Assignment Two

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1 Selection Sort

1.1 The Algorithm

Selection sort is a sorting algorithm that, for each iteration of the array, selects the smallest (or largest) element of the unsorted part of the array and places the element into its sorted position. As shown in the pseudocode for the sort in Algorithm 1, selection sort works with the subset of the array in the range $[i,\ n)$ in each iteration because the elements in the indices less than i are already sorted and do not have to be checked. Thus, as more elements get sorted, the quicker each iteration becomes because a smaller portion of the array is compared until $i = n - 2$, which is the final iteration of the algorithm. Selection sort is also very consistent in that it runs in the same amount of time regardless of the order of the elements and has both a best and worst case of $O(n^2)$, which will be analyzed in further detail in Section 1.2.

Algorithm 1 Selection Sort Algorithm

```
procedure SelectionSort(arr)
    for i ← 0, n − 2 do    // Iterate through the second to last element as an array of size 1 is sorted
        smallestIndex ← i
        for j ← i + 1, n − 1 do    // Iterate through the remainder of the array
            if arr[j] < arr[smallestIndex] then
                smallestIndex ← j    // Set the new smallest index if a smaller element is found
            end if
        end for
        swap(arr, i, smallestIndex)    // Place the smallest item in the subarray into its sorted place
    end for
end procedure
```

1.2 Asymptotic Analysis and Comparisons

Listing 1 contains the C++ code implementing selection sort on lines 3-24. Line 3 defines a loop that iterates $n - 1$ times and contains 2 assignments and a comparison, all of which operate in constant time for each iteration. Thus, line 3 will take $(n - 1) * C_1$ time, where C_1 is the time needed for each of the operations.

Next, line 5 is an assignment, which runs in constant time and executes $n-1$ times because it is in the outer loop, resulting in a time of $(n-1)*C_2$, where C_2 is the time needed for the assignment. Line 8, similar to line 3, defines a loop with 3 constant time expressions, which can be marked as C_3. However, since it is nested inside of the loop on line 3, the total number of iterations of the inner loop is more complex. In the first iteration of the outer loop, the inner loop runs $n-1$ times. From there, each corresponding iteration of the outer loop results in one less iteration of the inner loop with a minimum of 1 pass on the inner loop when $i = n-2$. Therefore, the total number of times the inner loop on line 8 will be called is $\sum_{k=1}^{n-1} k$, which by the formula for the sum of the first N natural numbers, is equal to $\frac{(n-1)(n-1+1)}{2} = \frac{1}{2}n^2 - \frac{1}{2}n$. Thus, the total time to execute line 8 is $(\frac{1}{2}n^2 - \frac{1}{2}n) * C_3$. Next, line 10 contains a comparison that, since it is nested inside the inner loop, will run in $(\frac{1}{2}n^2 - \frac{1}{2}n) * C_4$ time, where C_4 is the time needed to make the comparison. Line 12 is a simple assignment and, just like line 10, will run in $(\frac{1}{2}n^2 - \frac{1}{2}n) * C_5$, where C_5 is the time to perform the assignment. The comparison and assignment on lines 15 and 16 are purely for collecting data and not part of the algorithm and, therefore, will be excluded from the asymptotic analysis of selection sort. Line 18 is the end of the inner loop, and represents an unconditional branch back to the top of the loop, which means it runs the same number of iterations as the loop, which is $(\frac{1}{2}n^2 - \frac{1}{2}n) * C_6$, where C_6 is the time needed to execute the branch. Next, lines 22-24 are all assigments, which run in constant time, and are located in the outer loop. Thus, they run in $(n-1)*C_7$ time, where C_7 is the time needed to perform the swap. Lastly, line 24 is the close and unconditional branch for the outer loop, which will run in $(n-1)*C_8$ time, where C_8 is the time to execute the unconditional branch. Overall, when adding up the runtimes of each line and dropping the constants, the sum is $4*(n-1) + 4*(\frac{1}{2}n^2 - \frac{1}{2}n) = 2n^2 + 2n - 4 \approx n^2 + n$ is $O(n^2)$.

