() {
    uint8_t data[] = {0x01, 0x02};
    assertBoolEquals(true, writeSPIDevice(data, 2), "Test 231.1 - Write SPI data");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate data length.
 - Handle chip select correctly.
 - Check write success.
 - Test with various data sizes.
- **Expert Tips:**
 - Explain SPI: "Send data with chip select."
 - In interviews, clarify: "Ask about SPI mode or clock polarity."
 - Suggest optimization: "Use DMA for large writes."
 - Test edge cases: "Zero length, invalid data."

Problem 232: Parse a Packet from a Serial Communication Stream

Issue Description

Parse a packet from a serial stream with format <start><length><data><checksum>.

Problem Decomposition & Solution Steps

- **Input:** Serial stream bytes.
- **Output:** Parsed packet data.
- **Approach:** Read stream, validate format, extract data.
- **Algorithm:** Serial Packet Parsing
 - **Explanation:** Check start byte, read length, validate checksum.
- **Steps:**
 1. Read start byte and validate.
 2. Read length and data.
 3. Verify checksum.
- **Complexity:** Time O(n), Space O(n) for n data bytes.

Algorithm Explanation

The serial packet parsing algorithm reads a start byte (e.g., 0x55), a length byte, the specified number of data bytes, and a checksum.

It validates the format and checksum (sum of data bytes).

This is O(n) for n data bytes, with O(n) space for the packet.

Coding Part (with Unit Tests)

```
#define SERIAL_START 0x55

typedef struct SerialPacket {
    uint8_t data[16];
    uint8_t length;
} SerialPacket;
```

```

// Mock serial read
uint8_t mockSerialBuffer[] = {0x55, 3, 0x01, 0x02, 0x03, 0x06};
int mockSerialIndex = 0;

uint8_t readSerialByte() {
    return mockSerialBuffer[mockSerialIndex++];
}

// Parse serial packet
bool parseSerialPacket(SerialPacket* packet) {
    if (readSerialByte() != SERIAL_START) return false;
    packet->length = readSerialByte();
    if (packet->length > 16) return false;
    uint8_t checksum = 0;
    for (uint8_t i = 0; i < packet->length; i++) {
        packet->data[i] = readSerialByte();
        checksum += packet->data[i];
    }
    return readSerialByte() == checksum;
}

// Unit tests
void testSerialPacket() {
    mockSerialIndex = 0;
    SerialPacket packet;
    assertBoolEquals(true, parseSerialPacket(&packet) && packet.length == 3 && packet.data[0] == 0x01,
    "Test 232.1 - Valid serial packet");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate start byte and length.
 - Compute checksum correctly.
 - Handle buffer overruns.
 - Test with valid/invalid packets.
- **Expert Tips:**
 - Explain parsing: "Validate format, check checksum."
 - In interviews, clarify: "Ask about packet format or baud rate."
 - Suggest optimization: "Use DMA for serial data."
 - Test edge cases: "Invalid start, bad checksum."

Problem 233: Implement a Watchdog Timer Reset Function

Issue Description

Implement a function to reset a watchdog timer to prevent system reset.

Problem Decomposition & Solution Steps

- **Input:** None (or watchdog register).
- **Output:** Watchdog timer reset.
- **Approach:** Mock watchdog reset operation.
- **Algorithm:** Watchdog Reset

- **Explanation:** Write to watchdog register to reset timer.
- **Steps:**
 1. Validate watchdog state.
 2. Write reset value to register.
 3. Confirm reset.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The watchdog reset algorithm writes a specific value to a mock watchdog register to reset the timer, preventing a system reset.

This is O(1) per operation, with O(1) space for the register access.

Coding Part (with Unit Tests)

```
// Mock watchdog register
typedef struct {
    uint32_t resetCount;
} WatchdogRegister;

// Reset watchdog
void resetWatchdog(WatchdogRegister* wdt) {
    wdt->resetCount++;
}

// Unit tests
void testWatchdogReset() {
    WatchdogRegister wdt = {0};
    resetWatchdog(&wdt);
    assertEquals(1, wdt.resetCount, "Test 233.1 - Watchdog reset");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Reset periodically before timeout.
 - Use hardware-specific register.
 - Keep function simple and fast.
 - Test reset functionality.
- **Expert Tips:**
 - Explain watchdog: "Reset timer to prevent system reset."
 - In interviews, clarify: "Ask about watchdog timeout period."
 - Suggest optimization: "Integrate with main loop or interrupts."
 - Test edge cases: "Multiple resets, disabled watchdog."

Problem 234: Handle Low-Power Mode Transitions

Issue Description

Manage transitions to/from low-power mode in an embedded system.

Problem Decomposition & Solution Steps

- **Input:** Current system state, low-power trigger.
- **Output:** Enter/exit low-power mode.
- **Approach:** Save state, enter mode, restore on exit.
- **Algorithm:** Low-Power Transition
 - **Explanation:** Save registers, set low-power mode, restore on wake.
- **Steps:**
 1. Save critical registers/state.
 2. Enter low-power mode (mock).
 3. Restore state on wake.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The low-power transition algorithm saves critical system state (e.g., registers), sets a mock low-power mode flag, and restores state on wake.

This ensures safe mode transitions.

It's O(1) for fixed state, with O(1) space for saved data.

Coding Part (with Unit Tests)

```
typedef struct SystemState {  
    uint32_t registers;  
    bool isLowPower;  
} SystemState;  
  
// Enter low-power mode  
void enterLowPower(SystemState* state) {  
    state->registers = 0xDEADBEEF; // Save state  
    state->isLowPower = true;  
}  
  
// Exit low-power mode  
void exitLowPower(SystemState* state) {  
    state->isLowPower = false;  
    // Restore state (mock)  
}  
  
// Unit tests  
void testLowPower() {  
    SystemState state = {0, false};  
    enterLowPower(&state);  
    assertBoolEquals(true, state.isLowPower, "Test 234.1 - Enter low-power mode");  
    exitLowPower(&state);  
    assertBoolEquals(false, state.isLowPower, "Test 234.2 - Exit low-power mode");  
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Save critical state before entering.
 - Minimize wake-up latency.
 - Validate mode transitions.

- Test enter/exit cycles.
- **Expert Tips:**
 - Explain low-power: "Save state, enter mode, restore on wake."
 - In interviews, clarify: "Ask about specific low-power modes."
 - Suggest optimization: "Use hardware-specific sleep instructions."
 - Test edge cases: "Interrupted transitions, no state saved."

Problem 235: Implement a Ring Buffer for Real-Time Data Logging

Issue Description

Implement a ring buffer for real-time data logging in an embedded system.

Problem Decomposition & Solution Steps

- **Input:** Data values, buffer capacity.
- **Output:** Ring buffer with log/retrieve operations.
- **Approach:** Use circular buffer with overwrite on full.
- **Algorithm:** Ring Buffer
 - **Explanation:** Store data in fixed array, overwrite old data when full.
- **Steps:**
 1. Initialize buffer with fixed size.
 2. Log data at tail, overwrite if full.
 3. Retrieve data from head.
- **Complexity:** Time O(1), Space O(n).

Algorithm Explanation

The ring buffer algorithm uses a fixed-size array with head and tail pointers.

Logging adds data at tail, overwriting the oldest data (at head) if full.

Retrieval reads from head.

This is O(1) per operation, with O(n) space for the buffer.

Coding Part (with Unit Tests)

```
#define LOG_BUFFER_SIZE 8

typedef struct RingBuffer {
    uint32_t data[LOG_BUFFER_SIZE];
    uint32_t head, tail;
    bool isFull;
} RingBuffer;

// Initialize ring buffer
void initRingBuffer(RingBuffer* buffer) {
    buffer->head = buffer->tail = 0;
    buffer->isFull = false;
}
```

```

// Log data
void logData(RingBuffer* buffer, uint32_t value) {
    buffer->data[buffer->tail] = value;
    buffer->tail = (buffer->tail + 1) % LOG_BUFFER_SIZE;
    if (buffer->isFull) {
        buffer->head = (buffer->head + 1) % LOG_BUFFER_SIZE;
    } else if (buffer->tail == buffer->head) {
        buffer->isFull = true;
    }
}

// Retrieve data
bool getLogData(RingBuffer* buffer, uint32_t* value) {
    if (!buffer->isFull && buffer->head == buffer->tail) return false;
    *value = buffer->data[buffer->head];
    buffer->head = (buffer->head + 1) % LOG_BUFFER_SIZE;
    buffer->isFull = false;
    return true;
}

// Unit tests
void testRingBuffer() {
    RingBuffer buffer;
    initRingBuffer(&buffer);
    logData(&buffer, 100);
    uint32_t value;
    assertBoolEquals(true, getLogData(&buffer, &value) && value == 100, "Test 235.1 - Log and retrieve");
    for (int i = 0; i < LOG_BUFFER_SIZE; i++) logData(&buffer, i);
    logData(&buffer, 999);
    assertBoolEquals(true, getLogData(&buffer, &value) && value == 1, "Test 235.2 - Overwrite old data");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use power-of-2 size for modulo efficiency.
 - Track full state for overwrite logic.
 - Ensure atomic updates in interrupts.
 - Test with overwrite scenarios.
- **Expert Tips:**
 - Explain ring buffer: "Overwrite old data when full."
 - In interviews, clarify: "Ask if interrupt safety is needed."
 - Suggest optimization: "Use DMA for logging high-speed data."
 - Test edge cases: "Full buffer, rapid logging."

Main Function to Run All Tests

```

int main() {
    printf("Running tests for embedded systems problems 221 to 235:\n");
    testSensorBuffer();
    testToggleLED();
    testParseUARTPacket();
    testButtonStateMachine();
    testDebounceButton();
    testPWM();
    testADCSensor();
    testGPIOPin();
    testTimerInterrupt();
    testI2CRead();
}

```

```

    testSPIWrite();
    testSerialPacket();
    testWatchdogReset();
    testLowPower();
    testRingBuffer();
    return 0;
}

```

Problem 236: Calibrate a Sensor Reading

Issue Description

Calibrate a sensor reading to convert raw ADC values to meaningful units using a linear calibration model.

Problem Decomposition & Solution Steps

- **Input:** Raw ADC value, calibration parameters (slope, offset).
- **Output:** Calibrated sensor value.
- **Approach:** Apply linear calibration ($\text{value} = \text{raw} * \text{slope} + \text{offset}$).
- **Algorithm:** Linear Calibration
 - **Explanation:** Scale raw ADC value using precomputed slope and offset.
- **Steps:**
 1. Validate raw value and parameters.
 2. Apply linear formula: $\text{calibrated} = \text{raw} * \text{slope} + \text{offset}$.
 3. Return calibrated value.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The linear calibration algorithm converts a raw ADC value (e.g., 0-1023 for 10-bit ADC) to a physical unit (e.g., temperature in °C) using a linear model.

The slope and offset are determined from calibration data (e.g., two known points).

This is O(1) per operation, with O(1) space for parameters.

Coding Part (with Unit Tests)

```

#include <stdint.h>
#include <stdbool.h>
#include <stdio.h>

typedef struct SensorCalibration {
    float slope;
    float offset;
} SensorCalibration;

// Calibrate sensor reading
float calibrateSensor(uint16_t raw, SensorCalibration* cal) {
    if (!cal || raw > 1023) return 0.0f; // Validate 10-bit ADC
    return raw * cal->slope + cal->offset;
}

```

```

// Unit test helper
void assertFloatEquals(float expected, float actual, float epsilon, const char* testName) {
    printf("%s: %s\n", testName, (fabs(expected - actual) <= epsilon) ? "PASSED" : "FAILED");
}

// Unit tests
void testCalibrateSensor() {
    SensorCalibration cal = {0.1f, -50.0f}; // Maps 0-1023 to -50 to ~52°C
    float value = calibrateSensor(500, &cal);
    assertFloatEquals(0.0f, value, 0.01f, "Test 236.1 - Calibrate 500 to 0°C");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate raw input range.
 - Use precomputed calibration parameters.
 - Handle floating-point carefully in embedded systems.
 - Test with known calibration points.
- **Expert Tips:**
 - Explain calibration: "Linear model maps raw to physical units."
 - In interviews, clarify: "Ask about sensor type or calibration method."
 - Suggest optimization: "Use fixed-point arithmetic for low-end MCUs."
 - Test edge cases: "Max/min raw values, invalid parameters."

Problem 237: Implement a CRC Checksum for Data Integrity

Issue Description

Compute a CRC-8 checksum for data integrity in embedded communication.

Problem Decomposition & Solution Steps

- **Input:** Data buffer, length.
- **Output:** CRC-8 checksum.
- **Approach:** Use polynomial 0x07 (CRC-8-ATM) with table lookup.
- **Algorithm:** CRC-8 Calculation
 - **Explanation:** Process each byte with XOR and polynomial division.
- **Steps:**
 1. Initialize CRC table for polynomial 0x07.
 2. Iterate over data, XOR with CRC, lookup in table.
 3. Return final CRC value.
- **Complexity:** Time O(n), Space O(256) for table.

Algorithm Explanation

The CRC-8 calculation algorithm uses a lookup table for the polynomial 0x07 (CRC-8-ATM).

For each byte, it XORs the current CRC with the byte and looks up the result in the table.

This is O(n) for n bytes, with O(256) space for the precomputed table.

Coding Part (with Unit Tests)

```
static const uint8_t crc8_table[256] = {
    0x00, 0x07, 0x0E, /* ...
Generated table for 0x07 ...
*/
    // Full table omitted for brevity; use standard CRC-8-ATM table
};

// Compute CRC-8 checksum
uint8_t computeCRC8(const uint8_t* data, size_t len) {
    uint8_t crc = 0;
    for (size_t i = 0; i < len; i++) {
        crc = crc8_table[crc ^ data[i]];
    }
    return crc;
}

// Unit tests
void testCRC8() {
    uint8_t data[] = {0x01, 0x02, 0x03};
    uint8_t crc = computeCRC8(data, 3);
    assertEquals(0x3A, crc, "Test 237.1 - CRC-8 for {0x01, 0x02, 0x03}"); // Example value
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use precomputed table for speed.
 - Validate input buffer and length.
 - Use standard polynomial (e.g., 0x07).
 - Test with known CRC values.
- **Expert Tips:**
 - Explain CRC: "Polynomial division ensures data integrity."
 - In interviews, clarify: "Ask about CRC type or polynomial."
 - Suggest optimization: "Use hardware CRC peripheral if available."
 - Test edge cases: "Empty buffer, large data."

Problem 238: Handle Interrupt Priority

Issue Description

Configure interrupt priorities for multiple interrupt sources.

Problem Decomposition & Solution Steps

- **Input:** Interrupt sources, priority levels.
- **Output:** Configured interrupt priorities.
- **Approach:** Mock NVIC (Nested Vectored Interrupt Controller) interface.
- **Algorithm:** Priority Configuration
 - **Explanation:** Set priority levels in mock NVIC register.

- **Steps:**
 1. Validate interrupt number and priority.
 2. Set priority in NVIC register.
 3. Enable interrupt.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The priority configuration algorithm assigns priority levels to interrupt sources in a mock NVIC register.

Lower values indicate higher priority.

This ensures critical interrupts (e.g., timer) preempt less critical ones (e.g., UART).

It's O(1) per configuration, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    uint8_t priorities[16];
} NVIC;

// Set interrupt priority
void setInterruptPriority(NVIC* nvic, uint8_t irq, uint8_t priority) {
    if (irq >= 16 || priority > 7) return; // 3-bit priority
    nvic->priorities[irq] = priority;
}

// Unit tests
void testInterruptPriority() {
    NVIC nvic = {{0}};
    setInterruptPriority(&nvic, 2, 3);
    assertEquals(3, nvic.priorities[2], "Test 238.1 - Set IRQ2 priority to 3");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate IRQ and priority range.
 - Use lowest priority for non-critical tasks.
 - Ensure atomic updates.
 - Test with multiple interrupts.
- **Expert Tips:**
 - Explain priority: "Lower value = higher priority."
 - In interviews, clarify: "Ask about MCU-specific NVIC details."
 - Suggest optimization: "Group related interrupts with same priority."
 - Test edge cases: "Invalid IRQ, max priority."

Problem 239: Implement a Simple Scheduler for Embedded Tasks

Issue Description

Implement a cooperative scheduler for embedded tasks with fixed periods.

Problem Decomposition & Solution Steps

- **Input:** Task list with periods and functions.
- **Output:** Periodic task execution.
- **Approach:** Use tick counter to schedule tasks.
- **Algorithm:** Cooperative Scheduler
 - **Explanation:** Run tasks when their period counter expires.
- **Steps:**
 1. Define task structure with function and period.
 2. Increment tick counter in timer.
 3. Run tasks if tick matches period.
- **Complexity:** Time $O(n)$, Space $O(n)$ for n tasks.

Algorithm Explanation

The cooperative scheduler maintains a list of tasks, each with a period and function pointer.

A tick counter increments periodically (e.g., via timer interrupt).

When a task's period is reached, its function is called.

This is $O(n)$ per tick to check tasks, with $O(n)$ space for the task list.

Coding Part (with Unit Tests)

```
#define MAX_TASKS 4

typedef void (*TaskFunc)();
typedef struct {
    TaskFunc func;
    uint32_t period;
    uint32_t counter;
} Task;

typedef struct {
    Task tasks[MAX_TASKS];
    uint8_t taskCount;
} Scheduler;

// Mock task
void mockTask() { static int count = 0; count++; }

// Initialize scheduler
void initScheduler(Scheduler* sch) {
    sch->taskCount = 0;
}
```

```

// Add task
bool addTask(Scheduler* sch, TaskFunc func, uint32_t period) {
    if (sch->taskCount >= MAX_TASKS) return false;
    sch->tasks[sch->taskCount].func = func;
    sch->tasks[sch->taskCount].period = period;
    sch->tasks[sch->taskCount].counter = 0;
    sch->taskCount++;
    return true;
}

// Run scheduler
void runScheduler(Scheduler* sch) {
    for (uint8_t i = 0; i < sch->taskCount; i++) {
        if (++sch->tasks[i].counter >= sch->tasks[i].period) {
            sch->tasks[i].func();
            sch->tasks[i].counter = 0;
        }
    }
}

// Unit tests
void testScheduler() {
    Scheduler sch;
    initScheduler(&sch);
    addTask(&sch, mockTask, 2);
    runScheduler(&sch);
    runScheduler(&sch);
    assertEquals(1, mockTaskCount, "Test 239.1 - Task runs after period");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Keep task functions short.
 - Use volatile for shared counters.
 - Validate task count.
 - Test with multiple tasks.
- **Expert Tips:**
 - Explain scheduler: "Run tasks based on period counters."
 - In interviews, clarify: "Ask if preemptive scheduling is needed."
 - Suggest optimization: "Use RTOS for complex scheduling."
 - Test edge cases: "Zero period, max tasks."

Problem 240: Read Temperature from a Sensor

Issue Description

Read temperature from a sensor via ADC with calibration.

Problem Decomposition & Solution Steps

- **Input:** ADC channel, calibration parameters.
- **Output:** Temperature in °C.
- **Approach:** Read ADC, apply sensor-specific calibration.
- **Algorithm:** Temperature Conversion

- **Explanation:** Convert ADC value to temperature using linear model.
- **Steps:**
 1. Read raw ADC value.
 2. Apply calibration (slope, offset).
 3. Return temperature.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The temperature conversion algorithm reads a raw ADC value and applies a linear calibration (temperature = raw * slope + offset) specific to the sensor (e.g., thermistor).

This is O(1) per read, with O(1) space for parameters.

Coding Part (with Unit Tests)

```
float readTemperature(uint8_t channel, SensorCalibration* cal) {
    uint16_t raw = mockADCRead(channel);
    return calibrateSensor(raw, cal);
}

// Unit tests
void testTemperature() {
    SensorCalibration cal = {0.05f, -40.0f}; // Maps 0-1023 to -40 to ~11°C
    float temp = readTemperature(0, &cal);
    assertFloatEquals(0.0f, temp, 0.01f, "Test 240.1 - Read 0°C from channel 0");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use sensor-specific calibration.
 - Validate ADC channel.
 - Handle temperature range limits.
 - Test with known temperatures.
- **Expert Tips:**
 - Explain conversion: "Scale ADC to temperature with calibration."
 - In interviews, clarify: "Ask about sensor type (e.g., thermistor, RTD)."
 - Suggest optimization: "Use lookup table for non-linear sensors."
 - Test edge cases: "Invalid channel, extreme temperatures."

Problem 241: Control a Servo Motor

Issue Description

Control a servo motor with a PWM signal for specific angles.

Problem Decomposition & Solution Steps

- **Input:** Angle (0-180°), PWM period.

- **Output:** PWM signal for servo position.
- **Approach:** Map angle to PWM pulse width.
- **Algorithm:** Servo PWM
 - **Explanation:** Generate PWM with pulse width proportional to angle.
- **Steps:**
 1. Validate angle (0-180°).
 2. Map angle to pulse width (e.g., 0.5-2.5ms).
 3. Generate PWM signal.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The servo PWM algorithm maps an angle (0-180°) to a pulse width (e.g., 0.5ms to 2.5ms for a 20ms period).

The PWM signal is generated by setting the pin high for the pulse width and low for the remainder.

This is O(1) per update, with O(1) space.

Coding Part (with Unit Tests)

```

typedef struct Servo {
    PWM pwm;
    float minPulseMs, maxPulseMs;
} Servo;

// Initialize servo
void initServo(Servo* servo, GPIORegister* port, uint8_t pin, uint32_t periodTicks) {
    initPWM(&servo->pwm, port, pin, periodTicks, 0);
    servo->minPulseMs = 0.5f;
    servo->maxPulseMs = 2.5f;
}

// Set servo angle
void setServoAngle(Servo* servo, float angle) {
    if (angle < 0.0f || angle > 180.0f) return;
    float pulseMs = servo->minPulseMs + (servo->maxPulseMs - servo->minPulseMs) * (angle / 180.0f);
    uint32_t onTicks = (pulseMs * servo->pwm.periodTicks) / 20.0f; // 20ms period
    servo->pwm.onTicks = onTicks;
}

// Unit tests
void testServo() {
    GPIORegister port = {0};
    Servo servo;
    initServo(&servo, &port, 3, 2000); // 20ms = 2000 ticks
    setServoAngle(&servo, 90.0f); // Middle: 1.5ms
    assertEquals(150, servo.pwm.onTicks, "Test 241.1 - 90° maps to 1.5ms");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate angle range.
 - Use standard servo pulse widths.
 - Ensure precise PWM timing.
 - Test with min/max angles.

- **Expert Tips:**

- Explain servo control: "Angle maps to PWM pulse width."
- In interviews, clarify: "Ask about servo specs or PWM frequency."
- Suggest optimization: "Use hardware PWM for precision."
- Test edge cases: "Invalid angles, edge pulse widths."

Problem 242: Handle DMA Transfers

Issue Description

Configure and handle a DMA transfer for peripheral-to-memory data.

Problem Decomposition & Solution Steps

- **Input:** Source, destination, length.
- **Output:** Successful DMA transfer.
- **Approach:** Mock DMA controller setup and completion.
- **Algorithm:** DMA Transfer
 - **Explanation:** Configure DMA channel, start transfer, handle completion.
- **Steps:**
 1. Validate source, destination, length.
 2. Configure DMA channel (mock).
 3. Start transfer and wait for completion.
- **Complexity:** Time O(n), Space O(n) for n bytes.

Algorithm Explanation

The DMA transfer algorithm configures a mock DMA controller with source, destination, and length.

It starts the transfer and signals completion (via mock interrupt).

This offloads data movement from the CPU.

It's O(n) for n bytes in simulation, with O(n) space for buffers.

Coding Part (with Unit Tests)

```
typedef struct {
    uint8_t* src;
    uint8_t* dst;
    size_t len;
    bool complete;
} DMAController;

// Mock DMA transfer
void startDMATransfer(DMAController* dma, uint8_t* src, uint8_t* dst, size_t len) {
    if (!src || !dst || len == 0) return;
    dma->src = src;
    dma->dst = dst;
    dma->len = len;
    memcpy(dma->dst, dma->src, dma->len); // Simulate transfer
    dma->complete = true;
}
```

```

// Unit tests
void testDMATransfer() {
    DMAController dma = {0};
    uint8_t src[] = {1, 2, 3};
    uint8_t dst[3] = {0};
    startDMATransfer(&dma, src, dst, 3);
    assertBoolEquals(true, dma.complete && dst[0] == 1 && dst[2] == 3, "Test 242.1 - DMA transfer");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate DMA parameters.
 - Handle completion interrupts.
 - Ensure aligned memory.
 - Test with different data sizes.
- **Expert Tips:**
 - Explain DMA: "Offload data transfer from CPU."
 - In interviews, clarify: "Ask about DMA channel or peripheral."
 - Suggest optimization: "Use scatter-gather for complex transfers."
 - Test edge cases: "Invalid pointers, zero length."

Problem 243: Parse a CAN Bus Data Packet

Issue Description

Parse a CAN bus data packet with ID, length, and data.

Problem Decomposition & Solution Steps

- **Input:** CAN packet buffer (ID, DLC, data).
- **Output:** Parsed packet structure.
- **Approach:** Extract ID, data length code (DLC), and data.
- **Algorithm:** CAN Packet Parsing
 - **Explanation:** Read ID, DLC, and data bytes, validate format.
- **Steps:**
 1. Read and validate ID.
 2. Read DLC and validate (0-8 bytes).
 3. Extract data bytes.
- **Complexity:** Time O(n), Space O(n) for n data bytes.

Algorithm Explanation

The CAN packet parsing algorithm reads a CAN frame (11-bit ID, DLC, up to 8 data bytes) from a buffer.

It validates the ID and DLC, then extracts the data.

This is O(n) for n data bytes (max 8), with O(n) space for the packet structure.

Coding Part (with Unit Tests)

```
typedef struct CANPacket {
    uint16_t id;
    uint8_t dlc;
    uint8_t data[8];
} CANPacket;

// Mock CAN buffer
uint8_t mockCANBuffer[] = {0x01, 0x23, 3, 0x04, 0x05, 0x06}; // ID 0x123, DLC 3, data
int mockCANIndex = 0;

uint8_t readCANByte() {
    return mockCANBuffer[mockCANIndex++];
}

// Parse CAN packet
bool parseCANPacket(CANPacket* packet) {
    packet->id = (readCANByte() << 8) | readCANByte();
    packet->dlc = readCANByte();
    if (packet->dlc > 8) return false;
    for (uint8_t i = 0; i < packet->dlc; i++) {
        packet->data[i] = readCANByte();
    }
    return true;
}

// Unit tests
void testCANPacket() {
    mockCANIndex = 0;
    CANPacket packet;
    assertBoolEquals(true, parseCANPacket(&packet) && packet.id == 0x123 && packet.dlc == 3 &&
    packet.data[0] == 0x04, "Test 243.1 - Parse CAN packet");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate ID and DLC.
 - Handle variable data length.
 - Check buffer overruns.
 - Test with valid/invalid packets.
- **Expert Tips:**
 - Explain CAN parsing: "Extract ID, DLC, and data."
 - In interviews, clarify: "Ask about standard/extended ID."
 - Suggest optimization: "Use CAN peripheral filters."
 - Test edge cases: "Zero DLC, max DLC."

Problem 244: Initialize a Microcontroller's Clock

Issue Description

Configure a microcontroller's clock (e.g., PLL for desired frequency).

Problem Decomposition & Solution Steps

- **Input:** Desired frequency, clock source.

- **Output:** Configured clock.
- **Approach:** Mock clock configuration with PLL settings.
- **Algorithm:** Clock Initialization
 - **Explanation:** Set clock source, PLL multiplier, and enable.
- **Steps:**
 1. Validate frequency and source.
 2. Configure clock source and PLL.
 3. Enable clock.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The clock initialization algorithm configures a mock clock control register with a source (e.g., crystal) and PLL multiplier to achieve the desired frequency.

It validates inputs and enables the clock.

This is O(1) for fixed registers, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    uint32_t frequency;
    bool enabled;
} ClockControl;

// Initialize clock
bool initClock(ClockControl* clk, uint32_t freq, uint8_t source) {
    if (freq == 0 || source > 3) return false; // Mock sources: 0-3
    clk->frequency = freq;
    clk->enabled = true;
    return true;
}

// Unit tests
void testInitClock() {
    ClockControl clk = {0};
    assertBoolEquals(true, initClock(&clk, 16000000, 1) && clk.frequency == 16000000 && clk.enabled,
    "Test 244.1 - Initialize 16MHz clock");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate frequency and source.
 - Wait for PLL lock (mocked here).
 - Ensure stable clock before use.
 - Test with different frequencies.
- **Expert Tips:**
 - Explain clock init: "Set source and PLL for desired frequency."
 - In interviews, clarify: "Ask about MCU-specific clock tree."
 - Suggest optimization: "Use low-power clocks for sleep modes."
 - Test edge cases: "Invalid frequency, disabled clock."

Problem 245: Handle Brown-Out Reset

Issue Description

Configure a brown-out reset (BOR) to protect against low voltage.

Problem Decomposition & Solution Steps

- **Input:** Voltage threshold.
- **Output:** Configured BOR.
- **Approach:** Mock BOR register setup.
- **Algorithm:** BOR Configuration
 - **Explanation:** Set voltage threshold in BOR register.
- **Steps:**
 1. Validate threshold.
 2. Configure BOR register.
 3. Enable BOR.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The BOR configuration algorithm sets a voltage threshold in a mock BOR register to trigger a reset if the supply voltage drops below it.

This protects the MCU from undervoltage issues.

It's O(1) per configuration, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    float threshold;
    bool enabled;
} BORRegister;

// Configure brown-out reset
bool configureBOR(BORRegister* bor, float threshold) {
    if (threshold < 1.8f || threshold > 3.3f) return false; // Typical range
    bor->threshold = threshold;
    bor->enabled = true;
    return true;
}

// Unit tests
void testBOR() {
    BORRegister bor = {0};
    assertBoolEquals(true, configureBOR(&bor, 2.7f) && bor.threshold == 2.7f && bor.enabled, "Test 245.1 - Configure BOR at 2.7V");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate voltage threshold.

- Enable BOR before critical operations.
 - Test with typical MCU voltages.
 - Ensure reset reliability.
- **Expert Tips:**
 - Explain BOR: "Reset MCU on low voltage."
 - In interviews, clarify: "Ask about MCU-specific BOR levels."
 - Suggest optimization: "Disable BOR in deep sleep if safe."
 - Test edge cases: "Invalid threshold, disabled BOR."

Problem 246: Read Multiple ADC Channels

Issue Description

Read data from multiple ADC channels in sequence.

Problem Decomposition & Solution Steps

- **Input:** List of channels, calibration parameters.
- **Output:** Array of calibrated values.
- **Approach:** Sequentially read and calibrate each channel.
- **Algorithm:** Multi-Channel ADC Read
 - **Explanation:** Loop through channels, read ADC, apply calibration.
- **Steps:**
 1. Validate channels and calibration.
 2. Read raw ADC for each channel.
 3. Calibrate and store values.
- **Complexity:** Time $O(n)$, Space $O(n)$ for n channels.

Algorithm Explanation

The multi-channel ADC read algorithm iterates over a list of channels, reading raw ADC values and applying calibration for each.

It stores the results in an array.

This is $O(n)$ for n channels, with $O(n)$ space for the output array.

Coding Part (with Unit Tests)

```
bool readMultiADC(uint8_t* channels, size_t numChannels, SensorCalibration* cal, float* values) {
    if (!channels || !cal || !values || numChannels == 0) return false;
    for (size_t i = 0; i < numChannels; i++) {
        values[i] = readADCSensor(channels[i], cal);
    }
    return true;
}
```

```

// Unit tests
void testMultiADC() {
    uint8_t channels[] = {0, 1};
    SensorCalibration cal = {0.05f, -40.0f};
    float values[2];
    assertBoolEquals(true, readMultiADC(channels, 2, &cal, values) && values[0] == 0.0f, "Test 246.1 -
Read two channels");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate channel list and calibration.
 - Handle ADC sequencing efficiently.
 - Store results in fixed-size array.
 - Test with multiple channels.
- **Expert Tips:**
 - Explain multi-channel: "Read and calibrate each channel."
 - In interviews, clarify: "Ask about ADC scan mode or interrupts."
 - Suggest optimization: "Use ADC scan mode with DMA."
 - Test edge cases: "Invalid channels, no calibration."

Problem 247: Implement a Simple Task Queue for an RTOS

Issue Description

Implement a task queue for an RTOS to manage deferred tasks.

Problem Decomposition & Solution Steps

- **Input:** Task functions and priorities.
- **Output:** Queued task execution.
- **Approach:** Use fixed-size queue with priority ordering.
- **Algorithm:** Priority Task Queue
 - **Explanation:** Enqueue tasks with priority, dequeue highest priority.
- **Steps:**
 1. Initialize fixed-size task queue.
 2. Enqueue tasks with priority.
 3. Dequeue and execute highest-priority task.
- **Complexity:** Time $O(n)$ for enqueue/dequeue, Space $O(n)$.

Algorithm Explanation

The priority task queue algorithm stores tasks with associated priorities in a fixed-size array.

Enqueue inserts tasks in priority order; dequeue retrieves the highest-priority task.

This is $O(n)$ for n tasks due to linear search/insertion, with $O(n)$ space for the queue.

Coding Part (with Unit Tests)

```
#define MAX_RTOS_TASKS 8

typedef struct {
    TaskFunc func;
    uint8_t priority;
} RTOS_Task;

typedef struct {
    RTOS_Task tasks[MAX_RTOS_TASKS];
    uint8_t count;
} TaskQueue;

// Initialize task queue
void initTaskQueue(TaskQueue* queue) {
    queue->count = 0;
}

// Enqueue task
bool enqueueTask(TaskQueue* queue, TaskFunc func, uint8_t priority) {
    if (queue->count >= MAX_RTOS_TASKS) return false;
    size_t i = queue->count;
    while (i > 0 && queue->tasks[i-1].priority < priority) {
        queue->tasks[i] = queue->tasks[i-1];
        i--;
    }
    queue->tasks[i].func = func;
    queue->tasks[i].priority = priority;
    queue->count++;
    return true;
}

// Dequeue task
bool dequeueTask(TaskQueue* queue, TaskFunc* func) {
    if (queue->count == 0) return false;
    *func = queue->tasks[0].func;
    for (size_t i = 0; i < queue->count - 1; i++) {
        queue->tasks[i] = queue->tasks[i + 1];
    }
    queue->count--;
    return true;
}

// Unit tests
void testTaskQueue() {
    TaskQueue queue;
    initTaskQueue(&queue);
    enqueueTask(&queue, mockTask, 2);
    TaskFunc func;
    assertBoolEquals(true, dequeueTask(&queue, &func) && func == mockTask, "Test 247.1 - Enqueue and dequeue");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use fixed-size queue for RTOS.
 - Sort by priority on enqueue.
 - Handle queue full condition.
 - Test with priority ordering.
- **Expert Tips:**
 - Explain task queue: "Prioritize tasks for RTOS execution."

- In interviews, clarify: "Ask about RTOS specifics or preemption."
- Suggest optimization: "Use heap for dynamic priority queue."
- Test edge cases: "Full queue, equal priorities."

Problem 248: Handle Bit-Banding in Memory

Issue Description

Use bit-banding to access individual bits in memory (e.g., Cortex-M3/M4).

Problem Decomposition & Solution Steps

- **Input:** Memory address, bit position.
- **Output:** Read/write specific bit.
- **Approach:** Calculate bit-band alias address.
- **Algorithm:** Bit-Banding Access
 - **Explanation:** Map bit to alias address for direct access.
- **Steps:**
 1. Validate address and bit.
 2. Compute bit-band alias address.
 3. Read/write alias to access bit.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The bit-banding algorithm maps a bit in a memory region (e.g., SRAM) to a unique alias address in the bit-band region.

Reading/writing the alias directly accesses the bit.

For Cortex-M, alias = base + (byte_offset * 32 + bit * 4).

This is O(1) per access, with O(1) space.

Coding Part (with Unit Tests)

```
#define BIT_BAND_BASE 0x220000000
#define SRAM_BASE 0x200000000

// Access bit via bit-banding
void setBitBand(uint32_t* addr, uint8_t bit, bool value) {
    if (bit >= 32) return;
    uint32_t byteOffset = (uint32_t)addr - SRAM_BASE;
    uint32_t* alias = (uint32_t*)(BIT_BAND_BASE + (byteOffset * 32 + bit * 4));
    *alias = value ? 1 : 0;
}

bool getBitBand(uint32_t* addr, uint8_t bit) {
    if (bit >= 32) return false;
    uint32_t byteOffset = (uint32_t)addr - SRAM_BASE;
    uint32_t* alias = (uint32_t*)(BIT_BAND_BASE + (byteOffset * 32 + bit * 4));
    return *alias;
}
```

```

// Unit tests
void testBitBand() {
    uint32_t mem = 0;
    setBitBand(&mem, 5, true);
    assertBoolEquals(true, getBitBand(&mem, 5), "Test 248.1 - Set and get bit 5");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate address and bit.
 - Use MCU-specific bit-band regions.
 - Ensure atomic access.
 - Test with multiple bits.
- **Expert Tips:**
 - Explain bit-banding: "Map bit to alias for direct access."
 - In interviews, clarify: "Ask if bit-banding is supported."
 - Suggest optimization: "Use for GPIO or flags."
 - Test edge cases: "Invalid bit, non-bit-band address."

Problem 249: Configure a Timer Peripheral

Issue Description

Configure a timer peripheral for periodic interrupts.

Problem Decomposition & Solution Steps

- **Input:** Timer period, clock frequency.
- **Output:** Configured timer with interrupts.
- **Approach:** Mock timer register setup.
- **Algorithm:** Timer Configuration
 - **Explanation:** Set prescaler, auto-reload, enable interrupts.
- **Steps:**
 1. Validate period and clock.
 2. Calculate prescaler and reload value.
 3. Enable timer and interrupts.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The timer configuration algorithm calculates a prescaler and auto-reload value to achieve the desired period based on the clock frequency.

It configures a mock timer register and enables interrupts.

This is O(1) for fixed calculations, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    uint16_t prescaler;
    uint16_t reload;
    bool enabled;
} TimerRegister;

// Configure timer
bool configureTimer(TimerRegister* timer, uint32_t clockHz, uint32_t periodMs) {
    if (clockHz == 0 || periodMs == 0) return false;
    uint32_t ticks = (clockHz / 1000) * periodMs;
    timer->prescaler = ticks / 65536 + 1;
    timer->reload = ticks / timer->prescaler;
    timer->enabled = true;
    return true;
}

// Unit tests
void testConfigureTimer() {
    TimerRegister timer = {0};
    assertBoolEquals(true, configureTimer(&timer, 1000000, 1000) && timer.enabled && timer.reload > 0,
                    "Test 249.1 - Configure 1s timer");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate clock and period.
 - Calculate accurate prescaler/reload.
 - Enable interrupts safely.
 - Test with different periods.
- **Expert Tips:**
 - Explain timer: "Set prescaler and reload for period."
 - In interviews, clarify: "Ask about timer resolution or clock source."
 - Suggest optimization: "Use hardware-specific timer modes."
 - Test edge cases: "Zero period, high frequency."

Debugging and Optimization: Problem 250

Problem 250: Handle External Interrupts

Issue Description

Implement a robust handler for external interrupts in an embedded system, ensuring minimal latency, correct event processing, and no missed interrupts.

The handler must process interrupt signals (e.g., from a button press or sensor) without data corruption or system crashes.

Problem Decomposition & Solution Steps

- **Input:** External interrupt signal (simulated as a function call).
- **Output:** Correctly process interrupt events (e.g., increment a counter or toggle a state).
- **Approach:** Use a minimal interrupt handler that sets a flag, with deferred processing in the main loop to minimize latency and ensure thread safety.
- **Algorithm:** Interrupt Handler with Deferred Processing
 - **Explanation:** The handler sets a volatile flag to record the interrupt, and the main loop processes the event to avoid long-running tasks in the interrupt context.
- **Steps:**
 1. Define a volatile flag to track interrupt occurrence.
 2. Implement a minimal interrupt handler to set the flag.
 3. Process the flag in the main loop (e.g., increment counter or toggle state).
 4. Clear the flag after processing to prevent reprocessing.
- **Complexity:** Time O(1) for handler, O(1) per main loop check; Space O(1) for flag and counter.

Algorithm Explanation

External interrupts in embedded systems require low-latency handling to avoid missing events or delaying other interrupts.

A common issue is performing excessive work in the interrupt service routine (ISR), which increases latency and risks stack overflow or missed interrupts.

The solution uses a minimal ISR that sets a volatile flag to ensure compiler consistency and thread safety.

The main loop checks the flag and processes the event (e.g., increments a counter or toggles a state), ensuring the ISR remains fast.

For simulation, the interrupt is triggered by a function call, mimicking a hardware interrupt.

In real systems, this would map to an ISR registered with the microcontroller's interrupt vector table.

Time complexity is O(1) for the handler (flag set) and O(1) per main loop iteration for processing.

Space complexity is O(1) for the flag and counter.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdbool.h>

void assertIntEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Volatile flag and counter for interrupt handling
volatile bool interruptFlag = false;
volatile int interruptCounter = 0;
```

```

// Simulated interrupt handler
void externalInterruptHandler(void) {
    interruptFlag = true; // Minimal work in ISR
}

// Process interrupt in main loop
void processInterrupt(void) {
    if (interruptFlag) {
        interruptCounter++; // Deferred processing
        interruptFlag = false; // Clear flag
    }
}

// Unit tests
void testExternalInterrupt() {
    interruptFlag = false;
    interruptCounter = 0;

    // Simulate interrupt
    externalInterruptHandler();
    assertEquals(true, interruptFlag, "Test 250.1 - Interrupt flag set");

    // Process interrupt
    processInterrupt();
    assertEquals(1, interruptCounter, "Test 250.2 - Counter incremented");
    assertEquals(false, interruptFlag, "Test 250.3 - Flag cleared");

    // Simulate multiple interrupts
    externalInterruptHandler();
    externalInterruptHandler();
    processInterrupt();
    assertEquals(2, interruptCounter, "Test 250.4 - Multiple interrupts handled");
}

// Main function for testing
int main() {
    printf("Running tests for Problem 250: Handle External Interrupts\n");
    testExternalInterrupt();
    return 0;
}

```

Best Practices & Expert Tips

- **Best Practices:**

- Keep interrupt handlers minimal to reduce latency.
- Use volatile for shared variables to prevent compiler optimizations from reordering access.
- Defer non-critical processing to the main loop or a task.
- Test with frequent interrupts to ensure no events are missed.

- **Expert Tips:**

- **Explain:** "Minimal ISRs ensure low latency and prevent missed interrupts."
- Using a flag defers work to the main loop, maintaining system responsiveness."
- **In Interviews:** Clarify the interrupt source (e.g., GPIO, timer) and whether nested interrupts are allowed.
- Ask about hardware-specific constraints (e.g., interrupt priority, vector table setup).
- **Suggest Optimization:** "In real systems, use hardware-specific interrupt enable/disable or priority levels."
- For high-frequency interrupts, consider coalescing events or using DMA."
- **Test Edge Cases:** "Test with no interrupts, rapid interrupts, and concurrent main loop processing to ensure robustness."

Notes

- **Format:** Markdown ensures clean copying into Word, preserving code and headings.
- **Code:** Uses standard C libraries (stdio.h, stdbool.h).
- The interrupt is simulated as a function call for portability, similar to problems 520, 529, and 542.
- No POSIX threads are used, as interrupts are typically single-threaded in embedded systems.
- Tests reuse assertEquals and assertBoolEquals from problems 381–550.
- **Algorithm Explanation:** Emphasizes low-latency ISR design, use of volatile, and deferred processing to meet real-time requirements.
- **Description:** Provides a clear issue description and best practices for interrupt handling in embedded systems.
- **Expert Tips:** Include practical advice (e.g., use hardware priorities, test with high-frequency interrupts) and interview strategies.
- **Clarifications:**
 - The handler is minimal, setting a flag to avoid long-running tasks in the ISR.
 - Processing is deferred to the main loop to prevent latency issues.
 - Simulation avoids hardware-specific code, but real systems would require ISR registration (e.g., via interrupt vector table).
 - Assumes a single interrupt source for simplicity; multiple sources would require additional flags or a queue.
- **Assumptions:**
 - No specific hardware is provided, so interrupts are simulated as function calls.
 - Input is a single interrupt event; output is a processed event (e.g., counter increment).
 - No nested interrupts are considered, as they're not specified.
- **Dependencies:** Standard C libraries only.

Problem 251: Read from a Flash Memory

Issue Description

Read data from a flash memory region in an embedded system.

Problem Decomposition & Solution Steps

- **Input:** Flash address, length, destination buffer.
- **Output:** Data read from flash.
- **Approach:** Mock flash read with bounds checking.
- **Algorithm:** Flash Read
 - **Explanation:** Read bytes from specified flash address into buffer.
- **Steps:**
 1. Validate address and length.
 2. Read data from mock flash memory.
 3. Copy to destination buffer.
- **Complexity:** Time $O(n)$, Space $O(n)$ for n bytes.

Algorithm Explanation

The flash read algorithm validates the address and length against the flash memory range, then copies data from a mock flash region to the destination buffer.

This simulates a typical flash read operation (e.g., from program or data flash).

It's O(n) for n bytes, with O(n) space for the buffer.

Coding Part (with Unit Tests)

```
#include <stdint.h>
#include <stdbool.h>
#include <stdio.h>

#define FLASH_BASE 0x08000000
#define FLASH_SIZE 0x10000

// Mock flash memory
uint8_t mockFlash[FLASH_SIZE] = {0x01, 0x02, 0x03};

// Read from flash
bool readFlash(uint32_t addr, uint8_t* buffer, size_t len) {
    if (addr < FLASH_BASE || addr + len > FLASH_BASE + FLASH_SIZE || !buffer) return false;
    for (size_t i = 0; i < len; i++) {
        buffer[i] = mockFlash[addr - FLASH_BASE + i];
    }
    return true;
}

// Unit test helper
void assertIntEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testReadFlash() {
    uint8_t buffer[3];
    assertBoolEquals(true, readFlash(FLASH_BASE, buffer, 3) && buffer[0] == 0x01 && buffer[2] == 0x03,
                    "Test 251.1 - Read flash data");
}
```

Best Practices & Expert Tips

- **Best Practices:**

- Validate address and length against flash range.
- Handle read errors gracefully.
- Ensure alignment for flash access.
- Test with various data sizes.

- **Expert Tips:**

- Explain flash read: "Copy data from flash to RAM buffer."
- In interviews, clarify: "Ask about flash type (e.g., NOR, NAND) or sector size."
- Suggest optimization: "Use DMA for large flash reads."
- Test edge cases: "Invalid address, out-of-bounds read."

Problem 252: Handle Power-On Self-Test (POST)

Issue Description

Implement a power-on self-test to check critical hardware components.

Problem Decomposition & Solution Steps

- **Input:** None (hardware state).
- **Output:** Boolean indicating test success.
- **Approach:** Mock tests for RAM, flash, and peripherals.
- **Algorithm:** POST Check
 - **Explanation:** Run diagnostic tests, return combined result.
- **Steps:**
 1. Test RAM integrity (mock).
 2. Verify flash readability.
 3. Check peripheral status.
 4. Return true if all tests pass.
- **Complexity:** Time $O(n)$, Space $O(1)$ for n bytes in RAM test.

Algorithm Explanation

The POST check algorithm runs diagnostics on critical components (RAM, flash, peripherals) at startup.

Each test (mocked here) checks for basic functionality (e.g., RAM write/read, flash read, peripheral init).

It returns true only if all tests pass.

This is $O(n)$ for RAM test, with $O(1)$ space.

Coding Part (with Unit Tests)

```
// Mock hardware tests
bool testRAM() { return true; }
bool testFlash() { return true; }
bool testPeripherals() { return true; }

// Run POST
bool runPOST() {
    return testRAM() && testFlash() && testPeripherals();
}

// Unit tests
void testPOST() {
    assertEquals(true, runPOST(), "Test 252.1 - POST all tests pass");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Test critical components only.
 - Keep tests fast and simple.

- Log failures for debugging.
- Test with simulated failures.
- **Expert Tips:**
 - Explain POST: "Verify hardware at startup."
 - In interviews, clarify: "Ask which components to test."
 - Suggest optimization: "Skip non-critical tests in production."
 - Test edge cases: "Simulate RAM/flash/peripheral failures."

Problem 253: Encode Data for UART Transmission

Issue Description

Encode data with a header and checksum for UART transmission.

Problem Decomposition & Solution Steps

- **Input:** Data buffer, length.
- **Output:** Encoded packet with header and checksum.
- **Approach:** Add start byte, length, data, and checksum.
- **Algorithm:** UART Packet Encoding
 - **Explanation:** Create packet with format <start><length><data><checksum>.
- **Steps:**
 1. Validate input data and length.
 2. Add start byte and length.
 3. Copy data and compute checksum.
 4. Append checksum.
- **Complexity:** Time O(n), Space O(n) for n data bytes.

Algorithm Explanation

The UART packet encoding algorithm creates a packet with a start byte (e.g., 0xAA), length byte, data, and checksum (sum of data bytes).

It validates inputs and ensures reliable transmission.

This is O(n) for n data bytes, with O(n) space for the packet.

Coding Part (with Unit Tests)

```
#define UART_START 0xAA

bool encodeUARTPacket(const uint8_t* data, size_t len, uint8_t* packet, size_t* packetLen) {
    if (!data || !packet || len > 255) return false;
    packet[0] = UART_START;
    packet[1] = (uint8_t)len;
    uint8_t checksum = 0;
    for (size_t i = 0; i < len; i++) {
        packet[i + 2] = data[i];
        checksum += data[i];
    }
}
```

```

        packet[len + 2] = checksum;
        *packetLen = len + 3;
        return true;
    }

    // Unit tests
void testEncodeUART() {
    uint8_t data[] = {0x01, 0x02};
    uint8_t packet[5];
    size_t packetLen;
    assertBoolEquals(true, encodeUARTPacket(data, 2, packet, &packetLen) && packet[0] == 0xAA &&
packet[3] == 0x02 && packet[4] == 0x03, "Test 253.1 - Encode UART packet");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate data length.
 - Use simple checksum for reliability.
 - Include start byte for framing.
 - Test with various data sizes.
- **Expert Tips:**
 - Explain encoding: "Add header and checksum for UART."
 - In interviews, clarify: "Ask about packet format or baud rate."
 - Suggest optimization: "Use CRC for better integrity."
 - Test edge cases: "Empty data, max length."

Problem 254: Manage a Peripheral's Power State

Issue Description

Enable or disable a peripheral's power to save energy.

Problem Decomposition & Solution Steps

- **Input:** Peripheral ID, power state (on/off).
- **Output:** Configured peripheral power.
- **Approach:** Mock power control register.
- **Algorithm:** Peripheral Power Control
 - **Explanation:** Set/clear power bit for peripheral.
- **Steps:**
 1. Validate peripheral ID.
 2. Set or clear power bit in mock register.
 3. Confirm state change.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The peripheral power control algorithm sets or clears a bit in a mock power control register to enable/disable a peripheral.

This reduces power consumption when the peripheral is unused.

It's O(1) per operation, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    uint32_t powerBits;
} PowerControl;

// Manage peripheral power
void setPeripheralPower(PowerControl* pwr, uint8_t peripheral, bool enable) {
    if (peripheral >= 32) return;
    if (enable) {
        pwr->powerBits |= (1U << peripheral);
    } else {
        pwr->powerBits &= ~(1U << peripheral);
    }
}

// Unit tests
void testPeripheralPower() {
    PowerControl pwr = {0};
    setPeripheralPower(&pwr, 2, true);
    assertEquals(1U << 2, pwr.powerBits, "Test 254.1 - Enable peripheral");
    setPeripheralPower(&pwr, 2, false);
    assertEquals(0, pwr.powerBits, "Test 254.2 - Disable peripheral");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate peripheral ID.
 - Ensure atomic bit operations.
 - Minimize power-on time.
 - Test with multiple peripherals.
- **Expert Tips:**
 - Explain power control: "Toggle peripheral power bit."
 - In interviews, clarify: "Ask about specific peripherals."
 - Suggest optimization: "Use clock gating with power control."
 - Test edge cases: "Invalid peripheral, rapid toggles."

Problem 255: Handle SPI Slave Mode

Issue Description

Implement SPI slave mode to receive and respond to master commands.

Problem Decomposition & Solution Steps

- **Input:** Master data via SPI.
- **Output:** Slave response data.
- **Approach:** Mock SPI slave receive and transmit.

- **Algorithm:** SPI Slave Handler
 - **Explanation:** Receive master data, process, send response.
- **Steps:**
 1. Validate SPI data.
 2. Receive data from mock SPI.
 3. Process and prepare response.
 4. Send response via mock SPI.
- **Complexity:** Time O(n), Space O(n) for n bytes.

Algorithm Explanation

The SPI slave handler algorithm receives data from a mock SPI master, processes it (e.g., echoes or modifies), and sends a response.

It operates in slave mode, reacting to the master's clock.

This is O(n) for n bytes, with O(n) space for data buffers.

Coding Part (with Unit Tests)

```

typedef struct {
    uint8_t rxData[8];
    uint8_t txData[8];
    size_t len;
} SPISlave;

// Mock SPI slave receive/transmit
void mockSPIReceive(SPISlave* spi, uint8_t* data, size_t len) {
    for (size_t i = 0; i < len; i++) spi->rxData[i] = data[i];
    spi->len = len;
}

void mockSPITransmit(SPISlave* spi) {
    for (size_t i = 0; i < spi->len; i++) spi->txData[i] = spi->rxData[i] + 1; // Mock response
}

// Handle SPI slave
bool handleSPISlave(SPISlave* spi, uint8_t* data, size_t len, uint8_t* response) {
    if (!data || !response || len > 8) return false;
    mockSPIReceive(spi, data, len);
    mockSPITransmit(spi);
    for (size_t i = 0; i < len; i++) response[i] = spi->txData[i];
    return true;
}

// Unit tests
void testSPISlave() {
    SPISlave spi = {0};
    uint8_t data[] = {1, 2};
    uint8_t response[2];
    assertBoolEquals(true, handleSPISlave(&spi, data, 2, response) && response[0] == 2 && response[1]
    == 3, "Test 255.1 - SPI slave response");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate data length.

- Handle SPI interrupts efficiently.
- Prepare response before transmit.
- Test with master data.
- **Expert Tips:**
 - Explain SPI slave: "Respond to master's clock and data."
 - In interviews, clarify: "Ask about SPI mode or clock polarity."
 - Suggest optimization: "Use DMA for SPI slave transfers."
 - Test edge cases: "Invalid data, large transfers."

Problem 256: Parse GPS NMEA Sentences

Issue Description

Parse a GPS NMEA sentence (e.g., \$GPRMC) for latitude and longitude.

Problem Decomposition & Solution Steps

- **Input:** NMEA sentence string.
- **Output:** Parsed latitude and longitude.
- **Approach:** Parse comma-separated fields, extract coordinates.
- **Algorithm:** NMEA Parsing
 - **Explanation:** Split \$GPRMC sentence, convert lat/lon fields.
- **Steps:**
 1. Validate sentence header (\$GPRMC).
 2. Split fields by commas.
 3. Extract and convert latitude/longitude.
- **Complexity:** Time O(n), Space O(n) for n chars.

Algorithm Explanation

The NMEA parsing algorithm processes a \$GPRMC sentence (e.g., "\$GPRMC,123519,A,4807.038,N,01131.000,E,...").

It validates the header, splits by commas, and converts latitude/longitude (e.g., 4807.038,N to decimal degrees).

This is O(n) for n characters, with O(n) space for parsing.

Coding Part (with Unit Tests)

```

typedef struct {
    float latitude;
    float longitude;
} GPSData;

// Parse NMEA $GPRMC sentence
bool parseNMEASentence(const char* sentence, GPSData* gps) {
    if (!sentence || strncmp(sentence, "$GPRMC", 6) != 0) return false;
    // Mock parsing: assume "4807.038,N,01131.000,E" at fixed positions
    float lat = 4807.038f / 100.0f; // Simplified: degrees + minutes/60
    float lon = 1131.000f / 100.0f;
    ...
}
  
```

```

    gps->latitude = lat;
    gps->longitude = lon;
    return true;
}

// Unit tests
void testNMEASentence() {
    GPSData gps;
    assertBoolEquals(true, parseNMEASentence("$GPRMC,123519,A,4807.038,N,01131.000,E", &gps) &&
    gps.latitude > 48.0f && gps.longitude > 11.0f, "Test 256.1 - Parse GPS coordinates");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate sentence header and format.
 - Handle missing or invalid fields.
 - Convert coordinates accurately.
 - Test with real NMEA data.
- **Expert Tips:**
 - Explain NMEA: "Parse comma-separated GPS fields."
 - In interviews, clarify: "Ask about specific NMEA sentences."
 - Suggest optimization: "Use state machine for streaming parse."
 - Test edge cases: "Invalid sentence, missing fields."

Problem 257: Handle I2C Bus Errors

Issue Description

Detect and recover from I2C bus errors (e.g., arbitration loss, timeout).

Problem Decomposition & Solution Steps

- **Input:** I2C status register.
- **Output:** Error detection and recovery.
- **Approach:** Mock I2C error check and reset.
- **Algorithm:** I2C Error Handling
 - **Explanation:** Check error flags, reset bus if needed.
- **Steps:**
 1. Read mock I2C status register.
 2. Detect errors (e.g., timeout, arbitration loss).
 3. Reset I2C peripheral if error detected.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The I2C error handling algorithm checks a mock I2C status register for error flags (e.g., timeout, arbitration loss).

If an error is detected, it resets the I2C peripheral to recover the bus.

This is O(1) per check, with O(1) space for status.

Coding Part (with Unit Tests)

```
typedef struct {
    bool timeout;
    bool arbLost;
    bool reset;
} I2CStatus;

// Handle I2C errors
bool handleI2CError(I2CStatus* status) {
    if (status->timeout || status->arbLost) {
        status->reset = true;
        status->timeout = status->arbLost = false;
        return true;
    }
    return false;
}

// Unit tests
void testI2CError() {
    I2CStatus status = {true, false, false};
    assertBoolEquals(true, handleI2CError(&status) && status.reset && !status.timeout, "Test 257.1 - Handle timeout error");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Check all relevant error flags.
 - Reset peripheral on error.
 - Log errors for debugging.
 - Test with simulated errors.
- **Expert Tips:**
 - Explain I2C errors: "Detect and recover from bus issues."
 - In interviews, clarify: "Ask about specific I2C errors."
 - Suggest optimization: "Implement bus clear for stuck SDA."
 - Test edge cases: "Multiple errors, no errors."

Problem 258: Configure a GPIO Interrupt

Issue Description

Configure a GPIO pin for interrupt generation (e.g., rising edge).

Problem Decomposition & Solution Steps

- **Input:** Pin number, trigger type.
- **Output:** Configured GPIO interrupt.
- **Approach:** Mock EXTI setup for GPIO pin.
- **Algorithm:** GPIO Interrupt Configuration
 - **Explanation:** Set pin as input, configure interrupt trigger.

- **Steps:**
 1. Validate pin and trigger.
 2. Configure pin as input.
 3. Set interrupt trigger in EXTI.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The GPIO interrupt configuration algorithm sets a GPIO pin as input and configures a mock EXTI register for the desired trigger (e.g., rising edge).

This enables interrupt generation on pin state changes.

It's O(1) per configuration, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    uint8_t pin;
    bool risingEdge;
    bool inputMode;
} GPIOInterrupt;

// Configure GPIO interrupt
void configureGPIOInterrupt(GPIOInterrupt* gpio, uint8_t pin, bool risingEdge) {
    if (pin >= 16) return;
    gpio->pin = pin;
    gpio->risingEdge = risingEdge;
    gpio->inputMode = true;
}

// Unit tests
void testGPIOInterrupt() {
    GPIOInterrupt gpio = {0};
    configureGPIOInterrupt(&gpio, 5, true);
    assertBoolEquals(true, gpio.inputMode && gpio.risingEdge && gpio.pin == 5, "Test 258.1 - Configure rising edge interrupt");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate pin and trigger.
 - Set pin as input before interrupt.
 - Ensure interrupt is enabled.
 - Test with different triggers.
- **Expert Tips:**
 - Explain GPIO interrupt: "Trigger ISR on pin change."
 - In interviews, clarify: "Ask about trigger type or debouncing."
 - Suggest optimization: "Debounce in software for noisy inputs."
 - Test edge cases: "Invalid pin, multiple triggers."

Problem 259: Manage a Timer's Overflow

Issue Description

Handle timer overflow to maintain accurate timing.

Problem Decomposition & Solution Steps

- **Input:** Timer ticks, overflow count.
- **Output:** Extended timer value.
- **Approach:** Track overflows in interrupt, combine with timer.
- **Algorithm:** Timer Overflow Handling
 - **Explanation:** Increment overflow counter in ISR, combine with timer.
- **Steps:**
 1. Initialize overflow counter.
 2. Increment counter on timer overflow.
 3. Combine overflow and timer for total ticks.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The timer overflow handling algorithm tracks the number of timer overflows in an ISR.

The total time is calculated as (overflows * timer_max + current_timer).

This extends the timer's range beyond its register size.

It's O(1) per operation, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    uint16_t ticks;
    uint32_t overflows;
} Timer;

// Handle timer overflow
void timerOverflowHandler(Timer* timer) {
    timer->overflows++;
}

// Get total ticks
uint64_t getTotalTicks(Timer* timer) {
    return ((uint64_t)timer->overflows << 16) | timer->ticks;
}

// Unit tests
void testTimerOverflow() {
    Timer timer = {0xFFFF, 1};
    timerOverflowHandler(&timer);
    assertEquals((1ULL << 16) | 0xFFFF, getTotalTicks(&timer), "Test 259.1 - Handle overflow");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use volatile for overflow counter.
 - Handle ISR atomically.
 - Combine overflow and ticks accurately.
 - Test with multiple overflows.
- **Expert Tips:**
 - Explain overflow: "Extend timer with overflow counter."
 - In interviews, clarify: "Ask about timer resolution."
 - Suggest optimization: "Use 32-bit timer for longer range."
 - Test edge cases: "No overflow, max overflows."

Problem 260: Handle a UART Timeout

Issue Description

Detect and handle a UART receive timeout.

Problem Decomposition & Solution Steps

- **Input:** UART data stream, timeout period.
- **Output:** Timeout detection and recovery.
- **Approach:** Use timer to detect UART inactivity.
- **Algorithm:** UART Timeout Detection
 - **Explanation:** Start timer on data, trigger timeout if no data.
- **Steps:**
 1. Start timer on UART receive.
 2. Reset timer on new data.
 3. Signal timeout if timer expires.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The UART timeout detection algorithm starts a timer when data is received.

Each new byte resets the timer.

If the timer expires (no data for timeout period), it signals a timeout.

This is O(1) per operation, with O(1) space for timer state.

Coding Part (with Unit Tests)

```
typedef struct {
    bool receiving;
    uint32_t timer;
    bool timeout;
} UARTTimeout;
```

```

// Handle UART receive
void handleUARTReceive(UARTTimeout* uart) {
    uart->receiving = true;
    uart->timer = 0;
}

// Update UART timeout
void updateUARTTimeout(UARTTimeout* uart, uint32_t timeoutTicks) {
    if (uart->receiving) {
        if (++uart->timer >= timeoutTicks) {
            uart->timeout = true;
            uart->receiving = false;
        }
    }
}

// Unit tests
void testUARTTimeout() {
    UARTTimeout uart = {0};
    handleUARTReceive(&uart);
    updateUARTTimeout(&uart, 2);
    updateUARTTimeout(&uart, 2);
    assertBoolEquals(true, uart.timeout, "Test 260.1 - Detect UART timeout");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Reset timer on each byte.
 - Use reasonable timeout period.
 - Clear state on timeout.
 - Test with data and timeouts.
- **Expert Tips:**
 - Explain timeout: "Detect inactivity with timer."
 - In interviews, clarify: "Ask about timeout duration."
 - Suggest optimization: "Use hardware UART timeout feature."
 - Test edge cases: "No data, rapid data."

Problem 261: Read a Rotary Encoder

Issue Description

Read position changes from a rotary encoder.

Problem Decomposition & Solution Steps

- **Input:** Encoder A/B pin states.
- **Output:** Position increment/decrement.
- **Approach:** Detect state transitions to determine direction.
- **Algorithm:** Quadrature Decoding
 - **Explanation:** Use A/B phase changes to track rotation.
- **Steps:**
 1. Read current A/B states.

2. Compare with previous states.
 3. Update position based on transition.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The quadrature decoding algorithm reads the A/B pins of a rotary encoder.

State transitions (e.g., 00->01 vs.

00->10) indicate clockwise or counterclockwise rotation.

The position is incremented or decremented accordingly.

This is O(1) per update, with O(1) space.

Coding Part (with Unit Tests)

```

typedef struct {
    bool a, b;
    int32_t position;
} RotaryEncoder;

// Update encoder
void updateEncoder(RotaryEncoder* enc, bool a, bool b) {
    static const int8_t transitions[4][4] = {
        {0, 1, -1, 0}, {-1, 0, 0, 1}, {1, 0, 0, -1}, {0, -1, 1, 0}
    };
    int oldState = (enc->a << 1) | enc->b;
    int newState = (a << 1) | b;
    enc->position += transitions[oldState][newState];
    enc->a = a;
    enc->b = b;
}

// Unit tests
void testRotaryEncoder() {
    RotaryEncoder enc = {0, 0, 0};
    updateEncoder(&enc, 1, 0); // Clockwise step
    assertEquals(1, enc.position, "Test 261.1 - Clockwise rotation");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use transition table for accuracy.
 - Debounce inputs if needed.
 - Track position atomically.
 - Test with rotation sequences.
- **Expert Tips:**
 - Explain quadrature: "A/B phases determine direction."
 - In interviews, clarify: "Ask about encoder resolution."
 - Suggest optimization: "Use hardware quadrature decoder."
 - Test edge cases: "Rapid rotations, noise."

Problem 262: Manage a Sleep Mode Transition

Issue Description

Manage transitions to/from sleep mode to save power.

Problem Decomposition & Solution Steps

- **Input:** System state, sleep trigger.
- **Output:** Enter/exit sleep mode.
- **Approach:** Save state, enter sleep, restore on wake.
- **Algorithm:** Sleep Mode Transition
 - **Explanation:** Save registers, enter sleep, restore on wake.
- **Steps:**
 1. Save critical state.
 2. Enter sleep mode (mock).
 3. Restore state on wake.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The sleep mode transition algorithm saves critical system state (e.g., registers), enters a mock sleep mode, and restores state on wake.

This minimizes power consumption while preserving functionality.

It's O(1) for fixed state, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    uint32_t savedState;
    bool isSleeping;
} SystemState;

// Enter sleep mode
void enterSleep(SystemState* state) {
    state->savedState = 0x12345678; // Mock save
    state->isSleeping = true;
}

// Exit sleep mode
void exitSleep(SystemState* state) {
    state->isSleeping = false;
    // Mock restore
}

// Unit tests
void testSleepMode() {
    SystemState state = {0};
    enterSleep(&state);
    assertBoolEquals(true, state.isSleeping, "Test 262.1 - Enter sleep mode");
    exitSleep(&state);
    assertBoolEquals(false, state.isSleeping, "Test 262.2 - Exit sleep mode");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Save critical state before sleep.
 - Minimize wake-up latency.
 - Validate transitions.
 - Test sleep/wake cycles.
- **Expert Tips:**
 - Explain sleep mode: "Save state, reduce power, restore."
 - In interviews, clarify: "Ask about specific sleep mode."
 - Suggest optimization: "Disable unused peripherals."
 - Test edge cases: "Interrupted sleep, no state saved."

Problem 263: Handle a Fault Interrupt

Issue Description

Handle a fault interrupt (e.g., hard fault) in an embedded system.

Problem Decomposition & Solution Steps

- **Input:** Fault status register.
- **Output:** Fault handling (e.g., reset or log).
- **Approach:** Mock fault register check and recovery.
- **Algorithm:** Fault Handler
 - **Explanation:** Check fault cause, take recovery action.
- **Steps:**
 1. Read fault status.
 2. Log fault cause (mock).
 3. Reset or recover system.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The fault handler algorithm reads a mock fault status register to identify the cause (e.g., bus fault, memory fault).

It logs the fault (mocked) and initiates recovery (e.g., reset).

This is O(1) per interrupt, with O(1) space for status.

Coding Part (with Unit Tests)

```
typedef struct {
    bool busFault;
    bool reset;
} FaultStatus;
```

```

// Handle fault interrupt
void handleFault(FaultStatus* status) {
    if (status->busFault) {
        status->reset = true; // Mock recovery
        status->busFault = false;
    }
}

// Unit tests
void testFaultHandler() {
    FaultStatus status = {true, false};
    handleFault(&status);
    assertBoolEquals(true, status.reset && !status.busFault, "Test 263.1 - Handle bus fault");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Identify fault cause in ISR.
 - Keep handler minimal.
 - Log faults for debugging.
 - Test with different fault types.
- **Expert Tips:**
 - Explain fault handler: "Diagnose and recover from faults."
 - In interviews, clarify: "Ask about specific fault types."
 - Suggest optimization: "Use fault stack for debugging."
 - Test edge cases: "No fault, multiple faults."

Problem 264: Configure a PWM Duty Cycle

Issue Description

Configure the duty cycle of a PWM signal.

Problem Decomposition & Solution Steps

- **Input:** Duty cycle percentage, PWM period.
- **Output:** Configured PWM signal.
- **Approach:** Update PWM on-time based on duty cycle.
- **Algorithm:** PWM Duty Cycle Configuration
 - **Explanation:** Calculate on-time from duty cycle and period.
- **Steps:**
 1. Validate duty cycle (0-100%).
 2. Calculate on-time ticks.
 3. Update PWM register.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The PWM duty cycle configuration algorithm calculates the on-time ($\text{duty} * \text{period} / 100$) and updates the PWM register.

This adjusts the PWM signal's high duration.

It's O(1) per update, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    uint32_t periodTicks;
    uint32_t onTicks;
} PWMRegister;

// Configure PWM duty cycle
void configurePWMDuty(PWMRegister* pwm, uint8_t dutyPercent) {
    if (dutyPercent > 100) return;
    pwm->onTicks = (pwm->periodTicks * dutyPercent) / 100;
}

// Unit tests
void testPWMDuty() {
    PWMRegister pwm = {1000, 0};
    configurePWMDuty(&pwm, 50);
    assertEquals(500, pwm.onTicks, "Test 264.1 - Set 50% duty cycle");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate duty cycle range.
 - Ensure precise calculations.
 - Update PWM atomically.
 - Test with various duty cycles.
- **Expert Tips:**
 - Explain PWM: "Adjust on-time for duty cycle."
 - In interviews, clarify: "Ask about PWM frequency."
 - Suggest optimization: "Use hardware PWM registers."
 - Test edge cases: "0% or 100% duty, invalid duty."

Problem 265: Read from an EEPROM

Issue Description

Read data from an EEPROM via I2C.

Problem Decomposition & Solution Steps

- **Input:** EEPROM address, data length.
- **Output:** Data read from EEPROM.
- **Approach:** Mock I2C read from EEPROM.
- **Algorithm:** EEPROM Read
 - **Explanation:** Send address, read data via I2C.
- **Steps:**
 1. Validate address and length.
 2. Send EEPROM address over I2C.

- 3. Read data into buffer.
- **Complexity:** Time O(n), Space O(n) for n bytes.

Algorithm Explanation

The EEPROM read algorithm sends the memory address to the EEPROM via I2C, then reads the specified number of bytes.

It validates inputs to ensure safe access.

This is O(n) for n bytes, with O(n) space for the data buffer.

Coding Part (with Unit Tests)

```
bool readEEPROM(uint8_t deviceAddr, uint16_t memAddr, uint8_t* data, size_t len) {
    if (!data || len == 0) return false;
    return readI2CDevice(deviceAddr, memAddr, data, len); // Reuse from Problem 230
}

// Unit tests
void testEEPROMRead() {
    uint8_t data[3];
    assertBoolEquals(true, readEEPROM(0x50, 0x10, data, 3) && data[0] == 1, "Test 265.1 - Read EEPROM data");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate address and length.
 - Handle I2C errors.
 - Respect EEPROM page boundaries.
 - Test with different addresses.
- **Expert Tips:**
 - Explain EEPROM read: "I2C read with memory address."
 - In interviews, clarify: "Ask about EEPROM size or I2C speed."
 - Suggest optimization: "Use page reads for efficiency."
 - Test edge cases: "Invalid address, large reads."

Problem 266: Handle a Real-Time Clock (RTC)

Issue Description

Read and set time on a real-time clock (RTC).

Problem Decomposition & Solution Steps

- **Input:** RTC register, time to set.
- **Output:** Current time or successful set.
- **Approach:** Mock RTC read/write operations.

- **Algorithm:** RTC Handling
 - **Explanation:** Read/write time fields in RTC register.
- **Steps:**
 1. Validate time format.
 2. Read/write RTC registers (mock).
 3. Return current time or set success.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The RTC handling algorithm reads or writes time fields (hours, minutes, seconds) in a mock RTC register.

It validates the time format for correctness.

This is O(1) for fixed fields, with O(1) space for time data.

Coding Part (with Unit Tests)

```

typedef struct {
    uint8_t hours, minutes, seconds;
} RTC;

// Set RTC time
bool setRTCTime(RTC* rtc, uint8_t hours, uint8_t minutes, uint8_t seconds) {
    if (hours > 23 || minutes > 59 || seconds > 59) return false;
    rtc->hours = hours;
    rtc->minutes = minutes;
    rtc->seconds = seconds;
    return true;
}

// Read RTC time
void readRTCTime(RTC* rtc, uint8_t* hours, uint8_t* minutes, uint8_t* seconds) {
    *hours = rtc->hours;
    *minutes = rtc->minutes;
    *seconds = rtc->seconds;
}

// Unit tests
void testRTC() {
    RTC rtc;
    setRTCTime(&rtc, 12, 30, 45);
    uint8_t h, m, s;
    readRTCTime(&rtc, &h, &m, &s);
    assertBoolEquals(true, h == 12 && m == 30 && s == 45, "Test 266.1 - Set and read RTC time");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate time fields.
 - Use atomic RTC access.
 - Handle RTC interrupts if needed.
 - Test with valid/invalid times.
- **Expert Tips:**
 - Explain RTC: "Track time with dedicated hardware."

- In interviews, clarify: "Ask about RTC format or backup battery."
- Suggest optimization: "Use hardware RTC for accuracy."
- Test edge cases: "Invalid time, midnight rollover."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for embedded systems problems 251 to 266:\n");
    testReadFlash();
    testPOST();
    testEncodeUART();
    testPeripheralPower();
    testSPISlave();
    testNMEASentence();
    testI2CError();
    testGPIOInterrupt();
    testTimerOverflow();
    testUARTTimeout();
    testRotaryEncoder();
    testSleepMode();
    testFaultHandler();
    testPWMDuty();
    testEEPROMRead();
    testRTC();
    return 0;
}
```

Problem 267: Manage a Sensor's Calibration

Issue Description

Store and apply calibration parameters for a sensor to convert raw data to physical units.

Problem Decomposition & Solution Steps

- **Input:** Raw sensor value, calibration data (slope, offset).
- **Output:** Calibrated sensor value.
- **Approach:** Store calibration in struct, apply linear transformation.
- **Algorithm:** Sensor Calibration Management
 - **Explanation:** Save calibration parameters, apply to raw data.
- **Steps:**
 1. Initialize calibration struct with slope and offset.
 2. Validate raw value and calibration.
 3. Apply linear formula: $\text{value} = \text{raw} * \text{slope} + \text{offset}$.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The sensor calibration management algorithm stores calibration parameters (slope, offset) in a struct.

It applies a linear transformation to raw sensor data (e.g., ADC value) to produce a physical unit (e.g., temperature).

This is O(1) per operation, with O(1) space for parameters.

Coding Part (with Unit Tests)

```
#include <stdint.h>
#include <stdbool.h>
#include <stdio.h>
#include <math.h>

typedef struct SensorCalibration {
    float slope;
    float offset;
    bool valid;
} SensorCalibration;

// Initialize calibration
void initSensorCalibration(SensorCalibration* cal, float slope, float offset) {
    cal->slope = slope;
    cal->offset = offset;
    cal->valid = true;
}

// Apply calibration
float applySensorCalibration(SensorCalibration* cal, uint16_t raw) {
    if (!cal->valid || raw > 1023) return 0.0f; // 10-bit ADC
    return raw * cal->slope + cal->offset;
}

// Unit test helper
void assertFloatEquals(float expected, float actual, float epsilon, const char* testName) {
    printf("%s: %s\n", testName, (fabs(expected - actual) <= epsilon) ? "PASSED" : "FAILED");
}

// Unit tests
void testSensorCalibration() {
    SensorCalibration cal;
    initSensorCalibration(&cal, 0.1f, -50.0f); // Maps 0-1023 to -50 to ~52°C
    float value = applySensorCalibration(&cal, 500);
    assertFloatEquals(0.0f, value, 0.01f, "Test 267.1 - Calibrate 500 to 0°C");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate calibration parameters.
 - Store parameters in non-volatile memory (e.g., EEPROM).
 - Handle invalid raw values.
 - Test with known calibration points.
- **Expert Tips:**
 - Explain calibration: "Linear transformation for sensor data."
 - In interviews, clarify: "Ask about sensor type or calibration method."
 - Suggest optimization: "Use fixed-point for low-end MCUs."
 - Test edge cases: "Invalid calibration, max/min raw values."

Problem 268: Handle a Multi-Channel ADC Interrupt

Issue Description

Handle an ADC interrupt for multiple channels, storing results.

Problem Decomposition & Solution Steps

- **Input:** ADC interrupt, channel data.
- **Output:** Stored ADC values for each channel.
- **Approach:** Mock ADC interrupt, store results in buffer.
- **Algorithm:** Multi-Channel ADC Interrupt Handler
 - **Explanation:** Process interrupt, store channel data.
- **Steps:**
 1. Validate channel and data.
 2. Read ADC value in ISR.
 3. Store in channel-specific buffer.
 4. Clear interrupt flag.
- **Complexity:** Time O(1), Space O(n) for n channels.

Algorithm Explanation

The multi-channel ADC interrupt handler processes an ADC conversion complete interrupt, reads the value, and stores it in a channel-specific buffer. It clears the interrupt flag to allow further conversions.

This is O(1) per interrupt, with O(n) space for n channels.

Coding Part (with Unit Tests)

```
#define MAX_ADC_CHANNELS 4

typedef struct {
    uint16_t values[MAX_ADC_CHANNELS];
    uint8_t currentChannel;
} ADCController;

// Mock ADC read
uint16_t mockADCRead(uint8_t channel) {
    return 512 + channel; // Simulate different values per channel
}

// ADC interrupt handler
void adcInterruptHandler(ADCController* adc) {
    if (adc->currentChannel < MAX_ADC_CHANNELS) {
        adc->values[adc->currentChannel] = mockADCRead(adc->currentChannel);
        adc->currentChannel = (adc->currentChannel + 1) % MAX_ADC_CHANNELS;
    }
}

// Unit tests
void testADCInterrupt() {
    ADCController adc = {0};
    adc.currentChannel = 0;
    adcInterruptHandler(&adc);
    assertEquals(512, adc.values[0], "Test 268.1 - ADC channel 0 value");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate channel index.
 - Keep ISR short and atomic.
 - Use DMA for efficiency (mocked here).
 - Test with multiple channels.
- **Expert Tips:**
 - Explain ADC ISR: "Store channel data on conversion."
 - In interviews, clarify: "Ask about ADC scan mode."
 - Suggest optimization: "Use DMA for multi-channel reads."
 - Test edge cases: "Invalid channel, rapid interrupts."

Problem 269: Encode Data for SPI Transmission

Issue Description

Encode data with a header for SPI transmission.

Problem Decomposition & Solution Steps

- **Input:** Data buffer, length.
- **Output:** Encoded SPI packet.
- **Approach:** Add header (e.g., command byte), copy data.
- **Algorithm:** SPI Packet Encoding
 - **Explanation:** Create packet with command header and data.
- **Steps:**
 1. Validate data and length.
 2. Add command byte to packet.
 3. Copy data to packet.
- **Complexity:** Time $O(n)$, Space $O(n)$ for n data bytes.

Algorithm Explanation

The SPI packet encoding algorithm adds a command byte (e.g., 0x01 for write) to the data buffer, creating a packet for SPI transmission.

It validates inputs to ensure reliable transfer.

This is $O(n)$ for n data bytes, with $O(n)$ space for the packet.

Coding Part (with Unit Tests)

```
#define SPI_HEADER 0x01

bool encodeSPIPacket(const uint8_t* data, size_t len, uint8_t* packet, size_t* packetLen) {
    if (!data || !packet || len > 255) return false;
    packet[0] = SPI_HEADER;
    for (size_t i = 0; i < len; i++) {
        packet[i + 1] = data[i];
    }
    *packetLen = len + 1;
    return true;
}

// Unit tests
void testEncodeSPI() {
    uint8_t data[] = {0x02, 0x03};
    uint8_t packet[3];
    size_t packetLen;
    assertBoolEquals(true, encodeSPIPacket(data, 2, packet, &packetLen) && packet[0] == 0x01 &&
    packet[1] == 0x02, "Test 269.1 - Encode SPI packet");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate data length.
 - Use consistent header format.
 - Handle chip select separately.
 - Test with various data sizes.
- **Expert Tips:**
 - Explain SPI encoding: "Add header for master-slave communication."
 - In interviews, clarify: "Ask about SPI protocol or command set."
 - Suggest optimization: "Use DMA for large SPI transfers."
 - Test edge cases: "Empty data, max length."

Problem 270: Manage a Peripheral's Clock Gating

Issue Description

Enable or disable a peripheral's clock to save power.

Problem Decomposition & Solution Steps

- **Input:** Peripheral ID, clock enable/disable.
- **Output:** Configured clock state.
- **Approach:** Mock clock gating register.
- **Algorithm:** Clock Gating Control
 - **Explanation:** Set/clear clock enable bit for peripheral.
- **Steps:**
 1. Validate peripheral ID.
 2. Set or clear clock bit in register.

- 3. Confirm state change.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The clock gating control algorithm sets or clears a bit in a mock clock control register to enable/disable a peripheral's clock.

This reduces power consumption when the peripheral is idle.

It's O(1) per operation, with O(1) space.

Coding Part (with Unit Tests)

```

typedef struct {
    uint32_t clockBits;
} ClockGate;

// Manage peripheral clock
void setPeripheralClock(ClockGate* clk, uint8_t peripheral, bool enable) {
    if (peripheral >= 32) return;
    if (enable) {
        clk->clockBits |= (1U << peripheral);
    } else {
        clk->clockBits &= ~(1U << peripheral);
    }
}

// Unit tests
void testPeripheralClock() {
    ClockGate clk = {0};
    setPeripheralClock(&clk, 3, true);
    assertEquals(1U << 3, clk.clockBits, "Test 270.1 - Enable peripheral clock");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate peripheral ID.
 - Ensure atomic bit operations.
 - Disable unused clocks.
 - Test with multiple peripherals.
- **Expert Tips:**
 - Explain clock gating: "Control peripheral clock for power savings."
 - In interviews, clarify: "Ask about clock tree or peripheral."
 - Suggest optimization: "Combine with power control."
 - Test edge cases: "Invalid peripheral, rapid toggles."

Problem 271: Handle a UART Buffer Overflow

Issue Description

Detect and handle a UART receive buffer overflow.

Problem Decomposition & Solution Steps

- **Input:** UART receive buffer, data input.
- **Output:** Overflow detection and recovery.
- **Approach:** Monitor buffer, discard or flag on overflow.
- **Algorithm:** UART Buffer Overflow Handler
 - **Explanation:** Check buffer capacity, handle overflow condition.
- **Steps:**
 1. Check buffer count.
 2. If full, flag overflow and discard new data.
 3. Otherwise, add data to buffer.
- **Complexity:** Time O(1), Space O(n) for n-byte buffer.

Algorithm Explanation

The UART buffer overflow handler checks if the receive buffer is full before adding new data.

On overflow, it sets a flag and discards the data (or could reset the buffer).

This is O(1) per operation, with O(n) space for the buffer.

Coding Part (with Unit Tests)

```
#define UART_BUFFER_SIZE 8

typedef struct {
    uint8_t data[UART_BUFFER_SIZE];
    uint8_t count;
    bool overflow;
} UARTBuffer;

// Add data to UART buffer
bool addUARTData(UARTBuffer* buf, uint8_t data) {
    if (buf->count >= UART_BUFFER_SIZE) {
        buf->overflow = true;
        return false;
    }
    buf->data[buf->count++] = data;
    return true;
}

// Unit tests
void testUARTOverflow() {
    UARTBuffer buf = {0};
    for (int i = 0; i < UART_BUFFER_SIZE; i++) addUARTData(&buf, i);
    assertBoolEquals(false, addUARTData(&buf, 99) && buf.overflow, "Test 271.1 - Detect UART overflow");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Monitor buffer capacity.
 - Flag overflow for recovery.
 - Clear buffer if needed.
 - Test with full buffer.
- **Expert Tips:**
 - Explain overflow: "Discard data when buffer is full."
 - In interviews, clarify: "Ask about recovery strategy."
 - Suggest optimization: "Use DMA to avoid overflows."
 - Test edge cases: "Rapid data, empty buffer."

Problem 272: Configure an SPI Master Mode

Issue Description

Configure an SPI peripheral in master mode.

Problem Decomposition & Solution Steps

- **Input:** Clock frequency, mode (e.g., CPOL/CPHA).
- **Output:** Configured SPI master.
- **Approach:** Mock SPI register setup.
- **Algorithm:** SPI Master Configuration
 - **Explanation:** Set clock, mode, and enable SPI.
- **Steps:**
 1. Validate clock and mode.
 2. Configure SPI control register.
 3. Enable SPI master.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The SPI master configuration algorithm sets up a mock SPI control register with the desired clock frequency and mode (e.g., CPOL=0, CPHA=0).

It enables the SPI peripheral in master mode.

This is O(1) per configuration, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    uint32_t clock;
    uint8_t mode;
    bool master;
} SPIControl;
```

```

// Configure SPI master
bool configureSPIMaster(SPIControl* spi, uint32_t clock, uint8_t mode) {
    if (clock == 0 || mode > 3) return false;
    spi->clock = clock;
    spi->mode = mode;
    spi->master = true;
    return true;
}

// Unit tests
void testSPIMaster() {
    SPIControl spi = {0};
    assertBoolEquals(true, configureSPIMaster(&spi, 1000000, 0) && spi.master && spi.clock == 1000000,
    "Test 272.1 - Configure SPI master");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate clock and mode.
 - Set chip select separately.
 - Ensure stable clock.
 - Test with different modes.
- **Expert Tips:**
 - Explain SPI master: "Control clock and data transfer."
 - In interviews, clarify: "Ask about SPI mode or clock divider."
 - Suggest optimization: "Use hardware SPI for speed."
 - Test edge cases: "Invalid mode, zero clock."

Problem 273: Read a Pressure Sensor via I2C

Issue Description

Read pressure data from an I2C pressure sensor with calibration.

Problem Decomposition & Solution Steps

- **Input:** I2C device address, register, calibration.
- **Output:** Calibrated pressure value.
- **Approach:** Mock I2C read, apply calibration.
- **Algorithm:** Pressure Sensor Read
 - **Explanation:** Read raw data via I2C, convert to pressure.
- **Steps:**
 1. Read raw data from sensor.
 2. Validate data and calibration.
 3. Apply calibration to get pressure.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The pressure sensor read algorithm uses I2C to read raw data from a sensor register, then applies a linear calibration (pressure = raw * slope + offset) to convert to physical units (e.g., kPa).

This is O(1) per read, with O(1) space.

Coding Part (with Unit Tests)

```
float readPressureSensor(uint8_t deviceAddr, uint8_t regAddr, SensorCalibration* cal) {
    uint8_t data[2];
    if (!readI2CDevice(deviceAddr, regAddr, data, 2)) return 0.0f;
    uint16_t raw = (data[0] << 8) | data[1];
    return applySensorCalibration(cal, raw);
}

// Unit tests
void testPressureSensor() {
    SensorCalibration cal = {0.01f, 0.0f}; // Maps 0-65535 to 0-655.35 kPa
    float pressure = readPressureSensor(0x50, 0x10, &cal);
    assertFloatEquals(0.01f * (1 << 8), pressure, 0.01f, "Test 273.1 - Read pressure");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate I2C read and calibration.
 - Use sensor-specific register addresses.
 - Handle communication errors.
 - Test with known pressures.
- **Expert Tips:**
 - Explain pressure read: "I2C read with calibration."
 - In interviews, clarify: "Ask about sensor model or units."
 - Suggest optimization: "Use burst read for multiple registers."
 - Test edge cases: "Invalid address, failed I2C."

Problem 274: Handle a Timer Capture Interrupt

Issue Description

Handle a timer capture interrupt to measure input signal timing.

Problem Decomposition & Solution Steps

- **Input:** Timer capture event.
- **Output:** Captured time value.
- **Approach:** Mock timer capture, store value in ISR.
- **Algorithm:** Timer Capture Handler
 - **Explanation:** Read capture register, store time.
- **Steps:**
 1. Validate capture event.
 2. Read timer capture value.

- 3. Store in buffer and clear flag.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The timer capture handler reads the timer's capture register when an input signal triggers an interrupt (e.g., rising edge).

It stores the captured time and clears the interrupt flag.

This is O(1) per interrupt, with O(1) space for the captured value.

Coding Part (with Unit Tests)

```

typedef struct {
    uint32_t capturedValue;
    bool captureFlag;
} TimerCapture;

// Mock timer capture
uint32_t mockTimerCapture() { return 1000; }

// Timer capture interrupt handler
void timerCaptureHandler(TimerCapture* timer) {
    if (timer->captureFlag) {
        timer->capturedValue = mockTimerCapture();
        timer->captureFlag = false;
    }
}

// Unit tests
void testTimerCapture() {
    TimerCapture timer = {0, true};
    timerCaptureHandler(&timer);
    assertEquals(1000, timer.capturedValue, "Test 274.1 - Capture timer value");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Clear capture flag in ISR.
 - Store values atomically.
 - Validate capture event.
 - Test with signal inputs.
- **Expert Tips:**
 - Explain capture: "Measure signal timing with timer."
 - In interviews, clarify: "Ask about capture edge or timer resolution."
 - Suggest optimization: "Use DMA for capture data."
 - Test edge cases: "No capture, rapid events."

Problem 275: Manage a Peripheral's Interrupt Priority

Issue Description

Configure interrupt priority for a peripheral (e.g., UART, timer).

Problem Decomposition & Solution Steps

- **Input:** Peripheral IRQ, priority level.
- **Output:** Configured interrupt priority.
- **Approach:** Mock NVIC setup for peripheral.
- **Algorithm:** Interrupt Priority Management
 - **Explanation:** Set priority in NVIC register.
- **Steps:**
 1. Validate IRQ and priority.
 2. Set priority in mock NVIC.
 3. Enable interrupt.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The interrupt priority management algorithm sets a priority level for a peripheral's IRQ in a mock NVIC register.

Lower values indicate higher priority.

This ensures proper interrupt handling order.

It's O(1) per configuration, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    uint8_t priorities[16];
} NVIC;

// Set peripheral interrupt priority
void setPeripheralPriority(NVIC* nvic, uint8_t irq, uint8_t priority) {
    if (irq >= 16 || priority > 7) return; // 3-bit priority
    nvic->priorities[irq] = priority;
}

// Unit tests
void testPeripheralPriority() {
    NVIC nvic = {{0}};
    setPeripheralPriority(&nvic, 4, 2);
    assertEquals(2, nvic.priorities[4], "Test 275.1 - Set IRQ4 priority to 2");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate IRQ and priority.
 - Use low priorities for non-critical interrupts.

- Ensure atomic updates.
- Test with multiple IRQs.
- **Expert Tips:**
 - Explain priority: "Lower value = higher priority."
 - In interviews, clarify: "Ask about MCU-specific NVIC."
 - Suggest optimization: "Group similar priorities."
 - Test edge cases: "Invalid IRQ, max priority."

Problem 276: Parse a Modbus Packet

Issue Description

Parse a Modbus RTU packet for function code and data.

Problem Decomposition & Solution Steps

- **Input:** Modbus packet buffer.
- **Output:** Parsed function code and data.
- **Approach:** Validate packet, extract fields.
- **Algorithm:** Modbus Packet Parsing
 - **Explanation:** Check address, function code, CRC, extract data.
- **Steps:**
 1. Validate slave address and CRC.
 2. Extract function code and data.
 3. Return parsed packet.
- **Complexity:** Time $O(n)$, Space $O(n)$ for n data bytes.

Algorithm Explanation

The Modbus packet parsing algorithm validates a Modbus RTU packet (slave address, function code, data, CRC).

It extracts the function code and data if the CRC is valid.

This is $O(n)$ for n bytes, with $O(n)$ space for the parsed data.

Coding Part (with Unit Tests)

```
typedef struct {
    uint8_t slaveAddr;
    uint8_t funcCode;
    uint8_t data[8];
    uint8_t dataLen;
} ModbusPacket;

// Mock Modbus buffer
uint8_t mockModbusBuffer[] = {0x01, 0x03, 0x00, 0x02, 0xC4, 0x0B}; // Addr, func, data, CRC
int mockModbusIndex = 0;

uint8_t readModbusByte() { return mockModbusBuffer[mockModbusIndex++]; }
```

```

// Parse Modbus packet
bool parseModbusPacket(ModbusPacket* packet) {
    packet->slaveAddr = readModbusByte();
    packet->funcCode = readModbusByte();
    packet->dataLen = 2; // Mock fixed length
    for (uint8_t i = 0; i < packet->dataLen; i++) {
        packet->data[i] = readModbusByte();
    }
    uint16_t crc = (readModbusByte() << 8) | readModbusByte();
    return true; // Mock CRC check
}

// Unit tests
void testModbusPacket() {
    mockModbusIndex = 0;
    ModbusPacket packet;
    assertBoolEquals(true, parseModbusPacket(&packet) && packet.slaveAddr == 0x01 && packet.funcCode == 0x03, "Test 276.1 - Parse Modbus packet");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate address and CRC.
 - Handle variable data length.
 - Check packet format.
 - Test with valid/invalid packets.
- **Expert Tips:**
 - Explain Modbus: "Parse RTU packet for address and data."
 - In interviews, clarify: "Ask about Modbus RTU or ASCII."
 - Suggest optimization: "Use hardware CRC for validation."
 - Test edge cases: "Invalid CRC, wrong address."

Problem 277: Handle a Power Failure Interrupt

Issue Description

Handle a power failure interrupt to save critical data.

Problem Decomposition & Solution Steps

- **Input:** Power failure interrupt.
- **Output:** Save critical state.
- **Approach:** Mock power failure ISR, save state.
- **Algorithm:** Power Failure Handler
 - **Explanation:** Detect power failure, save state to non-volatile memory.
- **Steps:**
 1. Detect power failure interrupt.
 2. Save critical data (mock).
 3. Clear interrupt flag.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The power failure handler detects a power failure interrupt, saves critical system state (e.g., registers) to a mock non-volatile memory, and clears the interrupt flag.

This ensures data preservation during power loss.

It's O(1) per interrupt, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    bool powerFailure;
    uint32_t savedState;
} PowerFailure;

// Power failure interrupt handler
void powerFailureHandler(PowerFailure* pwr) {
    if (pwr->powerFailure) {
        pwr->savedState = 0xDEADBEEF; // Mock save
        pwr->powerFailure = false;
    }
}

// Unit tests
void testPowerFailure() {
    PowerFailure pwr = {true, 0};
    powerFailureHandler(&pwr);
    assertEquals(0xDEADBEEF, pwr.savedState, "Test 277.1 - Save state on power failure");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Save minimal critical data.
 - Keep ISR short.
 - Clear interrupt flag.
 - Test with simulated failures.
- **Expert Tips:**
 - Explain power failure: "Save state on low voltage."
 - In interviews, clarify: "Ask about critical data or storage."
 - Suggest optimization: "Use backup SRAM or EEPROM."
 - Test edge cases: "No failure, rapid interrupts."

Problem 278: Configure a GPIO Pin as Input/Output

Issue Description

Configure a GPIO pin as input or output.

Problem Decomposition & Solution Steps

- **Input:** Pin number, mode (input/output).
- **Output:** Configured GPIO pin.

- **Approach:** Mock GPIO mode register setup.
- **Algorithm:** GPIO Mode Configuration
 - **Explanation:** Set pin mode in register.
- **Steps:**
 1. Validate pin and mode.
 2. Set mode bit in GPIO register.
 3. Confirm configuration.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The GPIO mode configuration algorithm sets a pin as input or output in a mock GPIO mode register.

This controls whether the pin drives a signal (output) or reads one (input).

It's O(1) per configuration, with O(1) space.

Coding Part (with Unit Tests)

```

typedef struct {
    uint32_t modeBits; // 1=output, 0=input
} GPIORegister;

// Configure GPIO pin
void configureGPIOPin(GPIORegister* gpio, uint8_t pin, bool isOutput) {
    if (pin >= 32) return;
    if (isOutput) {
        gpio->modeBits |= (1U << pin);
    } else {
        gpio->modeBits &= ~(1U << pin);
    }
}

// Unit tests
void testGPIOPinConfig() {
    GPIORegister gpio = {0};
    configureGPIOPin(&gpio, 5, true);
    assertEquals(1U << 5, gpio.modeBits, "Test 278.1 - Configure pin as output");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate pin number.
 - Set mode before use.
 - Ensure atomic updates.
 - Test with input/output modes.
- **Expert Tips:**
 - Explain GPIO config: "Set pin as input or output."
 - In interviews, clarify: "Ask about pull-up/down resistors."
 - Suggest optimization: "Use hardware-specific registers."
 - Test edge cases: "Invalid pin, mode switch."

Problem 279: Handle a CAN Bus Timeout

Issue Description

Detect and handle a CAN bus timeout during transmission.

Problem Decomposition & Solution Steps

- **Input:** CAN bus status, timeout period.
- **Output:** Timeout detection and recovery.
- **Approach:** Monitor CAN transmission, reset on timeout.
- **Algorithm:** CAN Timeout Handler
 - **Explanation:** Check transmission status, reset if timed out.
- **Steps:**
 1. Start timer on CAN transmit.
 2. Check for completion or timeout.
 3. Reset CAN peripheral on timeout.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The CAN timeout handler starts a timer when a CAN transmission begins.

If the transmission doesn't complete within the timeout period, it resets the CAN peripheral.

This is O(1) per check, with O(1) space for status.

Coding Part (with Unit Tests)

```
typedef struct {
    bool transmitting;
    uint32_t timer;
    bool timeout;
} CANBus;

// Start CAN transmission
void startCANTransmit(CANBus* can) {
    can->transmitting = true;
    can->timer = 0;
}

// Handle CAN timeout
void handleCANTimeout(CANBus* can, uint32_t timeoutTicks) {
    if (can->transmitting && ++can->timer >= timeoutTicks) {
        can->timeout = true;
        can->transmitting = false;
    }
}

// Unit tests
void testCANTimeout() {
    CANBus can = {0};
    startCANTransmit(&can);
    handleCANTimeout(&can, 1);
    assertBoolEquals(true, can.timeout, "Test 279.1 - Detect CAN timeout");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Reset timer on transmit start.
 - Clear state on timeout.
 - Use reasonable timeout period.
 - Test with active transmissions.
- **Expert Tips:**
 - Explain CAN timeout: "Reset on stalled transmission."
 - In interviews, clarify: "Ask about timeout duration or CAN bitrate."
 - Suggest optimization: "Use hardware CAN timeout."
 - Test edge cases: "No timeout, rapid transmits."

Problem 280: Read from a Temperature Sensor via SPI

Issue Description

Read temperature data from an SPI temperature sensor with calibration.

Problem Decomposition & Solution Steps

- **Input:** SPI device, calibration parameters.
- **Output:** Calibrated temperature value.
- **Approach:** Mock SPI read, apply calibration.
- **Algorithm:** SPI Temperature Read
 - **Explanation:** Read raw data via SPI, convert to temperature.
- **Steps:**
 1. Send read command via SPI.
 2. Read raw temperature data.
 3. Apply calibration.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The SPI temperature read algorithm sends a read command to the sensor via SPI, retrieves raw data, and applies a linear calibration to convert to temperature (e.g., °C).

This is O(1) for fixed-size reads, with O(1) space.

Coding Part (with Unit Tests)

```
float readSPITemperature(SPIControl* spi, SensorCalibration* cal) {  
    uint8_t data[] = {0x01}; // Read command  
    uint8_t response[2];  
    writeSPIDevice(data, 1); // Reuse from Problem 231  
    readI2CDevice(0x50, 0x10, response, 2); // Mock SPI read  
    uint16_t raw = (response[0] << 8) | response[1];  
    return applySensorCalibration(cal, raw);  
}
```

```

// Unit tests
void testSPITemperature() {
    SPIControl spi = {0};
    SensorCalibration cal = {0.05f, -40.0f};
    float temp = readSPITemperature(&spi, &cal);
    assertFloatEquals(0.0f, temp, 0.01f, "Test 280.1 - Read temperature");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate SPI communication.
 - Use sensor-specific commands.
 - Apply accurate calibration.
 - Test with known temperatures.
- **Expert Tips:**
 - Explain SPI read: "Send command, read and calibrate data."
 - In interviews, clarify: "Ask about sensor model or SPI mode."
 - Suggest optimization: "Use burst read for efficiency."
 - Test edge cases: "Failed SPI, invalid data."

Problem 281: Manage a Low-Power Sleep Mode

Issue Description

Manage transitions to/from low-power sleep mode.

Problem Decomposition & Solution Steps

- **Input:** System state, sleep trigger.
- **Output:** Enter/exit sleep mode.
- **Approach:** Save state, enter sleep, restore on wake.
- **Algorithm:** Low-Power Sleep Transition
 - **Explanation:** Save registers, enter sleep, restore state.
- **Steps:**
 1. Save critical state.
 2. Enter sleep mode (mock).
 3. Restore state on wake.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The low-power sleep transition algorithm saves critical system state, enters a mock sleep mode to reduce power, and restores state on wake.

This is O(1) for fixed state, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    uint32_t savedState;
    bool isSleeping;
} SystemState;

// Enter low-power sleep
void enterLowPowerSleep(SystemState* state) {
    state->savedState = 0x12345678; // Mock save
    state->isSleeping = true;
}

// Exit low-power sleep
void exitLowPowerSleep(SystemState* state) {
    state->isSleeping = false;
    // Mock restore
}

// Unit tests
void testLowPowerSleep() {
    SystemState state = {0};
    enterLowPowerSleep(&state);
    assertBoolEquals(true, state.isSleeping, "Test 281.1 - Enter sleep mode");
    exitLowPowerSleep(&state);
    assertBoolEquals(false, state.isSleeping, "Test 281.2 - Exit sleep mode");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Save minimal state.
 - Minimize wake-up latency.
 - Validate transitions.
 - Test sleep/wake cycles.
- **Expert Tips:**
 - Explain sleep mode: "Reduce power, preserve state."
 - In interviews, clarify: "Ask about sleep mode specifics."
 - Suggest optimization: "Disable clocks and peripherals."
 - Test edge cases: "Interrupted sleep, no state saved."

Problem 282: Handle a UART Parity Error

Issue Description

Detect and handle a UART parity error during reception.

Problem Decomposition & Solution Steps

- **Input:** UART status register.
- **Output:** Error detection and recovery.
- **Approach:** Check parity error flag, discard bad data.
- **Algorithm:** UART Parity Error Handler

- **Explanation:** Detect parity error, clear flag, discard data.
- **Steps:**
 1. Check UART status for parity error.
 2. Discard corrupted data.
 3. Clear error flag.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The UART parity error handler checks the UART status register for a parity error.

If detected, it discards the received data and clears the error flag to resume reception.

This is O(1) per interrupt, with O(1) space.

Coding Part (with Unit Tests)

```

typedef struct {
    bool parityError;
    uint8_t data;
} UARTStatus;

// Handle UART parity error
bool handleUARTParityError(UARTStatus* uart) {
    if (uart->parityError) {
        uart->data = 0; // Discard data
        uart->parityError = false;
        return true;
    }
    return false;
}

// Unit tests
void testUARTParityError() {
    UARTStatus uart = {true, 0xFF};
    assertBoolEquals(true, handleUARTParityError(&uart) && uart.data == 0 && !uart.parityError, "Test 282.1 - Handle parity error");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Check parity error flag.
 - Discard corrupted data.
 - Clear flag to resume.
 - Test with error conditions.
- **Expert Tips:**
 - Explain parity error: "Detect invalid data via parity bit."
 - In interviews, clarify: "Ask about parity type (odd/even)."
 - Suggest optimization: "Use hardware parity checking."
 - Test edge cases: "No error, multiple errors."

Problem 283: Configure a Watchdog Timer

Issue Description

Configure a watchdog timer to reset the system on timeout.

Problem Decomposition & Solution Steps

- **Input:** Timeout period.
- **Output:** Configured watchdog timer.
- **Approach:** Mock watchdog register setup.
- **Algorithm:** Watchdog Configuration
 - **Explanation:** Set timeout in watchdog register, enable.
- **Steps:**
 1. Validate timeout period.
 2. Configure watchdog register.
 3. Enable watchdog.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The watchdog configuration algorithm sets a timeout period in a mock watchdog register and enables the timer.

If the watchdog isn't reset before timeout, it triggers a system reset.

This is O(1) per configuration, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    uint32_t timeout;
    bool enabled;
} WatchdogRegister;

// Configure watchdog
bool configureWatchdog(WatchdogRegister* wdt, uint32_t timeoutMs) {
    if (timeoutMs == 0) return false;
    wdt->timeout = timeoutMs;
    wdt->enabled = true;
    return true;
}

// Unit tests
void testWatchdogConfig() {
    WatchdogRegister wdt = {0};
    assertBoolEquals(true, configureWatchdog(&wdt, 1000) && wdt.enabled && wdt.timeout == 1000, "Test 283.1 - Configure watchdog");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate timeout period.
 - Enable watchdog after setup.

- Reset periodically in main loop.
- Test with different timeouts.
- **Expert Tips:**
 - Explain watchdog: "Reset system on timeout."
 - In interviews, clarify: "Ask about watchdog constraints."
 - Suggest optimization: "Use windowed watchdog for safety."
 - Test edge cases: "Zero timeout, disabled watchdog."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for embedded systems problems 267 to 283:\n");
    testSensorCalibration();
    testADCInterrupt();
    testEncodeSPI();
    testPeripheralClock();
    testUARTOverflow();
    testSPIMaster();
    testPressureSensor();
    testTimerCapture();
    testPeripheralPriority();
    testModbusPacket();
    testPowerFailure();
    testGPIOPinConfig();
    testCANTimeout();
    testSPITemperature();
    testLowPowerSleep();
    testUARTParityError();
    testWatchdogConfig();
    return 0;
}
```

Problem 284: Handle a Multi-Channel DMA Transfer

Issue Description

Configure and handle a multi-channel DMA transfer for multiple peripherals.

Problem Decomposition & Solution Steps

- **Input:** Source/destination addresses, lengths, channel IDs.
- **Output:** Successful DMA transfers across channels.
- **Approach:** Mock DMA controller for multiple channels.
- **Algorithm:** Multi-Channel DMA Transfer
 - **Explanation:** Configure each channel, start transfers, handle completion.
- **Steps:**
 1. Validate channel parameters.
 2. Configure DMA channels (mock).
 3. Start transfers and monitor completion.
- **Complexity:** Time $O(n)$, Space $O(n)$ for n bytes across channels.

Algorithm Explanation

The multi-channel DMA transfer algorithm configures multiple DMA channels with source, destination, and length.

It starts transfers and monitors completion (via mock interrupts).

This offloads data movement from the CPU, with O(n) time for n bytes and O(n) space for buffers.

Coding Part (with Unit Tests)

```
#include <stdint.h>
#include <stdbool.h>
#include <stdio.h>
#include <string.h>

#define MAX_DMA_CHANNELS 4

typedef struct {
    uint8_t* src;
    uint8_t* dst;
    size_t len;
    bool complete;
} DMAChannel;

typedef struct {
    DMAChannel channels[MAX_DMA_CHANNELS];
} DMAController;

// Configure and start multi-channel DMA
bool startMultiChannelDMA(DMAController* dma, uint8_t* src[], uint8_t* dst[], size_t len[], size_t numChannels) {
    if (numChannels > MAX_DMA_CHANNELS) return false;
    for (size_t i = 0; i < numChannels; i++) {
        if (!src[i] || !dst[i] || len[i] == 0) return false;
        dma->channels[i].src = src[i];
        dma->channels[i].dst = dst[i];
        dma->channels[i].len = len[i];
        memcpy(dma->channels[i].dst, dma->channels[i].src, len[i]); // Simulate transfer
        dma->channels[i].complete = true;
    }
    return true;
}

// Unit test helper
void assertIntEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testMultiChannelDMA() {
    DMAController dma = {0};
    uint8_t src1[] = {1, 2}, src2[] = {3, 4};
    uint8_t dst1[2] = {0}, dst2[2] = {0};
    uint8_t* src[] = {src1, src2};
    uint8_t* dst[] = {dst1, dst2};
    size_t len[] = {2, 2};
    assertBoolEquals(true, startMultiChannelDMA(&dma, src, dst, len, 2) && dst1[0] == 1 && dst2[0] == 3, "Test 284.1 - Multi-channel DMA");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate channel parameters.
 - Handle completion interrupts.
 - Ensure memory alignment.
 - Test with multiple channels.
- **Expert Tips:**
 - Explain multi-channel DMA: "Parallel transfers for peripherals."
 - In interviews, clarify: "Ask about channel count or priorities."
 - Suggest optimization: "Use scatter-gather for complex transfers."
 - Test edge cases: "Invalid pointers, zero length."

Problem 285: Read from a Gyroscope Sensor

Issue Description

Read angular velocity from a gyroscope sensor via I2C.

Problem Decomposition & Solution Steps

- **Input:** I2C device address, register, calibration.
- **Output:** Calibrated angular velocity (e.g., deg/s).
- **Approach:** Mock I2C read, apply calibration.
- **Algorithm:** Gyroscope Read
 - **Explanation:** Read raw data, convert to angular velocity.
- **Steps:**
 1. Send register address via I2C.
 2. Read raw gyroscope data.
 3. Apply calibration (e.g., scale factor).
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The gyroscope read algorithm sends a register address to the sensor via I2C, reads raw data (e.g., 16-bit X/Y/Z axes), and applies a calibration scale to convert to angular velocity (deg/s).

This is O(1) for fixed-size reads, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct SensorCalibration {
    float scale;
    bool valid;
} SensorCalibration;

float readGyroscope(uint8_t deviceAddr, uint8_t regAddr, SensorCalibration* cal) {
    uint8_t data[2];
    if (!readI2CDevice(deviceAddr, regAddr, data, 2)) return 0.0f; // From Problem 230
    int16_t raw = (data[0] << 8) | data[1];
    return cal->valid ? raw * cal->scale : 0.0f;
}
```

```

// Unit tests
void testGyroscopeRead() {
    SensorCalibration cal = {0.1f, true}; // Maps raw to deg/s
    float gyro = readGyroscope(0x6B, 0x28, &cal);
    assertFloatEquals(0.1f * (1 << 8), gyro, 0.01f, "Test 285.1 - Read gyroscope");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate I2C read and calibration.
 - Use sensor-specific registers.
 - Handle communication errors.
 - Test with known angular velocities.
- **Expert Tips:**
 - Explain gyro read: "I2C read with scale factor."
 - In interviews, clarify: "Ask about gyro axes or sensitivity."
 - Suggest optimization: "Use burst read for multi-axis data."
 - Test edge cases: "Failed I2C, invalid calibration."

Problem 286: Handle an I2C Slave Mode

Issue Description

Implement I2C slave mode to receive and respond to master requests.

Problem Decomposition & Solution Steps

- **Input:** Master data via I2C.
- **Output:** Slave response data.
- **Approach:** Mock I2C slave receive and transmit.
- **Algorithm:** I2C Slave Handler
 - **Explanation:** Receive master data, process, send response.
- **Steps:**
 1. Validate received data.
 2. Process data in ISR.
 3. Prepare and send response.
- **Complexity:** Time O(n), Space O(n) for n bytes.

Algorithm Explanation

The I2C slave handler receives data from a master in a mock ISR, processes it (e.g., echoes or modifies), and sends a response.

It operates in slave mode, responding to the master's address and clock.

This is O(n) for n bytes, with O(n) space for buffers.

Coding Part (with Unit Tests)

```
typedef struct {
    uint8_t rxData[8];
    uint8_t txData[8];
    size_t len;
} I2CSlave;

// Mock I2C slave receive/transmit
void mockI2CReceive(I2CSlave* i2c, uint8_t* data, size_t len) {
    for (size_t i = 0; i < len; i++) i2c->rxData[i] = data[i];
    i2c->len = len;
}

void mockI2CTransmit(I2CSlave* i2c) {
    for (size_t i = 0; i < i2c->len; i++) i2c->txData[i] = i2c->rxData[i] + 1;
}

// Handle I2C slave
bool handleI2CSlave(I2CSlave* i2c, uint8_t* data, size_t len, uint8_t* response) {
    if (!data || !response || len > 8) return false;
    mockI2CReceive(i2c, data, len);
    mockI2CTransmit(i2c);
    for (size_t i = 0; i < len; i++) response[i] = i2c->txData[i];
    return true;
}

// Unit tests
void testI2CSlave() {
    I2CSlave i2c = {0};
    uint8_t data[] = {1, 2};
    uint8_t response[2];
    assertBoolEquals(true, handleI2CSlave(&i2c, data, 2, response) && response[0] == 2, "Test 286.1 - I2C slave response");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate data length.
 - Handle I2C interrupts efficiently.
 - Prepare response before transmit.
 - Test with master data.
- **Expert Tips:**
 - Explain I2C slave: "Respond to master's address and data."
 - In interviews, clarify: "Ask about I2C address or clock stretching."
 - Suggest optimization: "Use DMA for I2C slave transfers."
 - Test edge cases: "Invalid data, large transfers."

Problem 287: Manage a Peripheral's Clock Frequency

Issue Description

Configure a peripheral's clock frequency (e.g., for UART, SPI).

Problem Decomposition & Solution Steps

- **Input:** Peripheral ID, desired frequency.
- **Output:** Configured clock frequency.
- **Approach:** Mock clock divider setup.
- **Algorithm:** Clock Frequency Configuration
 - **Explanation:** Calculate and set clock divider.
- **Steps:**
 1. Validate frequency and peripheral.
 2. Calculate divider from system clock.
 3. Set divider in mock register.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The clock frequency configuration algorithm calculates a divider to achieve the desired peripheral clock frequency from the system clock.

It sets the divider in a mock register.

This is O(1) per configuration, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    uint32_t divider;
    uint32_t frequency;
} ClockControl;

// Configure peripheral clock frequency
bool configurePeripheralClock(ClockControl* clk, uint32_t systemClock, uint32_t desiredFreq) {
    if (desiredFreq == 0 || systemClock < desiredFreq) return false;
    clk->divider = systemClock / desiredFreq;
    clk->frequency = systemClock / clk->divider;
    return true;
}

// Unit tests
void testPeripheralClockFreq() {
    ClockControl clk = {0};
    assertBoolEquals(true, configurePeripheralClock(&clk, 16000000, 4000000) && clk.divider == 4,
    "Test 287.1 - Set 4MHz clock");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate frequency range.
 - Ensure divider accuracy.
 - Update clock atomically.
 - Test with different frequencies.
- **Expert Tips:**
 - Explain clock config: "Set divider for peripheral frequency."
 - In interviews, clarify: "Ask about system clock or peripheral."

- Suggest optimization: "Use PLL for precise frequencies."
- Test edge cases: "Zero frequency, max divider."

Problem 288: Handle a Timer Compare Interrupt

Issue Description

Handle a timer compare interrupt for periodic events.

Problem Decomposition & Solution Steps

- **Input:** Timer compare event.
- **Output:** Action on compare match (e.g., toggle pin).
- **Approach:** Mock timer compare ISR.
- **Algorithm:** Timer Compare Handler
 - **Explanation:** Check compare flag, perform action, clear flag.
- **Steps:**
 1. Validate compare event.
 2. Perform action (e.g., toggle GPIO).
 3. Clear compare flag.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The timer compare handler checks the compare flag in a mock timer register.

On a match, it performs an action (e.g., toggles a GPIO pin) and clears the flag.

This is O(1) per interrupt, with O(1) space.

Coding Part (with Unit Tests)

```

typedef struct {
    bool compareFlag;
    uint32_t output;
} TimerCompare;

// Timer compare interrupt handler
void timerCompareHandler(TimerCompare* timer, uint32_t* outputPin) {
    if (timer->compareFlag) {
        *outputPin ^= 1; // Toggle pin
        timer->compareFlag = false;
    }
}

// Unit tests
void testTimerCompare() {
    TimerCompare timer = {true, 0};
    uint32_t outputPin = 0;
    timerCompareHandler(&timer, &outputPin);
    assertEquals(1, outputPin, "Test 288.1 - Toggle pin on compare");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Clear compare flag in ISR.
 - Keep ISR short.
 - Validate event.
 - Test with periodic events.
- **Expert Tips:**
 - Explain compare ISR: "Trigger action on timer match."
 - In interviews, clarify: "Ask about compare value or action."
 - Suggest optimization: "Use hardware output compare."
 - Test edge cases: "No compare, rapid interrupts."

Problem 289: Parse a Serial Protocol Packet

Issue Description

Parse a custom serial protocol packet with header, data, and checksum.

Problem Decomposition & Solution Steps

- **Input:** Serial packet buffer.
- **Output:** Parsed packet data.
- **Approach:** Validate header, extract data, check checksum.
- **Algorithm:** Serial Packet Parsing
 - **Explanation:** Check start byte, length, data, and checksum.
- **Steps:**
 1. Validate start byte and length.
 2. Extract data.
 3. Verify checksum.
- **Complexity:** Time $O(n)$, Space $O(n)$ for n data bytes.

Algorithm Explanation

The serial packet parsing algorithm validates a packet with a start byte, length, data, and checksum.

It extracts the data if the checksum (sum of data bytes) is valid.

This is $O(n)$ for n bytes, with $O(n)$ space for the data.

Coding Part (with Unit Tests)

```
typedef struct {
    uint8_t data[8];
    uint8_t len;
} SerialPacket;
```

```

// Mock serial buffer
uint8_t mockSerialBuffer[] = {0xAA, 2, 0x01, 0x02, 0x03}; // Start, len, data, checksum
int mockSerialIndex = 0;

uint8_t readSerialByte() { return mockSerialBuffer[mockSerialIndex++]; }

// Parse serial packet
bool parseSerialPacket(SerialPacket* packet) {
    if (readSerialByte() != 0xAA) return false;
    packet->len = readSerialByte();
    if (packet->len > 8) return false;
    uint8_t checksum = 0;
    for (uint8_t i = 0; i < packet->len; i++) {
        packet->data[i] = readSerialByte();
        checksum += packet->data[i];
    }
    return readSerialByte() == checksum;
}

// Unit tests
void testSerialPacket() {
    mockSerialIndex = 0;
    SerialPacket packet;
    assertBoolEquals(true, parseSerialPacket(&packet) && packet.len == 2 && packet.data[0] == 0x01,
    "Test 289.1 - Parse serial packet");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate packet format.
 - Check checksum for integrity.
 - Handle variable data length.
 - Test with valid/invalid packets.
- **Expert Tips:**
 - Explain serial parsing: "Validate and extract packet data."
 - In interviews, clarify: "Ask about protocol format."
 - Suggest optimization: "Use state machine for streaming."
 - Test edge cases: "Invalid start, wrong checksum."

Problem 290: Handle a Brown-Out Interrupt

Issue Description

Handle a brown-out interrupt to protect against low voltage.

Problem Decomposition & Solution Steps

- **Input:** Brown-out interrupt status.
- **Output:** Save state or reset.
- **Approach:** Mock brown-out ISR, save critical data.
- **Algorithm:** Brown-Out Handler
 - **Explanation:** Detect brown-out, save state, initiate reset.
- **Steps:**
 1. Check brown-out flag.
 2. Save critical state (mock).

- 3. Clear flag or reset system.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The brown-out handler checks a mock brown-out flag, saves critical state to non-volatile memory (mocked), and clears the flag or resets.

This protects against voltage drops.

It's O(1) per interrupt, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    bool brownOut;
    uint32_t savedState;
} BrownOutStatus;

// Brown-out interrupt handler
void brownOutHandler(BrownOutStatus* status) {
    if (status->brownOut) {
        status->savedState = 0xDEADBEEF; // Mock save
        status->brownOut = false;
    }
}

// Unit tests
void testBrownOut() {
    BrownOutStatus status = {true, 0};
    brownOutHandler(&status);
    assertEquals(0xDEADBEEF, status.savedState, "Test 290.1 - Handle brown-out");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Save minimal state.
 - Keep ISR short.
 - Clear brown-out flag.
 - Test with simulated brown-outs.
- **Expert Tips:**
 - Explain brown-out: "Protect against low voltage."
 - In interviews, clarify: "Ask about voltage threshold."
 - Suggest optimization: "Use backup SRAM for state."
 - Test edge cases: "No brown-out, rapid interrupts."

Problem 291: Configure a PWM Frequency

Issue Description

Configure the frequency of a PWM signal.

Problem Decomposition & Solution Steps

- **Input:** Desired frequency, system clock.
- **Output:** Configured PWM frequency.
- **Approach:** Calculate period from frequency, update PWM.
- **Algorithm:** PWM Frequency Configuration
 - **Explanation:** Set period based on frequency and clock.
- **Steps:**
 1. Validate frequency and clock.
 2. Calculate period ticks.
 3. Update PWM register.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The PWM frequency configuration algorithm calculates the period (ticks = clock / frequency) and updates the PWM register.

This sets the PWM signal's frequency.

It's O(1) per configuration, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    uint32_t periodTicks;
} PWMRegister;

// Configure PWM frequency
bool configurePWMFrequency(PWMRegister* pwm, uint32_t systemClock, uint32_t freq) {
    if (freq == 0 || systemClock < freq) return false;
    pwm->periodTicks = systemClock / freq;
    return true;
}

// Unit tests
void testConfigureFrequency() {
    PWMRegister pwm = {0};
    assertBoolEquals(true, configurePWMFrequency(&pwm, 1000000, 1000) && pwm.periodTicks == 1000,
                    "Test 291.1 - Set 1kHz PWM");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate frequency range.
 - Ensure accurate period calculation.
 - Update PWM atomically.
 - Test with different frequencies.
- **Expert Tips:**
 - Explain PWM frequency: "Set period from clock and frequency."
 - In interviews, clarify: "Ask about PWM resolution."
 - Suggest optimization: "Use hardware prescaler."

- Test edge cases: "Zero frequency, max frequency."

Problem 292: Read from a Flash Memory Sector

Issue Description

Read data from a specific flash memory sector.

Problem Decomposition & Solution Steps

- **Input:** Sector number, offset, length, buffer.
- **Output:** Data read from flash sector.
- **Approach:** Mock flash sector read with bounds checking.
- **Algorithm:** Flash Sector Read
 - **Explanation:** Map sector/offset to address, read data.
- **Steps:**
 1. Validate sector, offset, and length.
 2. Calculate flash address.
 3. Read data into buffer.
- **Complexity:** Time O(n), Space O(n) for n bytes.

Algorithm Explanation

The flash sector read algorithm maps a sector number and offset to a flash address, validates bounds, and reads data into a buffer.

It simulates reading a specific sector (e.g., 4KB).

This is O(n) for n bytes, with O(n) space for the buffer.

Coding Part (with Unit Tests)

```
#define FLASH_BASE 0x08000000
#define SECTOR_SIZE 4096

bool readFlashSector(uint32_t sector, uint32_t offset, uint8_t* buffer, size_t len) {
    if (offset + len > SECTOR_SIZE) return false;
    uint32_t addr = FLASH_BASE + sector * SECTOR_SIZE + offset;
    return readFlash(addr, buffer, len); // From Problem 251
}

// Unit tests
void testFlashSector() {
    uint8_t buffer[3];
    assertBoolEquals(true, readFlashSector(0, 0, buffer, 3) && buffer[0] == 0x01, "Test 292.1 - Read flash sector");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate sector and offset.
 - Respect sector boundaries.
 - Handle read errors.
 - Test with different sectors.
- **Expert Tips:**
 - Explain flash sector: "Read specific sector with offset."
 - In interviews, clarify: "Ask about sector size or flash type."
 - Suggest optimization: "Use DMA for large reads."
 - Test edge cases: "Invalid sector, offset overflow."

Problem 293: Handle a Real-Time Clock Alarm

Issue Description

Handle an RTC alarm interrupt for scheduled events.

Problem Decomposition & Solution Steps

- **Input:** RTC alarm event.
- **Output:** Action on alarm (e.g., set flag).
- **Approach:** Mock RTC alarm ISR.
- **Algorithm:** RTC Alarm Handler
 - **Explanation:** Check alarm flag, perform action, clear flag.
- **Steps:**
 1. Validate alarm event.
 2. Perform action (e.g., set flag).
 3. Clear alarm flag.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The RTC alarm handler checks the alarm flag in a mock RTC register.

On alarm, it performs an action (e.g., sets a flag) and clears the interrupt.

This is O(1) per interrupt, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    bool alarmFlag;
    bool alarmTriggered;
} RTC;
```

```

// RTC alarm interrupt handler
void rtcAlarmHandler(RTC* rtc) {
    if (rtc->alarmFlag) {
        rtc->alarmTriggered = true;
        rtc->alarmFlag = false;
    }
}

// Unit tests
void testRTCAlarm() {
    RTC rtc = {true, false};
    rtcAlarmHandler(&rtc);
    assertBoolEquals(true, rtc.alarmTriggered && !rtc.alarmFlag, "Test 293.1 - Handle RTC alarm");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Clear alarm flag in ISR.
 - Keep ISR minimal.
 - Validate alarm event.
 - Test with alarm triggers.
- **Expert Tips:**
 - Explain RTC alarm: "Trigger action at set time."
 - In interviews, clarify: "Ask about alarm frequency."
 - Suggest optimization: "Use RTC for low-power wake."
 - Test edge cases: "No alarm, rapid alarms."

Problem 294: Manage a Sensor's Power State

Issue Description

Enable or disable a sensor's power to save energy.

Problem Decomposition & Solution Steps

- **Input:** Sensor ID, power state (on/off).
- **Output:** Configured sensor power.
- **Approach:** Mock power control register.
- **Algorithm:** Sensor Power Control
 - **Explanation:** Set/clear power bit for sensor.
- **Steps:**
 1. Validate sensor ID.
 2. Set or clear power bit.
 3. Confirm state change.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The sensor power control algorithm sets or clears a bit in a mock power register to enable/disable a sensor's power.

This reduces power consumption when the sensor is idle.

It's O(1) per operation, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    uint32_t powerBits;
} SensorPower;

// Manage sensor power
void setSensorPower(SensorPower* pwr, uint8_t sensor, bool enable) {
    if (sensor >= 32) return;
    if (enable) {
        pwr->powerBits |= (1U << sensor);
    } else {
        pwr->powerBits &= ~(1U << sensor);
    }
}

// Unit tests
void testSensorPower() {
    SensorPower pwr = {0};
    setSensorPower(&pwr, 2, true);
    assertEquals(1U << 2, pwr.powerBits, "Test 294.1 - Enable sensor power");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate sensor ID.
 - Ensure atomic bit operations.
 - Minimize power-on time.
 - Test with multiple sensors.
- **Expert Tips:**
 - Explain power control: "Toggle sensor power bit."
 - In interviews, clarify: "Ask about sensor type."
 - Suggest optimization: "Combine with clock gating."
 - Test edge cases: "Invalid sensor, rapid toggles."

Problem 295: Handle a UART Interrupt for Data Reception

Issue Description

Handle a UART receive interrupt to store incoming data.

Problem Decomposition & Solution Steps

- **Input:** UART receive interrupt.
- **Output:** Stored received data.
- **Approach:** Mock UART ISR, store data in buffer.
- **Algorithm:** UART Receive Interrupt Handler

- **Explanation:** Read data, store in buffer, clear flag.
- **Steps:**
 1. Check receive interrupt flag.
 2. Read UART data register.
 3. Store in buffer.
 4. Clear flag.
- **Complexity:** Time O(1), Space O(n) for n-byte buffer.

Algorithm Explanation

The UART receive interrupt handler checks the receive flag, reads the UART data register, and stores the data in a buffer.

It clears the flag to allow further interrupts.

This is O(1) per interrupt, with O(n) space for the buffer.

Coding Part (with Unit Tests)

```

typedef struct {
    uint8_t data[8];
    uint8_t count;
    bool rxFlag;
} UART;

// Mock UART read
uint8_t mockUARTRead() { return 0x55; }

// UART receive interrupt handler
void uartReceiveHandler(UART* uart) {
    if (uart->rxFlag && uart->count < 8) {
        uart->data[uart->count++] = mockUARTRead();
        uart->rxFlag = false;
    }
}

// Unit tests
void testUARTReceive() {
    UART uart = {0};
    uart.rxFlag = true;
    uartReceiveHandler(&uart);
    assertEquals(0x55, uart.data[0], "Test 295.1 - Receive UART data");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Check buffer capacity.
 - Clear interrupt flag.
 - Keep ISR short.
 - Test with incoming data.
- **Expert Tips:**
 - Explain UART ISR: "Store received data in buffer."
 - In interviews, clarify: "Ask about buffer size or baud rate."
 - Suggest optimization: "Use DMA for UART reception."

- Test edge cases: "Full buffer, rapid data."

Problem 296: Implement a Function to Read a Humidity Sensor

Issue Description

Read relative humidity from a sensor via I2C.

Problem Decomposition & Solution Steps

- **Input:** I2C device address, register, calibration.
- **Output:** Calibrated humidity (%RH).
- **Approach:** Mock I2C read, apply calibration.
- **Algorithm:** Humidity Sensor Read
 - **Explanation:** Read raw data, convert to humidity.
- **Steps:**
 1. Send register address via I2C.
 2. Read raw humidity data.
 3. Apply calibration.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The humidity sensor read algorithm sends a register address to the sensor via I2C, reads raw data (e.g., 16-bit), and applies a linear calibration to convert to relative humidity (%RH).

This is O(1) for fixed-size reads, with O(1) space.

Coding Part (with Unit Tests)

```
float readHumiditySensor(uint8_t deviceAddr, uint8_t regAddr, SensorCalibration* cal) {
    uint8_t data[2];
    if (!readI2CDevice(deviceAddr, regAddr, data, 2)) return 0.0f;
    uint16_t raw = (data[0] << 8) | data[1];
    return cal->valid ? raw * cal->scale : 0.0f;
}

// Unit tests
void testHumiditySensor() {
    SensorCalibration cal = {0.05f, true}; // Maps 0-65535 to 0-100% RH
    float humidity = readHumiditySensor(0x44, 0x2C, &cal);
    assertFloatEquals(0.05f * (1 << 8), humidity, 0.01f, "Test 296.1 - Read humidity");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate I2C read and calibration.
 - Use sensor-specific registers.
 - Handle errors gracefully.

- Test with known humidity values.
- **Expert Tips:**
 - Explain humidity read: "I2C read with calibration."
 - In interviews, clarify: "Ask about sensor model or range."
 - Suggest optimization: "Read temperature for compensation."
 - Test edge cases: "Failed I2C, invalid calibration."

Problem 297: Handle a SPI Bus Arbitration Error

Issue Description

Detect and recover from an SPI bus arbitration error.

Problem Decomposition & Solution Steps

- **Input:** SPI status register.
- **Output:** Error detection and recovery.
- **Approach:** Check arbitration error, reset SPI.
- **Algorithm:** SPI Arbitration Error Handler
 - **Explanation:** Detect error, reset SPI peripheral.
- **Steps:**
 1. Check arbitration error flag.
 2. Reset SPI peripheral.
 3. Clear error flag.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The SPI arbitration error handler checks the SPI status register for an arbitration error (e.g., multi-master conflict).

It resets the SPI peripheral and clears the error flag.

This is O(1) per interrupt, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    bool arbError;
    bool reset;
} SPIStatus;

// Handle SPI arbitration error
bool handleSPIArbitrationError(SPIStatus* status) {
    if (status->arbError) {
        status->reset = true;
        status->arbError = false;
        return true;
    }
    return false;
}
```

```

// Unit tests
void testSPIArbitrationError() {
    SPIStatus status = {true, false};
    assertBoolEquals(true, handleSPIArbitrationError(&status) && status.reset && !status.arbError,
    "Test 297.1 - Handle SPI arbitration error");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Check arbitration error flag.
 - Reset SPI peripheral.
 - Log errors for debugging.
 - Test with simulated errors.
- **Expert Tips:**
 - Explain arbitration error: "Resolve multi-master conflicts."
 - In interviews, clarify: "Ask about SPI master/slave setup."
 - Suggest optimization: "Avoid multi-master if possible."
 - Test edge cases: "No error, multiple errors."

Problem 298: Configure a Timer for One-Shot Mode

Issue Description

Configure a timer for one-shot mode to trigger a single event.

Problem Decomposition & Solution Steps

- **Input:** Timeout period, system clock.
- **Output:** Configured one-shot timer.
- **Approach:** Mock timer setup for single trigger.
- **Algorithm:** One-Shot Timer Configuration
 - **Explanation:** Set period, disable auto-reload.
- **Steps:**
 1. Validate period and clock.
 2. Calculate timer ticks.
 3. Configure timer without auto-reload.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The one-shot timer configuration algorithm calculates the timer ticks from the system clock and desired period, then configures a mock timer to trigger once without auto-reloading.

This is O(1) per configuration, with O(1) space.

Coding Part (with Unit Tests)

```
typedef struct {
    uint32_t ticks;
    bool oneShot;
} TimerRegister;

// Configure one-shot timer
bool configureOneShotTimer(TimerRegister* timer, uint32_t systemClock, uint32_t periodMs) {
    if (periodMs == 0 || systemClock == 0) return false;
    timer->ticks = (systemClock / 1000) * periodMs;
    timer->oneShot = true;
    return true;
}

// Unit tests
void testOneShotTimer() {
    TimerRegister timer = {0};
    assertBoolEquals(true, configureOneShotTimer(&timer, 1000000, 1000) && timer.ticks == 1000000 &&
        timer.oneShot, "Test 298.1 - Configure one-shot timer");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate period and clock.
 - Disable auto-reload for one-shot.
 - Ensure accurate ticks.
 - Test with different periods.
- **Expert Tips:**
 - Explain one-shot timer: "Single trigger without reload."
 - In interviews, clarify: "Ask about timer resolution."
 - Suggest optimization: "Use hardware one-shot mode."
 - Test edge cases: "Zero period, large period."

Problem 299: Parse a Bluetooth LE Advertisement Packet

Issue Description

Parse a Bluetooth LE advertisement packet for device name and UUID.

Problem Decomposition & Solution Steps

- **Input:** BLE packet buffer.
- **Output:** Parsed device name and UUID.
- **Approach:** Extract fields from advertisement data.
- **Algorithm:** BLE Packet Parsing
 - **Explanation:** Parse length-type-value fields for name and UUID.
- **Steps:**
 1. Validate packet format.
 2. Extract name (type 0x09) and UUID (type 0x07).
 3. Store parsed data.
- **Complexity:** Time O(n), Space O(n) for n bytes.

Algorithm Explanation

The BLE packet parsing algorithm processes a Bluetooth LE advertisement packet, which uses length-type-value (LTV) fields.

It extracts the device name (type 0x09) and UUID (type 0x07) by iterating through the packet.

This is O(n) for n bytes, with O(n) space for parsed data.

Coding Part (with Unit Tests)

```
typedef struct {
    char name[16];
    uint8_t uuid[16];
} BLEPacket;

// Mock BLE buffer
uint8_t mockBLEBuffer[] = {0x02, 0x01, 0x06, 0x05, 0x09, 'T', 'E', 'S', 'T'}; // Flags, name=TEST
int mockBLEIndex = 0;

uint8_t readBLEByte() { return mockBLEBuffer[mockBLEIndex++]; }

// Parse BLE advertisement packet
bool parseBLEPacket(BLEPacket* packet) {
    while (mockBLEIndex < sizeof(mockBLEBuffer)) {
        uint8_t len = readBLEByte();
        if (len == 0) return false;
        uint8_t type = readBLEByte();
        if (type == 0x09) { // Device name
            for (uint8_t i = 0; i < len - 1 && i < 15; i++) {
                packet->name[i] = readBLEByte();
            }
            packet->name[len - 1] = '\0';
        } else {
            mockBLEIndex += len - 1; // Skip other fields
        }
    }
    return true;
}

// Unit tests
void testBLEPacket() {
    mockBLEIndex = 0;
    BLEPacket packet = {0};
    assertBoolEquals(true, parseBLEPacket(&packet) && strcmp(packet.name, "TEST") == 0, "Test 299.1 - Parse BLE name");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate LTV format.
 - Handle variable-length fields.
 - Check buffer overruns.
 - Test with real BLE packets.
- **Expert Tips:**
 - Explain BLE parsing: "Extract name and UUID from LTV fields."
 - In interviews, clarify: "Ask about advertisement types."

- Suggest optimization: "Parse only required fields."
- Test edge cases: "Invalid packet, missing name."

Problem 300: Handle a Low-Battery Interrupt

Issue Description

Handle a low-battery interrupt to alert or save state.

Problem Decomposition & Solution Steps

- **Input:** Low-battery interrupt status.
- **Output:** Action on low battery (e.g., set flag).
- **Approach:** Mock low-battery ISR, save state.
- **Algorithm:** Low-Battery Handler
 - **Explanation:** Detect low battery, save state, clear flag.
- **Steps:**
 1. Check low-battery flag.
 2. Save state or set alert (mock).
 3. Clear interrupt flag.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The low-battery handler checks a mock low-battery flag, saves critical state or sets an alert (mocked), and clears the flag.

This ensures the system responds to low battery conditions.

It's O(1) per interrupt, with O(1) space.

Coding Part (with Unit Tests)

```

typedef struct {
    bool lowBattery;
    bool alertTriggered;
} BatteryStatus;

// Low-battery interrupt handler
void lowBatteryHandler(BatteryStatus* status) {
    if (status->lowBattery) {
        status->alertTriggered = true;
        status->lowBattery = false;
    }
}

// Unit tests
void testLowBattery() {
    BatteryStatus status = {true, false};
    lowBatteryHandler(&status);
    assertBoolEquals(true, status.alertTriggered && !status.lowBattery, "Test 300.1 - Handle low
battery");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Clear low-battery flag.
 - Save minimal state.
 - Keep ISR short.
 - Test with simulated low battery.
- **Expert Tips:**
 - Explain low-battery ISR: "Alert or save on low voltage."
 - In interviews, clarify: "Ask about battery threshold."
 - Suggest optimization: "Enter low-power mode on interrupt."
 - Test edge cases: "No low battery, rapid interrupts."

Main Function to Run All Tests

```
int main() {  
    printf("Running tests for embedded systems problems 284 to 300:\n");  
    testMultiChannelDMA();  
    testGyroscopeRead();  
    testI2CSlave();  
    testPeripheralClockFreq();  
    testTimerCompare();  
    testSerialPacket();  
    testBrownOut();  
    testPWMFrequency();  
    testFlashSector();  
    testRTCAAlarm();  
    testSensorPower();  
    testUARTReceive();  
    testHumiditySensor();  
    testSPIArbitrationError();  
    testOneShotTimer();  
    testBLEPacket();  
    testLowBattery();  
    return 0;  
}
```

Data Structures

(80 Problems)

Problem 301: Implement a Singly Linked List with Insert and Delete

Issue Description

Implement a singly linked list with functions to insert a node at the head and delete a node by value.

Problem Decomposition & Solution Steps

- **Input:** Value to insert/delete, linked list head.
- **Output:** Updated linked list.
- **Approach:** Use a struct for nodes, manage pointers for insert/delete.
- **Algorithm:** Linked List Insert/Delete
 - **Explanation:** Insert adds a node at the head; delete removes the first node with the given value.
- **Steps:**
 1. For insert: Allocate node, set value and next, update head.
 2. For delete: Traverse list, remove node with matching value.
- **Complexity:** Insert O(1), Delete O(n), Space O(1).

Algorithm Explanation

The insert algorithm allocates a new node, sets its value and next pointer to the current head, and updates the head.

The delete algorithm traverses the list, updates pointers to skip the matching node, and frees it.

Insert is O(1), delete is O(n) for n nodes, with O(1) space for pointers.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>

typedef struct ListNode {
    int val;
    struct ListNode* next;
} ListNode;

// Insert at head
ListNode* insertNode(ListNode* head, int val) {
    ListNode* newNode = (ListNode*)malloc(sizeof(ListNode));
    newNode->val = val;
    newNode->next = head;
    return newNode;
}

// Delete node by value
ListNode* deleteNode(ListNode* head, int val) {
    if (!head) return NULL;
    if (head->val == val) {
        ListNode* temp = head->next;
        free(head);
        return temp;
    }
    ListNode* curr = head;
    while (curr->next && curr->next->val != val) {
        curr = curr->next;
    }
    if (curr->next) {
        curr->next = curr->next->next;
        free(curr->next);
    }
    return head;
}
```

```

    }
    if (curr->next) {
        ListNode* temp = curr->next;
        curr->next = temp->next;
        free(temp);
    }
    return head;
}

// Unit test helper
void assertEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testLinkedList() {
    ListNode* head = NULL;
    head = insertNode(head, 1);
    head = insertNode(head, 2);
    assertEquals(2, head->val, "Test 301.1 - Insert 2");
    head = deleteNode(head, 1);
    assertEquals(2, head->val, "Test 301.2 - Delete 1");
    free(head);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Check for NULL pointers.
 - Free deleted nodes to prevent leaks.
 - Handle edge cases (empty list, single node).
 - Test insert/delete sequences.
- **Expert Tips:**
 - Explain insert: "Add node at head for O(1) complexity."
 - In interviews, clarify: "Ask about insertion position."
 - Suggest optimization: "Use tail pointer for O(1) tail insert."
 - Test edge cases: "Empty list, delete non-existent value."

Problem 302: Reverse a Singly Linked List

Issue Description

Reverse the order of nodes in a singly linked list.

Problem Decomposition & Solution Steps

- **Input:** Head of linked list.
- **Output:** Head of reversed linked list.
- **Approach:** Iteratively reverse pointers.
- **Algorithm:** Linked List Reversal
 - **Explanation:** Change each node's next pointer to the previous node.
- **Steps:**
 1. Initialize previous as NULL, current as head.

2. For each node, save next, reverse pointer, update pointers.
 3. Return new head (last node).
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The reversal algorithm iterates through the list, reversing each node's next pointer to point to the previous node.

It uses three pointers (prev, curr, next) to avoid losing references.

This is O(n) for n nodes, with O(1) space for pointers.

Coding Part (with Unit Tests)

```
ListNode* reverseList(ListNode* head) {
    ListNode *prev = NULL, *curr = head, *next;
    while (curr) {
        next = curr->next;
        curr->next = prev;
        prev = curr;
        curr = next;
    }
    return prev;
}

// Unit tests
void testReverseList() {
    ListNode* head = insertNode(NULL, 1);
    head = insertNode(head, 2);
    head = reverseList(head);
    assertEquals(1, head->val, "Test 302.1 - Reverse list head");
    free(head->next);
    free(head);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle empty or single-node lists.
 - Use iterative approach to save space.
 - Verify pointer updates.
 - Test with multiple nodes.
- **Expert Tips:**
 - Explain reversal: "Iterate and reverse next pointers."
 - In interviews, clarify: "Ask about iterative vs. recursive."
 - Suggest optimization: "Recursive for clarity, iterative for space."
 - Test edge cases: "Empty list, single node."

Problem 303: Detect a Cycle in a Linked List

Issue Description

Detect if a singly linked list has a cycle using Floyd's cycle detection.

Problem Decomposition & Solution Steps

- **Input:** Head of linked list.
- **Output:** Boolean indicating cycle presence.
- **Approach:** Use two pointers (slow/fast) to detect cycle.
- **Algorithm:** Floyd's Cycle Detection
 - **Explanation:** Slow moves one step, fast moves two; they meet if cycle exists.
- **Steps:**
 1. Initialize slow and fast pointers to head.
 2. Move slow by 1, fast by 2 until they meet or fast reaches end.
 3. Return true if they meet, false otherwise.
- **Complexity:** Time $O(n)$, Space $O(1)$.

Algorithm Explanation

Floyd's cycle detection (hare-tortoise) uses two pointers: slow moves one step, fast moves two.

If they meet, a cycle exists; if fast reaches NULL, there's no cycle.

This is $O(n)$ for n nodes, with $O(1)$ space.

Coding Part (with Unit Tests)

```
bool hasCycle(ListNode* head) {  
    ListNode *slow = head, *fast = head;  
    while (fast && fast->next) {  
        slow = slow->next;  
        fast = fast->next->next;  
        if (slow == fast) return true;  
    }  
    return false;  
}  
  
// Unit tests  
void testCycleDetection() {  
    ListNode* head = insertNode(NULL, 1);  
    head->next = head; // Create cycle  
    assertBoolEquals(true, hasCycle(head), "Test 303.1 - Detect cycle");  
    head->next = NULL;  
    assertBoolEquals(false, hasCycle(head), "Test 303.2 - No cycle");  
    free(head);  
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Check for NULL fast/next pointers.
 - Use Floyd's algorithm for $O(1)$ space.

- Handle edge cases (empty list).
- Test with/without cycles.
- **Expert Tips:**
 - Explain Floyd's: "Slow/fast pointers meet in cycle."
 - In interviews, clarify: "Ask about space constraints."
 - Suggest optimization: "Hash table for $O(n)$ space alternative."
 - Test edge cases: "Cycle at head, no cycle."

Problem 304: Merge Two Sorted Linked Lists

Issue Description

Merge two sorted singly linked lists into one sorted list.

Problem Decomposition & Solution Steps

- **Input:** Heads of two sorted linked lists.
- **Output:** Head of merged sorted list.
- **Approach:** Compare nodes, merge iteratively.
- **Algorithm:** Merge Sorted Lists
 - **Explanation:** Compare nodes from both lists, build merged list.
- **Steps:**
 1. Initialize dummy node for merged list.
 2. Compare heads, append smaller value.
 3. Advance pointers and repeat until one list is empty.
 4. Append remaining nodes.
- **Complexity:** Time $O(n + m)$, Space $O(1)$.

Algorithm Explanation

The merge algorithm uses a dummy node to simplify pointer handling.

It compares heads of both lists, appends the smaller value to the merged list, and advances the corresponding pointer.

Remaining nodes are appended at the end.

This is $O(n + m)$ for n and m nodes, with $O(1)$ space (excluding input).

Coding Part (with Unit Tests)

```
ListNode* mergeTwoLists(ListNode* l1, ListNode* l2) {
    ListNode dummy = {0, NULL}, *tail = &dummy;
    while (l1 && l2) {
        if (l1->val <= l2->val) {
            tail->next = l1;
            l1 = l1->next;
        } else {
            tail->next = l2;
            l2 = l2->next;
        }
        tail = tail->next;
    }
    tail->next = l1 ? l1 : l2;
    return dummy.next;
}

// Unit tests
void testMergeLists() {
    ListNode* l1 = insertNode(NULL, 1);
    l1 = insertNode(l1, 3);
    ListNode* l2 = insertNode(NULL, 2);
    ListNode* merged = mergeTwoLists(l1, l2);
    assertEquals(1, merged->val, "Test 304.1 - Merge sorted lists");
    free(merged->next->next);
    free(merged->next);
    free(merged);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use dummy node for simplicity.
 - Handle empty lists.
 - Preserve sorted order.
 - Test with unequal list lengths.
- **Expert Tips:**
 - Explain merge: "Compare and append smaller nodes."
 - In interviews, clarify: "Ask about in-place merge."
 - Suggest optimization: "Recursive merge for clarity."
 - Test edge cases: "Empty lists, one empty list."

Problem 305: Implement a Stack Using an Array

Issue Description

Implement a stack with push, pop, and peek operations using an array.

Problem Decomposition & Solution Steps

- **Input:** Values to push/pop, stack capacity.
- **Output:** Stack operations (push/pop/peek).
- **Approach:** Use fixed-size array with top index.

- **Algorithm:** Array-Based Stack
 - **Explanation:** Push adds to top, pop removes from top, peek reads top.
- **Steps:**
 1. Initialize array and top index.
 2. Push: Increment top, store value.
 3. Pop: Return value, decrement top.
 4. Peek: Return top value.
- **Complexity:** Time O(1) per operation, Space O(n).

Algorithm Explanation

The stack uses a fixed-size array with a top index tracking the stack's top element.

Push increments top and stores the value; pop returns the top value and decrements top; peek reads the top value.

All operations are O(1), with O(n) space for n elements.

Coding Part (with Unit Tests)

```
#define MAX_STACK_SIZE 100

typedef struct {
    int data[MAX_STACK_SIZE];
    int top;
} Stack;

// Initialize stack
void initStack(Stack* stack) {
    stack->top = -1;
}

// Push to stack
bool push(Stack* stack, int val) {
    if (stack->top >= MAX_STACK_SIZE - 1) return false;
    stack->data[++stack->top] = val;
    return true;
}

// Pop from stack
bool pop(Stack* stack, int* val) {
    if (stack->top < 0) return false;
    *val = stack->data[stack->top--];
    return true;
}

// Peek stack
bool peek(Stack* stack, int* val) {
    if (stack->top < 0) return false;
    *val = stack->data[stack->top];
    return true;
}
```

```

// Unit tests
void testStack() {
    Stack stack;
    initStack(&stack);
    push(&stack, 1);
    int val;
    peek(&stack, &val);
    assertEquals(1, val, "Test 305.1 - Push and peek");
    pop(&stack, &val);
    assertEquals(1, val, "Test 305.2 - Pop value");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Check for stack overflow/underflow.
 - Initialize top to -1.
 - Return success/failure status.
 - Test push/pop sequences.
- **Expert Tips:**
 - Explain stack: "LIFO with array-based top index."
 - In interviews, clarify: "Ask about dynamic resizing."
 - Suggest optimization: "Use dynamic array for flexibility."
 - Test edge cases: "Full stack, empty stack."

Problem 306: Implement a Queue Using Two Stacks

Issue Description

Implement a queue (FIFO) using two stacks.

Problem Decomposition & Solution Steps

- **Input:** Values to enqueue/dequeue.
- **Output:** Queue operations (enqueue/dequeue).
- **Approach:** Use one stack for enqueue, another for dequeue.
- **Algorithm:** Two-Stack Queue
 - **Explanation:** Enqueue to stack1; dequeue by moving stack1 to stack2.
- **Steps:**
 1. Enqueue: Push to stack1.
 2. Dequeue: If stack2 empty, pop stack1 to stack2; pop stack2.
- **Complexity:** Enqueue O(1), Dequeue amortized O(1), Space O(n).

Algorithm Explanation

The two-stack queue uses stack1 for enqueue (push) and stack2 for dequeue (pop).

If stack2 is empty, all elements from stack1 are popped and pushed to stack2, reversing order for FIFO.

Enqueue is O(1); dequeue is O(n) worst-case but amortized O(1), with O(n) space.

Coding Part (with Unit Tests)

```
typedef struct {
    Stack s1, s2;
} Queue;

// Initialize queue
void initQueue(Queue* q) {
    initStack(&q->s1);
    initStack(&q->s2);
}

// Enqueue
bool enqueue(Queue* q, int val) {
    return push(&q->s1, val);
}

// Dequeue
bool dequeue(Queue* q, int* val) {
    if (q->s2.top >= 0) return pop(&q->s2, val);
    while (q->s1.top >= 0) {
        int temp;
        pop(&q->s1, &temp);
        push(&q->s2, temp);
    }
    return pop(&q->s2, val);
}

// Unit tests
void testQueue() {
    Queue q;
    initQueue(&q);
    enqueue(&q, 1);
    enqueue(&q, 2);
    int val;
    dequeue(&q, &val);
    assertIntEquals(1, val, "Test 306.1 - Dequeue first element");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle empty stacks.
 - Optimize dequeue by reusing stack2.
 - Validate operations.
 - Test enqueue/dequeue sequences.
- **Expert Tips:**
 - Explain two-stack queue: "Use stack1 for enqueue, stack2 for dequeue."
 - In interviews, clarify: "Ask about operation frequency."
 - Suggest optimization: "Minimize stack transfers."
 - Test edge cases: "Empty queue, single element."

Problem 307: Implement a Circular Queue Using an Array

Issue Description

Implement a circular queue with enqueue, dequeue, and front operations.

Problem Decomposition & Solution Steps

- **Input:** Values to enqueue/dequeue, queue capacity.
- **Output:** Circular queue operations.
- **Approach:** Use array with front/rear pointers.
- **Algorithm:** Circular Queue
 - **Explanation:** Enqueue at rear, dequeue from front, wrap pointers.
- **Steps:**
 1. Initialize array, front, rear, and size.
 2. Enqueue: Add at rear, increment rear (mod capacity).
 3. Dequeue: Remove from front, increment front (mod capacity).
 4. Front: Return element at front.
- **Complexity:** Time O(1) per operation, Space O(n).

Algorithm Explanation

The circular queue uses a fixed-size array with front and rear pointers.

Enqueue adds elements at rear, wrapping around using modulo.

Dequeue removes from front, also wrapping.

Front reads the front element.

All operations are O(1), with O(n) space for n elements.

Coding Part (with Unit Tests)

```
#define MAX_QUEUE_SIZE 100

typedef struct {
    int data[MAX_QUEUE_SIZE];
    int front, rear, size;
} CircularQueue;

// Initialize circular queue
void initCircularQueue(CircularQueue* q) {
    q->front = 0;
    q->rear = -1;
    q->size = 0;
}

// Enqueue
bool enqueueCircular(CircularQueue* q, int val) {
    if (q->size >= MAX_QUEUE_SIZE) return false;
    q->rear = (q->rear + 1) % MAX_QUEUE_SIZE;
    q->data[q->rear] = val;
    q->size++;
    return true;
}

// Dequeue
bool dequeueCircular(CircularQueue* q, int* val) {
    if (q->size == 0) return false;
    *val = q->data[q->front];
    q->front = (q->front + 1) % MAX_QUEUE_SIZE;
    q->size--;
    return true;
}
```

```

// Get front
bool frontCircular(CircularQueue* q, int* val) {
    if (q->size == 0) return false;
    *val = q->data[q->front];
    return true;
}

// Unit tests
void testCircularQueue() {
    CircularQueue q;
    initCircularQueue(&q);
    enqueueCircular(&q, 1);
    int val;
    frontCircular(&q, &val);
    assertEquals(1, val, "Test 307.1 - Enqueue and front");
    dequeueCircular(&q, &val);
    assertEquals(1, val, "Test 307.2 - Dequeue");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track size to detect full/empty.
 - Use modulo for pointer wrapping.
 - Handle overflow/underflow.
 - Test wrap-around cases.
- **Expert Tips:**
 - Explain circular queue: "Efficient FIFO with array wrap-around."
 - In interviews, clarify: "Ask about capacity constraints."
 - Suggest optimization: "Use power-of-2 size for faster modulo."
 - Test edge cases: "Full queue, empty queue, wrap-around."

Problem 308: Find the Middle Node of a Linked List

Issue Description

Find the middle node of a singly linked list.

Problem Decomposition & Solution Steps

- **Input:** Head of linked list.
- **Output:** Pointer to middle node.
- **Approach:** Use two pointers (slow/fast) to find middle.
- **Algorithm:** Slow-Fast Pointer for Middle
 - **Explanation:** Slow moves one step, fast moves two; slow reaches middle when fast reaches end.
- **Steps:**
 1. Initialize slow and fast to head.
 2. Move slow by 1, fast by 2 until fast reaches end.
 3. Return slow (middle node).
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The slow-fast pointer algorithm uses two pointers: slow moves one step, fast moves two.

When fast reaches the end (NULL or last node), slow is at the middle.

For even-length lists, it returns the second middle node.

This is O(n) for n nodes, with O(1) space.

Coding Part (with Unit Tests)

```
ListNode* findMiddleNode(ListNode* head) {
    ListNode *slow = head, *fast = head;
    while (fast && fast->next) {
        slow = slow->next;
        fast = fast->next->next;
    }
    return slow;
}

// Unit tests
void testMiddleNode() {
    ListNode* head = insertNode(NULL, 1);
    head = insertNode(head, 2);
    head = insertNode(head, 3);
    ListNode* middle = findMiddleNode(head);
    assertEquals(2, middle->val, "Test 308.1 - Find middle node");
    free(head->next->next);
    free(head->next);
    free(head);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle empty or single-node lists.
 - Use slow-fast for O(1) space.
 - Return second middle for even lists.
 - Test with odd/even lengths.
- **Expert Tips:**
 - Explain slow-fast: "Slow reaches middle when fast reaches end."
 - In interviews, clarify: "Ask about even-length handling."
 - Suggest optimization: "Count nodes for alternative approach."
 - Test edge cases: "Empty list, two nodes."

Problem 309: Delete a Node from a Linked List

Issue Description

Delete a given node (not head or tail) from a singly linked list.

Problem Decomposition & Solution Steps

- **Input:** Pointer to node to delete (not head/tail).
- **Output:** Updated linked list.
- **Approach:** Copy next node's value, skip next node.
- **Algorithm:** Node Deletion
 - **Explanation:** Copy next node's value to current, update pointers.
- **Steps:**
 1. Validate node and next pointer.
 2. Copy next node's value to current.
 3. Update current's next to skip next node.
 4. Free next node.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The deletion algorithm assumes the node to delete is neither head nor tail.

It copies the next node's value to the current node, updates the current node's next pointer to skip the next node, and frees the next node.

This is O(1) with O(1) space.

Coding Part (with Unit Tests)

```
void deleteGivenNode(ListNode* node) {  
    if (!node || !node->next) return;  
    ListNode* temp = node->next;  
    node->val = temp->val;  
    node->next = temp->next;  
    free(temp);  
}  
  
// Unit tests  
void testDeleteNode() {  
    ListNode* head = insertNode(NULL, 1);  
    head = insertNode(head, 2);  
    head = insertNode(head, 3);  
    deleteGivenNode(head->next); // Delete 2  
    assertEquals(1, head->val, "Test 309.1 - Head after delete");  
    assertEquals(1, head->next->val, "Test 309.2 - Next after delete");  
    free(head->next);  
    free(head);  
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate node and next pointer.
 - Free deleted node.
 - Handle edge cases carefully.
 - Test with middle nodes.
- **Expert Tips:**
 - Explain deletion: "Copy next node's value, skip it."

- In interviews, clarify: "Ask about head/tail deletion."
- Suggest optimization: "Use for non-middle nodes if needed."
- Test edge cases: "Invalid node, last node."

Problem 310: Check if a Linked List is a Palindrome

Issue Description

Check if a singly linked list is a palindrome.

Problem Decomposition & Solution Steps

- **Input:** Head of linked list.
- **Output:** Boolean indicating palindrome.
- **Approach:** Find middle, reverse second half, compare.
- **Algorithm:** Palindrome Check
 - **Explanation:** Use slow-fast to find middle, reverse second half, compare with first.
- **Steps:**
 1. Find middle using slow-fast pointers.
 2. Reverse second half of list.
 3. Compare first and second halves.
 4. Restore list (optional).
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The palindrome check finds the middle node using slow-fast pointers, reverses the second half, and compares it with the first half.

If values match, it's a palindrome.

The list can be restored by reversing the second half again.

This is O(n) for n nodes, with O(1) space.

Coding Part (with Unit Tests)

```
bool isPalindrome(ListNode* head) {
    if (!head || !head->next) return true;
    ListNode* slow = head, *fast = head;
    while (fast->next && fast->next->next) {
        slow = slow->next;
        fast = fast->next->next;
    }
    ListNode* secondHalf = reverseList(slow->next);
    ListNode* p1 = head, *p2 = secondHalf;
    while (p2) {
        if (p1->val != p2->val) return false;
        p1 = p1->next;
        p2 = p2->next;
    }
    return true;
}
```

```

// Unit tests
void testPalindrome() {
    ListNode* head = insertNode(NULL, 1);
    head = insertNode(head, 2);
    head = insertNode(head, 1);
    assertBoolEquals(true, isPalindrome(head), "Test 310.1 - Palindrome 1-2-1");
    free(head->next->next);
    free(head->next);
    free(head);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle empty/single-node lists.
 - Use slow-fast for middle.
 - Restore list if required.
 - Test with odd/even lengths.
- **Expert Tips:**
 - Explain palindrome: "Reverse second half, compare."
 - In interviews, clarify: "Ask about modifying list."
 - Suggest optimization: "Use stack for O(n) space alternative."
 - Test edge cases: "Non-palindrome, single node."

Problem 311: Implement a Priority Queue Using a Heap

Issue Description

Implement a max-heap-based priority queue with insert and extract-max.

Problem Decomposition & Solution Steps

- **Input:** Values to insert, extract max.
- **Output:** Priority queue operations.
- **Approach:** Use array-based max-heap.
- **Algorithm:** Max-Heap Priority Queue
 - **Explanation:** Insert at end and bubble up; extract max from root, heapify.
- **Steps:**
 1. Insert: Add at end, bubble up to maintain heap.
 2. Extract max: Remove root, move last to root, heapify down.
- **Complexity:** Insert $O(\log n)$, Extract $O(\log n)$, Space $O(n)$.

Algorithm Explanation

The max-heap priority queue stores elements in an array where parent nodes are greater than children.

Insert adds an element at the end and bubbles it up by swapping with parents.

Extract-max removes the root, moves the last element to the root, and heapifies down.

Both operations are $O(\log n)$ for n elements, with $O(n)$ space.

Coding Part (with Unit Tests)

```
#define MAX_HEAP_SIZE 100

typedef struct {
    int data[MAX_HEAP_SIZE];
    int size;
} PriorityQueue;

// Initialize priority queue
void initPriorityQueue(PriorityQueue* pq) {
    pq->size = 0;
}

// Bubble up after insert
void bubbleUp(PriorityQueue* pq, int index) {
    while (index > 0) {
        int parent = (index - 1) / 2;
        if (pq->data[index] <= pq->data[parent]) break;
        int temp = pq->data[index];
        pq->data[index] = pq->data[parent];
        pq->data[parent] = temp;
        index = parent;
    }
}

// Heapify down after extract
void heapifyDown(PriorityQueue* pq, int index) {
    int maxIndex = index;
    while (true) {
        int left = 2 * index + 1, right = 2 * index + 2;
        if (left < pq->size && pq->data[left] > pq->data[maxIndex]) maxIndex = left;
        if (right < pq->size && pq->data[right] > pq->data[maxIndex]) maxIndex = right;
        if (maxIndex == index) break;
        int temp = pq->data[index];
        pq->data[index] = pq->data[maxIndex];
        pq->data[maxIndex] = temp;
        index = maxIndex;
    }
}

// Insert to priority queue
bool insertPQ(PriorityQueue* pq, int val) {
    if (pq->size >= MAX_HEAP_SIZE) return false;
    pq->data[pq->size++] = val;
    bubbleUp(pq, pq->size - 1);
    return true;
}

// Extract max from priority queue
bool extractMax(PriorityQueue* pq, int* val) {
    if (pq->size == 0) return false;
    *val = pq->data[0];
    pq->data[0] = pq->data[--pq->size];
    heapifyDown(pq, 0);
    return true;
}

// Unit tests
void testPriorityQueue() {
    PriorityQueue pq;
    initPriorityQueue(&pq);
    insertPQ(&pq, 5);
```

```

    insertPQ(&pq, 3);
    int val;
    extractMax(&pq, &val);
    assertEquals(5, val, "Test 311.1 - Extract max");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Check for heap overflow/underflow.
 - Maintain max-heap property.
 - Validate operations.
 - Test with multiple inserts/extracts.
- **Expert Tips:**
 - Explain max-heap: "Parent greater than children."
 - In interviews, clarify: "Ask about min-heap or resizing."
 - Suggest optimization: "Use dynamic array for flexibility."
 - Test edge cases: "Empty heap, single element."

Problem 312: Find the Intersection Point of Two Linked Lists

Issue Description

Find the node where two singly linked lists intersect.

Problem Decomposition & Solution Steps

- **Input:** Heads of two linked lists.
- **Output:** Intersection node or NULL.
- **Approach:** Equalize lengths, traverse together.
- **Algorithm:** Intersection Detection
 - **Explanation:** Traverse both lists, switch heads when reaching end.
- **Steps:**
 1. Traverse both lists, switching heads at end.
 2. If pointers meet, that's the intersection.
 3. Return NULL if no intersection.
- **Complexity:** Time $O(n + m)$, Space $O(1)$.

Algorithm Explanation

The intersection detection algorithm traverses both lists, switching to the other list's head when reaching the end.

If an intersection exists, pointers meet at the intersection node after equalizing lengths.

This is $O(n + m)$ for n and m nodes, with $O(1)$ space.

Coding Part (with Unit Tests)

```
ListNode* getIntersectionNode(ListNode* headA, ListNode* headB) {
    ListNode *a = headA, *b = headB;
    while (a != b) {
        a = a ? a->next : headB;
        b = b ? b->next : headA;
    }
    return a;
}

// Unit tests
void testIntersection() {
    ListNode* common = insertNode(NULL, 3);
    ListNode* l1 = insertNode(common, 1);
    ListNode* l2 = insertNode(common, 2);
    assertEquals(3, getIntersectionNode(l1, l2)->val, "Test 312.1 - Find intersection");
    free(common);
    free(l1);
    free(l2);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle no intersection case.
 - Use O(1) space approach.
 - Check for NULL inputs.
 - Test with intersecting lists.
- **Expert Tips:**
 - Explain intersection: "Equalize lengths, traverse together."
 - In interviews, clarify: "Ask about cycle or length."
 - Suggest optimization: "Length-based approach as alternative."
 - Test edge cases: "No intersection, same length."

Problem 313: Implement a Double-Ended Queue (Deque)

Issue Description

Implement a deque with push/pop from both ends.

Problem Decomposition & Solution Steps

- **Input:** Values to push/pop, front/back.
- **Output:** Deque operations.
- **Approach:** Use circular array for efficient access.
- **Algorithm:** Circular Deque
 - **Explanation:** Push/pop at front/rear with wrap-around.
- **Steps:**
 1. Initialize array, front, rear, size.
 2. Push front: Decrement front, add value.
 3. Push back: Increment rear, add value.
 4. Pop front/back: Remove and adjust pointers.
- **Complexity:** Time O(1) per operation, Space O(n).

Algorithm Explanation

The deque uses a circular array with front and rear pointers.

Push front decrements front (mod capacity) and adds a value; push back increments rear.

Pop front/back removes values and adjusts pointers.

All operations are O(1), with O(n) space for n elements.

Coding Part (with Unit Tests)

```
#define MAX_DEQUE_SIZE 100

typedef struct {
    int data[MAX_DEQUE_SIZE];
    int front, rear, size;
} Deque;

// Initialize deque
void initDeque(Deque* d) {
    d->front = 0;
    d->rear = -1;
    d->size = 0;
}

// Push front
bool pushFront(Deque* d, int val) {
    if (d->size >= MAX_DEQUE_SIZE) return false;
    d->front = (d->front - 1 + MAX_DEQUE_SIZE) % MAX_DEQUE_SIZE;
    d->data[d->front] = val;
    d->size++;
    return true;
}

// Push back
bool pushBack(Deque* d, int val) {
    if (d->size >= MAX_DEQUE_SIZE) return false;
    d->rear = (d->rear + 1) % MAX_DEQUE_SIZE;
    d->data[d->rear] = val;
    d->size++;
    return true;
}

// Pop front
bool popFront(Deque* d, int* val) {
    if (d->size == 0) return false;
    *val = d->data[d->front];
    d->front = (d->front + 1) % MAX_DEQUE_SIZE;
    d->size--;
    return true;
}

// Pop back
bool popBack(Deque* d, int* val) {
    if (d->size == 0) return false;
    *val = d->data[d->rear];
    d->rear = (d->rear - 1 + MAX_DEQUE_SIZE) % MAX_DEQUE_SIZE;
    d->size--;
    return true;
}
```

```

// Unit tests
void testDeque() {
    Deque d;
    initDeque(&d);
    pushFront(&d, 1);
    pushBack(&d, 2);
    int val;
    popFront(&d, &val);
    assertEquals(1, val, "Test 313.1 - Pop front");
    popBack(&d, &val);
    assertEquals(2, val, "Test 313.2 - Pop back");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track size for full/empty checks.
 - Use modulo for wrap-around.
 - Handle edge cases.
 - Test push/pop combinations.
- **Expert Tips:**
 - Explain deque: "FIFO/LIFO with front/back access."
 - In interviews, clarify: "Ask about array vs. linked list."
 - Suggest optimization: "Use dynamic array for resizing."
 - Test edge cases: "Full deque, empty deque."

Problem 314: Remove the nth Node from the End of a Linked List

Issue Description

Remove the nth node from the end of a singly linked list.

Problem Decomposition & Solution Steps

- **Input:** Head of linked list, n (position from end).
- **Output:** Updated linked list.
- **Approach:** Use two pointers with n-node gap.
- **Algorithm:** Two-Pointer Removal
 - **Explanation:** Advance fast pointer n steps, then move both until fast reaches end.
- **Steps:**
 1. Advance fast pointer n steps.
 2. Move slow and fast until fast reaches end.
 3. Remove node after slow.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The two-pointer removal algorithm advances a fast pointer n steps ahead, then moves both slow and fast pointers until fast reaches the end.

The slow pointer is then at the node before the one to delete.

This is O(n) for n nodes, with O(1) space.

Coding Part (with Unit Tests)

```
ListNode* removeNthFromEnd(ListNode* head, int n) {
    ListNode dummy = {0, head}, *slow = &dummy, *fast = head;
    for (int i = 0; i < n; i++) {
        if (!fast) return head;
        fast = fast->next;
    }
    while (fast) {
        slow = slow->next;
        fast = fast->next;
    }
    ListNode* temp = slow->next;
    slow->next = temp->next;
    free(temp);
    return dummy.next;
}

// Unit tests
void testRemoveNth() {
    ListNode* head = insertNode(NULL, 1);
    head = insertNode(head, 2);
    head = insertNode(head, 3);
    head = removeNthFromEnd(head, 2);
    assertEquals(3, head->val, "Test 314.1 - Remove 2nd from end");
    free(head->next);
    free(head);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use dummy node for head deletion.
 - Validate n and list length.
 - Free deleted node.
 - Test with different n values.
- **Expert Tips:**
 - Explain two-pointer: "Maintain n-node gap to find target."
 - In interviews, clarify: "Ask about valid n range."
 - Suggest optimization: "Count length as alternative."
 - Test edge cases: "n equals list length, single node."

Problem 315: Implement a Binary Search Tree (Insert and Search)

Issue Description

Implement a binary search tree (BST) with insert and search operations.

Problem Decomposition & Solution Steps

- **Input:** Values to insert, value to search.
- **Output:** Inserted BST, search result (node or NULL).
- **Approach:** Use recursive insert and search.
- **Algorithm:** BST Insert/Search
 - **Explanation:** Insert maintains BST property; search finds node.
- **Steps:**
 1. Insert: Recursively find position, add node.
 2. Search: Recursively traverse based on value comparison.
- **Complexity:** Time $O(h)$ (h is tree height), Space $O(h)$ for recursion.

Algorithm Explanation

The BST insert algorithm recursively traverses the tree, inserting a new node in the correct position based on value comparison (left if smaller, right if larger).

Search follows the same logic to find a node.

For a balanced tree, operations are $O(\log n)$; worst-case $O(n)$ for n nodes, with $O(h)$ space for recursion.

Coding Part (with Unit Tests)

```
typedef struct TreeNode {
    int val;
    struct TreeNode *left, *right;
} TreeNode;

// Insert into BST
TreeNode* insertBST(TreeNode* root, int val) {
    if (!root) {
        TreeNode* newNode = (TreeNode*)malloc(sizeof(TreeNode));
        newNode->val = val;
        newNode->left = newNode->right = NULL;
        return newNode;
    }
    if (val < root->val) {
        root->left = insertBST(root->left, val);
    } else {
        root->right = insertBST(root->right, val);
    }
    return root;
}

// Search BST
TreeNode* searchBST(TreeNode* root, int val) {
    if (!root || root->val == val) return root;
    return val < root->val ? searchBST(root->left, val) : searchBST(root->right, val);
}

// Unit tests
void testBST() {
    TreeNode* root = NULL;
    root = insertBST(root, 5);
    root = insertBST(root, 3);
    TreeNode* node = searchBST(root, 3);
    assertEquals(3, node->val, "Test 315.1 - Insert and search");
    free(root->left);
    free(root);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Maintain BST property ($\text{left} < \text{root} < \text{right}$).
 - Handle duplicate values.
 - Free nodes on cleanup.
 - Test with multiple inserts/searches.
- **Expert Tips:**
 - Explain BST: "Ordered tree for efficient search."
 - In interviews, clarify: "Ask about duplicates or balancing."
 - Suggest optimization: "Use AVL/red-black for balance."
 - Test edge cases: "Empty tree, non-existent value."

Problem 316: Find the kth Node from the End of a Linked List

Issue Description

Find the kth node from the end of a singly linked list.

Problem Decomposition & Solution Steps

- **Input:** Head of linked list, k (position from end).
- **Output:** kth node from end or NULL.
- **Approach:** Use two pointers with k-node gap.
- **Algorithm:** Two-Pointer kth Node
 - **Explanation:** Advance fast k steps, move both until fast reaches end.
- **Steps:**
 1. Advance fast pointer k steps.
 2. Move slow and fast until fast reaches end.
 3. Return slow (kth node from end).
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The two-pointer algorithm advances a fast pointer k steps ahead, then moves both slow and fast pointers until fast reaches the end.

The slow pointer is at the kth node from the end.

This is O(n) for n nodes, with O(1) space.

Coding Part (with Unit Tests)

```
ListNode* findKthFromEnd(ListNode* head, int k) {  
    ListNode* fast = head, *slow = head;  
    for (int i = 0; i < k; i++) {  
        if (!fast) return NULL;  
        fast = fast->next;  
    }
```

```

        while (fast) {
            slow = slow->next;
            fast = fast->next;
        }
        return slow;
    }

// Unit tests
void testKthFromEnd() {
    ListNode* head = insertNode(NULL, 1);
    head = insertNode(head, 2);
    head = insertNode(head, 3);
    ListNode* kth = findKthFromEnd(head, 2);
    assertEquals(2, kth->val, "Test 316.1 - 2nd from end");
    free(head->next);
    free(head->next);
    free(head);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate k and list length.
 - Handle NULL cases.
 - Use two-pointer approach.
 - Test with different k values.
- **Expert Tips:**
 - Explain two-pointer: "Maintain k-node gap."
 - In interviews, clarify: "Ask about valid k range."
 - Suggest optimization: "Count length as alternative."
 - Test edge cases: "k larger than length, k=1."

Main Function to Run All Tests

```

int main() {
    printf("Running tests for data structures problems 301 to 316:\n");
    testLinkedList();
    testReverseList();
    testCycleDetection();
    testMergeLists();
    testStack();
    testQueue();
    testCircularQueue();
    testMiddleNode();
    testDeleteNode();
    testPalindrome();
    testPriorityQueue();
    testIntersection();
    testDeque();
    testRemoveNth();
    testBST();
    testKthFromEnd();
    return 0;
}

```

Problem 317: Implement a Stack with a getMin() Function

Issue Description

Implement a stack with push, pop, and getMin operations, where getMin returns the minimum element in O(1) time.

Problem Decomposition & Solution Steps

- **Input:** Values to push/pop, get minimum.
- **Output:** Stack operations, minimum value.
- **Approach:** Use two stacks: one for data, one for minimums.
- **Algorithm:** Min Stack
 - **Explanation:** Push/pop on data stack; maintain min stack with current minimums.
- **Steps:**
 1. Push: Add to data stack; update min stack if value \leq current min.
 2. Pop: Remove from data stack; pop min stack if values match.
 3. GetMin: Return top of min stack.
- **Complexity:** Time O(1) per operation, Space O(n).

Algorithm Explanation

The min stack uses two arrays: one for data, one for tracking minimums.

Push adds a value to the data stack and to the min stack if it's \leq the current minimum.

Pop removes from the data stack and min stack if the popped value equals the current minimum.

GetMin reads the min stack's top.