As shown in Table 5.1, selection sort is very consistent with the number of comparisons made as, regardless of the state of the list, it always makes $\frac{1}{2}n^2 - \frac{1}{2}n$ comparisons. This is no coincidence as it is also the number of times the algorithm's inner loop iterates, which means that the selection sort will run very consistently for all lists, no matter the state of the array prior to running the algorithm.

2 Insertion Sort

2.1 The Algorithm

Insertion sort in a sorting algorithm that places an element in its sorted position by sliding previously sorted elements over until the sorted position is found. As shown in Algorithm 2, the element that is being sorted is only compared to elements in positions $[0, i-1]$ because these are the elements that have been worked with so far and are known to be in order. Therefore, the elements in this area, as described before, are shifted over until one is less than the value being sorted or until $j < 0$, which will break out of the while loop. Unlike selection sort, the performance of insertion sort varies based on the state of the input array, which will be explored more in detail in Section 2.2.

Algorithm 2 Insertion Sort Algorithm

procedure InsertionSort(arr)
  for $i \leftarrow 1,\ n-1$ **do** *// Start at index 1 because the first element is already sorted*
    $currentVal \leftarrow arr[i]$
    $j \leftarrow i-1$
    while $j \geq 0$ **and** $currentVal < arr[j]$ **do** *// Find the position to place the element*
      $arr[j+1] \leftarrow arr[j]$ *// Shift the element over because it is greater than the current value*
      $j \leftarrow j-1$
    end while
    $arr[j+1] \leftarrow currentVal$ *// Place the element in its sorted position*
  end for
end procedure

2.2 Asymptotic Analysis and Comparisons

The code implementation of insertion sort is in Listing 2 on lines 4-33. The worst case for insertion sort is when the list is in reverse order. In this scenario, every element that gets compared to in the inner loop will be greater than the element being sorted, which means that the inner loop will run until $j < 0$ so the item gets placed in the front of the array. As explored in Section 1.2, the total number of iterations in the case of a reversed list for insertion sort will be $\sum_{k=1}^{n-1} k$, which solves to be an $O(n^2)$ runtime. However, the best case for insertion sort is when the array is already sorted. In this situation, the outer loop will still be run, but the inner loop will never be entered because the element being sorted is always going to be greater than or equal to the element in the position before it. Therefore, since the array is only being iterated through from the outer loop, the runtime of insertion sort improves to $\Omega(n)$.

In Table 5.1, insertion sort is shown to have 3 very different outcomes for the lists that were used for testing relative to selection sort. First, insertion sort used about half the number of comparisons as selection sort for a list of 666 shuffled magic items. This is because the inner loop of insertion sort may terminate when $arr[j] < currentVal$ (see line 16 in Listing 2) and in a randomly shuffled list, the probability of $arr[j] < currentVal$ will be around 50%. Therefore, insertion sort will on average be about 50% more efficient than selection sort, but is still classified as $O(n^2)$ beause it is still running at a function of n^2. Next, when the list is already sorted, insertion sort only makes $n - 1$ comparisons. As previously mentioned, the best case for insertion sort is $\Omega(n)$ because the inner loop will never be entered as the second condition for $arr[j] < currentVal$ will always return false. This means there will be only 1 comparison made for each iteration of the outer loop, which equates to $n - 1$ comparisions. Lastly, the worst case for insertion sort is when the list is in reverse order because every element will have to compare itself with all of the elements in the sorted portion of the array. This causes insertion sort to have the same number of comparisons as selection sort for a reversed list at $\frac{1}{2}n^2 - \frac{1}{2}n$, which is also the same number of iterations as the inner loop for insertion sort and makes insertion sort $O(n^2)$.

3 Merge Sort

3.1 The Algorithm

Merge sort is a divide and conquer sorting algorithm that continues to divide an array up until it has n subarrays of size 1, which, by definition, are all sorted. From there, the subarrays are merged together by comparing the elements in each subarray to determine the sorted order of the combined subarrays. Eventually, the full array will be merged back together will all of the elements fully sorted. As displayed in Algorithm 3 in the $MergeSort$ procedure, since the sort is a divide and conquer algorithm, merge sort takes advantage of recursion to make the problem smaller until it reaches its base case of $length(arr) <= 1$, which is shown on line 2. Additionally, on lines 4 and 5, merge sort always divides a given array in half, which makes its performance very predictable and consistent, which will be discussed more in detail in Section 3.2.

3.2 Asymptotic Analysis and Comparisons

The C++ implementation of merge sort can be found in Listing 3, more specifically lines 6-24. As shown on lines 17 and 20, the array is always split in half for each successive call of merge sort until the subarray is of length 1. The recursion tree for merge sort is displayed in Figure 3.1.

As shown in the recursion tree, the array is broken up into smaller subarrays until the subarray is small enough that it is solved using a constant time operation. Additionally, the last call is on an array of size $\frac{n}{2^k}$. Since the array is being divided in half each time, k is the number of levels in the tree, which is $log_2 n$.

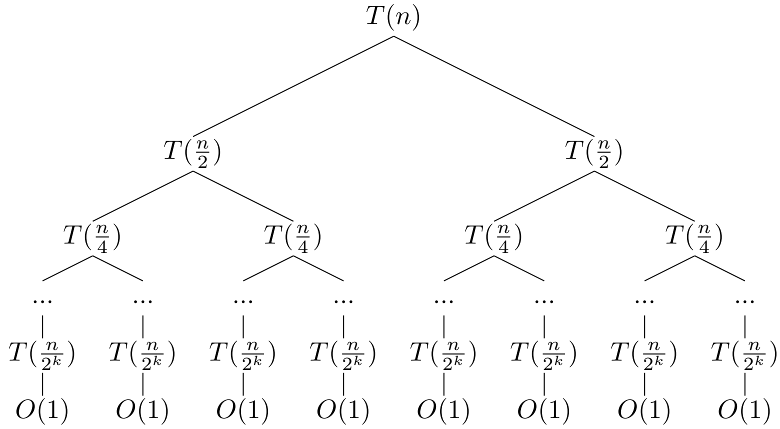
Next, after the 2 subarrays are sorted, they are merged together for the conquer phase, which is on lines 26-74 of Listing 3. The beginning of the function (lines 28-36) are all assignments, which run in constant

Algorithm 3 Merge Sort Algorithm

```
procedure MergeSort(arr)
    if length(arr) > 1 then    // An array of size 1 is already sorted
        mid = floor((length(arr))/2)    // Get the middle index of the array for splitting it in half
        MergeSort(arr[0 : mid])    // Perform merge sort on the first half of the array (index 0 - mid, inclusive)
        MergeSort(arr[mid + 1 : length(arr) − 1])    // Perform merge sort on the second half of the array
        Merge(arr, mid)    // Merge the 2 subarrays together in order
    end if
end procedure

procedure Merge(arr, mid)
    leftIndex ← 0    // Index for the left subarray
    rightIndex ← mid + 1    // Index for the right subarray
    newArr ← [ ]
    for i ← 0, length(arr) − 1 do    // Iterate through all elements
        if rightIndex >= length(arr) then    // All the right subarray items are already in newArr
            newArr[i] = arr[leftIndex]    // Add the next item from the left subarray
            leftIndex + +
        else if leftIndex > mid then    // All the right subarray items are already in newArr
            newArr[i] = arr[rightIndex]    // Add the next item from the right subarray
            rightIndex + +
        else if arr[leftIndex] < arr[rightIndex] then    // The next element from the left subarray is less than the next element from the right subarray
            newArr[i] = arr[leftIndex]    // Add the next item from the left subarray
            leftIndex + +
        else
            newArr[i] = arr[rightIndex]    // Add the next item from the right subarray
            rightIndex + +
        end if
    end for
    for j ← 0, length(arr) − 1 do
        arr[j] ← newArr[j]    // Transfer the sorted elements to the original array
    end for
end procedure
```

Figure 3.1: Recursion tree for merge sort.



time. Next, there is a for loop that iterates through the length of the subarray being merged. The body is a large if-else block with comparisons and assignments, which is all $O(1)$ and makes the loop it is contained in run in $O(n)$ time. Lastly, lines 71-73 define a loop that iterates through each element in the subarray, which is also $O(n)$. Therefore, the runtime for the merge function is about $2n + 1$, which is $O(n)$.