All operations are O(1), with O(n) space for n elements.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>

#define MAX_STACK_SIZE 100

typedef struct {
    int data[MAX_STACK_SIZE];
    int min[MAX_STACK_SIZE];
    int top;
} MinStack;

// Initialize min stack
void initMinStack(MinStack* stack) {
    stack->top = -1;
}
```

```

// Push to min stack
bool pushMinStack(MinStack* stack, int val) {
    if (stack->top >= MAX_STACK_SIZE - 1) return false;
    stack->data[++stack->top] = val;
    if (stack->top == 0 || val <= stack->min[stack->top - 1]) {
        stack->min[stack->top] = val;
    } else {
        stack->min[stack->top] = stack->min[stack->top - 1];
    }
    return true;
}

// Pop from min stack
bool popMinStack(MinStack* stack, int* val) {
    if (stack->top < 0) return false;
    *val = stack->data[stack->top--];
    return true;
}

// Get minimum
bool getMin(MinStack* stack, int* val) {
    if (stack->top < 0) return false;
    *val = stack->min[stack->top];
    return true;
}

// Unit test helper
void assertIntEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit test helper
void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testMinStack() {
    MinStack stack;
    initMinStack(&stack);
    pushMinStack(&stack, 3);
    pushMinStack(&stack, 5);
    pushMinStack(&stack, 2);
    int min;
    getMin(&stack, &min);
    assertIntEquals(2, min, "Test 317.1 - Get minimum");
    int val;
    popMinStack(&stack, &val);
    getMin(&stack, &min);
    assertIntEquals(3, min, "Test 317.2 - Min after pop");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Check for stack overflow/underflow.
 - Maintain min stack for O(1) getMin.
 - Update min stack only when necessary.
 - Test push/pop/getMin sequences.
- **Expert Tips:**
 - Explain min stack: "Track minimums with second stack."
 - In interviews, clarify: "Ask about space optimization."

- Suggest optimization: "Use single stack with differences."
- Test edge cases: "Empty stack, same minimums."

Problem 318: Implement a Queue Using a Linked List

Issue Description

Implement a queue (FIFO) with enqueue and dequeue operations using a linked list.

Problem Decomposition & Solution Steps

- **Input:** Values to enqueue/dequeue.
- **Output:** Queue operations.
- **Approach:** Use singly linked list with head and tail pointers.
- **Algorithm:** Linked List Queue
 - **Explanation:** Enqueue at tail, dequeue from head.
- **Steps:**
 1. Enqueue: Add node at tail, update tail.
 2. Dequeue: Remove node from head, update head.
- **Complexity:** Time O(1) per operation, Space O(n).

Algorithm Explanation

The linked list queue maintains head and tail pointers.

Enqueue creates a new node, sets it as the tail's next, and updates the tail.

Dequeue removes the head node and updates the head.

Both operations are O(1), with O(n) space for n nodes.

Coding Part (with Unit Tests)

```
typedef struct ListNode {
    int val;
    struct ListNode* next;
} ListNode;

typedef struct {
    ListNode *head, *tail;
} QueueLL;

// Initialize queue
void initQueueLL(QueueLL* q) {
    q->head = q->tail = NULL;
}
```

```

// Enqueue
bool enqueueLL(QueueLL* q, int val) {
    ListNode* newNode = (ListNode*)malloc(sizeof(ListNode));
    if (!newNode) return false;
    newNode->val = val;
    newNode->next = NULL;
    if (!q->head) {
        q->head = q->tail = newNode;
    } else {
        q->tail->next = newNode;
        q->tail = newNode;
    }
    return true;
}

// Dequeue
bool dequeueLL(QueueLL* q, int* val) {
    if (!q->head) return false;
    ListNode* temp = q->head;
    *val = temp->val;
    q->head = q->head->next;
    if (!q->head) q->tail = NULL;
    free(temp);
    return true;
}

// Unit tests
void testQueueLL() {
    QueueLL q;
    initQueueLL(&q);
    enqueueLL(&q, 1);
    enqueueLL(&q, 2);
    int val;
    dequeueLL(&q, &val);
    assertIntEquals(1, val, "Test 318.1 - Dequeue first");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Maintain tail pointer for O(1) enqueue.
 - Free dequeued nodes.
 - Handle empty queue.
 - Test enqueue/dequeue sequences.
- **Expert Tips:**
 - Explain queue: "FIFO with head/tail pointers."
 - In interviews, clarify: "Ask about memory constraints."
 - Suggest optimization: "Use doubly linked list for flexibility."
 - Test edge cases: "Empty queue, single node."

Problem 319: Reverse a Linked List in Groups of k

Issue Description

Reverse a singly linked list in groups of k nodes.

Problem Decomposition & Solution Steps

- **Input:** Head of linked list, k.
- **Output:** Head of list with k-node groups reversed.
- **Approach:** Reverse k nodes at a time, link groups.
- **Algorithm:** K-Group Reversal
 - **Explanation:** Reverse k nodes, recurse for next group.
- **Steps:**
 1. Check if k nodes exist.
 2. Reverse k nodes using prev/curr/next pointers.
 3. Recurse for remaining nodes.
 4. Link reversed group to next group.
- **Complexity:** Time O(n), Space O(n/k) for recursion.

Algorithm Explanation

The k-group reversal algorithm checks if k nodes exist, reverses them by updating next pointers, and recursively processes the next group.

The reversed group's tail links to the next group's head.

This is O(n) for n nodes, with O(n/k) recursion depth.

Coding Part (with Unit Tests)

```
ListNode* reverseKGroup(ListNode* head, int k) {  
    if (!head || k == 1) return head;  
    ListNode* curr = head;  
    int count = 0;  
    while (curr && count < k) {  
        curr = curr->next;  
        count++;  
    }  
    if (count < k) return head;  
    ListNode* nextGroup = reverseKGroup(curr, k);  
    ListNode *prev = NULL, *next;  
    curr = head;  
    for (int i = 0; i < k; i++) {  
        next = curr->next;  
        curr->next = prev;  
        prev = curr;  
        curr = next;  
    }  
    head->next = nextGroup;  
    return prev;  
}  
  
// Unit tests  
void testReverseKGroup() {  
    ListNode* head = insertNode(NULL, 1); // From Problem 301  
    head = insertNode(head, 2);  
    head = insertNode(head, 3);  
    head = reverseKGroup(head, 2);  
    assertEquals(2, head->val, "Test 319.1 - Reverse k=2");  
    free(head->next->next);  
    free(head->next);  
    free(head);  
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate k and list length.
 - Handle partial groups.
 - Link reversed groups correctly.
 - Test with different k values.
- **Expert Tips:**
 - Explain k-group: "Reverse k nodes, recurse for rest."
 - In interviews, clarify: "Ask about handling partial groups."
 - Suggest optimization: "Iterative for O(1) space."
 - Test edge cases: "k=1, k larger than list."

Problem 320: Implement a Trie for String Storage

Issue Description

Implement a trie to store and search strings.

Problem Decomposition & Solution Steps

- **Input:** Strings to insert, string to search.
- **Output:** Trie operations, search result.
- **Approach:** Use trie node with 26 children (lowercase letters).
- **Algorithm:** Trie Insert/Search
 - **Explanation:** Insert builds paths for characters; search checks path.
- **Steps:**
 1. Insert: Create nodes for each character, mark end.
 2. Search: Traverse nodes for characters, check end flag.
- **Complexity:** Time $O(m)$ per operation (m is string length), Space $O(m)$.

Algorithm Explanation

The trie uses a node with 26 children (for a-z) and an end-of-word flag.

Insert creates a path for each character, marking the last node.

Search follows the path, returning true if the end flag is set.

Both operations are $O(m)$ for string length m , with $O(m)$ space per string.

Coding Part (with Unit Tests)

```
typedef struct TrieNode {
    struct TrieNode* children[26];
    bool isEnd;
} TrieNode;
```

```

typedef struct {
    TrieNode* root;
} Trie;

// Initialize trie
Trie* initTrie() {
    Trie* trie = (Trie*)malloc(sizeof(Trie));
    trie->root = (TrieNode*)malloc(sizeof(TrieNode));
    for (int i = 0; i < 26; i++) trie->root->children[i] = NULL;
    trie->root->isEnd = false;
    return trie;
}

// Insert string
void insertTrie(Trie* trie, const char* str) {
    TrieNode* node = trie->root;
    for (int i = 0; str[i]; i++) {
        int idx = str[i] - 'a';
        if (!node->children[idx]) {
            node->children[idx] = (TrieNode*)malloc(sizeof(TrieNode));
            for (int j = 0; j < 26; j++) node->children[idx]->children[j] = NULL;
            node->children[idx]->isEnd = false;
        }
        node = node->children[idx];
    }
    node->isEnd = true;
}

// Search string
bool searchTrie(Trie* trie, const char* str) {
    TrieNode* node = trie->root;
    for (int i = 0; str[i]; i++) {
        int idx = str[i] - 'a';
        if (!node->children[idx]) return false;
        node = node->children[idx];
    }
    return node->isEnd;
}

// Unit tests
void testTrie() {
    Trie* trie = initTrie();
    insertTrie(trie, "test");
    assertBoolEquals(true, searchTrie(trie, "test"), "Test 320.1 - Insert and search");
    assertBoolEquals(false, searchTrie(trie, "tes"), "Test 320.2 - Non-existent string");
    // Free trie (simplified for brevity)
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Initialize children to NULL.
 - Handle lowercase letters only (for simplicity).
 - Free trie nodes on cleanup.
 - Test with multiple strings.
- **Expert Tips:**
 - Explain trie: "Tree for prefix-based string storage."
 - In interviews, clarify: "Ask about character set."
 - Suggest optimization: "Use array for small alphabets."
 - Test edge cases: "Empty string, prefix search."

Problem 321: Find the Lowest Common Ancestor in a BST

Issue Description

Find the lowest common ancestor (LCA) of two nodes in a BST.

Problem Decomposition & Solution Steps

- **Input:** BST root, two node values.
- **Output:** LCA node.
- **Approach:** Use BST property to traverse to LCA.
- **Algorithm:** BST LCA
 - **Explanation:** Traverse based on value comparison.
- **Steps:**
 1. Compare node values with root.
 2. If both smaller, go left; if both larger, go right.
 3. If split, root is LCA.
- **Complexity:** Time O(h), Space O(1) (iterative).

Algorithm Explanation

The LCA algorithm uses the BST property: if both values are less than the root, traverse left; if both greater, traverse right; if one is less and one greater, the root is the LCA.

This is O(h) for tree height h, with O(1) space for iterative solution.

Coding Part (with Unit Tests)

```
TreeNode* lowestCommonAncestorBST(TreeNode* root, int p, int q) {
    while (root) {
        if (p < root->val && q < root->val) {
            root = root->left;
        } else if (p > root->val && q > root->val) {
            root = root->right;
        } else {
            return root;
        }
    }
    return NULL;
}

// Unit tests
void testLCA_BST() {
    TreeNode* root = insertBST(NULL, 5); // From Problem 315
    root = insertBST(root, 3);
    root = insertBST(root, 7);
    TreeNode* lca = lowestCommonAncestorBST(root, 3, 7);
    assertEquals(5, lca->val, "Test 321.1 - LCA of 3 and 7");
    free(root->left);
    free(root->right);
    free(root);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use BST property for efficiency.
 - Handle NULL root.
 - Assume values exist in tree.
 - Test with different node pairs.
- **Expert Tips:**
 - Explain LCA: "Find node splitting two values."
 - In interviews, clarify: "Ask about non-BST or missing values."
 - Suggest optimization: "Recursive for clarity."
 - Test edge cases: "Same node, root as LCA."

Problem 322: Balance a BST

Issue Description

Balance a BST to ensure $O(\log n)$ height.

Problem Decomposition & Solution Steps

- **Input:** BST root.
- **Output:** Balanced BST root.
- **Approach:** Convert to sorted array, rebuild balanced BST.
- **Algorithm:** BST Balancing
 - **Explanation:** In-order traversal to array, build BST from sorted array.
- **Steps:**
 1. Perform in-order traversal to get sorted array.
 2. Build balanced BST by selecting middle element as root.
 3. Recursively build left/right subtrees.
- **Complexity:** Time $O(n)$, Space $O(n)$.

Algorithm Explanation

The balancing algorithm performs an in-order traversal to store nodes in a sorted array ($O(n)$).

It then builds a balanced BST by recursively selecting the middle element as the root, ensuring $O(\log n)$ height.

This is $O(n)$ time and space for n nodes.

Coding Part (with Unit Tests)

```
void inOrderToArray(TreeNode* root, int* arr, int* index) {
    if (!root) return;
    inOrderToArray(root->left, arr, index);
    arr[(*index)++] = root->val;
    inOrderToArray(root->right, arr, index);
}
```

```

TreeNode* sortedArrayToBST(int* arr, int start, int end) {
    if (start > end) return NULL;
    int mid = start + (end - start) / 2;
    TreeNode* root = (TreeNode*)malloc(sizeof(TreeNode));
    root->val = arr[mid];
    root->left = sortedArrayToBST(arr, start, mid - 1);
    root->right = sortedArrayToBST(arr, mid + 1, end);
    return root;
}

TreeNode* balanceBST(TreeNode* root) {
    int arr[100], index = 0;
    inOrderToArray(root, arr, &index);
    return sortedArrayToBST(arr, 0, index - 1);
}

// Unit tests
void testBalanceBST() {
    TreeNode* root = insertBST(NULL, 1);
    root = insertBST(root, 2);
    root = insertBST(root, 3);
    root = balanceBST(root);
    assertEquals(2, root->val, "Test 322.1 - Balanced root");
    free(root->left);
    free(root->right);
    free(root);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use in-order for sorted values.
 - Handle empty tree.
 - Free original nodes.
 - Test with unbalanced trees.
- **Expert Tips:**
 - Explain balancing: "Convert to sorted array, rebuild BST."
 - In interviews, clarify: "Ask about AVL/red-black trees."
 - Suggest optimization: "Use AVL for self-balancing."
 - Test edge cases: "Single node, linear tree."

Problem 323: Check if a Binary Tree is a BST

Issue Description

Check if a binary tree satisfies the BST property.

Problem Decomposition & Solution Steps

- **Input:** Binary tree root.
- **Output:** Boolean indicating BST.
- **Approach:** Check if each node's value is within valid range.
- **Algorithm:** BST Validation
 - **Explanation:** Recursively validate node values in range [min, max].

- **Steps:**
 1. For each node, check value in [min, max].
 2. Update ranges for left ($\max = \text{node-}>\text{val}$) and right ($\min = \text{node-}>\text{val}$).
 3. Recurse for subtrees.
- **Complexity:** Time $O(n)$, Space $O(h)$ for recursion.

Algorithm Explanation

The BST validation algorithm recursively checks if each node's value lies within a valid range.

The root starts with $[-\infty, +\infty]$, left subtree uses $[\min, \text{parent-} > \text{val}]$, and right uses $[\text{parent-} > \text{val}, \max]$.

This is $O(n)$ for n nodes, with $O(h)$ space for recursion depth h .

Coding Part (with Unit Tests)

```
#include <limits.h>

bool isValidBSTHelper(TreeNode* root, long min, long max) {
    if (!root) return true;
    if (root->val <= min || root->val >= max) return false;
    return isValidBSTHelper(root->left, min, root->val) && isValidBSTHelper(root->right, root->val, max);
}

bool isValidBST(TreeNode* root) {
    return isValidBSTHelper(root, LONG_MIN, LONG_MAX);
}

// Unit tests
void testIsValidBST() {
    TreeNode* root = insertBST(NULL, 2);
    root = insertBST(root, 1);
    root = insertBST(root, 3);
    assertBoolEquals(true, isValidBST(root), "Test 323.1 - Valid BST");
    free(root->left);
    free(root->right);
    free(root);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use long for min/max to handle edge cases.
 - Validate entire subtrees.
 - Handle empty tree.
 - Test with valid/invalid BSTs.
- **Expert Tips:**
 - Explain BST check: "Ensure values in valid range."
 - In interviews, clarify: "Ask about duplicates."
 - Suggest optimization: "In-order traversal alternative."
 - Test edge cases: "Invalid BST, single node."

Problem 324: Traverse a Tree In-Order

Issue Description

Perform an in-order traversal of a binary tree.

Problem Decomposition & Solution Steps

- **Input:** Binary tree root.
- **Output:** Array of node values in in-order.
- **Approach:** Recursively traverse left, root, right.
- **Algorithm:** In-Order Traversal
 - **Explanation:** Visit left subtree, root, right subtree.
- **Steps:**
 1. Recurse on left subtree.
 2. Visit root (store value).
 3. Recurse on right subtree.
- **Complexity:** Time $O(n)$, Space $O(n + h)$ for array and recursion.

Algorithm Explanation

In-order traversal visits nodes in left-root-right order, producing sorted values for a BST.

It recursively traverses the left subtree, adds the root's value to an array, then traverses the right subtree.

This is $O(n)$ for n nodes, with $O(n)$ space for the output array and $O(h)$ for recursion.

Coding Part (with Unit Tests)

```
void inOrderTraversalHelper(TreeNode* root, int* arr, int* index) {
    if (!root) return;
    inOrderTraversalHelper(root->left, arr, index);
    arr[(*index)++] = root->val;
    inOrderTraversalHelper(root->right, arr, index);
}

int* inOrderTraversal(TreeNode* root, int* returnSize) {
    int* arr = (int*)malloc(100 * sizeof(int));
    *returnSize = 0;
    inOrderTraversalHelper(root, arr, returnSize);
    return arr;
}

// Unit tests
void testInOrderTraversal() {
    TreeNode* root = insertBST(NULL, 2);
    root = insertBST(root, 1);
    root = insertBST(root, 3);
    int returnSize;
    int* result = inOrderTraversal(root, &returnSize);
    assertEquals(1, result[0], "Test 324.1 - In-order first element");
    free(result);
    free(root->left);
    free(root->right);
    free(root);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle NULL nodes.
 - Use array for output.
 - Free allocated memory.
 - Test with different tree structures.
- **Expert Tips:**
 - Explain in-order: "Left-root-right for sorted BST output."
 - In interviews, clarify: "Ask about iterative solution."
 - Suggest optimization: "Use stack for iterative traversal."
 - Test edge cases: "Empty tree, single node."

Problem 325: Find the Height of a Binary Tree

Issue Description

Find the height of a binary tree (longest path from root to leaf).

Problem Decomposition & Solution Steps

- **Input:** Binary tree root.
- **Output:** Height (integer).
- **Approach:** Recursively compute max height of subtrees.
- **Algorithm:** Tree Height
 - **Explanation:** Height is max of left/right subtree heights + 1.
- **Steps:**
 1. If NULL, return -1 (empty tree).
 2. Recursively compute left and right heights.
 3. Return $\max(\text{left}, \text{right}) + 1$.
- **Complexity:** Time $O(n)$, Space $O(h)$ for recursion.

Algorithm Explanation

The height algorithm recursively computes the height of left and right subtrees.

The tree's height is the maximum of these plus 1 (for the root).

An empty tree has height -1.

This is $O(n)$ for n nodes, with $O(h)$ space for recursion depth h .

Coding Part (with Unit Tests)

```
int treeHeight(TreeNode* root) {  
    if (!root) return -1;  
    int leftHeight = treeHeight(root->left);  
    int rightHeight = treeHeight(root->right);  
    return leftHeight > rightHeight ? leftHeight + 1 : rightHeight + 1;  
}
```

```

// Unit tests
void testTreeHeight() {
    TreeNode* root = insertBST(NULL, 1);
    root = insertBST(root, 2);
    root = insertBST(root, 3);
    assertEquals(1, treeHeight(root), "Test 325.1 - Tree height");
    free(root->left);
    free(root->right);
    free(root);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle empty tree (-1 height).
 - Use recursive approach for simplicity.
 - Test with unbalanced trees.
- **Expert Tips:**
 - Explain height: "Longest root-to-leaf path."
 - In interviews, clarify: "Ask about height definition (edges/nodes)."
 - Suggest optimization: "Iterative with stack for large trees."
 - Test edge cases: "Empty tree, single node."

Problem 326: Delete a Node from a BST

Issue Description

Delete a node with a given value from a BST.

Problem Decomposition & Solution Steps

- **Input:** BST root, value to delete.
- **Output:** Updated BST root.
- **Approach:** Find node, handle cases (leaf, one child, two children).
- **Algorithm:** BST Deletion
 - **Explanation:** Replace node with successor or adjust pointers.
- **Steps:**
 1. Find node to delete.
 2. If leaf, remove it.
 3. If one child, replace with child.
 4. If two children, replace with in-order successor.
- **Complexity:** Time O(h), Space O(h) for recursion.

Algorithm Explanation

The BST deletion algorithm finds the node with the given value.

If it's a leaf, remove it; if it has one child, replace with the child; if it has two children, replace with the in-order successor (smallest in right subtree) and delete the successor.

This is O(h) for tree height h, with O(h) space for recursion.

Coding Part (with Unit Tests)

```
TreeNode* findMinBST(TreeNode* root) {
    while (root->left) root = root->left;
    return root;
}

TreeNode* deleteBST(TreeNode* root, int val) {
    if (!root) return NULL;
    if (val < root->val) {
        root->left = deleteBST(root->left, val);
    } else if (val > root->val) {
        root->right = deleteBST(root->right, val);
    } else {
        if (!root->left) {
            TreeNode* temp = root->right;
            free(root);
            return temp;
        } else if (!root->right) {
            TreeNode* temp = root->left;
            free(root);
            return temp;
        }
        TreeNode* successor = findMinBST(root->right);
        root->val = successor->val;
        root->right = deleteBST(root->right, successor->val);
    }
    return root;
}

// Unit tests
void testDeleteBST() {
    TreeNode* root = insertBST(NULL, 5);
    root = insertBST(root, 3);
    root = insertBST(root, 7);
    root = deleteBST(root, 3);
    assertBoolEquals(true, searchBST(root, 3) == NULL, "Test 326.1 - Delete node");
    free(root->right);
    free(root);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Maintain BST property.
 - Handle all cases (leaf, one/two children).
 - Free deleted nodes.
 - Test with different node types.
- **Expert Tips:**
 - Explain deletion: "Replace with successor for two children."
 - In interviews, clarify: "Ask about predecessor vs. successor."
 - Suggest optimization: "Iterative for O(1) space."
 - Test edge cases: "Non-existent value, root deletion."

Problem 327: Merge Two Binary Trees

Issue Description

Merge two binary trees by summing node values.

Problem Decomposition & Solution Steps

- **Input:** Roots of two binary trees.
- **Output:** Merged binary tree.
- **Approach:** Recursively merge nodes, summing values.
- **Algorithm:** Tree Merge
 - **Explanation:** Sum corresponding nodes, recurse for subtrees.
- **Steps:**
 1. If one node is NULL, return other.
 2. Sum node values, create new node.
 3. Recursively merge left and right subtrees.
- **Complexity:** Time $O(\min(n, m))$, Space $O(\min(h_1, h_2))$ for recursion.

Algorithm Explanation

The merge algorithm recursively processes both trees.

If one node is NULL, use the other; otherwise, sum the values, create a new node, and recurse for left and right subtrees.

This is $O(\min(n, m))$ for n and m nodes, with $O(\min(h_1, h_2))$ space for recursion.

Coding Part (with Unit Tests)

```
TreeNode* mergeTrees(TreeNode* t1, TreeNode* t2) {
    if (!t1) return t2;
    if (!t2) return t1;
    TreeNode* merged = (TreeNode*)malloc(sizeof(TreeNode));
    merged->val = t1->val + t2->val;
    merged->left = mergeTrees(t1->left, t2->left);
    merged->right = mergeTrees(t1->right, t2->right);
    return merged;
}

// Unit tests
void testMergeTrees() {
    TreeNode* t1 = insertBST(NULL, 1);
    TreeNode* t2 = insertBST(NULL, 2);
    TreeNode* merged = mergeTrees(t1, t2);
    assertEquals(3, merged->val, "Test 327.1 - Merge root values");
    free(merged);
    free(t1);
    free(t2);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle NULL nodes.
 - Allocate new nodes for merge.
 - Free original trees if needed.
 - Test with different tree shapes.
- **Expert Tips:**
 - Explain merge: "Sum corresponding nodes recursively."
 - In interviews, clarify: "Ask about in-place merge."
 - Suggest optimization: "Modify one tree to save memory."
 - Test edge cases: "One empty tree, same structure."

Problem 328: Implement a Circular Linked List with Insert

Issue Description

Implement a circular linked list with insertion at the head.

Problem Decomposition & Solution Steps

- **Input:** Value to insert, circular list head.
- **Output:** Updated circular linked list.
- **Approach:** Use singly linked list with last node pointing to head.
- **Algorithm:** Circular List Insert
 - **Explanation:** Insert at head, update last node's next pointer.
- **Steps:**
 1. Allocate new node.
 2. If empty, point to itself.
 3. Otherwise, insert at head, update last node's next.
- **Complexity:** Time $O(n)$ for insert (to find last), Space $O(1)$.

Algorithm Explanation

The circular linked list insert algorithm allocates a new node.

If the list is empty, the node points to itself.

Otherwise, it's inserted at the head, and the last node's next pointer is updated to the new head.

Finding the last node takes $O(n)$, with $O(1)$ space for pointers.

Coding Part (with Unit Tests)

```
ListNode* insertCircular(ListNode* head, int val) {
    ListNode* newNode = (ListNode*)malloc(sizeof(ListNode));
    newNode->val = val;
    if (!head) {
        newNode->next = newNode;
        return newNode;
    }
    newNode->next = head;
    ListNode* curr = head;
    while (curr->next != head) curr = curr->next;
    curr->next = newNode;
    return newNode;
}

// Unit tests
void testCircularList() {
    ListNode* head = insertCircular(NULL, 1);
    head = insertCircular(head, 2);
    assertEquals(2, head->val, "Test 328.1 - Insert head");
    head->next->next = NULL; // Break cycle for cleanup
    free(head->next);
    free(head);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Update last node's next pointer.
 - Handle empty list.
 - Break cycle before freeing.
 - Test with multiple inserts.
- **Expert Tips:**
 - Explain circular list: "Last node points to head."
 - In interviews, clarify: "Ask about insertion position."
 - Suggest optimization: "Use tail pointer for O(1) insert."
 - Test edge cases: "Empty list, single node."

Problem 329: Check if a Binary Tree is Balanced

Issue Description

Check if a binary tree is height-balanced (difference in subtree heights ≤ 1).

Problem Decomposition & Solution Steps

- **Input:** Binary tree root.
- **Output:** Boolean indicating balanced tree.
- **Approach:** Compute heights, check balance recursively.
- **Algorithm:** Balanced Tree Check
 - **Explanation:** Check if subtree height difference ≤ 1 .
- **Steps:**
 1. Recursively compute left/right heights.
 2. Return -1 if unbalanced, else height.

- 3. Tree is balanced if root's check returns non-negative.
- **Complexity:** Time O(n), Space O(h) for recursion.

Algorithm Explanation

The balanced tree check computes subtree heights recursively.

If the height difference exceeds 1, return -1 (unbalanced); otherwise, return the height.

The tree is balanced if the root's check returns a non-negative height.

This is O(n) for n nodes, with O(h) space for recursion.

Coding Part (with Unit Tests)

```

int checkHeight(TreeNode* root) {
    if (!root) return -1;
    int leftHeight = checkHeight(root->left);
    if (leftHeight == -1) return -1;
    int rightHeight = checkHeight(root->right);
    if (rightHeight == -1 || abs(leftHeight - rightHeight) > 1) return -1;
    return (leftHeight > rightHeight ? leftHeight : rightHeight) + 1;
}

bool isBalanced(TreeNode* root) {
    return checkHeight(root) != -1;
}

// Unit tests
void testIsBalanced() {
    TreeNode* root = insertBST(NULL, 1);
    root = insertBST(root, 2);
    root = insertBST(root, 3);
    assertBoolEquals(false, isBalanced(root), "Test 329.1 - Unbalanced BST");
    free(root->left);
    free(root->right);
    free(root);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Combine height and balance checks.
 - Handle empty tree.
 - Use -1 for unbalanced indicator.
 - Test with balanced/unbalanced trees.
- **Expert Tips:**
 - Explain balance: "Height difference ≤ 1 for all nodes."
 - In interviews, clarify: "Ask about balance definition."
 - Suggest optimization: "Top-down approach for clarity."
 - Test edge cases: "Empty tree, single path."

Problem 330: Serialize a Binary Tree

Issue Description

Serialize a binary tree to a string and deserialize it back.

Problem Decomposition & Solution Steps

- **Input:** Binary tree root (serialize), string (deserialize).
- **Output:** String (serialize), tree root (deserialize).
- **Approach:** Use pre-order traversal with NULL markers.
- **Algorithm:** Serialize/Deserialize
 - **Explanation:** Serialize with pre-order; deserialize with queue.
- **Steps:**
 1. Serialize: Pre-order traverse, append values/NULL.
 2. Deserialize: Split string, rebuild tree recursively.
- **Complexity:** Time $O(n)$, Space $O(n)$ for both.

Algorithm Explanation

Serialization uses pre-order traversal (root, left, right), appending node values and “null” for NULL nodes.

Deserialization splits the string into a queue and recursively rebuilds the tree by processing values in pre-order.

Both are $O(n)$ for n nodes, with $O(n)$ space for the string/queue.

Coding Part (with Unit Tests)

```
void serializeHelper(TreeNode* root, char* str, int* index) {
    if (!root) {
        *index += sprintf(str + *index, "null,");
        return;
    }
    *index += sprintf(str + *index, "%d,", root->val);
    serializeHelper(root->left, str, index);
    serializeHelper(root->right, str, index);
}

char* serialize(TreeNode* root) {
    char* str = (char*)malloc(1000 * sizeof(char));
    int index = 0;
    serializeHelper(root, str, &index);
    str[index] = '\0';
    return str;
}

TreeNode* deserializeHelper(char** tokens, int* index) {
    if (strcmp(tokens[*index], "null") == 0) {
        (*index)++;
        return NULL;
    }
    TreeNode* root = (TreeNode*)malloc(sizeof(TreeNode));
    root->val = atoi(tokens[(*index)++]);
    root->left = deserializeHelper(tokens, index);
    root->right = deserializeHelper(tokens, index);
    return root;
}
```

```

TreeNode* deserialize(char* str) {
    char* tokens[100];
    int tokenCount = 0;
    char* token = strtok(str, ",");
    while (token) {
        tokens[tokenCount++] = token;
        token = strtok(NULL, ",");
    }
    int index = 0;
    return deserializeHelper(tokens, &index);
}

// Unit tests
void testSerialize() {
    TreeNode* root = insertBST(NULL, 1);
    root = insertBST(root, 2);
    char* serialized = serialize(root);
    TreeNode* deserialized = deserialize(serialized);
    assertEquals(1, deserialized->val, "Test 330.1 - Serialize/deserialize");
    free(serialized);
    free(deserialized);
    free(root->left);
    free(root);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use NULL markers for structure.
 - Handle string parsing carefully.
 - Free allocated memory.
 - Test with complex trees.
- **Expert Tips:**
 - Explain serialize: "Pre-order with NULL markers."
 - In interviews, clarify: "Ask about serialization format."
 - Suggest optimization: "Use level-order for compactness."
 - Test edge cases: "Empty tree, single node."

Problem 331: Find the Maximum Path Sum in a Binary Tree

Issue Description

Find the maximum path sum in a binary tree (any node to any node).

Problem Decomposition & Solution Steps

- **Input:** Binary tree root.
- **Output:** Maximum path sum.
- **Approach:** Recursively compute max path through each node.
- **Algorithm:** Max Path Sum
 - **Explanation:** Track max path through root, return max branch.
- **Steps:**
 1. Recursively compute max path for left/right subtrees.
 2. Update global max with path through root.
 3. Return max branch sum for parent.

- **Complexity:** Time O(n), Space O(h) for recursion.

Algorithm Explanation

The max path sum algorithm computes the maximum path through each node (left + root + right) and updates a global maximum.

For parent nodes, it returns the maximum branch sum (root + max(left, right)).

This is O(n) for n nodes, with O(h) space for recursion.

Coding Part (with Unit Tests)

```

int maxPathSumHelper(TreeNode* root, int* globalMax) {
    if (!root) return 0;
    int left = maxPathSumHelper(root->left, globalMax);
    int right = maxPathSumHelper(root->right, globalMax);
    left = left > 0 ? left : 0;
    right = right > 0 ? right : 0;
    *globalMax = (*globalMax > left + root->val + right) ? *globalMax : left + root->val + right;
    return (left > right ? left : right) + root->val;
}

int maxPathSum(TreeNode* root) {
    int globalMax = INT_MIN;
    maxPathSumHelper(root, &globalMax);
    return globalMax;
}

// Unit tests
void testMaxPathSum() {
    TreeNode* root = insertBST(NULL, 1);
    root = insertBST(root, 2);
    root = insertBST(root, 3);
    assertEquals(6, maxPathSum(root), "Test 331.1 - Max path sum");
    free(root->left);
    free(root->right);
    free(root);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle negative sums (use 0 if negative).
 - Track global maximum.
 - Handle single-node case.
 - Test with negative values.
- **Expert Tips:**
 - Explain max path: "Max sum through any path."
 - In interviews, clarify: "Ask about path constraints."
 - Suggest optimization: "Handle edge cases explicitly."
 - Test edge cases: "Negative values, single node."

Problem 332: Implement a Queue with O(1) Enqueue and Dequeue

Issue Description

Implement a queue with O(1) enqueue and dequeue using an array.

Problem Decomposition & Solution Steps

- **Input:** Values to enqueue/dequeue.
- **Output:** Queue operations.
- **Approach:** Use circular array (same as Problem 307).
- **Algorithm:** Circular Queue
 - **Explanation:** Enqueue at rear, dequeue from front, wrap pointers.
- **Steps:**
 1. Initialize array, front, rear, size.
 2. Enqueue: Add at rear, increment rear (mod capacity).
 3. Dequeue: Remove from front, increment front (mod capacity).
- **Complexity:** Time O(1) per operation, Space O(n).

Algorithm Explanation

The circular queue uses a fixed-size array with front and rear pointers.

Enqueue adds at rear, wrapping with modulo.

Dequeue removes from front, also wrapping.

All operations are O(1), with O(n) space for n elements.

This reuses Problem 307's implementation for consistency.

Coding Part (with Unit Tests)

```
#define MAX_QUEUE_SIZE 100

typedef struct {
    int data[MAX_QUEUE_SIZE];
    int front, rear, size;
} CircularQueue;

// Initialize circular queue
void initCircularQueue(CircularQueue* q) {
    q->front = 0;
    q->rear = -1;
    q->size = 0;
}

// Enqueue
bool enqueueCircular(CircularQueue* q, int val) {
    if (q->size >= MAX_QUEUE_SIZE) return false;
    q->rear = (q->rear + 1) % MAX_QUEUE_SIZE;
    q->data[q->rear] = val;
    q->size++;
    return true;
}
```

```

// Dequeue
bool dequeueCircular(CircularQueue* q, int* val) {
    if (q->size == 0) return false;
    *val = q->data[q->front];
    q->front = (q->front + 1) % MAX_QUEUE_SIZE;
    q->size--;
    return true;
}

// Unit tests
void testCircularQueue01() {
    CircularQueue q;
    initCircularQueue(&q);
    enqueueCircular(&q, 1);
    int val;
    dequeueCircular(&q, &val);
    assertEquals(1, val, "Test 332.1 - O(1) dequeue");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track size for full/empty checks.
 - Use modulo for wrap-around.
 - Handle overflow/underflow.
 - Test O(1) operations.
- **Expert Tips:**
 - Explain circular queue: "O(1) FIFO with array wrap."
 - In interviews, clarify: "Ask about resizing or linked list."
 - Suggest optimization: "Power-of-2 size for fast modulo."
 - Test edge cases: "Full queue, empty queue."

Main Function to Run All Tests

```

int main() {
    printf("Running tests for data structures problems 317 to 332:\n");
    testMinStack();
    testQueueLL();
    testReverseKGroup();
    testTrie();
    testLCA_BST();
    testBalanceBST();
    testIsValidBST();
    testInOrderTraversal();
    testTreeHeight();
    testDeleteBST();
    testMergeTrees();
    testCircularList();
    testIsBalanced();
    testSerialize();
    testMaxPathSum();
    testCircularQueue01();
    return 0;
}

```

Problem 333: Reverse a Stack Using Recursion

Issue Description

Reverse a stack using only recursive calls and the stack's own operations.

Problem Decomposition & Solution Steps

- **Input:** Stack (array-based from Problem 305).
- **Output:** Reversed stack.
- **Approach:** Use recursion to pop elements and insert at bottom.
- **Algorithm:** Recursive Stack Reversal
 - **Explanation:** Pop top element, recurse, insert popped element at bottom.
- **Steps:**
 1. Pop top element.
 2. Recursively reverse remaining stack.
 3. Insert popped element at bottom using recursion.
- **Complexity:** Time $O(n^2)$, Space $O(n)$ for recursion.

Algorithm Explanation

The recursive reversal pops the top element, recursively reverses the remaining stack, and inserts the popped element at the bottom by recursively popping and pushing elements.

This is $O(n^2)$ due to repeated push/pop for each element, with $O(n)$ space for recursion.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>

#define MAX_STACK_SIZE 100

typedef struct {
    int data[MAX_STACK_SIZE];
    int top;
} Stack;

// Initialize stack (from Problem 305)
void initStack(Stack* stack) {
    stack->top = -1;
}

// Push to stack
bool push(Stack* stack, int val) {
    if (stack->top >= MAX_STACK_SIZE - 1) return false;
    stack->data[++stack->top] = val;
    return true;
}

// Pop from stack
bool pop(Stack* stack, int* val) {
    if (stack->top < 0) return false;
    *val = stack->data[stack->top--];
    return true;
}
```

```

// Insert at bottom
void insertAtBottom(Stack* stack, int val) {
    if (stack->top < 0) {
        push(stack, val);
        return;
    }
    int temp;
    pop(stack, &temp);
    insertAtBottom(stack, val);
    push(stack, temp);
}

// Reverse stack
void reverseStack(Stack* stack) {
    if (stack->top < 0) return;
    int val;
    pop(stack, &val);
    reverseStack(stack);
    insertAtBottom(stack, val);
}

// Unit test helper
void assertEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit test helper
void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testReverseStack() {
    Stack stack;
    initStack(&stack);
    push(&stack, 1);
    push(&stack, 2);
    push(&stack, 3);
    reverseStack(&stack);
    int val;
    pop(&stack, &val);
    assertEquals(1, val, "Test 333.1 - Reverse stack top");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Check stack bounds.
 - Use recursion carefully to avoid overflow.
 - Test with multiple elements.
- **Expert Tips:**
 - Explain recursion: "Pop and insert at bottom recursively."
 - In interviews, clarify: "Ask about auxiliary space."
 - Suggest optimization: "Use another stack for O(n) space."
 - Test edge cases: "Empty stack, single element."

Problem 334: Clone a Linked List with Random Pointers

Issue Description

Clone a linked list where each node has a random pointer.

Problem Decomposition & Solution Steps

- **Input:** Head of linked list with next and random pointers.
- **Output:** Head of cloned list.
- **Approach:** Interleave cloned nodes, set random pointers, separate lists.
- **Algorithm:** Interleave and Split
 - **Explanation:** Interleave original and cloned nodes, copy random pointers, split lists.
- **Steps:**
 1. Interleave cloned nodes (original->clone->original->clone).
 2. Set clone random pointers using original's random.next.
 3. Separate original and cloned lists.
- **Complexity:** Time O(n), Space O(1) excluding output.

Algorithm Explanation

The algorithm interleaves cloned nodes with the original list ($O(n)$), sets random pointers by using the interleaved structure ($O(n)$), and separates the lists ($O(n)$).

This achieves $O(n)$ time with $O(1)$ space, excluding the cloned list's space.

Coding Part (with Unit Tests)

```
typedef struct RandomListNode {
    int val;
    struct RandomListNode *next, *random;
} RandomListNode;

RandomListNode* copyRandomList(RandomListNode* head) {
    if (!head) return NULL;
    // Step 1: Interleave
    RandomListNode* curr = head;
    while (curr) {
        RandomListNode* clone = (RandomListNode*)malloc(sizeof(RandomListNode));
        clone->val = curr->val;
        clone->next = curr->next;
        curr->next = clone;
        curr = clone->next;
    }
    // Step 2: Set random pointers
    curr = head;
    while (curr) {
        if (curr->random) curr->next->random = curr->random->next;
        curr = curr->next->next;
    }
    // Step 3: Separate lists
    RandomListNode dummy = {0, NULL}, *cloneCurr = &dummy;
    curr = head;
    while (curr) {
        cloneCurr->next = curr->next;
        curr->next = curr->next->next;
        cloneCurr = cloneCurr->next;
    }
}
```

```

        curr = curr->next;
    }
    return dummy.next;
}

// Unit tests
void testCopyRandomList() {
    RandomListNode* head = (RandomListNode*)malloc(sizeof(RandomListNode));
    head->val = 1; head->next = NULL; head->random = head;
    RandomListNode* clone = copyRandomList(head);
    assertEquals(1, clone->val, "Test 334.1 - Clone value");
    free(clone);
    free(head);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle NULL random pointers.
 - Free memory in tests.
 - Validate interleave/separation.
 - Test with random pointers.
- **Expert Tips:**
 - Explain interleave: "Clone nodes between originals."
 - In interviews, clarify: "Ask about space constraints."
 - Suggest optimization: "Hash map for O(n) space."
 - Test edge cases: "No random pointers, single node."

Problem 335: Find the Diameter of a Binary Tree

Issue Description

Find the diameter of a binary tree (longest path between any two nodes).

Problem Decomposition & Solution Steps

- **Input:** Binary tree root.
- **Output:** Diameter (integer).
- **Approach:** Compute height and diameter recursively.
- **Algorithm:** Tree Diameter
 - **Explanation:** Diameter is max of left+right heights or subtree diameters.
- **Steps:**
 1. Compute left/right heights and diameters.
 2. Update global max with left+right+2.
 3. Return height for parent.
- **Complexity:** Time O(n), Space O(h) for recursion.

Algorithm Explanation

The diameter algorithm computes the height of each subtree and updates a global maximum with the sum of left and right heights (path through root) or the maximum subtree diameter.

It returns the height for parent calculations.

This is O(n) for n nodes, with O(h) space for recursion.

Coding Part (with Unit Tests)

```
typedef struct TreeNode {
    int val;
    struct TreeNode *left, *right;
} TreeNode;

int diameterHelper(TreeNode* root, int* maxDiameter) {
    if (!root) return -1;
    int left = diameterHelper(root->left, maxDiameter);
    int right = diameterHelper(root->right, maxDiameter);
    *maxDiameter = (*maxDiameter > left + right + 2) ? *maxDiameter : left + right + 2;
    return (left > right ? left : right) + 1;
}

int diameterOfBinaryTree(TreeNode* root) {
    int maxDiameter = 0;
    diameterHelper(root, &maxDiameter);
    return maxDiameter;
}

// Unit tests
void testDiameter() {
    TreeNode* root = (TreeNode*)malloc(sizeof(TreeNode));
    root->val = 1; root->left = root->right = NULL;
    root->left = (TreeNode*)malloc(sizeof(TreeNode));
    root->left->val = 2; root->left->left = root->left->right = NULL;
    assertEquals(1, diameterOfBinaryTree(root), "Test 335.1 - Diameter");
    free(root->left);
    free(root);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Track global maximum diameter.
 - Handle empty tree.
 - Use height-based approach.
 - Test with unbalanced trees.
- **Expert Tips:**
 - Explain diameter: "Longest path through or within subtrees."
 - In interviews, clarify: "Ask about edge vs. node count."
 - Suggest optimization: "Combine with height computation."
 - Test edge cases: "Single node, linear tree."

Problem 336: Check if a Tree is a Mirror

Issue Description

Check if a binary tree is a mirror of itself (symmetric).

Problem Decomposition & Solution Steps

- **Input:** Binary tree root.
- **Output:** Boolean indicating symmetry.
- **Approach:** Compare left and right subtrees recursively.
- **Algorithm:** Mirror Check
 - **Explanation:** Left subtree mirrors right subtree.
- **Steps:**
 1. Compare left and right subtrees.
 2. Check if values match and subtrees are mirrored.
 3. Recurse for left's left with right's right, and vice versa.
- **Complexity:** Time $O(n)$, Space $O(h)$ for recursion.

Algorithm Explanation

The mirror check recursively compares the left and right subtrees.

For each pair, ensure values match, left's left mirrors right's right, and left's right mirrors right's left.

This is $O(n)$ for n nodes, with $O(h)$ space for recursion.

Coding Part (with Unit Tests)

```
bool isMirrorHelper(TreeNode* left, TreeNode* right) {
    if (!left && !right) return true;
    if (!left || !right) return false;
    return left->val == right->val &&
           isMirrorHelper(left->left, right->right) &&
           isMirrorHelper(left->right, right->left);
}

bool isSymmetric(TreeNode* root) {
    if (!root) return true;
    return isMirrorHelper(root->left, root->right);
}

// Unit tests
void testIsSymmetric() {
    TreeNode* root = (TreeNode*)malloc(sizeof(TreeNode));
    root->val = 1; root->left = root->right = NULL;
    root->left = (TreeNode*)malloc(sizeof(TreeNode));
    root->right = (TreeNode*)malloc(sizeof(TreeNode));
    root->left->val = root->right->val = 2;
    root->left->left = root->left->right = root->right->left = root->right->right = NULL;
    assertBoolEquals(true, isSymmetric(root), "Test 336.1 - Symmetric tree");
    free(root->left);
    free(root->right);
    free(root);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle NULL subtrees.
 - Check value and structure symmetry.
 - Test with symmetric/asymmetric trees.
- **Expert Tips:**
 - Explain mirror: "Left mirrors right recursively."
 - In interviews, clarify: "Ask about value-only symmetry."
 - Suggest optimization: "Iterative with queue."
 - Test edge cases: "Empty tree, single node."

Problem 337: Merge Two Sorted Arrays into a BST

Issue Description

Merge two sorted arrays into a single BST.

Problem Decomposition & Solution Steps

- **Input:** Two sorted arrays.
- **Output:** BST root.
- **Approach:** Merge arrays, build BST from sorted array.
- **Algorithm:** Merge and BST Construction
 - **Explanation:** Merge arrays, use middle element as root.
- **Steps:**
 1. Merge sorted arrays into one sorted array.
 2. Build balanced BST by selecting middle element.
 3. Recursively build left/right subtrees.
- **Complexity:** Time $O(n + m + k \log k)$, Space $O(n + m)$ ($k = n + m$).

Algorithm Explanation

The algorithm merges two sorted arrays into one ($O(n + m)$), then builds a balanced BST by selecting the middle element as the root and recursively constructing subtrees ($O(k \log k)$ for $k = n + m$).

Total time is $O(n + m + k \log k)$, with $O(n + m)$ space.

Coding Part (with Unit Tests)

```
TreeNode* sortedArrayToBST(int* arr, int start, int end) {
    if (start > end) return NULL;
    int mid = start + (end - start) / 2;
    TreeNode* root = (TreeNode*)malloc(sizeof(TreeNode));
    root->val = arr[mid];
    root->left = sortedArrayToBST(arr, start, mid - 1);
    root->right = sortedArrayToBST(arr, mid + 1, end);
    return root;
}
```

```

TreeNode* mergeArraysToBST(int* arr1, int n1, int* arr2, int n2) {
    int* merged = (int*)malloc((n1 + n2) * sizeof(int));
    int i = 0, j = 0, k = 0;
    while (i < n1 && j < n2) {
        merged[k++] = arr1[i] <= arr2[j] ? arr1[i++] : arr2[j++];
    }
    while (i < n1) merged[k++] = arr1[i++];
    while (j < n2) merged[k++] = arr2[j++];
    TreeNode* root = sortedArrayToBST(merged, 0, k - 1);
    free(merged);
    return root;
}

// Unit tests
void testMergeArraysToBST() {
    int arr1[] = {1, 3}, arr2[] = {2, 4};
    TreeNode* root = mergeArraysToBST(arr1, 2, arr2, 2);
    assertEquals(2, root->val, "Test 337.1 - BST root");
    free(root->left);
    free(root->right);
    free(root);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Merge arrays efficiently.
 - Build balanced BST.
 - Free merged array.
 - Test with different array sizes.
- **Expert Tips:**
 - Explain merge: "Combine sorted arrays, build balanced BST."
 - In interviews, clarify: "Ask about duplicates."
 - Suggest optimization: "Direct BST insertion for O(n log n)."
 - Test edge cases: "Empty arrays, single element."

Problem 338: Find the kth Smallest Element in a BST

Issue Description

Find the kth smallest element in a BST.

Problem Decomposition & Solution Steps

- **Input:** BST root, k.
- **Output:** kth smallest value.
- **Approach:** In-order traversal with counter.
- **Algorithm:** In-Order kth Element
 - **Explanation:** In-order traversal gives sorted order, track kth element.
- **Steps:**
 1. Perform in-order traversal.
 2. Decrement k, return when k = 0.
- **Complexity:** Time O(h + k), Space O(h) for recursion.

Algorithm Explanation

The in-order traversal visits nodes in ascending order.

By tracking a counter, the kth visited node is the kth smallest.

The algorithm stops when k reaches 0.

This is $O(h + k)$ for tree height h and kth element, with $O(h)$ space for recursion.

Coding Part (with Unit Tests)

```
void kthSmallestHelper(TreeNode* root, int* k, int* result) {
    if (!root || *k <= 0) return;
    kthSmallestHelper(root->left, k, result);
    if (--(*k) == 0) *result = root->val;
    kthSmallestHelper(root->right, k, result);
}

int kthSmallest(TreeNode* root, int k) {
    int result = 0;
    kthSmallestHelper(root, &k, &result);
    return result;
}

// Unit tests
void testKthSmallest() {
    TreeNode* root = insertBST(NULL, 3); // From Problem 315
    root = insertBST(root, 1);
    root = insertBST(root, 4);
    assertEquals(3, kthSmallest(root, 2), "Test 338.1 - 2nd smallest");
    free(root->left);
    free(root->right);
    free(root);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use in-order for sorted order.
 - Validate k range.
 - Handle empty tree.
 - Test with different k values.
- **Expert Tips:**
 - Explain kth smallest: "In-order traversal with counter."
 - In interviews, clarify: "Ask about valid k."
 - Suggest optimization: "Use iterative in-order."
 - Test edge cases: "k=1, k=size of tree."

Problem 339: Check for a Loop Using Floyd's Algorithm

Issue Description

Check for a loop in a linked list using Floyd's cycle detection algorithm.

Problem Decomposition & Solution Steps

- **Input:** Head of linked list.
- **Output:** Boolean indicating cycle.
- **Approach:** Use slow and fast pointers (same as Problem 303).
- **Algorithm:** Floyd's Cycle Detection
 - **Explanation:** Slow moves one step, fast moves two; they meet if cycle exists.
- **Steps:**
 1. Initialize slow and fast to head.
 2. Move slow by 1, fast by 2 until they meet or fast reaches NULL.
 3. Return true if meeting, false otherwise.
- **Complexity:** Time $O(n)$, Space $O(1)$.

Algorithm Explanation

Floyd's cycle detection uses two pointers: slow moves one step, fast moves two.

If they meet, a cycle exists; if fast reaches NULL, there's no cycle.

This is $O(n)$ for n nodes, with $O(1)$ space.

This reuses Problem 303's implementation.

Coding Part (with Unit Tests)

```
typedef struct ListNode {
    int val;
    struct ListNode* next;
} ListNode;

bool hasCycle(ListNode* head) {
    ListNode *slow = head, *fast = head;
    while (fast && fast->next) {
        slow = slow->next;
        fast = fast->next->next;
        if (slow == fast) return true;
    }
    return false;
}

// Unit tests
void testHasCycle() {
    ListNode* head = (ListNode*)malloc(sizeof(ListNode));
    head->val = 1; head->next = head; // Create cycle
    assertBoolEquals(true, hasCycle(head), "Test 339.1 - Detect cycle");
    head->next = NULL;
    assertBoolEquals(false, hasCycle(head), "Test 339.2 - No cycle");
    free(head);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Check for NULL fast/next.
 - Use Floyd's for O(1) space.
 - Test with/without cycles.
- **Expert Tips:**
 - Explain Floyd's: "Slow/fast pointers meet in cycle."
 - In interviews, clarify: "Ask about space constraints."
 - Suggest optimization: "Hash table for O(n) space."
 - Test edge cases: "Empty list, single node."

Problem 340: Rotate a Linked List

Issue Description

Rotate a linked list to the right by k places.

Problem Decomposition & Solution Steps

- **Input:** Head of linked list, k.
- **Output:** Rotated linked list head.
- **Approach:** Find new tail, connect to head, update pointers.
- **Algorithm:** Linked List Rotation
 - **Explanation:** Move last k nodes to front.
- **Steps:**
 1. Find list length and last node.
 2. Compute effective k ($k \% \text{length}$).
 3. Find new tail ($\text{length} - k - 1$).
 4. Update pointers to rotate.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The rotation algorithm computes the list length, reduces k modulo length, finds the new tail ($\text{length} - k - 1$ nodes from head), sets its next to NULL, connects the old last node to the head, and returns the new head.

This is O(n) for n nodes, with O(1) space.

Coding Part (with Unit Tests)

```
ListNode* rotateRight(ListNode* head, int k) {  
    if (!head || !head->next || k == 0) return head;  
    ListNode* curr = head;  
    int length = 1;  
    while (curr->next) {  
        curr = curr->next;  
        length++;  
    }  
    curr->next = head;  
    head = curr;  
    curr = head;  
    for (int i = 0; i < k % length; i++) {  
        curr = curr->next;  
    }  
    head = curr->next;  
    curr->next = NULL;  
    return head;  
}
```

```

        k = k % length;
        if (k == 0) return head;
        curr->next = head; // Make circular
        curr = head;
        for (int i = 0; i < length - k - 1; i++) {
            curr = curr->next;
        }
        head = curr->next;
        curr->next = NULL;
        return head;
    }

    // Unit tests
    void testRotateRight() {
        ListNode* head = insertNode(NULL, 1); // From Problem 301
        head = insertNode(head, 2);
        head = rotateRight(head, 1);
        assertEquals(1, head->val, "Test 340.1 - Rotate right");
        free(head->next);
        free(head);
    }
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle $k > \text{length}$ with modulo.
 - Make list circular temporarily.
 - Test with different k values.
- **Expert Tips:**
 - Explain rotation: "Move last k nodes to front."
 - In interviews, clarify: "Ask about k range."
 - Suggest optimization: "Use two pointers for clarity."
 - Test edge cases: " $k=0$, single node."

Problem 341: Find the k th Largest Element in a BST

Issue Description

Find the k th largest element in a BST.

Problem Decomposition & Solution Steps

- **Input:** BST root, k .
- **Output:** k th largest value.
- **Approach:** Reverse in-order traversal with counter.
- **Algorithm:** Reverse In-Order k th Element
 - **Explanation:** Reverse in-order (right-root-left) gives descending order.
- **Steps:**
 1. Perform reverse in-order traversal.
 2. Decrement k , return when $k = 0$.
- **Complexity:** Time $O(h + k)$, Space $O(h)$ for recursion.

Algorithm Explanation

Reverse in-order traversal visits nodes in descending order (right-root-left).

By tracking a counter, the kth visited node is the kth largest.

The algorithm stops when k reaches 0.

This is $O(h + k)$ for tree height h and kth element, with $O(h)$ space for recursion.

Coding Part (with Unit Tests)

```
void KthLargestHelper(TreeNode* root, int* k, int* result) {
    if (!root || *k <= 0) return;
    KthLargestHelper(root->right, k, result);
    if (--(*k) == 0) *result = root->val;
    KthLargestHelper(root->left, k, result);
}

int KthLargest(TreeNode* root, int k) {
    int result = 0;
    KthLargestHelper(root, &k, &result);
    return result;
}

// Unit tests
void testKthLargest() {
    TreeNode* root = insertBST(NULL, 3);
    root = insertBST(root, 1);
    root = insertBST(root, 4);
    assertEquals(3, KthLargest(root, 2), "Test 341.1 - 2nd largest");
    free(root->left);
    free(root->right);
    free(root);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use reverse in-order for descending order.
 - Validate k range.
 - Handle empty tree.
 - Test with different k values.
- **Expert Tips:**
 - Explain kth largest: "Reverse in-order with counter."
 - In interviews, clarify: "Ask about valid k."
 - Suggest optimization: "Iterative reverse in-order."
 - Test edge cases: "k=1, k=size of tree."

Problem 342: Check if a Tree is a Complete Binary Tree

Issue Description

Check if a binary tree is complete (all levels except last are full, last level filled left-to-right).

Problem Decomposition & Solution Steps

- **Input:** Binary tree root.
- **Output:** Boolean indicating complete tree.
- **Approach:** Use level-order traversal with queue.
- **Algorithm:** Complete Tree Check
 - **Explanation:** Check for NULL nodes and ensure no non-NULL after NULL.
- **Steps:**
 1. Perform level-order traversal with queue.
 2. After first NULL, ensure all remaining nodes are NULL.
- **Complexity:** Time $O(n)$, Space $O(w)$ for queue (w is max width).

Algorithm Explanation

The algorithm uses a queue for level-order traversal.

It processes nodes until a NULL is encountered, then ensures all remaining nodes are NULL.

If a non-NULL node appears after a NULL, the tree is not complete.

This is $O(n)$ for n nodes, with $O(w)$ space for the queue.

Coding Part (with Unit Tests)

```
#define MAX_QUEUE_SIZE 100

typedef struct {
    TreeNode* data[MAX_QUEUE_SIZE];
    int front, rear;
} Queue;

void initQueue(Queue* q) {
    q->front = q->rear = -1;
}

bool enqueue(Queue* q, TreeNode* node) {
    if (q->rear >= MAX_QUEUE_SIZE - 1) return false;
    q->data[++q->rear] = node;
    if (q->front == -1) q->front = 0;
    return true;
}

bool dequeue(Queue* q, TreeNode** node) {
    if (q->front == -1 || q->front > q->rear) return false;
    *node = q->data[q->front++];
    return true;
}
```

```

bool isCompleteTree(TreeNode* root) {
    if (!root) return true;
    Queue q; initQueue(&q);
    enqueue(&q, root);
    bool seenNull = false;
    while (q.front <= q.rear) {
        TreeNode* node;
        dequeue(&q, &node);
        if (!node) {
            seenNull = true;
            continue;
        }
        if (seenNull) return false;
        enqueue(&q, node->left);
        enqueue(&q, node->right);
    }
    return true;
}

// Unit tests
void testIsCompleteTree() {
    TreeNode* root = insertBST(NULL, 1);
    root->left = (TreeNode*)malloc(sizeof(TreeNode));
    root->left->val = 2; root->left->left = root->left->right = NULL;
    root->right = (TreeNode*)malloc(sizeof(TreeNode));
    root->right->val = 3; root->right->left = root->right->right = NULL;
    assertBoolEquals(true, isCompleteTree(root), "Test 342.1 - Complete tree");
    free(root->left);
    free(root->right);
    free(root);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use level-order for completeness check.
 - Track NULL nodes.
 - Test with complete/incomplete trees.
- **Expert Tips:**
 - Explain complete tree: "Full levels, last level left-filled."
 - In interviews, clarify: "Ask about empty tree."
 - Suggest optimization: "Count nodes for alternative."
 - Test edge cases: "Empty tree, single node."

Problem 343: Deserialize a Binary Tree

Issue Description

Deserialize a binary tree from a string (reuses Problem 330's serialization format).

Problem Decomposition & Solution Steps

- **Input:** String (pre-order with NULL markers).
- **Output:** Binary tree root.
- **Approach:** Parse string, rebuild tree recursively.

- **Algorithm:** Deserialize Pre-Order
 - **Explanation:** Use pre-order traversal to rebuild tree.
- **Steps:**
 1. Split string into tokens.
 2. Recursively build tree using pre-order order.
 3. Handle NULL markers.
- **Complexity:** Time $O(n)$, Space $O(n)$ for tokens.

Algorithm Explanation

The deserialization algorithm splits the string into tokens (values or “null”) and recursively builds the tree in pre-order (root, left, right).

Each recursive call processes one token, creating a node or returning NULL.

This is $O(n)$ for n nodes, with $O(n)$ space for tokens.

Coding Part (with Unit Tests)

```
TreeNode* deserializeHelper(char** tokens, int* index) {
    if (strcmp(tokens[*index], "null") == 0) {
        (*index)++;
        return NULL;
    }
    TreeNode* root = (TreeNode*)malloc(sizeof(TreeNode));
    root->val = atoi(tokens[(*index)++]);
    root->left = deserializeHelper(tokens, index);
    root->right = deserializeHelper(tokens, index);
    return root;
}

TreeNode* deserialize(char* str) {
    char* tokens[100];
    int tokenCount = 0;
    char* token = strtok(str, ",");
    while (token) {
        tokens[tokenCount++] = token;
        token = strtok(NULL, ",");
    }
    int index = 0;
    return deserializeHelper(tokens, &index);
}

// Unit tests
void testDeserialize() {
    char str[] = "1,2,null,null,3,null,null";
    TreeNode* root = deserialize(str);
    assertEquals(1, root->val, "Test 343.1 - Deserialize root");
    free(root->left);
    free(root->right);
    free(root);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle NULL markers.
 - Validate string format.

- Free allocated nodes.
- Test with complex trees.
- **Expert Tips:**
 - Explain deserialize: "Rebuild with pre-order tokens."
 - In interviews, clarify: "Ask about serialization format."
 - Suggest optimization: "Level-order for compactness."
 - Test edge cases: "Empty string, single node."

Problem 344: Find the Sum of All Nodes in a Binary Tree

Issue Description

Compute the sum of all node values in a binary tree.

Problem Decomposition & Solution Steps

- **Input:** Binary tree root.
- **Output:** Sum of node values.
- **Approach:** Recursively sum nodes.
- **Algorithm:** Tree Sum
 - **Explanation:** Sum root and left/right subtrees.
- **Steps:**
 1. If NULL, return 0.
 2. Return root value + left sum + right sum.
- **Complexity:** Time O(n), Space O(h) for recursion.

Algorithm Explanation

The sum algorithm recursively computes the sum of left and right subtrees and adds the root's value.

An empty tree returns 0.

This is O(n) for n nodes, with O(h) space for recursion depth h.

Coding Part (with Unit Tests)

```
int sumOfNodes(TreeNode* root) {
    if (!root) return 0;
    return root->val + sumOfNodes(root->left) + sumOfNodes(root->right);
}

// Unit tests
void testSumOfNodes() {
    TreeNode* root = insertBST(NULL, 1);
    root = insertBST(root, 2);
    root = insertBST(root, 3);
    assertEquals(6, sumOfNodes(root), "Test 344.1 - Sum of nodes");
    free(root->left);
    free(root->right);
    free(root);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle empty tree.
 - Use recursive approach for simplicity.
 - Test with positive/negative values.
- **Expert Tips:**
 - Explain sum: "Recursively add all node values."
 - In interviews, clarify: "Ask about negative values."
 - Suggest optimization: "Iterative with stack."
 - Test edge cases: "Empty tree, single node."

Problem 345: Convert a BST to a Sorted Linked List

Issue Description

Convert a BST to a sorted singly linked list (in-order).

Problem Decomposition & Solution Steps

- **Input:** BST root.
- **Output:** Head of sorted linked list.
- **Approach:** In-order traversal to build list.
- **Algorithm:** BST to Linked List
 - **Explanation:** In-order traversal creates sorted list.
- **Steps:**
 1. Perform in-order traversal.
 2. Link nodes into a list.
 3. Use dummy node for simplicity.
- **Complexity:** Time $O(n)$, Space $O(h)$ for recursion.

Algorithm Explanation

The algorithm uses in-order traversal to visit BST nodes in ascending order, linking each node into a singly linked list.

A dummy node simplifies head management.

This is $O(n)$ for n nodes, with $O(h)$ space for recursion.

Coding Part (with Unit Tests)

```
void bstToListHelper(TreeNode* root, ListNode** curr) {  
    if (!root) return;  
    bstToListHelper(root->left, curr);  
    ListNode* newNode = (ListNode*)malloc(sizeof(ListNode));  
    newNode->val = root->val;  
    newNode->next = NULL;  
    (*curr)->next = newNode;  
    *curr = newNode;  
    bstToListHelper(root->right, curr);  
}
```

```

ListNode* bstToSortedList(TreeNode* root) {
    ListNode dummy = {0, NULL}, *curr = &dummy;
    bstToListHelper(root, &curr);
    return dummy.next;
}

// Unit tests
void testBSTToList() {
    TreeNode* root = insertBST(NULL, 2);
    root = insertBST(root, 1);
    root = insertBST(root, 3);
    ListNode* list = bstToSortedList(root);
    assertEquals(1, list->val, "Test 345.1 - Sorted list head");
    free(list->next->next);
    free(list->next);
    free(list);
    free(root->left);
    free(root->right);
    free(root);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use in-order for sorted order.
 - Use dummy node for list head.
 - Free original tree if needed.
 - Test with different BSTs.
- **Expert Tips:**
 - Explain conversion: "In-order to sorted list."
 - In interviews, clarify: "Ask about modifying BST."
 - Suggest optimization: "Iterative in-order."
 - Test edge cases: "Empty BST, single node."

Problem 346: Check if Two Binary Trees are Identical

Issue Description

Check if two binary trees are identical in structure and values.

Problem Decomposition & Solution Steps

- **Input:** Roots of two binary trees.
- **Output:** Boolean indicating identical trees.
- **Approach:** Recursively compare nodes.
- **Algorithm:** Tree Comparison
 - **Explanation:** Compare values and subtrees recursively.
- **Steps:**
 1. Check if both nodes are NULL or one is NULL.
 2. Compare node values.
 3. Recursively compare left and right subtrees.
- **Complexity:** Time O(min(n, m)), Space O(min(h1, h2)) for recursion.

Algorithm Explanation

The comparison algorithm checks if both nodes are NULL (identical), one is NULL (not identical), or values differ.

It then recursively compares left and right subtrees.

This is $O(\min(n, m))$ for n and m nodes, with $O(\min(h_1, h_2))$ space for recursion.

Coding Part (with Unit Tests)

```
bool isSameTree(TreeNode* p, TreeNode* q) {
    if (!p && !q) return true;
    if (!p || !q) return false;
    return p->val == q->val && isSameTree(p->left, q->left) && isSameTree(p->right, q->right);
}

// Unit tests
void testIsSameTree() {
    TreeNode* p = insertBST(NULL, 1);
    p = insertBST(p, 2);
    TreeNode* q = insertBST(NULL, 1);
    q = insertBST(q, 2);
    assertBoolEquals(true, isSameTree(p, q), "Test 346.1 - Identical trees");
    free(p->left);
    free(p);
    free(q->left);
    free(q);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle NULL cases.
 - Compare structure and values.
 - Test with identical/different trees.
- **Expert Tips:**
 - Explain comparison: "Recursive value and structure check."
 - In interviews, clarify: "Ask about value-only comparison."
 - Suggest optimization: "Iterative with stack."
 - Test edge cases: "Empty trees, single node."

Problem 347: Find the Maximum Depth of a Tree

Issue Description

Find the maximum depth of a binary tree (same as height, Problem 325).

Problem Decomposition & Solution Steps

- **Input:** Binary tree root.
- **Output:** Maximum depth (integer).
- **Approach:** Recursively compute max depth.

- **Algorithm:** Tree Depth
 - **Explanation:** Max of left/right depths + 1.
- **Steps:**
 1. If NULL, return 0.
 2. Compute left/right depths.
 3. Return max + 1.
- **Complexity:** Time O(n), Space O(h) for recursion.

Algorithm Explanation

The depth algorithm computes the maximum depth of left and right subtrees and returns the maximum plus 1.

An empty tree has depth 0.

This is O(n) for n nodes, with O(h) space for recursion.

This reuses Problem 325's implementation (adjusted for depth=0 for empty tree).

Coding Part (with Unit Tests)

```
int maxDepth(TreeNode* root) {
    if (!root) return 0;
    int leftDepth = maxDepth(root->left);
    int rightDepth = maxDepth(root->right);
    return (leftDepth > rightDepth ? leftDepth : rightDepth) + 1;
}

// Unit tests
void testMaxDepth() {
    TreeNode* root = insertBST(NULL, 1);
    root = insertBST(root, 2);
    assertEquals(2, maxDepth(root), "Test 347.1 - Max depth");
    free(root->left);
    free(root);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle empty tree (depth 0).
 - Use recursive approach.
 - Test with unbalanced trees.
- **Expert Tips:**
 - Explain depth: "Longest root-to-leaf path."
 - In interviews, clarify: "Ask about depth vs. height."
 - Suggest optimization: "Iterative with queue."
 - Test edge cases: "Empty tree, single node."

Problem 348: Merge Two BSTs

Issue Description

Merge two BSTs into a single BST.

Problem Decomposition & Solution Steps

- **Input:** Roots of two BSTs.
- **Output:** Root of merged BST.
- **Approach:** Convert to sorted arrays, merge, build BST.
- **Algorithm:** Merge BSTs
 - **Explanation:** In-order to arrays, merge arrays, build balanced BST.
- **Steps:**
 1. Perform in-order traversal for both BSTs.
 2. Merge sorted arrays.
 3. Build balanced BST from merged array.
- **Complexity:** Time $O(n + m + k \log k)$, Space $O(n + m)$ ($k = n + m$).

Algorithm Explanation

The algorithm performs in-order traversals to get sorted arrays ($O(n + m)$), merges them into one sorted array ($O(n + m)$), and builds a balanced BST by selecting middle elements ($O(k \log k)$).

Total time is $O(n + m + k \log k)$, with $O(n + m)$ space for arrays.

Coding Part (with Unit Tests)

```
void inOrderToArray(TreeNode* root, int* arr, int* index) {
    if (!root) return;
    inOrderToArray(root->left, arr, index);
    arr[(*index)++] = root->val;
    inOrderToArray(root->right, arr, index);
}

TreeNode* mergeBSTs(TreeNode* root1, TreeNode* root2) {
    int arr1[100], arr2[100], merged[200];
    int idx1 = 0, idx2 = 0, idxM = 0;
    inOrderToArray(root1, arr1, &idx1);
    inOrderToArray(root2, arr2, &idx2);
    int i = 0, j = 0;
    while (i < idx1 && j < idx2) {
        merged[idxM++] = arr1[i] <= arr2[j] ? arr1[i++] : arr2[j++];
    }
    while (i < idx1) merged[idxM++] = arr1[i++];
    while (j < idx2) merged[idxM++] = arr2[j++];
    return sortedArrayToBST(merged, 0, idxM - 1); // From Problem 337
}

// Unit tests
void testMergeBSTs() {
    TreeNode* root1 = insertBST(NULL, 2);
    root1 = insertBST(root1, 1);
    TreeNode* root2 = insertBST(NULL, 3);
    TreeNode* merged = mergeBSTs(root1, root2);
    assertEquals(2, merged->val, "Test 348.1 - Merged BST root");
    free(merged->left);
}
```

```

    free(merged->right);
    free(merged);
    free(root1->left);
    free(root1);
    free(root2);
}

```

Best Practices & Expert Tips

- **Best Practices:**

- Use in-order for sorted arrays.
- Merge efficiently.
- Build balanced BST.
- Test with different BST sizes.

- **Expert Tips:**

- Explain merge: "Convert to arrays, build balanced BST."
- In interviews, clarify: "Ask about duplicates."
- Suggest optimization: "Direct insertion for O(n log n)."
- Test edge cases: "Empty BSTs, single node."

Main Function to Run All Tests

```

int main() {
    printf("Running tests for data structures problems 333 to 348:\n");
    testReverseStack();
    testCopyRandomList();
    testDiameter();
    testIsSymmetric();
    testMergeArraysToBST();
    testKthSmallest();
    testHasCycle();
    testRotateRight();
    testKthLargest();
    testIsCompleteTree();
    testDeserialize();
    testSumOfNodes();
    testBSTToList();
    testIsSameTree();
    testMaxDepth();
    testMergeBSTs();
    return 0;
}

```

Problem 349: Find the kth Node in a Linked List

Issue Description

Find the kth node in a singly linked list (1-based indexing).

Problem Decomposition & Solution Steps

- **Input:** Head of linked list, k.
- **Output:** kth node pointer or NULL.
- **Approach:** Traverse list k times.

- **Algorithm:** kth Node
 - **Explanation:** Move pointer k steps from head.
- **Steps:**
 1. Validate k and list.
 2. Traverse k nodes, return pointer.
 3. Return NULL if k exceeds length.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The algorithm traverses the list k times from the head.

If k exceeds the list length or is invalid, return NULL.

Otherwise, return the kth node.

This is O(n) for n nodes, with O(1) space.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>

typedef struct ListNode {
    int val;
    struct ListNode* next;
} ListNode;

ListNode* kthNode(ListNode* head, int k) {
    if (k <= 0) return NULL;
    ListNode* curr = head;
    while (curr && k > 1) {
        curr = curr->next;
        k--;
    }
    return curr;
}

// Unit test helper
void assertIntEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit test helper
void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Helper: Insert node (from Problem 301)
ListNode* insertNode(ListNode* head, int val) {
    ListNode* newNode = (ListNode*)malloc(sizeof(ListNode));
    newNode->val = val;
    newNode->next = head;
    return newNode;
}
```

```

// Unit tests
void testKthNode() {
    ListNode* head = insertNode(NULL, 3);
    head = insertNode(head, 2);
    head = insertNode(head, 1);
    ListNode* kth = kthNode(head, 2);
    assertEquals(2, kth ? kth->val : -1, "Test 349.1 - 2nd node");
    free(head->next->next);
    free(head->next);
    free(head);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate $k > 0$.
 - Handle NULL head or $k > \text{length}$.
 - Test with different k values.
- **Expert Tips:**
 - Explain k th node: "Traverse k steps from head."
 - In interviews, clarify: "Ask about 1-based or 0-based indexing."
 - Suggest optimization: "Two-pointer for k th from end."
 - Test edge cases: " $k=1$, $k > \text{length}$, empty list."

Problem 350: Check if a Tree is Height-Balanced

Issue Description

Check if a binary tree is height-balanced (reuses Problem 329).

Problem Decomposition & Solution Steps

- **Input:** Binary tree root.
- **Output:** Boolean indicating balanced tree.
- **Approach:** Compute heights, check balance recursively.
- **Algorithm:** Balanced Tree Check
 - **Explanation:** Height difference ≤ 1 for all nodes.
- **Steps:**
 1. Compute left/right heights recursively.
 2. Return -1 if unbalanced, else height.
 3. Tree is balanced if root's check is non-negative.
- **Complexity:** Time $O(n)$, Space $O(h)$ for recursion.

Algorithm Explanation

The algorithm recursively computes subtree heights.

If the height difference exceeds 1, return -1; otherwise, return height.

The tree is balanced if the root's check returns non-negative.

This is $O(n)$ for n nodes, with $O(h)$ space for recursion (same as Problem 329).

Coding Part (with Unit Tests)

```
typedef struct TreeNode {
    int val;
    struct TreeNode *left, *right;
} TreeNode;

int checkHeight(TreeNode* root) {
    if (!root) return -1;
    int leftHeight = checkHeight(root->left);
    if (leftHeight == -1) return -1;
    int rightHeight = checkHeight(root->right);
    if (rightHeight == -1 || abs(leftHeight - rightHeight) > 1) return -1;
    return (leftHeight > rightHeight ? leftHeight : rightHeight) + 1;
}

bool isBalanced(TreeNode* root) {
    return checkHeight(root) != -1;
}

// Helper: Insert BST node (from Problem 315)
TreeNode* insertBST(TreeNode* root, int val) {
    if (!root) {
        root = (TreeNode*)malloc(sizeof(TreeNode));
        root->val = val;
        root->left = root->right = NULL;
        return root;
    }
    if (val < root->val) root->left = insertBST(root->left, val);
    else root->right = insertBST(root->right, val);
    return root;
}

// Unit tests
void testIsBalanced() {
    TreeNode* root = insertBST(NULL, 1);
    root = insertBST(root, 2);
    root = insertBST(root, 3);
    assertBoolEquals(false, isBalanced(root), "Test 350.1 - Unbalanced tree");
    free(root->left);
    free(root->right);
    free(root);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Combine height and balance checks.
 - Handle empty tree.
 - Test with balanced/unbalanced trees.
- **Expert Tips:**
 - Explain balance: "Height difference ≤ 1 for all nodes."
 - In interviews, clarify: "Ask about height definition."
 - Suggest optimization: "Top-down for clarity."
 - Test edge cases: "Empty tree, single path."

Problem 351: Perform Level-Order Traversal

Issue Description

Perform a level-order (breadth-first) traversal of a binary tree.

Problem Decomposition & Solution Steps

- **Input:** Binary tree root.
- **Output:** Array of node values in level order.
- **Approach:** Use queue for BFS.
- **Algorithm:** Level-Order Traversal
 - **Explanation:** Process nodes level by level using queue.
- **Steps:**
 1. Initialize queue with root.
 2. Dequeue node, add value, enqueue children.
 3. Repeat until queue is empty.
- **Complexity:** Time $O(n)$, Space $O(w + n)$ for queue and output.

Algorithm Explanation

The level-order traversal uses a queue to process nodes level by level.

Each node is dequeued, its value is added to the result, and its children are enqueued.

This is $O(n)$ for n nodes, with $O(w)$ space for the queue (w is max width) and $O(n)$ for the output array.

Coding Part (with Unit Tests)

```
#define MAX_QUEUE_SIZE 100

typedef struct {
    TreeNode* data[MAX_QUEUE_SIZE];
    int front, rear;
} Queue;

void initQueue(Queue* q) {
    q->front = q->rear = -1;
}

bool enqueue(Queue* q, TreeNode* node) {
    if (q->rear >= MAX_QUEUE_SIZE - 1) return false;
    q->data[++q->rear] = node;
    if (q->front == -1) q->front = 0;
    return true;
}

bool dequeue(Queue* q, TreeNode** node) {
    if (q->front == -1 || q->front > q->rear) return false;
    *node = q->data[q->front++];
    return true;
}
```

```

int* levelOrder(TreeNode* root, int* returnSize) {
    int* result = (int*)malloc(100 * sizeof(int));
    *returnSize = 0;
    if (!root) return result;
    Queue q; initQueue(&q);
    enqueue(&q, root);
    while (q.front <= q.rear) {
        TreeNode* node;
        dequeue(&q, &node);
        result[(*returnSize)++] = node->val;
        if (node->left) enqueue(&q, node->left);
        if (node->right) enqueue(&q, node->right);
    }
    return result;
}

// Unit tests
void testLevelOrder() {
    TreeNode* root = insertBST(NULL, 1);
    root = insertBST(root, 2);
    root = insertBST(root, 3);
    int returnSize;
    int* result = levelOrder(root, &returnSize);
    assertEquals(1, result[0], "Test 351.1 - Level-order root");
    free(result);
    free(root->left);
    free(root->right);
    free(root);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use queue for level-order.
 - Handle empty tree.
 - Free allocated memory.
 - Test with different tree structures.
- **Expert Tips:**
 - Explain level-order: "BFS with queue."
 - In interviews, clarify: "Ask about level separation."
 - Suggest optimization: "Dynamic array for output."
 - Test edge cases: "Empty tree, single node."

Problem 352: Find the Sum of Leaf Nodes in a Tree

Issue Description

Compute the sum of all leaf node values in a binary tree.

Problem Decomposition & Solution Steps

- **Input:** Binary tree root.
- **Output:** Sum of leaf node values.
- **Approach:** Recursively sum leaf nodes.
- **Algorithm:** Leaf Sum

- **Explanation:** Sum values of nodes with no children.
- **Steps:**
 1. If NULL, return 0.
 2. If leaf (no children), return node value.
 3. Recurse for left/right subtrees.
- **Complexity:** Time O(n), Space O(h) for recursion.

Algorithm Explanation

The algorithm recursively traverses the tree.

If a node is a leaf (no left or right child), its value is added to the sum.

Otherwise, sum the left and right subtrees.

This is O(n) for n nodes, with O(h) space for recursion.

Coding Part (with Unit Tests)

```
int sumOfLeaves(TreeNode* root) {
    if (!root) return 0;
    if (!root->left && !root->right) return root->val;
    return sumOfLeaves(root->left) + sumOfLeaves(root->right);
}

// Unit tests
void testSumOfLeaves() {
    TreeNode* root = insertBST(NULL, 1);
    root = insertBST(root, 2);
    root = insertBST(root, 3);
    assertEquals(5, sumOfLeaves(root), "Test 352.1 - Sum of leaves");
    free(root->left);
    free(root->right);
    free(root);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Identify leaves correctly.
 - Handle empty tree.
 - Test with leaf-only trees.
- **Expert Tips:**
 - Explain leaf sum: "Sum nodes with no children."
 - In interviews, clarify: "Ask about negative values."
 - Suggest optimization: "Iterative with stack."
 - Test edge cases: "Empty tree, single leaf."

Problem 353: Reverse a Queue

Issue Description

Reverse a queue using its own operations.

Problem Decomposition & Solution Steps

- **Input:** Queue (circular array from Problem 332).
- **Output:** Reversed queue.
- **Approach:** Use stack to reverse elements.
- **Algorithm:** Queue Reversal
 - **Explanation:** Dequeue to stack, pop to queue.
- **Steps:**
 1. Dequeue all elements to stack.
 2. Pop stack and enqueue back.
- **Complexity:** Time O(n), Space O(n) for stack.

Algorithm Explanation

The algorithm dequeues all elements to a stack (reversing order), then pops from the stack and enqueues back to the queue.

This is O(n) for n elements, with O(n) space for the stack.

Coding Part (with Unit Tests)

```
#define MAX_QUEUE_SIZE 100

typedef struct {
    int data[MAX_QUEUE_SIZE];
    int front, rear, size;
} CircularQueue;

typedef struct {
    int data[MAX_QUEUE_SIZE];
    int top;
} Stack;

void initCircularQueue(CircularQueue* q) {
    q->front = 0; q->rear = -1; q->size = 0;
}

bool enqueueCircular(CircularQueue* q, int val) {
    if (q->size >= MAX_QUEUE_SIZE) return false;
    q->rear = (q->rear + 1) % MAX_QUEUE_SIZE;
    q->data[q->rear] = val;
    q->size++;
    return true;
}

bool dequeueCircular(CircularQueue* q, int* val) {
    if (q->size == 0) return false;
    *val = q->data[q->front];
    q->front = (q->front + 1) % MAX_QUEUE_SIZE;
    q->size--;
    return true;
}
```

```

void initStack(Stack* s) {
    s->top = -1;
}

bool push(Stack* s, int val) {
    if (s->top >= MAX_QUEUE_SIZE - 1) return false;
    s->data[++s->top] = val;
    return true;
}

bool pop(Stack* s, int* val) {
    if (s->top < 0) return false;
    *val = s->data[s->top--];
    return true;
}

void reverseQueue(CircularQueue* q) {
    Stack s; initStack(&s);
    int val;
    while (dequeueCircular(q, &val)) push(&s, val);
    while (pop(&s, &val)) enqueueCircular(q, val);
}

// Unit tests
void testReverseQueue() {
    CircularQueue q; initCircularQueue(&q);
    enqueueCircular(&q, 1);
    enqueueCircular(&q, 2);
    reverseQueue(&q);
    int val;
    dequeueCircular(&q, &val);
    assertEquals(2, val, "Test 353.1 - Reversed queue");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use stack for reversal.
 - Handle empty queue.
 - Test with multiple elements.
- **Expert Tips:**
 - Explain reversal: "Use stack to reverse order."
 - In interviews, clarify: "Ask about in-place reversal."
 - Suggest optimization: "Recursion for no extra space."
 - Test edge cases: "Empty queue, single element."

Problem 354: Check if a Linked List is Sorted

Issue Description

Check if a singly linked list is sorted in ascending order.

Problem Decomposition & Solution Steps

- **Input:** Head of linked list.
- **Output:** Boolean indicating sorted list.
- **Approach:** Compare adjacent nodes.

- **Algorithm:** Sorted List Check
 - **Explanation:** Ensure each node's value \leq next node's.
- **Steps:**
 1. Traverse list.
 2. Compare current and next node values.
 3. Return false if out of order.
- **Complexity:** Time $O(n)$, Space $O(1)$.

Algorithm Explanation

The algorithm traverses the list, comparing each node's value with the next.

If any value is greater than the next, the list is not sorted.

This is $O(n)$ for n nodes, with $O(1)$ space.

Coding Part (with Unit Tests)

```
bool isSortedList(ListNode* head) {
    ListNode* curr = head;
    while (curr && curr->next) {
        if (curr->val > curr->next->val) return false;
        curr = curr->next;
    }
    return true;
}

// Unit tests
void testIsSortedList() {
    ListNode* head = insertNode(NULL, 2);
    head = insertNode(head, 1);
    assertBoolEquals(true, isSortedList(head), "Test 354.1 - Sorted list");
    free(head->next);
    free(head);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Check adjacent nodes.
 - Handle empty or single-node list.
 - Test with sorted/unsorted lists.
- **Expert Tips:**
 - Explain sorted check: "Compare adjacent values."
 - In interviews, clarify: "Ask about descending order."
 - Suggest optimization: "Early exit on violation."
 - Test edge cases: "Empty list, single node."

Problem 355: Find the Lowest Common Ancestor in a Tree

Issue Description

Find the lowest common ancestor (LCA) of two nodes in a binary tree (not necessarily BST).

Problem Decomposition & Solution Steps

- **Input:** Binary tree root, two node values.
- **Output:** LCA node.
- **Approach:** Recursively find paths to nodes, find common ancestor.
- **Algorithm:** LCA in Binary Tree
 - **Explanation:** Return node if it or its subtree contains both values.
- **Steps:**
 1. If root is NULL or matches a value, return root.
 2. Recurse for left/right subtrees.
 3. If both subtrees return non-NUL, root is LCA.
- **Complexity:** Time O(n), Space O(h) for recursion.

Algorithm Explanation

The algorithm recursively searches for the two nodes.

If the root matches either value or is NULL, return it.

If both left and right subtrees return non-NUL pointers, the root is the LCA.

If only one subtree returns non-NUL, propagate it.

This is O(n) for n nodes, with O(h) space.

Coding Part (with Unit Tests)

```
TreeNode* lowestCommonAncestor(TreeNode* root, int p, int q) {
    if (!root || root->val == p || root->val == q) return root;
    TreeNode* left = lowestCommonAncestor(root->left, p, q);
    TreeNode* right = lowestCommonAncestor(root->right, p, q);
    if (left && right) return root;
    return left ? left : right;
}

// Unit tests
void testLCA() {
    TreeNode* root = insertBST(NULL, 3);
    root = insertBST(root, 5);
    root = insertBST(root, 1);
    TreeNode* lca = lowestCommonAncestor(root, 5, 1);
    assertEquals(3, lca->val, "Test 355.1 - LCA of 5 and 1");
    free(root->left);
    free(root->right);
    free(root);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Assume nodes exist in tree.
 - Handle NULL root.
 - Test with different node pairs.
- **Expert Tips:**
 - Explain LCA: "Lowest node with both values in subtrees."
 - In interviews, clarify: "Ask about non-existent nodes."
 - Suggest optimization: "Path-based approach."
 - Test edge cases: "Same node, root as LCA."

Problem 356: Convert a Sorted Array to a BST

Issue Description

Convert a sorted array to a balanced BST (reuses Problem 337's construction).

Problem Decomposition & Solution Steps

- **Input:** Sorted array.
- **Output:** Root of balanced BST.
- **Approach:** Use middle element as root, recurse for subarrays.
- **Algorithm:** Sorted Array to BST
 - **Explanation:** Middle element ensures balance.
- **Steps:**
 1. Select middle element as root.
 2. Recursively build left subtree (left half).
 3. Recursively build right subtree (right half).
- **Complexity:** Time O(n), Space O(log n) for recursion.

Algorithm Explanation

The algorithm selects the middle element of the array as the root to ensure balance, then recursively builds left and right subtrees from the left and right halves.

This is O(n) for n elements, with O(log n) space for recursion.

Coding Part (with Unit Tests)

```
TreeNode* sortedArrayToBST(int* arr, int start, int end) {  
    if (start > end) return NULL;  
    int mid = start + (end - start) / 2;  
    TreeNode* root = (TreeNode*)malloc(sizeof(TreeNode));  
    root->val = arr[mid];  
    root->left = sortedArrayToBST(arr, start, mid - 1);  
    root->right = sortedArrayToBST(arr, mid + 1, end);  
    return root;  
}
```

```

TreeNode* sortedArrayToBSTWrapper(int* arr, int n) {
    return sortedArrayToBST(arr, 0, n - 1);
}

// Unit tests
void testSortedArrayToBST() {
    int arr[] = {1, 2, 3};
    TreeNode* root = sortedArrayToBSTWrapper(arr, 3);
    assertEquals(2, root->val, "Test 356.1 - BST root");
    free(root->left);
    free(root->right);
    free(root);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use middle element for balance.
 - Handle empty array.
 - Test with different array sizes.
- **Expert Tips:**
 - Explain BST construction: "Middle element as root."
 - In interviews, clarify: "Ask about duplicates."
 - Suggest optimization: "Iterative for large arrays."
 - Test edge cases: "Empty array, single element."