At each level of the tree, the merge function will work with exactly n elements. For instance, in the first level of the tree, the left subarray will be merged from 2 subarrays of size $\frac{n}{4}$, which means that the merge function will work with $\frac{n}{2}$ elements. However, since there are 2 subarrays of size $\frac{n}{2}$, the merge function will be called again to handle the other subarray and, therefore, the level will end up merging n elements. Thus, one can multiply n by the number of levels to get the runtime complexity, which is $O(n * log_2 n)$.

As shown in Table 5.1, merge sort is significantly more efficient at sorting the magic items by using around 5,500 comparisons, which is a little less than the algorithm's runtime of $O(n * log_2 n)$. The reason for the number of comparisons being less than 6246.67 ($666 * log_2 666$) is explained on lines 41 and 45 in Listing 3 as the merging of an entire subarray before the other will result in the algorithm merging the remainder of the other subarray without needing to compare the elements. Regardless, the number of comparisons is still not far from $O(n * log_2 n)$. Additionaly, merge sort is very similar to selection sort in that it will perform consistently for any permutation of an array of size n. This is shown in the smaller test cases, which perform almost identically despite being in differing orders. Also, one interesting point to note is the performance of insertion sort versus merge sort for the already sorted list. Since insertion sort has a best case of $\Omega(n)$, it is more efficient than merge sort when the array is already mostly sorted. This leads to the idea of hybrid algorithms that may use one sort up until a certain point and switch to a second algorithm that is more efficient in the end game of the sorting process.

4 Quicksort

4.1 The Algorithm

Quicksort is similar to merge sort in that it is a divide and conquer sorting algorithm. Rather than dividing an array in half and then eventually merging the 2 subarrays back together, quicksort divides an array into 2 partitions around a pivot value so that all elements in the left partition are less than the pivot value and all elements in the right partition are greater than the pivot value. In other words, the elements are getting sorted as they are being divided up, which will result in the entire array being sorted once there are n subarrays of size 1. The performance of quicksort is also dependent on the method used to choose the pivot, which will be discussed in detail in Section 4.2.

Algorithm 4 Quicksort Algorithm

```
procedure QUICKSORT(arr)
    if length(arr) > 1 then    // An array of size 1 is already sorted
        p ← choosePivotIndex(arr)    // More details on how to choose a pivot element in Section 4.2
        newPivotIndex ← Partition(arr, p)    // Partition the array around the pivot
        Quicksort(arr[0 : newPivotIndex − 1])    // Run quicksort on the left partition
        Quicksort(arr[newPivotIndex + 1 : length(arr) − 1])    // Run quicksort on the right partition
    end if
end procedure

procedure PARTITION(arr, pivotIndex)
    swap(arr, pivotIndex, length(arr) − 1)    // Move the pivot to the end of the array
    lastLowPartitionIndex ← −1    // Initially no elements are in the low partition
    for i ← 0, length(arr) − 2 do    // Iterate through all but the pivot
        if arr[i] < arr[length(arr) − 1] then
            lastLowPartitionIndex + +    // Found another element for the low partition
            swap(arr, i, lastLowPartitionIndex)    // Place the element in the low partition
        end if
    end for
    swap(arr, length(arr) − 1, lastLowPartitionIndex + 1)    // Place the pivot in the appropriate place
    returnlastLowPartitionIndex + 1
end procedure
```

4.2 Asyptotic Analysis and Comparisons

The C++ implementation for quicksort and partitioning can be found in Listing 4. Since quicksort divides the array into 2 partitions and continues to work until the subarray is of size 1, the recursion tree for quicksort will be the same as merge sort (see Figure 3.1) assuming that the partitions are balanced and approximately the same size. Additionally, the work done to partition the array is $O(n)$ because it iterates through the entire array once (length of subarrays * number of subarrays in the level of the tree). Therefore, on average, the runtime complexity for quicksort will be the same as merge sort at $O(n * log_2 n)$.