Problem 357: Find the Diameter of a Tree

Issue Description

Find the diameter of a binary tree (reuses Problem 335).

Problem Decomposition & Solution Steps

- **Input:** Binary tree root.
- **Output:** Diameter (integer).
- **Approach:** Compute height and diameter recursively.
- **Algorithm:** Tree Diameter
 - **Explanation:** Max of left+right heights or subtree diameters.
- **Steps:**
 1. Compute left/right heights and diameters.
 2. Update global max with left+right+2.
 3. Return height for parent.
- **Complexity:** Time O(n), Space O(h) for recursion.

Algorithm Explanation

The algorithm computes subtree heights and updates a global maximum with the sum of left and right heights or the maximum subtree diameter.

It returns the height for parent calculations.

This is O(n) for n nodes, with O(h) space (same as Problem 335).

Coding Part (with Unit Tests)

```
int diameterHelper(TreeNode* root, int* maxDiameter) {
    if (!root) return -1;
    int left = diameterHelper(root->left, maxDiameter);
    int right = diameterHelper(root->right, maxDiameter);
    *maxDiameter = (*maxDiameter > left + right + 2) ? *maxDiameter : left + right + 2;
    return (left > right ? left : right) + 1;
}

int diameterOfBinaryTree(TreeNode* root) {
    int maxDiameter = 0;
    diameterHelper(root, &maxDiameter);
    return maxDiameter;
}

// Unit tests
void testDiameter() {
    TreeNode* root = insertBST(NULL, 1);
    root = insertBST(root, 2);
    assertEquals(1, diameterOfBinaryTree(root), "Test 357.1 - Diameter");
    free(root->left);
    free(root);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Track global maximum.
 - Handle empty tree.
 - Test with unbalanced trees.
- **Expert Tips:**
 - Explain diameter: "Longest path through or within subtrees."
 - In interviews, clarify: "Ask about edge vs. node count."
 - Suggest optimization: "Combine with height."
 - Test edge cases: "Single node, linear tree."

Problem 358: Check if a Tree is a Full Binary Tree

Issue Description

Check if a binary tree is full (every node has 0 or 2 children).

Problem Decomposition & Solution Steps

- **Input:** Binary tree root.
- **Output:** Boolean indicating full tree.
- **Approach:** Recursively check node children.

- **Algorithm:** Full Tree Check
 - **Explanation:** Ensure nodes have 0 or 2 children.
- **Steps:**
 1. If NULL, return true.
 2. If node has one child, return false.
 3. Recurse for left/right subtrees.
- **Complexity:** Time O(n), Space O(h) for recursion.

Algorithm Explanation

The algorithm recursively checks each node.

If a node has exactly one child (left or right), return false.

If it has 0 or 2 children, recurse for subtrees.

This is O(n) for n nodes, with O(h) space for recursion.

Coding Part (with Unit Tests)

```
bool isFullBinaryTree(TreeNode* root) {
    if (!root) return true;
    if ((root->left && !root->right) || (!root->left && root->right)) return false;
    return isFullBinaryTree(root->left) && isFullBinaryTree(root->right);
}

// Unit tests
void testIsFullBinaryTree() {
    TreeNode* root = insertBST(NULL, 1);
    root->left = (TreeNode*)malloc(sizeof(TreeNode));
    root->left->val = 2; root->left->left = root->left->right = NULL;
    root->right = (TreeNode*)malloc(sizeof(TreeNode));
    root->right->val = 3; root->right->left = root->right->right = NULL;
    assertBoolEquals(true, isFullBinaryTree(root), "Test 358.1 - Full tree");
    free(root->left);
    free(root->right);
    free(root);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Check for 0 or 2 children.
 - Handle empty tree.
 - Test with full/non-full trees.
- **Expert Tips:**
 - Explain full tree: "Nodes have 0 or 2 children."
 - In interviews, clarify: "Ask about leaf definition."
 - Suggest optimization: "Level-order for completeness."
 - Test edge cases: "Empty tree, single node."

Problem 359: Find the Sum of All Paths in a Tree

Issue Description

Compute the sum of all root-to-leaf path sums in a binary tree.

Problem Decomposition & Solution Steps

- **Input:** Binary tree root.
- **Output:** Total sum of path sums.
- **Approach:** Recursively compute path sums.
- **Algorithm:** Path Sum
 - **Explanation:** Sum paths from root to each leaf.
- **Steps:**
 1. Track current path sum.
 2. If leaf, add path sum to total.
 3. Recurse for left/right with updated sum.
- **Complexity:** Time $O(n)$, Space $O(h)$ for recursion.

Algorithm Explanation

The algorithm recursively traverses the tree, maintaining the current path sum.

When a leaf is reached, the path sum is added to the total.

This is $O(n)$ for n nodes, with $O(h)$ space for recursion.

Coding Part (with Unit Tests)

```
void pathSumHelper(TreeNode* root, int currSum, int* totalSum) {
    if (!root) return;
    currSum += root->val;
    if (!root->left && !root->right) {
        *totalSum += currSum;
        return;
    }
    pathSumHelper(root->left, currSum, totalSum);
    pathSumHelper(root->right, currSum, totalSum);
}

int sumOfAllPaths(TreeNode* root) {
    int totalSum = 0;
    pathSumHelper(root, 0, &totalSum);
    return totalSum;
}

// Unit tests
void testSumOfAllPaths() {
    TreeNode* root = insertBST(NULL, 1);
    root->left = (TreeNode*)malloc(sizeof(TreeNode));
    root->left->val = 2; root->left->left = root->left->right = NULL;
    assertEquals(3, sumOfAllPaths(root), "Test 359.1 - Sum of paths");
    free(root->left);
    free(root);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Track path sums recursively.
 - Handle leaf nodes correctly.
 - Test with multiple paths.
- **Expert Tips:**
 - Explain path sum: "Sum all root-to-leaf paths."
 - In interviews, clarify: "Ask about negative values."
 - Suggest optimization: "Iterative with stack."
 - Test edge cases: "Single path, single node."

Problem 360: Convert a Linked List to a BST

Issue Description

Convert a sorted singly linked list to a balanced BST.

Problem Decomposition & Solution Steps

- **Input:** Head of sorted linked list.
- **Output:** Root of balanced BST.
- **Approach:** Find middle node, use as root, recurse.
- **Algorithm:** Linked List to BST
 - **Explanation:** Use slow/fast pointers to find middle.
- **Steps:**
 1. Find middle node (slow/fast pointers).
 2. Make middle node root.
 3. Recurse for left (before middle) and right (after middle).
- **Complexity:** Time $O(n \log n)$, Space $O(\log n)$ for recursion.

Algorithm Explanation

The algorithm uses slow and fast pointers to find the middle node, which becomes the root.

The list before the middle forms the left subtree, and the list after forms the right subtree.

This is $O(n \log n)$ due to multiple list traversals, with $O(\log n)$ space for recursion.

Coding Part (with Unit Tests)

```
TreeNode* sortedListToBSTHelper(ListNode** head, int start, int end) {  
    if (start > end) return NULL;  
    int mid = start + (end - start) / 2;  
    TreeNode* left = sortedListToBSTHelper(head, start, mid - 1);  
    TreeNode* root = (TreeNode*)malloc(sizeof(TreeNode));  
    root->val = (*head)->val;  
    root->left = left;  
    *head = (*head)->next;  
    root->right = sortedListToBSTHelper(head, mid + 1, end);  
    return root;  
}
```

```

TreeNode* sortedListToBST(ListNode* head) {
    int length = 0;
    ListNode* curr = head;
    while (curr) {
        length++;
        curr = curr->next;
    }
    return sortedListToBSTHelper(&head, 0, length - 1);
}

// Unit tests
void testListToBST() {
    ListNode* head = insertNode(NULL, 3);
    head = insertNode(head, 2);
    head = insertNode(head, 1);
    TreeNode* root = sortedListToBST(head);
    assertEquals(2, root->val, "Test 360.1 - BST root");
    free(root->left);
    free(root->right);
    free(root);
    free(head);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Ensure list is sorted.
 - Use slow/fast pointers.
 - Test with different list lengths.
- **Expert Tips:**
 - Explain conversion: "Middle node as root for balance."
 - In interviews, clarify: "Ask about unsorted list."
 - Suggest optimization: "Convert to array first."
 - Test edge cases: "Empty list, single node."

Problem 361: Implement a Hash Table with Chaining

Issue Description

Implement a hash table with chaining for collision resolution.

Problem Decomposition & Solution Steps

- **Input:** Key-value pairs, operations (insert, search).
- **Output:** Hash table operations.
- **Approach:** Use array of linked lists for chaining.
- **Algorithm:** Hash Table with Chaining
 - **Explanation:** Hash keys to indices, store in linked lists.
- **Steps:**
 1. Initialize array of linked lists.
 2. Insert: Hash key, add to list at index.
 3. Search: Hash key, search list at index.
- **Complexity:** Time O(1) average, O(n) worst; Space O(n).

Algorithm Explanation

The hash table uses an array of linked lists.

Keys are hashed to an index, and key-value pairs are stored in the list at that index.

Insert adds to the list; search traverses the list.

Average time is O(1) with good hashing, worst-case O(n) for collisions, with O(n) space.

Coding Part (with Unit Tests)

```
#define TABLE_SIZE 100

typedef struct HashNode {
    int key, value;
    struct HashNode* next;
} HashNode;

typedef struct {
    HashNode* table[TABLE_SIZE];
} HashTable;

int hashFunction(int key) {
    return key % TABLE_SIZE;
}

void initHashTable(HashTable* ht) {
    for (int i = 0; i < TABLE_SIZE; i++) ht->table[i] = NULL;
}

void insertHash(HashTable* ht, int key, int value) {
    int index = hashFunction(key);
    HashNode* newNode = (HashNode*)malloc(sizeof(HashNode));
    newNode->key = key;
    newNode->value = value;
    newNode->next = ht->table[index];
    ht->table[index] = newNode;
}

bool searchHash(HashTable* ht, int key, int* value) {
    int index = hashFunction(key);
    HashNode* curr = ht->table[index];
    while (curr) {
        if (curr->key == key) {
            *value = curr->value;
            return true;
        }
        curr = curr->next;
    }
    return false;
}

// Unit tests
void testHashTable() {
    HashTable ht; initHashTable(&ht);
    insertHash(&ht, 1, 100);
    int value;
    assertBoolEquals(true, searchHash(&ht, 1, &value), "Test 361.1 - Hash search");
    assertEquals(100, value, "Test 361.2 - Hash value");
    free(ht.table[hashFunction(1)]);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use simple hash function.
 - Handle collisions with chaining.
 - Free memory in cleanup.
 - Test with collisions.
- **Expert Tips:**
 - Explain hashing: "Map keys to indices, chain collisions."
 - In interviews, clarify: "Ask about hash function."
 - Suggest optimization: "Dynamic resizing for load factor."
 - Test edge cases: "Empty table, multiple collisions."

Problem 362: Find the Left View of a Binary Tree

Issue Description

Find the left view of a binary tree (first node at each level).

Problem Decomposition & Solution Steps

- **Input:** Binary tree root.
- **Output:** Array of leftmost node values.
- **Approach:** Use level-order or recursive traversal.
- **Algorithm:** Left View
 - **Explanation:** Track first node at each level.
- **Steps:**
 1. Use recursive right-to-left traversal.
 2. Track max level seen.
 3. Add first node at each new level.
- **Complexity:** Time $O(n)$, Space $O(h + k)$ for recursion and output.

Algorithm Explanation

The algorithm uses a right-to-left recursive traversal, tracking the maximum level seen.

The first node at each new level is added to the result.

This is $O(n)$ for n nodes, with $O(h)$ space for recursion and $O(k)$ for output (k is height).

Coding Part (with Unit Tests)

```
void leftViewHelper(TreeNode* root, int level, int* maxLevel, int* result, int* index) {  
    if (!root) return;  
    if (level > *maxLevel) {  
        result[(*index)++] = root->val;  
        *maxLevel = level;  
    }  
    leftViewHelper(root->left, level + 1, maxLevel, result, index);  
    leftViewHelper(root->right, level + 1, maxLevel, result, index);  
}
```

```

int* leftView(TreeNode* root, int* returnSize) {
    int* result = (int*)malloc(100 * sizeof(int));
    *returnSize = 0;
    int maxLevel = -1;
    leftViewHelper(root, 0, &maxLevel, result, returnSize);
    return result;
}

// Unit tests
void testLeftView() {
    TreeNode* root = insertBST(NULL, 1);
    root = insertBST(root, 2);
    root = insertBST(root, 3);
    int returnSize;
    int* result = leftView(root, &returnSize);
    assertEquals(1, result[0], "Test 362.1 - Left view root");
    free(result);
    free(root->left);
    free(root->right);
    free(root);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track levels correctly.
 - Use right-to-left for left view.
 - Test with skewed trees.
- **Expert Tips:**
 - Explain left view: "First node per level."
 - In interviews, clarify: "Ask about right view."
 - Suggest optimization: "Level-order with queue."
 - Test edge cases: "Empty tree, single path."

Problem 363: Implement a Graph Using Adjacency List

Issue Description

Implement a graph using an adjacency list with add edge and print operations.

Problem Decomposition & Solution Steps

- **Input:** Vertices, edges.
- **Output:** Graph operations.
- **Approach:** Use array of linked lists.
- **Algorithm:** Adjacency List Graph
 - **Explanation:** Each vertex stores list of adjacent vertices.
- **Steps:**
 1. Initialize array of linked lists.
 2. Add edge: Append to list at source vertex.
 3. Print: Traverse each vertex's list.
- **Complexity:** Time $O(1)$ for add edge, $O(V + E)$ for print; Space $O(V + E)$.

Algorithm Explanation

The graph uses an array of linked lists, where each index (vertex) stores a list of adjacent vertices.

Adding an edge appends to the source vertex's list ($O(1)$).

Printing traverses all lists ($O(V + E)$ for V vertices, E edges).

Space is $O(V + E)$.

Coding Part (with Unit Tests)

```
typedef struct Graph {
    ListNode** adjList;
    int vertices;
} Graph;

Graph* createGraph(int vertices) {
    Graph* g = (Graph*)malloc(sizeof(Graph));
    g->vertices = vertices;
    g->adjList = (ListNode**)malloc(vertices * sizeof(ListNode*));
    for (int i = 0; i < vertices; i++) g->adjList[i] = NULL;
    return g;
}

void addEdge(Graph* g, int src, int dest) {
    ListNode* newNode = (ListNode*)malloc(sizeof(ListNode));
    newNode->val = dest;
    newNode->next = g->adjList[src];
    g->adjList[src] = newNode;
}

void printGraph(Graph* g) {
    for (int i = 0; i < g->vertices; i++) {
        printf("Vertex %d: ", i);
        ListNode* curr = g->adjList[i];
        while (curr) {
            printf("%d ", curr->val);
            curr = curr->next;
        }
        printf("\n");
    }
}

// Unit tests
void testGraph() {
    Graph* g = createGraph(3);
    addEdge(g, 0, 1);
    addEdge(g, 1, 2);
    assertEquals(1, g->adjList[0]->val, "Test 363.1 - Edge 0->1");
    free(g->adjList[0]);
    free(g->adjList[1]);
    free(g);
}
```

Best Practices & Expert Tips

- **Best Practices:**

- Initialize adjacency lists.
- Handle directed/undirected edges.

- Free memory in cleanup.
- Test with sparse/dense graphs.
- **Expert Tips:**
 - Explain adjacency list: "Lists for each vertex's neighbors."
 - In interviews, clarify: "Ask about directed vs. undirected."
 - Suggest optimization: "Use adjacency matrix for dense graphs."
 - Test edge cases: "Empty graph, single edge."

Problem 364: Detect a Cycle in a Graph Using DFS

Issue Description

Detect a cycle in a directed graph using DFS.

Problem Decomposition & Solution Steps

- **Input:** Graph (adjacency list).
- **Output:** Boolean indicating cycle.
- **Approach:** Use DFS with recursion stack.
- **Algorithm:** DFS Cycle Detection
 - **Explanation:** Track visited nodes and recursion stack.
- **Steps:**
 1. Initialize visited and recursion stack arrays.
 2. Perform DFS, mark nodes in recursion stack.
 3. If visited node is in stack, cycle exists.
- **Complexity:** Time $O(V + E)$, Space $O(V)$.

Algorithm Explanation

The DFS algorithm marks nodes as visited and in the recursion stack.

If a visited node is encountered in the stack, a cycle exists.

After DFS completes for a node, remove it from the stack.

This is $O(V + E)$ for V vertices and E edges, with $O(V)$ space for arrays.

Coding Part (with Unit Tests)

```
bool dfsCycleHelper(Graph* g, int v, bool* visited, bool* recStack) {
    visited[v] = true;
    recStack[v] = true;
    ListNode* curr = g->adjList[v];
    while (curr) {
        int u = curr->val;
        if (!visited[u] && dfsCycleHelper(g, u, visited, recStack)) return true;
        else if (recStack[u]) return true;
        curr = curr->next;
    }
    recStack[v] = false;
    return false;
}
```

```

bool hasCycleGraph(Graph* g) {
    bool* visited = (bool*)calloc(g->vertices, sizeof(bool));
    bool* recStack = (bool*)calloc(g->vertices, sizeof(bool));
    for (int i = 0; i < g->vertices; i++) {
        if (!visited[i] && dfsCycleHelper(g, i, visited, recStack)) {
            free(visited);
            free(recStack);
            return true;
        }
    }
    free(visited);
    free(recStack);
    return false;
}

// Unit tests
void testHasCycleGraph() {
    Graph* g = createGraph(3);
    addEdge(g, 0, 1);
    addEdge(g, 1, 2);
    addEdge(g, 2, 0);
    assertBoolEquals(true, hasCycleGraph(g), "Test 364.1 - Cycle detected");
    free(g->adjList[0]);
    free(g->adjList[1]);
    free(g->adjList[2]);
    free(g);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use recursion stack for cycle detection.
 - Handle disconnected components.
 - Free memory for arrays.
 - Test with cyclic/acyclic graphs.
- **Expert Tips:**
 - Explain DFS cycle: "Back edge in recursion stack."
 - In interviews, clarify: "Ask about undirected graphs."
 - Suggest optimization: "BFS or Union-Find for undirected."
 - Test edge cases: "Empty graph, single vertex."

Main Function to Run All Tests

```

int main() {
    printf("Running tests for data structures problems 349 to 364:\n");
    testKthNode();
    testIsBalanced();
    testLevelOrder();
    testSumOfLeaves();
    testReverseQueue();
    testIsSortedList();
    testLCA();
    testSortedArrayToBST();
    testDiameter();
    testIsFullBinaryTree();
    testSumOfAllPaths();
    testListToBST();
    testHashTable();
    testLeftView();
    testGraph();
    testHasCycleGraph();
    return 0;
}

```

Problem 365: Find the Shortest Path in an Unweighted Graph

Issue Description

Find the shortest path between two vertices in an unweighted graph using BFS.

Problem Decomposition & Solution Steps

- **Input:** Graph (adjacency list), source, destination vertices.
- **Output:** Array of vertices in shortest path.
- **Approach:** Use BFS to find shortest path.
- **Algorithm:** BFS Shortest Path
 - **Explanation:** BFS ensures shortest path in unweighted graph.
- **Steps:**
 1. Initialize queue, visited array, and parent array.
 2. Perform BFS from source, track parents.
 3. Reconstruct path from destination to source using parents.
- **Complexity:** Time $O(V + E)$, Space $O(V)$ for queue/arrays.

Algorithm Explanation

BFS explores vertices level by level, ensuring the first time the destination is reached is via the shortest path.

A parent array tracks the path, and the result is reconstructed by backtracking from destination to source.

Time is $O(V + E)$ for V vertices and E edges, with $O(V)$ space.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>
#include <string.h>

#define MAX_VERTICES 100

typedef struct ListNode {
    int val;
    struct ListNode* next;
} ListNode;

typedef struct Graph {
    ListNode* adjList[MAX_VERTICES];
    int vertices;
} Graph;

// Helper: Create graph (from Problem 363)
Graph* createGraph(int vertices) {
    Graph* g = (Graph*)malloc(sizeof(Graph));
    g->vertices = vertices;
    for (int i = 0; i < vertices; i++) g->adjList[i] = NULL;
    return g;
}
```

```

// Helper: Add edge (from Problem 363)
void addEdge(Graph* g, int src, int dest) {
    ListNode* newNode = (ListNode*)malloc(sizeof(ListNode));
    newNode->val = dest;
    newNode->next = g->adjList[src];
    g->adjList[src] = newNode;
}

#define MAX_QUEUE_SIZE 100
typedef struct {
    int data[MAX_QUEUE_SIZE];
    int front, rear;
} Queue;

void initQueue(Queue* q) {
    q->front = q->rear = -1;
}

bool enqueue(Queue* q, int val) {
    if (q->rear >= MAX_QUEUE_SIZE - 1) return false;
    q->data[++q->rear] = val;
    if (q->front == -1) q->front = 0;
    return true;
}

bool dequeue(Queue* q, int* val) {
    if (q->front == -1 || q->front > q->rear) return false;
    *val = q->data[q->front++];
    return true;
}

int* shortestPath(Graph* g, int src, int dest, int* returnSize) {
    bool visited[MAX_VERTICES] = {false};
    int parent[MAX_VERTICES];
    memset(parent, -1, sizeof(parent));
    Queue q; initQueue(&q);
    enqueue(&q, src);
    visited[src] = true;
    while (q.front <= q.rear) {
        int v;
        dequeue(&q, &v);
        if (v == dest) break;
        ListNode* curr = g->adjList[v];
        while (curr) {
            if (!visited[curr->val]) {
                visited[curr->val] = true;
                parent[curr->val] = v;
                enqueue(&q, curr->val);
            }
            curr = curr->next;
        }
    }
    int* path = (int*)malloc(MAX_VERTICES * sizeof(int));
    *returnSize = 0;
    if (!visited[dest]) return path;
    int curr = dest;
    while (curr != -1) {
        path[(*returnSize)++] = curr;
        curr = parent[curr];
    }
    for (int i = 0; i < *returnSize / 2; i++) {
        int temp = path[i];
        path[i] = path[*returnSize - 1 - i];
        path[*returnSize - 1 - i] = temp;
    }
    return path;
}

```

```

// Unit test helpers
void assertEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

void assertEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testShortestPath() {
    Graph* g = createGraph(4);
    addEdge(g, 0, 1);
    addEdge(g, 1, 2);
    addEdge(g, 2, 3);
    int returnSize;
    int* path = shortestPath(g, 0, 3, &returnSize);
    assertEquals(3, path[returnSize - 1], "Test 365.1 - Shortest path end");
    free(path);
    free(g->adjList[0]);
    free(g->adjList[1]);
    free(g->adjList[2]);
    free(g);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use BFS for unweighted graphs.
 - Track parents for path reconstruction.
 - Handle unreachable destinations.
 - Test with disconnected graphs.
- **Expert Tips:**
 - Explain BFS: "Ensures shortest path by level."
 - In interviews, clarify: "Ask about directed vs. undirected."
 - Suggest optimization: "Bidirectional BFS for faster search."
 - Test edge cases: "No path, single vertex."

Problem 366: Implement a Min-Heap from Scratch

Issue Description

Implement a min-heap with insert, extract-min, and get-min operations.

Problem Decomposition & Solution Steps

- **Input:** Values to insert, operations.
- **Output:** Min-heap operations.
- **Approach:** Use array-based heap with heapify.
- **Algorithm:** Min-Heap
 - **Explanation:** Maintain heap property (parent \leq children).
- **Steps:**
 1. Insert: Add at end, bubble up.
 2. Extract-min: Remove root, heapify down.

3. Get-min: Return root value.
- **Complexity:** Time $O(\log n)$ for insert/extract, $O(1)$ for get-min; Space $O(n)$.

Algorithm Explanation

The min-heap is an array where each parent's value is \leq its children.

Insert adds at the end and bubbles up ($O(\log n)$).

Extract-min swaps root with last, removes last, and heapifies down ($O(\log n)$).

Get-min returns root ($O(1)$).

Space is $O(n)$ for n elements.

Coding Part (with Unit Tests)

```
#define MAX_HEAP_SIZE 100

typedef struct {
    int data[MAX_HEAP_SIZE];
    int size;
} MinHeap;

void initMinHeap(MinHeap* h) {
    h->size = 0;
}

int parent(int i) { return (i - 1) / 2; }
int left(int i) { return 2 * i + 1; }
int right(int i) { return 2 * i + 2; }

void swap(int* a, int* b) {
    int temp = *a;
    *a = *b;
    *b = temp;
}

void heapifyUp(MinHeap* h, int i) {
    while (i > 0 && h->data[parent(i)] > h->data[i]) {
        swap(&h->data[i], &h->data[parent(i)]);
        i = parent(i);
    }
}

void heapifyDown(MinHeap* h, int i) {
    int min = i;
    if (left(i) < h->size && h->data[left(i)] < h->data[min]) min = left(i);
    if (right(i) < h->size && h->data[right(i)] < h->data[min]) min = right(i);
    if (min != i) {
        swap(&h->data[i], &h->data[min]);
        heapifyDown(h, min);
    }
}

bool insertMinHeap(MinHeap* h, int val) {
    if (h->size >= MAX_HEAP_SIZE) return false;
    h->data[h->size] = val;
    heapifyUp(h, h->size);
    h->size++;
    return true;
}
```

```

bool extractMin(MinHeap* h, int* val) {
    if (h->size == 0) return false;
    *val = h->data[0];
    h->data[0] = h->data[--h->size];
    heapifyDown(h, 0);
    return true;
}

int getMin(MinHeap* h) {
    return h->size > 0 ? h->data[0] : -1;
}

// Unit tests
void testMinHeap() {
    MinHeap h; initMinHeap(&h);
    insertMinHeap(&h, 3);
    insertMinHeap(&h, 1);
    assertIntEquals(1, getMin(&h), "Test 366.1 - Min value");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Maintain heap property.
 - Handle empty/full heap.
 - Test with multiple insertions.
- **Expert Tips:**
 - Explain heapify: "Bubble up/down to maintain order."
 - In interviews, clarify: "Ask about priority queue."
 - Suggest optimization: "Dynamic array for resizing."
 - Test edge cases: "Empty heap, single element."

Problem 367: Find the Right View of a Binary Tree

Issue Description

Find the right view of a binary tree (last node at each level).

Problem Decomposition & Solution Steps

- **Input:** Binary tree root.
- **Output:** Array of rightmost node values.
- **Approach:** Recursive left-to-right traversal.
- **Algorithm:** Right View
 - **Explanation:** Track last node at each level.
- **Steps:**
 1. Use left-to-right recursive traversal.
 2. Track max level seen.
 3. Add last node at each new level.
- **Complexity:** Time O(n), Space O(h + k) for recursion and output.

Algorithm Explanation

The algorithm uses a left-to-right recursive traversal, tracking the maximum level seen.

The last node at each new level (rightmost) is added to the result.

This is $O(n)$ for n nodes, with $O(h)$ space for recursion and $O(k)$ for output (k is height).

Coding Part (with Unit Tests)

```
typedef struct TreeNode {
    int val;
    struct TreeNode *left, *right;
} TreeNode;

void rightViewHelper(TreeNode* root, int level, int* maxLevel, int* result, int* index) {
    if (!root) return;
    if (level > *maxLevel) {
        result[(*index)++] = root->val;
        *maxLevel = level;
    }
    rightViewHelper(root->right, level + 1, maxLevel, result, index);
    rightViewHelper(root->left, level + 1, maxLevel, result, index);
}

int* rightView(TreeNode* root, int* returnSize) {
    int* result = (int*)malloc(100 * sizeof(int));
    *returnSize = 0;
    int maxLevel = -1;
    rightViewHelper(root, 0, &maxLevel, result, returnSize);
    return result;
}

// Helper: Insert BST node (from Problem 315)
TreeNode* insertBST(TreeNode* root, int val) {
    if (!root) {
        root = (TreeNode*)malloc(sizeof(TreeNode));
        root->val = val;
        root->left = root->right = NULL;
        return root;
    }
    if (val < root->val) root->left = insertBST(root->left, val);
    else root->right = insertBST(root->right, val);
    return root;
}

// Unit tests
void testRightView() {
    TreeNode* root = insertBST(NULL, 1);
    root = insertBST(root, 2);
    root = insertBST(root, 3);
    int returnSize;
    int* result = rightView(root, &returnSize);
    assertEquals(3, result[returnSize - 1], "Test 367.1 - Right view last");
    free(result);
    free(root->left);
    free(root->right);
    free(root);
}
```

Best Practices & Expert Tips

- **Best Practices:**

- Use left-to-right for right view.
- Track levels correctly.
- Test with skewed trees.

- **Expert Tips:**

- Explain right view: "Last node per level."
- In interviews, clarify: "Ask about level-order output."
- Suggest optimization: "Level-order with queue."
- Test edge cases: "Empty tree, single path."

Problem 368: Implement a Max-Heap from Scratch

Issue Description

Implement a max-heap with insert, extract-max, and get-max operations.

Problem Decomposition & Solution Steps

- **Input:** Values to insert, operations.
- **Output:** Max-heap operations.
- **Approach:** Use array-based heap with heapify.
- **Algorithm:** Max-Heap
 - **Explanation:** Maintain heap property (parent \geq children).
- **Steps:**
 1. Insert: Add at end, bubble up.
 2. Extract-max: Remove root, heapify down.
 3. Get-max: Return root value.
- **Complexity:** Time $O(\log n)$ for insert/extract, $O(1)$ for get-max; Space $O(n)$.

Algorithm Explanation

The max-heap is an array where each parent's value is \geq its children.

Insert adds at the end and bubbles up ($O(\log n)$).

Extract-max swaps root with last, removes last, and heapifies down ($O(\log n)$).

Get-max returns root ($O(1)$).

Space is $O(n)$ for n elements.

Coding Part (with Unit Tests)

```
typedef struct {
    int data[MAX_HEAP_SIZE];
    int size;
} MaxHeap;

void initMaxHeap(MaxHeap* h) {
    h->size = 0;
}
```

```

void heapifyUpMax(MaxHeap* h, int i) {
    while (i > 0 && h->data[parent(i)] < h->data[i]) {
        swap(&h->data[i], &h->data[parent(i)]);
        i = parent(i);
    }
}

void heapifyDownMax(MaxHeap* h, int i) {
    int max = i;
    if (left(i) < h->size && h->data[left(i)] > h->data[max]) max = left(i);
    if (right(i) < h->size && h->data[right(i)] > h->data[max]) max = right(i);
    if (max != i) {
        swap(&h->data[i], &h->data[max]);
        heapifyDownMax(h, max);
    }
}

bool insertMaxHeap(MaxHeap* h, int val) {
    if (h->size >= MAX_HEAP_SIZE) return false;
    h->data[h->size] = val;
    heapifyUpMax(h, h->size);
    h->size++;
    return true;
}

bool extractMax(MaxHeap* h, int* val) {
    if (h->size == 0) return false;
    *val = h->data[0];
    h->data[0] = h->data[--h->size];
    heapifyDownMax(h, 0);
    return true;
}

int getMax(MaxHeap* h) {
    return h->size > 0 ? h->data[0] : -1;
}

// Unit tests
void testMaxHeap() {
    MaxHeap h; initMaxHeap(&h);
    insertMaxHeap(&h, 1);
    insertMaxHeap(&h, 3);
    assertEquals(3, getMax(&h), "Test 368.1 - Max value");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Maintain max-heap property.
 - Handle empty/full heap.
 - Test with multiple insertions.
- **Expert Tips:**
 - Explain heapify: "Bubble up/down for max property."
 - In interviews, clarify: "Ask about priority queue."
 - Suggest optimization: "Dynamic array for resizing."
 - Test edge cases: "Empty heap, single element."

Problem 369: Check if a Graph is Bipartite

Issue Description

Check if a graph is bipartite (vertices can be divided into two disjoint sets).

Problem Decomposition & Solution Steps

- **Input:** Graph (adjacency list).
- **Output:** Boolean indicating bipartite.
- **Approach:** Use BFS with coloring.
- **Algorithm:** Bipartite Check
 - **Explanation:** Color vertices with two colors, ensure no adjacent same colors.
- **Steps:**
 1. Initialize color array (-1 for uncolored).
 2. Perform BFS, color nodes alternately (0 and 1).
 3. If adjacent nodes have same color, return false.
- **Complexity:** Time $O(V + E)$, Space $O(V)$ for queue/color array.

Algorithm Explanation

The algorithm uses BFS to color vertices alternately (0 or 1).

If an adjacent node is already colored with the same color, the graph is not bipartite.

All components are checked for disconnected graphs.

Time is $O(V + E)$, space is $O(V)$.

Coding Part (with Unit Tests)

```
bool isBipartiteHelper(Graph* g, int src, int* colors) {
    colors[src] = 0;
    Queue q; initQueue(&q);
    enqueue(&q, src);
    while (q.front <= q.rear) {
        int v;
        dequeue(&q, &v);
        ListNode* curr = g->adjList[v];
        while (curr) {
            int u = curr->val;
            if (colors[u] == -1) {
                colors[u] = 1 - colors[v];
                enqueue(&q, u);
            } else if (colors[u] == colors[v]) {
                return false;
            }
            curr = curr->next;
        }
    }
    return true;
}
```

```

bool isBipartite(Graph* g) {
    int colors[MAX_VERTICES];
    memset(colors, -1, sizeof(colors));
    for (int i = 0; i < g->vertices; i++) {
        if (colors[i] == -1 && !isBipartiteHelper(g, i, colors)) {
            return false;
        }
    }
    return true;
}

// Unit tests
void testIsBipartite() {
    Graph* g = createGraph(4);
    addEdge(g, 0, 1);
    addEdge(g, 1, 2);
    addEdge(g, 2, 3);
    addEdge(g, 3, 0);
    assertBoolEquals(true, isBipartite(g), "Test 369.1 - Bipartite graph");
    free(g->adjList[0]);
    free(g->adjList[1]);
    free(g->adjList[2]);
    free(g->adjList[3]);
    free(g);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use two colors (0, 1).
 - Handle disconnected components.
 - Test with bipartite/non-bipartite graphs.
- **Expert Tips:**
 - Explain bipartite: "No adjacent nodes with same color."
 - In interviews, clarify: "Ask about undirected assumption."
 - Suggest optimization: "DFS for cycle detection."
 - Test edge cases: "Empty graph, single vertex."

Problem 370: Find the Number of Nodes in a Complete Binary Tree

Issue Description

Count the number of nodes in a complete binary tree efficiently.

Problem Decomposition & Solution Steps

- **Input:** Complete binary tree root.
- **Output:** Number of nodes.
- **Approach:** Use height-based counting.
- **Algorithm:** Complete Tree Node Count
 - **Explanation:** Use left/right heights for $O(\log^2 n)$.
- **Steps:**
 1. Compute left and right heights.
 2. If equal, return $2^h - 1$.

- 3. Else, recurse for left/right subtrees.
- **Complexity:** Time $O(\log^2 n)$, Space $O(\log n)$ for recursion.

Algorithm Explanation

For a complete binary tree, if left and right heights are equal, the tree is perfect ($2^h - 1$ nodes).

Otherwise, recursively count nodes in left and right subtrees.

Height computation is $O(\log n)$, and recursion depth is $O(\log n)$, giving $O(\log^2 n)$ time, with $O(\log n)$ space.

Coding Part (with Unit Tests)

```

int heightLeft(TreeNode* root) {
    int h = 0;
    while (root) {
        root = root->left;
        h++;
    }
    return h - 1;
}

int heightRight(TreeNode* root) {
    int h = 0;
    while (root) {
        root = root->right;
        h++;
    }
    return h - 1;
}

int countNodes(TreeNode* root) {
    if (!root) return 0;
    int leftH = heightLeft(root);
    int rightH = heightRight(root);
    if (leftH == rightH) return (1 << (leftH + 1)) - 1;
    return 1 + countNodes(root->left) + countNodes(root->right);
}

// Unit tests
void testCountNodes() {
    TreeNode* root = insertBST(NULL, 1);
    root->left = (TreeNode*)malloc(sizeof(TreeNode));
    root->left->val = 2; root->left->left = root->left->right = NULL;
    root->right = (TreeNode*)malloc(sizeof(TreeNode));
    root->right->val = 3; root->right->left = root->right->right = NULL;
    assertEquals(3, countNodes(root), "Test 370.1 - Node count");
    free(root->left);
    free(root->right);
    free(root);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Exploit complete tree property.
 - Compute heights efficiently.
 - Test with complete trees.
- **Expert Tips:**

- Explain counting: "Use heights for $O(\log^2 n)$."
- In interviews, clarify: "Ask about complete definition."
- Suggest optimization: "Level-order for $O(n)$."
- Test edge cases: "Empty tree, perfect tree."

Problem 371: Implement a Trie with Wildcard Search

Issue Description

Implement a trie with insert and wildcard search ('.' matches any character).

Problem Decomposition & Solution Steps

- **Input:** Words to insert, pattern with '.' for search.
- **Output:** Trie operations, search result.
- **Approach:** Use trie with recursive wildcard search.
- **Algorithm:** Trie with Wildcard
 - **Explanation:** Store characters in trie, handle '.' in search.
- **Steps:**
 1. Insert: Add characters to trie nodes.
 2. Search: Recursively match pattern, try all children for '.'.
- **Complexity:** Time $O(m)$ for insert, $O(26^m)$ for wildcard search; Space $O(N)$.

Algorithm Explanation

The trie stores words as paths of character nodes.

Insert adds nodes for each character ($O(m)$ for word length m).

Wildcard search matches pattern characters, recursively exploring all children for '.' ($O(26^m)$ in worst case).

Space is $O(N)$ for total characters.

Coding Part (with Unit Tests)

```
#define ALPHABET_SIZE 26

typedef struct TrieNode {
    struct TrieNode* children[ALPHABET_SIZE];
    bool isEnd;
} TrieNode;

TrieNode* createTrieNode() {
    TrieNode* node = (TrieNode*)malloc(sizeof(TrieNode));
    for (int i = 0; i < ALPHABET_SIZE; i++) node->children[i] = NULL;
    node->isEnd = false;
    return node;
}
```

```

void insertTrie(TrieNode* root, const char* word) {
    TrieNode* curr = root;
    for (int i = 0; word[i]; i++) {
        int idx = word[i] - 'a';
        if (!curr->children[idx]) curr->children[idx] = createTrieNode();
        curr = curr->children[idx];
    }
    curr->isEnd = true;
}

bool searchTrieWildcard(TrieNode* root, const char* pattern, int idx) {
    if (!root) return false;
    if (!pattern[idx]) return root->isEnd;
    if (pattern[idx] == '.') {
        for (int i = 0; i < ALPHABET_SIZE; i++) {
            if (searchTrieWildcard(root->children[i], pattern, idx + 1)) return true;
        }
        return false;
    }
    int c = pattern[idx] - 'a';
    return searchTrieWildcard(root->children[c], pattern, idx + 1);
}

// Unit tests
void testTrieWildcard() {
    TrieNode* root = createTrieNode();
    insertTrie(root, "cat");
    assertBoolEquals(true, searchTrieWildcard(root, "c.t", 0), "Test 371.1 - Wildcard search");
    for (int i = 0; i < ALPHABET_SIZE; i++) {
        if (root->children[i]) free(root->children[i]);
    }
    free(root);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle lowercase letters only.
 - Free trie nodes recursively.
 - Test with wildcard patterns.
- **Expert Tips:**
 - Explain wildcard: "Try all children for '!'."
 - In interviews, clarify: "Ask about case sensitivity."
 - Suggest optimization: "Bitmask for faster search."
 - Test edge cases: "Empty trie, all wildcards."

Problem 372: Find the Top View of a Binary Tree

Issue Description

Find the top view of a binary tree (first node at each horizontal distance).

Problem Decomposition & Solution Steps

- **Input:** Binary tree root.
- **Output:** Array of nodes visible from top.

- **Approach:** Use level-order with horizontal distance.
- **Algorithm:** Top View
 - **Explanation:** Track first node at each horizontal distance.
- **Steps:**
 1. Use queue with node and horizontal distance.
 2. Store first node for each distance in map.
 3. Return nodes in order of distance.
- **Complexity:** Time $O(n)$, Space $O(w + k)$ for queue and map.

Algorithm Explanation

The algorithm uses level-order traversal, tracking each node's horizontal distance (HD).

The first node at each HD is stored in a map.

Nodes are returned in sorted HD order.

Time is $O(n)$ for n nodes, with $O(w)$ for queue (w is max width) and $O(k)$ for output.

Coding Part (with Unit Tests)

```

typedef struct {
    TreeNode* node;
    int hd;
} QueueNode;

void topView(TreeNode* root, int* result, int* returnSize) {
    if (!root) return;
    int map[200] = {0}, hdMap[200], mapSize = 0;
    Queue q; initQueue(&q);
    QueueNode qn = {root, 0};
    enqueue(&q, &qn);
    map[100] = root->val; hdMap[mapSize++] = 0;
    while (q.front <= q.rear) {
        dequeue(&q, &qn);
        TreeNode* node = qn.node;
        if (node->left) {
            QueueNode left = {node->left, qn.hd - 1};
            if (!map[100 + left.hd]) {
                map[100 + left.hd] = left.node->val;
                hdMap[mapSize++] = left.hd;
            }
            enqueue(&q, &left);
        }
        if (node->right) {
            QueueNode right = {node->right, qn.hd + 1};
            if (!map[100 + right.hd]) {
                map[100 + right.hd] = right.node->val;
                hdMap[mapSize++] = right.hd;
            }
            enqueue(&q, &right);
        }
    }
    for (int i = -100; i <= 100; i++) {
        if (map[100 + i]) result[(*returnSize)++] = map[100 + i];
    }
}

```

```

// Unit tests
void testTopView() {
    TreeNode* root = insertBST(NULL, 1);
    root->left = (TreeNode*)malloc(sizeof(TreeNode));
    root->left->val = 2; root->left->left = root->left->right = NULL;
    int result[100], returnSize = 0;
    topView(root, result, &returnSize);
    assertEquals(2, result[0], "Test 372.1 - Top view first");
    free(root->left);
    free(root);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track horizontal distances.
 - Use map for first nodes.
 - Test with skewed trees.
- **Expert Tips:**
 - Explain top view: "First node per horizontal distance."
 - In interviews, clarify: "Ask about order of output."
 - Suggest optimization: "Pre-order traversal."
 - Test edge cases: "Empty tree, single node."

Problem 373: Implement a Graph Using Adjacency Matrix

Issue Description

Implement a graph using an adjacency matrix with add edge and print operations.

Problem Decomposition & Solution Steps

- **Input:** Vertices, edges.
- **Output:** Graph operations.
- **Approach:** Use 2D array for adjacency matrix.
- **Algorithm:** Adjacency Matrix Graph
 - **Explanation:** $\text{Matrix}[i][j] = 1$ if edge exists.
- **Steps:**
 1. Initialize matrix with zeros.
 2. Add edge: Set $\text{matrix}[\text{src}][\text{dest}] = 1$.
 3. Print: Display matrix.
- **Complexity:** Time $O(1)$ for add edge, $O(V^2)$ for print; Space $O(V^2)$.

Algorithm Explanation

The adjacency matrix is a $V \times V$ array where $\text{matrix}[i][j] = 1$ indicates an edge from i to j .

Adding an edge is $O(1)$.

Printing traverses the matrix ($O(V^2)$).

Space is $O(V^2)$ for V vertices.

Coding Part (with Unit Tests)

```
typedef struct {
    int matrix[MAX_VERTICES][MAX_VERTICES];
    int vertices;
} MatrixGraph;

MatrixGraph* createMatrixGraph(int vertices) {
    MatrixGraph* g = (MatrixGraph*)malloc(sizeof(MatrixGraph));
    g->vertices = vertices;
    memset(g->matrix, 0, sizeof(g->matrix));
    return g;
}

void addEdgeMatrix(MatrixGraph* g, int src, int dest) {
    g->matrix[src][dest] = 1;
}

void printMatrixGraph(MatrixGraph* g) {
    for (int i = 0; i < g->vertices; i++) {
        printf("Vertex %d: ", i);
        for (int j = 0; j < g->vertices; j++) {
            if (g->matrix[i][j]) printf("%d ", j);
        }
        printf("\n");
    }
}

// Unit tests
void testMatrixGraph() {
    MatrixGraph* g = createMatrixGraph(3);
    addEdgeMatrix(g, 0, 1);
    assertEquals(1, g->matrix[0][1], "Test 373.1 - Edge 0->1");
    free(g);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Initialize matrix to zeros.
 - Handle directed/undirected edges.
 - Test with sparse/dense graphs.
- **Expert Tips:**
 - Explain matrix: " $O(1)$ edge check, $O(V^2)$ space."
 - In interviews, clarify: "Ask about edge weights."
 - Suggest optimization: "Adjacency list for sparse graphs."
 - Test edge cases: "Empty graph, single edge."

Problem 374: Find the Number of Islands in a Matrix (Graph)

Issue Description

Count the number of islands (connected 1s) in a binary matrix using DFS.

Problem Decomposition & Solution Steps

- **Input:** Binary matrix (0s and 1s).
- **Output:** Number of islands.
- **Approach:** Use DFS to mark connected regions.
- **Algorithm:** Island Count
 - **Explanation:** Each unvisited 1 starts a new island.
- **Steps:**
 1. Iterate through matrix.
 2. For each unvisited 1, use DFS to mark connected 1s.
 3. Increment island count.
- **Complexity:** Time $O(R \times C)$, Space $O(R \times C)$ for visited array/recursion.

Algorithm Explanation

The algorithm scans the matrix.

For each unvisited 1, DFS marks all connected 1s as visited and increments the island count.

DFS explores 4 directions (up, down, left, right).

Time is $O(R \times C)$ for R rows and C columns, with $O(R \times C)$ space for recursion/visited array.

Coding Part (with Unit Tests)

```
void dfsIsland(int** grid, int rows, int cols, int r, int c, bool** visited) {
    if (r < 0 || r >= rows || c < 0 || c >= cols || !grid[r][c] || visited[r][c]) return;
    visited[r][c] = true;
    dfsIsland(grid, rows, cols, r - 1, c, visited);
    dfsIsland(grid, rows, cols, r + 1, c, visited);
    dfsIsland(grid, rows, cols, r, c - 1, visited);
    dfsIsland(grid, rows, cols, r, c + 1, visited);
}

int numIslands(int** grid, int rows, int cols) {
    bool** visited = (bool**)malloc(rows * sizeof(bool*));
    for (int i = 0; i < rows; i++) {
        visited[i] = (bool*)calloc(cols, sizeof(bool));
    }
    int islands = 0;
    for (int i = 0; i < rows; i++) {
        for (int j = 0; j < cols; j++) {
            if (grid[i][j] && !visited[i][j]) {
                dfsIsland(grid, rows, cols, i, j, visited);
                islands++;
            }
        }
    }
    for (int i = 0; i < rows; i++) free(visited[i]);
    free(visited);
    return islands;
}

// Unit tests
void testNumIslands() {
    int grid[3][3] = {{1, 0, 1}, {0, 1, 0}, {1, 0, 1}};
    int* gridPtr[3] = {grid[0], grid[1], grid[2]};
    assertEquals(2, numIslands(gridPtr, 3, 3), "Test 374.1 - Island count");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use DFS for connected components.
 - Handle boundary checks.
 - Free visited array.
 - Test with different matrix sizes.
- **Expert Tips:**
 - Explain islands: "Connected 1s via DFS."
 - In interviews, clarify: "Ask about diagonal connections."
 - Suggest optimization: "BFS or Union-Find."
 - Test edge cases: "Empty matrix, single island."

Problem 375: Check if a Tree is a Subtree of Another Tree

Issue Description

Check if one binary tree is a subtree of another.

Problem Decomposition & Solution Steps

- **Input:** Two binary tree roots (main and sub).
- **Output:** Boolean indicating if sub is a subtree.
- **Approach:** Check if sub matches any subtree.
- **Algorithm:** Subtree Check
 - **Explanation:** Compare trees recursively, check all subtrees.
- **Steps:**
 1. Check if trees are identical (same structure/values).
 2. Recursively check left/right subtrees of main tree.
- **Complexity:** Time $O(m \times n)$, Space $O(h)$ for recursion.

Algorithm Explanation

The algorithm checks if the sub tree matches the main tree or any of its subtrees.

The `isSameTree` helper (from Problem 346) checks identical trees.

For each node in the main tree, check if it matches the sub tree.

Time is $O(m \times n)$ for m and n nodes, with $O(h)$ space for recursion.

Coding Part (with Unit Tests)

```
bool isSameTree(TreeNode* p, TreeNode* q) {  
    if (!p && !q) return true;  
    if (!p || !q) return false;  
    return p->val == q->val && isSameTree(p->left, q->left) && isSameTree(p->right, q->right);  
}
```

```

bool isSubtree(TreeNode* mainTree, TreeNode* subTree) {
    if (!subTree) return true;
    if (!mainTree) return false;
    return isSameTree(mainTree, subTree) ||
           isSubtree(mainTree->left, subTree) ||
           isSubtree(mainTree->right, subTree);
}

// Unit tests
void testIsSubtree() {
    TreeNode* main = insertBST(NULL, 1);
    main->left = (TreeNode*)malloc(sizeof(TreeNode));
    main->left->val = 2; main->left->left = main->left->right = NULL;
    TreeNode* sub = (TreeNode*)malloc(sizeof(TreeNode));
    sub->val = 2; sub->left = sub->right = NULL;
    assertBoolEquals(true, isSubtree(main, sub), "Test 375.1 - Subtree check");
    free(main->left);
    free(main);
    free(sub);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Reuse identical tree check.
 - Handle NULL cases.
 - Test with matching/non-matching subtrees.
- **Expert Tips:**
 - Explain subtree: "Check if sub matches any subtree."
 - In interviews, clarify: "Ask about empty subtree."
 - Suggest optimization: "Serialize trees for comparison."
 - Test edge cases: "Empty trees, single node."

Problem 376: Find the kth Largest Element in a Heap

Issue Description

Find the kth largest element in a max-heap.

Problem Decomposition & Solution Steps

- **Input:** Max-heap, k.
- **Output:** kth largest value.
- **Approach:** Extract k times from max-heap.
- **Algorithm:** kth Largest in Heap
 - **Explanation:** Extract-max k times to get kth largest.
- **Steps:**
 1. Copy heap to avoid modification.
 2. Extract-max k times.
 3. Return last extracted value.
- **Complexity:** Time O(k log n), Space O(n) for copy.

Algorithm Explanation

The algorithm copies the max-heap to preserve it, then performs extract-max k times.

The kth extracted value is the kth largest.

Each extract-max is $O(\log n)$, so total time is $O(k \log n)$ for n elements, with $O(n)$ space for the copy.

Coding Part (with Unit Tests)

```
int kthLargestHeap(MaxHeap* h, int k) {
    MaxHeap temp = *h;
    int val;
    for (int i = 0; i < k; i++) {
        if (!extractMax(&temp, &val)) return -1;
    }
    return val;
}

// Unit tests
void testKthLargestHeap() {
    MaxHeap h; initMaxHeap(&h);
    insertMaxHeap(&h, 3);
    insertMaxHeap(&h, 1);
    assertEquals(1, kthLargestHeap(&h, 2), "Test 376.1 - 2nd largest");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Copy heap to preserve original.
 - Validate k range.
 - Test with different k values.
- **Expert Tips:**
 - Explain kth largest: "Extract k times from max-heap."
 - In interviews, clarify: "Ask about modifying heap."
 - Suggest optimization: "Quick-select for $O(n)$."
 - Test edge cases: "k=1, k=size of heap."

Problem 377: Find the Vertical Order Traversal of a Binary Tree

Issue Description

Perform a vertical order traversal of a binary tree (nodes at same horizontal distance).

Problem Decomposition & Solution Steps

- **Input:** Binary tree root.
- **Output:** Array of nodes grouped by horizontal distance.
- **Approach:** Use level-order with horizontal distance.
- **Algorithm:** Vertical Order

- **Explanation:** Group nodes by horizontal distance.
- **Steps:**
 1. Use queue with node and horizontal distance.
 2. Store nodes in map by distance.
 3. Return nodes in order of distance.
- **Complexity:** Time O(n), Space O(n) for map/queue.

Algorithm Explanation

The algorithm uses level-order traversal, tracking each node's horizontal distance (HD).

Nodes are stored in a map by HD.

The map is traversed in HD order to produce the output.

Time is O(n) for n nodes, with O(n) space for map and queue.

Coding Part (with Unit Tests)

```

typedef struct {
    int values[100];
    int size;
} VerticalList;

void verticalOrder(TreeNode* root, int* result, int* returnSize) {
    if (!root) return;
    VerticalList map[200];
    for (int i = 0; i < 200; i++) map[i].size = 0;
    Queue q; initQueue(&q);
    QueueNode qn = {root, 0};
    enqueue(&q, 0);
    int minHD = 0, maxHD = 0;
    while (q.front <= q.rear) {
        dequeue(&q, &qn.hd);
        TreeNode* node = qn.node;
        map[100 + qn.hd].values[map[100 + qn.hd].size++] = node->val;
        if (qn.hd < minHD) minHD = qn.hd;
        if (qn.hd > maxHD) maxHD = qn.hd;
        if (node->left) {
            QueueNode left = {node->left, qn.hd - 1};
            enqueue(&q, 0);
        }
        if (node->right) {
            QueueNode right = {node->right, qn.hd + 1};
            enqueue(&q, 0);
        }
    }
    for (int i = minHD; i <= maxHD; i++) {
        for (int j = 0; j < map[100 + i].size; j++) {
            result[(*returnSize)++] = map[100 + i].values[j];
        }
    }
}

```

```

// Unit tests
void testVerticalOrder() {
    TreeNode* root = insertBST(NULL, 1);
    root->left = (TreeNode*)malloc(sizeof(TreeNode));
    root->left->val = 2; root->left->left = root->left->right = NULL;
    int result[100], returnSize = 0;
    verticalOrder(root, result, &returnSize);
    assertEquals(2, result[0], "Test 377.1 - Vertical order first");
    free(root->left);
    free(root);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track horizontal distances.
 - Use map for grouping.
 - Test with complex trees.
- **Expert Tips:**
 - Explain vertical order: "Nodes by horizontal distance."
 - In interviews, clarify: "Ask about order within distance."
 - Suggest optimization: "Pre-order for simplicity."
 - Test edge cases: "Empty tree, single column."

Problem 378: Implement a Disjoint-Set (Union-Find) Data Structure

Issue Description

Implement a disjoint-set with union and find operations.

Problem Decomposition & Solution Steps

- **Input:** Elements, union/find operations.
- **Output:** Disjoint-set operations.
- **Approach:** Use array with path compression and union by rank.
- **Algorithm:** Union-Find
 - **Explanation:** Track parent and rank for efficient unions.
- **Steps:**
 1. Initialize parent array (each element is own parent).
 2. Find: Follow parent pointers with path compression.
 3. Union: Merge by rank to minimize tree height.
- **Complexity:** Time $O(\alpha(n))$ amortized for find/union; Space $O(n)$.

Algorithm Explanation

The disjoint-set uses a parent array where each element points to its parent (root for set).

Find uses path compression to flatten trees ($O(\alpha(n))$ amortized).

Union merges by rank to keep trees shallow ($O(\alpha(n))$).

Space is O(n) for arrays.

Coding Part (with Unit Tests)

```
typedef struct {
    int parent[MAX_VERTICES];
    int rank[MAX_VERTICES];
} DisjointSet;

void initDisjointSet(DisjointSet* ds, int n) {
    for (int i = 0; i < n; i++) {
        ds->parent[i] = i;
        ds->rank[i] = 0;
    }
}

int find(DisjointSet* ds, int x) {
    if (ds->parent[x] != x) {
        ds->parent[x] = find(ds, ds->parent[x]); // Path compression
    }
    return ds->parent[x];
}

void unionSet(DisjointSet* ds, int x, int y) {
    int px = find(ds, x), py = find(ds, y);
    if (px == py) return;
    if (ds->rank[px] < ds->rank[py]) ds->parent[px] = py;
    else if (ds->rank[px] > ds->rank[py]) ds->parent[py] = px;
    else {
        ds->parent[py] = px;
        ds->rank[px]++;
    }
}

// Unit tests
void testDisjointSet() {
    DisjointSet ds;
    initDisjointSet(&ds, 5);
    unionSet(&ds, 0, 1);
    assertEquals(find(&ds, 0), find(&ds, 1), "Test 378.1 - Same set");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use path compression and union by rank.
 - Initialize parent/rank arrays.
 - Test with multiple unions.
- **Expert Tips:**
 - Explain union-find: "Efficient set operations."
 - In interviews, clarify: "Ask about weighted union."
 - Suggest optimization: "Path halving for find."
 - Test edge cases: "Single element, all merged."

Problem 379: Find the Shortest Path in a Weighted Graph (Dijkstra's)

Issue Description

Find the shortest path in a weighted graph using Dijkstra's algorithm.

Problem Decomposition & Solution Steps

- **Input:** Graph (adjacency list with weights), source vertex.
- **Output:** Array of shortest distances.
- **Approach:** Use min-heap for Dijkstra's algorithm.
- **Algorithm:** Dijkstra's
 - **Explanation:** Greedily select minimum distance vertex.
- **Steps:**
 1. Initialize distances (infinity except source = 0).
 2. Use min-heap to select minimum distance vertex.
 3. Update distances for neighbors.
- **Complexity:** Time $O((V + E) \log V)$, Space $O(V)$ for heap/arrays.

Algorithm Explanation

Dijkstra's algorithm maintains a min-heap of vertices by distance.

It extracts the minimum, updates neighbors' distances if shorter paths are found, and repeats until all vertices are processed.

Time is $O((V + E) \log V)$ using a heap, with $O(V)$ space.

Coding Part (with Unit Tests)

```
typedef struct Edge {
    int dest, weight;
    struct Edge* next;
} Edge;

typedef struct {
    Edge* adjList[MAX_VERTICES];
    int vertices;
} WeightedGraph;

WeightedGraph* createWeightedGraph(int vertices) {
    WeightedGraph* g = (WeightedGraph*)malloc(sizeof(WeightedGraph));
    g->vertices = vertices;
    for (int i = 0; i < vertices; i++) g->adjList[i] = NULL;
    return g;
}

void addEdgeWeighted(WeightedGraph* g, int src, int dest, int weight) {
    Edge* newEdge = (Edge*)malloc(sizeof(Edge));
    newEdge->dest = dest;
    newEdge->weight = weight;
    newEdge->next = g->adjList[src];
    g->adjList[src] = newEdge;
}
```

```

int* dijkstra(WeightedGraph* g, int src, int* returnSize) {
    int* dist = (int*)malloc(g->vertices * sizeof(int));
    bool visited[MAX_VERTICES] = {false};
    MinHeap h; initMinHeap(&h);
    for (int i = 0; i < g->vertices; i++) dist[i] = INT_MAX;
    dist[src] = 0;
    insertMinHeap(&h, src);
    while (h.size > 0) {
        int v;
        extractMin(&h, &v);
        if (visited[v]) continue;
        visited[v] = true;
        Edge* curr = g->adjList[v];
        while (curr) {
            if (!visited[curr->dest] && dist[v] + curr->weight < dist[curr->dest]) {
                dist[curr->dest] = dist[v] + curr->weight;
                insertMinHeap(&h, curr->dest);
            }
            curr = curr->next;
        }
    }
    *returnSize = g->vertices;
    return dist;
}

// Unit tests
void testDijkstra() {
    WeightedGraph* g = createWeightedGraph(3);
    addEdgeWeighted(g, 0, 1, 1);
    addEdgeWeighted(g, 1, 2, 1);
    int returnSize;
    int* dist = dijkstra(g, 0, &returnSize);
    assertEquals(2, dist[2], "Test 379.1 - Shortest path to 2");
    free(dist);
    free(g->adjList[0]);
    free(g->adjList[1]);
    free(g);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use min-heap for efficiency.
 - Handle unreachable vertices.
 - Test with weighted graphs.
- **Expert Tips:**
 - Explain Dijkstra's: "Greedy shortest path."
 - In interviews, clarify: "Ask about negative weights."
 - Suggest optimization: "Fibonacci heap for $O(V \log V + E)$."
 - Test edge cases: "No path, single vertex."

Problem 380: Implement a Function to Check if a Graph is Connected

Issue Description

Check if an undirected graph is connected using DFS.

Problem Decomposition & Solution Steps

- **Input:** Graph (adjacency list).
- **Output:** Boolean indicating connectivity.
- **Approach:** Use DFS from one vertex, check all reached.
- **Algorithm:** Graph Connectivity
 - **Explanation:** DFS from any vertex should visit all vertices.
- **Steps:**
 1. Perform DFS from vertex 0.
 2. Count visited vertices.
 3. Return true if count equals total vertices.
- **Complexity:** Time $O(V + E)$, Space $O(V)$ for visited array.

Algorithm Explanation

DFS explores all reachable vertices from a starting vertex.

For an undirected graph, if all vertices are visited, the graph is connected.

Time is $O(V + E)$ for V vertices and E edges, with $O(V)$ space for the visited array.

Coding Part (with Unit Tests)

```
void dfsConnected(Graph* g, int v, bool* visited) {
    visited[v] = true;
    ListNode* curr = g->adjList[v];
    while (curr) {
        if (!visited[curr->val]) dfsConnected(g, curr->val, visited);
        curr = curr->next;
    }
}

bool isConnected(Graph* g) {
    if (g->vertices == 0) return true;
    bool visited[MAX_VERTICES] = {false};
    dfsConnected(g, 0, visited);
    for (int i = 0; i < g->vertices; i++) {
        if (!visited[i]) return false;
    }
    return true;
}

// Unit tests
void testIsConnected() {
    Graph* g = createGraph(3);
    addEdge(g, 0, 1);
    addEdge(g, 1, 2);
    assertBoolEquals(true, isConnected(g), "Test 380.1 - Connected graph");
    free(g->adjList[0]);
    free(g->adjList[1]);
    free(g);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use DFS for connectivity.

- Handle empty graph.
 - Test with connected/disconnected graphs.
- **Expert Tips:**
 - Explain connectivity: "All vertices reachable from one."
 - In interviews, clarify: "Ask about directed graphs."
 - Suggest optimization: "BFS or Union-Find."
 - Test edge cases: "Empty graph, single vertex."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for data structures problems 365 to 380:\n");
    testShortestPath();
    testMinHeap();
    testRightView();
    testMaxHeap();
    testIsBipartite();
    testCountNodes();
    testTrieWildcard();
    testTopView();
    testMatrixGraph();
    testNumIslands();
    testIsSubtree();
    testKthLargestHeap();
    testVerticalOrder();
    testDisjointSet();
    testDijkstra();
    testIsConnected();
    return 0;
}
```

Algorithms

(70 Problems)

Problem 381: Sort an Array Using Quicksort

Issue Description

Sort an array using the quicksort algorithm.

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array (in-place).
- **Approach:** Use quicksort with pivot partitioning.
- **Algorithm:** Quicksort
 - **Explanation:** Choose pivot, partition array, recurse on subarrays.
- **Steps:**
 1. Select pivot (e.g., last element).
 2. Partition array around pivot.
 3. Recursively sort subarrays.
- **Complexity:** Time $O(n \log n)$ average, $O(n^2)$ worst; Space $O(\log n)$.

Algorithm Explanation

Quicksort selects a pivot, partitions the array so elements $<$ pivot are on the left and elements $>$ pivot are on the right, then recursively sorts subarrays.

Partitioning is $O(n)$, and recursion depth is $O(\log n)$ on average, giving $O(n \log n)$ time.

Worst-case $O(n^2)$ occurs with poor pivots.

Space is $O(\log n)$ for recursion.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>

void swap(int* a, int* b) {
    int temp = *a;
    *a = *b;
    *b = temp;
}

int partition(int* arr, int low, int high) {
    int pivot = arr[high];
    int i = low - 1;
    for (int j = low; j < high; j++) {
        if (arr[j] <= pivot) {
            i++;
            swap(&arr[i], &arr[j]);
        }
    }
    swap(&arr[i + 1], &arr[high]);
    return i + 1;
}
```

```

void quicksort(int* arr, int low, int high) {
    if (low < high) {
        int pi = partition(arr, low, high);
        quicksort(arr, low, pi - 1);
        quicksort(arr, pi + 1, high);
    }
}

void quicksortWrapper(int* arr, int n) {
    quicksort(arr, 0, n - 1);
}

// Unit test helper
void assertEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testQuicksort() {
    int arr[] = {5, 2, 9, 1, 5};
    quicksortWrapper(arr, 5);
    assertEquals(1, arr[0], "Test 381.1 - First element sorted");
    assertEquals(9, arr[4], "Test 381.2 - Last element sorted");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Choose pivot wisely (e.g., random or median).
 - Handle duplicates in partitioning.
 - Test with unsorted/sorted arrays.
- **Expert Tips:**
 - Explain quicksort: "Divide and conquer with pivot."
 - In interviews, clarify: "Ask about pivot choice."
 - Suggest optimization: "Random pivot or three-way partitioning."
 - Test edge cases: "Empty array, single element, duplicates."

Problem 382: Implement Binary Search on a Sorted Array

Issue Description

Implement binary search to find an element in a sorted array.

Problem Decomposition & Solution Steps

- **Input:** Sorted array, target value.
- **Output:** Index of target or -1 if not found.
- **Approach:** Use binary search to divide search space.
- **Algorithm:** Binary Search
 - **Explanation:** Halve search space each step.

- **Steps:**
 1. Initialize low and high pointers.
 2. Compute mid, compare with target.
 3. Adjust low/high based on comparison.
- **Complexity:** Time O(log n), Space O(1).

Algorithm Explanation

Binary search halves the search space by comparing the middle element with the target.

If target equals mid, return index.

If target is less, search left half; if greater, search right half.

Time is O(log n) for n elements, with O(1) space.

Coding Part (with Unit Tests)

```
int binarySearch(int* arr, int n, int target) {
    int low = 0, high = n - 1;
    while (low <= high) {
        int mid = low + (high - low) / 2;
        if (arr[mid] == target) return mid;
        if (arr[mid] < target) low = mid + 1;
        else high = mid - 1;
    }
    return -1;
}

// Unit tests
void testBinarySearch() {
    int arr[] = {1, 2, 3, 4, 5};
    assertEquals(2, binarySearch(arr, 5, 3), "Test 382.1 - Find element");
    assertEquals(-1, binarySearch(arr, 5, 6), "Test 382.2 - Element not found");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Ensure array is sorted.
 - Use $mid = \text{low} + (\text{high} - \text{low}) / 2$ to avoid overflow.
 - Test with present/absent targets.
- **Expert Tips:**
 - Explain binary search: "Halve search space each step."
 - In interviews, clarify: "Ask about duplicates."
 - Suggest optimization: "Iterative over recursive."
 - Test edge cases: "Empty array, single element."

Problem 383: Find the Maximum Sum Subarray (Kadane's Algorithm)

Issue Description

Find the subarray with the maximum sum using Kadane's algorithm.

Problem Decomposition & Solution Steps

- **Input:** Array of integers (positive/negative).
- **Output:** Maximum sum of contiguous subarray.
- **Approach:** Use Kadane's algorithm for dynamic programming.
- **Algorithm:** Kadane's
 - **Explanation:** Track max sum ending at each position.
- **Steps:**
 1. Initialize max_so_far and max_ending_here.
 2. For each element, update max_ending_here.
 3. Update max_so_far if max_ending_here is greater.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

Kadane's algorithm scans the array, maintaining the maximum sum ending at the current position (max_ending_here) and the overall maximum sum (max_so_far).

At each element, either include it in the current subarray or start a new subarray.

Time is O(n) for n elements, with O(1) space.

Coding Part (with Unit Tests)

```
int maxSubArray(int* arr, int n) {
    int max_so_far = arr[0], max_ending_here = arr[0];
    for (int i = 1; i < n; i++) {
        max_ending_here = max_ending_here + arr[i] > arr[i] ? max_ending_here + arr[i] : arr[i];
        if (max_ending_here > max_so_far) max_so_far = max_ending_here;
    }
    return max_so_far;
}

// Unit tests
void testMaxSubArray() {
    int arr[] = {-2, 1, -3, 4, -1, 2, 1, -5, 4};
    assertEquals(6, maxSubArray(arr, 9), "Test 383.1 - Max subarray sum");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Initialize with first element.
 - Handle negative numbers.
 - Test with all-negative arrays.
- **Expert Tips:**
 - Explain Kadane's: "Track max sum ending at each index."

- In interviews, clarify: "Ask about returning subarray indices."
- Suggest optimization: "Handle all-negative case."
- Test edge cases: "Single element, all negative."

Problem 384: Implement Merge Sort for an Array

Issue Description

Sort an array using the merge sort algorithm.

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array (in-place or new array).
- **Approach:** Use merge sort with divide-and-conquer.
- **Algorithm:** Merge Sort
 - **Explanation:** Divide array, sort halves, merge results.
- **Steps:**
 1. Divide array into two halves.
 2. Recursively sort each half.
 3. Merge sorted halves into result.
- **Complexity:** Time $O(n \log n)$, Space $O(n)$.

Algorithm Explanation

Merge sort divides the array into two halves, recursively sorts them, and merges the sorted halves.

Merging combines two sorted arrays into one, comparing elements and placing them in order.

Time is $O(n \log n)$ for n elements ($O(\log n)$ depth, $O(n)$ per merge), with $O(n)$ space for temporary arrays.

Coding Part (with Unit Tests)

```
void merge(int* arr, int l, int m, int r) {
    int n1 = m - l + 1, n2 = r - m;
    int L[100], R[100];
    for (int i = 0; i < n1; i++) L[i] = arr[l + i];
    for (int i = 0; i < n2; i++) R[i] = arr[m + 1 + i];
    int i = 0, j = 0, k = l;
    while (i < n1 && j < n2) {
        arr[k++] = L[i] <= R[j] ? L[i++] : R[j++];
    }
    while (i < n1) arr[k++] = L[i++];
    while (j < n2) arr[k++] = R[j++];
}

void mergeSort(int* arr, int l, int r) {
    if (l < r) {
        int m = l + (r - l) / 2;
        mergeSort(arr, l, m);
        mergeSort(arr, m + 1, r);
        merge(arr, l, m, r);
    }
}
```

```

void mergeSortWrapper(int* arr, int n) {
    mergeSort(arr, 0, n - 1);
}

// Unit tests
void testMergeSort() {
    int arr[] = {5, 2, 9, 1, 5};
    mergeSortWrapper(arr, 5);
    assertEquals(1, arr[0], "Test 384.1 - First element sorted");
    assertEquals(9, arr[4], "Test 384.2 - Last element sorted");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use temporary arrays for merging.
 - Avoid index errors in merge.
 - Test with unsorted/sorted arrays.
- **Expert Tips:**
 - Explain merge sort: "Stable divide-and-conquer."
 - In interviews, clarify: "Ask about in-place sorting."
 - Suggest optimization: "Bottom-up merge sort."
 - Test edge cases: "Empty array, single element."

Problem 385: Find the kth Smallest Element in an Unsorted Array

Issue Description

Find the kth smallest element in an unsorted array.

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, k.
- **Output:** kth smallest element.
- **Approach:** Use quickselect (variant of quicksort).
- **Algorithm:** Quickselect
 - **Explanation:** Partition array, recurse on relevant side.
- **Steps:**
 1. Select pivot, partition array.
 2. If pivot index = k-1, return pivot.
 3. Recurse on left (if k < pivot index) or right.
- **Complexity:** Time O(n) average, O(n²) worst; Space O(1).

Algorithm Explanation

Quickselect uses quicksort's partitioning to place the pivot in its final sorted position.

If the pivot's index is k-1, it's the kth smallest.

Otherwise, recurse on the side containing the kth element.

Average time is $O(n)$, worst-case $O(n^2)$.

Space is $O(1)$ (in-place).

Coding Part (with Unit Tests)

```
int quickselect(int* arr, int low, int high, int k) {
    if (low == high) return arr[low];
    int pi = partition(arr, low, high);
    if (k - 1 == pi) return arr[pi];
    if (k - 1 < pi) return quickselect(arr, low, pi - 1, k);
    return quickselect(arr, pi + 1, high, k);
}

int findKthSmallest(int* arr, int n, int k) {
    if (k < 1 || k > n) return -1;
    return quickselect(arr, 0, n - 1, k);
}

// Unit tests
void testKthSmallest() {
    int arr[] = {7, 10, 4, 3, 20, 15};
    assertEquals(7, findKthSmallest(arr, 6, 3), "Test 385.1 - 3rd smallest");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate k range.
 - Use quicksort's partition function.
 - Test with different k values.
- **Expert Tips:**
 - Explain quickselect: "Partition to find kth element."
 - In interviews, clarify: "Ask about duplicates."
 - Suggest optimization: "Median-of-medians for $O(n)$ worst case."
 - Test edge cases: "k=1, k=n, invalid k."

Problem 386: Implement a Function to Perform Selection Sort

Issue Description

Sort an array using the selection sort algorithm.

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array (in-place).
- **Approach:** Repeatedly select minimum element.
- **Algorithm:** Selection Sort
 - **Explanation:** Find min, swap with current position.
- **Steps:**
 1. For each index, find minimum in remaining array.

2. Swap minimum with current index.
 3. Repeat until array is sorted.
- **Complexity:** Time $O(n^2)$, Space $O(1)$.

Algorithm Explanation

Selection sort iterates through the array, finding the minimum element in the unsorted portion and swapping it with the current position.

Each iteration places one element in its final position.

Time is $O(n^2)$ for n elements (n iterations, each scanning $n-i$ elements), with $O(1)$ space.

Coding Part (with Unit Tests)

```
void selectionSort(int* arr, int n) {
    for (int i = 0; i < n - 1; i++) {
        int min_idx = i;
        for (int j = i + 1; j < n; j++) {
            if (arr[j] < arr[min_idx]) min_idx = j;
        }
        swap(&arr[i], &arr[min_idx]);
    }

    // Unit tests
    void testSelectionSort() {
        int arr[] = {64, 34, 25, 12, 22};
        selectionSort(arr, 5);
        assertEquals(12, arr[0], "Test 386.1 - First element sorted");
        assertEquals(64, arr[4], "Test 386.2 - Last element sorted");
    }
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Find minimum efficiently.
 - Handle duplicates.
 - Test with unsorted/sorted arrays.
- **Expert Tips:**
 - Explain selection sort: "Select min and swap."
 - In interviews, clarify: "Ask about stability."
 - Suggest optimization: "Use for small arrays."
 - Test edge cases: "Empty array, single element."

Problem 387: Find the Longest Increasing Subsequence

Issue Description

Find the length of the longest increasing subsequence (LIS) in an array.

Problem Decomposition & Solution Steps

- **Input:** Array of integers.
- **Output:** Length of LIS.
- **Approach:** Use dynamic programming.
- **Algorithm:** Longest Increasing Subsequence
 - **Explanation:** Compute LIS ending at each index.
- **Steps:**
 1. Initialize dp array with 1s (each element is an LIS of length 1).
 2. For each index, check previous elements for increasing sequence.
 3. Update dp[i] with max length found.
- **Complexity:** Time $O(n^2)$, Space $O(n)$.

Algorithm Explanation

The algorithm uses a dp array where $dp[i]$ is the LIS length ending at index i .

For each i , check all previous indices j where $arr[j] < arr[i]$, and update $dp[i] = \max(dp[j] + 1, dp[i])$.

The maximum dp value is the LIS length.

Time is $O(n^2)$ for n elements, with $O(n)$ space.

Coding Part (with Unit Tests)

```
int lengthOfLIS(int* arr, int n) {
    int dp[100] = {0};
    for (int i = 0; i < n; i++) dp[i] = 1;
    int max_len = 1;
    for (int i = 1; i < n; i++) {
        for (int j = 0; j < i; j++) {
            if (arr[i] > arr[j] && dp[j] + 1 > dp[i]) {
                dp[i] = dp[j] + 1;
            }
        }
        if (dp[i] > max_len) max_len = dp[i];
    }
    return max_len;
}

// Unit tests
void testLengthOfLIS() {
    int arr[] = {10, 22, 9, 33, 21, 50, 41, 60};
    assertEquals(5, lengthOfLIS(arr, 8), "Test 387.1 - LIS length");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Initialize dp with 1s.
 - Handle non-increasing sequences.
 - Test with different array patterns.
- **Expert Tips:**
 - Explain LIS: "Longest strictly increasing subsequence."

- In interviews, clarify: "Ask about non-strict increasing."
- Suggest optimization: "O(n log n) with binary search."
- Test edge cases: "Empty array, single element."

Problem 388: Implement a Function to Perform Insertion Sort

Issue Description

Sort an array using the insertion sort algorithm.

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array (in-place).
- **Approach:** Build sorted portion incrementally.
- **Algorithm:** Insertion Sort
 - **Explanation:** Insert each element into sorted portion.
- **Steps:**
 1. Start with first element (sorted).
 2. For each subsequent element, insert into correct position.
 3. Shift larger elements right.
- **Complexity:** Time $O(n^2)$, Space $O(1)$.

Algorithm Explanation

Insertion sort builds a sorted portion from the start.

For each element, it inserts it into the correct position in the sorted portion by shifting larger elements right.

Time is $O(n^2)$ for n elements (n iterations, each potentially shifting n elements), with $O(1)$ space.

Coding Part (with Unit Tests)

```
void insertionSort(int* arr, int n) {
    for (int i = 1; i < n; i++) {
        int key = arr[i];
        int j = i - 1;
        while (j >= 0 && arr[j] > key) {
            arr[j + 1] = arr[j];
            j--;
        }
        arr[j + 1] = key;
    }

    // Unit tests
    void testInsertionSort() {
        int arr[] = {12, 11, 13, 5, 6};
        insertionSort(arr, 5);
        assertEquals(5, arr[0], "Test 388.1 - First element sorted");
        assertEquals(13, arr[4], "Test 388.2 - Last element sorted");
    }
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Shift elements during insertion.
 - Handle duplicates.
 - Test with unsorted/sorted arrays.
- **Expert Tips:**
 - Explain insertion sort: "Build sorted portion incrementally."
 - In interviews, clarify: "Ask about stability."
 - Suggest optimization: "Binary search for insertion point."
 - Test edge cases: "Empty array, single element."

Problem 389: Find the Minimum Number of Platforms Needed for Trains

Issue Description

Given arrival and departure times of trains, find the minimum number of platforms needed.

Problem Decomposition & Solution Steps

- **Input:** Arrival and departure time arrays, size.
- **Output:** Minimum number of platforms.
- **Approach:** Sort events and track overlaps.
- **Algorithm:** Minimum Platforms
 - **Explanation:** Count maximum overlapping trains.
- **Steps:**
 1. Create arrays of arrival/departure events.
 2. Sort events by time.
 3. Sweep through events, increment for arrivals, decrement for departures.
 4. Track maximum platforms needed.
- **Complexity:** Time $O(n \log n)$, Space $O(n)$.

Algorithm Explanation

The algorithm treats arrivals and departures as events, sorts them by time, and processes them in order.

Increment platform count for arrivals, decrement for departures, and track the maximum count.

Sorting takes $O(n \log n)$, processing is $O(n)$, total time is $O(n \log n)$, with $O(n)$ space for events.

Coding Part (with Unit Tests)

```
int findMinPlatforms(int* arr, int* dep, int n) {  
    int events[200];  
    for (int i = 0; i < n; i++) {  
        events[2 * i] = arr[i];  
        events[2 * i + 1] = dep[i];  
    }  
    quicksort(events, 0, 2 * n - 1);  
    int max_platforms = 0, curr_platforms = 0;
```

```

    for (int i = 0; i < 2 * n; i++) {
        if (i % 2 == 0) curr_platforms++;
        else curr_platforms--;
        if (curr_platforms > max_platforms) max_platforms = curr_platforms;
    }
    return max_platforms;
}

// Unit tests
void testMinPlatforms() {
    int arr[] = {900, 940, 950};
    int dep[] = {910, 1200, 1120};
    assertEquals(3, findMinPlatforms(arr, dep, 3), "Test 389.1 - Min platforms");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Sort events correctly.
 - Handle overlapping trains.
 - Test with tight schedules.
- **Expert Tips:**
 - Explain platforms: "Max overlapping trains."
 - In interviews, clarify: "Ask about time format."
 - Suggest optimization: "Separate arrival/departure arrays."
 - Test edge cases: "Single train, all overlapping."

Problem 390: Implement a Function to Perform Heap Sort

Issue Description

Sort an array using the heap sort algorithm.

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array (in-place).
- **Approach:** Build max-heap, extract max repeatedly.
- **Algorithm:** Heap Sort
 - **Explanation:** Use max-heap to place largest elements at end.
- **Steps:**
 1. Build max-heap from array.
 2. Swap root with last element, reduce heap size.
 3. Heapify root, repeat.
- **Complexity:** Time $O(n \log n)$, Space $O(1)$.

Algorithm Explanation

Heap sort builds a max-heap ($O(n)$), then repeatedly extracts the maximum (root) by swapping with the last element and heapifying the root ($O(\log n)$ per extraction).

Total time is $O(n \log n)$ for n elements, with $O(1)$ space (in-place).

Coding Part (with Unit Tests)

```
void heapify(int* arr, int n, int i) {
    int largest = i;
    int left = 2 * i + 1, right = 2 * i + 2;
    if (left < n && arr[left] > arr[largest]) largest = left;
    if (right < n && arr[right] > arr[largest]) largest = right;
    if (largest != i) {
        swap(&arr[i], &arr[largest]);
        heapify(arr, n, largest);
    }
}

void heapSort(int* arr, int n) {
    for (int i = n / 2 - 1; i >= 0; i--) heapify(arr, n, i);
    for (int i = n - 1; i > 0; i--) {
        swap(&arr[0], &arr[i]);
        heapify(arr, i, 0);
    }
}

// Unit tests
void testHeapSort() {
    int arr[] = {12, 11, 13, 5, 6};
    heapSort(arr, 5);
    assertEquals(5, arr[0], "Test 390.1 - First element sorted");
    assertEquals(13, arr[4], "Test 390.2 - Last element sorted");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Build heap correctly.
 - Handle in-place sorting.
 - Test with unsorted/sorted arrays.
- **Expert Tips:**
 - Explain heap sort: "Max-heap to sort in-place."
 - In interviews, clarify: "Ask about min-heap variant."
 - Suggest optimization: "Use for large datasets."
 - Test edge cases: "Empty array, single element."

Problem 391: Find the Longest Common Subsequence of Two Strings

Issue Description

Find the length of the longest common subsequence (LCS) of two strings.

Problem Decomposition & Solution Steps

- **Input:** Two strings.
- **Output:** Length of LCS.
- **Approach:** Use dynamic programming.

- **Algorithm:** Longest Common Subsequence
 - **Explanation:** Build dp table for subsequence lengths.
- **Steps:**
 1. Initialize dp table.
 2. If characters match, $dp[i][j] = dp[i-1][j-1] + 1$.
 3. Else, take max of $dp[i-1][j]$ or $dp[i][j-1]$.
- **Complexity:** Time $O(mn)$, Space $O(mn)$.

Algorithm Explanation

The LCS algorithm uses a dp table where $dp[i][j]$ is the LCS length for prefixes of lengths i and j.

If characters match, increment the diagonal value; else, take the maximum of left or top.

Time is $O(mn)$ for strings of lengths m and n, with $O(mn)$ space.

Coding Part (with Unit Tests)

```
int longestCommonSubsequence(const char* s1, const char* s2) {
    int m = strlen(s1), n = strlen(s2);
    int dp[100][100] = {0};
    for (int i = 1; i <= m; i++) {
        for (int j = 1; j <= n; j++) {
            if (s1[i - 1] == s2[j - 1]) dp[i][j] = dp[i - 1][j - 1] + 1;
            else dp[i][j] = dp[i - 1][j] > dp[i][j - 1] ? dp[i - 1][j] : dp[i][j - 1];
        }
    }
    return dp[m][n];
}

// Unit tests
void testLCS() {
    assertEquals(3, longestCommonSubsequence("ABCDGH", "AEDFHR"), "Test 391.1 - LCS length");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Initialize dp table correctly.
 - Handle empty strings.
 - Test with different string pairs.
- **Expert Tips:**
 - Explain LCS: "Longest subsequence, not contiguous."
 - In interviews, clarify: "Ask about returning subsequence."
 - Suggest optimization: "Space-optimized $O(\min(m,n))$."
 - Test edge cases: "Empty strings, no common chars."

Problem 392: Implement a Function to Perform Counting Sort

Issue Description

Sort an array of non-negative integers using counting sort.

Problem Decomposition & Solution Steps

- **Input:** Array of non-negative integers, size.
- **Output:** Sorted array.
- **Approach:** Use counting sort for integer range.
- **Algorithm:** Counting Sort
 - **Explanation:** Count occurrences, reconstruct array.
- **Steps:**
 1. Find max element to determine range.
 2. Count occurrences in count array.
 3. Reconstruct sorted array from counts.
- **Complexity:** Time $O(n + k)$, Space $O(n + k)$.

Algorithm Explanation

Counting sort counts occurrences of each value in a count array, then reconstructs the sorted array by placing elements according to their counts.

Time is $O(n + k)$ for n elements and range k , with $O(n + k)$ space for count and output arrays.

Coding Part (with Unit Tests)

```
void countingSort(int* arr, int n) {
    int max = arr[0];
    for (int i = 1; i < n; i++) if (arr[i] > max) max = arr[i];
    int count[100] = {0};
    for (int i = 0; i < n; i++) count[arr[i]]++;
    int k = 0;
    for (int i = 0; i <= max; i++) {
        while (count[i]--) arr[k++] = i;
    }
}

// Unit tests
void testCountingSort() {
    int arr[] = {4, 2, 2, 8, 3};
    countingSort(arr, 5);
    assertEquals(2, arr[0], "Test 392.1 - First element sorted");
    assertEquals(8, arr[4], "Test 392.2 - Last element sorted");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Find max element accurately.
 - Handle duplicates.
 - Test with integer ranges.
- **Expert Tips:**

- Explain counting sort: "Non-comparison sort for integers."
- In interviews, clarify: "Ask about negative numbers."
- Suggest optimization: "Stable counting sort."
- Test edge cases: "Empty array, single value."

Problem 393: Find the Minimum Spanning Tree Using Kruskal's Algorithm

Issue Description

Find the minimum spanning tree (MST) of a weighted undirected graph using Kruskal's algorithm.

Problem Decomposition & Solution Steps

- **Input:** Weighted graph (adjacency list), vertices.
- **Output:** List of edges in MST.
- **Approach:** Use Kruskal's with union-find.
- **Algorithm:** Kruskal's
 - **Explanation:** Sort edges, add if no cycle using union-find.
- **Steps:**
 1. Collect all edges, sort by weight.
 2. Initialize union-find structure.
 3. Add edges if they don't form a cycle.
- **Complexity:** Time $O(E \log E)$, Space $O(V + E)$.

Algorithm Explanation

Kruskal's algorithm sorts edges by weight ($O(E \log E)$), then iterates through them, adding an edge to the MST if it doesn't form a cycle (checked via union-find, $O(\alpha(V))$ amortized).

Total time is $O(E \log E)$ for E edges, with $O(V + E)$ space for union-find and edges.

Coding Part (with Unit Tests)

```

typedef struct Edge {
    int src, dest, weight;
} Edge;
int compareEdges(const void* a, const void* b) {
    return ((Edge*)a)->weight - ((Edge*)b)->weight;
}
void kruskalMST(WeightedGraph* g, Edge* result, int* returnSize) {
    Edge edges[100];
    int edgeCount = 0;
    for (int i = 0; i < g->vertices; i++) {
        Edge* curr = g->adjList[i];
        while (curr) {
            if (i < curr->dest) {
                edges[edgeCount].src = i;
                edges[edgeCount].dest = curr->dest;
                edges[edgeCount].weight = curr->weight;
                edgeCount++;
            }
            curr = curr->next;
        }
    }
    qsort(edges, edgeCount, sizeof(Edge), compareEdges);
}

```

```

DisjointSet ds;
initDisjointSet(&ds, g->vertices);
*returnSize = 0;
for (int i = 0; i < edgeCount && *returnSize < g->vertices - 1; i++) {
    if (find(&ds, edges[i].src) != find(&ds, edges[i].dest)) {
        unionSet(&ds, edges[i].src, edges[i].dest);
        result[(*returnSize)++] = edges[i];
    }
}
}

// Unit tests
void testKruskalMST() {
    WeightedGraph* g = createWeightedGraph(4);
    addEdgeWeighted(g, 0, 1, 1);
    addEdgeWeighted(g, 1, 0, 1);
    addEdgeWeighted(g, 1, 2, 2);
    addEdgeWeighted(g, 2, 1, 2);
    Edge result[10];
    int returnSize;
    kruskalMST(g, result, &returnSize);
    assertEquals(1, result[0].weight, "Test 393.1 - MST edge weight");
    free(g->adjList[0]);
    free(g->adjList[1]);
    free(g->adjList[2]);
    free(g);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Sort edges correctly.
 - Use union-find for cycle detection.
 - Test with weighted graphs.
- **Expert Tips:**
 - Explain Kruskal's: "Greedy MST with union-find."
 - In interviews, clarify: "Ask about undirected assumption."
 - Suggest optimization: "Prim's for dense graphs."
 - Test edge cases: "Single vertex, disconnected graph."

Problem 394: Implement a Function to Perform Radix Sort

Issue Description

Sort an array of non-negative integers using radix sort.

Problem Decomposition & Solution Steps

- **Input:** Array of non-negative integers, size.
- **Output:** Sorted array.
- **Approach:** Use radix sort with counting sort per digit.
- **Algorithm:** Radix Sort
 - **Explanation:** Sort by each digit using counting sort.
- **Steps:**

1. Find max element to determine number of digits.
 2. Apply counting sort for each digit place.
 3. Process digits from least to most significant.
- **Complexity:** Time $O(d(n + k))$, Space $O(n + k)$.

Algorithm Explanation

Radix sort processes digits from least to most significant, using counting sort for each digit ($O(n + k)$ per digit, where k is base, e.g., 10).

For d digits, total time is $O(d(n + k))$.

Space is $O(n + k)$ for output and count arrays.

Coding Part (with Unit Tests)

```
void countingSortByDigit(int* arr, int n, int exp) {
    int output[100], count[10] = {0};
    for (int i = 0; i < n; i++) count[(arr[i] / exp) % 10]++;
    for (int i = 1; i < 10; i++) count[i] += count[i - 1];
    for (int i = n - 1; i >= 0; i--) {
        output[count[(arr[i] / exp) % 10] - 1] = arr[i];
        count[(arr[i] / exp) % 10]--;
    }
    for (int i = 0; i < n; i++) arr[i] = output[i];
}

void radixSort(int* arr, int n) {
    int max = arr[0];
    for (int i = 1; i < n; i++) if (arr[i] > max) max = arr[i];
    for (int exp = 1; max / exp > 0; exp *= 10) {
        countingSortByDigit(arr, n, exp);
    }
}

// Unit tests
void testRadixSort() {
    int arr[] = {170, 45, 75, 90, 802};
    radixSort(arr, 5);
    assertEquals(45, arr[0], "Test 394.1 - First element sorted");
    assertEquals(802, arr[4], "Test 394.2 - Last element sorted");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use counting sort per digit.
 - Handle non-negative integers.
 - Test with large numbers.
- **Expert Tips:**
 - Explain radix sort: "Sort by digits using counting sort."
 - In interviews, clarify: "Ask about base choice."
 - Suggest optimization: "LSD vs.
 - MSD radix sort."
 - Test edge cases: "Empty array, single digit."

Problem 395: Find the Shortest Path Using Bellman-Ford Algorithm

Issue Description

Find shortest paths from a source in a weighted graph using Bellman-Ford.

Problem Decomposition & Solution Steps

- **Input:** Weighted graph (adjacency list), source vertex.
- **Output:** Array of shortest distances.
- **Approach:** Use Bellman-Ford for negative weights.
- **Algorithm:** Bellman-Ford
 - **Explanation:** Relax edges repeatedly, check for negative cycles.
- **Steps:**
 1. Initialize distances (infinity except source = 0).
 2. Relax all edges V-1 times.
 3. Check for negative cycles.
- **Complexity:** Time $O(V \times E)$, Space $O(V)$.

Algorithm Explanation

Bellman-Ford relaxes all edges $V-1$ times to compute shortest paths, handling negative weights.

A final pass checks for negative cycles (if distances decrease, cycle exists).

Time is $O(V \times E)$ for V vertices and E edges, with $O(V)$ space for distances.

Coding Part (with Unit Tests)

```
#define INF 999999

int* bellmanFord(WeightedGraph* g, int src, int* returnSize) {
    int* dist = (int*)malloc(g->vertices * sizeof(int));
    for (int i = 0; i < g->vertices; i++) dist[i] = INF;
    dist[src] = 0;
    for (int i = 0; i < g->vertices - 1; i++) {
        for (int u = 0; u < g->vertices; u++) {
            Edge* curr = g->adjList[u];
            while (curr) {
                if (dist[u] != INF && dist[u] + curr->weight < dist[curr->dest]) {
                    dist[curr->dest] = dist[u] + curr->weight;
                }
                curr = curr->next;
            }
        }
    }
    *returnSize = g->vertices;
    return dist;
}

// Unit tests
void testBellmanFord() {
    WeightedGraph* g = createWeightedGraph(3);
    addEdgeWeighted(g, 0, 1, 1);
    addEdgeWeighted(g, 1, 2, 1);
    int returnSize;
```

```

int* dist = bellmanFord(g, 0, &returnSize);
assertIntEquals(2, dist[2], "Test 395.1 - Shortest path to 2");
free(dist);
free(g->adjList[0]);
free(g->adjList[1]);
free(g);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle negative weights.
 - Check for negative cycles.
 - Test with weighted graphs.
- **Expert Tips:**
 - Explain Bellman-Ford: "Handles negative weights."
 - In interviews, clarify: "Ask about cycle detection."
 - Suggest optimization: "Early stop if no updates."
 - Test edge cases: "No path, negative weights."

Problem 396: Implement a Function to Perform Topological Sort

Issue Description

Perform topological sort on a directed acyclic graph (DAG).

Problem Decomposition & Solution Steps

- **Input:** Graph (adjacency list).
- **Output:** Array of vertices in topological order.
- **Approach:** Use DFS with stack.
- **Algorithm:** Topological Sort
 - **Explanation:** Order vertices so u comes before v if edge u->v.
- **Steps:**
 1. Perform DFS, push vertices to stack after processing.
 2. Pop stack to get topological order.
- **Complexity:** Time $O(V + E)$, Space $O(V)$.

Algorithm Explanation

Topological sort uses DFS to visit vertices, pushing each to a stack after its children are processed.

Popping the stack gives the topological order (parents before children).

Time is $O(V + E)$ for V vertices and E edges, with $O(V)$ space for stack/visited array.

Coding Part (with Unit Tests)

```
void dfsTopo(Graph* g, int v, bool* visited, int* stack, int* top) {
    visited[v] = true;
    ListNode* curr = g->adjList[v];
    while (curr) {
        if (!visited[curr->val]) dfsTopo(g, curr->val, visited, stack, top);
        curr = curr->next;
    }
    stack[(*top)++] = v;
}

int* topologicalSort(Graph* g, int* returnSize) {
    bool visited[MAX_VERTICES] = {false};
    int stack[MAX_VERTICES], top = 0;
    for (int i = 0; i < g->vertices; i++) {
        if (!visited[i]) dfsTopo(g, i, visited, stack, &top);
    }
    int* result = (int*)malloc(g->vertices * sizeof(int));
    *returnSize = g->vertices;
    for (int i = 0; i < g->vertices; i++) {
        result[i] = stack[g->vertices - 1 - i];
    }
    return result;
}

// Unit tests
void testTopologicalSort() {
    Graph* g = createGraph(3);
    addEdge(g, 0, 1);
    addEdge(g, 1, 2);
    int returnSize;
    int* result = topologicalSort(g, &returnSize);
    assertEquals(0, result[0], "Test 396.1 - Topological order first");
    free(result);
    free(g->adjList[0]);
    free(g->adjList[1]);
    free(g);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle disconnected components.
 - Assume DAG (no cycles).
 - Test with different DAGs.
- **Expert Tips:**
 - Explain topological sort: "Order vertices by dependencies."
 - In interviews, clarify: "Ask about cycle handling."
 - Suggest optimization: "Kahn's algorithm with BFS."
 - Test edge cases: "Empty graph, single vertex."

Problem 397: Find the Longest Palindromic Subsequence

Issue Description

Find the length of the longest palindromic subsequence in a string.

Problem Decomposition & Solution Steps

- **Input:** String.
- **Output:** Length of longest palindromic subsequence.
- **Approach:** Use dynamic programming.
- **Algorithm:** Longest Palindromic Subsequence
 - **Explanation:** Use LCS of string and its reverse.
- **Steps:**
 1. Reverse the string.
 2. Compute LCS of original and reversed strings.
- **Complexity:** Time $O(n^2)$, Space $O(n^2)$.

Algorithm Explanation

The longest palindromic subsequence is the LCS of the string and its reverse, as a palindrome reads the same forward and backward.

Using the LCS algorithm (Problem 391), compute $dp[i][j]$ for prefixes of the string and its reverse.

Time is $O(n^2)$ for length n , with $O(n^2)$ space.

Coding Part (with Unit Tests)

```
int longestPalindromicSubsequence(const char* s) {
    int n = strlen(s);
    char rev[100];
    for (int i = 0; i < n; i++) rev[i] = s[n - 1 - i];
    rev[n] = '\0';
    return longestCommonSubsequence(s, rev);
}

// Unit tests
void testLPS() {
    assertEquals(4, longestPalindromicSubsequence("BBABCBCAB"), "Test 397.1 - LPS length");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Reuse LCS implementation.
 - Handle empty strings.
 - Test with palindromic/non-palindromic strings.
- **Expert Tips:**
 - Explain LPS: "LCS of string and its reverse."
 - In interviews, clarify: "Ask about returning subsequence."
 - Suggest optimization: "Space-optimized $O(n)$ space."
 - Test edge cases: "Empty string, single char."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for algorithms problems 381 to 397:\n");
    testQuicksort();
    testBinarySearch();
    testMaxSubArray();
    testMergeSort();
    testKthSmallest();
    testSelectionSort();
    testLengthOfLIS();
    testInsertionSort();
    testMinPlatforms();
    testHeapSort();
    testLCS();
    testCountingSort();
    testKruskalMST();
    testRadixSort();
    testBellmanFord();
    testTopologicalSort();
    testLPS();
    return 0;
}
```

Problem 398: Implement a Function to Perform Bucket Sort

Issue Description

Sort an array of floating-point numbers (0 to 1) using bucket sort.

Problem Decomposition & Solution Steps

- **Input:** Array of floats in [0,1], size.
- **Output:** Sorted array.
- **Approach:** Distribute elements into buckets, sort each bucket.
- **Algorithm:** Bucket Sort
 - **Explanation:** Place elements in buckets based on value, sort buckets.
- **Steps:**
 1. Create n empty buckets.
 2. Distribute elements into buckets based on value.
 3. Sort each bucket (using insertion sort).
 4. Concatenate buckets.
- **Complexity:** Time $O(n^2)$ worst, $O(n + k)$ average; Space $O(n + k)$.

Algorithm Explanation

Bucket sort divides the range [0,1] into n buckets, places each element into the appropriate bucket based on its value, sorts each bucket (using insertion sort for small size), and concatenates the results.

Average time is $O(n + k)$ for n elements and k buckets, with $O(n + k)$ space.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>
#include <string.h>

typedef struct Bucket {
    float data[100];
    int size;
} Bucket;

void insertionSortBucket(float* arr, int n) {
    for (int i = 1; i < n; i++) {
        float key = arr[i];
        int j = i - 1;
        while (j >= 0 && arr[j] > key) {
            arr[j + 1] = arr[j];
            j--;
        }
        arr[j + 1] = key;
    }
}

void bucketSort(float* arr, int n) {
    Bucket buckets[100];
    for (int i = 0; i < n; i++) buckets[i].size = 0;
    for (int i = 0; i < n; i++) {
        int idx = (int)(n * arr[i]);
        buckets[idx].data[buckets[idx].size++] = arr[i];
    }
    for (int i = 0; i < n; i++) {
        insertionSortBucket(buckets[i].data, buckets[i].size);
    }
    int k = 0;
    for (int i = 0; i < n; i++) {
        for (int j = 0; j < buckets[i].size; j++) {
            arr[k++] = buckets[i].data[j];
        }
    }
}

// Unit test helpers
void assertEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

void assertFloatEquals(float expected, float actual, const char* testName) {
    printf("%s: %s\n", testName, fabs(expected - actual) < 0.001 ? "PASSED" : "FAILED");
}

// Unit tests
void testBucketSort() {
    float arr[] = {0.78, 0.17, 0.39, 0.26, 0.72};
    bucketSort(arr, 5);
    assertEquals(0.17, arr[0], "Test 398.1 - First element sorted");
    assertEquals(0.78, arr[4], "Test 398.2 - Last element sorted");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Ensure input in [0,1).
 - Use insertion sort for small buckets.
 - Test with uniform/non-uniform distributions.
- **Expert Tips:**
 - Explain bucket sort: "Distribute and sort buckets."
 - In interviews, clarify: "Ask about input range."
 - Suggest optimization: "Adjust bucket size."
 - Test edge cases: "Empty array, single element."

Problem 399: Find the Maximum Flow in a Graph (Ford-Fulkerson)

Issue Description

Find the maximum flow in a directed graph using Ford-Fulkerson.

Problem Decomposition & Solution Steps

- **Input:** Graph (adjacency matrix with capacities), source, sink.
- **Output:** Maximum flow value.
- **Approach:** Use Ford-Fulkerson with BFS for augmenting paths.
- **Algorithm:** Ford-Fulkerson (Edmonds-Karp)
 - **Explanation:** Find augmenting paths, update residual graph.
- **Steps:**
 1. Initialize residual graph.
 2. Find augmenting path using BFS.
 3. Update residual capacities, add flow.
 4. Repeat until no augmenting path exists.
- **Complexity:** Time $O(Ef)$ where f is max flow; Space $O(V^2)$.

Algorithm Explanation

Ford-Fulkerson finds augmenting paths (using BFS for Edmonds-Karp) from source to sink, calculates bottleneck capacity, and updates residual capacities.

Repeat until no path exists.

Time is $O(Ef)$ for E edges and max flow f , with $O(V^2)$ space for adjacency matrix.

Coding Part (with Unit Tests)

```
#define MAX_VERTICES 100

bool bfs(int graph[MAX_VERTICES][MAX_VERTICES], int V, int s, int t, int* parent) {
    bool visited[MAX_VERTICES] = {false};
    int queue[MAX_VERTICES], front = 0, rear = -1;
    queue[++rear] = s;
    visited[s] = true;
    parent[s] = -1;
```

```

        while (front <= rear) {
            int u = queue[front++];
            for (int v = 0; v < V; v++) {
                if (!visited[v] && graph[u][v] > 0) {
                    queue[++rear] = v;
                    visited[v] = true;
                    parent[v] = u;
                }
            }
        }
        return visited[t];
    }

    int fordFulkerson(int graph[MAX_VERTICES][MAX_VERTICES], int V, int s, int t) {
        int residual[MAX_VERTICES][MAX_VERTICES];
        memcpy(residual, graph, sizeof(residual));
        int parent[MAX_VERTICES], max_flow = 0;
        while (bfs(residual, V, s, t, parent)) {
            int path_flow = INT_MAX;
            for (int v = t; v != s; v = parent[v]) {
                int u = parent[v];
                if (residual[u][v] < path_flow) path_flow = residual[u][v];
            }
            for (int v = t; v != s; v = parent[v]) {
                int u = parent[v];
                residual[u][v] -= path_flow;
                residual[v][u] += path_flow;
            }
            max_flow += path_flow;
        }
        return max_flow;
    }

    // Unit tests
    void testFordFulkerson() {
        int graph[3][3] = {{0, 16, 13}, {0, 0, 12}, {0, 0, 0}};
        assertEquals(25, fordFulkerson(graph, 3, 0, 2), "Test 399.1 - Max flow");
    }
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use BFS for shortest augmenting paths.
 - Handle residual graph updates.
 - Test with different graph capacities.
- **Expert Tips:**
 - Explain Ford-Fulkerson: "Maximize flow via augmenting paths."
 - In interviews, clarify: "Ask about capacity constraints."
 - Suggest optimization: "Dinic's algorithm for $O(V^2E)$."
 - Test edge cases: "No path, single edge."

Problem 400: Implement a Function to Perform Shell Sort

Issue Description

Sort an array using the shell sort algorithm.

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array (in-place).
- **Approach:** Use shell sort with diminishing gaps.
- **Algorithm:** Shell Sort
 - **Explanation:** Insertion sort with gaps, reduce gap size.
- **Steps:**
 1. Start with large gap (e.g., $n/2$).
 2. Perform insertion sort for elements at gap distance.
 3. Reduce gap, repeat until gap = 1.
- **Complexity:** Time $O(n^{1.3})$ average, Space $O(1)$.

Algorithm Explanation

Shell sort generalizes insertion sort by sorting elements at a gap distance, reducing the gap each iteration (e.g., $n/2, n/4, \dots, 1$).

The final pass is standard insertion sort.

Average time is $O(n^{1.3})$ depending on gap sequence, with $O(1)$ space.

Coding Part (with Unit Tests)

```
void shellSort(int* arr, int n) {
    for (int gap = n / 2; gap > 0; gap /= 2) {
        for (int i = gap; i < n; i++) {
            int temp = arr[i];
            int j;
            for (j = i; j >= gap && arr[j - gap] > temp; j -= gap) {
                arr[j] = arr[j - gap];
            }
            arr[j] = temp;
        }
    }
}

// Unit tests
void testShellSort() {
    int arr[] = {12, 34, 54, 2, 3};
    shellSort(arr, 5);
    assertEquals(2, arr[0], "Test 400.1 - First element sorted");
    assertEquals(54, arr[4], "Test 400.2 - Last element sorted");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Choose effective gap sequence.
 - Ensure final gap is 1.
 - Test with different array sizes.
- **Expert Tips:**
 - Explain shell sort: "Insertion sort with gaps."
 - In interviews, clarify: "Ask about gap sequence."

- Suggest optimization: "Knuth's gap sequence."
- Test edge cases: "Empty array, single element."

Problem 401: Find the Minimum Cost Path in a Matrix

Issue Description

Find the minimum cost path from top-left to bottom-right in a cost matrix.

Problem Decomposition & Solution Steps

- **Input:** 2D matrix of costs, dimensions.
- **Output:** Minimum cost to reach bottom-right.
- **Approach:** Use dynamic programming.
- **Algorithm:** Minimum Cost Path
 - **Explanation:** Sum minimum costs to each cell.
- **Steps:**
 1. Initialize dp table with first cell.
 2. Fill first row and column.
 3. For each cell, take min of paths from above/left.
- **Complexity:** Time O(mn), Space O(mn).

Algorithm Explanation

The algorithm uses a dp table where $dp[i][j]$ is the minimum cost to reach (i,j) .

Initialize the first cell, fill the first row and column, then for each cell, compute $dp[i][j] = cost[i][j] + \min(dp[i-1][j], dp[i][j-1])$.

Time is $O(mn)$ for $m \times n$ matrix, with $O(mn)$ space.

Coding Part (with Unit Tests)

```
int minCostPath(int** cost, int m, int n) {
    int dp[100][100];
    dp[0][0] = cost[0][0];
    for (int i = 1; i < m; i++) dp[i][0] = dp[i-1][0] + cost[i][0];
    for (int j = 1; j < n; j++) dp[0][j] = dp[0][j-1] + cost[0][j];
    for (int i = 1; i < m; i++) {
        for (int j = 1; j < n; j++) {
            dp[i][j] = cost[i][j] + (dp[i-1][j] < dp[i][j-1] ? dp[i-1][j] : dp[i][j-1]);
        }
    }
    return dp[m-1][n-1];
}

// Unit tests
void testMinCostPath() {
    int cost[3][3] = {{1, 2, 3}, {4, 8, 2}, {1, 5, 3}};
    int* costPtr[3] = {cost[0], cost[1], cost[2]};
    assertEquals(8, minCostPath(costPtr, 3, 3), "Test 401.1 - Min cost path");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Initialize dp table correctly.
 - Handle boundary cells.
 - Test with different matrix sizes.
- **Expert Tips:**
 - Explain min cost path: "DP for minimum path sum."
 - In interviews, clarify: "Ask about diagonal moves."
 - Suggest optimization: "Space-optimized O(n) space."
 - Test edge cases: "1×1 matrix, single row/column."

Problem 402: Implement a Function to Perform Cycle Sort

Issue Description

Sort an array of distinct integers (0 to n-1) using cycle sort.

Problem Decomposition & Solution Steps

- **Input:** Array of distinct integers [0, n-1], size.
- **Output:** Sorted array (in-place).
- **Approach:** Use cycle sort to minimize writes.
- **Algorithm:** Cycle Sort
 - **Explanation:** Place each element in its correct position via cycles.
- **Steps:**
 1. For each position, find correct position of current element.
 2. Swap to form cycle until element is in place.
 3. Mark visited positions.
- **Complexity:** Time $O(n^2)$, Space $O(1)$.

Algorithm Explanation

Cycle sort identifies cycles where each element is moved to its correct position (value = index).

For each element, swap it to its correct position, continue the cycle until complete.

Minimizes writes, but time is $O(n^2)$ for n elements, with $O(1)$ space.

Coding Part (with Unit Tests)

```
void cycleSort(int* arr, int n) {  
    for (int start = 0; start < n - 1; start++) {  
        int item = arr[start];  
        int pos = start;  
        for (int i = start + 1; i < n; i++) {  
            if (arr[i] < item) pos++;  
        }  
        if (pos == start) continue;  
        else {  
            while (pos != start) {  
                swap(arr[pos], arr[pos - 1]);  
                pos = pos - 1;  
            }  
        }  
    }  
}
```

```

        while (item == arr[pos]) pos++;
        swap(&arr[pos], &item);
        while (pos != start) {
            pos = start;
            for (int i = start + 1; i < n; i++) {
                if (arr[i] < item) pos++;
            }
            while (item == arr[pos]) pos++;
            swap(&arr[pos], &item);
        }
    }

// Unit tests
void testCycleSort() {
    int arr[] = {3, 1, 4, 0, 2};
    cycleSort(arr, 5);
    assertEquals(0, arr[0], "Test 402.1 - First element sorted");
    assertEquals(4, arr[4], "Test 402.2 - Last element sorted");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Assume distinct integers [0, n-1].
 - Minimize writes in cycles.
 - Test with permuted arrays.
- **Expert Tips:**
 - Explain cycle sort: "Minimize writes via cycles."
 - In interviews, clarify: "Ask about input constraints."
 - Suggest optimization: "Use for write-sensitive memory."
 - Test edge cases: "Empty array, single element."

Problem 403: Find the Longest Common Substring

Issue Description

Find the length of the longest common substring of two strings.

Problem Decomposition & Solution Steps

- **Input:** Two strings.
- **Output:** Length of longest common substring.
- **Approach:** Use dynamic programming.
- **Algorithm:** Longest Common Substring
 - **Explanation:** Track lengths of matching substrings.
- **Steps:**
 1. Initialize dp table.
 2. If characters match, $dp[i][j] = dp[i-1][j-1] + 1$.
 3. Else, $dp[i][j] = 0$.
 4. Track maximum length.
- **Complexity:** Time $O(mn)$, Space $O(mn)$.

Algorithm Explanation

The algorithm uses a dp table where $dp[i][j]$ is the length of the common substring ending at $s1[i-1]$ and $s2[j-1]$.

If characters match, increment the diagonal value; else, set to 0.

Track the maximum length.

Time is $O(mn)$ for strings of lengths m and n , with $O(mn)$ space.

Coding Part (with Unit Tests)

```
int longestCommonSubstring(const char* s1, const char* s2) {
    int m = strlen(s1), n = strlen(s2);
    int dp[100][100] = {0}, max_len = 0;
    for (int i = 1; i <= m; i++) {
        for (int j = 1; j <= n; j++) {
            if (s1[i-1] == s2[j-1]) {
                dp[i][j] = dp[i-1][j-1] + 1;
                if (dp[i][j] > max_len) max_len = dp[i][j];
            }
        }
    }
    return max_len;
}

// Unit tests
void testLongestCommonSubstring() {
    assertEquals(2, longestCommonSubstring("ABCD", "ABDC"), "Test 403.1 - Longest common
    substring");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Track maximum length in dp.
 - Handle empty strings.
 - Test with different string pairs.
- **Expert Tips:**
 - Explain substring: "Contiguous common sequence."
 - In interviews, clarify: "Ask about returning substring."
 - Suggest optimization: "Space-optimized $O(n)$ space."
 - Test edge cases: "Empty strings, no common substring."

Problem 404: Implement a Function to Perform Cocktail Sort

Issue Description

Sort an array using the cocktail sort algorithm (bidirectional bubble sort).

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array (in-place).
- **Approach:** Use bidirectional bubble sort.
- **Algorithm:** Cocktail Sort
 - **Explanation:** Bubble sort in both directions.
- **Steps:**
 1. Initialize swapped flag.
 2. Forward pass: Bubble largest to end.
 3. Backward pass: Bubble smallest to start.
 4. Repeat until no swaps.
- **Complexity:** Time $O(n^2)$, Space $O(1)$.

Algorithm Explanation

Cocktail sort alternates forward and backward passes of bubble sort, moving the largest element to the end and smallest to the start in each iteration.

Stops when no swaps occur.

Time is $O(n^2)$ for n elements, with $O(1)$ space.

Coding Part (with Unit Tests)

```
void cocktailSort(int* arr, int n) {
    bool swapped = true;
    int start = 0, end = n - 1;
    while (swapped) {
        swapped = false;
        for (int i = start; i < end; i++) {
            if (arr[i] > arr[i + 1]) {
                swap(&arr[i], &arr[i + 1]);
                swapped = true;
            }
        }
        end--;
        if (!swapped) break;
        for (int i = end - 1; i >= start; i--) {
            if (arr[i] > arr[i + 1]) {
                swap(&arr[i], &arr[i + 1]);
                swapped = true;
            }
        }
        start++;
    }
}

// Unit tests
void testCocktailSort() {
    int arr[] = {5, 1, 4, 2, 8};
    cocktailSort(arr, 5);
    assertEquals(1, arr[0], "Test 404.1 - First element sorted");
    assertEquals(8, arr[4], "Test 404.2 - Last element sorted");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Track swapped flag to stop early.
 - Update start/end bounds.
 - Test with unsorted/sorted arrays.
- **Expert Tips:**
 - Explain cocktail sort: "Bidirectional bubble sort."
 - In interviews, clarify: "Ask about stability."
 - Suggest optimization: "Use for small arrays."
 - Test edge cases: "Empty array, single element."

Problem 405: Find the kth Largest Element Using Quickselect

Issue Description

Find the k th largest element in an unsorted array using quickselect.

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, k .
- **Output:** k th largest element.
- **Approach:** Use quickselect with partitioning.
- **Algorithm:** Quickselect
 - **Explanation:** Partition array, recurse on relevant side.
- **Steps:**
 1. Select pivot, partition array.
 2. If pivot index = $n-k$, return pivot.
 3. Recurse on left (if $k > n$ -pivot index) or right.
- **Complexity:** Time $O(n)$ average, $O(n^2)$ worst; Space $O(1)$.

Algorithm Explanation

Quickselect partitions the array around a pivot, placing it in its final sorted position.

If the pivot's index is $n-k$, it's the k th largest.

Otherwise, recurse on the appropriate side.

Average time is $O(n)$ for n elements, with $O(1)$ space (in-place).

Coding Part (with Unit Tests)

```
int partition(int* arr, int low, int high) {
    int pivot = arr[high];
    int i = low - 1;
    for (int j = low; j < high; j++) {
        if (arr[j] <= pivot) {
            i++;
            swap(&arr[i], &arr[j]);
        }
    }
}
```

```

    }
    swap(&arr[i + 1], &arr[high]);
    return i + 1;
}

int quickselect(int* arr, int low, int high, int k) {
    if (low == high) return arr[low];
    int pi = partition(arr, low, high);
    if (k == pi) return arr[pi];
    if (k < pi) return quickselect(arr, low, pi - 1, k);
    return quickselect(arr, pi + 1, high, k);
}

int findKthLargest(int* arr, int n, int k) {
    if (k < 1 || k > n) return -1;
    return quickselect(arr, 0, n - 1, n - k);
}

// Unit tests
void testKthLargest() {
    int arr[] = {3, 2, 1, 5, 6, 4};
    assertEquals(5, findKthLargest(arr, 6, 2), "Test 405.1 - 2nd largest");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate k range.
 - Reuse quicksort's partition.
 - Test with different k values.
- **Expert Tips:**
 - Explain quickselect: "Partition for kth largest."
 - In interviews, clarify: "Ask about duplicates."
 - Suggest optimization: "Median-of-medians for O(n)."
 - Test edge cases: "k=1, k=n, invalid k."

Problem 406: Implement a Function to Perform Comb Sort

Issue Description

Sort an array using the comb sort algorithm.

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array (in-place).
- **Approach:** Use comb sort with shrinking gap.
- **Algorithm:** Comb Sort
 - **Explanation:** Bubble sort with larger gaps, shrink gap.
- **Steps:**
 1. Start with gap = n, shrink by factor (e.g., 1.3).
 2. Compare and swap elements at gap distance.
 3. Repeat until gap = 1 and no swaps.

- **Complexity:** Time $O(n^2)$ worst, $O(n \log n)$ average; Space $O(1)$.

Algorithm Explanation

Comb sort improves bubble sort by using a larger initial gap, shrinking it each iteration (e.g., by 1.3).

Compare and swap elements at gap distance until gap = 1 and no swaps occur.

Average time is $O(n \log n)$, worst is $O(n^2)$, with $O(1)$ space.

Coding Part (with Unit Tests)

```
void combSort(int* arr, int n) {
    int gap = n;
    bool swapped = true;
    while (gap > 1 || swapped) {
        gap = (gap * 10) / 13;
        if (gap < 1) gap = 1;
        swapped = false;
        for (int i = 0; i < n - gap; i++) {
            if (arr[i] > arr[i + gap]) {
                swap(&arr[i], &arr[i + gap]);
                swapped = true;
            }
        }
    }

    // Unit tests
    void testCombSort() {
        int arr[] = {8, 4, 1, 56, 3};
        combSort(arr, 5);
        assertEquals(1, arr[0], "Test 406.1 - First element sorted");
        assertEquals(56, arr[4], "Test 406.2 - Last element sorted");
    }
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use shrink factor ~1.3.
 - Track swaps to stop early.
 - Test with different array sizes.
- **Expert Tips:**
 - Explain comb sort: "Bubble sort with shrinking gaps."
 - In interviews, clarify: "Ask about shrink factor."
 - Suggest optimization: "Tune gap sequence."
 - Test edge cases: "Empty array, single element."

Problem 407: Find the Minimum Number of Coins for a Given Amount

Issue Description

Find the minimum number of coins to make a given amount using given denominations.

Problem Decomposition & Solution Steps

- **Input:** Array of coin denominations, amount.
- **Output:** Minimum number of coins.
- **Approach:** Use dynamic programming.
- **Algorithm:** Coin Change
 - **Explanation:** Compute min coins for each amount up to target.
- **Steps:**
 1. Initialize dp array with infinity except $dp[0] = 0$.
 2. For each amount, try each coin, update min coins.
 3. Return $dp[\text{amount}]$ or -1 if impossible.
- **Complexity:** Time $O(\text{amount} \times n)$, Space $O(\text{amount})$.

Algorithm Explanation

The algorithm uses a dp array where $dp[i]$ is the minimum coins for amount i.

For each amount from 1 to target, try each coin and update $dp[i] = \min(dp[i], dp[i - \text{coin}] + 1)$.

Time is $O(\text{amount} \times n)$ for n coins, with $O(\text{amount})$ space.

Coding Part (with Unit Tests)

```
int coinChange(int* coins, int n, int amount) {  
    int dp[10001] = {0};  
    for (int i = 1; i <= amount; i++) dp[i] = INT_MAX;  
    for (int i = 1; i <= amount; i++) {  
        for (int j = 0; j < n; j++) {  
            if (coins[j] <= i && dp[i - coins[j]] != INT_MAX) {  
                dp[i] = dp[i] < dp[i - coins[j]] + 1 ? dp[i] : dp[i - coins[j]] + 1;  
            }  
        }  
    }  
    return dp[amount] == INT_MAX ? -1 : dp[amount];  
}  
  
// Unit tests  
void testCoinChange() {  
    int coins[] = {1, 5, 10};  
    assertEquals(3, coinChange(coins, 3, 12), "Test 407.1 - Min coins");  
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Initialize dp with infinity.
 - Handle impossible amounts.
 - Test with different denominations.
- **Expert Tips:**
 - Explain coin change: "DP for minimum coins."
 - In interviews, clarify: "Ask about unlimited coins."
 - Suggest optimization: "Greedy for specific denominations."
 - Test edge cases: "Amount=0, impossible amount."

Problem 408: Implement a Function to Perform Strand Sort

Issue Description

Sort an array using the strand sort algorithm.

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array.
- **Approach:** Extract increasing strands, merge with sorted list.
- **Algorithm:** Strand Sort
 - **Explanation:** Build sorted list by merging increasing subsequences.
- **Steps:**
 1. Extract increasing subsequence (strand).
 2. Merge strand with sorted output.
 3. Repeat until input is empty.
- **Complexity:** Time $O(n^2)$ worst, Space $O(n)$.

Algorithm Explanation

Strand sort extracts an increasing subsequence (strand) from the input, merges it with the sorted output, and repeats until the input is empty.

Merging is $O(n)$, and extracting strands can take $O(n)$ per iteration, giving $O(n^2)$ worst-case time, with $O(n)$ space for output.

Coding Part (with Unit Tests)

```
void mergeStrands(int* input, int n, int* output, int* outSize) {  
    int temp[100], tempSize = 0;  
    temp[0] = input[0];  
    tempSize = 1;  
    for (int i = 1; i < n; i++) {  
        if (input[i] >= temp[tempSize - 1]) {  
            temp[tempSize++] = input[i];  
        }  
    }  
    int i = 0, j = 0, k = 0;  
    int merged[100];  
    while (i < tempSize && j < *outSize) {  
        merged[k++] = temp[i] <= output[j] ? temp[i++] : output[j++];  
    }  
    while (i < tempSize) merged[k++] = temp[i++];  
    while (j < *outSize) merged[k++] = output[j++];  
    memcpy(output, merged, k * sizeof(int));  
    *outSize = k;  
}  
  
void strandSort(int* arr, int n) {  
    int output[100], outSize = 0;  
    while (n > 0) {  
        mergeStrands(arr, n, output, &outSize);  
        int temp[100], tempSize = 0;  
        for (int i = 0; i < n; i++) {  
            bool inStrand = false;
```

```

        for (int j = 0; j < outSize; j++) {
            if (arr[i] == output[j]) {
                inStrand = true;
                break;
            }
        }
        if (!inStrand) temp[tempSize++] = arr[i];
    }
    memcpy(arr, temp, tempSize * sizeof(int));
    n = tempSize;
}
memcpy(arr, output, outSize * sizeof(int));
}

// Unit tests
void testStrandSort() {
    int arr[] = {4, 2, 1, 3};
    strandSort(arr, 4);
    assertEquals(1, arr[0], "Test 408.1 - First element sorted");
    assertEquals(4, arr[3], "Test 408.2 - Last element sorted");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Extract increasing strands.
 - Merge efficiently.
 - Test with different array patterns.
- **Expert Tips:**
 - Explain strand sort: "Merge increasing subsequences."
 - In interviews, clarify: "Ask about stability."
 - Suggest optimization: "Use linked lists for strands."
 - Test edge cases: "Empty array, sorted array."

Problem 409: Find the Longest Valid Parentheses Substring

Issue Description

Find the length of the longest valid parentheses substring.

Problem Decomposition & Solution Steps

- **Input:** String of parentheses.
- **Output:** Length of longest valid substring.
- **Approach:** Use stack to track valid pairs.
- **Algorithm:** Longest Valid Parentheses
 - **Explanation:** Track indices of unmatched parentheses.
- **Steps:**
 1. Use stack to store indices of '(' and boundaries.
 2. For '(', push index; for ')', pop and compute length.
 3. Track maximum valid length.
- **Complexity:** Time O(n), Space O(n).

Algorithm Explanation

The algorithm uses a stack to store indices of '(' and boundaries (-1 initially).

For '(', push index; for ')', pop and compute length from current index to top of stack.

If stack is empty, push current index as new boundary.

Time is O(n) for n characters, with O(n) space for stack.

Coding Part (with Unit Tests)

```
int longestValidParentheses(const char* s) {
    int stack[100], top = -1;
    stack[++top] = -1;
    int max_len = 0;
    for (int i = 0; s[i]; i++) {
        if (s[i] == '(') {
            stack[++top] = i;
        } else {
            top--;
            if (top == -1) {
                stack[++top] = i;
            } else {
                int len = i - stack[top];
                if (len > max_len) max_len = len;
            }
        }
    }
    return max_len;
}

// Unit tests
void testLongestValidParentheses() {
    assertEquals(4, longestValidParentheses("(()()")), "Test 409.1 - Longest valid parentheses");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use stack for index tracking.
 - Handle empty stack cases.
 - Test with valid/invalid strings.
- **Expert Tips:**
 - Explain valid parentheses: "Track lengths with stack."
 - In interviews, clarify: "Ask about returning substring."
 - Suggest optimization: "O(1) space with two-pass scan."
 - Test edge cases: "Empty string, no valid pairs."

Problem 410: Implement a Function to Perform Pigeonhole Sort

Issue Description

Sort an array of integers in a known range using pigeonhole sort.

Problem Decomposition & Solution Steps

- **Input:** Array of integers in range [min, max], size.
- **Output:** Sorted array.
- **Approach:** Use pigeonhole principle to place elements.
- **Algorithm:** Pigeonhole Sort
 - **Explanation:** Place elements in holes, collect in order.
- **Steps:**
 1. Find min and max to determine range.
 2. Create pigeonholes for range.
 3. Place elements in holes, collect in sorted order.
- **Complexity:** Time $O(n + \text{range})$, Space $O(\text{range})$.

Algorithm Explanation

Pigeonhole sort places each element in a "hole" corresponding to its value, then collects elements in order.

For range $R = \text{max} - \text{min} + 1$, create R holes, count occurrences, and reconstruct the array.

Time is $O(n + R)$ for n elements, with $O(R)$ space.

Coding Part (with Unit Tests)

```
void pigeonholeSort(int* arr, int n) {
    int min = arr[0], max = arr[0];
    for (int i = 1; i < n; i++) {
        if (arr[i] < min) min = arr[i];
        if (arr[i] > max) max = arr[i];
    }
    int range = max - min + 1;
    int holes[100] = {0};
    for (int i = 0; i < n; i++) holes[arr[i] - min]++;
    int k = 0;
    for (int i = 0; i < range; i++) {
        while (holes[i]--) arr[k++] = i + min;
    }
}

// Unit tests
void testPigeonholeSort() {
    int arr[] = {8, 3, 2, 7, 4};
    pigeonholeSort(arr, 5);
    assertEquals(2, arr[0], "Test 410.1 - First element sorted");
    assertEquals(8, arr[4], "Test 410.2 - Last element sorted");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Compute range accurately.
 - Handle duplicates in holes.
 - Test with different ranges.
- **Expert Tips:**
 - Explain pigeonhole sort: "Place elements in value-based holes."
 - In interviews, clarify: "Ask about range constraints."
 - Suggest optimization: "Use for small ranges."
 - Test edge cases: "Empty array, single value."

Problem 411: Find the Minimum Number of Jumps to Reach the End of an Array

Issue Description

Find the minimum number of jumps to reach the end of an array, where each element is the max jump length.

Problem Decomposition & Solution Steps

- **Input:** Array of jump lengths, size.
- **Output:** Minimum number of jumps.
- **Approach:** Use greedy approach.
- **Algorithm:** Minimum Jumps
 - **Explanation:** Choose max reachable position at each step.
- **Steps:**
 1. Initialize current reach, max reach, and jumps.
 2. For each index, update max reach.
 3. When current index equals current reach, jump and update.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The greedy algorithm tracks the current reachable index and the maximum reachable index.

At each step, update max reach.

When the current index equals the current reach, increment jumps and update current reach.

Time is O(n) for n elements, with O(1) space.

Coding Part (with Unit Tests)

```
int minJumps(int* arr, int n) {  
    if (n <= 1) return 0;  
    int jumps = 1, currReach = arr[0], maxReach = arr[0];  
    for (int i = 1; i < n; i++) {  
        if (i == n - 1) return jumps;  
        if (i + arr[i] > maxReach) maxReach = i + arr[i];  
        currReach = max(maxReach, i + arr[i]);  
        if (currReach == i) jumps++;  
    }  
}
```

```

        if (i == currReach) {
            jumps++;
            currReach = maxReach;
            if (currReach >= n - 1) return jumps;
        }
    }
    return -1;
}

// Unit tests
void testMinJumps() {
    int arr[] = {2, 3, 1, 1, 4};
    assertEquals(2, minJumps(arr, 5), "Test 411.1 - Min jumps");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle unreachable end.
 - Update max reach correctly.
 - Test with different jump patterns.
- **Expert Tips:**
 - Explain min jumps: "Greedy max reach per jump."
 - In interviews, clarify: "Ask about zero jumps."
 - Suggest optimization: "BFS for alternative approach."
 - Test edge cases: "Single element, unreachable end."

Problem 412: Implement a Function to Perform Bitonic Sort

Issue Description

Sort an array of length 2^k using bitonic sort.

Problem Decomposition & Solution Steps

- **Input:** Array of length 2^k .
- **Output:** Sorted array (in-place).
- **Approach:** Use bitonic sort for parallel sorting.
- **Algorithm:** Bitonic Sort
 - **Explanation:** Create bitonic sequence, merge into sorted.
- **Steps:**
 1. Recursively create bitonic sequence.
 2. Compare and swap elements in bitonic merges.
 3. Repeat for smaller bitonic sequences.
- **Complexity:** Time $O(\log^2 n)$, Space $O(1)$.

Algorithm Explanation

Bitonic sort creates a bitonic sequence (monotonic up then down), then merges it into a sorted sequence by comparing and swapping elements at specific distances.

For $n = 2^k$, it performs $O(\log n)$ stages, each with $O(\log n)$ comparisons, giving $O(\log^2 n)$ time, with $O(1)$ space.

Coding Part (with Unit Tests)

```
void compAndSwap(int* arr, int i, int j, int dir) {
    if ((arr[i] > arr[j] && dir == 1) || (arr[i] < arr[j] && dir == 0)) {
        swap(&arr[i], &arr[j]);
    }
}

void bitonicMerge(int* arr, int low, int cnt, int dir) {
    if (cnt > 1) {
        int k = cnt / 2;
        for (int i = low; i < low + k; i++) {
            compAndSwap(arr, i, i + k, dir);
        }
        bitonicMerge(arr, low, k, dir);
        bitonicMerge(arr, low + k, k, dir);
    }
}

void bitonicSort(int* arr, int low, int cnt, int dir) {
    if (cnt > 1) {
        int k = cnt / 2;
        bitonicSort(arr, low, k, 1);
        bitonicSort(arr, low + k, k, 0);
        bitonicMerge(arr, low, cnt, dir);
    }
}

void bitonicSortWrapper(int* arr, int n) {
    bitonicSort(arr, 0, n, 1);
}

// Unit tests
void testBitonicSort() {
    int arr[] = {3, 7, 4, 8, 6, 2, 1, 5};
    bitonicSortWrapper(arr, 8);
    assertEquals(1, arr[0], "Test 412.1 - First element sorted");
    assertEquals(8, arr[7], "Test 412.2 - Last element sorted");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Ensure n is power of 2.
 - Handle direction in merges.
 - Test with bitonic sequences.
- **Expert Tips:**
 - Explain bitonic sort: "Parallel sort for 2^k sizes."
 - In interviews, clarify: "Ask about input size."
 - Suggest optimization: "Use for parallel systems."
 - Test edge cases: " $n=2$, sorted array."

Problem 413: Find the Maximum Profit from Stock Prices

Issue Description

Find the maximum profit from buying and selling a stock once, given daily prices.

Problem Decomposition & Solution Steps

- **Input:** Array of stock prices, size.
- **Output:** Maximum profit (or 0 if none).
- **Approach:** Track minimum price and max profit.
- **Algorithm:** Maximum Profit
 - **Explanation:** Buy at min price, sell at max difference.
- **Steps:**
 1. Initialize min price and max profit.
 2. For each price, update min price.
 3. Update max profit if current price - min price is larger.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The algorithm scans the array, tracking the minimum price seen so far.

For each price, compute profit as price - min price, and update max profit if larger.

Time is O(n) for n prices, with O(1) space.

Coding Part (with Unit Tests)

```
int maxProfit(int* prices, int n) {
    if (n < 2) return 0;
    int min_price = prices[0], max_profit = 0;
    for (int i = 1; i < n; i++) {
        if (prices[i] < min_price) min_price = prices[i];
        else {
            int profit = prices[i] - min_price;
            if (profit > max_profit) max_profit = profit;
        }
    }
    return max_profit;
}

// Unit tests
void testMaxProfit() {
    int prices[] = {7, 1, 5, 3, 6, 4};
    assertEquals(5, maxProfit(prices, 6), "Test 413.1 - Max profit");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Track min price efficiently.
 - Handle no-profit cases.
 - Test with increasing/decreasing prices.

- **Expert Tips:**

- Explain max profit: "Buy low, sell high in one pass."
- In interviews, clarify: "Ask about multiple transactions."
- Suggest optimization: "Extend for k transactions."
- Test edge cases: "Single price, no profit."

Main Function to Run All Tests

```
int main() {  
    printf("Running tests for algorithms problems 398 to 413:\n");  
    testBucketSort();  
    testFordFulkerson();  
    testShellSort();  
    testMinCostPath();  
    testCycleSort();  
    testLongestCommonSubstring();  
    testCocktailSort();  
    testKthLargest();  
    testCombSort();  
    testCoinChange();  
    testStrandSort();  
    testLongestValidParentheses();  
    testPigeonholeSort();  
    testMinJumps();  
    testBitonicSort();  
    testMaxProfit();  
    return 0;  
}
```

Problem 414: Implement a Function to Perform Gnome Sort

Issue Description

Sort an array using the gnome sort algorithm.

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array (in-place).
- **Approach:** Use gnome sort, a comparison-based sort.
- **Algorithm:** Gnome Sort
 - **Explanation:** Move forward if in order, swap and move back otherwise.
- **Steps:**
 1. Start at index 0.
 2. If current element is in order with next, move forward.
 3. Else, swap with previous and move back.
 4. Repeat until end.
- **Complexity:** Time $O(n^2)$, Space $O(1)$.

Algorithm Explanation

Gnome sort iterates through the array like a gnome sorting a garden.

If the current element is greater than or equal to the previous, move forward.

Otherwise, swap with the previous element and move back.

Time is $O(n^2)$ for n elements, with $O(1)$ space (in-place).

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>
#include <string.h>
#include <limits.h>

void swap(int* a, int* b) {
    int temp = *a;
    *a = *b;
    *b = temp;
}

void gnomeSort(int* arr, int n) {
    int pos = 0;
    while (pos < n) {
        if (pos == 0 || arr[pos] >= arr[pos - 1]) {
            pos++;
        } else {
            swap(&arr[pos], &arr[pos - 1]);
            pos--;
        }
    }
}

// Unit test helpers
void assertIntEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

// Unit tests
void testGnomeSort() {
    int arr[] = {5, 2, 9, 1, 5};
    gnomeSort(arr, 5);
    assertIntEquals(1, arr[0], "Test 414.1 - First element sorted");
    assertIntEquals(9, arr[4], "Test 414.2 - Last element sorted");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Check bounds to avoid index errors.
 - Handle duplicates correctly.
 - Test with unsorted/sorted arrays.
- **Expert Tips:**
 - Explain gnome sort: "Simple forward/backward swap sort."
 - In interviews, clarify: "Ask about stability."
 - Suggest optimization: "Use for small arrays."

- Test edge cases: "Empty array, single element."

Problem 415: Find the Shortest Common Supersequence

Issue Description

Find the length of the shortest common supersequence (SCS) of two strings.

Problem Decomposition & Solution Steps

- **Input:** Two strings.
- **Output:** Length of SCS.
- **Approach:** Use dynamic programming with LCS.
- **Algorithm:** Shortest Common Supersequence
 - **Explanation:** SCS length = $m + n - \text{LCS length}$.
- **Steps:**
 1. Compute LCS length of the two strings.
 2. Return $m + n - \text{LCS length}$.
- **Complexity:** Time $O(mn)$, Space $O(mn)$.

Algorithm Explanation

The SCS is the shortest string containing both input strings as subsequences.

The length is the sum of the string lengths minus their LCS length, as common characters are counted once.

Use the LCS algorithm (Problem 391) to compute this.

Time is $O(mn)$ for strings of lengths m and n , with $O(mn)$ space.

Coding Part (with Unit Tests)

```

int longestCommonSubsequence(const char* s1, const char* s2) {
    int m = strlen(s1), n = strlen(s2);
    int dp[100][100] = {0};
    for (int i = 1; i <= m; i++) {
        for (int j = 1; j <= n; j++) {
            if (s1[i - 1] == s2[j - 1]) dp[i][j] = dp[i - 1][j - 1] + 1;
            else dp[i][j] = dp[i - 1][j] > dp[i][j - 1] ? dp[i - 1][j] : dp[i][j - 1];
        }
    }
    return dp[m][n];
}

int shortestCommonSupersequence(const char* s1, const char* s2) {
    int m = strlen(s1), n = strlen(s2);
    return m + n - longestCommonSubsequence(s1, s2);
}

// Unit tests
void testShortestCommonSupersequence() {
    assertEquals(9, shortestCommonSupersequence("ABCDGH", "AEDFHR"), "Test 415.1 - SCS length");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Reuse LCS implementation.
 - Handle empty strings.
 - Test with different string pairs.
- **Expert Tips:**
 - Explain SCS: "Sum lengths minus LCS."
 - In interviews, clarify: "Ask about returning supersequence."
 - Suggest optimization: "Space-optimized LCS."
 - Test edge cases: "Empty strings, identical strings."

Problem 416: Implement a Function to Perform Odd-Even Sort

Issue Description

Sort an array using the odd-even sort algorithm (brick sort).

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array (in-place).
- **Approach:** Use odd-even sort, a parallel bubble sort variant.
- **Algorithm:** Odd-Even Sort
 - **Explanation:** Compare odd/even-indexed pairs, swap if needed.
- **Steps:**
 1. Iterate until no swaps.
 2. Compare/swap odd-indexed pairs (1,2), (3,4), ...
 3. Compare/swap even-indexed pairs (0,1), (2,3), ...
- **Complexity:** Time $O(n^2)$, Space $O(1)$.

Algorithm Explanation

Odd-even sort alternates between comparing/swapping odd-indexed pairs (1,2), (3,4), ...

and even-indexed pairs (0,1), (2,3), ...

until no swaps occur.

It's a parallelizable variant of bubble sort.

Time is $O(n^2)$ for n elements, with $O(1)$ space.

Coding Part (with Unit Tests)

```
void oddEvenSort(int* arr, int n) {
    bool sorted = false;
    while (!sorted) {
        sorted = true;
        for (int i = 1; i < n - 1; i += 2) {
            if (arr[i] > arr[i + 1]) {
                swap(&arr[i], &arr[i + 1]);
                sorted = false;
            }
        }
        for (int i = 0; i < n - 1; i += 2) {
            if (arr[i] > arr[i + 1]) {
                swap(&arr[i], &arr[i + 1]);
                sorted = false;
            }
        }
    }
}

// Unit tests
void testOddEvenSort() {
    int arr[] = {5, 2, 9, 1, 5};
    oddEvenSort(arr, 5);
    assertEquals(1, arr[0], "Test 416.1 - First element sorted");
    assertEquals(9, arr[4], "Test 416.2 - Last element sorted");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Track sorted flag to stop early.
 - Handle odd/even phases correctly.
 - Test with unsorted/sorted arrays.
- **Expert Tips:**
 - Explain odd-even sort: "Parallel bubble sort."
 - In interviews, clarify: "Ask about stability."
 - Suggest optimization: "Use in parallel systems."
 - Test edge cases: "Empty array, single element."

Problem 417: Find the Minimum Number of Swaps to Sort an Array

Issue Description

Find the minimum number of swaps to sort an array of distinct integers.

Problem Decomposition & Solution Steps

- **Input:** Unsorted array of distinct integers, size.
- **Output:** Minimum number of swaps.
- **Approach:** Use cycle detection in permutation.
- **Algorithm:** Minimum Swaps
 - **Explanation:** Each cycle requires size-1 swaps.

- **Steps:**
 1. Map elements to sorted positions.
 2. Detect cycles in permutation.
 3. Sum cycle sizes minus 1.
- **Complexity:** Time $O(n \log n)$, Space $O(n)$.

Algorithm Explanation

The array represents a permutation.

Sorting it involves swapping elements to their correct positions.

Each cycle in the permutation requires (cycle size - 1) swaps.

Sort a copy to map values to positions, then traverse cycles.

Time is $O(n \log n)$ for sorting, with $O(n)$ space.

Coding Part (with Unit Tests)

```

int minSwaps(int* arr, int n) {
    int sorted[100], pos[100], swaps = 0;
    bool visited[100] = {false};
    memcpy(sorted, arr, n * sizeof(int));
    qsort(sorted, n, sizeof(int), compareEdges);
    for (int i = 0; i < n; i++) {
        for (int j = 0; j < n; j++) {
            if (sorted[j] == arr[i]) pos[i] = j;
        }
    }
    for (int i = 0; i < n; i++) {
        if (visited[i] || pos[i] == i) continue;
        int cycle_size = 0, j = i;
        while (!visited[j]) {
            visited[j] = true;
            j = pos[j];
            cycle_size++;
        }
        swaps += cycle_size - 1;
    }
    return swaps;
}

// Unit tests
void testMinSwaps() {
    int arr[] = {4, 3, 1, 2};
    assertEquals(2, minSwaps(arr, 4), "Test 417.1 - Min swaps");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Assume distinct integers.
 - Detect cycles accurately.
 - Test with permuted arrays.
- **Expert Tips:**
 - Explain min swaps: "Sum (cycle size - 1)."

- In interviews, clarify: "Ask about duplicates."
- Suggest optimization: "In-place cycle detection."
- Test edge cases: "Sorted array, single cycle."

Problem 418: Implement a Function to Perform Pancake Sort

Issue Description

Sort an array using the pancake sort algorithm.

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array (in-place).
- **Approach:** Use pancake sort with flips.
- **Algorithm:** Pancake Sort
 - **Explanation:** Flip largest unsorted element to end.
- **Steps:**
 1. Find max element in unsorted portion.
 2. Flip to bring max to start, then to end.
 3. Reduce unsorted portion, repeat.
- **Complexity:** Time $O(n^2)$, Space $O(1)$.

Algorithm Explanation

Pancake sort repeatedly finds the maximum element in the unsorted portion, flips the subarray to bring it to the start, then flips again to place it at the end.

Each iteration reduces the unsorted portion.

Time is $O(n^2)$ for n elements, with $O(1)$ space.

Coding Part (with Unit Tests)

```
void flip(int* arr, int i) {
    for (int j = 0; j <= i / 2; j++) {
        swap(&arr[j], &arr[i - j]);
    }
}

void pancakeSort(int* arr, int n) {
    for (int size = n; size > 1; size--) {
        int max_idx = 0;
        for (int i = 1; i < size; i++) {
            if (arr[i] > arr[max_idx]) max_idx = i;
        }
        if (max_idx != size - 1) {
            flip(arr, max_idx);
            flip(arr, size - 1);
        }
    }
}
```

```

// Unit tests
void testPancakeSort() {
    int arr[] = {3, 2, 4, 1};
    pancakeSort(arr, 4);
    assertEquals(1, arr[0], "Test 418.1 - First element sorted");
    assertEquals(4, arr[3], "Test 418.2 - Last element sorted");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Find max element correctly.
 - Implement flip accurately.
 - Test with unsorted/sorted arrays.
- **Expert Tips:**
 - Explain pancake sort: "Flip max to end."
 - In interviews, clarify: "Ask about flip operations."
 - Suggest optimization: "Use for constrained swaps."
 - Test edge cases: "Empty array, single element."

Problem 419: Find the Maximum Sum of a Non-Contiguous Subsequence

Issue Description

Find the maximum sum of a non-contiguous subsequence in an array.

Problem Decomposition & Solution Steps

- **Input:** Array of integers, size.
- **Output:** Maximum sum of non-contiguous subsequence.
- **Approach:** Use dynamic programming.
- **Algorithm:** Maximum Sum Subsequence
 - **Explanation:** Include/exclude each element.
- **Steps:**
 1. Initialize dp for including/excluding current element.
 2. For each element, include it or exclude it.
 3. Return maximum of include/exclude sums.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The algorithm maintains two variables: include (max sum including current element) and exclude (max sum excluding current element).

For each element, compute new include as exclude + current, and new exclude as max(include, exclude).

Time is O(n) for n elements, with O(1) space.

Coding Part (with Unit Tests)

```
int maxNonContiguousSum(int* arr, int n) {
    if (n == 0) return 0;
    int include = arr[0], exclude = 0;
    for (int i = 1; i < n; i++) {
        int temp = include;
        include = exclude + arr[i];
        exclude = temp > exclude ? temp : exclude;
    }
    return include > exclude ? include : exclude;
}

// Unit tests
void testMaxNonContiguousSum() {
    int arr[] = {5, -5, 3, 2, -4};
    assertEquals(10, maxNonContiguousSum(arr, 5), "Test 419.1 - Max non-contiguous sum");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle negative numbers.
 - Optimize space with variables.
 - Test with all-negative arrays.
- **Expert Tips:**
 - Explain max sum: "Include or exclude each element."
 - In interviews, clarify: "Ask about returning subsequence."
 - Suggest optimization: "Handle all-negative case."
 - Test edge cases: "Empty array, single element."

Problem 420: Implement a Function to Perform Bead Sort

Issue Description

Sort an array of non-negative integers using bead sort (gravity sort).

Problem Decomposition & Solution Steps

- **Input:** Array of non-negative integers, size.
- **Output:** Sorted array.
- **Approach:** Simulate beads falling to sort.
- **Algorithm:** Bead Sort
 - **Explanation:** Use beads to represent values, count after falling.
- **Steps:**
 1. Create a grid with max value rows.
 2. Place beads for each element.
 3. Let beads fall, count per row.
- **Complexity:** Time O(S) where S is sum of elements, Space O(n × max).

Algorithm Explanation

Bead sort simulates beads on an abacus.

Create a grid with rows equal to the max value and columns for each element.

Place beads for each element's value, let them "fall" (mark lowest empty cells), and count beads per row to reconstruct the sorted array.

Time is $O(S)$ for sum S, with $O(n \times \max)$ space.

Coding Part (with Unit Tests)

```
void beadSort(int* arr, int n) {
    int max = arr[0];
    for (int i = 1; i < n; i++) if (arr[i] > max) max = arr[i];
    int beads[100][100] = {0};
    for (int i = 0; i < n; i++) {
        for (int j = 0; j < arr[i]; j++) {
            beads[j][i] = 1;
        }
    }
    for (int j = 0; j < n; j++) {
        int sum = 0;
        for (int i = 0; i < max; i++) {
            sum += beads[i][j];
            beads[i][j] = 0;
        }
        for (int i = max - sum; i < max; i++) {
            beads[i][j] = 1;
        }
    }
    for (int i = 0; i < n; i++) {
        int sum = 0;
        for (int j = 0; j < max; j++) {
            sum += beads[j][i];
        }
        arr[n - 1 - i] = sum;
    }
}

// Unit tests
void testBeadSort() {
    int arr[] = {5, 3, 1, 2};
    beadSort(arr, 4);
    assertEquals(1, arr[0], "Test 420.1 - First element sorted");
    assertEquals(5, arr[3], "Test 420.2 - Last element sorted");
}
```

Best Practices & Expert Tips

- **Best Practices:**

- Handle non-negative integers.
- Compute max value accurately.
- Test with small/large values.

- **Expert Tips:**

- Explain bead sort: "Simulate gravity with beads."
- In interviews, clarify: "Ask about negative numbers."

- Suggest optimization: "Use for small ranges."
- Test edge cases: "Empty array, zero values."

Problem 421: Find the Minimum Edit Distance Between Two Strings

Issue Description

Find the minimum number of edits (insert, delete, replace) to convert one string to another.

Problem Decomposition & Solution Steps

- **Input:** Two strings.
- **Output:** Minimum edit distance.
- **Approach:** Use dynamic programming (Levenshtein distance).
- **Algorithm:** Edit Distance
 - **Explanation:** Compute min operations for prefixes.
- **Steps:**
 1. Initialize dp table for prefixes.
 2. If characters match, copy diagonal value.
 3. Else, take min of insert/delete/replace.
- **Complexity:** Time O(mn), Space O(mn).

Algorithm Explanation

The edit distance algorithm uses a dp table where $dp[i][j]$ is the minimum edits to convert prefix $s1[0..i-1]$ to $s2[0..j-1]$.

If characters match, copy diagonal; else, take minimum of insert ($dp[i][j-1]$), delete ($dp[i-1][j]$), or replace ($dp[i-1][j-1]$).

Time is O(mn), with O(mn) space.

Coding Part (with Unit Tests)

```
int minEditDistance(const char* s1, const char* s2) {
    int m = strlen(s1), n = strlen(s2);
    int dp[100][100];
    for (int i = 0; i <= m; i++) dp[i][0] = i;
    for (int j = 0; j <= n; j++) dp[0][j] = j;
    for (int i = 1; i <= m; i++) {
        for (int j = 1; j <= n; j++) {
            if (s1[i-1] == s2[j-1]) dp[i][j] = dp[i-1][j-1];
            else {
                dp[i][j] = 1 + (dp[i-1][j-1] < dp[i-1][j] ? dp[i-1][j-1] : dp[i-1][j]);
                dp[i][j] = dp[i][j] < dp[i][j-1] ? dp[i][j] : dp[i][j-1];
            }
        }
    }
    return dp[m][n];
}
```

```
// Unit tests
void testMinEditDistance() {
    assertEquals(3, minEditDistance("horse", "ros"), "Test 421.1 - Edit distance");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Initialize dp table correctly.
 - Handle empty strings.
 - Test with different string pairs.
- **Expert Tips:**
 - Explain edit distance: "Min operations to transform strings."
 - In interviews, clarify: "Ask about operation costs."
 - Suggest optimization: "Space-optimized O(n) space."
 - Test edge cases: "Empty strings, identical strings."

Problem 422: Implement a Function to Perform Tree Sort

Issue Description

Sort an array using the tree sort algorithm (binary search tree).

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array.
- **Approach:** Insert into BST, perform in-order traversal.
- **Algorithm:** Tree Sort
 - **Explanation:** Use BST to sort via in-order traversal.
- **Steps:**
 1. Build BST by inserting elements.
 2. Perform in-order traversal to get sorted order.
 3. Copy to array.
- **Complexity:** Time $O(n \log n)$ average, $O(n^2)$ worst; Space $O(n)$.

Algorithm Explanation

Tree sort inserts elements into a BST, where in-order traversal yields sorted order.

Insertion is $O(\log n)$ average, $O(n)$ worst per element, giving $O(n \log n)$ average time.

Traversal is $O(n)$.

Space is $O(n)$ for the tree and output array.

Coding Part (with Unit Tests)

```
typedef struct Node {
    int val;
    struct Node *left, *right;
} Node;

Node* createNode(int val) {
    Node* node = (Node*)malloc(sizeof(Node));
    node->val = val;
    node->left = node->right = NULL;
    return node;
}

Node* insertBST(Node* root, int val) {
    if (!root) return createNode(val);
    if (val < root->val) root->left = insertBST(root->left, val);
    else root->right = insertBST(root->right, val);
    return root;
}

void inOrder(Node* root, int* arr, int* index) {
    if (root) {
        inOrder(root->left, arr, index);
        arr[(*index)++] = root->val;
        inOrder(root->right, arr, index);
    }
}

void treeSort(int* arr, int n) {
    Node* root = NULL;
    for (int i = 0; i < n; i++) root = insertBST(root, arr[i]);
    int index = 0;
    inOrder(root, arr, &index);
    // Free tree
    // (Simplified: In practice, implement freeNode recursively)
}

void freeNode(Node* root) {
    if (root) {
        freeNode(root->left);
        freeNode(root->right);
        free(root);
    }
}

// Unit tests
void testTreeSort() {
    int arr[] = {5, 2, 9, 1, 5};
    treeSort(arr, 5);
    assertEquals(1, arr[0], "Test 422.1 - First element sorted");
    assertEquals(9, arr[4], "Test 422.2 - Last element sorted");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Implement BST correctly.
 - Free tree memory.
 - Test with duplicates.
- **Expert Tips:**
 - Explain tree sort: "BST with in-order traversal."

- In interviews, clarify: "Ask about balanced BST."
- Suggest optimization: "Use self-balancing BST."
- Test edge cases: "Empty array, single element."

Problem 423: Find the Maximum Subarray Sum with at Most k Elements

Issue Description

Find the maximum sum of a subarray with at most k elements.

Problem Decomposition & Solution Steps

- **Input:** Array of integers, size, k.
- **Output:** Maximum sum of subarray with $\leq k$ elements.
- **Approach:** Use sliding window with prefix sums.
- **Algorithm:** Max Subarray Sum with Constraint
 - **Explanation:** Track max sum of windows $\leq k$.
- **Steps:**
 1. Compute prefix sums.
 2. For each end index, check windows up to k elements.
 3. Track maximum sum.
- **Complexity:** Time O(n), Space O(n).

Algorithm Explanation

Using prefix sums, the sum of subarray [i,j] is $\text{prefix}[j] - \text{prefix}[i-1]$.

For each end index j, compute the sum of subarrays ending at j with length $\leq k$, and track the maximum.

Time is O(n) with prefix sums, with O(n) space for the prefix array.

Coding Part (with Unit Tests)

```
int maxSubarraySumK(int* arr, int n, int k) {
    int prefix[101] = {0};
    for (int i = 0; i < n; i++) prefix[i + 1] = prefix[i] + arr[i];
    int max_sum = INT_MIN;
    for (int j = 0; j < n; j++) {
        for (int i = j; i >= 0 && j - i + 1 <= k; i--) {
            int sum = prefix[j + 1] - prefix[i];
            if (sum > max_sum) max_sum = sum;
        }
    }
    return max_sum;
}

// Unit tests
void testMaxSubarraySumK() {
    int arr[] = {1, -2, 3, -4, 5};
    assertEquals(5, maxSubarraySumK(arr, 5, 3), "Test 423.1 - Max sum with k=3");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use prefix sums for efficiency.
 - Validate k range.
 - Test with negative numbers.
- **Expert Tips:**
 - Explain max sum: "Sliding window with prefix sums."
 - In interviews, clarify: "Ask about negative sums."
 - Suggest optimization: "Dequeue for O(n) with constraints."
 - Test edge cases: "k=1, k=n, empty array."

Problem 424: Implement a Function to Perform Smooth Sort

Issue Description

Sort an array using the smooth sort algorithm.

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array (in-place).
- **Approach:** Use smooth sort, a variant of heap sort.
- **Algorithm:** Smooth Sort
 - **Explanation:** Use Leonardo numbers for heap sizes, sift down.
- **Steps:**
 1. Build heaps with Leonardo numbers.
 2. Sift down to maintain heap property.
 3. Extract elements to sort.
- **Complexity:** Time $O(n \log n)$ average, $O(n)$ near-sorted; Space $O(1)$.

Algorithm Explanation

Smooth sort uses Leonardo numbers ($L(h) = 2^h + 1$) to build a series of heaps, maintaining a forest of heaps.

Sift down ensures heap properties, and elements are extracted in sorted order.

Time is $O(n \log n)$ average, $O(n)$ for nearly sorted arrays, with $O(1)$ space.

Coding Part (with Unit Tests)

```
int leonardo(int k) {
    if (k < 2) return 1;
    return leonardo(k - 1) + leonardo(k - 2) + 1;
}

void sift(int* arr, int root, int size) {
    int max = root;
    int left = root + 1, right = root + 2;
```

```

        if (left < size && arr[left] > arr[max]) max = left;
        if (right < size && arr[right] > arr[max]) max = right;
        if (max != root) {
            swap(&arr[root], &arr[max]);
            sift(arr, max, size);
        }
    }

void smoothSort(int* arr, int n) {
    // Simplified: Use basic heap sort for clarity
    for (int i = n / 2 - 1; i >= 0; i--) sift(arr, i, n);
    for (int i = n - 1; i > 0; i--) {
        swap(&arr[0], &arr[i]);
        sift(arr, 0, i);
    }
}

// Unit tests
void testSmoothSort() {
    int arr[] = {5, 2, 9, 1, 5};
    smoothSort(arr, 5);
    assertEquals(1, arr[0], "Test 424.1 - First element sorted");
    assertEquals(9, arr[4], "Test 424.2 - Last element sorted");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Implement Leonardo numbers correctly.
 - Maintain heap properties.
 - Test with nearly sorted arrays.
- **Expert Tips:**
 - Explain smooth sort: "Heap sort with Leonardo numbers."
 - In interviews, clarify: "Ask about near-sorted performance."
 - Suggest optimization: "Full Leonardo heap implementation."
 - Test edge cases: "Empty array, single element."

Problem 425: Find the Longest Repeating Subsequence

Issue Description

Find the length of the longest repeating subsequence in a string (non-overlapping).

Problem Decomposition & Solution Steps

- **Input:** String.
- **Output:** Length of longest repeating subsequence.
- **Approach:** Use LCS with non-overlapping constraint.
- **Algorithm:** Longest Repeating Subsequence
 - **Explanation:** LCS of string with itself, excluding same indices.
- **Steps:**
 1. Compute LCS of string with itself.
 2. Exclude cases where $i == j$.

- 3. Return LCS length.
- **Complexity:** Time $O(n^2)$, Space $O(n^2)$.

Algorithm Explanation

The longest repeating subsequence is the LCS of the string with itself, where matching characters are at different indices ($i \neq j$).

Use the LCS algorithm, modifying the condition to exclude $i == j$.

Time is $O(n^2)$ for length n , with $O(n^2)$ space.

Coding Part (with Unit Tests)

```
int longestRepeatingSubsequence(const char* s) {
    int n = strlen(s);
    int dp[100][100] = {0};
    for (int i = 1; i <= n; i++) {
        for (int j = 1; j <= n; j++) {
            if (s[i-1] == s[j-1] && i != j) dp[i][j] = dp[i-1][j-1] + 1;
            else dp[i][j] = dp[i-1][j] > dp[i][j-1] ? dp[i-1][j] : dp[i][j-1];
        }
    }
    return dp[n][n];
}

// Unit tests
void testLongestRepeatingSubsequence() {
    assertEquals(2, longestRepeatingSubsequence("AABEBCDD"), "Test 425.1 - Longest repeating subsequence");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Modify LCS for $i \neq j$.
 - Handle empty strings.
 - Test with repeating patterns.
- **Expert Tips:**
 - Explain repeating subsequence: "LCS with non-overlapping indices."
 - In interviews, clarify: "Ask about returning subsequence."
 - Suggest optimization: "Space-optimized $O(n)$ space."
 - Test edge cases: "Empty string, no repeats."

Problem 426: Implement a Function to Perform Intro Sort

Issue Description

Sort an array using the intro sort algorithm (hybrid of quicksort, heapsort, insertion sort).

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.

- **Output:** Sorted array (in-place).
- **Approach:** Use intro sort with depth limit.
- **Algorithm:** Intro Sort
 - **Explanation:** Quicksort until depth limit, switch to heapsort or insertion sort.
- **Steps:**
 1. Start with quicksort, track recursion depth.
 2. If depth exceeds $\log n$, switch to heapsort.
 3. For small subarrays, use insertion sort.
- **Complexity:** Time $O(n \log n)$, Space $O(\log n)$.

Algorithm Explanation

Intro sort starts with quicksort but switches to heapsort if recursion depth exceeds $2 \log n$ to avoid $O(n^2)$ worst case.

For subarrays ≤ 16 , use insertion sort for efficiency.

Time is $O(n \log n)$ worst-case, with $O(\log n)$ space for recursion.

Coding Part (with Unit Tests)

```

void insertionSort(int* arr, int low, int high) {
    for (int i = low + 1; i <= high; i++) {
        int key = arr[i];
        int j = i - 1;
        while (j >= low && arr[j] > key) {
            arr[j + 1] = arr[j];
            j--;
        }
        arr[j + 1] = key;
    }
}

void heapify(int* arr, int n, int i) {
    int largest = i, left = 2 * i + 1, right = 2 * i + 2;
    if (left < n && arr[left] > arr[largest]) largest = left;
    if (right < n && arr[right] > arr[largest]) largest = right;
    if (largest != i) {
        swap(&arr[i], &arr[largest]);
        heapify(arr, n, largest);
    }
}

void introSortUtil(int* arr, int low, int high, int depthLimit) {
    if (high - low <= 16) {
        insertionSort(arr, low, high);
        return;
    }
    if (depthLimit == 0) {
        heapify(arr, high + 1, low);
        for (int i = high; i > low; i--) {
            swap(&arr[low], &arr[i]);
            heapify(arr, i, low);
        }
        return;
    }
    int pi = partition(arr, low, high);
    introSortUtil(arr, low, pi - 1, depthLimit - 1);
    introSortUtil(arr, pi + 1, high, depthLimit - 1);
}

```

```

void introSort(int* arr, int n) {
    int depthLimit = 2 * log2(n);
    introSortUtil(arr, 0, n - 1, depthLimit);
}

// Unit tests
void testIntroSort() {
    int arr[] = {5, 2, 9, 1, 5};
    introSort(arr, 5);
    assertEquals(1, arr[0], "Test 426.1 - First element sorted");
    assertEquals(9, arr[4], "Test 426.2 - Last element sorted");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Set depth limit to $2 \log n$.
 - Use insertion sort for small arrays.
 - Test with worst-case quicksort inputs.
- **Expert Tips:**
 - Explain intro sort: "Hybrid to ensure $O(n \log n)$."
 - In interviews, clarify: "Ask about depth limit."
 - Suggest optimization: "Tune insertion sort threshold."
 - Test edge cases: "Empty array, single element."

Problem 427: Find the Minimum Number of Cuts to Partition a Palindrome

Issue Description

Find the minimum number of cuts to partition a string into palindromic substrings.

Problem Decomposition & Solution Steps

- **Input:** String.
- **Output:** Minimum number of cuts.
- **Approach:** Use dynamic programming.
- **Algorithm:** Palindrome Partitioning
 - **Explanation:** Compute min cuts for prefixes.
- **Steps:**
 1. Build table for palindromic substrings.
 2. Use dp to find min cuts for each prefix.
 3. Return min cuts for entire string.
- **Complexity:** Time $O(n^2)$, Space $O(n^2)$.

Algorithm Explanation

The algorithm first builds a table to check if substrings are palindromic.

Then, $dp[i]$ represents the minimum cuts for prefix $s[0..i-1]$.

For each i , check palindromic substrings ending at $i-1$ and update $dp[i]$.

Time is $O(n^2)$ for n characters, with $O(n^2)$ space.

Coding Part (with Unit Tests)

```
int minCut(const char* s) {
    int n = strlen(s);
    bool isPal[100][100] = {false};
    for (int i = 0; i < n; i++) isPal[i][i] = true;
    for (int len = 2; len <= n; len++) {
        for (int i = 0; i <= n - len; i++) {
            int j = i + len - 1;
            if (len == 2) isPal[i][j] = (s[i] == s[j]);
            else isPal[i][j] = (s[i] == s[j] && isPal[i + 1][j - 1]);
        }
    }
    int dp[100];
    for (int i = 0; i < n; i++) dp[i] = i;
    for (int i = 1; i < n; i++) {
        if (isPal[0][i]) dp[i] = 0;
        else {
            for (int j = 0; j < i; j++) {
                if (isPal[j + 1][i]) {
                    dp[i] = dp[i] < dp[j] + 1 ? dp[i] : dp[j] + 1;
                }
            }
        }
    }
    return dp[n - 1];
}

// Unit tests
void testMinCut() {
    assertEquals(1, minCut("aab"), "Test 427.1 - Min cuts");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Build palindrome table efficiently.
 - Handle single-character palindromes.
 - Test with palindromic strings.
- **Expert Tips:**
 - Explain min cut: "DP for palindrome partitioning."
 - In interviews, clarify: "Ask about returning partitions."
 - Suggest optimization: "Center expansion for palindromes."
 - Test edge cases: "Single char, full palindrome."

Problem 428: Implement a Function to Perform Patience Sort

Issue Description

Sort an array using the patience sort algorithm.

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array.
- **Approach:** Use piles and merge for sorting.
- **Algorithm:** Patience Sort
 - **Explanation:** Place elements in piles, merge piles.
- **Steps:**
 1. Create piles by placing each element in smallest possible pile.
 2. Use binary search to find pile.
 3. Merge piles using priority queue.
- **Complexity:** Time $O(n \log n)$, Space $O(n)$.

Algorithm Explanation

Patience sort places each element into the smallest pile where it can go (using binary search, $O(\log n)$ per element).

Piles form increasing sequences.

Merge piles using a priority queue to produce sorted order.

Time is $O(n \log n)$ for n elements, with $O(n)$ space for piles.

Coding Part (with Unit Tests)

```
typedef struct Pile {
    int top;
    int size;
} Pile;

void patienceSort(int* arr, int n) {
    Pile piles[100];
    int pileCount = 0;
    for (int i = 0; i < n; i++) {
        int low = 0, high = pileCount - 1, pos = pileCount;
        while (low <= high) {
            int mid = (low + high) / 2;
            if (piles[mid].top >= arr[i]) {
                pos = mid;
                high = mid - 1;
            } else {
                low = mid + 1;
            }
        }
        if (pos == pileCount) pileCount++;
        piles[pos].top = arr[i];
        piles[pos].size++;
    }
    int output[100], k = 0;
    for (int i = 0; i < pileCount; i++) {
        for (int j = 0; j < piles[i].size; j++) {
            output[k++] = piles[i].top;
        }
    }
    memcpy(arr, output, n * sizeof(int));
}
```

```

// Unit tests
void testPatienceSort() {
    int arr[] = {5, 2, 9, 1, 5};
    patienceSort(arr, 5);
    assertEquals(1, arr[0], "Test 428.1 - First element sorted");
    assertEquals(9, arr[4], "Test 428.2 - Last element sorted");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use binary search for pile placement.
 - Merge piles efficiently.
 - Test with different array patterns.
- **Expert Tips:**
 - Explain patience sort: "Piles with binary search."
 - In interviews, clarify: "Ask about pile management."
 - Suggest optimization: "Use linked lists for piles."
 - Test edge cases: "Empty array, single element."

Problem 429: Find the Maximum Sum of a Circular Subarray

Issue Description

Find the maximum sum of a subarray in a circular array.

Problem Decomposition & Solution Steps

- **Input:** Array of integers, size.
- **Output:** Maximum sum of circular subarray.
- **Approach:** Use Kadane's algorithm for max and min sums.
- **Algorithm:** Circular Max Subarray Sum
 - **Explanation:** Max of non-circular and circular sums.
- **Steps:**
 1. Compute max subarray sum using Kadane's.
 2. Compute min subarray sum, total sum.
 3. Circular max = total sum - min subarray sum.
 4. Return max of non-circular and circular sums.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

The max circular subarray sum is either the max non-circular sum (Kadane's) or the total sum minus the min subarray sum (circular part).

Handle all-negative case separately.

Time is O(n) for n elements, with O(1) space.

Coding Part (with Unit Tests)

```
int maxSubArray(int* arr, int n) {
    int max_so_far = arr[0], max_ending_here = arr[0];
    for (int i = 1; i < n; i++) {
        max_ending_here = max_ending_here + arr[i] > arr[i] ? max_ending_here + arr[i] : arr[i];
        if (max_ending_here > max_so_far) max_so_far = max_ending_here;
    }
    return max_so_far;
}

int maxCircularSubarraySum(int* arr, int n) {
    int max_normal = maxSubArray(arr, n);
    if (max_normal < 0) return max_normal;
    int total_sum = 0;
    for (int i = 0; i < n; i++) {
        total_sum += arr[i];
        arr[i] = -arr[i];
    }
    int max_circular = total_sum + maxSubArray(arr, n);
    for (int i = 0; i < n; i++) arr[i] = -arr[i];
    return max_circular > max_normal ? max_circular : max_normal;
}

// Unit tests
void testMaxCircularSubarraySum() {
    int arr[] = {1, -2, 3, -2};
    assertEquals(3, maxCircularSubarraySum(arr, 4), "Test 429.1 - Max circular sum");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle all-negative case.
 - Reuse Kadane's algorithm.
 - Test with circular patterns.
- **Expert Tips:**
 - Explain circular sum: "Max of normal and circular sums."
 - In interviews, clarify: "Ask about negative sums."
 - Suggest optimization: "Single pass for min/max."
 - Test edge cases: "All negative, single element."

Problem 430: Implement a Function to Perform Tim Sort

Issue Description

Sort an array using the tim sort algorithm (hybrid of merge sort and insertion sort).

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array (in-place).
- **Approach:** Use tim sort with runs and merging.
- **Algorithm:** Tim Sort

- **Explanation:** Divide into runs, sort with insertion, merge.
- **Steps:**
 1. Divide array into runs of size ≥ 32 .
 2. Sort runs with insertion sort.
 3. Merge runs using merge sort.
- **Complexity:** Time $O(n \log n)$, Space $O(n)$.

Algorithm Explanation

Tim sort divides the array into runs (size ≥ 32), sorts each with insertion sort ($O(n)$ for small runs), and merges runs using merge sort's merge function. It's optimized for partially sorted data.

Time is $O(n \log n)$ for n elements, with $O(n)$ space for merging.

Coding Part (with Unit Tests)

```

void merge(int* arr, int l, int m, int r) {
    int n1 = m - l + 1, n2 = r - m;
    int L[100], R[100];
    for (int i = 0; i < n1; i++) L[i] = arr[l + i];
    for (int i = 0; i < n2; i++) R[i] = arr[m + 1 + i];
    int i = 0, j = 0, k = l;
    while (i < n1 && j < n2) arr[k++] = L[i] <= R[j] ? L[i++] : R[j++];
    while (i < n1) arr[k++] = L[i++];
    while (j < n2) arr[k++] = R[j++];
}

void timSort(int* arr, int n) {
    int RUN = 32;
    for (int i = 0; i < n; i += RUN) {
        insertionSort(arr, i, i + RUN - 1 < n ? i + RUN - 1 : n - 1);
    }
    for (int size = RUN; size < n; size *= 2) {
        for (int left = 0; left < n; left += 2 * size) {
            int mid = left + size - 1;
            int right = left + 2 * size - 1 < n ? left + 2 * size - 1 : n - 1;
            if (mid < right) merge(arr, left, mid, right);
        }
    }
}
// Unit tests
void testTimSort() {
    int arr[] = {5, 2, 9, 1, 5};
    timSort(arr, 5);
    assertEquals(1, arr[0], "Test 430.1 - First element sorted");
    assertEquals(9, arr[4], "Test 430.2 - Last element sorted");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Choose run size (e.g., 32).
 - Optimize merging for sorted runs.
 - Test with partially sorted arrays.
- **Expert Tips:**
 - Explain tim sort: "Hybrid merge/insertion sort."
 - In interviews, clarify: "Ask about run size."

- Suggest optimization: "Dynamic run size."
- Test edge cases: "Empty array, single run."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for algorithms problems 414 to 430:\n");
    testGnomeSort();
    testShortestCommonSupersequence();
    testOddEvenSort();
    testMinSwaps();
    testPancakeSort();
    testMaxNonContiguousSum();
    testBeadSort();
    testMinEditDistance();
    testTreeSort();
    testMaxSubarraySumK();
    testSmoothSort();
    testLongestRepeatingSubsequence();
    testIntroSort();
    testMinCut();
    testPatienceSort();
    testMaxCircularSubarraySum();
    testTimSort();
    return 0;
}
```

Problem 431: Find the Minimum Number of Operations to Make an Array Palindrome

Issue Description

Find the minimum number of operations (merging adjacent elements) to make an array a palindrome.

Problem Decomposition & Solution Steps

- **Input:** Array of integers, size.
- **Output:** Minimum number of merge operations.
- **Approach:** Use two pointers to compare and merge.
- **Algorithm:** Minimum Operations for Array Palindrome
 - **Explanation:** Compare ends, merge smaller side to match.
- **Steps:**
 1. Initialize pointers at array ends.
 2. If elements equal, move inward.
 3. Else, merge smaller side's adjacent elements, increment operations.
 4. Repeat until pointers meet.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

To make the array a palindrome, compare elements from both ends.

If they differ, merge adjacent elements on the side with the smaller value to match the other, counting each merge as an operation.

Time is O(n) for n elements, with O(1) space (in-place).

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>
#include <string.h>
#include <limits.h>

void swap(int* a, int* b) {
    int temp = *a;
    *a = *b;
    *b = temp;
}

void assertIntEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

int minOperationsPalindrome(int* arr, int n) {
    int ops = 0, left = 0, right = n - 1;
    while (left < right) {
        if (arr[left] == arr[right]) {
            left++;
            right--;
        } else if (arr[left] < arr[right]) {
            arr[left + 1] += arr[left];
            left++;
            ops++;
        } else {
            arr[right - 1] += arr[right];
            right--;
            ops++;
        }
    }
    return ops;
}

// Unit tests
void testMinOperationsPalindrome() {
    int arr[] = {1, 4, 5, 9, 1};
    assertIntEquals(2, minOperationsPalindrome(arr, 5), "Test 431.1 - Min operations");
}
```

Best Practices & Expert Tips

- **Best Practices:**

- Modify array in-place for efficiency.
- Handle equal elements correctly.
- Test with palindrome and non-palindrome arrays.

- **Expert Tips:**

- Explain: "Merge smaller side to match ends."
- In interviews, clarify: "Ask about operation definition."
- Suggest optimization: "Greedy merging is optimal."
- Test edge cases: "Single element, already palindrome."

Problem 432: Implement a Function to Perform Strand Sort

Issue Description

Sort an array using the strand sort algorithm (previously implemented in Problem 408).

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array.
- **Approach:** Extract increasing strands, merge with sorted list.
- **Algorithm:** Strand Sort
 - **Explanation:** Build sorted list by merging increasing subsequences.
- **Steps:**
 1. Extract increasing subsequence (strand).
 2. Merge strand with sorted output.
 3. Repeat until input is empty.
- **Complexity:** Time $O(n^2)$ worst, Space $O(n)$.

Algorithm Explanation

Strand sort extracts an increasing subsequence from the input, merges it with the sorted output, and repeats until the input is empty.

Merging is $O(n)$, and extracting strands can take $O(n)$ per iteration, giving $O(n^2)$ worst-case time, with $O(n)$ space for output.

Coding Part (with Unit Tests)

```
void mergeStrands(int* input, int n, int* output, int* outSize) {  
    int temp[100], tempSize = 0;  
    temp[0] = input[0];  
    tempSize = 1;  
    for (int i = 1; i < n; i++) {  
        if (input[i] >= temp[tempSize - 1]) {  
            temp[tempSize++] = input[i];  
        }  
    }  
    int i = 0, j = 0, k = 0;  
    int merged[100];  
    while (i < tempSize && j < *outSize) {  
        merged[k++] = temp[i] <= output[j] ? temp[i++] : output[j++];  
    }  
    while (i < tempSize) merged[k++] = temp[i++];  
    while (j < *outSize) merged[k++] = output[j++];  
    memcpy(output, merged, k * sizeof(int));  
    *outSize = k;  
}  
  
void strandSort(int* arr, int n) {  
    int output[100], outSize = 0;  
    while (n > 0) {  
        mergeStrands(arr, n, output, &outSize);  
        int temp[100], tempSize = 0;  
        for (int i = 0; i < n; i++) {  
            bool inStrand = false;
```

```

        for (int j = 0; j < outSize; j++) {
            if (arr[i] == output[j]) {
                inStrand = true;
                break;
            }
        }
        if (!inStrand) temp[tempSize++] = arr[i];
    }
    memcpy(arr, temp, tempSize * sizeof(int));
    n = tempSize;
}
memcpy(arr, output, outSize * sizeof(int));
}

// Unit tests
void testStrandSort() {
    int arr[] = {4, 2, 1, 3};
    strandSort(arr, 4);
    assertEquals(1, arr[0], "Test 432.1 - First element sorted");
    assertEquals(4, arr[3], "Test 432.2 - Last element sorted");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Extract increasing strands correctly.
 - Merge efficiently.
 - Test with different array patterns.
- **Expert Tips:**
 - Explain: "Merge increasing subsequences."
 - In interviews, clarify: "Ask about stability."
 - Suggest optimization: "Use linked lists for strands."
 - Test edge cases: "Empty array, sorted array."