However, as mentioned in Section 4.1, how the pivot is chosen will impact the runtime in the worst case scenario, which is an already sorted array or a reversed array. In these situations, if the pivot is either the first or last element in the array, the partitions would be of size 0 and size $n - 1$ because the pivot is either going to be greater than all the elements or less than all the elements. As a result, the algorithm would work like selection sort in that it would make sure the one element gets swapped into place and have to iterate through the rest of the array, which is not known to be sorted. Therefore, in these situations, quicksort downgrades to $O(n^2)$.

Therefore, the main problem with quicksort is how to guarantee somewhat balanced partitions. One solution is to use the median of 3 method to pick the partition. The implementation for this approach is found on lines 21-71 of Listing 4. Instead of choosing 1 pivot, the median of 3 approach picks 3 random elements in the array for potential use as the actual pivot and then uses the middle element as the pivot. As a result, there will always be at least 1 element in each partition for all levels of the recursion tree. Even if the partitions are unbalanced, quicksort will still run in linearithmic time, but the logarithm will just have a different base to represent the uneven divide in the elements, and $O(n)$ work will still be done for partitioning at each level of the recursion tree. Also, as shown in the implementation of the median of 3 approach, only random number computations, assignments, and comparisons are needed, which all run in constant time and do not impact the overall runtime complexity of quicksort.

As shown in Table 5.1, both the number of comparisons and runtime are most similar to those for merge sort, at approximately $n * log_2 n$ comparisons, which lines up with the algorithm's complexity of $O(n * log_2 n)$. The number of comparisons for quicksort, however, is greater than that for merge sort for 2 main reasons: quicksort does not have an autocomplete on its partition like merge sort has for merging and there is a tradeoff with the number of comparisons made to prevent $O(n^2)$ runtime. First, since quicksort partitions the array when dividing, every element has to be compared to ensure it is placed in the correct partition. This is very different from merge sort, which just places the rest of a subarray into the merged array when the other subarray being merged is completely merged (lines 41-49 of Listing 3). Also, as shown in lines 36-71, several comparisons have to be made to pick a pivot that prevents quicksort from downgrading to $O(n^2)$, which is a tradeoff that is made because of how much more efficient $O(n * log_2 n)$ is compared to $O(n^2)$. Also, despite having more comparisons than merge sort, quick sort often ran in less time. Although constants are dropped when doing a Big-Oh analysis, the merge function has much larger constants than the partition function for quicksort. As shown in the merge function on lines 26-74 of Listing 3, there are 2 loops that iterate through the length of the merged subarray, which means that merge sort actually does $2n$ work for each level of the recursion tree. On the other hand, quicksort's partition function on lines 82-114 of Listing 4 only iterates through the array once and does n work at each level of the tree, which can save more time as the size of the array increases.

5 Appendix

5.1 Comparisons Table

Algorithm	List	Comparisons	Time
Selection Sort	666 magic items, shuffled	221445	19916376 ns
	20 Yankees greats, sorted	190	12564 ns
	20 Yankees greats, reversed	190	12104 ns
Insertion Sort	666 magic items, shuffled	112474	8952454 ns
	20 Yankees greats, sorted	19	1586 ns
	20 Yankees greats, reversed	190	13012 ns
Merge Sort	666 magic items, shuffled	5404	1069105 ns
	20 Yankees greats, sorted	48	9518 ns
	20 Yankees greats, reversed	40	6164 ns
Quicksort	666 magic items, shuffled	8092	951497 ns
	20 Yankees greats, sorted	72	8052 ns
	20 Yankees greats, reversed	75	8463 ns

Table 5.1: A table of the number of comparisons made and time to complete each sort on a variety of lists.