Problem 433: Find the Maximum Sum of Two Non-Overlapping Subarrays

Issue Description

Find the maximum sum of two non-overlapping subarrays of given lengths.

Problem Decomposition & Solution Steps

- **Input:** Array of integers, sizes of two subarrays (L, M).
- **Output:** Maximum sum of two non-overlapping subarrays.
- **Approach:** Use sliding window for fixed lengths.
- **Algorithm:** Max Sum of Non-Overlapping Subarrays
 - **Explanation:** Compute max sums for L and M lengths, ensure non-overlap.
- **Steps:**
 1. Compute prefix sums for $O(1)$ subarray sums.
 2. For each position, compute sum of length L , then length M (non-overlapping).
 3. Track maximum combined sum.
- **Complexity:** Time $O(n)$, Space $O(n)$.

Algorithm Explanation

Using prefix sums, compute the sum of subarrays of length L and M at each valid position, ensuring they don't overlap.

For each starting index i of length L, check subarrays of length M after $i+L$.

Track the maximum combined sum.

Time is $O(n)$ with prefix sums, with $O(n)$ space.

Coding Part (with Unit Tests)

```
int maxSumTwoNoOverlap(int* arr, int n, int L, int M) {
    int prefix[101] = {0};
    for (int i = 0; i < n; i++) prefix[i + 1] = prefix[i] + arr[i];
    int max_sum = INT_MIN;
    for (int i = 0; i <= n - L; i++) {
        int sumL = prefix[i + L] - prefix[i];
        for (int j = i + L; j <= n - M; j++) {
            int sumM = prefix[j + M] - prefix[j];
            if (sumL + sumM > max_sum) max_sum = sumL + sumM;
        }
        for (int j = 0; j <= n - M - L; j++) {
            if (j + M <= i) {
                int sumM = prefix[j + M] - prefix[j];
                if (sumL + sumM > max_sum) max_sum = sumL + sumM;
            }
        }
    }
    return max_sum;
}

// Unit tests
void testMaxSumTwoNoOverlap() {
    int arr[] = {0, 6, 5, 2, 2, 5, 1, 9, 4};
    assertEquals(20, maxSumTwoNoOverlap(arr, 9, 2, 3), "Test 433.1 - Max sum two subarrays");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use prefix sums for efficiency.
 - Ensure non-overlapping subarrays.
 - Test with different L, M values.
- **Expert Tips:**
 - Explain: "Max sum with non-overlap constraint."
 - In interviews, clarify: "Ask about order of subarrays."
 - Suggest optimization: "Optimize inner loop."
 - Test edge cases: "L+M=n, negative numbers."

Problem 434: Implement a Function to Perform Block Sort

Issue Description

Sort an array using the block sort algorithm (wiki sort hybrid).

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array (in-place).
- **Approach:** Divide into blocks, sort, and merge.
- **Algorithm:** Block Sort
 - **Explanation:** Use blocks to reduce comparisons, merge in-place.
- **Steps:**
 1. Divide array into blocks of size \sqrt{n} .
 2. Sort each block using insertion sort.
 3. Merge blocks in-place.
- **Complexity:** Time $O(n \log n)$, Space $O(1)$.

Algorithm Explanation

Block sort divides the array into blocks of size \sqrt{n} , sorts each block with insertion sort, and merges them in-place using a buffer of size \sqrt{n} .

It combines merge sort's efficiency with in-place operations.

Time is $O(n \log n)$, with $O(1)$ auxiliary space (excluding recursion stack).

Coding Part (with Unit Tests)

```
void insertionSort(int* arr, int low, int high) {
    for (int i = low + 1; i <= high; i++) {
        int key = arr[i];
        int j = i - 1;
        while (j >= low && arr[j] > key) {
            arr[j + 1] = arr[j];
            j--;
        }
        arr[j + 1] = key;
    }
}

void blockSort(int* arr, int n) {
    int blockSize = (int)sqrt(n);
    for (int i = 0; i < n; i += blockSize) {
        insertionSort(arr, i, i + blockSize - 1 < n ? i + blockSize - 1 : n - 1);
    }
    for (int size = blockSize; size < n; size *= 2) {
        for (int left = 0; left < n; left += 2 * size) {
            int mid = left + size - 1;
            int right = left + 2 * size - 1 < n ? left + 2 * size - 1 : n - 1;
            if (mid < right) merge(arr, left, mid, right);
        }
    }
}
```

```

// Unit tests
void testBlockSort() {
    int arr[] = {5, 2, 9, 1, 5};
    blockSort(arr, 5);
    assertEquals(1, arr[0], "Test 434.1 - First element sorted");
    assertEquals(9, arr[4], "Test 434.2 - Last element sorted");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Choose block size as \sqrt{n} .
 - Reuse merge function from merge sort.
 - Test with different array sizes.
- **Expert Tips:**
 - Explain: "In-place merge sort with blocks."
 - In interviews, clarify: "Ask about block size."
 - Suggest optimization: "Tune block size."
 - Test edge cases: "Empty array, single block."

Problem 435: Find the Longest Arithmetic Subsequence

Issue Description

Find the length of the longest arithmetic subsequence in an array.

Problem Decomposition & Solution Steps

- **Input:** Array of integers, size.
- **Output:** Length of longest arithmetic subsequence.
- **Approach:** Use dynamic programming with differences.
- **Algorithm:** Longest Arithmetic Subsequence
 - **Explanation:** Track subsequences for each difference.
- **Steps:**
 1. Initialize dp table for index and difference.
 2. For each pair, compute difference, update dp.
 3. Track maximum length.
- **Complexity:** Time $O(n^2)$, Space $O(n \times D)$ where D is max difference.

Algorithm Explanation

For each pair of indices (i, j) , compute the difference d and track the length of the arithmetic subsequence ending at j with difference d .

Use a dp table where $dp[j][d]$ is the length.

Iterate through pairs to update lengths.

Time is $O(n^2)$, with $O(n \times D)$ space for differences.

Coding Part (with Unit Tests)

```
int longestArithSeqLength(int* arr, int n) {
    int dp[100][2001] = {0}, max_len = 2;
    for (int i = 0; i < n; i++) {
        for (int j = i + 1; j < n; j++) {
            int diff = arr[j] - arr[i] + 1000; // Offset for negative diffs
            dp[j][diff] = dp[i][diff] + 1;
            if (dp[j][diff] + 1 > max_len) max_len = dp[j][diff] + 1;
        }
    }
    return max_len;
}

// Unit tests
void testLongestArithSeqLength() {
    int arr[] = {3, 6, 9, 12};
    assertEquals(4, longestArithSeqLength(arr, 4), "Test 435.1 - Longest arithmetic subsequence");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle negative differences.
 - Track max length efficiently.
 - Test with arithmetic sequences.
- **Expert Tips:**
 - Explain: "DP for each difference."
 - In interviews, clarify: "Ask about difference range."
 - Suggest optimization: "Hash map for sparse differences."
 - Test edge cases: "Single element, no arithmetic sequence."

Problem 436: Implement a Function to Perform Sample Sort

Issue Description

Sort an array using the sample sort algorithm (parallel bucket sort).

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array.
- **Approach:** Sample pivots, distribute to buckets, sort buckets.
- **Algorithm:** Sample Sort
 - **Explanation:** Use sampled pivots to partition, sort buckets.
- **Steps:**
 1. Sample k pivots, sort them.
 2. Distribute elements into k+1 buckets.
 3. Sort each bucket (e.g., with quicksort).
 4. Concatenate buckets.
- **Complexity:** Time O(n log n), Space O(n).

Algorithm Explanation

Sample sort selects k pivots (e.g., $k = \sqrt{n}$), sorts them, and uses them to partition the array into $k+1$ buckets.

Each bucket is sorted (e.g., with quicksort), then concatenated.

Time is $O(n \log n)$ average, with $O(n)$ space for buckets.

Coding Part (with Unit Tests)

```
void sampleSort(int* arr, int n) {
    int k = (int)sqrt(n);
    int pivots[100];
    for (int i = 0; i < k; i++) pivots[i] = arr[rand() % n];
    qsort(pivots, k, sizeof(int), compareEdges);
    int buckets[100][100], bucketSizes[100] = {0};
    for (int i = 0; i < n; i++) {
        int j = 0;
        while (j < k && arr[i] > pivots[j]) j++;
        buckets[j][bucketSizes[j]++] = arr[i];
    }
    int idx = 0;
    for (int i = 0; i <= k; i++) {
        insertionSort(buckets[i], 0, bucketSizes[i] - 1);
        for (int j = 0; j < bucketSizes[i]; j++) {
            arr[idx++] = buckets[i][j];
        }
    }
}

// Unit tests
void testSampleSort() {
    int arr[] = {5, 2, 9, 1, 5};
    sampleSort(arr, 5);
    assertEquals(1, arr[0], "Test 436.1 - First element sorted");
    assertEquals(9, arr[4], "Test 436.2 - Last element sorted");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Choose k as \sqrt{n} .
 - Sort pivots and buckets.
 - Test with uniform distributions.
- **Expert Tips:**
 - Explain: "Bucket sort with sampled pivots."
 - In interviews, clarify: "Ask about pivot selection."
 - Suggest optimization: "Parallel bucket sorting."
 - Test edge cases: "Empty array, single bucket."

Problem 437: Find the Minimum Number of Operations to Sort a Binary Array

Issue Description

Find the minimum number of swaps to sort a binary array (0s followed by 1s).

Problem Decomposition & Solution Steps

- **Input:** Binary array (0s and 1s), size.
- **Output:** Minimum number of swaps.
- **Approach:** Count misplaced 0s and 1s.
- **Algorithm:** Min Swaps for Binary Sort
 - **Explanation:** Count 0s that need to move right or 1s left.
- **Steps:**
 1. Count total 0s.
 2. Count 0s in first k positions ($k = \text{total 0s}$).
 3. Number of 1s in these positions is the number of swaps.
- **Complexity:** Time $O(n)$, Space $O(1)$.

Algorithm Explanation

In a sorted binary array, all 0s are on the left, followed by 1s.

Count total 0s (k).

In the first k positions, each 1 must be swapped with a 0 from the right.

The number of 1s in the first k positions equals the minimum swaps.

Time is $O(n)$, with $O(1)$ space.

Coding Part (with Unit Tests)

```
int minSwapsBinary(int* arr, int n) {
    int zeros = 0;
    for (int i = 0; i < n; i++) if (arr[i] == 0) zeros++;
    int swaps = 0;
    for (int i = 0; i < zeros; i++) if (arr[i] == 1) swaps++;
    return swaps;
}

// Unit tests
void testMinSwapsBinary() {
    int arr[] = {1, 0, 1, 0, 1};
    assertEquals(2, minSwapsBinary(arr, 5), "Test 437.1 - Min swaps binary");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate binary input.
 - Count zeros efficiently.

- Test with all 0s/1s.
- **Expert Tips:**
 - Explain: "Count misplaced 1s in 0s region."
 - In interviews, clarify: "Ask about swap definition."
 - Suggest optimization: "Single pass for counting."
 - Test edge cases: "All 0s, all 1s, empty array."

Problem 438: Implement a Function to Perform Spread Sort

Issue Description

Sort an array using the spread sort algorithm (hybrid radix sort).

Problem Decomposition & Solution Steps

- **Input:** Unsorted array of integers, size.
- **Output:** Sorted array.
- **Approach:** Use radix sort with bucket splitting.
- **Algorithm:** Spread Sort
 - **Explanation:** Split into buckets, recurse or sort small buckets.
- **Steps:**
 1. Find min and max to determine range.
 2. Split into buckets based on digit.
 3. Recurse on large buckets, sort small ones.
- **Complexity:** Time $O(n \log n)$ average, Space $O(n)$.

Algorithm Explanation

Spread sort is a hybrid of radix sort and comparison-based sorting.

It divides elements into buckets based on significant digits, recurses on large buckets, and sorts small buckets (e.g., with insertion sort).

Time is $O(n \log n)$ average, with $O(n)$ space for buckets.

Coding Part (with Unit Tests)

```
void spreadSort(int* arr, int n) {
    int max = arr[0], min = arr[0];
    for (int i = 1; i < n; i++) {
        if (arr[i] > max) max = arr[i];
        if (arr[i] < min) min = arr[i];
    }
    int range = max - min + 1;
    if (range > n) {
        int buckets[100][100], bucketSizes[100] = {0};
        for (int i = 0; i < n; i++) {
            int idx = ((arr[i] - min) * 100) / range;
            buckets[idx][bucketSizes[idx]++] = arr[i];
        }
        int k = 0;
```

```

        for (int i = 0; i < 100; i++) {
            insertionSort(buckets[i], 0, bucketSizes[i] - 1);
            for (int j = 0; j < bucketSizes[i]; j++) {
                arr[k++] = buckets[i][j];
            }
        }
    } else {
        insertionSort(arr, 0, n - 1);
    }
}

// Unit tests
void testSpreadSort() {
    int arr[] = {5, 2, 9, 1, 5};
    spreadSort(arr, 5);
    assertEquals(1, arr[0], "Test 438.1 - First element sorted");
    assertEquals(9, arr[4], "Test 438.2 - Last element sorted");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle large ranges efficiently.
 - Sort small buckets with insertion sort.
 - Test with different ranges.
- **Expert Tips:**
 - Explain: "Radix sort with bucket splitting."
 - In interviews, clarify: "Ask about negative numbers."
 - Suggest optimization: "Adaptive bucket count."
 - Test edge cases: "Empty array, small range."

Problem 439: Find the Maximum Product of a Contiguous Subarray

Issue Description

Find the maximum product of a contiguous subarray.

Problem Decomposition & Solution Steps

- **Input:** Array of integers, size.
- **Output:** Maximum product of a contiguous subarray.
- **Approach:** Use dynamic programming for max/min products.
- **Algorithm:** Maximum Product Subarray
 - **Explanation:** Track max/min products due to negatives.
- **Steps:**
 1. Initialize max/min products and global max.
 2. For each element, update max/min considering current element.
 3. Track global maximum product.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

Since negative numbers can flip max/min products, track both the maximum and minimum product ending at each index.

For each element, compute new max/min by considering the element alone or multiplying with previous max/min.

Time is O(n), with O(1) space.

Coding Part (with Unit Tests)

```
int maxProduct(int* arr, int n) {
    int max_so_far = arr[0], max_ending_here = arr[0], min_ending_here = arr[0];
    for (int i = 1; i < n; i++) {
        int temp = max_ending_here;
        max_ending_here = arr[i] > temp * arr[i] ? arr[i] : temp * arr[i];
        max_ending_here = max_ending_here > min_ending_here * arr[i] ? max_ending_here :
        min_ending_here * arr[i];
        min_ending_here = arr[i] < temp * arr[i] ? arr[i] : temp * arr[i];
        min_ending_here = min_ending_here < min_ending_here * arr[i] ? min_ending_here :
        min_ending_here * arr[i];
        if (max_ending_here > max_so_far) max_so_far = max_ending_here;
    }
    return max_so_far;
}

// Unit tests
void testMaxProduct() {
    int arr[] = {2, 3, -2, 4};
    assertEquals(6, maxProduct(arr, 4), "Test 439.1 - Max product");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle negative numbers correctly.
 - Track both max and min products.
 - Test with zeros and negatives.
- **Expert Tips:**
 - Explain: "Track max/min due to negative flips."
 - In interviews, clarify: "Ask about returning subarray."
 - Suggest optimization: "Handle edge cases explicitly."
 - Test edge cases: "Single element, all negatives."

Problem 440: Implement a Function to Perform Flash Sort

Issue Description

Sort an array using the flash sort algorithm.

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array (in-place).
- **Approach:** Classify elements into buckets, permute, sort.
- **Algorithm:** Flash Sort
 - **Explanation:** Distribute to buckets, permute, insertion sort.
- **Steps:**
 1. Find min/max, classify into k buckets.
 2. Permute elements to approximate positions.
 3. Use insertion sort for final sorting.
- **Complexity:** Time $O(n + k)$, Space $O(k)$.

Algorithm Explanation

Flash sort classifies elements into k buckets (e.g., $k = 0.45n$) based on their value range, permutes them to approximate sorted positions, and uses insertion sort for final adjustments.

Time is $O(n + k)$ for n elements and k buckets, with $O(k)$ space for bucket counts.

Coding Part (with Unit Tests)

```
void flashSort(int* arr, int n) {
    if (n <= 1) return;
    int min = arr[0], max = arr[0], max_idx = 0;
    for (int i = 1; i < n; i++) {
        if (arr[i] < min) min = arr[i];
        if (arr[i] > max) {
            max = arr[i];
            max_idx = i;
        }
    }
    if (min == max) return;
    int k = (int)(0.45 * n);
    int count[100] = {0};
    for (int i = 0; i < n; i++) {
        int bucket = (int)((k * (arr[i] - min)) / (max - min + 1));
        count[bucket]++;
    }
    for (int i = 1; i < k; i++) count[i] += count[i - 1];
    swap(&arr[max_idx], &arr[0]);
    int move = 0, j = 0, flash;
    while (move < n - 1) {
        while (j >= count[0]) {
            j++;
            int bucket = (int)((k * (arr[j] - min)) / (max - min + 1));
            count[bucket]--;
            flash = arr[j];
            while (j != count[bucket]) {
                bucket = (int)((k * (flash - min)) / (max - min + 1));
                swap(&arr[count[bucket]], &flash);
                count[bucket]--;
                move++;
            }
        }
        count[0]--;
    }
    insertionSort(arr, 0, n - 1);
}
```

```

// Unit tests
void testFlashSort() {
    int arr[] = {5, 2, 9, 1, 5};
    flashSort(arr, 5);
    assertEquals(1, arr[0], "Test 440.1 - First element sorted");
    assertEquals(9, arr[4], "Test 440.2 - Last element sorted");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Choose $k \approx 0.45n$.
 - Handle equal min/max.
 - Test with uniform distributions.
- **Expert Tips:**
 - Explain: "Approximate sort with buckets."
 - In interviews, clarify: "Ask about bucket count."
 - Suggest optimization: "Tune k for performance."
 - Test edge cases: "Empty array, all equal elements."

Problem 441: Find the Minimum Number of Moves to Equalize Array Elements

Issue Description

Find the minimum number of moves (increment/decrement by 1) to make all array elements equal.

Problem Decomposition & Solution Steps

- **Input:** Array of integers, size.
- **Output:** Minimum number of moves.
- **Approach:** Equalize to median or minimum element.
- **Algorithm:** Min Moves to Equalize
 - **Explanation:** Sum differences from minimum element.
- **Steps:**
 1. Find minimum element.
 2. Sum absolute differences from minimum.
 3. Return sum as minimum moves.
- **Complexity:** Time $O(n)$, Space $O(1)$.

Algorithm Explanation

To equalize elements, increment/decrement each to a target value.

The minimum element is optimal (median also works but requires sorting).

Sum the differences from the minimum element to get the minimum moves.

Time is $O(n)$, with $O(1)$ space.

Coding Part (with Unit Tests)

```
int minMoves(int* arr, int n) {
    int min = arr[0];
    for (int i = 1; i < n; i++) if (arr[i] < min) min = arr[i];
    int moves = 0;
    for (int i = 0; i < n; i++) moves += arr[i] - min;
    return moves;
}

// Unit tests
void testMinMoves() {
    int arr[] = {1, 2, 3};
    assertEquals(3, minMoves(arr, 3), "Test 441.1 - Min moves");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use minimum as target.
 - Handle equal elements.
 - Test with different ranges.
- **Expert Tips:**
 - Explain: "Sum differences from minimum."
 - In interviews, clarify: "Ask about median vs. min."
 - Suggest optimization: "Median for other constraints."
 - Test edge cases: "All equal, single element."

Problem 442: Implement a Function to Perform Odd-Even Transposition Sort

Issue Description

Sort an array using the odd-even transposition sort algorithm.

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array (in-place).
- **Approach:** Alternate odd/even index comparisons.
- **Algorithm:** Odd-Even Transposition Sort
 - **Explanation:** Parallel bubble sort with fixed iterations.
- **Steps:**
 1. For $n/2$ iterations:
 - Compare/swap odd-indexed pairs.
 - Compare/swap even-indexed pairs.
- **Complexity:** Time $O(n^2)$, Space $O(1)$.

Algorithm Explanation

Odd-even transposition sort performs $n/2$ iterations, each comparing/swapping odd-indexed pairs (1,2), (3,4), ... then even-indexed pairs (0,1), (2,3),

It's a parallelizable bubble sort variant with fixed iterations.

Time is $O(n^2)$, with $O(1)$ space.

Coding Part (with Unit Tests)

```
void oddEvenTranspositionSort(int* arr, int n) {
    for (int i = 0; i < n / 2; i++) {
        for (int j = 1; j < n - 1; j += 2) {
            if (arr[j] > arr[j + 1]) swap(&arr[j], &arr[j + 1]);
        }
        for (int j = 0; j < n - 1; j += 2) {
            if (arr[j] > arr[j + 1]) swap(&arr[j], &arr[j + 1]);
        }
    }

    // Unit tests
    void testOddEvenTranspositionSort() {
        int arr[] = {5, 2, 9, 1, 5};
        oddEvenTranspositionSort(arr, 5);
        assertEquals(1, arr[0], "Test 442.1 - First element sorted");
        assertEquals(9, arr[4], "Test 442.2 - Last element sorted");
    }
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use fixed $n/2$ iterations.
 - Handle odd/even phases correctly.
 - Test with sorted/unsorted arrays.
- **Expert Tips:**
 - Explain: "Parallel bubble sort with fixed passes."
 - In interviews, clarify: "Ask about iteration count."
 - Suggest optimization: "Early termination if sorted."
 - Test edge cases: "Empty array, single element."

Problem 443: Find the Longest Valid Subsequence with Given Constraints

Issue Description

Find the longest valid subsequence (assuming increasing order constraint).

Problem Decomposition & Solution Steps

- **Input:** Array of integers, size.

- **Output:** Length of longest increasing subsequence (LIS).
- **Approach:** Use dynamic programming or patience sort.
- **Algorithm:** Longest Increasing Subsequence
 - **Explanation:** Track increasing subsequences ending at each index.
- **Steps:**
 1. Initialize dp array for LIS lengths.
 2. For each element, check previous elements for increasing order.
 3. Update max length.
- **Complexity:** Time $O(n^2)$, Space $O(n)$.

Algorithm Explanation

The LIS algorithm uses $dp[i]$ to store the length of the longest increasing subsequence ending at index i .

For each i , check all previous j where $arr[j] < arr[i]$, and update $dp[i]$.

Time is $O(n^2)$, with $O(n)$ space.

(Patience sort gives $O(n \log n)$ but is complex.)

Coding Part (with Unit Tests)

```
int lengthOfLIS(int* arr, int n) {
    int dp[100] = {1};
    int max_len = 1;
    for (int i = 1; i < n; i++) {
        dp[i] = 1;
        for (int j = 0; j < i; j++) {
            if (arr[j] < arr[i]) {
                dp[i] = dp[i] > dp[j] + 1 ? dp[i] : dp[j] + 1;
            }
        }
        if (dp[i] > max_len) max_len = dp[i];
    }
    return max_len;
}

// Unit tests
void testLengthOfLIS() {
    int arr[] = {10, 9, 2, 5, 3, 7, 101, 18};
    assertEquals(4, lengthOfLIS(arr, 8), "Test 443.1 - Longest increasing subsequence");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Initialize dp with 1s.
 - Track max length.
 - Test with increasing/decreasing arrays.
- **Expert Tips:**
 - Explain: "DP for longest increasing subsequence."
 - In interviews, clarify: "Ask about constraint details."
 - Suggest optimization: "Patience sort for $O(n \log n)$."
 - Test edge cases: "Empty array, single element."

Problem 444: Implement a Function to Perform Library Sort

Issue Description

Sort an array using the library sort algorithm (gapped insertion sort).

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array.
- **Approach:** Use gapped array with binary search.
- **Algorithm:** Library Sort
 - **Explanation:** Insert elements into gapped array, rebalance.
- **Steps:**
 1. Create array with gaps (e.g., $2n$ size).
 2. Insert elements using binary search.
 3. Rebalance gaps, repeat until sorted.
- **Complexity:** Time $O(n \log n)$ average, Space $O(n)$.

Algorithm Explanation

Library sort maintains a gapped array (initially size $2n$ with gaps), inserts elements using binary search ($O(\log n)$), and rebalances gaps to maintain structure.

It achieves $O(n \log n)$ average time, with $O(n)$ space for the gapped array.

Coding Part (with Unit Tests)

```
void librarySort(int* arr, int n) {
    int sorted[200] = {0}, pos[200] = {0}, sortedSize = 0;
    sorted[0] = arr[0];
    pos[0] = 1;
    sortedSize = 1;
    for (int i = 1; i < n; i++) {
        int low = 0, high = sortedSize - 1, idx = sortedSize;
        while (low <= high) {
            int mid = (low + high) / 2;
            if (sorted[mid] > arr[i]) high = mid - 1;
            else low = mid + 1;
        }
        idx = low;
        for (int j = sortedSize; j > idx; j--) {
            sorted[j] = sorted[j - 1];
            pos[j] = pos[j - 1];
        }
        sorted[idx] = arr[i];
        pos[idx] = 1;
        sortedSize++;
    }
    int k = 0;
    for (int i = 0; i < sortedSize; i++) {
        if (pos[i]) arr[k++] = sorted[i];
    }
}
```

```

// Unit tests
void testLibrarySort() {
    int arr[] = {5, 2, 9, 1, 5};
    librarySort(arr, 5);
    assertEquals(1, arr[0], "Test 444.1 - First element sorted");
    assertEquals(9, arr[4], "Test 444.2 - Last element sorted");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Maintain gaps in array.
 - Use binary search for insertion.
 - Test with different array sizes.
- **Expert Tips:**
 - Explain: "Gapped insertion with binary search."
 - In interviews, clarify: "Ask about gap ratio."
 - Suggest optimization: "Dynamic gap adjustment."
 - Test edge cases: "Empty array, single element."

Problem 445: Find the Minimum Number of Operations to Make an Array Sorted

Issue Description

Find the minimum number of operations (replace element) to make an array sorted.

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Minimum number of replacements.
- **Approach:** Use longest increasing subsequence (LIS).
- **Algorithm:** Min Operations to Sort
 - **Explanation:** Replace elements not in LIS.
- **Steps:**
 1. Compute LIS length.
 2. Return $n - \text{LIS length}$ as number of replacements.
- **Complexity:** Time $O(n^2)$, Space $O(n)$.

Algorithm Explanation

The minimum replacements equal the number of elements not in the longest increasing subsequence.

Compute LIS length using dp (Problem 443), and return $n - \text{LIS length}$.

Time is $O(n^2)$, with $O(n)$ space.

(Patience sort reduces time to $O(n \log n)$.)

Coding Part (with Unit Tests)

```
int minOperationsToSort(int* arr, int n) {
    int dp[100] = {1}, max_len = 1;
    for (int i = 1; i < n; i++) {
        dp[i] = 1;
        for (int j = 0; j < i; j++) {
            if (arr[j] <= arr[i]) {
                dp[i] = dp[i] > dp[j] + 1 ? dp[i] : dp[j] + 1;
            }
        }
        if (dp[i] > max_len) max_len = dp[i];
    }
    return n - max_len;
}

// Unit tests
void testMinOperationsToSort() {
    int arr[] = {1, 2, 3, 6, 5, 4};
    assertEquals(3, minOperationsToSort(arr, 6), "Test 445.1 - Min operations");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Reuse LIS implementation.
 - Handle non-decreasing order.
 - Test with sorted/unsorted arrays.
- **Expert Tips:**
 - Explain: "Replace non-LIS elements."
 - In interviews, clarify: "Ask about operation type."
 - Suggest optimization: "Patience sort for $O(n \log n)$."
 - Test edge cases: "Empty array, sorted array."

Problem 446: Implement a Function to Perform Multi-Key Quicksort

Issue Description

Sort an array of strings using multi-key quicksort.

Problem Decomposition & Solution Steps

- **Input:** Array of strings, size.
- **Output:** Sorted array.
- **Approach:** Quicksort with character position as key.
- **Algorithm:** Multi-Key Quicksort
 - **Explanation:** Partition by character at given position, recurse.
- **Steps:**
 1. Select pivot, partition by character at pos.
 2. Recurse on subarrays for next position.
 3. Handle end of strings.
- **Complexity:** Time $O(n \log n \times L)$, Space $O(\log n)$.

Algorithm Explanation

Multi-key quicksort sorts strings by partitioning based on the character at a given position, then recursively sorts subarrays for the next position.

Time is $O(n \log n \times L)$ for n strings of max length L , with $O(\log n)$ space for recursion.

Coding Part (with Unit Tests)

```
void multiKeyQuicksortUtil(char** arr, int low, int high, int pos) {
    if (low >= high) return;
    int pivot = arr[low][pos];
    int i = low - 1, j = high + 1;
    while (i < j) {
        do i++; while (arr[i][pos] < pivot || (arr[i][pos] == pivot && arr[i][pos]));
        do j--; while (arr[j][pos] > pivot || (arr[j][pos] == pivot && arr[j][pos]));
        if (i < j) {
            char* temp = arr[i];
            arr[i] = arr[j];
            arr[j] = temp;
        }
    }
    multiKeyQuicksortUtil(arr, low, j, pos + 1);
    multiKeyQuicksortUtil(arr, j + 1, high, pos + 1);
}

void multiKeyQuicksort(char** arr, int n) {
    multiKeyQuicksortUtil(arr, 0, n - 1, 0);
}

// Unit tests
void testMultiKeyQuicksort() {
    char* arr[] = {"cat", "bat", "rat"};
    multiKeyQuicksort(arr, 3);
    assertBoolEquals(true, strcmp(arr[0], "bat") == 0, "Test 446.1 - First element sorted");
    assertBoolEquals(true, strcmp(arr[2], "rat") == 0, "Test 446.2 - Last element sorted");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle end of strings.
 - Use stable partitioning.
 - Test with different string lengths.
- **Expert Tips:**
 - Explain: "Quicksort by character position."
 - In interviews, clarify: "Ask about string lengths."
 - Suggest optimization: "Use radix sort for strings."
 - Test edge cases: "Empty strings, identical strings."

Problem 447: Find the Maximum Sum of a Subarray with No Adjacent Elements

Issue Description

Find the maximum sum of a subarray with no adjacent elements.

Problem Decomposition & Solution Steps

- **Input:** Array of integers, size.
- **Output:** Maximum sum with no adjacent elements.
- **Approach:** Use dynamic programming.
- **Algorithm:** Max Sum No Adjacent
 - **Explanation:** Include/exclude each element, avoid adjacency.
- **Steps:**
 1. Initialize include/exclude sums.
 2. For each element, update include as exclude + current.
 3. Update exclude as max of previous include/exclude.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

Similar to Problem 419, track include (sum including current element) and exclude (sum excluding current element).

Update include as exclude + current, and exclude as max of previous include/exclude.

Time is O(n), with O(1) space.

Coding Part (with Unit Tests)

```
int maxSumNoAdjacent(int* arr, int n) {
    if (n == 0) return 0;
    int include = arr[0], exclude = 0;
    for (int i = 1; i < n; i++) {
        int temp = include;
        include = exclude + arr[i];
        exclude = temp > exclude ? temp : exclude;
    }
    return include > exclude ? include : exclude;
}

// Unit tests
void testMaxSumNoAdjacent() {
    int arr[] = {5, 5, 10, 100, 10, 5};
    assertEquals(110, maxSumNoAdjacent(arr, 6), "Test 447.1 - Max sum no adjacent");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Handle empty arrays.
 - Optimize with O(1) space.
 - Test with negative numbers.

- **Expert Tips:**
 - Explain: "DP with no adjacent elements."
 - In interviews, clarify: "Ask about negative numbers."
 - Suggest optimization: "Handle all-negative case."
 - Test edge cases: "Empty array, single element."

Problem 448: Implement a Function to Perform Tournament Sort

Issue Description

Sort an array using the tournament sort algorithm.

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array.
- **Approach:** Use tournament tree (min-heap) to sort.
- **Algorithm:** Tournament Sort
 - **Explanation:** Build min-heap, extract min repeatedly.
- **Steps:**
 1. Build a min-heap from array.
 2. Extract min element, rebuild heap.
 3. Repeat until sorted.
- **Complexity:** Time $O(n \log n)$, Space $O(n)$.

Algorithm Explanation

Tournament sort builds a min-heap (tournament tree), extracts the minimum element, and rebuilds the heap.

Each extraction is $O(\log n)$, and n extractions give $O(n \log n)$ time.

Space is $O(n)$ for the heap.

Coding Part (with Unit Tests)

```
void tournamentSort(int* arr, int n) {
    int heap[100], heapSize = n;
    for (int i = 0; i < n; i++) heap[i] = arr[i];
    for (int i = n / 2 - 1; i >= 0; i--) heapify(heap, n, i);
    for (int i = 0; i < n; i++) {
        arr[i] = heap[0];
        heap[0] = heap[--heapSize];
        heapify(heap, heapSize, 0);
    }
}
// Unit tests
void testTournamentSort() {
    int arr[] = {5, 2, 9, 1, 5};
    tournamentSort(arr, 5);
    assertEquals(1, arr[0], "Test 448.1 - First element sorted");
    assertEquals(9, arr[4], "Test 448.2 - Last element sorted");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Build heap correctly.
 - Extract min efficiently.
 - Test with different array sizes.
- **Expert Tips:**
 - Explain: "Min-heap for tournament-style sorting."
 - In interviews, clarify: "Ask about heap type."
 - Suggest optimization: "Use for parallel systems."
 - Test edge cases: "Empty array, single element."

Problem 449: Find the Minimum Number of Operations to Make an Array Increasing

Issue Description

Find the minimum number of operations (increment element) to make an array strictly increasing.

Problem Decomposition & Solution Steps

- **Input:** Array of integers, size.
- **Output:** Minimum number of increments.
- **Approach:** Greedy approach to adjust elements.
- **Algorithm:** Min Operations for Increasing
 - **Explanation:** Increment each element to be greater than previous.
- **Steps:**
 1. Initialize operations count.
 2. For each element, increment to be $>$ previous.
 3. Sum increments needed.
- **Complexity:** Time $O(n)$, Space $O(1)$.

Algorithm Explanation

To make the array strictly increasing, each element must be greater than the previous.

For each index i , if $\text{arr}[i] \leq \text{arr}[i-1]$, increment $\text{arr}[i]$ to $\text{arr}[i-1] + 1$. Sum all increments.

Time is $O(n)$, with $O(1)$ space.

Coding Part (with Unit Tests)

```
int minOperationsIncreasing(int* arr, int n) {  
    int ops = 0;  
    for (int i = 1; i < n; i++) {  
        if (arr[i] <= arr[i - 1]) {  
            int diff = arr[i - 1] - arr[i] + 1;  
            ops += diff;  
            arr[i] += diff;  
        }  
    }  
    return ops;  
}
```

```
// Unit tests
void testMinOperationsIncreasing() {
    int arr[] = {1, 1, 1};
    assertEquals(3, minOperationsIncreasing(arr, 3), "Test 449.1 - Min operations");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Modify array in-place.
 - Handle equal elements.
 - Test with increasing arrays.
- **Expert Tips:**
 - Explain: "Greedy increment for strict increase."
 - In interviews, clarify: "Ask about strict vs. non-strict."
 - Suggest optimization: "Single pass is optimal."
 - Test edge cases: "Single element, already increasing."

Problem 450: Implement a Function to Perform Wiki Sort

Issue Description

Sort an array using the wiki sort algorithm (in-place block merge sort).

Problem Decomposition & Solution Steps

- **Input:** Unsorted array, size.
- **Output:** Sorted array (in-place).
- **Approach:** Use block merge sort with in-place merging.
- **Algorithm:** Wiki Sort
 - **Explanation:** Divide into blocks, merge in-place.
- **Steps:**
 1. Divide array into blocks of size \sqrt{n} .
 2. Sort blocks with insertion sort.
 3. Merge blocks in-place.
- **Complexity:** Time $O(n \log n)$, Space $O(1)$.

Algorithm Explanation

Wiki sort is an in-place variant of block sort (Problem 434).

It divides the array into \sqrt{n} -sized blocks, sorts them with insertion sort, and merges them in-place using a small buffer.

Time is $O(n \log n)$, with $O(1)$ auxiliary space (excluding recursion).

Coding Part (with Unit Tests)

```
void wikiSort(int* arr, int n) {
    int blockSize = (int)sqrt(n);
    for (int i = 0; i < n; i += blockSize) {
        insertionSort(arr, i, i + blockSize - 1 < n ? i + blockSize - 1 : n - 1);
    }
    for (int size = blockSize; size < n; size *= 2) {
        for (int left = 0; left < n; left += 2 * size) {
            int mid = left + size - 1;
            int right = left + 2 * size - 1 < n ? left + 2 * size - 1 : n - 1;
            if (mid < right) merge(arr, left, mid, right);
        }
    }
}

// Unit tests
void testWikiSort() {
    int arr[] = {5, 2, 9, 1, 5};
    wikiSort(arr, 5);
    assertEquals(1, arr[0], "Test 450.1 - First element sorted");
    assertEquals(9, arr[4], "Test 450.2 - Last element sorted");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use \sqrt{n} block size.
 - Merge in-place efficiently.
 - Test with different array sizes.
- **Expert Tips:**
 - Explain: "In-place block merge sort."
 - In interviews, clarify: "Ask about merge strategy."
 - Suggest optimization: "Optimize buffer size."
 - Test edge cases: "Empty array, single block."

Problem 451: Find the Maximum Sum of a Subarray with k Distinct Elements

Issue Description

Find the maximum sum of a subarray with exactly k distinct elements.

Problem Decomposition & Solution Steps

- **Input:** Array of integers, size, k .
- **Output:** Maximum sum of subarray with k distinct elements.
- **Approach:** Use sliding window with hash map.
- **Algorithm:** Max Sum with k Distinct
 - **Explanation:** Track distinct elements in window, compute sum.
- **Steps:**
 1. Use sliding window with hash map to track frequencies.
 2. Shrink window if distinct count > k .
 3. Update max sum when distinct count = k .
- **Complexity:** Time $O(n)$, Space $O(n)$.

Algorithm Explanation

Use a sliding window with a hash map to track element frequencies.

Expand the window by adding elements, shrink when distinct count exceeds k, and update max sum when exactly k distinct elements are present.

Time is O(n), with O(n) space for the hash map.

Coding Part (with Unit Tests)

```
int maxSumKDistinct(int* arr, int n, int k) {
    int map[1001] = {0}, distinct = 0, max_sum = 0, curr_sum = 0;
    int left = 0;
    for (int right = 0; right < n; right++) {
        curr_sum += arr[right];
        if (map[arr[right]] == 0) distinct++;
        map[arr[right]]++;
        while (distinct > k && left <= right) {
            curr_sum -= arr[left];
            map[arr[left]]--;
            if (map[arr[left]] == 0) distinct--;
            left++;
        }
        if (distinct == k) max_sum = curr_sum > max_sum ? curr_sum : max_sum;
    }
    return max_sum;
}

// Unit tests
void testMaxSumKDistinct() {
    int arr[] = {1, 2, 1, 3, 4, 2};
    assertEquals(12, maxSumKDistinct(arr, 6, 3), "Test 451.1 - Max sum k distinct");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use hash map for frequency.
 - Maintain exact k distinct elements.
 - Test with different k values.
- **Expert Tips:**
 - Explain: "Sliding window with k distinct elements."
 - In interviews, clarify: "Ask about exact vs. at most k."
 - Suggest optimization: "Optimize hash map size."
 - Test edge cases: "k > n, no k distinct subarray."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for algorithms problems 431 to 451:\n");
    testMinOperationsPalindrome();
    testStrandSort();
    testMaxSumTwoNoOverlap();
    testBlockSort();
    testLongestArithSeqLength();
    testSampleSort();
    testMinSwapsBinary();
    testSpreadSort();
    testMaxProduct();
    testFlashSort();
    testMinMoves();
    testOddEvenTranspositionSort();
    testLengthOfLIS();
    testLibrarySort();
    testMinOperationsToSort();
    testMultiKeyQuicksort();
    testMaxSumNoAdjacent();
    testTournamentSort();
    testMinOperationsIncreasing();
    testWikiSort();
    testMaxSumKDistinct();
    return 0;
}
```

Real-Time Systems and RTOS

(50 Problems)

Problem 451: Implement a Simple Task Scheduler for an RTOS

Issue Description

Implement a round-robin task scheduler for an RTOS with fixed time slices.

Problem Decomposition & Solution Steps

- **Input:** List of tasks with function pointers.
- **Output:** Execute tasks in round-robin fashion.
- **Approach:** Use a task queue and timer tick to schedule.
- **Algorithm:** Round-Robin Scheduler
 - **Explanation:** Cycle through ready tasks, allocate time slice.
- **Steps:**
 1. Maintain a task control block (TCB) array with task ID, function, and state.
 2. On each timer tick, select next ready task.
 3. Execute task function for fixed time slice.
 4. Move to next task in queue.
- **Complexity:** Time O(1) per tick, Space O(n) for n tasks.

Algorithm Explanation

The scheduler maintains a TCB array with task details (ID, function, state).

A timer tick (simulated) triggers the scheduler to select the next ready task in a circular queue.

Each task runs for a fixed time slice before yielding.

Time is O(1) per tick, with O(n) space for TCBs.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>
#include <string.h>

#define MAX_TASKS 10
#define TIME_SLICE 10

typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
} TCB;

TCB tasks[MAX_TASKS];
int taskCount = 0;
int currentTask = 0;

void assertEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}
```

```

}

void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

void addTask(void (*taskFunc)(void)) {
    if (taskCount < MAX_TASKS) {
        tasks[taskCount].id = taskCount;
        tasks[taskCount].taskFunc = taskFunc;
        tasks[taskCount].ready = true;
        taskCount++;
    }
}

void schedule(void) {
    if (taskCount == 0) return;
    if (tasks[currentTask].ready) {
        tasks[currentTask].taskFunc();
    }
    currentTask = (currentTask + 1) % taskCount;
}

// Sample task
int task1Counter = 0;
void task1(void) { task1Counter++; }

// Unit tests
void testScheduler() {
    task1Counter = 0;
    addTask(task1);
    schedule();
    assertEquals(1, task1Counter, "Test 451.1 - Task executed");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use fixed-size TCB array for simplicity.
 - Ensure fair time slicing.
 - Test with multiple tasks.
- **Expert Tips:**
 - Explain: "Round-robin with fixed time slices."
 - In interviews, clarify: "Ask about preemption."
 - Suggest optimization: "Priority-based scheduling."
 - Test edge cases: "No tasks, single task."

Problem 452: Handle a Timer Interrupt

Issue Description

Handle a timer interrupt to trigger task scheduling.

Problem Decomposition & Solution Steps

- **Input:** Timer interrupt signal (simulated).
- **Output:** Update scheduler state, invoke scheduler.

- **Approach:** Simulate timer interrupt with a function call.
- **Algorithm:** Timer Interrupt Handler
 - **Explanation:** Increment tick count, call scheduler.
- **Steps:**
 1. Define interrupt handler function.
 2. Increment global tick counter.
 3. Call scheduler to switch tasks.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The timer interrupt handler increments a global tick counter and calls the scheduler to select the next task.

In a real RTOS, this would be triggered by hardware; here, it's simulated as a function call.

Time is O(1), with O(1) space.

Coding Part (with Unit Tests)

```
int tickCount = 0;

void timerInterruptHandler(void) {
    tickCount++;
    schedule();
}

// Unit tests
void testTimerInterrupt() {
    tickCount = 0;
    timerInterruptHandler();
    assertEquals(1, tickCount, "Test 452.1 - Tick incremented");
    assertEquals(1, task1Counter, "Test 452.2 - Scheduler called");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Keep handler lightweight.
 - Protect shared resources (tickCount).
 - Test with frequent interrupts.
- **Expert Tips:**
 - Explain: "Triggers scheduling on tick."
 - In interviews, clarify: "Ask about interrupt priority."
 - Suggest optimization: "Disable interrupts during handler."
 - Test edge cases: "No tasks, high-frequency interrupts."

Problem 453: Implement a Semaphore for Task Synchronization

Issue Description

Implement a binary semaphore for task synchronization.

Problem Decomposition & Solution Steps

- **Input:** Semaphore operations (wait, signal).
- **Output:** Control task execution based on semaphore state.
- **Approach:** Use a semaphore structure with count and wait queue.
- **Algorithm:** Binary Semaphore
 - **Explanation:** Wait blocks if count is 0, signal increments or unblocks.
- **Steps:**
 1. Define semaphore with count and wait queue.
 2. Wait: Decrement count or block task.
 3. Signal: Increment count or unblock task.
- **Complexity:** Time O(1) for wait/signal, Space O(n) for wait queue.

Algorithm Explanation

A binary semaphore has a count (0 or 1).

Wait decrements the count if 1, else blocks the task (marks not ready).

Signal increments the count if < 1, else unblocks a waiting task.

Time is O(1) for operations, with O(n) space for the wait queue.

Coding Part (with Unit Tests)

```
typedef struct {
    int count;
    int waitQueue[MAX_TASKS];
    int waitCount;
} Semaphore;

void initSemaphore(Semaphore* sem) {
    sem->count = 1;
    sem->waitCount = 0;
}

void waitSemaphore(Semaphore* sem, int taskId) {
    if (sem->count > 0) {
        sem->count--;
    } else {
        sem->waitQueue[sem->waitCount++] = taskId;
        tasks[taskId].ready = false;
    }
}

void signalSemaphore(Semaphore* sem) {
    if (sem->waitCount > 0) {
        int taskId = sem->waitQueue[--sem->waitCount];
        tasks[taskId].ready = true;
    } else {
        sem->count++;
    }
}
```

```

// Unit tests
void testSemaphore() {
    Semaphore sem;
    initSemaphore(&sem);
    waitSemaphore(&sem, 0);
    assertEquals(0, sem.count, "Test 453.1 - Semaphore acquired");
    waitSemaphore(&sem, 1);
    assertEquals(1, sem.waitCount, "Test 453.2 - Task blocked");
    signalSemaphore(&sem);
    assertEquals(true, tasks[1].ready, "Test 453.3 - Task unblocked");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Initialize semaphore count.
 - Handle wait queue carefully.
 - Test with multiple tasks.
- **Expert Tips:**
 - Explain: "Binary semaphore for synchronization."
 - In interviews, clarify: "Ask about counting semaphores."
 - Suggest optimization: "Use priority-based unblocking."
 - Test edge cases: "No waiting tasks, full queue."

Problem 454: Manage Task Priorities

Issue Description

Implement a priority-based task scheduler.

Problem Decomposition & Solution Steps

- **Input:** Tasks with priorities.
- **Output:** Schedule highest-priority ready task.
- **Approach:** Modify TCB with priority, select highest-priority task.
- **Algorithm:** Priority Scheduler
 - **Explanation:** Choose task with highest priority on each tick.
- **Steps:**
 1. Add priority to TCB.
 2. On tick, find ready task with highest priority.
 3. Execute selected task.
- **Complexity:** Time $O(n)$ per tick, Space $O(n)$.

Algorithm Explanation

Extend the TCB to include a priority field.

On each tick, scan the TCB array for the ready task with the highest priority (lower number = higher priority).

Execute that task.

Time is $O(n)$ per tick to find the highest-priority task, with $O(n)$ space for TCBs.

Coding Part (with Unit Tests)

```
typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    int priority; // Lower number = higher priority
} TCB_Priority;

TCB_Priority tasksP[MAX_TASKS];
int taskPCount = 0;

void addTaskPriority(void (*taskFunc)(void), int priority) {
    if (taskPCount < MAX_TASKS) {
        tasksP[taskPCount].id = taskPCount;
        tasksP[taskPCount].taskFunc = taskFunc;
        tasksP[taskPCount].ready = true;
        tasksP[taskPCount].priority = priority;
        taskPCount++;
    }
}

void schedulePriority(void) {
    int highestPriority = INT_MAX, nextTask = -1;
    for (int i = 0; i < taskPCount; i++) {
        if (tasksP[i].ready && tasksP[i].priority < highestPriority) {
            highestPriority = tasksP[i].priority;
            nextTask = i;
        }
    }
    if (nextTask != -1) {
        tasksP[nextTask].taskFunc();
    }
}

// Sample task
int task2Counter = 0;
void task2(void) { task2Counter++; }

// Unit tests
void testPriorityScheduler() {
    taskPCount = 0;
    task2Counter = 0;
    addTaskPriority(task1, 2);
    addTaskPriority(task2, 1);
    schedulePriority();
    assertEquals(1, task2Counter, "Test 454.1 - Higher priority task executed");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use lower numbers for higher priority.
 - Handle no ready tasks.
 - Test with equal priorities.
- **Expert Tips:**
 - Explain: "Select highest-priority ready task."
 - In interviews, clarify: "Ask about priority range."

- Suggest optimization: "Use priority queue."
- Test edge cases: "No tasks, same priorities."

Problem 455: Implement a Message Queue for Inter-Task Communication

Issue Description

Implement a message queue for tasks to send/receive messages.

Problem Decomposition & Solution Steps

- **Input:** Messages sent/received by tasks.
- **Output:** Reliable message passing.
- **Approach:** Use a circular buffer for the queue.
- **Algorithm:** Message Queue
 - **Explanation:** Enqueue messages, dequeue for receiving tasks.
- **Steps:**
 1. Define queue with fixed-size buffer.
 2. Send: Add message to queue if not full.
 3. Receive: Remove message if not empty.
- **Complexity:** Time O(1) for send/receive, Space O(n).

Algorithm Explanation

The message queue uses a circular buffer with head/tail pointers.

Send adds a message to the tail if not full; receive removes from the head if not empty.

Tasks block (mark not ready) if the queue is empty on receive.

Time is O(1), with O(n) space for the buffer.

Coding Part (with Unit Tests)

```
#define QUEUE_SIZE 10

typedef struct {
    int messages[QUEUE_SIZE];
    int head, tail, count;
} MessageQueue;

void initQueue(MessageQueue* q) {
    q->head = q->tail = q->count = 0;
}

bool sendMessage(MessageQueue* q, int msg) {
    if (q->count >= QUEUE_SIZE) return false;
    q->messages[q->tail] = msg;
    q->tail = (q->tail + 1) % QUEUE_SIZE;
    q->count++;
    return true;
}

bool receiveMessage(MessageQueue* q, int* msg, int taskId) {
```

```

        if (q->count == 0) {
            tasks[taskId].ready = false;
            return false;
        }
        *msg = q->messages[q->head];
        q->head = (q->head + 1) % QUEUE_SIZE;
        q->count--;
        return true;
    }

    // Unit tests
    void testMessageQueue() {
        MessageQueue q;
        initQueue(&q);
        assertBoolEquals(true, sendMessage(&q, 42), "Test 455.1 - Message sent");
        int msg;
        assertBoolEquals(true, receiveMessage(&q, &msg, 0), "Test 455.2 - Message received");
        assertIntEquals(42, msg, "Test 455.3 - Correct message");
    }
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use circular buffer to avoid overflow.
 - Handle full/empty queue.
 - Test with multiple senders/receivers.
- **Expert Tips:**
 - Explain: "Circular buffer for message passing."
 - In interviews, clarify: "Ask about message types."
 - Suggest optimization: "Dynamic queue size."
 - Test edge cases: "Empty queue, full queue."

Problem 456: Handle a Real-Time Clock Interrupt

Issue Description

Handle a real-time clock (RTC) interrupt to update system time.

Problem Decomposition & Solution Steps

- **Input:** RTC interrupt signal (simulated).
- **Output:** Update system time, trigger scheduler.
- **Approach:** Simulate RTC interrupt, increment time.
- **Algorithm:** RTC Interrupt Handler
 - **Explanation:** Update time, call scheduler.
- **Steps:**
 1. Define RTC handler.
 2. Increment system time (milliseconds).
 3. Call scheduler to handle tasks.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

The RTC interrupt handler increments a system time counter (in milliseconds) and calls the scheduler to ensure time-sensitive tasks run.

In a real system, this is triggered by hardware; here, it's simulated.

Time is O(1), with O(1) space.

Coding Part (with Unit Tests)

```
long long systemTime = 0;

void rtcInterruptHandler(void) {
    systemTime += 10; // 10ms per tick
    schedule();
}

// Unit tests
void testRTCInterrupt() {
    systemTime = 0;
    rtcInterruptHandler();
    assertEquals(10, systemTime, "Test 456.1 - Time incremented");
    assertEquals(2, task1Counter, "Test 456.2 - Scheduler called");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Keep handler fast.
 - Update time accurately.
 - Test with different tick intervals.
- **Expert Tips:**
 - Explain: "RTC updates system time."
 - In interviews, clarify: "Ask about tick resolution."
 - Suggest optimization: "Use high-resolution timers."
 - Test edge cases: "No tasks, frequent interrupts."

Problem 457: Switch Between Tasks

Issue Description

Implement task switching with context save/restore.

Problem Decomposition & Solution Steps

- **Input:** Current and next task contexts.
- **Output:** Switch execution to next task.
- **Approach:** Simulate context switch with TCB state.
- **Algorithm:** Context Switch
 - **Explanation:** Save current task state, restore next task.
- **Steps:**

1. Save current task's state (simulated).
 2. Select next task (e.g., via scheduler).
 3. Restore next task's state.
- **Complexity:** Time O(1), Space O(n).

Algorithm Explanation

Context switching saves the current task's state (e.g., registers, PC) and restores the next task's state.

Here, we simulate by updating TCB states and calling the next task's function.

In a real RTOS, this involves stack pointer updates.

Time is O(1), with O(n) space for TCBs.

Coding Part (with Unit Tests)

```

typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    int context; // Simulated context (e.g., register state)
} TCB_Context;

TCB_Context tasksC[MAX_TASKS];
int taskCCount = 0;

void addTaskContext(void (*taskFunc)(void)) {
    if (taskCCount < MAX_TASKS) {
        tasksC[taskCCount].id = taskCCount;
        tasksC[taskCCount].taskFunc = taskFunc;
        tasksC[taskCCount].ready = true;
        tasksC[taskCCount].context = 0;
        taskCCount++;
    }
}

void switchTasks(int current, int next) {
    tasksC[current].context++; // Simulate saving state
    tasksC[next].context++; // Simulate restoring state
    if (tasksC[next].ready) {
        tasksC[next].taskFunc();
    }
}

// Unit tests
void testSwitchTasks() {
    taskCCount = 0;
    task1Counter = 0;
    addTaskContext(task1);
    addTaskContext(task2);
    switchTasks(0, 1);
    assertEquals(1, tasksC[0].context, "Test 457.1 - Current context saved");
    assertEquals(1, tasksC[1].context, "Test 457.2 - Next context restored");
    assertEquals(1, task2Counter, "Test 457.3 - Next task executed");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Save/restore context correctly.
 - Ensure next task is ready.
 - Test with multiple tasks.
- **Expert Tips:**
 - Explain: "Save/restore task state."
 - In interviews, clarify: "Ask about hardware context."
 - Suggest optimization: "Minimize context size."
 - Test edge cases: "No ready tasks, single task."

Problem 458: Handle a Deadline Miss in RTOS

Issue Description

Detect and handle a task missing its deadline.

Problem Decomposition & Solution Steps

- **Input:** Task with deadline, current time.
- **Output:** Flag deadline miss, take action (e.g., log).
- **Approach:** Check deadline against system time.
- **Algorithm:** Deadline Miss Handler
 - **Explanation:** Compare task deadline with current time.
- **Steps:**
 1. Add deadline to TCB.
 2. On tick, check if current task missed deadline.
 3. Log miss and optionally reschedule.
- **Complexity:** Time O(1) per tick, Space O(n).

Algorithm Explanation

Each task's TCB includes a deadline.

On each timer tick, check if the current task's deadline is exceeded (systemTime > deadline).

If missed, log the event and optionally mark the task not ready.

Time is O(1) per check, with O(n) space for TCBs.

Coding Part (with Unit Tests)

```
typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    long long deadline;
} TCB_Deadline;

TCB_Deadline tasksD[MAX_TASKS];
```

```

int taskDCount = 0;
int deadlineMissCount = 0;

void addTaskDeadline(void (*taskFunc)(void), long long deadline) {
    if (taskDCount < MAX_TASKS) {
        tasksD[taskDCount].id = taskDCount;
        tasksD[taskDCount].taskFunc = taskFunc;
        tasksD[taskDCount].ready = true;
        tasksD[taskDCount].deadline = deadline;
        taskDCount++;
    }
}

void checkDeadlineMiss(int taskId) {
    if (systemTime > tasksD[taskId].deadline) {
        deadlineMissCount++;
        tasksD[taskId].ready = false;
    }
}

// Unit tests
void testDeadlineMiss() {
    taskDCount = 0;
    deadlineMissCount = 0;
    systemTime = 20;
    addTaskDeadline(task1, 10);
    checkDeadlineMiss(0);
    assertEquals(1, deadlineMissCount, "Test 458.1 - Deadline miss detected");
    assertEquals(false, tasksD[0].ready, "Test 458.2 - Task marked not ready");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track deadlines accurately.
 - Handle misses gracefully.
 - Test with tight deadlines.
- **Expert Tips:**
 - Explain: "Check deadline against system time."
 - In interviews, clarify: "Ask about miss handling policy."
 - Suggest optimization: "Earliest Deadline First scheduling."
 - Test edge cases: "No misses, all missed."

Problem 459: Implement a Mutex for Resource Protection

Issue Description

Implement a mutex for protecting shared resources.

Problem Decomposition & Solution Steps

- **Input:** Mutex operations (lock, unlock).
- **Output:** Control access to shared resource.
- **Approach:** Use a mutex structure with owner and wait queue.
- **Algorithm:** Mutex
 - **Explanation:** Lock blocks if owned, unlock releases.

- **Steps:**
 1. Define mutex with owner and wait queue.
 2. Lock: Acquire if free, else block task.
 3. Unlock: Release and unblock waiting task.
- **Complexity:** Time O(1) for lock/unlock, Space O(n).

Algorithm Explanation

A mutex has an owner (task ID or -1 if free) and a wait queue.

Lock sets the owner if free, else blocks the task.

Unlock clears the owner and unblocks a waiting task.

Time is O(1), with O(n) space for the wait queue.

Coding Part (with Unit Tests)

```

typedef struct {
    int owner; // -1 if free
    int waitQueue[MAX_TASKS];
    int waitCount;
} Mutex;

void initMutex(Mutex* mutex) {
    mutex->owner = -1;
    mutex->waitCount = 0;
}

void lockMutex(Mutex* mutex, int taskId) {
    if (mutex->owner == -1) {
        mutex->owner = taskId;
    } else {
        mutex->waitQueue[mutex->waitCount++] = taskId;
        tasks[taskId].ready = false;
    }
}

void unlockMutex(Mutex* mutex) {
    if (mutex->waitCount > 0) {
        int taskId = mutex->waitQueue[0];
        for (int i = 0; i < mutex->waitCount - 1; i++) {
            mutex->waitQueue[i] = mutex->waitQueue[i + 1];
        }
        mutex->waitCount--;
        mutex->owner = taskId;
        tasks[taskId].ready = true;
    } else {
        mutex->owner = -1;
    }
}

// Unit tests
void testMutex() {
    Mutex mutex;
    initMutex(&mutex);
    lockMutex(&mutex, 0);
    assertEquals(0, mutex.owner, "Test 459.1 - Mutex acquired");
    lockMutex(&mutex, 1);
    assertEquals(1, mutex.waitCount, "Test 459.2 - Task blocked");
}

```

```
    unlockMutex(&mutex);
    assertEquals(1, mutex.owner, "Test 459.3 - Next task acquired mutex");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Initialize mutex state.
 - Handle wait queue correctly.
 - Test with concurrent access.
- **Expert Tips:**
 - Explain: "Mutex for exclusive resource access."
 - In interviews, clarify: "Ask about priority inversion."
 - Suggest optimization: "Use priority inheritance."
 - Test edge cases: "No waiting tasks, single task."

Problem 460: Manage Task Delays

Issue Description

Implement task delay functionality to pause tasks for a specified time.

Problem Decomposition & Solution Steps

- **Input:** Task ID, delay duration.
- **Output:** Suspend task until delay expires.
- **Approach:** Use system time to track delay expiration.
- **Algorithm:** Task Delay
 - **Explanation:** Mark task not ready, set wake-up time.
- **Steps:**
 1. Add wake-up time to TCB.
 2. On delay, set wake-up time and mark task not ready.
 3. On tick, check if wake-up time reached.
- **Complexity:** Time O(n) per tick, Space O(n).

Algorithm Explanation

Each task's TCB includes a wake-up time.

The delay function sets the wake-up time to systemTime + delay and marks the task not ready.

On each tick, check if systemTime ≥ wake-up time to mark tasks ready.

Time is O(n) per tick to check all tasks, with O(n) space.

Coding Part (with Unit Tests)

```
typedef struct {
```

```

        int id;
        void (*taskFunc)(void);
        bool ready;
        long long wakeUpTime;
    } TCB_Delay;

TCB_Delay tasksDelay[MAX_TASKS];
int taskDelayCount = 0;

void addTaskDelay(void (*taskFunc)(void)) {
    if (taskDelayCount < MAX_TASKS) {
        tasksDelay[taskDelayCount].id = taskDelayCount;
        tasksDelay[taskDelayCount].taskFunc = taskFunc;
        tasksDelay[taskDelayCount].ready = true;
        tasksDelay[taskDelayCount].wakeUpTime = 0;
        taskDelayCount++;
    }
}

void delayTask(int taskId, long long delay) {
    tasksDelay[taskId].wakeUpTime = systemTime + delay;
    tasksDelay[taskId].ready = false;
}

void checkDelays(void) {
    for (int i = 0; i < taskDelayCount; i++) {
        if (!tasksDelay[i].ready && systemTime >= tasksDelay[i].wakeUpTime) {
            tasksDelay[i].ready = true;
        }
    }
}

// Unit tests
void testTaskDelay() {
    taskDelayCount = 0;
    systemTime = 0;
    addTaskDelay(task1);
    delayTask(0, 20);
    assertBoolEquals(false, tasksDelay[0].ready, "Test 460.1 - Task delayed");
    systemTime = 30;
    checkDelays();
    assertBoolEquals(true, tasksDelay[0].ready, "Test 460.2 - Task resumed");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track wake-up times accurately.
 - Check delays on each tick.
 - Test with varying delay periods.
- **Expert Tips:**
 - Explain: "Suspend tasks until delay expires."
 - In interviews, clarify: "Ask about timer resolution."
 - Suggest optimization: "Use timer queue for efficiency."
 - Test edge cases: "Zero delay, long delays."

Problem 461: Handle Task Preemption in an RTOS

Issue Description

Implement preemptive scheduling based on task priorities.

Problem Decomposition & Solution Steps

- **Input:** Tasks with priorities, interrupt trigger.
- **Output:** Switch to higher-priority task on interrupt.
- **Approach:** Check priorities on timer interrupt.
- **Algorithm:** Preemptive Scheduler
 - **Explanation:** Preempt current task if higher-priority task is ready.
- **Steps:**
 1. Use priority-based TCB (Problem 454).
 2. On interrupt, check for higher-priority ready task.
 3. Switch if higher priority found.
- **Complexity:** Time $O(n)$ per tick, Space $O(n)$.

Algorithm Explanation

On each timer interrupt, check for a ready task with higher priority than the current task.

If found, switch to it using context switch (Problem 457).

Time is $O(n)$ to scan tasks, with $O(n)$ space for TCBs.

Coding Part (with Unit Tests)

```
int currentTaskP = -1;

void preemptTask(void) {
    int highestPriority = INT_MAX, nextTask = -1;
    for (int i = 0; i < taskPCount; i++) {
        if (tasksP[i].ready && tasksP[i].priority < highestPriority) {
            highestPriority = tasksP[i].priority;
            nextTask = i;
        }
    }
    if (nextTask != -1 && (currentTaskP == -1 || tasksP[nextTask].priority <
tasksP[currentTaskP].priority)) {
        switchTasks(currentTaskP, nextTask);
        currentTaskP = nextTask;
    }
}

// Unit tests
void testPreemption() {
    taskPCount = 0;
    currentTaskP = -1;
    task2Counter = 0;
    addTaskPriority(task1, 2);
    addTaskPriority(task2, 1);
    preemptTask();
    assertEquals(1, currentTaskP, "Test 461.1 - Higher priority task preempted");
    assertEquals(2, task2Counter, "Test 461.2 - Task executed");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Compare priorities correctly.
 - Use context switch for preemption.
 - Test with priority changes.
- **Expert Tips:**
 - Explain: "Preempt for higher-priority task."
 - In interviews, clarify: "Ask about preemption frequency."
 - Suggest optimization: "Use priority queue."
 - Test edge cases: "No higher-priority tasks, equal priorities."

Problem 462: Manage a Task's Stack Size

Issue Description

Allocate and manage stack size for tasks.

Problem Decomposition & Solution Steps

- **Input:** Task with stack size requirement.
- **Output:** Allocate stack, track usage.
- **Approach:** Simulate stack allocation in TCB.
- **Algorithm:** Stack Management
 - **Explanation:** Allocate fixed stack, monitor overflow.
- **Steps:**
 1. Add stack size and pointer to TCB.
 2. Allocate stack on task creation.
 3. Check for stack overflow (simulated).
- **Complexity:** Time $O(1)$ for allocation, Space $O(n \times S)$ for stacks.

Algorithm Explanation

Each task's TCB includes a stack size and pointer.

On task creation, allocate a fixed-size stack (simulated as an array).

Monitor stack usage (simulated check) to prevent overflow.

Time is $O(1)$ for allocation, with $O(n \times S)$ space for n tasks with stack size S .

Coding Part (with Unit Tests)

```
#define STACK_SIZE 100

typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    int stack[STACK_SIZE];
    int stackTop;
}
```

```

    } TCB_Stack;

    TCB_Stack tasksS[MAX_TASKS];
    int taskSCount = 0;

    void addTaskStack(void (*taskFunc)(void)) {
        if (taskSCount < MAX_TASKS) {
            tasksS[taskSCount].id = taskSCount;
            tasksS[taskSCount].taskFunc = taskFunc;
            tasksS[taskSCount].ready = true;
            tasksS[taskSCount].stackTop = 0;
            taskSCount++;
        }
    }

    bool pushStack(int taskId, int value) {
        if (tasksS[taskId].stackTop >= STACK_SIZE) return false;
        tasksS[taskId].stack[tasksS[taskId].stackTop++] = value;
        return true;
    }

    // Unit tests
    void testStackManagement() {
        taskSCount = 0;
        addTaskStack(task1);
        assertBoolEquals(true, pushStack(0, 42), "Test 462.1 - Stack push");
        assertIntEquals(42, tasksS[0].stack[0], "Test 462.2 - Stack value");
    }
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Allocate fixed stack sizes.
 - Check for overflow.
 - Test with large stack usage.
- **Expert Tips:**
 - Explain: "Allocate and monitor task stacks."
 - In interviews, clarify: "Ask about stack size limits."
 - Suggest optimization: "Dynamic stack allocation."
 - Test edge cases: "Stack overflow, empty stack."

Problem 463: Handle a Semaphore Timeout

Issue Description

Implement semaphore wait with timeout.

Problem Decomposition & Solution Steps

- **Input:** Semaphore, task ID, timeout duration.
- **Output:** Wait with timeout or acquire semaphore.
- **Approach:** Extend semaphore with timeout handling.
- **Algorithm:** Semaphore with Timeout
 - **Explanation:** Wait until semaphore acquired or timeout expires.

- **Steps:**
 1. Extend semaphore wait with timeout.
 2. Set task's wake-up time if blocked.
 3. Unblock on timeout or signal.
- **Complexity:** Time O(1) for wait/signal, Space O(n).

Algorithm Explanation

Extend the semaphore wait (Problem 453) to include a timeout.

If the semaphore is unavailable, set the task's wake-up time to systemTime + timeout and block.

On each tick, check if timeout expired to unblock the task.

Time is O(1) for operations, with O(n) space.

Coding Part (with Unit Tests)

```

typedef struct {
    int count;
    int waitQueue[MAX_TASKS];
    long long waitTimeouts[MAX_TASKS];
    int waitCount;
} SemaphoreTimeout;

SemaphoreTimeout semT;

void initSemaphoreTimeout(SemaphoreTimeout* sem) {
    sem->count = 1;
    sem->waitCount = 0;
}

void waitSemaphoreTimeout(SemaphoreTimeout* sem, int taskId, long long timeout) {
    if (sem->count > 0) {
        sem->count--;
    } else {
        sem->waitQueue[sem->waitCount] = taskId;
        sem->waitTimeouts[sem->waitCount] = systemTime + timeout;
        sem->waitCount++;
        tasksDelay[taskId].ready = false;
    }
}

void checkSemaphoreTimeouts(SemaphoreTimeout* sem) {
    for (int i = 0; i < sem->waitCount; i++) {
        if (systemTime >= sem->waitTimeouts[i]) {
            tasksDelay[sem->waitQueue[i]].ready = true;
            for (int j = i; j < sem->waitCount - 1; j++) {
                sem->waitQueue[j] = sem->waitQueue[j + 1];
                sem->waitTimeouts[j] = sem->waitTimeouts[j + 1];
            }
            sem->waitCount--;
            i--;
        }
    }
}

// Unit tests
void testSemaphoreTimeout() {
    initSemaphoreTimeout(&semT);
}

```

```

taskDelayCount = 0;
addTaskDelay(task1);
waitSemaphoreTimeout(&semT, 0, 20);
assertIntEquals(0, semT.count, "Test 463.1 - Semaphore acquired");
waitSemaphoreTimeout(&semT, 1, 10);
systemTime = 15;
checkSemaphoreTimeouts(&semT);
assertBoolEquals(true, tasksDelay[1].ready, "Test 463.2 - Timeout triggered");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track timeouts in wait queue.
 - Check timeouts on ticks.
 - Test with short/long timeouts.
- **Expert Tips:**
 - Explain: "Wait with timeout for semaphore."
 - In interviews, clarify: "Ask about timeout units."
 - Suggest optimization: "Use timer queue for timeouts."
 - Test edge cases: "Zero timeout, no waiting tasks."

Problem 464: Monitor Task Execution Time

Issue Description

Track the execution time of tasks.

Problem Decomposition & Solution Steps

- **Input:** Task execution start/stop events.
- **Output:** Record execution time for each task.
- **Approach:** Add execution time tracking to TCB.
- **Algorithm:** Execution Time Monitoring
 - **Explanation:** Start/stop timer on task execution.
- **Steps:**
 1. Add execution time field to TCB.
 2. Record start time on task execution.
 3. Update execution time on task switch.
- **Complexity:** Time O(1) per task switch, Space O(n).

Algorithm Explanation

Each task's TCB tracks total execution time and start time.

On task execution, record the start time.

On task switch or completion, add the elapsed time ($systemTime - startTime$) to the total.

Time is O(1) per switch, with O(n) space for TCBs.

Coding Part (with Unit Tests)

```
typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    long long execTime;
    long long startTime;
} TCB_ExecTime;

TCB_ExecTime tasksE[MAX_TASKS];
int taskECount = 0;

void addTaskExecTime(void (*taskFunc)(void)) {
    if (taskECount < MAX_TASKS) {
        tasksE[taskECount].id = taskECount;
        tasksE[taskECount].taskFunc = taskFunc;
        tasksE[taskECount].ready = true;
        tasksE[taskECount].execTime = 0;
        tasksE[taskECount].startTime = 0;
        taskECount++;
    }
}

void startTaskExec(int taskId) {
    tasksE[taskId].startTime = systemTime;
}

void stopTaskExec(int taskId) {
    tasksE[taskId].execTime += systemTime - tasksE[taskId].startTime;
}

// Unit tests
void testExecTime() {
    taskECount = 0;
    systemTime = 0;
    addTaskExecTime(task1);
    startTaskExec(0);
    systemTime = 10;
    stopTaskExec(0);
    assertEquals(10, tasksE[0].execTime, "Test 464.1 - Execution time tracked");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Update times on task switch.
 - Use system time for accuracy.
 - Test with multiple task switches.
- **Expert Tips:**
 - Explain: "Track execution time per task."
 - In interviews, clarify: "Ask about time resolution."
 - Suggest optimization: "Use hardware timers."
 - Test edge cases: "Zero execution, frequent switches."

Problem 465: Handle a Priority Ceiling Protocol

Issue Description

Implement priority ceiling protocol to prevent priority inversion.

Problem Decomposition & Solution Steps

- **Input:** Mutex with priority ceiling, task priorities.
- **Output:** Adjust task priorities to avoid inversion.
- **Approach:** Extend mutex with ceiling priority.
- **Algorithm:** Priority Ceiling Protocol
 - **Explanation:** Raise task priority to ceiling when locking.
- **Steps:**
 1. Assign ceiling priority to mutex (highest accessing task's priority).
 2. On lock, raise task's priority to ceiling.
 3. On unlock, restore original priority.
- **Complexity:** Time O(1) for lock/unlock, Space O(n).

Algorithm Explanation

The priority ceiling protocol assigns each mutex a ceiling priority (highest priority of any task that uses it).

When a task locks the mutex, its priority is raised to the ceiling to prevent inversion.

On unlock, restore the original priority.

Time is O(1), with O(n) space for TCBs.

Coding Part (with Unit Tests)

```
typedef struct {
    int owner;
    int waitQueue[MAX_TASKS];
    int waitCount;
    int ceilingPriority;
} MutexCeiling;

MutexCeiling mutexC;

void initMutexCeiling(MutexCeiling* mutex, int ceiling) {
    mutex->owner = -1;
    mutex->waitCount = 0;
    mutex->ceilingPriority = ceiling;
}

void lockMutexCeiling(MutexCeiling* mutex, int taskId) {
    if (mutex->owner == -1) {
        mutex->owner = taskId;
        tasksP[taskId].priority = mutex->ceilingPriority;
    }
}
```

```

    } else {
        mutex->waitQueue[mutex->waitCount++] = taskId;
        tasksP[taskId].ready = false;
    }
}

void unlockMutexCeiling(MutexCeiling* mutex, int taskId) {
    tasksP[taskId].priority = taskId; // Restore original
    if (mutex->waitCount > 0) {
        int nextTask = mutex->waitQueue[0];
        for (int i = 0; i < mutex->waitCount - 1; i++) {
            mutex->waitQueue[i] = mutex->waitQueue[i + 1];
        }
        mutex->waitCount--;
        mutex->owner = nextTask;
        tasksP[nextTask].ready = true;
        tasksP[nextTask].priority = mutex->ceilingPriority;
    } else {
        mutex->owner = -1;
    }
}

// Unit tests
void testPriorityCeiling() {
    taskPCount = 0;
    addTaskPriority(task1, 2);
    addTaskPriority(task2, 1);
    initMutexCeiling(&mutexC, 0);
    lockMutexCeiling(&mutexC, 1);
    assertEquals(0, tasksP[1].priority, "Test 465.1 - Priority raised");
    unlockMutexCeiling(&mutexC, 1);
    assertEquals(1, tasksP[1].priority, "Test 465.2 - Priority restored");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Set ceiling to highest task priority.
 - Restore priority on unlock.
 - Test with priority inversion scenarios.
- **Expert Tips:**
 - Explain: "Raise priority to avoid inversion."
 - In interviews, clarify: "Ask about ceiling calculation."
 - Suggest optimization: "Use priority inheritance."
 - Test edge cases: "Single task, no waiting tasks."

Problem 466: Manage a Task's Context Switch

Issue Description

Implement full context switch with stack and register save/restore.

Problem Decomposition & Solution Steps

- **Input:** Current and next task contexts.
- **Output:** Switch execution with full state save/restore.

- **Approach:** Extend TCB with stack and registers.
- **Algorithm:** Full Context Switch
 - **Explanation:** Save/restore stack pointer and registers.
- **Steps:**
 1. Extend TCB with stack and register state.
 2. Save current task's stack pointer and registers.
 3. Restore next task's stack pointer and registers.
- **Complexity:** Time O(1), Space O($n \times S$).

Algorithm Explanation

A full context switch saves the current task's stack pointer and registers (simulated as an array) and restores the next task's state.

In a real RTOS, this involves hardware-specific operations.

Here, we simulate with stack and register arrays.

Time is O(1), with O($n \times S$) space for stacks.

Coding Part (with Unit Tests)

```

typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    int stack[STACK_SIZE];
    int stackTop;
    int registers[4]; // Simulated registers
} TCB_FullContext;

TCB_FullContext tasksFC[MAX_TASKS];
int taskFCCount = 0;

void addTaskFullContext(void (*taskFunc)(void)) {
    if (taskFCCount < MAX_TASKS) {
        tasksFC[taskFCCount].id = taskFCCount;
        tasksFC[taskFCCount].taskFunc = taskFunc;
        tasksFC[taskFCCount].ready = true;
        tasksFC[taskFCCount].stackTop = 0;
        for (int i = 0; i < 4; i++) tasksFC[taskFCCount].registers[i] = 0;
        taskFCCount++;
    }
}

void contextSwitch(int current, int next) {
    if (current != -1) {
        tasksFC[current].stack[tasksFC[current].stackTop++] = current; // Simulate stack save
        tasksFC[current].registers[0]++; // Simulate register save
    }
    if (tasksFC[next].ready) {
        tasksFC[next].stackTop = tasksFC[next].stackTop > 0 ? tasksFC[next].stackTop - 1 : 0;
        tasksFC[next].taskFunc();
    }
}

// Unit tests
void testContextSwitch() {
    taskFCCount = 0;
  
```

```

task2Counter = 0;
addTaskFullContext(task1);
addTaskFullContext(task2);
contextSwitch(0, 1);
assertIntEquals(1, tasksFC[0].registers[0], "Test 466.1 - Current registers saved");
assertIntEquals(1, task2Counter, "Test 466.2 - Next task executed");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Save/restore all necessary state.
 - Ensure valid next task.
 - Test with frequent switches.
- **Expert Tips:**
 - Explain: "Full state save/restore."
 - In interviews, clarify: "Ask about hardware specifics."
 - Suggest optimization: "Minimize saved state."
 - Test edge cases: "No tasks, single task."

Problem 467: Handle a Message Queue Overflow

Issue Description

Handle overflow in a message queue.

Problem Decomposition & Solution Steps

- **Input:** Message queue, new message.
- **Output:** Handle overflow gracefully (e.g., reject or overwrite).
- **Approach:** Extend message queue with overflow handling.
- **Algorithm:** Message Queue Overflow
 - **Explanation:** Reject new messages or overwrite oldest.
- **Steps:**
 1. Check if queue is full on send.
 2. If full, reject message (return false).
 3. Log overflow event.
- **Complexity:** Time O(1), Space O(n).

Algorithm Explanation

Extend the message queue (Problem 455) to handle overflow by rejecting new messages when the queue is full ($\text{count} \geq \text{QUEUE_SIZE}$).

Log the overflow event for debugging.

Alternative strategies (e.g., overwrite) can be used based on requirements.

Time is O(1), with O(n) space.

Coding Part (with Unit Tests)

```
int overflowCount = 0;

bool sendMessageWithOverflow(MessageQueue* q, int msg) {
    if (q->count >= QUEUE_SIZE) {
        overflowCount++;
        return false;
    }
    q->messages[q->tail] = msg;
    q->tail = (q->tail + 1) % QUEUE_SIZE;
    q->count++;
    return true;
}

// Unit tests
void testMessageQueueOverflow() {
    MessageQueue q;
    initQueue(&q);
    for (int i = 0; i < QUEUE_SIZE; i++) sendMessageWithOverflow(&q, i);
    overflowCount = 0;
    assertBoolEquals(false, sendMessageWithOverflow(&q, 999), "Test 467.1 - Message rejected");
    assertIntEquals(1, overflowCount, "Test 467.2 - Overflow logged");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Reject messages on overflow.
 - Log overflow events.
 - Test with full queue.
- **Expert Tips:**
 - Explain: "Handle queue overflow gracefully."
 - In interviews, clarify: "Ask about overflow policy."
 - Suggest optimization: "Dynamic queue resizing."
 - Test edge cases: "Empty queue, repeated overflows."

Problem 468: Manage a Real-Time Timer Interrupt

Issue Description

Handle a real-time timer interrupt for precise timing.

Problem Decomposition & Solution Steps

- **Input:** Timer interrupt signal (simulated).
- **Output:** Update timers, trigger scheduler.
- **Approach:** Simulate high-precision timer interrupt.
- **Algorithm:** Real-Time Timer Interrupt
 - **Explanation:** Update timer, check delays, schedule.
- **Steps:**

1. Define timer interrupt handler.
 2. Increment high-precision timer.
 3. Check task delays and semaphores.
 4. Call scheduler.
- **Complexity:** Time $O(n)$ per tick, Space $O(n)$.

Algorithm Explanation

The real-time timer interrupt increments a high-precision timer (e.g., 1ms resolution), checks task delays (Problem 460) and semaphore timeouts (Problem 463), and calls the scheduler.

Time is $O(n)$ to check all tasks/semaphores, with $O(n)$ space for TCBs.

Coding Part (with Unit Tests)

```
long long preciseTime = 0;

void realTimeTimerInterrupt(void) {
    preciseTime += 1; // 1ms tick
    checkDelays();
    checkSemaphoreTimeouts(&semT);
    schedule();
}

// Unit tests
void testRealTimeTimerInterrupt() {
    preciseTime = 0;
    taskDelayCount = 0;
    addTaskDelay(task1);
    delayTask(0, 5);
    realTimeTimerInterrupt();
    assertEquals(1, preciseTime, "Test 468.1 - Timer incremented");
    preciseTime = 6;
    realTimeTimerInterrupt();
    assertEquals(true, tasksDelay[0].ready, "Test 468.2 - Delay expired");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use high-precision timer.
 - Check delays/timeouts on each tick.
 - Test with precise timing requirements.
- **Expert Tips:**
 - Explain: "High-precision timer for RTOS."
 - In interviews, clarify: "Ask about timer resolution."
 - Suggest optimization: "Use hardware timer interrupts."
 - Test edge cases: "No delays, frequent ticks."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for RTOS problems 451 to 468:\n");
    testScheduler();
    testTimerInterrupt();
    testSemaphore();
```

```

    testPriorityScheduler();
    testMessageQueue();
    testRTCInterrupt();
    testSwitchTasks();
    testDeadlineMiss();
    testMutex();
    testTaskDelay();
    testPreemption();
    testStackManagement();
    testSemaphoreTimeout();
    testExecTime();
    testPriorityCeiling();
    testContextSwitch();
    testMessageQueueOverflow();
    testRealTimeTimerInterrupt();
    return 0;
}

```

Problem 469: Handle Task Suspension and Resumption

Issue Description

Implement task suspension and resumption in an RTOS.

Problem Decomposition & Solution Steps

- **Input:** Task ID to suspend or resume.
- **Output:** Suspend (pause) or resume (make ready) a task.
- **Approach:** Extend TCB with a suspended state.
- **Algorithm:** Task Suspension and Resumption
 - **Explanation:** Mark task as suspended or ready.
- **Steps:**
 1. Add suspended field to TCB.
 2. Suspend: Mark task as suspended and not ready.
 3. Resume: Mark task as ready if not suspended.
- **Complexity:** Time O(1), Space O(n) for n tasks.

Algorithm Explanation

The TCB is extended with a suspended flag.

Suspending a task sets suspended = true and ready = false, preventing scheduling.

Resuming sets suspended = false and ready = true.

Time is O(1) for both operations, with O(n) space for TCBs.

Coding Part (with Unit Tests)

```

#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>
#include <string.h>
#include <limits.h>

```

```

#define MAX_TASKS 10
#define TIME_SLICE 10
#define STACK_SIZE 100

long long systemTime = 0;
typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
} TCB;

TCB tasks[MAX_TASKS];
int taskCount = 0;
int currentTask = 0;
int task1Counter = 0;
int task2Counter = 0;

void assertIntEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

void addTask(void (*taskFunc)(void)) {
    if (taskCount < MAX_TASKS) {
        tasks[taskCount].id = taskCount;
        tasks[taskCount].taskFunc = taskFunc;
        tasks[taskCount].ready = true;
        taskCount++;
    }
}

void task1(void) { task1Counter++; }
void task2(void) { task2Counter++; }

typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    bool suspended;
} TCB_Suspend;

TCB_Suspend tasksS[MAX_TASKS];
int taskSCount = 0;

void addTaskSuspend(void (*taskFunc)(void)) {
    if (taskSCount < MAX_TASKS) {
        tasksS[taskSCount].id = taskSCount;
        tasksS[taskSCount].taskFunc = taskFunc;
        tasksS[taskSCount].ready = true;
        tasksS[taskSCount].suspended = false;
        taskSCount++;
    }
}

void suspendTask(int taskId) {
    tasksS[taskId].suspended = true;
    tasksS[taskId].ready = false;
}

void resumeTask(int taskId) {
    tasksS[taskId].suspended = false;
    tasksS[taskId].ready = true;
}

```

```

// Unit tests
void testSuspendResume() {
    taskSCount = 0;
    addTaskSuspend(task1);
    suspendTask(0);
    assertBoolEquals(false, tasksS[0].ready, "Test 469.1 - Task suspended");
    assertBoolEquals(true, tasksS[0].suspended, "Test 469.2 - Suspend flag set");
    resumeTask(0);
    assertBoolEquals(true, tasksS[0].ready, "Test 469.3 - Task resumed");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Ensure suspended tasks are not scheduled.
 - Validate task ID before operations.
 - Test with multiple suspensions.
- **Expert Tips:**
 - Explain: "Toggle task state for suspension."
 - In interviews, clarify: "Ask about suspension duration."
 - Suggest optimization: "Track suspended tasks in a list."
 - Test edge cases: "Suspend already suspended, resume running."

Problem 470: Calculate Task Scheduling Latency

Issue Description

Measure the time from task readiness to execution (scheduling latency).

Problem Decomposition & Solution Steps

- **Input:** Task readiness and execution events.
- **Output:** Scheduling latency for each task.
- **Approach:** Track ready time in TCB, compute latency on execution.
- **Algorithm:** Scheduling Latency Calculation
 - **Explanation:** Record ready time, compute difference on execution.
- **Steps:**
 1. Add readyTime and latency to TCB.
 2. Set readyTime when task becomes ready.
 3. On execution, compute latency as systemTime - readyTime.
- **Complexity:** Time O(1) per task execution, Space O(n).

Algorithm Explanation

Extend TCB with readyTime and latency fields.

When a task becomes ready (e.g., via resume or semaphore signal), set readyTime to systemTime.

On execution, compute latency as the difference.

Time is O(1) per execution, with O(n) space for TCBs.

Coding Part (with Unit Tests)

```
typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    long long readyTime;
    long long latency;
} TCB_Latency;

TCB_Latency tasksL[MAX_TASKS];
int taskLCount = 0;

void addTaskLatency(void (*taskFunc)(void)) {
    if (taskLCount < MAX_TASKS) {
        tasksL[taskLCount].id = taskLCount;
        tasksL[taskLCount].taskFunc = taskFunc;
        tasksL[taskLCount].ready = true;
        tasksL[taskLCount].readyTime = systemTime;
        tasksL[taskLCount].latency = 0;
        taskLCount++;
    }
}

void executeTaskLatency(int taskId) {
    if (tasksL[taskId].ready) {
        tasksL[taskId].latency = systemTime - tasksL[taskId].readyTime;
        tasksL[taskId].taskFunc();
    }
}

// Unit tests
void testSchedulingLatency() {
    taskLCount = 0;
    systemTime = 10;
    addTaskLatency(task1);
    systemTime = 15;
    executeTaskLatency(0);
    assertEquals(5, tasksL[0].latency, "Test 470.1 - Latency calculated");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Update readyTime on state changes.
 - Compute latency only on execution.
 - Test with varying delays.
- **Expert Tips:**
 - Explain: "Measure time from ready to execution."
 - In interviews, clarify: "Ask about latency definition."
 - Suggest optimization: "Use high-resolution timers."
 - Test edge cases: "Immediate execution, long delays."

Problem 471: Implement a Function to Handle Task Deadlines

Issue Description

Manage task deadlines to ensure timely execution.

Problem Decomposition & Solution Steps

- **Input:** Task with deadline.
- **Output:** Schedule tasks to meet deadlines.
- **Approach:** Use Earliest Deadline First (EDF) scheduling.
- **Algorithm:** EDF Scheduler
 - **Explanation:** Select task with earliest deadline.
- **Steps:**
 1. Add deadline to TCB.
 2. On each tick, select ready task with earliest deadline.
 3. Execute selected task.
- **Complexity:** Time $O(n)$ per tick, Space $O(n)$.

Algorithm Explanation

Extend TCB with a deadline field.

On each timer tick, scan ready tasks and select the one with the earliest deadline (smallest deadline value).

Execute that task.

Time is $O(n)$ to find the earliest deadline, with $O(n)$ space for TCBs.

Coding Part (with Unit Tests)

```
typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    long long deadline;
} TCB_Deadline;

TCB_Deadline tasksD[MAX_TASKS];
int taskDCount = 0;
int currentTaskD = -1;

void addTaskDeadline(void (*taskFunc)(void), long long deadline) {
    if (taskDCount < MAX_TASKS) {
        tasksD[taskDCount].id = taskDCount;
        tasksD[taskDCount].taskFunc = taskFunc;
        tasksD[taskDCount].ready = true;
        tasksD[taskDCount].deadline = deadline;
        taskDCount++;
    }
}

void scheduleEDF(void) {
```

```

long long earliestDeadline = LLONG_MAX;
int nextTask = -1;
for (int i = 0; i < taskDCount; i++) {
    if (tasksD[i].ready && tasksD[i].deadline < earliestDeadline) {
        earliestDeadline = tasksD[i].deadline;
        nextTask = i;
    }
}
if (nextTask != -1) {
    currentTaskD = nextTask;
    tasksD[nextTask].taskFunc();
}
}

// Unit tests
void testEDF() {
    taskDCount = 0;
    task1Counter = 0;
    task2Counter = 0;
    addTaskDeadline(task1, 20);
    addTaskDeadline(task2, 10);
    scheduleEDF();
    assertEquals(1, task2Counter, "Test 471.1 - Earliest deadline task executed");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Select earliest deadline correctly.
 - Handle no ready tasks.
 - Test with tight deadlines.
- **Expert Tips:**
 - Explain: "EDF prioritizes earliest deadline."
 - In interviews, clarify: "Ask about deadline updates."
 - Suggest optimization: "Use a priority queue."
 - Test edge cases: "Equal deadlines, no tasks."

Problem 472: Manage a Task's Priority Inversion

Issue Description

Handle priority inversion using priority inheritance.

Problem Decomposition & Solution Steps

- **Input:** Mutex, task priorities.
- **Output:** Adjust priorities to avoid inversion.
- **Approach:** Extend mutex with priority inheritance.
- **Algorithm:** Priority Inheritance
 - **Explanation:** Raise low-priority task's priority when blocking higher-priority task.
- **Steps:**
 1. Add originalPriority to TCB.
 2. On mutex lock, if blocked, raise owner's priority.

- 3. On unlock, restore original priority.
- **Complexity:** Time O(1) for lock/unlock, Space O(n).

Algorithm Explanation

When a high-priority task is blocked by a low-priority task holding a mutex, raise the owner's priority to the blocked task's priority.

On unlock, restore the original priority.

This prevents inversion.

Time is O(1), with O(n) space for TCBs.

Coding Part (with Unit Tests)

```

typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    int priority;
    int originalPriority;
} TCB_Priority;

TCB_Priority tasksP[MAX_TASKS];
int taskPCount = 0;

typedef struct {
    int owner;
    int waitQueue[MAX_TASKS];
    int waitCount;
} Mutex;

Mutex mutexP;

void addTaskPriority(void (*taskFunc)(void), int priority) {
    if (taskPCount < MAX_TASKS) {
        tasksP[taskPCount].id = taskPCount;
        tasksP[taskPCount].taskFunc = taskFunc;
        tasksP[taskPCount].ready = true;
        tasksP[taskPCount].priority = priority;
        tasksP[taskPCount].originalPriority = priority;
        taskPCount++;
    }
}

void initMutex(Mutex* mutex) {
    mutex->owner = -1;
    mutex->waitCount = 0;
}

void lockMutexPriority(Mutex* mutex, int taskId) {
    if (mutex->owner == -1) {
        mutex->owner = taskId;
    } else {
        mutex->waitQueue[mutex->waitCount++] = taskId;
        if (tasksP[mutex->owner].priority > tasksP[taskId].priority) {
            tasksP[mutex->owner].priority = tasksP[taskId].priority;
        }
        tasksP[taskId].ready = false;
    }
}

```

```

}

void unlockMutexPriority(Mutex* mutex, int taskId) {
    tasksP[taskId].priority = tasksP[taskId].originalPriority;
    if (mutex->waitCount > 0) {
        int nextTask = mutex->waitQueue[0];
        for (int i = 0; i < mutex->waitCount - 1; i++) {
            mutex->waitQueue[i] = mutex->waitQueue[i + 1];
        }
        mutex->waitCount--;
        mutex->owner = nextTask;
        tasksP[nextTask].ready = true;
    } else {
        mutex->owner = -1;
    }
}

// Unit tests
void testPriorityInversion() {
    taskPCount = 0;
    addTaskPriority(task1, 2);
    addTaskPriority(task2, 1);
    initMutex(&mutexP);
    lockMutexPriority(&mutexP, 0);
    lockMutexPriority(&mutexP, 1);
    assertEquals(1, tasksP[0].priority, "Test 472.1 - Priority inherited");
    unlockMutexPriority(&mutexP, 0);
    assertEquals(2, tasksP[0].priority, "Test 472.2 - Priority restored");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Store original priority.
 - Update priority on blocking.
 - Test with multiple tasks.
- **Expert Tips:**
 - Explain: "Raise owner's priority to avoid inversion."
 - In interviews, clarify: "Ask about ceiling vs. inheritance."
 - Suggest optimization: "Limit priority changes."
 - Test edge cases: "No inversion, multiple blockers."

Problem 473: Implement a Function to Monitor CPU Idle Time

Issue Description

Track CPU idle time when no tasks are ready.

Problem Decomposition & Solution Steps

- **Input:** Scheduler ticks with no ready tasks.
- **Output:** Total CPU idle time.

- **Approach:** Increment idle time when no tasks run.
- **Algorithm:** CPU Idle Time Monitoring
 - **Explanation:** Count ticks when scheduler finds no ready tasks.
- **Steps:**
 1. Add global idleTime counter.
 2. On each tick, if no tasks ready, increment idleTime.
 3. Return idleTime when queried.
- **Complexity:** Time O(n) per tick, Space O(1).

Algorithm Explanation

In the scheduler, check if any tasks are ready.

If none, increment a global idleTime counter by the tick duration (e.g., 10ms).

Time is O(n) to check tasks, with O(1) space for the counter.

Coding Part (with Unit Tests)

```
long long idleTime = 0;

void scheduleWithIdle(void) {
    bool hasReady = false;
    for (int i = 0; i < taskCount; i++) {
        if (tasks[i].ready) {
            hasReady = true;
            currentTask = i;
            tasks[i].taskFunc();
            break;
        }
    }
    if (!hasReady) {
        idleTime += TIME_SLICE;
    }
}

// Unit tests
void testIdleTime() {
    taskCount = 0;
    idleTime = 0;
    scheduleWithIdle();
    assertEquals(TIME_SLICE, idleTime, "Test 473.1 - Idle time incremented");
    addTask(task1);
    idleTime = 0;
    scheduleWithIdle();
    assertEquals(0, idleTime, "Test 473.2 - No idle time with ready task");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Increment idle time only when no tasks run.
 - Use consistent tick duration.
 - Test with idle and busy periods.
- **Expert Tips:**
 - Explain: "Track idle time when no tasks ready."

- In interviews, clarify: "Ask about idle task."
- Suggest optimization: "Run low-priority idle task."
- Test edge cases: "Always idle, never idle."

Problem 474: Handle a Task's Resource Sharing

Issue Description

Manage resource sharing among tasks using semaphores.

Problem Decomposition & Solution Steps

- **Input:** Shared resource, multiple tasks.
- **Output:** Safe access to resource.
- **Approach:** Use semaphore to protect resource.
- **Algorithm:** Resource Sharing with Semaphore
 - **Explanation:** Use binary semaphore for exclusive access.
- **Steps:**
 1. Initialize semaphore for resource.
 2. Tasks acquire semaphore before accessing resource.
 3. Release semaphore after use.
- **Complexity:** Time O(1) for acquire/release, Space O(n).

Algorithm Explanation

A binary semaphore (Problem 453) ensures exclusive access to a shared resource.

Tasks call `waitSemaphore` before accessing the resource and `signalSemaphore` after.

If the semaphore is taken, the task blocks.

Time is O(1) for operations, with O(n) space for the wait queue.

Coding Part (with Unit Tests)

```

typedef struct {
    int count;
    int waitQueue[MAX_TASKS];
    int waitCount;
} Semaphore;

Semaphore resourceSem;

void initSemaphore(Semaphore* sem) {
    sem->count = 1;
    sem->waitCount = 0;
}

void accessResource(int taskId) {
    waitSemaphore(&resourceSem, taskId);
    // Simulate resource access
    tasks[taskId].taskFunc();
    signalSemaphore(&resourceSem);
}

```

```

// Unit tests
void testResourceSharing() {
    initSemaphore(&resourceSem);
    taskCount = 0;
    addTask(task1);
    addTask(task2);
    accessResource(0);
    assertEquals(0, resourceSem.count, "Test 474.1 - Resource locked");
    accessResource(1);
    assertEquals(1, resourceSem.waitCount, "Test 474.2 - Task blocked");
    signalSemaphore(&resourceSem);
    assertEquals(true, tasks[1].ready, "Test 474.3 - Task unblocked");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use semaphore for exclusive access.
 - Ensure proper release.
 - Test with concurrent access.
- **Expert Tips:**
 - Explain: "Semaphore ensures safe resource sharing."
 - In interviews, clarify: "Ask about resource types."
 - Suggest optimization: "Use mutex for complex resources."
 - Test edge cases: "Single task, multiple access attempts."

Problem 475: Implement a Function to Manage Task Dependencies

Issue Description

Handle task dependencies to ensure correct execution order.

Problem Decomposition & Solution Steps

- **Input:** Tasks with dependency lists.
- **Output:** Schedule tasks respecting dependencies.
- **Approach:** Use dependency array in TCB, check before execution.
- **Algorithm:** Dependency-Based Scheduling
 - **Explanation:** Run task only if dependencies are complete.
- **Steps:**
 1. Add dependency list to TCB.
 2. Check if all dependencies are complete before scheduling.
 3. Mark task complete after execution.
- **Complexity:** Time $O(n^2)$ per tick, Space $O(n^2)$.

Algorithm Explanation

Each TCB includes a dependency list (task IDs that must complete).

Before scheduling a task, check if all its dependencies are marked complete.

If so, execute; otherwise, skip.

Time is $O(n^2)$ to check dependencies for n tasks, with $O(n^2)$ space for dependency lists.

Coding Part (with Unit Tests)

```
typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    bool completed;
    int dependencies[MAX_TASKS];
    int depCount;
} TCB_Dependency;

TCB_Dependency tasksDep[MAX_TASKS];
int taskDepCount = 0;

void addTaskDependency(void (*taskFunc)(void), int* deps, int depCount) {
    if (taskDepCount < MAX_TASKS) {
        tasksDep[taskDepCount].id = taskDepCount;
        tasksDep[taskDepCount].taskFunc = taskFunc;
        tasksDep[taskDepCount].ready = true;
        tasksDep[taskDepCount].completed = false;
        tasksDep[taskDepCount].depCount = depCount;
        for (int i = 0; i < depCount; i++) {
            tasksDep[taskDepCount].dependencies[i] = deps[i];
        }
        taskDepCount++;
    }
}

bool canRunTask(int taskId) {
    for (int i = 0; i < tasksDep[taskId].depCount; i++) {
        if (!tasksDep[tasksDep[taskId].dependencies[i]].completed) {
            return false;
        }
    }
    return tasksDep[taskId].ready;
}

void scheduleDependency(void) {
    for (int i = 0; i < taskDepCount; i++) {
        if (canRunTask(i)) {
            tasksDep[i].taskFunc();
            tasksDep[i].completed = true;
        }
    }
}

// Unit tests
void testTaskDependency() {
    taskDepCount = 0;
    task1Counter = 0;
    task2Counter = 0;
    int deps[] = {0};
    addTaskDependency(task1, NULL, 0);
    addTaskDependency(task2, deps, 1);
    scheduleDependency();
}
```

```

        assertEquals(1, task1Counter, "Test 475.1 - Independent task ran");
        tasksDep[0].completed = true;
        scheduleDependency();
        assertEquals(1, task2Counter, "Test 475.2 - Dependent task ran");
    }
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate dependency lists.
 - Mark tasks complete after execution.
 - Test with complex dependencies.
- **Expert Tips:**
 - Explain: "Schedule tasks after dependencies complete."
 - In interviews, clarify: "Ask about cyclic dependencies."
 - Suggest optimization: "Use topological sort."
 - Test edge cases: "No dependencies, cyclic dependencies."

Problem 476: Handle a Real-Time Interrupt Nesting

Issue Description

Manage nested interrupts in a real-time system.

Problem Decomposition & Solution Steps

- **Input:** Multiple interrupt signals (simulated).
- **Output:** Handle interrupts in priority order, allow nesting.
- **Approach:** Simulate nested interrupts with a stack.
- **Algorithm:** Nested Interrupt Handler
 - **Explanation:** Push/pop interrupt context, handle higher-priority interrupts.
- **Steps:**
 1. Define interrupt stack for context.
 2. On interrupt, push current context, handle interrupt.
 3. Pop context after handling.
- **Complexity:** Time $O(1)$ per interrupt, Space $O(k)$ for k nested interrupts.

Algorithm Explanation

Simulate interrupt nesting with a stack to save/restore contexts (e.g., registers).

When an interrupt occurs, push the current context, handle the interrupt (e.g., call scheduler), and pop the context.

Higher-priority interrupts can preempt lower ones.

Time is $O(1)$ per interrupt, with $O(k)$ space for the stack.

Coding Part (with Unit Tests)

```
#define MAX_INTERRUPTS 10

typedef struct {
    int priority;
    void (*handler)(void);
} Interrupt;

Interrupt interruptStack[MAX_INTERRUPTS];
int interruptTop = -1;

void pushInterrupt(int priority, void (*handler)(void)) {
    if (interruptTop < MAX_INTERRUPTS - 1) {
        interruptStack[++interruptTop].priority = priority;
        interruptStack[interruptTop].handler = handler;
        handler();
    }
}

void popInterrupt(void) {
    if (interruptTop >= 0) interruptTop--;
}

void interruptHandler1(void) { task1Counter++; }

// Unit tests
void testInterruptNesting() {
    interruptTop = -1;
    task1Counter = 0;
    pushInterrupt(1, interruptHandler1);
    assertEquals(1, interruptTop + 1, "Test 476.1 - Interrupt pushed");
    assertEquals(1, task1Counter, "Test 476.2 - Handler executed");
    popInterrupt();
    assertEquals(-1, interruptTop, "Test 476.3 - Interrupt popped");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use priority to allow nesting.
 - Save/restore context correctly.
 - Test with multiple interrupts.
- **Expert Tips:**
 - Explain: "Stack-based interrupt nesting."
 - In interviews, clarify: "Ask about interrupt priorities."
 - Suggest optimization: "Disable lower-priority interrupts."
 - Test edge cases: "No interrupts, max nesting."

Problem 477: Implement a Function to Monitor Task Response Time

Issue Description

Measure task response time (from event to completion).

Problem Decomposition & Solution Steps

- **Input:** Task event and completion times.
- **Output:** Response time for each task.
- **Approach:** Track event and completion times in TCB.
- **Algorithm:** Response Time Monitoring
 - **Explanation:** Record event time, compute response on completion.
- **Steps:**
 1. Add eventTime and responseTime to TCB.
 2. Set eventTime on event (e.g., semaphore signal).
 3. On completion, compute response time.
- **Complexity:** Time $O(1)$ per event/completion, Space $O(n)$.

Algorithm Explanation

Extend TCB with eventTime and responseTime.

On an event (e.g., task becomes ready), set eventTime to systemTime.

On task completion (simulated by task execution), compute responseTime as systemTime - eventTime.

Time is $O(1)$, with $O(n)$ space.

Coding Part (with Unit Tests)

```
typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    long long eventTime;
    long long responseTime;
} TCB_Response;

TCB_Response tasksR[MAX_TASKS];
int taskRCount = 0;

void addTaskResponse(void (*taskFunc)(void)) {
    if (taskRCount < MAX_TASKS) {
        tasksR[taskRCount].id = taskRCount;
        tasksR[taskRCount].taskFunc = taskFunc;
        tasksR[taskRCount].ready = true;
        tasksR[taskRCount].eventTime = systemTime;
        tasksR[taskRCount].responseTime = 0;
        taskRCount++;
    }
}

void triggerEvent(int taskId) {
    tasksR[taskId].eventTime = systemTime;
    tasksR[taskId].ready = true;
}
```

```

    void completeTaskResponse(int taskId) {
        if (tasksR[taskId].ready) {
            tasksR[taskId].responseTime = systemTime - tasksR[taskId].eventTime;
            tasksR[taskId].taskFunc();
        }
    }

// Unit tests
void testResponseTime() {
    taskRCount = 0;
    systemTime = 10;
    addTaskResponse(task1);
    triggerEvent(0);
    systemTime = 20;
    completeTaskResponse(0);
    assertEquals(10, tasksR[0].responseTime, "Test 477.1 - Response time calculated");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Update eventTime on relevant events.
 - Compute response on completion.
 - Test with varying response times.
- **Expert Tips:**
 - Explain: "Measure event-to-completion time."
 - In interviews, clarify: "Ask about event definition."
 - Suggest optimization: "Use high-precision timers."
 - Test edge cases: "Immediate completion, long delays."

Problem 478: Manage a Task's Execution Budget

Issue Description

Enforce a task's CPU time budget per period.

Problem Decomposition & Solution Steps

- **Input:** Task with execution budget and period.
- **Output:** Limit task execution to budget.
- **Approach:** Track budget and period in TCB.
- **Algorithm:** Execution Budget Management
 - **Explanation:** Suspend task when budget exhausted until next period.
- **Steps:**
 1. Add budget, usedTime, and nextPeriod to TCB.
 2. On execution, deduct from budget.
 3. Suspend if budget exhausted; reset at next period.
- **Complexity:** Time O(1) per execution, Space O(n).

Algorithm Explanation

Each TCB tracks a task's budget (max CPU time per period), usedTime, and nextPeriod.

On execution, deduct time from budget.

If exhausted, suspend the task until systemTime reaches nextPeriod, then reset budget.

Time is O(1), with O(n) space.

Coding Part (with Unit Tests)

```
typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    long long budget;
    long long usedTime;
    long long nextPeriod;
    long long period;
} TCB_Budget;

TCB_Budget tasksB[MAX_TASKS];
int taskBCount = 0;

void addTaskBudget(void (*taskFunc)(void), long long budget, long long period) {
    if (taskBCount < MAX_TASKS) {
        tasksB[taskBCount].id = taskBCount;
        tasksB[taskBCount].taskFunc = taskFunc;
        tasksB[taskBCount].ready = true;
        tasksB[taskBCount].budget = budget;
        tasksB[taskBCount].usedTime = 0;
        tasksB[taskBCount].nextPeriod = systemTime + period;
        tasksB[taskBCount].period = period;
        taskBCount++;
    }
}

void executeTaskBudget(int taskId) {
    if (tasksB[taskId].ready && systemTime >= tasksB[taskId].nextPeriod) {
        tasksB[taskId].budget = tasksB[taskId].period; // Reset budget
        tasksB[taskId].nextPeriod += tasksB[taskId].period;
    }
    if (tasksB[taskId].ready && tasksB[taskId].budget >= TIME_SLICE) {
        tasksB[taskId].taskFunc();
        tasksB[taskId].usedTime += TIME_SLICE;
        tasksB[taskId].budget -= TIME_SLICE;
        if (tasksB[taskId].budget <= 0) tasksB[taskId].ready = false;
    }
}

// Unit tests
void testExecutionBudget() {
    taskBCount = 0;
    systemTime = 0;
    addTaskBudget(task1, 20, 50);
    executeTaskBudget(0);
    assertEquals(10, tasksB[0].usedTime, "Test 478.1 - Budget used");
    executeTaskBudget(0);
    assertEquals(false, tasksB[0].ready, "Test 478.2 - Task suspended after budget");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Reset budget at period start.
 - Suspend when budget exhausted.
 - Test with different budgets/periods.
- **Expert Tips:**
 - Explain: "Enforce CPU time limits per period."
 - In interviews, clarify: "Ask about budget units."
 - Suggest optimization: "Use rate monotonic scheduling."
 - Test edge cases: "Zero budget, long periods."

Problem 479: Handle a Task's Preemption Threshold

Issue Description

Implement preemption threshold to limit task preemption.

Problem Decomposition & Solution Steps

- **Input:** Tasks with priorities and preemption thresholds.
- **Output:** Allow preemption only above threshold.
- **Approach:** Extend TCB with threshold, check in scheduler.
- **Algorithm:** Preemption Threshold Scheduler
 - **Explanation:** Preempt only if new task's priority exceeds threshold.
- **Steps:**
 1. Add threshold to TCB.
 2. In scheduler, check if new task's priority > current task's threshold.
 3. Preempt if condition met.
- **Complexity:** Time $O(n)$ per tick, Space $O(n)$.

Algorithm Explanation

Each TCB includes a threshold (priority level above which preemption is allowed).

The scheduler checks if a ready task's priority is higher than the current task's threshold.

If so, preempt using context switch (Problem 466).

Time is $O(n)$ to find the next task, with $O(n)$ space.

Coding Part (with Unit Tests)

```
typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    int priority;
    int threshold;
```

```

    } TCB_Threshold;

    TCB_Threshold tasksT[MAX_TASKS];
    int taskTCount = 0;
    int currentTaskT = -1;

    void addTaskThreshold(void (*taskFunc)(void), int priority, int threshold) {
        if (taskTCount < MAX_TASKS) {
            tasksT[taskTCount].id = taskTCount;
            tasksT[taskTCount].taskFunc = taskFunc;
            tasksT[taskTCount].ready = true;
            tasksT[taskTCount].priority = priority;
            tasksT[taskTCount].threshold = threshold;
            taskTCount++;
        }
    }

    void scheduleThreshold(void) {
        int highestPriority = INT_MAX, nextTask = -1;
        for (int i = 0; i < taskTCount; i++) {
            if (tasksT[i].ready && tasksT[i].priority < highestPriority) {
                if (currentTaskT == -1 || tasksT[i].priority < tasksT[currentTaskT].threshold) {
                    highestPriority = tasksT[i].priority;
                    nextTask = i;
                }
            }
        }
        if (nextTask != -1 && nextTask != currentTaskT) {
            currentTaskT = nextTask;
            tasksT[nextTask].taskFunc();
        }
    }

    // Unit tests
    void testPreemptionThreshold() {
        taskTCount = 0;
        task1Counter = 0;
        task2Counter = 0;
        addTaskThreshold(task1, 2, 1);
        addTaskThreshold(task2, 1, 0);
        currentTaskT = 0;
        scheduleThreshold();
        assertEquals(1, task2Counter, "Test 479.1 - Task preempted");
        addTaskThreshold(task1, 2, 0);
        currentTaskT = 0;
        scheduleThreshold();
        assertEquals(0, task2Counter, "Test 479.2 - No preemption due to threshold");
    }
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Compare priority against threshold.
 - Ensure valid task selection.
 - Test with different thresholds.
- **Expert Tips:**
 - Explain: "Limit preemption with thresholds."
 - In interviews, clarify: "Ask about threshold range."
 - Suggest optimization: "Combine with priority inheritance."

- Test edge cases: "Equal priorities, high thresholds."

Problem 480: Implement a Function to Handle Task Migration

Issue Description

Migrate a task to another CPU (simulated).

Problem Decomposition & Solution Steps

- **Input:** Task ID, target CPU ID.
- **Output:** Move task to another CPU's task list.
- **Approach:** Simulate multiple CPUs with task lists.
- **Algorithm:** Task Migration
 - **Explanation:** Move TCB to target CPU's queue.
- **Steps:**
 1. Maintain task lists for each CPU.
 2. Remove task from source CPU's list.
 3. Add task to target CPU's list.
- **Complexity:** Time O(1), Space O(n).

Algorithm Explanation

Simulate multiple CPUs with separate TCB arrays.

To migrate a task, mark it not ready on the source CPU and add it to the target CPU's task list with ready = true.

In a real RTOS, this involves updating scheduler state.

Time is O(1), with O(n) space for task lists.

Coding Part (with Unit Tests)

```

typedef struct {
    TCB tasks[MAX_TASKS];
    int taskCount;
} CPU;

CPU cpus[2];

void initCPU(int cpuId) {
    cpus[cpuId].taskCount = 0;
}
void addTaskToCPU(void (*taskFunc)(void), int cpuId) {
    if (cpus[cpuId].taskCount < MAX_TASKS) {
        cpus[cpuId].tasks[cpus[cpuId].taskCount].id = cpus[cpuId].taskCount;
    }
}
  
```

```

        cpus[cpuId].tasks[cpus[cpuId].taskCount].taskFunc = taskFunc;
        cpus[cpuId].tasks[cpus[cpuId].taskCount].ready = true;
        cpus[cpuId].taskCount++;
    }
}
void migrateTask(int taskId, int sourceCPU, int targetCPU) {
    if (taskId < cpus[sourceCPU].taskCount) {
        cpus[sourceCPU].tasks[taskId].ready = false;
        addTaskToCPU(cpus[sourceCPU].tasks[taskId].taskFunc, targetCPU);
    }
}
// Unit tests
void testTaskMigration() {
    initCPU(0);
    initCPU(1);
    addTaskToCPU(task1, 0);
    migrateTask(0, 0, 1);
    assertBoolEquals(false, cpus[0].tasks[0].ready, "Test 480.1 - Task removed from source");
    assertIntEquals(1, cpus[1].taskCount, "Test 480.2 - Task added to target");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Update task state on migration.
 - Validate CPU and task IDs.
 - Test with multiple CPUs.
- **Expert Tips:**
 - Explain: "Move task between CPU queues."
 - In interviews, clarify: "Ask about migration triggers."
 - Suggest optimization: "Minimize state transfer."
 - Test edge cases: "No tasks, invalid CPU."

Problem 481: Manage a Task's Stack Overflow Detection

Issue Description

Detect stack overflow for tasks.

Problem Decomposition & Solution Steps

- **Input:** Task with stack usage.
- **Output:** Flag stack overflow.
- **Approach:** Monitor stack pointer in TCB.
- **Algorithm:** Stack Overflow Detection
 - **Explanation:** Check if stack usage exceeds allocated size.
- **Steps:**
 1. Add stack and stackTop to TCB.
 2. On stack push, check if stackTop exceeds limit.
 3. Flag overflow if limit reached.
- **Complexity:** Time O(1) per push, Space O($n \times S$).

Algorithm Explanation

Each TCB includes a fixed-size stack and stackTop.

On each stack push (simulated), check if $\text{stackTop} \geq \text{STACK_SIZE}$.

If so, flag an overflow (e.g., suspend task).

Time is $O(1)$ per push, with $O(n \times S)$ space for stacks.

Coding Part (with Unit Tests)

```
typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    int stack[STACK_SIZE];
    int stackTop;
    bool overflow;
} TCB_Stack;

TCB_Stack tasksS0[MAX_TASKS];
int taskS0Count = 0;

void addTaskStack(void (*taskFunc)(void)) {
    if (taskS0Count < MAX_TASKS) {
        tasksS0[taskS0Count].id = taskS0Count;
        tasksS0[taskS0Count].taskFunc = taskFunc;
        tasksS0[taskS0Count].ready = true;
        tasksS0[taskS0Count].stackTop = 0;
        tasksS0[taskS0Count].overflow = false;
        taskS0Count++;
    }
}

bool pushStack(int taskId, int value) {
    if (tasksS0[taskId].stackTop >= STACK_SIZE) {
        tasksS0[taskId].overflow = true;
        tasksS0[taskId].ready = false;
        return false;
    }
    tasksS0[taskId].stack[tasksS0[taskId].stackTop++] = value;
    return true;
}

// Unit tests
void testStackOverflow() {
    taskS0Count = 0;
    addTaskStack(task1);
    for (int i = 0; i < STACK_SIZE; i++) pushStack(0, i);
    assertEquals(true, pushStack(0, 999), "Test 481.1 - Stack push within limit");
    assertEquals(false, pushStack(0, 999), "Test 481.2 - Stack overflow detected");
    assertEquals(true, tasksS0[0].overflow, "Test 481.3 - Overflow flag set");
}
```

Best Practices & Expert Tips

- **Best Practices:**

- Check stack bounds on each push.
- Suspend task on overflow.

- Test with large stack usage.
- **Expert Tips:**
 - Explain: "Detect stack overflow by bounds checking."
 - In interviews, clarify: "Ask about overflow handling."
 - Suggest optimization: "Use guard pages."
 - Test edge cases: "Empty stack, immediate overflow."

Problem 482: Implement a Function to Handle Task Synchronization Errors

Issue Description

Detect and handle synchronization errors (e.g., deadlock, missed signals).

Problem Decomposition & Solution Steps

- **Input:** Semaphore operations, task states.
- **Output:** Detect errors like missed signals or deadlocks.
- **Approach:** Monitor semaphore wait queue and timeouts.
- **Algorithm:** Synchronization Error Detection
 - **Explanation:** Flag errors if tasks wait indefinitely.
- **Steps:**
 1. Extend semaphore with timeout tracking.
 2. Flag error if task waits beyond max time.
 3. Log missed signals or deadlocks.
- **Complexity:** Time $O(n)$ per tick, Space $O(n)$.

Algorithm Explanation

Extend the semaphore (Problem 463) to track wait times.

On each tick, check if any task in the wait queue has exceeded a max wait time (e.g., 100ms).

If so, flag a synchronization error (potential deadlock or missed signal).

Time is $O(n)$ to check wait queue, with $O(n)$ space.

Coding Part (with Unit Tests)

```
typedef struct {
    int count;
    int waitQueue[MAX_TASKS];
    long long waitTimes[MAX_TASKS];
    int waitCount;
} SemaphoreSync;

SemaphoreSync semSync;
int syncErrorCount = 0;
```

```

void initSemaphoreSync(SemaphoreSync* sem) {
    sem->count = 1;
    sem->waitCount = 0;
}
void waitSemaphoreSync(SemaphoreSync* sem, int taskId) {
    if (sem->count > 0) {
        sem->count--;
    } else {
        sem->waitQueue[sem->waitCount] = taskId;
        sem->waitTimes[sem->waitCount] = systemTime;
        sem->waitCount++;
        tasks[taskId].ready = false;
    }
}

void checkSyncErrors(SemaphoreSync* sem) {
    for (int i = 0; i < sem->waitCount; i++) {
        if (systemTime - sem->waitTimes[i] > 100) { // Max wait 100ms
            syncErrorCount++;
            tasks[sem->waitQueue[i]].ready = true;
            for (int j = i; j < sem->waitCount - 1; j++) {
                sem->waitQueue[j] = sem->waitQueue[j + 1];
                sem->waitTimes[j] = sem->waitTimes[j + 1];
            }
            sem->waitCount--;
            i--;
        }
    }
}

// Unit tests
void testSyncErrors() {
    initSemaphoreSync(&semSync);
    taskCount = 0;
    addTask(task1);
    waitSemaphoreSync(&semSync, 0);
    systemTime = 150;
    checkSyncErrors(&semSync);
    assertEquals(1, syncErrorCount, "Test 482.1 - Sync error detected");
    assertEquals(true, tasks[0].ready, "Test 482.2 - Task unblocked");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Set reasonable max wait time.
 - Unblock tasks on error.
 - Test with long waits.
- **Expert Tips:**
 - Explain: "Detect prolonged waits as errors."
 - In interviews, clarify: "Ask about error types."
 - Suggest optimization: "Use deadlock detection algorithms."
 - Test edge cases: "No errors, multiple waits."

Problem 483: Monitor Task Jitter in an RTOS

Issue Description

Measure task jitter (variation in execution timing).

Problem Decomposition & Solution Steps

- **Input:** Task execution times.
- **Output:** Jitter as max deviation from expected period.
- **Approach:** Track execution times, compute deviations.
- **Algorithm:** Jitter Monitoring
 - **Explanation:** Measure difference from expected execution time.
- **Steps:**
 1. Add lastExecTime, period, and jitter to TCB.
 2. On execution, compute deviation from expected time.
 3. Update max jitter if deviation is larger.
- **Complexity:** Time O(1) per execution, Space O(n).

Algorithm Explanation

Each TCB tracks lastExecTime, period, and jitter.

On execution, compute the deviation as $|systemTime - (lastExecTime + period)|$.

Update jitter if the deviation is larger.

Time is O(1) per execution, with O(n) space for TCBs.

Coding Part (with Unit Tests)

```
typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    long long lastExecTime;
    long long period;
    long long jitter;
} TCB_Jitter;

TCB_Jitter tasksJ[MAX_TASKS];
int taskJCount = 0;

void addTaskJitter(void (*taskFunc)(void), long long period) {
    if (taskJCount < MAX_TASKS) {
        tasksJ[taskJCount].id = taskJCount;
        tasksJ[taskJCount].taskFunc = taskFunc;
        tasksJ[taskJCount].ready = true;
        tasksJ[taskJCount].lastExecTime = 0;
        tasksJ[taskJCount].period = period;
        tasksJ[taskJCount].jitter = 0;
        taskJCount++;
    }
}

void executeTaskJitter(int taskId) {
    if (tasksJ[taskJCount].ready) {
        long long expectedTime = tasksJ[taskId].lastExecTime + tasksJ[taskId].period;
        long long deviation = llabs(systemTime - expectedTime);
        if (deviation > tasksJ[taskId].jitter) tasksJ[taskId].jitter = deviation;
        tasksJ[taskId].lastExecTime = systemTime;
    }
}
```

```

        tasksJ[taskId].taskFunc();
    }

// Unit tests
void testJitter() {
    taskJCount = 0;
    systemTime = 0;
    addTaskJitter(task1, 10);
    executeTaskJitter(0);
    systemTime = 12;
    executeTaskJitter(0);
    assertEquals(2, tasksJ[0].jitter, "Test 483.1 - Jitter calculated");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track execution times accurately.
 - Update jitter on each execution.
 - Test with varying periods.
- **Expert Tips:**
 - Explain: "Measure deviation from expected timing."
 - In interviews, clarify: "Ask about jitter tolerance."
 - Suggest optimization: "Use statistical jitter analysis."
 - Test edge cases: "No jitter, large deviations."

Problem 484: Handle a Task's Deadline Overrun

Issue Description

Detect and handle tasks that overrun their deadlines.

Problem Decomposition & Solution Steps

- **Input:** Task with deadline, current time.
- **Output:** Flag and handle deadline overruns.
- **Approach:** Check deadlines on execution, take action.
- **Algorithm:** Deadline Overrun Handler
 - **Explanation:** Suspend task and log overrun if deadline missed.
- **Steps:**
 1. Use TCB with deadline (Problem 471).
 2. On execution, check if systemTime > deadline.
 3. If overrun, suspend task and log.
- **Complexity:** Time O(1) per execution, Space O(n).

Algorithm Explanation

Using the TCB from Problem 471, check on each execution if systemTime exceeds the task's deadline.

If so, increment an overrun counter, suspend the task, and log the event.

Time is O(1) per check, with O(n) space for TCBs.

Coding Part (with Unit Tests)

```
int overrunCount = 0;

void checkDeadlineOverrun(int taskId) {
    if (systemTime > tasksD[taskId].deadline) {
        overrunCount++;
        tasksD[taskId].ready = false;
    }
}
// Unit tests
void testDeadlineOverrun() {
    taskDCount = 0;
    overrunCount = 0;
    systemTime = 20;
    addTaskDeadline(task1, 10);
    checkDeadlineOverrun(0);
    assertEquals(1, overrunCount, "Test 484.1 - Overrun detected");
    assertEquals(false, tasksD[0].ready, "Test 484.2 - Task suspended");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Check deadlines before execution.
 - Log overruns for debugging.
 - Test with tight deadlines.
- **Expert Tips:**
 - Explain: "Detect and handle deadline overruns."
 - In interviews, clarify: "Ask about overrun actions."
 - Suggest optimization: "Use EDF to minimize overruns."
 - Test edge cases: "No overruns, frequent overruns."

Problem 485: Implement a Function to Manage Task Queues

Issue Description

Manage multiple task queues (e.g., ready, waiting).

Problem Decomposition & Solution Steps

- **Input:** Tasks in different states (ready, waiting).
- **Output:** Organize tasks into separate queues.
- **Approach:** Use arrays for ready and waiting queues.
- **Algorithm:** Task Queue Management
 - **Explanation:** Move tasks between ready and waiting queues.
- **Steps:**
 1. Define ready and waiting queues.
 2. Add tasks to appropriate queue based on state.
 3. Move tasks (e.g., on semaphore signal or delay expiry).

- **Complexity:** Time O(n) for queue operations, Space O(n).

Algorithm Explanation

Maintain two queues: ready and waiting.

Tasks are added to the ready queue on creation or when unblocked (e.g., semaphore signal).

Tasks move to the waiting queue when blocked (e.g., semaphore wait).

The scheduler picks from the ready queue.

Time is O(n) for queue operations, with O(n) space.

Coding Part (with Unit Tests)

```

typedef struct {
    int taskIds[MAX_TASKS];
    int count;
} TaskQueue;

TaskQueue readyQueue, waitingQueue;

void initQueues(void) {
    readyQueue.count = 0;
    waitingQueue.count = 0;
}

void addToReadyQueue(int taskId) {
    readyQueue.taskIds[readyQueue.count++] = taskId;
    tasks[taskId].ready = true;
}

void addToWaitingQueue(int taskId) {
    waitingQueue.taskIds[waitingQueue.count++] = taskId;
    tasks[taskId].ready = false;
}

void moveToReadyQueue(int taskId) {
    for (int i = 0; i < waitingQueue.count; i++) {
        if (waitingQueue.taskIds[i] == taskId) {
            for (int j = i; j < waitingQueue.count - 1; j++) {
                waitingQueue.taskIds[j] = waitingQueue.taskIds[j + 1];
            }
            waitingQueue.count--;
            addToReadyQueue(taskId);
            break;
        }
    }
}
// Unit tests
void testTaskQueues() {
    initQueues();
    taskCount = 0;
    addTask(task1);
    addToReadyQueue(0);
    assertEquals(1, readyQueue.count, "Test 485.1 - Task added to ready queue");
    addToWaitingQueue(0);
    assertEquals(1, waitingQueue.count, "Test 485.2 - Task moved to waiting queue");
    moveToReadyQueue(0);
    assertEquals(1, readyQueue.count, "Test 485.3 - Task moved back to ready queue");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Maintain separate queues for clarity.
 - Update task state with queue changes.
 - Test with queue transitions.
- **Expert Tips:**
 - Explain: "Organize tasks by state in queues."
 - In interviews, clarify: "Ask about queue types."
 - Suggest optimization: "Use priority queues."
 - Test edge cases: "Empty queues, full queues."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for RTOS problems 469 to 485:\n");
    testSuspendResume();
    testSchedulingLatency();
    testEDF();
    testPriorityInversion();
    testIdleTime();
    testResourceSharing();
    testTaskDependency();
    testInterruptNesting();
    testResponseTime();
    testExecutionBudget();
    testPreemptionThreshold();
    testTaskMigration();
    testStackOverflow();
    testSyncErrors();
    testJitter();
    testDeadlineOverrun();
    testTaskQueues();
    return 0;
}
```

Problem 486: Handle a Task's Priority Inheritance

Issue Description

Implement priority inheritance to prevent priority inversion when tasks share resources.

Problem Decomposition & Solution Steps

- **Input:** Mutex, task priorities.
- **Output:** Dynamically adjust task priorities to avoid inversion.
- **Approach:** Extend mutex to adjust owner's priority when blocking higher-priority tasks.
- **Algorithm:** Priority Inheritance
 - **Explanation:** Raise owner's priority to match blocked task's priority.
- **Steps:**
 1. Add originalPriority to TCB (from Problem 472).

2. On mutex lock, if blocked, raise owner's priority to highest blocked task's priority.
 3. On unlock, restore owner's original priority.
- **Complexity:** Time O(n) for lock (to find highest priority), Space O(n).

Algorithm Explanation

When a task attempts to lock a mutex held by a lower-priority task, the owner's priority is raised to the highest priority among blocked tasks.

On unlock, restore the original priority.

This prevents priority inversion.

Time is O(n) to scan the wait queue, with O(n) space for TCBs and mutex.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>
#include <string.h>
#include <limits.h>

#define MAX_TASKS 10
#define TIME_SLICE 10

long long systemTime = 0;
typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    int priority;
    int originalPriority;
} TCB_Priority;

TCB_Priority tasksP[MAX_TASKS];
int taskPCount = 0;
int task1Counter = 0;
int task2Counter = 0;

void assertIntEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

void addTaskPriority(void (*taskFunc)(void), int priority) {
    if (taskPCount < MAX_TASKS) {
        tasksP[taskPCount].id = taskPCount;
        tasksP[taskPCount].taskFunc = taskFunc;
        tasksP[taskPCount].ready = true;
        tasksP[taskPCount].priority = priority;
        tasksP[taskPCount].originalPriority = priority;
        taskPCount++;
    }
}

void task1(void) { task1Counter++; }
void task2(void) { task2Counter++; }
```

```

typedef struct {
    int owner;
    int waitQueue[MAX_TASKS];
    int waitCount;
} Mutex;

Mutex mutexPI;

void initMutex(Mutex* mutex) {
    mutex->owner = -1;
    mutex->waitCount = 0;
}

void lockMutexPI(Mutex* mutex, int taskId) {
    if (mutex->owner == -1) {
        mutex->owner = taskId;
    } else {
        mutex->waitQueue[mutex->waitCount++] = taskId;
        int highestPriority = tasksP[taskId].priority;
        for (int i = 0; i < mutex->waitCount; i++) {
            if (tasksP[mutex->waitQueue[i]].priority < highestPriority) {
                highestPriority = tasksP[mutex->waitQueue[i]].priority;
            }
        }
        if (mutex->owner != -1 && tasksP[mutex->owner].priority > highestPriority) {
            tasksP[mutex->owner].priority = highestPriority;
        }
        tasksP[taskId].ready = false;
    }
}

void unlockMutexPI(Mutex* mutex) {
    if (mutex->owner != -1) {
        tasksP[mutex->owner].priority = tasksP[mutex->owner].originalPriority;
        if (mutex->waitCount > 0) {
            int nextTask = mutex->waitQueue[0];
            for (int i = 0; i < mutex->waitCount - 1; i++) {
                mutex->waitQueue[i] = mutex->waitQueue[i + 1];
            }
            mutex->waitCount--;
            mutex->owner = nextTask;
            tasksP[nextTask].ready = true;
        } else {
            mutex->owner = -1;
        }
    }
}

// Unit tests
void testPriorityInheritance() {
    taskPCount = 0;
    initMutex(&mutexPI);
    addTaskPriority(task1, 2);
    addTaskPriority(task2, 1);
    lockMutexPI(&mutexPI, 0);
    lockMutexPI(&mutexPI, 1);
    assertEquals(1, tasksP[0].priority, "Test 486.1 - Owner priority raised");
    unlockMutexPI(&mutexPI);
    assertEquals(2, tasksP[0].priority, "Test 486.2 - Priority restored");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track highest priority among blocked tasks.
 - Restore original priority on unlock.
 - Test with multiple blocked tasks.
- **Expert Tips:**
 - Explain: "Raise owner's priority to highest blocked task."
 - In interviews, clarify: "Compare with priority ceiling."
 - Suggest optimization: "Cache highest priority."
 - Test edge cases: "No blocked tasks, equal priorities."

Problem 487: Implement a Function to Monitor Task Utilization

Issue Description

Calculate task utilization as the fraction of CPU time used.

Problem Decomposition & Solution Steps

- **Input:** Task execution times, total time.
- **Output:** Utilization per task ($\text{execTime} / \text{totalTime}$).
- **Approach:** Track execution time in TCB, compute utilization.
- **Algorithm:** Task Utilization Monitoring
 - **Explanation:** Sum execution time, divide by total system time.
- **Steps:**
 1. Add execTime to TCB (from Problem 464).
 2. On execution, update execTime.
 3. Compute utilization as $\text{execTime} / \text{systemTime}$.
- **Complexity:** Time $O(1)$ per execution, Space $O(n)$.

Algorithm Explanation

Each TCB tracks execTime.

On task execution, add TIME_SLICE to execTime.

Utilization is computed as $\text{execTime} / \text{systemTime}$ when queried.

Time is $O(1)$ per execution, with $O(n)$ space for TCBs.

If systemTime is 0, return 0 to avoid division by zero.

Coding Part (with Unit Tests)

```
typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    long long execTime;
} TCB_Util;

TCB_Util tasksU[MAX_TASKS];
```

```

int taskUCount = 0;

void addTaskUtil(void (*taskFunc)(void)) {
    if (taskUCount < MAX_TASKS) {
        tasksU[taskUCount].id = taskUCount;
        tasksU[taskUCount].taskFunc = taskFunc;
        tasksU[taskUCount].ready = true;
        tasksU[taskUCount].execTime = 0;
        taskUCount++;
    }
}

void executeTaskUtil(int taskId) {
    if (tasksU[taskId].ready) {
        tasksU[taskId].taskFunc();
        tasksU[taskId].execTime += TIME_SLICE;
    }
}

float getUtilization(int taskId) {
    if (systemTime == 0) return 0.0f;
    return (float)tasksU[taskId].execTime / systemTime;
}

// Unit tests
void testUtilization() {
    taskUCount = 0;
    systemTime = 100;
    addTaskUtil(task1);
    executeTaskUtil(0);
    assertEquals(10, tasksU[0].execTime, "Test 487.1 - Execution time tracked");
    assertEquals(0.1f == getUtilization(0), true, "Test 487.2 - Utilization calculated");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Update execTime per execution.
 - Handle systemTime = 0 case.
 - Test with varying execution times.
- **Expert Tips:**
 - Explain: "Utilization as fraction of CPU time."
 - In interviews, clarify: "Ask about time window."
 - Suggest optimization: "Use rolling average."
 - Test edge cases: "No execution, zero system time."

Problem 488: Manage a Task's Periodic Execution

Issue Description

Ensure tasks execute at fixed periods.

Problem Decomposition & Solution Steps

- **Input:** Task with period.
- **Output:** Execute task every period.

- **Approach:** Track next execution time in TCB.
- **Algorithm:** Periodic Task Scheduling
 - **Explanation:** Run task when systemTime reaches next execution time.
- **Steps:**
 1. Add period and nextExecTime to TCB.
 2. On tick, check if systemTime \geq nextExecTime.
 3. Execute and update nextExecTime.
- **Complexity:** Time O(n) per tick, Space O(n).

Algorithm Explanation

Each TCB tracks period and nextExecTime.

On each tick, check if systemTime \geq nextExecTime for each task.

If true, execute and set nextExecTime += period.

Time is O(n) to check all tasks, with O(n) space for TCBs.

Coding Part (with Unit Tests)

```

typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    long long period;
    long long nextExecTime;
} TCB_Periodic;

TCB_Periodic tasksPer[MAX_TASKS];
int taskPerCount = 0;

void addTaskPeriodic(void (*taskFunc)(void), long long period) {
    if (taskPerCount < MAX_TASKS) {
        tasksPer[taskPerCount].id = taskPerCount;
        tasksPer[taskPerCount].taskFunc = taskFunc;
        tasksPer[taskPerCount].ready = true;
        tasksPer[taskPerCount].period = period;
        tasksPer[taskPerCount].nextExecTime = systemTime + period;
        taskPerCount++;
    }
}

void schedulePeriodic(void) {
    for (int i = 0; i < taskPerCount; i++) {
        if (tasksPer[i].ready && systemTime >= tasksPer[i].nextExecTime) {
            tasksPer[i].taskFunc();
            tasksPer[i].nextExecTime += tasksPer[i].period;
        }
    }
}

// Unit tests
void testPeriodicExecution() {
    taskPerCount = 0;
    task1Counter = 0;
    systemTime = 0;
    addTaskPeriodic(task1, 10);
    systemTime = 10;
}

```

```

        schedulePeriodic();
        assertEquals(1, task1Counter, "Test 488.1 - Task executed at period");
        assertEquals(20, tasksPer[0].nextExecTime, "Test 488.2 - Next execution time updated");
    }
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Update nextExecTime after execution.
 - Ensure period consistency.
 - Test with multiple periods.
- **Expert Tips:**
 - Explain: "Execute tasks at fixed intervals."
 - In interviews, clarify: "Ask about period jitter."
 - Suggest optimization: "Use timer queue for efficiency."
 - Test edge cases: "Short periods, missed executions."

Problem 489: Handle a Task's Interrupt-Driven Execution

Issue Description

Execute tasks in response to interrupts.

Problem Decomposition & Solution Steps

- **Input:** Interrupt signal (simulated), associated task.
- **Output:** Execute task when interrupt occurs.
- **Approach:** Map interrupts to tasks, trigger on interrupt.
- **Algorithm:** Interrupt-Driven Task Execution
 - **Explanation:** Call task function on interrupt.
- **Steps:**
 1. Define interrupt-to-task mapping.
 2. On interrupt, execute associated task if ready.
 3. Simulate interrupt with function call.
- **Complexity:** Time $O(1)$ per interrupt, Space $O(n)$.

Algorithm Explanation

Maintain a mapping of interrupts to task IDs.

When an interrupt occurs (simulated as a function call), check if the associated task is ready and execute it.

Time is $O(1)$ per interrupt, with $O(n)$ space for the mapping and TCBs.

Coding Part (with Unit Tests)

```

typedef struct {
    int taskId;
    void (*handler)(void);
}

```

```

} InterruptMap;

InterruptMap interruptMap[MAX_TASKS];
int interruptMapCount = 0;

void addInterruptTask(int taskId, void (*handler)(void)) {
    if (interruptMapCount < MAX_TASKS) {
        interruptMap[interruptMapCount].taskId = taskId;
        interruptMap[interruptMapCount].handler = handler;
        interruptMapCount++;
    }
}

void handleInterrupt(int interruptId) {
    for (int i = 0; i < interruptMapCount; i++) {
        if (interruptMap[i].taskId == interruptId && tasksP[interruptId].ready) {
            interruptMap[i].handler();
        }
    }
}

// Unit tests
void testInterruptDriven() {
    taskPCount = 0;
    interruptMapCount = 0;
    task1Counter = 0;
    addTaskPriority(task1, 1);
    addInterruptTask(0, task1);
    handleInterrupt(0);
    assertEquals(1, task1Counter, "Test 489.1 - Task executed on interrupt");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Map interrupts to tasks clearly.
 - Check task readiness.
 - Test with multiple interrupts.
- **Expert Tips:**
 - Explain: "Trigger tasks on interrupt events."
 - In interviews, clarify: "Ask about interrupt priorities."
 - Suggest optimization: "Use direct task pointers."
 - Test edge cases: "No tasks, invalid interrupts."

Problem 490: Implement a Function to Handle Task Termination

Issue Description

Safely terminate a task and clean up resources.

Problem Decomposition & Solution Steps

- **Input:** Task ID to terminate.
- **Output:** Remove task from scheduler, free resources.
- **Approach:** Mark task as terminated, remove from queues.
- **Algorithm:** Task Termination

- **Explanation:** Set task as not ready, clean up state.
- **Steps:**
 1. Add terminated flag to TCB.
 2. On termination, set ready = false, terminated = true.
 3. Remove from scheduler and queues.
- **Complexity:** Time O(n) for removal, Space O(n).

Algorithm Explanation

Extend TCB with a terminated flag.

On termination, set ready = false and terminated = true, and remove the task from the scheduler's task list.

In a real RTOS, free stack and resources.

Time is O(n) to shift tasks, with O(n) space.

Coding Part (with Unit Tests)

```

typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    bool terminated;
} TCB_Terminate;

TCB_Terminate tasksT[MAX_TASKS];
int taskTCount = 0;

void addTaskTerminate(void (*taskFunc)(void)) {
    if (taskTCount < MAX_TASKS) {
        tasksT[taskTCount].id = taskTCount;
        tasksT[taskTCount].taskFunc = taskFunc;
        tasksT[taskTCount].ready = true;
        tasksT[taskTCount].terminated = false;
        taskTCount++;
    }
}

void terminateTask(int taskId) {
    tasksT[taskId].ready = false;
    tasksT[taskId].terminated = true;
    for (int i = taskId; i < taskTCount - 1; i++) {
        tasksT[i] = tasksT[i + 1];
    }
    taskTCount--;
}

// Unit tests
void testTaskTermination() {
    taskTCount = 0;
    addTaskTerminate(task1);
    terminateTask(0);
    assertBoolEquals(true, tasksT[0].terminated, "Test 490.1 - Task terminated");
    assertEquals(0, taskTCount, "Test 490.2 - Task removed");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Clean up resources on termination.
 - Update task list correctly.
 - Test with active tasks.
- **Expert Tips:**
 - Explain: "Safely remove tasks from scheduler."
 - In interviews, clarify: "Ask about resource cleanup."
 - Suggest optimization: "Use task pool for reuse."
 - Test edge cases: "Single task, already terminated."

Problem 491: Manage a Task's Resource Contention

Issue Description

Handle contention for shared resources among tasks.

Problem Decomposition & Solution Steps

- **Input:** Multiple tasks accessing shared resource.
- **Output:** Safe access with minimal contention.
- **Approach:** Use mutex with priority inheritance (Problem 486).
- **Algorithm:** Resource Contention Management
 - **Explanation:** Use mutex to serialize access, inherit priority.
- **Steps:**
 1. Initialize mutex for resource.
 2. Tasks lock mutex before accessing resource.
 3. Unlock after use, with priority inheritance.
- **Complexity:** Time $O(n)$ for lock, Space $O(n)$.

Algorithm Explanation

Use a mutex (from Problem 486) to manage resource access.

Tasks lock the mutex before accessing the resource and unlock after.

Priority inheritance prevents inversion.

Time is $O(n)$ to check wait queue, with $O(n)$ space for mutex and TCBs.

Coding Part (with Unit Tests)

```
void accessResourcePI(int taskId) {
    lockMutexPI(&mutexPI, taskId);
    tasksP[taskId].taskFunc();
    unlockMutexPI(&mutexPI);
}
```

```

// Unit tests
void testResourceContention() {
    taskPCount = 0;
    initMutex(&mutexPI);
    addTaskPriority(task1, 2);
    addTaskPriority(task2, 1);
    accessResourcePI(0);
    assertEquals(0, mutexPI.owner, "Test 491.1 - Resource locked");
    accessResourcePI(1);
    assertEquals(1, tasksP[0].priority, "Test 491.2 - Priority inherited");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use mutex for contention control.
 - Apply priority inheritance.
 - Test with concurrent access.
- **Expert Tips:**
 - Explain: "Serialize access with priority inheritance."
 - In interviews, clarify: "Ask about contention frequency."
 - Suggest optimization: "Use reader-writer locks."
 - Test edge cases: "Single task, high contention."

Problem 492: Implement a Function to Handle Task Starvation

Issue Description

Prevent low-priority tasks from being starved by high-priority tasks.

Problem Decomposition & Solution Steps

- **Input:** Tasks with priorities.
- **Output:** Ensure low-priority tasks get CPU time.
- **Approach:** Use aging to increase priority of waiting tasks.
- **Algorithm:** Task Starvation Prevention
 - **Explanation:** Increment priority of waiting tasks over time.
- **Steps:**
 1. Add waitTime to TCB.
 2. On each tick, increment waitTime for non-running tasks.
 3. Increase priority if waitTime exceeds threshold.
- **Complexity:** Time O(n) per tick, Space O(n).

Algorithm Explanation

Each TCB tracks waitTime.

On each tick, increment waitTime for non-running tasks.

If waitTime exceeds a threshold (e.g., 50ms), decrease priority (higher priority).

Reset waitTime on execution.

Time is O(n) to update tasks, with O(n) space.

Coding Part (with Unit Tests)

```
typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    int priority;
    long long waitTime;
} TCB_Starvation;

TCB_Starvation tasksS[MAX_TASKS];
int taskSCount = 0;

void addTaskStarvation(void (*taskFunc)(void), int priority) {
    if (taskSCount < MAX_TASKS) {
        tasksS[taskSCount].id = taskSCount;
        tasksS[taskSCount].taskFunc = taskFunc;
        tasksS[taskSCount].ready = true;
        tasksS[taskSCount].priority = priority;
        tasksS[taskSCount].waitTime = 0;
        taskSCount++;
    }
}

void preventStarvation(void) {
    for (int i = 0; i < taskSCount; i++) {
        if (!tasksS[i].ready || i == currentTask) continue;
        tasksS[i].waitTime += TIME_SLICE;
        if (tasksS[i].waitTime >= 50 && tasksS[i].priority > 0) {
            tasksS[i].priority--;
        }
    }
}

void executeTaskStarvation(int taskId) {
    if (tasksS[taskId].ready) {
        tasksS[taskId].taskFunc();
        tasksS[taskId].waitTime = 0;
    }
}

// Unit tests
void testStarvationPrevention() {
    taskSCount = 0;
    systemTime = 0;
    addTaskStarvation(task1, 2);
    currentTask = -1;
    systemTime = 50;
    preventStarvation();
    assertEquals(1, tasksS[0].priority, "Test 492.1 - Priority increased");
    executeTaskStarvation(0);
    assertEquals(0, tasksS[0].waitTime, "Test 492.2 - Wait time reset");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Increment waitTime for non-running tasks.
 - Cap priority changes.
 - Test with high-priority tasks.
- **Expert Tips:**
 - Explain: "Aging prevents low-priority starvation."
 - In interviews, clarify: "Ask about aging rate."
 - Suggest optimization: "Use dynamic thresholds."
 - Test edge cases: "No starvation, constant high-priority."

Problem 493: Monitor Task Context Switch Overhead

Issue Description

Measure time spent in context switching.

Problem Decomposition & Solution Steps

- **Input:** Context switch events.
- **Output:** Total overhead time for switches.
- **Approach:** Track switch time in scheduler.
- **Algorithm:** Context Switch Overhead Monitoring
 - **Explanation:** Add fixed overhead per switch.
- **Steps:**
 1. Define global switchOverhead counter.
 2. On each context switch, add fixed overhead (e.g., 1ms).
 3. Track total overhead.
- **Complexity:** Time O(1) per switch, Space O(1).

Algorithm Explanation

On each context switch (Problem 466), add a fixed overhead (simulated as 1ms) to a global switchOverhead counter.

In a real RTOS, measure actual switch time using a high-resolution timer.

Time is O(1) per switch, with O(1) space.

Coding Part (with Unit Tests)

```
long long switchOverhead = 0;

void contextSwitchOverhead(int current, int next) {
    if (current != -1 && next != -1 && current != next) {
        switchOverhead += 1; // 1ms overhead
        tasksP[next].taskFunc();
    }
}
```

```

}

// Unit tests
void testContextSwitchOverhead() {
    switchOverhead = 0;
    taskPCount = 0;
    addTaskPriority(task1, 1);
    addTaskPriority(task2, 2);
    contextSwitchOverhead(0, 1);
    assertEquals(1, switchOverhead, "Test 493.1 - Overhead tracked");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use fixed overhead for simulation.
 - Track only actual switches.
 - Test with frequent switches.
- **Expert Tips:**
 - Explain: "Measure time spent switching tasks."
 - In interviews, clarify: "Ask about overhead measurement."
 - Suggest optimization: "Use hardware timers."
 - Test edge cases: "No switches, rapid switches."

Problem 494: Handle a Task's Real-Time Constraints

Issue Description

Ensure tasks meet real-time constraints (e.g., deadlines).

Problem Decomposition & Solution Steps

- **Input:** Tasks with deadlines and periods.
- **Output:** Schedule to meet constraints or flag violations.
- **Approach:** Use EDF scheduling with overrun detection.
- **Algorithm:** Real-Time Constraint Handling
 - **Explanation:** Schedule by earliest deadline, check overruns.
- **Steps:**
 1. Use TCB with deadline and period (Problem 488).
 2. Schedule using EDF (Problem 471).
 3. Check for deadline overruns (Problem 484).
- **Complexity:** Time O(n) per tick, Space O(n).

Algorithm Explanation

Combine EDF scheduling (Problem 471) with overrun detection (Problem 484).

On each tick, select the ready task with the earliest deadline.

Before execution, check if systemTime > deadline; if so, log overrun and suspend task.

Time is O(n) per tick, with O(n) space.

Coding Part (with Unit Tests)

```
int rtOverrunCount = 0;

void scheduleRealTime(void) {
    long long earliestDeadline = LLONG_MAX;
    int nextTask = -1;
    for (int i = 0; i < taskPerCount; i++) {
        if (tasksPer[i].ready && systemTime >= tasksPer[i].nextExecTime) {
            if (systemTime > tasksPer[i].deadline) {
                rtOverrunCount++;
                tasksPer[i].ready = false;
            } else if (tasksPer[i].deadline < earliestDeadline) {
                earliestDeadline = tasksPer[i].deadline;
                nextTask = i;
            }
        }
    }
    if (nextTask != -1) {
        tasksPer[nextTask].taskFunc();
        tasksPer[nextTask].nextExecTime += tasksPer[nextTask].period;
    }
}

// Unit tests
void testRealTimeConstraints() {
    taskPerCount = 0;
    rtOverrunCount = 0;
    systemTime = 20;
    addTaskPeriodic(task1, 10);
    tasksPer[0].deadline = 15;
    scheduleRealTime();
    assertEquals(1, rtOverrunCount, "Test 494.1 - Overrun detected");
    assertFalse(tasksPer[0].ready, "Test 494.2 - Task suspended");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use EDF for real-time scheduling.
 - Detect overruns before execution.
 - Test with tight constraints.
- **Expert Tips:**
 - Explain: "EDF with overrun detection."
 - In interviews, clarify: "Ask about constraint types."
 - Suggest optimization: "Use deadline monotonic scheduling."
 - Test edge cases: "No overruns, all tasks late."

Problem 495: Implement a Function to Manage Task Priorities Dynamically

Issue Description

Adjust task priorities at runtime based on conditions.

Problem Decomposition & Solution Steps

- **Input:** Task ID, new priority.
- **Output:** Update task priority, reschedule if needed.
- **Approach:** Allow runtime priority changes in TCB.
- **Algorithm:** Dynamic Priority Management
 - **Explanation:** Update priority and trigger scheduler.
- **Steps:**
 1. Add priority to TCB (from Problem 454).
 2. Provide function to update priority.
 3. Reschedule to reflect new priority.
- **Complexity:** Time O(n) for rescheduling, Space O(n).

Algorithm Explanation

Extend TCB with priority.

A function updates a task's priority and triggers the scheduler to select the highest-priority ready task.

Time is O(n) to reschedule, with O(n) space for TCBs.

Coding Part (with Unit Tests)

```
void setTaskPriority(int taskId, int newPriority) {  
    tasksP[taskId].priority = newPriority;  
    tasksP[taskId].originalPriority = newPriority;  
    // Trigger scheduler (simplified)  
    int highestPriority = INT_MAX, nextTask = -1;  
    for (int i = 0; i < taskPCount; i++) {  
        if (tasksP[i].ready && tasksP[i].priority < highestPriority) {  
            highestPriority = tasksP[i].priority;  
            nextTask = i;  
        }  
    }  
    if (nextTask != -1) tasksP[nextTask].taskFunc();  
}  
  
// Unit tests  
void testDynamicPriority() {  
    taskPCount = 0;  
    task1Counter = 0;  
    task2Counter = 0;  
    addTaskPriority(task1, 2);  
    addTaskPriority(task2, 1);  
    setTaskPriority(0, 0);  
    assertEquals(0, tasksP[0].priority, "Test 495.1 - Priority updated");  
    assertEquals(1, task1Counter, "Test 495.2 - Higher priority task executed");  
}
```

Best Practices & Expert Tips

- **Best Practices:**

- Validate new priority range.
 - Reschedule after updates.
 - Test with priority changes.
- **Expert Tips:**
 - Explain: "Runtime priority adjustment."
 - In interviews, clarify: "Ask about priority triggers."
 - Suggest optimization: "Use priority queue."
 - Test edge cases: "Same priority, invalid priorities."

Problem 496: Handle a Task's Fault Recovery

Issue Description

Recover tasks from faults (e.g., crashes, exceptions).

Problem Decomposition & Solution Steps

- **Input:** Task fault signal (simulated).
- **Output:** Restart or suspend task.
- **Approach:** Detect faults, reset task state.
- **Algorithm:** Fault Recovery
 - **Explanation:** On fault, reset task or suspend.
- **Steps:**
 1. Add faultCount and state to TCB.
 2. On fault, increment faultCount, reset state or suspend.
 3. Limit restarts to avoid infinite loops.
- **Complexity:** Time O(1) per fault, Space O(n).

Algorithm Explanation

Each TCB tracks faultCount and state (simulated as a counter).

On a fault (simulated), increment faultCount.

If below a threshold (e.g., 3), reset state and mark ready.

Otherwise, suspend.

Time is O(1), with O(n) space.

Coding Part (with Unit Tests)

```
typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    int faultCount;
    int state; // Simulated state
} TCB_Fault;

TCB_Fault tasksF[MAX_TASKS];
int taskFCount = 0;
```

```

void addTaskFault(void (*taskFunc)(void)) {
    if (taskFCount < MAX_TASKS) {
        tasksF[taskFCount].id = taskFCount;
        tasksF[taskFCount].taskFunc = taskFunc;
        tasksF[taskFCount].ready = true;
        tasksF[taskFCount].faultCount = 0;
        tasksF[taskFCount].state = 0;
        taskFCount++;
    }
}

void handleFault(int taskId) {
    tasksF[taskId].faultCount++;
    if (tasksF[taskId].faultCount < 3) {
        tasksF[taskId].state = 0; // Reset state
        tasksF[taskId].ready = true;
    } else {
        tasksF[taskId].ready = false; // Suspend
    }
}

// Unit tests
void testFaultRecovery() {
    taskFCount = 0;
    addTaskFault(task1);
    handleFault(0);
    assertEquals(1, tasksF[0].faultCount, "Test 496.1 - Fault recorded");
    assertEquals(true, tasksF[0].ready, "Test 496.2 - Task restarted");
    handleFault(0);
    handleFault(0);
    assertEquals(false, tasksF[0].ready, "Test 496.3 - Task suspended after max faults");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Limit fault recoveries.
 - Reset state carefully.
 - Test with repeated faults.
- **Expert Tips:**
 - Explain: "Restart tasks on faults, suspend after limit."
 - In interviews, clarify: "Ask about fault types."
 - Suggest optimization: "Log faults for debugging."
 - Test edge cases: "No faults, max faults exceeded."

Problem 497: Implement a Function to Monitor Task Latency

Issue Description

Measure task latency (time from ready to start of execution).

Problem Decomposition & Solution Steps

- **Input:** Task ready and execution start times.
- **Output:** Latency per task.

- **Approach:** Track ready time in TCB (Problem 470).
- **Algorithm:** Task Latency Monitoring
 - **Explanation:** Compute time from ready to execution start.
- **Steps:**
 1. Use TCB with readyTime and latency (Problem 470).
 2. Set readyTime when task becomes ready.
 3. On execution start, compute latency.
- **Complexity:** Time O(1) per execution, Space O(n).

Algorithm Explanation

Using the TCB from Problem 470, set readyTime when a task becomes ready (e.g., via resume).

On execution, compute latency as systemTime - readyTime.

Time is O(1), with O(n) space for TCBs.

Coding Part (with Unit Tests)

```

typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    long long readyTime;
    long long latency;
} TCB_Latency;

TCB_Latency tasksL[MAX_TASKS];
int taskLCount = 0;

void addTaskLatency(void (*taskFunc)(void)) {
    if (taskLCount < MAX_TASKS) {
        tasksL[taskLCount].id = taskLCount;
        tasksL[taskLCount].taskFunc = taskFunc;
        tasksL[taskLCount].ready = true;
        tasksL[taskLCount].readyTime = systemTime;
        tasksL[taskLCount].latency = 0;
        taskLCount++;
    }
}

void executeTaskLatency(int taskId) {
    if (tasksL[taskId].ready) {
        tasksL[taskId].latency = systemTime - tasksL[taskId].readyTime;
        tasksL[taskId].taskFunc();
    }
}

// Unit tests
void testTaskLatency() {
    taskLCount = 0;
    systemTime = 10;
    addTaskLatency(task1);
    systemTime = 15;
    executeTaskLatency(0);
    assertEquals(5, tasksL[0].latency, "Test 497.1 - Latency calculated");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Update readyTime on state changes.
 - Compute latency at execution start.
 - Test with varying delays.
- **Expert Tips:**
 - Explain: "Measure ready-to-execution latency."
 - In interviews, clarify: "Ask about latency metrics."
 - Suggest optimization: "Use high-resolution timers."
 - Test edge cases: "Immediate execution, long delays."

Problem 498: Manage a Task's Execution Time Budget

Issue Description

Enforce a task's CPU time budget per period (similar to Problem 478).

Problem Decomposition & Solution Steps

- **Input:** Task with budget and period.
- **Output:** Limit execution to budget, reset per period.
- **Approach:** Use TCB with budget tracking (Problem 478).
- **Algorithm:** Execution Budget Management
 - **Explanation:** Suspend task when budget exhausted, reset on period.
- **Steps:**
 1. Use TCB with budget, usedTime, period (Problem 478).
 2. Deduct from budget on execution.
 3. Suspend if budget exhausted; reset at nextPeriod.
- **Complexity:** Time O(1) per execution, Space O(n).

Algorithm Explanation

Using the TCB from Problem 478, deduct TIME_SLICE from budget on execution.

If budget ≤ 0 , suspend the task.

At nextPeriod, reset budget.

Time is O(1), with O(n) space for TCBs.

Coding Part (with Unit Tests)

```
typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    long long budget;
    long long usedTime;
    long long nextPeriod;
    long long period;
} TCB_Budget;

TCB_Budget tasksB[MAX_TASKS];
```

```

int taskBCount = 0;

void addTaskBudget(void (*taskFunc)(void), long long budget, long long period) {
    if (taskBCount < MAX_TASKS) {
        tasksB[taskBCount].id = taskBCount;
        tasksB[taskBCount].taskFunc = taskFunc;
        tasksB[taskBCount].ready = true;
        tasksB[taskBCount].budget = budget;
        tasksB[taskBCount].usedTime = 0;
        tasksB[taskBCount].nextPeriod = systemTime + period;
        tasksB[taskBCount].period = period;
        taskBCount++;
    }
}

void executeTaskBudget(int taskId) {
    if (tasksB[taskId].ready && systemTime >= tasksB[taskId].nextPeriod) {
        tasksB[taskId].budget = tasksB[taskId].period;
        tasksB[taskId].nextPeriod += tasksB[taskId].period;
    }
    if (tasksB[taskId].ready && tasksB[taskId].budget >= TIME_SLICE) {
        tasksB[taskId].taskFunc();
        tasksB[taskId].usedTime += TIME_SLICE;
        tasksB[taskId].budget -= TIME_SLICE;
        if (tasksB[taskId].budget <= 0) tasksB[taskId].ready = false;
    }
}

// Unit tests
void testExecutionBudget() {
    taskBCount = 0;
    systemTime = 0;
    addTaskBudget(task1, 20, 50);
    executeTaskBudget(0);
    assertEquals(10, tasksB[0].usedTime, "Test 498.1 - Budget used");
    executeTaskBudget(0);
    assertEquals(false, tasksB[0].ready, "Test 498.2 - Task suspended after budget");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Reset budget at period start.
 - Suspend when budget exhausted.
 - Test with different budgets/periods.
- **Expert Tips:**
 - Explain: "Limit CPU time per period."
 - In interviews, clarify: "Ask about budget enforcement."
 - Suggest optimization: "Use rate monotonic scheduling."
 - Test edge cases: "Zero budget, long periods."

Problem 499: Handle a Task's Inter-Task Communication Errors

Issue Description

Detect and handle errors in inter-task communication (e.g., message queue errors).

Problem Decomposition & Solution Steps

- **Input:** Message queue operations.
- **Output:** Flag errors like overflow or invalid messages.
- **Approach:** Extend message queue (Problem 455) with error detection.
- **Algorithm:** Communication Error Handling
 - **Explanation:** Log errors on queue overflow or invalid messages.
- **Steps:**
 1. Use message queue with error counter.
 2. On send, check for overflow; log error if full.
 3. On receive, check for invalid messages (simulated).
- **Complexity:** Time O(1) for send/receive, Space O(n).

Algorithm Explanation

Extend the message queue from Problem 455.

On send, if the queue is full, increment an error counter and reject the message.

On receive, check for invalid messages (e.g., negative values, simulated).

Time is O(1) for operations, with O(n) space for the queue.

Coding Part (with Unit Tests)

```
#define QUEUE_SIZE 10

typedef struct {
    int messages[QUEUE_SIZE];
    int head, tail, count;
    int errorCount;
} MessageQueue;

MessageQueue queue;

void initQueue(MessageQueue* q) {
    q->head = q->tail = q->count = q->errorCount = 0;
}

bool sendMessageError(MessageQueue* q, int msg) {
    if (q->count >= QUEUE_SIZE) {
        q->errorCount++;
        return false;
    }
    q->messages[q->tail] = msg;
    q->tail = (q->tail + 1) % QUEUE_SIZE;
    q->count++;
    return true;
}

bool receiveMessageError(MessageQueue* q, int* msg, int taskId) {
    if (q->count == 0) {
        q->errorCount++;
        return false;
    }
    *msg = q->messages[q->head];
    if (*msg < 0) q->errorCount++; // Simulated invalid message
    q->head = (q->head + 1) % QUEUE_SIZE;
    q->count--;
    return true;
}
```

```

}

// Unit tests
void testCommErrors() {
    initQueue(&queue);
    for (int i = 0; i < QUEUE_SIZE; i++) sendMessageError(&queue, i);
    assertEquals(false, sendMessageError(&queue, 999), "Test 499.1 - Overflow error");
    assertEquals(1, queue.errorCount, "Test 499.2 - Error counted");
    int msg;
    sendMessageError(&queue, -1); // Force invalid message
    receiveMessageError(&queue, &msg, 0);
    assertEquals(2, queue.errorCount, "Test 499.3 - Invalid message error");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Log all communication errors.
 - Handle queue overflow gracefully.
 - Test with invalid messages.
- **Expert Tips:**
 - Explain: "Detect queue overflow and invalid messages."
 - In interviews, clarify: "Ask about error types."
 - Suggest optimization: "Use error callbacks."
 - Test edge cases: "Empty queue, repeated errors."

Problem 500: Implement a Function to Manage Task Scheduling Policies

Issue Description

Support multiple scheduling policies (e.g., Round-Robin, Priority, EDF).

Problem Decomposition & Solution Steps

- **Input:** Scheduling policy, task list.
- **Output:** Schedule tasks based on selected policy.
- **Approach:** Implement a dispatcher to select policy.
- **Algorithm:** Multi-Policy Scheduler
 - **Explanation:** Switch between Round-Robin, Priority, and EDF based on flag.
- **Steps:**
 1. Define enum for policies (RR, Priority, EDF).
 2. Use TCB with all needed fields (priority, deadline, etc.).
 3. Dispatch to appropriate scheduler based on policy.
- **Complexity:** Time O(n) per tick, Space O(n).

Algorithm Explanation

Define a policy flag to select Round-Robin (Problem 451), Priority (Problem 454), or EDF (Problem 471).

The scheduler checks the policy and calls the corresponding function.

Each policy uses the same TCB with all fields (priority, deadline).

Time is O(n) per tick, with O(n) space.

Coding Part (with Unit Tests)

```
typedef enum { ROUND_ROBIN, PRIORITY, EDF } SchedulingPolicy;

typedef struct {
    int id;
    void (*taskFunc)(void);
    bool ready;
    int priority;
    long long deadline;
} TCB_Multi;

TCB_Multi tasksM[MAX_TASKS];
int taskMCount = 0;
SchedulingPolicy currentPolicy = ROUND_ROBIN;
int currentTaskM = 0;

void addTaskMulti(void (*taskFunc)(void), int priority, long long deadline) {
    if (taskMCount < MAX_TASKS) {
        tasksM[taskMCount].id = taskMCount;
        tasksM[taskMCount].taskFunc = taskFunc;
        tasksM[taskMCount].ready = true;
        tasksM[taskMCount].priority = priority;
        tasksM[taskMCount].deadline = deadline;
        taskMCount++;
    }
}

void scheduleMulti(void) {
    if (taskMCount == 0) return;
    if (currentPolicy == ROUND_ROBIN) {
        if (tasksM[currentTaskM].ready) tasksM[currentTaskM].taskFunc();
        currentTaskM = (currentTaskM + 1) % taskMCount;
    } else if (currentPolicy == PRIORITY) {
        int highestPriority = INT_MAX, nextTask = -1;
        for (int i = 0; i < taskMCount; i++) {
            if (tasksM[i].ready && tasksM[i].priority < highestPriority) {
                highestPriority = tasksM[i].priority;
                nextTask = i;
            }
        }
        if (nextTask != -1) tasksM[nextTask].taskFunc();
    } else if (currentPolicy == EDF) {
        long long earliestDeadline = LLONG_MAX;
        int nextTask = -1;
        for (int i = 0; i < taskMCount; i++) {
            if (tasksM[i].ready && tasksM[i].deadline < earliestDeadline) {
                earliestDeadline = tasksM[i].deadline;
                nextTask = i;
            }
        }
        if (nextTask != -1) tasksM[nextTask].taskFunc();
    }
}
```

```

}

void setSchedulingPolicy(SchedulingPolicy policy) {
    currentPolicy = policy;
}

// Unit tests
void testSchedulingPolicies() {
    taskMCount = 0;
    task1Counter = 0;
    task2Counter = 0;
    addTaskMulti(task1, 2, 20);
    addTaskMulti(task2, 1, 10);
    setSchedulingPolicy(PRIORITY);
    scheduleMulti();
    assertEquals(1, task2Counter, "Test 500.1 - Priority scheduling");
    setSchedulingPolicy(EDF);
    scheduleMulti();
    assertEquals(2, task2Counter, "Test 500.2 - EDF scheduling");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Support multiple policies cleanly.
 - Use unified TCB for flexibility.
 - Test with policy switches.
- **Expert Tips:**
 - Explain: "Switch between scheduling policies."
 - In interviews, clarify: "Ask about policy transitions."
 - Suggest optimization: "Use policy-specific data structures."
 - Test edge cases: "No tasks, policy changes."

Main Function to Run All Tests

```

int main() {
    printf("Running tests for RTOS problems 486 to 500:\n");
    testPriorityInheritance();
    testUtilization();
    testPeriodicExecution();
    testInterruptDriven();
    testTaskTermination();
    testResourceContention();
    testStarvationPrevention();
    testContextSwitchOverhead();
    testRealTimeConstraints();
    testDynamicPriority();
    testFaultRecovery();
    testTaskLatency();
    testExecutionBudget();
    testCommErrors();
    testSchedulingPolicies();
    return 0;
}

```

Debugging and Optimization (50 Problems)

Problem 501: Fix a Segmentation Fault in a Given Program

Issue Description

Fix a segmentation fault caused by accessing an invalid array index.

Problem Decomposition & Solution Steps

- **Input:** Array access with potential out-of-bounds error.
- **Output:** Safe array access with bounds checking.
- **Approach:** Add bounds checking before accessing array.
- **Algorithm:** Safe Array Access
 - **Explanation:** Check index against array bounds.
- **Steps:**
 1. Validate index < array size.
 2. Access array only if index is valid.
 3. Return error code or default value on invalid access.
- **Complexity:** Time O(1) per access, Space O(1).

Algorithm Explanation

A segmentation fault occurs when accessing an array index beyond its allocated size.

Add a bounds check ($\text{index} < \text{size}$) before access.

If invalid, return an error (-1).

Time is O(1) per access, with O(1) space.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>
#include <string.h>

#define MAX_SIZE 10

void assertIntEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}
```

```

void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

int accessArray(int* arr, int size, int index) {
    if (index < 0 || index >= size) {
        return -1; // Invalid index
    }
    return arr[index];
}

// Unit tests
void testSegFaultFix() {
    int arr[MAX_SIZE] = {0, 1, 2, 3, 4};
    assertEquals(2, accessArray(arr, 5, 2), "Test 501.1 - Valid index");
    assertEquals(-1, accessArray(arr, 5, 10), "Test 501.2 - Invalid index");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Always check array bounds.
 - Return error codes for invalid access.
 - Test boundary conditions (0, size-1, size).
- **Expert Tips:**
 - Explain: "Bounds checking prevents seg faults."
 - In interviews, clarify: "Ask about error handling."
 - Suggest optimization: "Use assertions in debug mode."
 - Test edge cases: "Negative index, empty array."

Problem 502: Optimize a Bubble Sort for Fewer Comparisons

Issue Description

Optimize bubble sort to reduce unnecessary comparisons.

Problem Decomposition & Solution Steps

- **Input:** Array to sort.
- **Output:** Sorted array with fewer comparisons.
- **Approach:** Add a flag to detect if swaps occurred.
- **Algorithm:** Optimized Bubble Sort
 - **Explanation:** Exit early if no swaps in a pass.
- **Steps:**
 1. In each pass, track if any swaps occur.
 2. If no swaps, array is sorted; exit.
 3. Swap adjacent elements if out of order.
- **Complexity:** Time $O(n^2)$ worst/average, $O(n)$ best; Space $O(1)$.

Algorithm Explanation

Standard bubble sort compares all adjacent pairs in each pass.

If no swaps occur in a pass, the array is sorted.

Adding a swapped flag allows early termination, reducing comparisons in nearly sorted arrays.

Time improves to $O(n)$ for best case, with $O(1)$ space.

Coding Part (with Unit Tests)

```
void bubbleSortOptimized(int* arr, int size) {
    for (int i = 0; i < size - 1; i++) {
        bool swapped = false;
        for (int j = 0; j < size - i - 1; j++) {
            if (arr[j] > arr[j + 1]) {
                int temp = arr[j];
                arr[j] = arr[j + 1];
                arr[j + 1] = temp;
                swapped = true;
            }
        }
        if (!swapped) break;
    }
}

// Unit tests
void testBubbleSortOptimized() {
    int arr1[] = {5, 3, 8, 1, 2};
    int expected1[] = {1, 2, 3, 5, 8};
    bubbleSortOptimized(arr1, 5);
    bool correct = true;
    for (int i = 0; i < 5; i++) if (arr1[i] != expected1[i]) correct = false;
    assertEquals(true, correct, "Test 502.1 - Sort unsorted array");
    int arr2[] = {1, 2, 3, 4, 5};
    bubbleSortOptimized(arr2, 5);
    assertEquals(true, arr2[0] == 1 && arr2[4] == 5, "Test 502.2 - Early exit sorted");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use swapped flag to exit early.
 - Minimize swaps with efficient checks.
 - Test with sorted/unsorted arrays.
- **Expert Tips:**
 - Explain: "Early exit reduces comparisons."
 - In interviews, clarify: "Compare with other sorts."
 - Suggest optimization: "Track last swap position."
 - Test edge cases: "Single element, reverse sorted."

Problem 503: Debug a Memory Leak in a Linked List Program

Issue Description

Fix a memory leak in a linked list where nodes are not freed.

Problem Decomposition & Solution Steps

- **Input:** Linked list with insert/delete operations.
- **Output:** Free all allocated nodes on deletion.
- **Approach:** Add proper deallocation in delete function.
- **Algorithm:** Memory-Safe Linked List
 - **Explanation:** Free nodes when deleting or destroying list.
- **Steps:**
 1. Define linked list node with next pointer.
 2. Free node in deleteNode function.
 3. Free entire list in destroyList.
- **Complexity:** Time $O(n)$ for deletion/destruction, Space $O(n)$.

Algorithm Explanation

A memory leak occurs when allocated nodes are not freed.

In deleteNode, free the target node after updating pointers. In destroyList, iterate and free all nodes.

Time is $O(n)$ to traverse the list, with $O(n)$ space for nodes.

Coding Part (with Unit Tests)

```
typedef struct Node {
    int data;
    struct Node* next;
} Node;

typedef struct {
    Node* head;
} LinkedList;

void initList(LinkedList* list) {
    list->head = NULL;
}

void insertNode(LinkedList* list, int data) {
    Node* newNode = (Node*)malloc(sizeof(Node));
    newNode->data = data;
    newNode->next = list->head;
    list->head = newNode;
}

void deleteNode(LinkedList* list, int data) {
    Node* curr = list->head;
    Node* prev = NULL;
    while (curr && curr->data != data) {
        prev = curr;
        curr = curr->next;
    }
}
```

```

        if (!curr) return;
        if (prev) prev->next = curr->next;
        else list->head = curr->next;
        free(curr); // Fix: Free the node
    }

    void destroyList(LinkedList* list) {
        Node* curr = list->head;
        while (curr) {
            Node* next = curr->next;
            free(curr);
            curr = next;
        }
        list->head = NULL;
    }

    // Unit tests
    void testMemoryLeakFix() {
        LinkedList list;
        initList(&list);
        insertNode(&list, 1);
        insertNode(&list, 2);
        deleteNode(&list, 1);
        assertIntEquals(2, list.head->data, "Test 503.1 - Node deleted");
        destroyList(&list);
        assertBoolEquals(true, list.head == NULL, "Test 503.2 - List destroyed");
    }
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Free nodes in all deletion paths.
 - Set pointers to NULL after freeing.
 - Test with valgrind for leaks.
- **Expert Tips:**
 - Explain: "Free nodes to prevent leaks."
 - In interviews, clarify: "Ask about leak detection tools."
 - Suggest optimization: "Use memory pools."
 - Test edge cases: "Empty list, single node."

Problem 504: Optimize a String Concatenation Function

Issue Description

Optimize a string concatenation function to reduce time complexity.

Problem Decomposition & Solution Steps

- **Input:** Two strings to concatenate.
- **Output:** Concatenated string with minimal allocations.
- **Approach:** Precompute result size, allocate once.
- **Algorithm:** Optimized String Concatenation
 - **Explanation:** Avoid repeated concatenations by computing total length.

- **Steps:**
 1. Compute lengths of input strings.
 2. Allocate result buffer once.
 3. Copy strings to result.
- **Complexity:** Time $O(n + m)$, Space $O(n + m)$ for strings of length n, m .

Algorithm Explanation

Naive concatenation repeatedly appends characters, causing multiple allocations.

Instead, compute total length ($\text{strlen}(s1) + \text{strlen}(s2)$), allocate a single buffer, and copy both strings using `strcpy` and `strcat`.

Time is $O(n + m)$ for copying, with $O(n + m)$ space.

Coding Part (with Unit Tests)

```
char* concatStrings(const char* s1, const char* s2) {
    size_t len1 = strlen(s1), len2 = strlen(s2);
    char* result = (char*)malloc(len1 + len2 + 1);
    strcpy(result, s1);
    strcat(result, s2);
    return result;
}

// Unit tests
void testConcatStrings() {
    char* result = concatStrings("Hello, ", "World!");
    assertBoolEquals(true, strcmp(result, "Hello, World!") == 0, "Test 504.1 - Strings concatenated");
    free(result);
    result = concatStrings("", "Test");
    assertBoolEquals(true, strcmp(result, "Test") == 0, "Test 504.2 - Empty string");
    free(result);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Allocate result buffer once.
 - Free result after use.
 - Test with empty strings.
- **Expert Tips:**
 - Explain: "Single allocation reduces overhead."
 - In interviews, clarify: "Ask about string length limits."
 - Suggest optimization: "Use dynamic buffers for large strings."
 - Test edge cases: "Empty strings, long strings."

Problem 505: Fix a Buffer Overflow in a String Copy Function

Issue Description

Fix a buffer overflow in a string copy function that writes past destination.

Problem Decomposition & Solution Steps

- **Input:** Source string, destination buffer, buffer size.
- **Output:** Safe string copy without overflow.
- **Approach:** Use bounds checking or strncpy.
- **Algorithm:** Safe String Copy
 - **Explanation:** Copy up to destination size, ensure null termination.
- **Steps:**
 1. Check source length against destination size.
 2. Copy using strncpy, limit to size-1.
 3. Add null terminator.
- **Complexity:** Time O(n), Space O(1) for copying n characters.

Algorithm Explanation

A buffer overflow occurs when copying a string longer than the destination buffer.

Use strncpy to copy up to size-1 characters, then add a null terminator.

Time is O(n) for copying, with O(1) extra space.

Coding Part (with Unit Tests)

```
void safeStrCopy(char* dest, const char* src, size_t size) {
    if (size == 0) return;
    strncpy(dest, src, size - 1);
    dest[size - 1] = '\0';
}

// Unit tests
void testBufferOverflowFix() {
    char dest[5];
    safeStrCopy(dest, "Hello", 5);
    assertBoolEquals(true, strcmp(dest, "Hell") == 0, "Test 505.1 - Safe copy");
    safeStrCopy(dest, "Hi", 5);
    assertBoolEquals(true, strcmp(dest, "Hi") == 0, "Test 505.2 - Short string");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use strncpy for safe copying.
 - Always null-terminate.
 - Test with small buffers.
- **Expert Tips:**
 - Explain: "Bounds checking prevents overflow."
 - In interviews, clarify: "Ask about buffer size handling."
 - Suggest optimization: "Use strlen for source check."
 - Test edge cases: "Zero size, long source."

Problem 506: Optimize a Function to Reduce Stack Usage

Issue Description

Optimize a recursive function to reduce stack usage.

Problem Decomposition & Solution Steps

- **Input:** Recursive function (e.g., factorial).
- **Output:** Iterative version with minimal stack usage.
- **Approach:** Convert recursion to iteration.
- **Algorithm:** Iterative Factorial
 - **Explanation:** Use a loop instead of recursive calls.
- **Steps:**
 1. Replace recursive calls with a loop.
 2. Accumulate result in a variable.
 3. Return final result.
- **Complexity:** Time $O(n)$, Space $O(1)$.

Algorithm Explanation

Recursive factorial uses $O(n)$ stack space for n calls.

An iterative version uses a loop to multiply numbers, storing the result in a variable.

Time is $O(n)$ for the loop, with $O(1)$ space (excluding input).

Coding Part (with Unit Tests)

```
unsigned long long factorialIterative(int n) {
    unsigned long long result = 1;
    for (int i = 1; i <= n; i++) {
        result *= i;
    }
    return result;
}

// Unit tests
void testFactorialOptimized() {
    assertEquals(1, factorialIterative(0), "Test 506.1 - Factorial 0");
    assertEquals(120, factorialIterative(5), "Test 506.2 - Factorial 5");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Convert recursion to iteration when possible.
 - Handle edge cases (e.g., $n=0$).
 - Test with large inputs.
- **Expert Tips:**
 - Explain: "Iteration eliminates stack growth."
 - In interviews, clarify: "Ask about tail recursion."

- Suggest optimization: "Use lookup tables for small n."
- Test edge cases: "Zero, large n."

Problem 507: Debug a Deadlock in a Multi-Threaded Program

Issue Description

Fix a deadlock caused by threads acquiring locks in different orders.

Problem Decomposition & Solution Steps

- **Input:** Two threads, two mutexes.
- **Output:** Deadlock-free lock acquisition.
- **Approach:** Enforce consistent lock order.
- **Algorithm:** Ordered Lock Acquisition
 - **Explanation:** Always acquire locks in the same order.
- **Steps:**
 1. Define a global lock order (e.g., lock1 then lock2).
 2. Ensure both threads follow this order.
 3. Release locks in reverse order.
- **Complexity:** Time O(1) for locking, Space O(1).

Algorithm Explanation

Deadlock occurs when Thread1 holds lock1 and waits for lock2, while Thread2 holds lock2 and waits for lock1.

By enforcing a consistent order (e.g., always lock1 then lock2), deadlock is prevented.

Time is O(1) for locking, with O(1) space for mutexes.

Coding Part (with Unit Tests)

```
#include <pthread.h>

pthread_mutex_t lock1, lock2;
int sharedResource1 = 0, sharedResource2 = 0;

void* thread1Func(void* arg) {
    pthread_mutex_lock(&lock1);
    pthread_mutex_lock(&lock2);
    sharedResource1++;
    sharedResource2++;
    pthread_mutex_unlock(&lock2);
    pthread_mutex_unlock(&lock1);
    return NULL;
}
void* thread2Func(void* arg) {
    pthread_mutex_lock(&lock1); // Same order as thread1
    pthread_mutex_lock(&lock2);
    sharedResource1++;
}
```

```

        sharedResource2++;
        pthread_mutex_unlock(&lock2);
        pthread_mutex_unlock(&lock1);
        return NULL;
    }
// Unit tests
void testDeadlockFix() {
    pthread_mutex_init(&lock1, NULL);
    pthread_mutex_init(&lock2, NULL);
    pthread_t t1, t2;
    pthread_create(&t1, NULL, thread1Func, NULL);
    pthread_create(&t2, NULL, thread2Func, NULL);
    pthread_join(t1, NULL);
    pthread_join(t2, NULL);
    assertEquals(2, sharedResource1, "Test 507.1 - Thread1 resource updated");
    assertEquals(2, sharedResource2, "Test 507.2 - Thread2 resource updated");
    pthread_mutex_destroy(&lock1);
    pthread_mutex_destroy(&lock2); }
```

Best Practices & Expert Tips

- **Best Practices:**
 - Enforce consistent lock order.
 - Release locks in reverse order.
 - Test with multiple threads.
- **Expert Tips:**
 - Explain: "Ordered locking prevents deadlock."
 - In interviews, clarify: "Ask about lock granularity."
 - Suggest optimization: "Use try-lock for timeouts."
 - Test edge cases: "Single thread, multiple locks."

Problem 508: Optimize a Matrix Multiplication Function

Issue Description

Optimize matrix multiplication to reduce CPU cycles.

Problem Decomposition & Solution Steps

- **Input:** Two matrices A ($m \times n$) and B ($n \times p$).
- **Output:** Result matrix C ($m \times p$) with fewer cycles.
- **Approach:** Transpose B to improve cache locality.
- **Algorithm:** Optimized Matrix Multiplication
 - **Explanation:** Transpose B to access elements sequentially.
- **Steps:**
 1. Transpose matrix B.
 2. Multiply A with transposed B, accessing rows sequentially.
 3. Store result in C.
- **Complexity:** Time $O(m \times n \times p)$, Space $O(m \times p + n \times p)$.

Algorithm Explanation

Standard matrix multiplication has poor cache locality due to non-sequential access of B.

Transposing B allows sequential access to its rows, improving cache hits.

Time remains $O(m \times n \times p)$, with $O(n \times p)$ extra space for the transposed matrix.

Coding Part (with Unit Tests)

```
#define ROWS_A 2
#define COLS_A 3
#define COLS_B 2

void matrixMultiplyOptimized(int A[ROWS_A][COLS_A], int B[COLS_A][COLS_B], int C[ROWS_A][COLS_B]) {
    int B_T[COLS_B][COLS_A]; // Transposed B
    for (int i = 0; i < COLS_A; i++)
        for (int j = 0; j < COLS_B; j++)
            B_T[j][i] = B[i][j];
    for (int i = 0; i < ROWS_A; i++)
        for (int j = 0; j < COLS_B; j++) {
            C[i][j] = 0;
            for (int k = 0; k < COLS_A; k++)
                C[i][j] += A[i][k] * B_T[j][k];
        }
}

// Unit tests
void testMatrixMultiplyOptimized() {
    int A[ROWS_A][COLS_A] = {{1, 2, 3}, {4, 5, 6}};
    int B[COLS_A][COLS_B] = {{7, 8}, {9, 10}, {11, 12}};
    int C[ROWS_A][COLS_B];
    matrixMultiplyOptimized(A, B, C);
    assertEquals(58, C[0][0], "Test 508.1 - C[0][0] correct");
    assertEquals(64, C[0][1], "Test 508.2 - C[0][1] correct");
    assertEquals(139, C[1][0], "Test 508.3 - C[1][0] correct");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Transpose B for cache efficiency.
 - Initialize result matrix to zero.
 - Test with small matrices.
- **Expert Tips:**
 - Explain: "Transpose improves cache locality."
 - In interviews, clarify: "Ask about matrix sizes."
 - Suggest optimization: "Use loop unrolling or SIMD."
 - Test edge cases: "1x1 matrices, zero matrices."

Problem 509: Fix an Off-by-One Error in a Loop

Issue Description

Fix an off-by-one error in a loop that processes an array incorrectly.

Problem Decomposition & Solution Steps

- **Input:** Array and loop with incorrect bounds.
- **Output:** Process all array elements correctly.
- **Approach:** Adjust loop bounds to include all elements.
- **Algorithm:** Corrected Loop
 - **Explanation:** Fix loop to iterate from 0 to size-1.
- **Steps:**
 1. Identify incorrect loop bounds (e.g., $i \leq \text{size}$).
 2. Fix to $i < \text{size}$.
 3. Process array elements.
- **Complexity:** Time $O(n)$, Space $O(1)$.

Algorithm Explanation

An off-by-one error often occurs when a loop iterates to size instead of size-1, causing out-of-bounds access.

Adjust the loop condition to $i < \text{size}$ to process elements 0 to size-1.

Time is $O(n)$ for iteration, with $O(1)$ space.

Coding Part (with Unit Tests)

```
int sumArray(int* arr, int size) {
    int sum = 0;
    for (int i = 0; i < size; i++) { // Fixed: i < size, not i <= size
        sum += arr[i];
    }
    return sum;
}

// Unit tests
void testOffByOneFix() {
    int arr[] = {1, 2, 3, 4, 5};
    assertEquals(15, sumArray(arr, 5), "Test 509.1 - Correct sum");
    int arr2[] = {1};
    assertEquals(1, sumArray(arr2, 1), "Test 509.2 - Single element");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use $i < \text{size}$ for zero-based arrays.
 - Validate array size.
 - Test boundary conditions.

- **Expert Tips:**

- Explain: "Correct bounds prevent off-by-one errors."
- In interviews, clarify: "Ask about loop direction."
- Suggest optimization: "Use assertions for bounds."
- Test edge cases: "Empty array, single element."

Problem 510: Optimize a Function to Reduce Memory Allocations

Issue Description

Optimize a function that performs excessive dynamic allocations.

Problem Decomposition & Solution Steps

- **Input:** Function creating temporary buffers repeatedly.
- **Output:** Minimize allocations using a static buffer.
- **Approach:** Use a single static buffer for temporary data.
- **Algorithm:** Optimized Buffer Usage
 - **Explanation:** Replace dynamic allocations with static buffer.
- **Steps:**
 1. Define a static buffer of sufficient size.
 2. Use buffer for temporary data.
 3. Avoid malloc/free in loop.
- **Complexity:** Time $O(n)$, Space $O(1)$ for fixed buffer.

Algorithm Explanation

A function creating temporary buffers in a loop (e.g., for string processing) causes frequent malloc/free calls.

Using a static buffer eliminates allocations, assuming the buffer size is sufficient.

Time is $O(n)$ for processing, with $O(1)$ space for the static buffer.

Coding Part (with Unit Tests)

```
#define MAX_BUFFER 100

void processString(const char* input, char* output) {
    static char buffer[MAX_BUFFER];
    strcpy(buffer, input);
    strcpy(output, buffer); // Simulate processing
}

// Unit tests
void testReduceAllocations() {
    char output[MAX_BUFFER];
    processString("Test", output);
    assertBoolEquals(true, strcmp(output, "Test") == 0, "Test 510.1 - String processed");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use static buffers for known sizes.
 - Ensure buffer is large enough.
 - Test with large inputs.
- **Expert Tips:**
 - Explain: "Static buffers reduce allocation overhead."
 - In interviews, clarify: "Ask about buffer size limits."
 - Suggest optimization: "Use stack allocation if thread-safe."
 - Test edge cases: "Large strings, empty input."

Problem 511: Debug a Null Pointer Dereference

Issue Description

Fix a null pointer dereference in a pointer-based function.

Problem Decomposition & Solution Steps

- **Input:** Function dereferencing a pointer without checking.
- **Output:** Safe pointer access with null check.
- **Approach:** Add null pointer validation.
- **Algorithm:** Safe Pointer Access
 - **Explanation:** Check for null before dereferencing.
- **Steps:**
 1. Validate pointer != NULL before use.
 2. Return error code (-1) if null.
 3. Process valid pointer.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

A null pointer dereference crashes when accessing a NULL pointer.

Add a check (ptr != NULL) before dereferencing.

Return -1 or handle gracefully if null.

Time is O(1), with O(1) space.

Coding Part (with Unit Tests)

```
int getValue(int* ptr) {  
    if (ptr == NULL) return -1;  
    return *ptr;  
}  
  
// Unit tests
```

```

void testNullPointerFix() {
    int x = 5;
    assertEquals(5, getValue(&x), "Test 511.1 - Valid pointer");
    assertEquals(-1, getValue(NULL), "Test 511.2 - Null pointer");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Check pointers before dereferencing.
 - Return error codes for null cases.
 - Test with null pointers.
- **Expert Tips:**
 - Explain: "Null checks prevent crashes."
 - In interviews, clarify: "Ask about error handling."
 - Suggest optimization: "Use assertions in debug mode."
 - Test edge cases: "Null pointer, valid pointer."

Problem 512: Optimize a Function to Reduce CPU Cycles

Issue Description

Optimize a function (e.g., sum of squares) to reduce CPU cycles.

Problem Decomposition & Solution Steps

- **Input:** Array of integers.
- **Output:** Sum of squares with fewer operations.
- **Approach:** Minimize redundant calculations.
- **Algorithm:** Optimized Sum of Squares
 - **Explanation:** Avoid repeated multiplications in loop.
- **Steps:**
 1. Compute square and add in single operation.
 2. Avoid redundant variable accesses.
 3. Use efficient data types.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

Naive sum of squares may use unnecessary variables or loops.

Compute $\text{arr}[i] * \text{arr}[i]$ directly in the sum, avoiding temporary variables.

Use long long to prevent overflow.

Time is O(n) for iteration, with O(1) space.

Coding Part (with Unit Tests)

```

long long sumOfSquares(int* arr, int size) {
    long long sum = 0;
    for (int i = 0; i < size; i++) {
        sum += (long long)arr[i] * arr[i];
    }
    return sum;
}

// Unit tests
void testSumOfSquaresOptimized() {
    int arr[] = {1, 2, 3};
    assertEquals(14, sumOfSquares(arr, 3), "Test 512.1 - Sum of squares");
    int arr2[] = {0};
    assertEquals(0, sumOfSquares(arr2, 1), "Test 512.2 - Zero case");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Minimize operations in loops.
 - Use appropriate data types for overflow.
 - Test with varied inputs.
- **Expert Tips:**
 - Explain: "Direct calculations reduce cycles."
 - In interviews, clarify: "Ask about input range."
 - Suggest optimization: "Use SIMD for large arrays."
 - Test edge cases: "Empty array, negative numbers."

Problem 513: Debug a Race Condition in a Multi-Threaded Program

Issue Description

Fix a race condition where threads access a shared variable without synchronization.

Problem Decomposition & Solution Steps

- **Input:** Threads incrementing a shared counter.
- **Output:** Synchronized access to ensure correct increments.
- **Approach:** Use a mutex to protect the counter.
- **Algorithm:** Synchronized Counter Increment
 - **Explanation:** Lock mutex before incrementing, unlock after.
- **Steps:**
 1. Initialize a mutex for the counter.
 2. Lock mutex before increment.
 3. Unlock after increment.
- **Complexity:** Time O(1) per increment, Space O(1).

Algorithm Explanation

A race condition occurs when multiple threads increment a shared counter concurrently, causing lost updates.

Protect the counter with a mutex, ensuring atomic increments.

Time is O(1) per increment, with O(1) space for the mutex.

Coding Part (with Unit Tests)

```
pthread_mutex_t counterMutex;
int sharedCounter = 0;

void* incrementThread(void* arg) {
    for (int i = 0; i < 1000; i++) {
        pthread_mutex_lock(&counterMutex);
        sharedCounter++;
        pthread_mutex_unlock(&counterMutex);
    }
    return NULL;
}
// Unit tests
void testRaceConditionFix() {
    sharedCounter = 0;
    pthread_mutex_init(&counterMutex, NULL);
    pthread_t t1, t2;
    pthread_create(&t1, NULL, incrementThread, NULL);
    pthread_create(&t2, NULL, incrementThread, NULL);
    pthread_join(t1, NULL);
    pthread_join(t2, NULL);
    assertEquals(2000, sharedCounter, "Test 513.1 - Counter incremented correctly");
    pthread_mutex_destroy(&counterMutex);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use mutex for shared resources.
 - Minimize lock scope.
 - Test with multiple threads.
- **Expert Tips:**
 - Explain: "Mutex ensures atomic updates."
 - In interviews, clarify: "Ask about atomic operations."
 - Suggest optimization: "Use atomic increments if available."
 - Test edge cases: "Single thread, high contention."

Problem 514: Optimize a Linked List Traversal for Cache Efficiency

Issue Description

Optimize linked list traversal to improve cache locality.

Problem Decomposition & Solution Steps

- **Input:** Linked list to traverse.
- **Output:** Faster traversal with better cache usage.
- **Approach:** Process multiple nodes per iteration (loop unrolling).

- **Algorithm:** Cache-Efficient Traversal
 - **Explanation:** Process k nodes per loop to improve locality.
- **Steps:**
 1. Traverse list, processing k nodes per iteration.
 2. Sum node values (example operation).
 3. Handle remaining nodes.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

Linked list traversal suffers from poor cache locality due to non-contiguous memory.

Processing multiple nodes (e.g., 4) per loop iteration reduces cache misses by prefetching nearby nodes.

Time remains O(n), with O(1) space.

Coding Part (with Unit Tests)

```
int sumListOptimized(LinkedList* list) {
    int sum = 0;
    Node* curr = list->head;
    while (curr) {
        // Process 4 nodes per iteration
        for (int i = 0; i < 4 && curr; i++) {
            sum += curr->data;
            curr = curr->next;
        }
    }
    return sum;
}

// Unit tests
void testListTraversalOptimized() {
    LinkedList list;
    initList(&list);
    insertNode(&list, 1);
    insertNode(&list, 2);
    insertNode(&list, 3);
    assertEquals(6, sumListOptimized(&list), "Test 514.1 - Sum correct");
    destroyList(&list);
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Process multiple nodes per loop.
 - Handle partial iterations.
 - Test with long lists.
- **Expert Tips:**
 - Explain: "Loop unrolling improves cache hits."
 - In interviews, clarify: "Ask about cache line size."
 - Suggest optimization: "Tune unroll factor to cache size."
 - Test edge cases: "Empty list, single node."

Problem 515: Fix an Infinite Loop in a Program

Issue Description

Fix an infinite loop caused by incorrect loop termination.

Problem Decomposition & Solution Steps

- **Input:** Loop with incorrect condition (e.g., while ($i < n$) with no i increment).
- **Output:** Terminate loop correctly.
- **Approach:** Ensure loop variable is updated.
- **Algorithm:** Corrected Loop
 - **Explanation:** Increment loop variable to reach termination.
- **Steps:**
 1. Identify missing increment in loop.
 2. Add increment (e.g., $i++$).
 3. Process array elements.
- **Complexity:** Time $O(n)$, Space $O(1)$.

Algorithm Explanation

An infinite loop occurs when the loop condition (e.g., $i < n$) never becomes false due to a missing increment.

Add $i++$ to ensure the loop terminates after n iterations.

Time is $O(n)$, with $O(1)$ space.

Coding Part (with Unit Tests)

```
int countElements(int* arr, int size) {  
    int count = 0;  
    for (int i = 0; i < size; i++) { // Fixed: Added i++  
        count += arr[i];  
    }  
    return count;  
}  
  
// Unit tests  
void testInfiniteLoopFix() {  
    int arr[] = {1, 2, 3};  
    assertEquals(6, countElements(arr, 3), "Test 515.1 - Loop terminates");  
    int arr2[] = {};  
    assertEquals(0, countElements(arr2, 0), "Test 515.2 - Empty array");  
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Ensure loop variable updates.
 - Use for loops for clarity.
 - Test with small inputs.
- **Expert Tips:**
 - Explain: "Increment ensures loop termination."

- In interviews, clarify: "Ask about loop condition."
- Suggest optimization: "Use debuggers to catch infinite loops."
- Test edge cases: "Empty array, single iteration."

Problem 516: Optimize a Function to Reduce Memory Fragmentation

Issue Description

Optimize a function to reduce memory fragmentation from frequent allocations.

Problem Decomposition & Solution Steps

- **Input:** Function with frequent malloc/free calls.
- **Output:** Minimize fragmentation using a memory pool.
- **Approach:** Use a fixed-size memory pool for allocations.
- **Algorithm:** Memory Pool Allocation
 - **Explanation:** Allocate from a pre-allocated pool instead of malloc.
- **Steps:**
 1. Initialize a fixed-size memory pool.
 2. Allocate from pool for small objects.
 3. Free back to pool for reuse.
- **Complexity:** Time O(1) for allocation/free, Space O(k) for pool size k.

Algorithm Explanation

Frequent malloc/free calls cause fragmentation.

A memory pool pre-allocates a fixed-size array of blocks, serving allocations from the pool.

Freeing returns blocks to the pool, reducing heap fragmentation.

Time is O(1) for allocation/free, with O(k) space for the pool.

Coding Part (with Unit Tests)

```
#define POOL_SIZE 10
#define BLOCK_SIZE 16

typedef struct {
    char blocks[POOL_SIZE][BLOCK_SIZE];
    bool used[POOL_SIZE];
} MemoryPool;

MemoryPool pool;

void initPool(MemoryPool* p) {
    for (int i = 0; i < POOL_SIZE; i++) p->used[i] = false;
}
```

```

void* poolAlloc(MemoryPool* p) {
    for (int i = 0; i < POOL_SIZE; i++) {
        if (!p->used[i]) {
            p->used[i] = true;
            return p->blocks[i];
        }
    }
    return NULL;
}

void poolFree(MemoryPool* p, void* ptr) {
    for (int i = 0; i < POOL_SIZE; i++) {
        if (ptr == p->blocks[i]) {
            p->used[i] = false;
            break;
        }
    }
}

// Unit tests
void testReduceFragmentation() {
    initPool(&pool);
    void* p1 = poolAlloc(&pool);
    assertBoolEquals(true, p1 != NULL, "Test 516.1 - Allocation from pool");
    poolFree(&pool, p1);
    void* p2 = poolAlloc(&pool);
    assertBoolEquals(true, p1 == p2, "Test 516.2 - Reused block");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use fixed-size blocks in pool.
 - Track used/free blocks.
 - Test with full pool.
- **Expert Tips:**
 - Explain: "Memory pool reduces fragmentation."
 - In interviews, clarify: "Ask about pool size."
 - Suggest optimization: "Use slab allocation for variable sizes."
 - Test edge cases: "No free blocks, multiple frees."

Problem 517: Debug a Stack Overflow in a Recursive Function

Issue Description

Fix a stack overflow in a recursive function (e.g., Fibonacci) with large inputs.

Problem Decomposition & Solution Steps

- **Input:** Recursive function causing stack overflow.
- **Output:** Iterative version to prevent overflow.
- **Approach:** Convert recursion to iteration.
- **Algorithm:** Iterative Fibonacci

- **Explanation:** Use loop to compute Fibonacci numbers.
- **Steps:**
 1. Replace recursive calls with a loop.
 2. Track previous two numbers.
 3. Compute next number iteratively.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

Recursive Fibonacci uses O(n) stack space for n calls, causing overflow for large n.

An iterative version tracks the last two numbers (prev, curr) in a loop, updating them to compute the next number.

Time is O(n), with O(1) space.

Coding Part (with Unit Tests)

```
unsigned long long fibonacciIterative(int n) {
    if (n <= 1) return n;
    unsigned long long prev = 0, curr = 1;
    for (int i = 2; i <= n; i++) {
        unsigned long long next = prev + curr;
        prev = curr;
        curr = next;
    }
    return curr;
}

// Unit tests
void testFibonacciStackFix() {
    assertEquals(0, fibonacciIterative(0), "Test 517.1 - Fib 0");
    assertEquals(5, fibonacciIterative(5), "Test 517.2 - Fib 5");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Convert deep recursion to iteration.
 - Handle base cases correctly.
 - Test with large inputs.
- **Expert Tips:**
 - Explain: "Iteration prevents stack overflow."
 - In interviews, clarify: "Ask about tail recursion."
 - Suggest optimization: "Use memoization for small n."
 - Test edge cases: "Zero, large n."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for Debugging and Optimization problems 501 to 517:\n");
    testSegFaultFix();
    testBubbleSortOptimized();
    testMemoryLeakFix();
    testConcatStrings();
    testBufferOverflowFix();
```

```

    testFactorialOptimized();
    testDeadlockFix();
    testMatrixMultiplyOptimized();
    testOffByOneFix();
    testReduceAllocations();
    testNullPointerFix();
    testSumOfSquaresOptimized();
    testRaceConditionFix();
    testListTraversalOptimized();
    testInfiniteLoopFix();
    testReduceFragmentation();
    testFibonacciStackFix();
    return 0;
}

```

Problem 518: Optimize a String Parsing Function for Speed

Issue Description

Optimize a string parsing function (e.g., splitting on delimiters) to reduce CPU cycles.

Problem Decomposition & Solution Steps

- **Input:** String and delimiter (e.g., comma).
- **Output:** Array of substrings with minimal overhead.
- **Approach:** Parse in a single pass, avoiding multiple scans.
- **Algorithm:** Single-Pass String Parsing
 - **Explanation:** Use pointers to track substring start/end, avoiding copies.
- **Steps:**
 1. Iterate through string once, tracking substring start.
 2. On delimiter, store substring pointer and length.
 3. Store results in pre-allocated array.
- **Complexity:** Time $O(n)$ for string length n , Space $O(k)$ for k substrings.

Algorithm Explanation

Naive parsing rescans the string for each delimiter or copies substrings, increasing time complexity.

A single-pass approach tracks substring start positions and null-terminates on delimiters, storing pointers in a result array.

Time is $O(n)$ for one scan, with $O(k)$ space for k substring pointers (excluding input).

Coding Part (with Unit Tests)

```

#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>
#include <string.h>

#define MAX_TOKENS 10

```

```

void assertIntEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}
int parseString(const char* str, char delimiter, char* tokens[], int maxTokens) {
    int count = 0;
    const char* start = str;
    char* mutableStr = strdup(str); // Modify copy of input
    char* curr = mutableStr;
    while (*curr && count < maxTokens) {
        if (*curr == delimiter) {
            *curr = '\0';
            tokens[count++] = start;
            start = curr + 1;
        }
        curr++;
    }
    if (start < curr && count < maxTokens) {
        tokens[count++] = start;
    }
    return count;
}

// Unit tests
void testParseString() {
    char* tokens[MAX_TOKENS];
    char input[] = "a,b,c";
    int count = parseString(input, ',', tokens, MAX_TOKENS);
    assertEquals(3, count, "Test 518.1 - Correct token count");
    assertEquals(true, strcmp(tokens[0], "a") == 0 && strcmp(tokens[1], "b") == 0 &&
    strcmp(tokens[2], "c") == 0, "Test 518.2 - Correct tokens");
    free(tokens[0]); // Free modified string
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Parse in a single pass.
 - Avoid unnecessary string copies.
 - Free modified string after use.
- **Expert Tips:**
 - Explain: "Single pass reduces CPU cycles."
 - In interviews, clarify: "Ask about delimiter types."
 - Suggest optimization: "Use static buffer for small strings."
 - Test edge cases: "Empty string, no delimiters."

Problem 519: Fix a Memory Corruption in a Dynamic Array

Issue Description

Fix memory corruption caused by overwriting dynamic array bounds.

Problem Decomposition & Solution Steps

- **Input:** Dynamic array with resize operation.
- **Output:** Safe resize without corrupting memory.
- **Approach:** Validate array bounds and use safe reallocation.
- **Algorithm:** Safe Dynamic Array Resize
 - **Explanation:** Check bounds and use realloc correctly.
- **Steps:**
 1. Track array capacity and size.
 2. Validate index during access/resize.
 3. Use realloc to resize, copy data safely.
- **Complexity:** Time O(n) for resize, Space O(n).

Algorithm Explanation

Memory corruption occurs when writing beyond allocated array bounds.

Maintain size (used elements) and capacity (allocated space).

During resize, use realloc to allocate new space, copy data, and update pointers.

Validate indices to prevent overwrites.

Time is O(n) for copying, with O(n) space.

Coding Part (with Unit Tests)

```

typedef struct {
    int* data;
    int size;
    int capacity;
} DynamicArray;

void initArray(DynamicArray* arr, int capacity) {
    arr->data = (int*)malloc(capacity * sizeof(int));
    arr->size = 0;
    arr->capacity = capacity;
}

bool addElement(DynamicArray* arr, int value) {
    if (arr->size >= arr->capacity) {
        int newCapacity = arr->capacity * 2;
        int* newData = (int*)realloc(arr->data, newCapacity * sizeof(int));
        if (!newData) return false;
        arr->data = newData;
        arr->capacity = newCapacity;
    }
    arr->data[arr->size++] = value;
    return true;
}

void freeArray(DynamicArray* arr) {
    free(arr->data);
    arr->data = NULL;
    arr->size = arr->capacity = 0;
}

```

```

// Unit tests
void testDynamicArrayFix() {
    DynamicArray arr;
    initArray(&arr, 2);
    addElement(&arr, 1);
    addElement(&arr, 2);
    addElement(&arr, 3); // Triggers resize
    assertEquals(3, arr.size, "Test 519.1 - Size correct");
    assertEquals(1, arr.data[0], "Test 519.2 - Data preserved");
    freeArray(&arr);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Track size and capacity separately.
 - Validate indices before access.
 - Free memory after use.
- **Expert Tips:**
 - Explain: "Safe reallocation prevents corruption."
 - In interviews, clarify: "Ask about resize strategy."
 - Suggest optimization: "Use geometric growth (e.g., 2x)."
 - Test edge cases: "Zero capacity, large resize."

Problem 520: Optimize a Function to Minimize Interrupt Latency

Issue Description

Optimize a function to reduce interrupt latency in an interrupt handler.

Problem Decomposition & Solution Steps

- **Input:** Interrupt handler function (simulated).
- **Output:** Minimize execution time to reduce latency.
- **Approach:** Simplify handler logic, avoid loops.
- **Algorithm:** Minimal Interrupt Handler
 - **Explanation:** Perform only critical operations in handler.
- **Steps:**
 1. Move non-critical work to main loop.
 2. Use flags to signal work.
 3. Simulate interrupt with function call.
- **Complexity:** Time O(1) for handler, Space O(1).

Algorithm Explanation

Interrupt handlers must execute quickly to minimize latency.

Avoid loops and complex operations in the handler, setting a flag to defer work to the main loop.

Simulate interrupts as function calls.

Time is O(1) for handler operations, with O(1) space for flags.

Coding Part (with Unit Tests)

```
volatile bool interruptFlag = false;

void interruptHandler(void) {
    interruptFlag = true; // Minimal work
}
void processInterrupt(void) {
    if (interruptFlag) {
        // Deferred work
        interruptFlag = false;
    }
}
// Unit tests
void testInterruptLatency() {
    interruptFlag = false;
    interruptHandler();
    assertBoolEquals(true, interruptFlag, "Test 520.1 - Flag set");
    processInterrupt();
    assertBoolEquals(false, interruptFlag, "Test 520.2 - Flag cleared");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Keep handlers minimal.
 - Defer work to main loop.
 - Test with frequent interrupts.
- **Expert Tips:**
 - Explain: "Minimal handlers reduce latency."
 - In interviews, clarify: "Ask about interrupt priorities."
 - Suggest optimization: "Use direct register access."
 - Test edge cases: "Multiple interrupts, no work."

Problem 521: Debug a Program with Incorrect Pointer Arithmetic

Issue Description

Fix incorrect pointer arithmetic causing invalid memory access.

Problem Decomposition & Solution Steps

- **Input:** Function with pointer arithmetic (e.g., array traversal).
- **Output:** Correct pointer increments.
- **Approach:** Use proper pointer arithmetic with type size.
- **Algorithm:** Correct Pointer Arithmetic
 - **Explanation:** Increment pointer by correct type size.
- **Steps:**
 1. Identify incorrect increment (e.g., `ptr++` instead of `ptr += sizeof(int)`).
 2. Use `ptr += 1` for typed pointer.

- 3. Access elements correctly.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

Incorrect pointer arithmetic (e.g., treating `int*` as `char*`) causes misaligned access.

Use typed pointers (e.g., `int*`) and increment with `ptr += 1`, which accounts for `sizeof(int)`.

Time is O(n) for traversal, with O(1) space.

Coding Part (with Unit Tests)

```
int sumArrayPointer(int* arr, int size) {
    int sum = 0;
    int* end = arr + size; // Correct: Use pointer arithmetic
    for (int* ptr = arr; ptr < end; ptr++) {
        sum += *ptr;
    }
    return sum;
}

// Unit tests
void testPointerArithmeticFix() {
    int arr[] = {1, 2, 3};
    assertEquals(6, sumArrayPointer(arr, 3), "Test 521.1 - Correct sum");
    int arr2[] = {0};
    assertEquals(0, sumArrayPointer(arr2, 1), "Test 521.2 - Single element");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use typed pointers for arithmetic.
 - Validate pointer bounds.
 - Test with different data types.
- **Expert Tips:**
 - Explain: "Typed pointers ensure correct increments."
 - In interviews, clarify: "Ask about pointer type."
 - Suggest optimization: "Use array indexing for clarity."
 - Test edge cases: "Empty array, large arrays."

Problem 522: Optimize a Matrix Traversal for Memory Efficiency

Issue Description

Optimize matrix traversal to reduce memory usage.

Problem Decomposition & Solution Steps

- **Input:** Matrix to traverse (e.g., sum elements).
- **Output:** Result with minimal memory overhead.
- **Approach:** Avoid temporary buffers, traverse in-place.
- **Algorithm:** In-Place Matrix Traversal
 - **Explanation:** Sum elements without extra storage.
- **Steps:**
 1. Traverse matrix row-by-row.
 2. Accumulate sum in a single variable.
 3. Avoid allocating temporary arrays.
- **Complexity:** Time $O(m \times n)$, Space $O(1)$ for $m \times n$ matrix.

Algorithm Explanation

Naive traversal may use temporary arrays for row/column storage.

Instead, traverse the matrix in-place, summing elements directly into a variable.

Access rows sequentially for cache efficiency.

Time is $O(m \times n)$, with $O(1)$ space (excluding input).

Coding Part (with Unit Tests)

```
#define ROWS 2
#define COLS 3

int sumMatrix(int matrix[ROWS][COLS]) {
    int sum = 0;
    for (int i = 0; i < ROWS; i++)
        for (int j = 0; j < COLS; j++)
            sum += matrix[i][j];
    return sum;
}

// Unit tests
void testMatrixTraversalOptimized() {
    int matrix[ROWS][COLS] = {{1, 2, 3}, {4, 5, 6}};
    assertEquals(21, sumMatrix(matrix), "Test 522.1 - Correct sum");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Traverse in-place to save memory.
 - Access rows sequentially for cache.
 - Test with small matrices.
- **Expert Tips:**
 - Explain: "In-place traversal minimizes memory."
 - In interviews, clarify: "Ask about matrix size."
 - Suggest optimization: "Use SIMD for large matrices."
 - Test edge cases: "1×1 matrix, empty matrix."

Problem 523: Fix a Logic Error in a Sorting Algorithm

Issue Description

Fix a logic error in bubble sort causing incorrect sorting.

Problem Decomposition & Solution Steps

- **Input:** Array and buggy bubble sort.
- **Output:** Correctly sorted array.
- **Approach:** Fix comparison direction in bubble sort.
- **Algorithm:** Corrected Bubble Sort
 - **Explanation:** Ensure correct comparison (e.g., $>$ for ascending).
- **Steps:**
 1. Identify incorrect comparison (e.g., $<$ instead of $>$).
 2. Fix to compare $\text{arr}[j] > \text{arr}[j+1]$ for ascending order.
 3. Swap elements if out of order.
- **Complexity:** Time $O(n^2)$, Space $O(1)$.

Algorithm Explanation

A logic error in bubble sort (e.g., using $<$ instead of $>$) causes descending order or incorrect sorting.

Fix the comparison to $\text{arr}[j] > \text{arr}[j+1]$ for ascending order.

Time is $O(n^2)$ for sorting, with $O(1)$ space.

Coding Part (with Unit Tests)

```
void bubbleSortFixed(int* arr, int size) {
    for (int i = 0; i < size - 1; i++)
        for (int j = 0; j < size - i - 1; j++)
            if (arr[j] > arr[j + 1]) { // Fixed: Correct comparison
                int temp = arr[j];
                arr[j] = arr[j + 1];
                arr[j + 1] = temp;
            }
}

// Unit tests
void testBubbleSortFix() {
    int arr[] = {5, 3, 1};
    bubbleSortFixed(arr, 3);
    assertEquals(true, arr[0] == 1 && arr[1] == 3 && arr[2] == 5, "Test 523.1 - Correctly sorted");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Verify comparison logic.

- Test with unsorted arrays.
- Use clear variable names.
- **Expert Tips:**
 - Explain: "Correct comparison ensures proper order."
 - In interviews, clarify: "Ask about sort direction."
 - Suggest optimization: "Add early exit (Problem 502)."
 - Test edge cases: "Sorted array, single element."

Problem 524: Optimize a Function to Reduce Power Consumption

Issue Description

Optimize a function to minimize power usage (e.g., reduce CPU cycles).

Problem Decomposition & Solution Steps

- **Input:** Function with excessive computations (e.g., polling loop).
- **Output:** Reduced power via sleep or efficient checks.
- **Approach:** Replace polling with event-driven logic.
- **Algorithm:** Event-Driven Check
 - **Explanation:** Use flags instead of busy-waiting.
- **Steps:**
 1. Replace polling loop with flag check.
 2. Set flag on event (simulated).
 3. Process only when flag is set.
- **Complexity:** Time $O(1)$ per check, Space $O(1)$.

Algorithm Explanation

Polling loops (e.g., checking a condition repeatedly) waste CPU cycles, increasing power usage.

Replace polling with a flag-based check, simulating an event-driven approach (e.g., interrupt or signal).

Time is $O(1)$ per check, with $O(1)$ space for flags.

Coding Part (with Unit Tests)

```

volatile bool eventFlag = false;

void processEvent(void) {
    if (eventFlag) {
        // Process event
        eventFlag = false;
    }
}

void triggerEvent(void) {
    eventFlag = true;
}

```

```

}

// Unit tests
void testPowerOptimization() {
    eventFlag = false;
    triggerEvent();
    assertEquals(true, eventFlag, "Test 524.1 - Event triggered");
    processEvent();
    assertEquals(false, eventFlag, "Test 524.2 - Event processed");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Avoid busy-waiting loops.
 - Use event-driven logic.
 - Test with frequent events.
- **Expert Tips:**
 - Explain: "Event-driven logic saves power."
 - In interviews, clarify: "Ask about hardware sleep modes."
 - Suggest optimization: "Use low-power interrupts."
 - Test edge cases: "No events, rapid events."

Problem 525: Debug a Program with Uninitialized Variables

Issue Description

Fix a program using uninitialized variables causing undefined behavior.

Problem Decomposition & Solution Steps

- **Input:** Function with uninitialized variables (e.g., sum).
- **Output:** Initialize variables to prevent undefined behavior.
- **Approach:** Initialize all variables before use.
- **Algorithm:** Initialized Variable Usage
 - **Explanation:** Set variables to default values (e.g., 0).
- **Steps:**
 1. Identify uninitialized variables (e.g., sum).
 2. Initialize to 0 or appropriate value.
 3. Process as normal.
- **Complexity:** Time O(n), Space O(1).

Algorithm Explanation

Uninitialized variables cause undefined behavior (e.g., random values).

Initialize variables (e.g., sum = 0) before use to ensure predictable results.

Time is O(n) for processing (e.g., array sum), with O(1) space.

Coding Part (with Unit Tests)

```
int sumArrayInitialized(int* arr, int size) {
    int sum = 0; // Fixed: Initialize sum
    for (int i = 0; i < size; i++) {
        sum += arr[i];
    }
    return sum;
}

// Unit tests
void testUninitializedFix() {
    int arr[] = {1, 2, 3};
    assertEquals(6, sumArrayInitialized(arr, 3), "Test 525.1 - Correct sum");
    int arr2[] = {};
    assertEquals(0, sumArrayInitialized(arr2, 0), "Test 525.2 - Empty array");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Initialize all variables.
 - Use compiler warnings (-Wuninitialized).
 - Test with empty inputs.
- **Expert Tips:**
 - Explain: "Initialization prevents undefined behavior."
 - In interviews, clarify: "Ask about compiler flags."
 - Suggest optimization: "Use static analysis tools."
 - Test edge cases: "Zero elements, large arrays."

Problem 526: Optimize a Bit Manipulation Function for Speed

Issue Description

Optimize a bit manipulation function (e.g., count set bits) for fewer cycles.

Problem Decomposition & Solution Steps

- **Input:** Integer to count set bits.
- **Output:** Number of 1s with minimal operations.
- **Approach:** Use Brian Kernighan's algorithm.
- **Algorithm:** Optimized Bit Counting
 - **Explanation:** Clear least significant set bit each iteration.
- **Steps:**
 1. Initialize count to 0.
 2. While n != 0, clear least set bit (n & (n-1)), increment count.
 3. Return count.

- **Complexity:** Time O(k) for k set bits, Space O(1).

Algorithm Explanation

Naive bit counting checks each bit (O(32) for 32-bit int).

Brian Kernighan's algorithm clears the least significant set bit using $n \& (n-1)$, iterating only for set bits (O(k)).

Time is O(k) where k is the number of 1s, with O(1) space.

Coding Part (with Unit Tests)

```
int countSetBits(int n) {
    int count = 0;
    while (n) {
        n &= (n - 1); // Clear least significant set bit
        count++;
    }
    return count;
}

// Unit tests
void testBitCountOptimized() {
    assertEquals(3, countSetBits(7), "Test 526.1 - Count bits in 7");
    assertEquals(0, countSetBits(0), "Test 526.2 - Zero bits");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use efficient bit operations.
 - Handle edge cases (e.g., 0).
 - Test with varied inputs.
- **Expert Tips:**
 - Explain: "Kernighan's algorithm minimizes iterations."
 - In interviews, clarify: "Ask about bit count use case."
 - Suggest optimization: "Use lookup tables for small inputs."
 - Test edge cases: "All 1s, negative numbers."

Problem 527: Debug a Memory Leak in a Tree Traversal

Issue Description

Fix a memory leak in a binary tree traversal where nodes are not freed.

Problem Decomposition & Solution Steps

- **Input:** Binary tree with traversal and deletion.
- **Output:** Free all nodes to prevent leaks.

- **Approach:** Implement post-order deletion.
- **Algorithm:** Safe Tree Deletion
 - **Explanation:** Free children before parent in post-order.
- **Steps:**
 1. Define binary tree node with left/right pointers.
 2. Implement recursive post-order deletion.
 3. Free each node after children.
- **Complexity:** Time $O(n)$, Space $O(h)$ for tree height h .

Algorithm Explanation

A memory leak occurs if tree nodes are not freed during deletion.

Use post-order traversal to free left and right children before the parent node.

Time is $O(n)$ to visit all nodes, with $O(h)$ space for recursion stack.

Coding Part (with Unit Tests)

```

typedef struct TreeNode {
    int data;
    struct TreeNode* left;
    struct TreeNode* right;
} TreeNode;

typedef struct {
    TreeNode* root;
} BinaryTree;

void initTree(BinaryTree* tree) {
    tree->root = NULL;
}

void insertTree(BinaryTree* tree, int data) {
    TreeNode* node = (TreeNode*)malloc(sizeof(TreeNode));
    node->data = data;
    node->left = node->right = NULL;
    tree->root = node; // Simplified: Insert as root
}

void freeTree(TreeNode* node) {
    if (!node) return;
    freeTree(node->left);
    freeTree(node->right);
    free(node);
}

// Unit tests
void testTreeLeakFix() {
    BinaryTree tree;
    initTree(&tree);
    insertTree(&tree, 1);
    freeTree(tree.root);
    assertBoolEquals(true, tree.root == NULL, "Test 527.1 - Tree freed");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Free nodes in post-order.
 - Set pointers to NULL after freeing.
 - Test with complex trees.
- **Expert Tips:**
 - Explain: "Post-order deletion prevents leaks."
 - In interviews, clarify: "Ask about tree structure."
 - Suggest optimization: "Use iterative deletion for deep trees."
 - Test edge cases: "Empty tree, single node."

Problem 528: Optimize a Function to Reduce Stack Usage in Recursion

Issue Description

Optimize a recursive function (e.g., tree height) to reduce stack usage.

Problem Decomposition & Solution Steps

- **Input:** Binary tree.
- **Output:** Tree height with minimal stack usage.
- **Approach:** Use tail recursion or iteration.
- **Algorithm:** Iterative Tree Height
 - **Explanation:** Use a stack to simulate recursion.
- **Steps:**
 1. Use an explicit stack to store nodes.
 2. Track max depth during traversal.
 3. Return height without recursive calls.
- **Complexity:** Time $O(n)$, Space $O(h)$ for tree height h .

Algorithm Explanation

Recursive tree height uses $O(h)$ stack space for recursion.

An iterative version uses an explicit stack to store nodes, tracking the maximum depth.

Time is $O(n)$ to visit all nodes, with $O(h)$ space for the stack.

Coding Part (with Unit Tests)

```
#define MAX_STACK 100

int treeHeightOptimized(BinaryTree* tree) {
    if (!tree->root) return 0;
    TreeNode* stack[MAX_STACK];
    int depths[MAX_STACK];
    int top = -1;
    int maxDepth = 0;
    stack[++top] = tree->root;
    depths[top] = 1;
    while (top >= 0) {
```

```

        TreeNode* node = stack[top];
        int depth = depths[top--];
        if (depth > maxDepth) maxDepth = depth;
        if (node->right) {
            stack[++top] = node->right;
            depths[top] = depth + 1;
        }
        if (node->left) {
            stack[++top] = node->left;
            depths[top] = depth + 1;
        }
    }
    return maxDepth;
}

// Unit tests
void testTreeHeightOptimized() {
    BinaryTree tree;
    initTree(&tree);
    insertTree(&tree, 1);
    assertEquals(1, treeHeightOptimized(&tree), "Test 528.1 - Single node height");
    freeTree(tree.root);
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use explicit stack for iteration.
 - Track depth explicitly.
 - Test with deep trees.
- **Expert Tips:**
 - Explain: "Iterative traversal reduces stack usage."
 - In interviews, clarify: "Ask about tree balance."
 - Suggest optimization: "Use tail recursion if supported."
 - Test edge cases: "Empty tree, unbalanced tree."

Problem 529: Debug a Program with Incorrect Interrupt Handling

Issue Description

Fix a program where an interrupt handler incorrectly modifies shared data.

Problem Decomposition & Solution Steps

- **Input:** Interrupt handler accessing shared variable.
- **Output:** Safe handler with synchronized access.
- **Approach:** Protect shared data with volatile and atomic operations.
- **Algorithm:** Safe Interrupt Handler
 - **Explanation:** Use volatile and avoid race conditions.
- **Steps:**
 1. Mark shared variable as volatile.
 2. Simulate interrupt with function call.

- 3. Update variable atomically.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

Incorrect interrupt handling may corrupt shared data due to race conditions.

Use volatile to ensure consistent reads/writes and update atomically (simulated here).

In a real system, disable interrupts or use locks.

Time is O(1) for updates, with O(1) space.

Coding Part (with Unit Tests)

```

volatile int interruptCounter = 0;

void interruptHandlerSafe(void) {
    interruptCounter++; // Atomic in simulation
}

// Unit tests
void testInterruptHandlerFix() {
    interruptCounter = 0;
    interruptHandlerSafe();
    assertEquals(1, interruptCounter, "Test 529.1 - Counter incremented");
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Use volatile for shared variables.
 - Ensure atomic updates.
 - Test with multiple interrupts.
- **Expert Tips:**
 - Explain: "Volatile prevents compiler optimizations."
 - In interviews, clarify: "Ask about interrupt safety."
 - Suggest optimization: "Use atomic intrinsics."
 - Test edge cases: "Frequent interrupts, no updates."

Problem 530: Optimize a Circular Buffer for Minimal Latency

Issue Description

Optimize a circular buffer to reduce access latency.

Problem Decomposition & Solution Steps

- **Input:** Circular buffer with enqueue/dequeue operations.
- **Output:** Fast operations with minimal checks.

- **Approach:** Use power-of-2 size for efficient indexing.
- **Algorithm:** Optimized Circular Buffer
 - **Explanation:** Use bitwise operations for wrap-around.
- **Steps:**
 1. Set buffer size to power of 2.
 2. Use & (size-1) for modulo.
 3. Enqueue/dequeue with minimal checks.
- **Complexity:** Time O(1), Space O(n) for buffer size n.

Algorithm Explanation

Naive circular buffers use modulo (%) for wrap-around, which is slow.

Using a power-of-2 size allows wrap-around with & (size-1), reducing latency.

Maintain head and tail indices for O(1) enqueue/dequeue, with O(n) space.

Coding Part (with Unit Tests)

```
#define BUFFER_SIZE 8 // Power of 2

typedef struct {
    int data[BUFFER_SIZE];
    int head, tail, count;
} CircularBuffer;

void initCircularBuffer(CircularBuffer* cb) {
    cb->head = cb->tail = cb->count = 0;
}

bool enqueueOptimized(CircularBuffer* cb, int value) {
    if (cb->count == BUFFER_SIZE) return false;
    cb->data[cb->tail] = value;
    cb->tail = (cb->tail + 1) & (BUFFER_SIZE - 1);
    cb->count++;
    return true;
}

bool dequeueOptimized(CircularBuffer* cb, int* value) {
    if (cb->count == 0) return false;
    *value = cb->data[cb->head];
    cb->head = (cb->head + 1) & (BUFFER_SIZE - 1);
    cb->count--;
    return true;
}

// Unit tests
void testCircularBufferOptimized() {
    CircularBuffer cb;
    initCircularBuffer(&cb);
    enqueueOptimized(&cb, 1);
    enqueueOptimized(&cb, 2);
    int value;
    dequeueOptimized(&cb, &value);
    assertEquals(1, value, "Test 530.1 - Dequeue correct");
    assertEquals(1, cb.count, "Test 530.2 - Count correct");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Use power-of-2 size for bitwise modulo.
 - Track count to check full/empty.
 - Test with full buffer.
- **Expert Tips:**
 - Explain: "Bitwise modulo reduces latency."
 - In interviews, clarify: "Ask about buffer size constraints."
 - Suggest optimization: "Use lock-free for multithreading."
 - Test edge cases: "Empty buffer, wrap-around."

Problem 531: Fix a Program with Incorrect Array Indexing

Issue Description

Fix a program accessing an array with incorrect indices (e.g., negative or out-of-bounds).

Problem Decomposition & Solution Steps

- **Input:** Array and function with invalid indexing.
- **Output:** Safe array access with bounds checking.
- **Approach:** Validate indices before access.
- **Algorithm:** Safe Array Access
 - **Explanation:** Check index ≥ 0 and $< \text{size}$.
- **Steps:**
 1. Validate index range.
 2. Access array only if valid.
 3. Return error code (-1) if invalid.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

Incorrect indexing (e.g., negative or beyond size) causes undefined behavior or crashes.

Check if $0 \leq \text{index} < \text{size}$ before access, returning -1 if invalid.

Time is O(1) per access, with O(1) space.

Coding Part (with Unit Tests)

```
int accessArraySafe(int* arr, int size, int index) {
    if (index < 0 || index >= size) return -1;
    return arr[index];
}

// Unit tests
void testArrayIndexingFix() {
    int arr[] = {1, 2, 3};
    assertEquals(2, accessArraySafe(arr, 3, 1), "Test 531.1 - Valid index");
    assertEquals(-1, accessArraySafe(arr, 3, -1), "Test 531.2 - Negative index");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Validate indices before access.
 - Return error codes for invalid indices.
 - Test boundary conditions.
- **Expert Tips:**
 - Explain: "Bounds checking prevents errors."
 - In interviews, clarify: "Ask about index sources."
 - Suggest optimization: "Use assertions in debug mode."
 - Test edge cases: "Zero size, edge indices."

Problem 532: Optimize a Function to Reduce Code Size

Issue Description

Optimize a function to reduce its compiled code size.

Problem Decomposition & Solution Steps

- **Input:** Function with redundant code (e.g., repeated logic).
- **Output:** Smaller code with same functionality.
- **Approach:** Factor out common code, use inline functions.
- **Algorithm:** Compact Function
 - **Explanation:** Reuse logic to reduce instruction count.
- **Steps:**
 1. Identify repeated logic (e.g., min/max checks).
 2. Factor into a helper function.
 3. Use inline to avoid call overhead.
- **Complexity:** Time O(1) for example function, Space O(1).

Algorithm Explanation

Redundant code (e.g., repeated min/max checks) increases code size.

Factor common logic into an inline helper function to reduce instructions without adding call overhead.

Time is O(1) for the example (min/max), with O(1) space.

Coding Part (with Unit Tests)

```
inline int min(int a, int b) {
    return a < b ? a : b;
}

int clampValue(int value, int low, int high) {
    return min(high, min(value, low)); // Reuses min
}

// Unit tests
void testCodeSizeOptimization() {
    assertEquals(5, clampValue(10, 0, 5), "Test 532.1 - Clamp to high");
```

```
    assertEquals(0, clampValue(-1, 0, 5), "Test 532.2 - Clamp to low");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Factor out repeated logic.
 - Use inline for small functions.
 - Test with compiler optimizations.
- **Expert Tips:**
 - Explain: "Factoring reduces code size."
 - In interviews, clarify: "Ask about compiler flags."
 - Suggest optimization: "Use -Os for size optimization."
 - Test edge cases: "Boundary values, no clamping."

Problem 533: Debug a Program with a Dangling Pointer

Issue Description

Fix a dangling pointer caused by accessing freed memory.

Problem Decomposition & Solution Steps

- **Input:** Function accessing memory after free.
- **Output:** Prevent access to freed memory.
- **Approach:** Set pointers to NULL after free.
- **Algorithm:** Safe Memory Deallocation
 - **Explanation:** Nullify pointers post-free to avoid use.
- **Steps:**
 1. Free allocated memory.
 2. Set pointer to NULL.
 3. Check for NULL before access.
- **Complexity:** Time O(1), Space O(1).

Algorithm Explanation

A dangling pointer occurs when accessing memory after free.

Set the pointer to NULL after freeing and check for NULL before access to prevent undefined behavior.

Time is O(1) for free/check, with O(1) space.

Coding Part (with Unit Tests)

```
int* createAndFree(void) {
    int* ptr = (int*)malloc(sizeof(int));
    *ptr = 42;
    free(ptr);
    ptr = NULL; // Fixed: Nullify pointer
```

```

        return ptr;
    }

    int accessSafe(int* ptr) {
        return ptr ? *ptr : -1;
    }

    // Unit tests
    void testDanglingPointerFix() {
        int* ptr = createAndFree();
        assertEquals(-1, accessSafe(ptr), "Test 533.1 - Dangling pointer avoided");
    }
}

```

Best Practices & Expert Tips

- **Best Practices:**
 - Set pointers to NULL after free.
 - Check for NULL before access.
 - Test with freed pointers.
- **Expert Tips:**
 - Explain: "Nullifying prevents dangling pointers."
 - In interviews, clarify: "Ask about memory patterns."
 - Suggest optimization: "Use memory debugging tools."
 - Test edge cases: "Multiple frees, NULL pointer."

Problem 534: Optimize a String Comparison for Case-Insensitive Checks

Issue Description

Optimize a case-insensitive string comparison for speed.

Problem Decomposition & Solution Steps

- **Input:** Two strings to compare case-insensitively.
- **Output:** Fast comparison result (0 if equal, else non-zero).
- **Approach:** Convert characters to lowercase on-the-fly.
- **Algorithm:** Optimized Case-Insensitive Comparison
 - **Explanation:** Avoid string copies by comparing in-place.
- **Steps:**
 1. Iterate both strings, converting chars to lowercase.
 2. Compare characters directly.
 3. Return 0 if equal, else difference.
- **Complexity:** Time $O(n)$, Space $O(1)$ for strings of length n .

Algorithm Explanation

Naive case-insensitive comparison creates lowercase copies, using $O(n)$ extra space.

Instead, compare characters by converting to lowercase (using `tolower`) during iteration, avoiding allocations.

Time is O(n) for comparison, with O(1) space.

Coding Part (with Unit Tests)

```
#include <ctype.h>

int strCaseCmp(const char* s1, const char* s2) {
    while (*s1 && *s2) {
        if (tolower(*s1) != tolower(*s2)) return tolower(*s1) - tolower(*s2);
        s1++;
        s2++;
    }
    return tolower(*s1) - tolower(*s2);
}

// Unit tests
void testCaseInsensitiveCmp() {
    assertEquals(0, strCaseCmp("Hello", "hello"), "Test 534.1 - Case-insensitive equal");
    assertEquals(true, strCaseCmp("Hello", "world") < 0, "Test 534.2 - Case-insensitive different");
}
```

Best Practices & Expert Tips

- **Best Practices:**
 - Compare in-place to avoid copies.
 - Use tolower for case conversion.
 - Test with mixed-case strings.
- **Expert Tips:**
 - Explain: "In-place comparison saves memory."
 - In interviews, clarify: "Ask about locale support."
 - Suggest optimization: "Use SIMD for large strings."
 - Test edge cases: "Empty strings, mixed case."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for Debugging and Optimization problems 518 to 534:\n");
    testParseString();
    testDynamicArrayFix();
    testInterruptLatency();
    testPointerArithmeticFix();
    testMatrixTraversalOptimized();
    testBubbleSortFix();
    testPowerOptimization();
    testUninitializedFix();
    testBitCountOptimized();
    testTreeLeakFix();
    testTreeHeightOptimized();
    testInterruptHandlerFix();
    testCircularBufferOptimized();
    testArrayIndexingFix();
    testCodeSizeOptimization();
    testDanglingPointerFix();
    testCaseInsensitiveCmp();
    return 0;
}
```

Problem 535: Fix a Program with Incorrect Bit Manipulation

Issue Description

Fix a program with incorrect bit manipulation (e.g., wrong shift direction).

Problem Decomposition & Solution Steps

Input: Integer and bit operation (e.g., set bit at position).

Output: Correct bit manipulation result.

Approach: Fix shift operator (e.g., << instead of >>).

Algorithm: Correct Bit Set

Explanation: Use left shift to set bit at position.

Steps:

- Identify incorrect shift (e.g., >> for setting bit).
- Use $1 \ll pos$ to create mask.
- Set bit using OR ($|$).

Complexity: Time O(1), Space O(1).

Algorithm Explanation

Incorrect bit manipulation (e.g., right shift instead of left) produces wrong masks.

To set bit at position pos, use $1 \ll pos$ to create a mask and OR with the number.

Time is O(1) for bit operations, with O(1) space.

Coding Part (with Unit Tests)

```
#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>

void assertEquals(int expected, int actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

void assertBoolEquals(bool expected, bool actual, const char* testName) {
    printf("%s: %s\n", testName, expected == actual ? "PASSED" : "FAILED");
}

int setBit(int num, int pos) {
    return num | (1 << pos); // Fixed: Use left shift
}

// Unit tests
void testBitManipulationFix() {
```

```
    assertEquals(5, setBit(4, 0), "Test 535.1 - Set bit 0");
    assertEquals(6, setBit(4, 1), "Test 535.2 - Set bit 1");
}
```

Best Practices & Expert Tips

Best Practices:

- Verify shift direction (`<<` vs `>>`).
- Use masks for bit operations.
- Test with edge bit positions.

Expert Tips:

- Explain: "Correct shifts ensure proper bit setting."
- In interviews, clarify: "Ask about bit position range."
- Suggest optimization: "Use lookup tables for frequent ops."
- Test edge cases: "Pos=0, pos=31."

Problem 536: Optimize a Function to Handle Large Datasets Efficiently

Issue Description

Optimize a function (e.g., sum of array) for large datasets.

Problem Decomposition & Solution Steps

Input: Large array of integers.

Output: Sum with minimal memory and CPU usage.

Approach: Use pointer arithmetic and batch processing.

Algorithm: Optimized Array Sum

Explanation: Process in batches to improve cache locality.

Steps:

1. Use pointer to traverse array.
2. Sum in batches (e.g., 4 elements per loop).
3. Return total sum.

Complexity: Time $O(n)$, Space $O(1)$ for array size n .

Algorithm Explanation

Naive array sum accesses elements individually, causing cache misses for large datasets.

Using pointer arithmetic and processing multiple elements per loop (e.g., 4) improves cache locality.

Time is O(n), with O(1) space (excluding input).

Coding Part (with Unit Tests)

```
long long sumLargeArray(int* arr, int size) {
    long long sum = 0;
    int* end = arr + size;
    while (arr + 4 <= end) {
        sum += arr[0] + arr[1] + arr[2] + arr[3]; // Batch of 4
        arr += 4;
    }
    while (arr < end) sum += *arr++; return sum; }
```

// Unit tests

```
void testLargeArraySum() {
    int arr[] = {1, 2, 3, 4, 5};
    assertEquals(15, sumLargeArray(arr, 5), "Test 536.1 - Correct sum");
    int arr2[] = {1};
    assertEquals(1, sumLargeArray(arr2, 1), "Test 536.2 - Single element");
}
```

Best Practices & Expert Tips

Best Practices:

- Use pointer arithmetic for speed.
- Process in cache-friendly batches.
- Test with large arrays.

Expert Tips:

- Explain: "Batch processing reduces cache misses."
- In interviews, clarify: "Ask about dataset size."
- Suggest optimization: "Use SIMD for larger batches."
- Test edge cases: "Empty array, non-multiple-of-4."

Problem 537: Debug a Program with a Faulty State Machine

Issue Description

Fix a state machine with incorrect state transitions.

Problem Decomposition & Solution Steps

Input: State machine with events and states.

Output: Correct state transitions.

Approach: Validate transitions and update state.

Algorithm: Correct State Machine

Explanation: Ensure valid state transitions for each event.

Steps:

1. Define states and events (e.g., ON/OFF, TOGGLE).
2. Fix transition logic (e.g., TOGGLE switches state).
3. Update state only on valid events.

Complexity: Time O(1) per transition, Space O(1).

Algorithm Explanation

A faulty state machine may transition to invalid states (e.g., ON to ON on TOGGLE).

Define explicit states (e.g., ON=1, OFF=0) and validate transitions (e.g., TOGGLE flips state).

Time is O(1) per transition, with O(1) space.

Coding Part (with Unit Tests)

```
typedef enum { OFF, ON } State;
typedef enum { TOGGLE } Event;

State processEvent(State current, Event event) {
    if (event == TOGGLE) {
        return current == ON ? OFF : ON; // Fixed: Correct toggle
    }
    return current;
}

// Unit tests
void testStateMachineFix() {
    State state = OFF;
    state = processEvent(state, TOGGLE);
    assertEquals(ON, state, "Test 537.1 - Toggle to ON");
    state = processEvent(state, TOGGLE);
    assertEquals(OFF, state, "Test 537.2 - Toggle to OFF");
}
```

Best Practices & Expert Tips

- **Best Practices:**

- Define explicit states/events.
- Validate transitions.
- Test all state-event pairs.

Expert Tips:

- Explain: "Explicit transitions prevent errors."
- In interviews, clarify: "Ask about state machine type."
- Suggest optimization: "Use lookup tables for complex states."
- Test edge cases: "Invalid events, initial state."

Problem 538: Optimize a Function to Reduce Context Switches

Issue Description

Optimize a multi-threaded function to minimize context switches.

Problem Decomposition & Solution Steps

Input: Threads performing frequent synchronization.

Output: Reduced context switches with efficient locking.

Approach: Use spinlocks for short critical sections.

Algorithm: Spinlock-Based Synchronization

Explanation: Avoid blocking to reduce switches.

Steps:

1. Use a spinlock for short critical section.
2. Access shared resource with minimal locking.
3. Simulate with pthread mutex for portability.

Complexity: Time O(1) per lock, Space O(1).

Algorithm Explanation

Frequent mutex locking/unlocking causes context switches.

For short critical sections, a spinlock (simulated here with a mutex) reduces switches by busy-waiting briefly.

Time is O(1) per lock, with O(1) space.

Coding Part (with Unit Tests)

```
#include <pthread.h>

pthread_mutex_t spinlock;
int sharedData = 0;

void* spinlockThread(void* arg) {
    for (int i = 0; i < 100; i++) {
        pthread_mutex_lock(&spinlock);
        sharedData++;
        pthread_mutex_unlock(&spinlock);
    }
    return NULL;
}

// Unit tests
```

```

void testContextSwitchOptimization() {
    sharedData = 0;
    pthread_mutex_init(&spinlock, NULL);
    pthread_t t1, t2;
    pthread_create(&t1, NULL, spinlockThread, NULL);
    pthread_create(&t2, NULL, spinlockThread, NULL);
    pthread_join(t1, NULL);
    pthread_join(t2, NULL);
    assertEquals(200, sharedData, "Test 538.1 - Data incremented");
    pthread_mutex_destroy(&spinlock);
}

```

Best Practices & Expert Tips

Best Practices:

- Use spinlocks for short sections.
- Minimize lock contention.
- Test with multiple threads.

Expert Tips:

- Explain: "Spinlocks reduce context switches."
- In interviews, clarify: "Ask about critical section length."
- Suggest optimization: "Use atomic operations if possible."
- Test edge cases: "High contention, single thread."

Problem 539: Fix a Program with Incorrect Memory Alignment

Issue Description

Fix a program accessing misaligned memory causing undefined behavior.

Problem Decomposition & Solution Steps

Input: Structure with unaligned data access.

Output: Properly aligned memory access.

Approach: Use alignas or padding for alignment.

Algorithm: Aligned Structure Access

Explanation: Ensure structure fields align to word boundaries.

Steps:

1. Define structure with aligned fields.

2. Use `alignas` (C11) or padding.
3. Access fields safely.

Complexity: Time O(1), Space O(1) extra for padding.

Algorithm Explanation

Misaligned memory access (e.g., unaligned int in struct) causes performance issues or crashes on some architectures.

Use `alignas` (or manual padding) to align fields to word boundaries (e.g., 4 bytes for int).

Time is O(1) for access, with O(1) extra space.

Coding Part (with Unit Tests)

```
#include <stdalign.h>

typedef struct {
    char c;
    alignas(4) int x; // Fixed: Align int to 4 bytes
} AlignedStruct;

int accessAligned(AlignedStruct* s) {
    return s->x;
}

// Unit tests
void testMemoryAlignmentFix() {
    AlignedStruct s = {'a', 42};
    assertEquals(42, accessAligned(&s), "Test 539.1 - Aligned access");
}
```

Best Practices & Expert Tips

Best Practices:

- Align fields to word boundaries.
- Use `alignas` for portability.
- Test on strict architectures.

Expert Tips:

- Explain: "Alignment prevents undefined behavior."
- In interviews, clarify: "Ask about target architecture."
- Suggest optimization: "Reorder fields for minimal padding."
- Test edge cases: "Mixed data types, large structs."

Problem 540: Optimize a Function to Minimize I/O Operations

Issue Description

Optimize a function performing excessive I/O (e.g., file writes).

Problem Decomposition & Solution Steps

Input: Function writing data frequently.

Output: Buffered writes to reduce I/O.

Approach: Use a buffer to batch writes.

Algorithm: Buffered I/O

Explanation: Write data in chunks to reduce calls.

Steps:

1. Initialize a fixed-size buffer.
2. Append data to buffer.
3. Flush buffer when full (simulated).

Complexity: Time $O(n)$, Space $O(k)$ for buffer size k .

Algorithm Explanation

Frequent I/O calls (e.g., `printf`) are slow.

Buffer data in memory and flush in larger chunks to reduce I/O operations.

Simulate file writes with `printf` for portability.

Time is $O(n)$ for processing n bytes, with $O(k)$ space for the buffer.

Coding Part (with Unit Tests)

```
#define IO_BUFFER_SIZE 16

typedef struct {
    char buffer[IO_BUFFER_SIZE];
    int pos;
} IOBuf;

void initIOBuf(IOBuf* buf) {
    buf->pos = 0;
}

void writeBuffered(IOBuf* buf, char c) {
    buf->buffer[buf->pos++] = c;
    if (buf->pos == IO_BUFFER_SIZE) {
        printf("%.*s", IO_BUFFER_SIZE, buf->buffer); // Simulated flush
        buf->pos = 0;
    }
}

// Unit tests
void testIOOptimization() {
```

```
I0Buf buf;
initI0Buf(&buf);
writeBuffered(&buf, 'a');
assertEquals(1, buf.pos, "Test 540.1 - Buffer position updated");
}
```

Best Practices & Expert Tips

Best Practices:

- Use fixed-size buffers for I/O.
- Flush only when necessary.
- Test with large data.

Expert Tips:

- Explain: "Buffering reduces I/O calls."
- In interviews, clarify: "Ask about I/O constraints."
- Suggest optimization: "Tune buffer size to system."
- Test edge cases: "Full buffer, single byte."

Problem 541: Debug a Program with Incorrect Semaphore Usage

Issue Description

Fix a program with incorrect semaphore usage causing deadlock or overuse.

Problem Decomposition & Solution Steps

Input: Producer-consumer with semaphore.

Output: Correct semaphore signaling.

Approach: Ensure proper wait/signal order.

Algorithm: Correct Semaphore Usage

Explanation: Signal after producing, wait before consuming.

Steps:

- Initialize semaphores for producer/consumer.
- Fix wait/signal in producer/consumer threads.
- Use pthread mutex for simulation.

Complexity: Time O(1) per operation, Space O(1).

Algorithm Explanation

Incorrect semaphore usage (e.g., signaling before waiting) causes deadlock or incorrect synchronization.

Ensure producer signals after adding data and consumer waits before accessing.

Simulate with mutex for simplicity.

Time is O(1) per operation, with O(1) space.

Coding Part (with Unit Tests)

```
pthread_mutex_t semMutex;
int sharedBuffer = 0;

void* producer(void* arg) {
    pthread_mutex_lock(&semMutex);
    sharedBuffer++;
    pthread_mutex_unlock(&semMutex); // Fixed: Signal after produce
    return NULL;
}

void* consumer(void* arg) {
    pthread_mutex_lock(&semMutex); // Fixed: Wait before consume
    sharedBuffer--;
    pthread_mutex_unlock(&semMutex);
    return NULL;
}

// Unit tests
void testSemaphoreFix() {
    sharedBuffer = 0;
    pthread_mutex_init(&semMutex, NULL);
    pthread_t prod, cons;
    pthread_create(&prod, NULL, producer, NULL);
    pthread_create(&cons, NULL, consumer, NULL);
    pthread_join(prod, NULL);
    pthread_join(cons, NULL);
    assertEquals(0, sharedBuffer, "Test 541.1 - Producer-consumer balanced");
    pthread_mutex_destroy(&semMutex);
}
```

Best Practices & Expert Tips

Best Practices:

- Signal after producing, wait before consuming.
- Initialize semaphores correctly.
- Test with multiple producers/consumers.

Expert Tips:

- Explain: "Correct order prevents deadlock."
- In interviews, clarify: "Ask about semaphore type."
- Suggest optimization: "Use real semaphores for production."

- Test edge cases: "Empty buffer, multiple threads."

Problem 542: Optimize a Function to Reduce Interrupt Overhead

Issue Description

Optimize an interrupt handler to minimize overhead.

Problem Decomposition & Solution Steps

Input: Interrupt handler with excessive work.

Output: Minimal handler with deferred work.

Approach: Move non-critical work to main loop.

Algorithm: Minimal Interrupt Handler

Explanation: Set flag in handler, process in main.

Steps:

1. Set flag in handler (simulated).
2. Defer processing to main loop.
3. Clear flag after processing.

Complexity: Time O(1) for handler, Space O(1).

Algorithm Explanation

Interrupt handlers with heavy work increase overhead, delaying other interrupts.

Perform only critical tasks (e.g., set flag) in the handler, deferring work to the main loop.

Simulate with a function call.

Time is O(1) for handler, with O(1) space.

Coding Part (with Unit Tests)

```

volatile bool interruptPending = false;

void interruptHandlerOptimized(void) {
    interruptPending = true; // Minimal work
}

void processInterruptOptimized(void) {
    if (interruptPending) {
        interruptPending = false; // Deferred work
    }
}

```

```
// Unit tests
void testInterruptOverhead() {
    interruptPending = false;
    interruptHandlerOptimized();
    assertEquals(true, interruptPending, "Test 542.1 - Interrupt flag set");
    processInterruptOptimized();
    assertEquals(false, interruptPending, "Test 542.2 - Flag cleared");
}
```

Best Practices & Expert Tips

Best Practices:

- Minimize handler work.
- Defer processing to main loop.
- Test with frequent interrupts.

Expert Tips:

- Explain: "Minimal handlers reduce overhead."
- In interviews, clarify: "Ask about interrupt frequency."
- Suggest optimization: "Use hardware-specific optimizations."
- Test edge cases: "No interrupts, rapid interrupts."

Problem 543: Fix a Program with Incorrect Task Scheduling

Issue Description

Fix a program with incorrect task scheduling causing missed deadlines.

Problem Decomposition & Solution Steps

Input: Task scheduler with priority-based tasks.

Output: Correct priority scheduling.

Approach: Implement priority queue for tasks.

Algorithm: Priority-Based Scheduling

Explanation: Schedule highest-priority task first.

Steps:

1. Define tasks with priorities.
2. Fix scheduling to select highest priority.
3. Execute tasks in priority order.

Complexity: Time O(n) per schedule, Space O(n).

Algorithm Explanation

Incorrect scheduling (e.g., FIFO instead of priority) misses high-priority deadlines.

Use a priority queue (simulated as array sort) to select the highest-priority task.

Time is $O(n)$ for linear scan, with $O(n)$ space for tasks.

Coding Part (with Unit Tests)

```
typedef struct {
    int id;
    int priority;
} Task;

void scheduleTask(Task* tasks, int size, int* nextTask) {
    int maxPriority = -1, maxIndex = 0;
    for (int i = 0; i < size; i++) {
        if (tasks[i].priority > maxPriority) {
            maxPriority = tasks[i].priority;
            maxIndex = i;
        }
    }
    *nextTask = tasks[maxIndex].id;
}

// Unit tests
void testSchedulingFix() {
    Task tasks[] = {{1, 10}, {2, 5}};
    int nextTask;
    scheduleTask(tasks, 2, &nextTask);
    assertEquals(1, nextTask, "Test 543.1 - Highest priority scheduled");
}
```

Best Practices & Expert Tips

Best Practices:

- Use priority-based scheduling.
- Validate task priorities.
- Test with varied priorities.

Expert Tips:

- Explain: "Priority scheduling meets deadlines."
- In interviews, clarify: "Ask about scheduling algorithm."
- Suggest optimization: "Use heap for $O(\log n)$ scheduling."
- Test edge cases: "Equal priorities, no tasks."

Problem 544: Optimize a Function to Minimize Cache Misses

Issue Description

Optimize a function (e.g., matrix sum) to reduce cache misses.

Problem Decomposition & Solution Steps

Input: Matrix to sum.

Output: Sum with minimal cache misses.

Approach: Traverse in row-major order.

Algorithm: Cache-Friendly Matrix Sum

Explanation: Access rows sequentially for locality.

Steps:

- Traverse matrix row-by-row.
- Sum elements in cache-friendly order.
- Avoid column-major access.

Complexity: Time $O(m \times n)$, Space $O(1)$.

Algorithm Explanation

Column-major traversal causes cache misses due to non-sequential memory access.

Row-major traversal accesses contiguous memory, improving cache locality.

Time is $O(m \times n)$ for $m \times n$ matrix, with $O(1)$ space (excluding input).

Coding Part (with Unit Tests)

```
#define ROWS 2
#define COLS 3

int sumMatrixOptimized(int matrix[ROWS][COLS]) {
    int sum = 0;
    for (int i = 0; i < ROWS; i++)
        for (int j = 0; j < COLS; j++) // Row-major
            sum += matrix[i][j];
    return sum;
}

// Unit tests
void testCacheMissOptimization() {
    int matrix[ROWS][COLS] = {{1, 2, 3}, {4, 5, 6}};
    assertEquals(21, sumMatrixOptimized(matrix), "Test 544.1 - Correct sum");
}
```

Best Practices & Expert Tips

Best Practices:

- Use row-major traversal.
- Minimize non-sequential access.
- Test with large matrices.

Expert Tips:

- Explain: "Row-major reduces cache misses."
- In interviews, clarify: "Ask about cache line size."
- Suggest optimization: "Use loop tiling for large matrices."
- Test edge cases: "1×1 matrix, large matrices."

Problem 545: Debug a Program with Incorrect Mutex Handling

Issue Description

Fix a program with incorrect mutex handling causing data corruption.

Problem Decomposition & Solution Steps

Input: Threads accessing shared data with mutex.

Output: Correct mutex locking to prevent corruption.

Approach: Ensure mutex protects all shared access.

Algorithm: Correct Mutex Usage

Explanation: Lock mutex before accessing shared data.

Steps:

1. Initialize mutex.
2. Lock before read/write, unlock after.
3. Test with multiple threads.

Complexity: Time O(1) per lock, Space O(1).

Algorithm Explanation

Incorrect mutex usage (e.g., missing locks) causes race conditions.

Ensure all shared data accesses are protected by locking/unlocking the mutex.

Time is O(1) per lock, with O(1) space.

Coding Part (with Unit Tests)

```
pthread_mutex_t mutex;
int sharedValue = 0;

void* incrementThread(void* arg) {
    pthread_mutex_lock(&mutex); // Fixed: Lock before access
    sharedValue++;
    pthread_mutex_unlock(&mutex);
    return NULL;
}

// Unit tests
void testMutexFix() {
    sharedValue = 0;
    pthread_mutex_init(&mutex, NULL);
    pthread_t t1, t2;
    pthread_create(&t1, NULL, incrementThread, NULL);
    pthread_create(&t2, NULL, incrementThread, NULL);
    pthread_join(t1, NULL);
    pthread_join(t2, NULL);
    assertEquals(2, sharedValue, "Test 545.1 - Correct increment");
    pthread_mutex_destroy(&mutex);
}
```

Best Practices & Expert Tips

Best Practices:

- Lock mutex for all shared access.
- Minimize lock scope.
- Test with high contention.

Expert Tips:

- Explain: "Mutex ensures data integrity."
- In interviews, clarify: "Ask about lock granularity."
- Suggest optimization: "Use read-write locks for reads."
- Test edge cases: "Single thread, multiple locks."

Problem 546: Optimize a Function to Reduce Power Usage in Embedded Systems

Issue Description

Optimize a function to minimize power in an embedded system.

Problem Decomposition & Solution Steps

Input: Function with busy-waiting (e.g., polling).

Output: Low-power function with sleep states.

Approach: Replace polling with sleep-based waiting.

Algorithm: Sleep-Based Waiting

Explanation: Simulate sleep to reduce CPU usage.

Steps:

1. Replace polling loop with flag check.
2. Simulate sleep with conditional wait.
3. Process on event.

Complexity: Time O(1) per check, Space O(1).

Algorithm Explanation

Polling loops consume power by keeping the CPU active.

Replace with a sleep-based approach, checking a flag and “sleeping” (simulated here).

In real systems, use hardware sleep modes.

Time is O(1) per check, with O(1) space.

Coding Part (with Unit Tests)

```
volatile bool eventReady = false;

void waitForEvent(void) {
    if (eventReady) {
        eventReady = false; // Process event
    }
}

void triggerEvent(void) {
    eventReady = true;
}

// Unit tests
void testPowerUsageOptimization() {
    eventReady = false;
    triggerEvent();
    assertEquals(true, eventReady, "Test 546.1 - Event triggered");
    waitForEvent();
    assertEquals(false, eventReady, "Test 546.2 - Event processed");
}
```

Best Practices & Expert Tips

Best Practices:

- Avoid polling in embedded systems.

- Use sleep modes or flags.
- Test with frequent events.

Expert Tips:

- Explain: "Sleep reduces power usage."
- In interviews, clarify: "Ask about hardware sleep modes."
- Suggest optimization: "Use interrupts for events."
- Test edge cases: "No events, rapid events."

Problem 547: Fix a Program with Incorrect ADC Readings

Issue Description

Fix a program with incorrect ADC readings due to uninitialized variables.

Problem Decomposition & Solution Steps

Input: Simulated ADC function with uninitialized buffer.

Output: Correct ADC readings with initialization.

Approach: Initialize ADC buffer before reading.

Algorithm: Correct ADC Read

Explanation: Initialize buffer to zero before use.

Steps:

1. Simulate ADC read with array.
2. Initialize buffer to zero.
3. Store simulated readings.

Complexity: Time $O(n)$, Space $O(n)$ for n samples.

Algorithm Explanation

Uninitialized ADC buffers cause random readings.

Initialize the buffer to zero before storing simulated ADC values.

In real systems, ensure ADC configuration (e.g., sampling rate) is correct.

Time is $O(n)$ for n samples, with $O(n)$ space.

Coding Part (with Unit Tests)

```

#define ADC_SAMPLES 4

void readADC(int* buffer, int size) {
    for (int i = 0; i < size; i++) {
        buffer[i] = 100 + i; // Simulated ADC read
    }
}

void initADCBuffer(int* buffer, int size) {
    for (int i = 0; i < size; i++) buffer[i] = 0; // Fixed: Initialize
}

// Unit tests
void testADCFix() {
    int buffer[ADC_SAMPLES];
    initADCBuffer(buffer, ADC_SAMPLES);
    readADC(buffer, ADC_SAMPLES);
    assertIntEquals(100, buffer[0], "Test 547.1 - First reading correct");
    assertIntEquals(103, buffer[3], "Test 547.2 - Last reading correct");
}

```

Best Practices & Expert Tips

Best Practices:

- Initialize ADC buffers.
- Validate ADC configuration.
- Test with multiple samples.

Expert Tips:

- Explain: "Initialization prevents random readings."
- In interviews, clarify: "Ask about ADC hardware."
- Suggest optimization: "Use DMA for ADC reads."
- Test edge cases: "Zero samples, large buffers."

Problem 548: Optimize a Function to Minimize Memory Copy Operations

Issue Description

Optimize a function with excessive memory copies (e.g., array processing).

Problem Decomposition & Solution Steps

Input: Function copying array elements.

Output: Process in-place to reduce copies.

Approach: Modify array directly.

Algorithm: In-Place Array Processing

Explanation: Avoid temporary arrays for operations.

Steps:

1. Process array elements in-place (e.g., increment).
2. Avoid creating temporary arrays.
3. Return modified array.

Complexity: Time O(n), Space O(1).

Algorithm Explanation

Copying arrays (e.g., to temporary storage) wastes memory and time.

Process the array in-place (e.g., increment each element) to eliminate copies.

Time is O(n) for n elements, with O(1) space (excluding input).

Coding Part (with Unit Tests)

```
void incrementArrayInPlace(int* arr, int size) {  
    for (int i = 0; i < size; i++) {  
        arr[i]++; // In-place modification  
    }  
  
    // Unit tests  
    void testMemoryCopyOptimization() {  
        int arr[] = {1, 2, 3};  
        incrementArrayInPlace(arr, 3);  
        assertEquals(2, arr[0], "Test 548.1 - First element incremented");  
        assertEquals(4, arr[2], "Test 548.2 - Last element incremented");  
    }  
}
```

Best Practices & Expert Tips

Best Practices:

- Process arrays in-place.
- Avoid unnecessary allocations.
- Test with large arrays.

Expert Tips:

- Explain: "In-place processing saves memory."
- In interviews, clarify: "Ask about data modification rules."
- Suggest optimization: "Use SIMD for bulk operations."
- Test edge cases: "Empty array, single element."

Problem 549: Debug a Program with Incorrect SPI Communication

Issue Description

Fix a program with incorrect SPI communication (e.g., wrong data order).

Problem Decomposition & Solution Steps

Input: Simulated SPI transfer with incorrect byte order.

Output: Correct data transfer.

Approach: Fix byte order in SPI transfer.

Algorithm: Correct SPI Transfer

Explanation: Ensure MSB-first transfer (simulated).

Steps:

1. Simulate SPI transfer with array.
2. Fix byte order to MSB-first.
3. Validate transferred data.

Complexity: Time $O(n)$, Space $O(n)$ for n bytes.

Algorithm Explanation

Incorrect SPI communication (e.g., LSB-first instead of MSB-first) corrupts data.

Simulate SPI by sending bytes in MSB-first order (array copy).

In real systems, configure SPI hardware correctly.

Time is $O(n)$ for n bytes, with $O(n)$ space.

Coding Part (with Unit Tests)

```
void spiTransfer(uint8_t* data, int size, uint8_t* output) {
    for (int i = 0; i < size; i++) {
        output[i] = data[i]; // Fixed: MSB-first (simulated)
    }
}

// Unit tests
void testSPIFix() {
    uint8_t data[] = {0xAA, 0xBB};
    uint8_t output[2];
    spiTransfer(data, 2, output);
    assertEquals(0xAA, output[0], "Test 549.1 - First byte correct");
    assertEquals(0xBB, output[1], "Test 549.2 - Second byte correct");
}
```

Best Practices & Expert Tips

Best Practices:

- Ensure correct byte order.
- Validate SPI configuration.
- Test with multiple bytes.

Expert Tips:

- Explain: "Correct byte order ensures valid transfer."
- In interviews, clarify: "Ask about SPI mode."
- Suggest optimization: "Use DMA for SPI transfers."
- Test edge cases: "Empty data, single byte."

Problem 550: Optimize a Function to Reduce Execution Time in a Real-Time System

Issue Description

Optimize a function for real-time system to meet deadlines.

Problem Decomposition & Solution Steps

Input: Function with complex computation (e.g., filtering).

Output: Fast execution for real-time constraints.

Approach: Use lookup table for common values.

Algorithm: Lookup-Based Filtering

Explanation: Precompute results to avoid calculations.

Steps:

1. Precompute filter values in lookup table.
2. Access table instead of computing.
3. Return filtered result.

Complexity: Time $O(1)$ per lookup, Space $O(k)$ for table size k.

Algorithm Explanation

Real-time systems require predictable, fast execution.

Computing filter values (e.g., sine) is slow; precompute results in a lookup table for $O(1)$ access.

Time is O(1) per lookup, with O(k) space for the table.

Coding Part (with Unit Tests)

```
#define TABLE_SIZE 10

int lookupTable[TABLE_SIZE] = {0, 1, 4, 9, 16, 25, 36, 49, 64, 81};

int filterOptimized(int input) {
    if (input < 0 || input >= TABLE_SIZE) return 0;
    return lookupTable[input]; // Fast lookup
}

// Unit tests
void testRealTimeOptimization() {
    assertEquals(16, filterOptimized(4), "Test 550.1 - Lookup correct");
    assertEquals(0, filterOptimized(10), "Test 550.2 - Out of bounds");
}
```

Best Practices & Expert Tips

Best Practices:

- Use lookup tables for predictable timing.
- Validate input range.
- Test with real-time constraints.

Expert Tips:

- Explain: "Lookups ensure real-time performance."
- In interviews, clarify: "Ask about input range."
- Suggest optimization: "Use interpolation for larger tables."
- Test edge cases: "Invalid inputs, table bounds."

Main Function to Run All Tests

```
int main() {
    printf("Running tests for Debugging and Optimization problems 535 to 550:\n");
    testBitManipulationFix();
    testLargeArraySum();
    testStateMachineFix();
    testContextSwitchOptimization();
    testMemoryAlignmentFix();
    testI00ptimization();
    testSemaphoreFix();
    testInterruptOverhead();
    testSchedulingFix();
    testCacheMissOptimization();
    testMutexFix();
    testPowerUsageOptimization();
    testADCfix();
    testMemoryCopyOptimization();
    testSPIFix();
    testRealTimeOptimization();
    return 0;
}
```