5.2 Selection Sort

```
void selectionSort(StringArr* data, int* comparisons) {
    // Iterate through the second to last element because the last element will already be sorted as is
    for (int i = 0; i < data->length - 1; i++) {
        // The smallest index is going to start as the start of the subset of the list
        int smallestIndex = i;

        // Iterate through the rest of the list
        for (int j = i + 1; j < data->length; j++) {
            // Compare the current element to the current smallest element in the subset
            if (data->arr[smallestIndex].compare(data->arr[j]) > 0) {
                // If the current element comes first, make it the new smallest element
                smallestIndex = j;
            }
```

```
            // Increment comparisons
            if (comparisons != nullptr) {
                (*comparisons)++;
            }
        }

        // Put the smallest index in its respective place
        std::string temp = data->arr[i];
        data->arr[i] = data->arr[smallestIndex];
        data->arr[smallestIndex] = temp;
    }
}
```

Listing 1: Selection Sort (C++)

5.3 Insertion Sort

```
void insertionSort(StringArr* data, int* comparisons) {
    // We begin with the second element because an array of size 1 is already sorted
    // So no need to check on the first element
    for (int i = 1; i < data->length; i++) {
        // Save the current element for later use
        std::string currentVal = data->arr[i];

        // Comparisons are going to start with the previous index
        int j = i - 1;

        // Continue until j is a valid index (< 0) or until we found an element that is less than the
        // current element that is being sorted
        while (j >= 0 && currentVal.compare(data->arr[j]) < 0) {
            // We made a comparison so increment it
            if (comparisons != nullptr) {
                (*comparisons)++;
            }

            // Shift the compared element over 1 to make room for the element being sorted
            data->arr[j + 1] = data->arr[j];
            j--;
        }

        // After the loop, we want to increment comparisons only if j >= 0 because
        // if j < 0, then the boolean expression would have immediately returned false without making
        // a comparison
        if (j >= 0 && comparisons != nullptr) {
            (*comparisons)++;
        }

        // Place the value in its proper place
        data->arr[j + 1] = currentVal;
    }
}
```

Listing 2: Insertion Sort (C++)

5.4 Merge Sort

```
void mergeSort(StringArr* data, int* comparisons) {
    // Sort the entire array
    mergeSortWithIndices(data, 0, data->length - 1, comparisons);
}

void mergeSortWithIndices(StringArr* data, int start, int end, int* comparisons) {
    // Base case is array of size 1 or size 0 (if the list is completely empty)
```

```cpp
    if (start >= end) {
        // No work is needed
        return;
    }

    // Get the midpoint for the sections
    int mid = (start + end) / 2;

    // Sort the first half
    mergeSortWithIndices(data, start, mid, comparisons);

    // Sort the second half
    mergeSortWithIndices(data, mid + 1, end, comparisons);

    // Merge both halves
    merge(data, start, end, mid, comparisons);
}

void merge(StringArr* data, int start, int end, int mid, int* comparisons) {
    // The left half is at the start
    int leftIndex = start;

    // The right half starts at the midpoint + 1
    int rightIndex = mid + 1;

    // Get the size of the array that the 2 halves will merge into
    // and create the merged sub array
    int subArrLength = end - start + 1;
    std::string newSubArr[subArrLength];

    // Iterate through the entire merged subarray
    for (int i = 0; i < subArrLength; i++) {
        // If the rightIndex > end, then the entire right half is already merged
        if (rightIndex > end) {
            // Add the next element from the left half
            newSubArr[i] = data->arr[leftIndex];
            leftIndex++;
        } else if (leftIndex > mid) { // If the leftIndex > mid, then the entire left half is already merged
            // Add the next element from the right half
            newSubArr[i] = data->arr[rightIndex];
            rightIndex++;
        } else if (data->arr[leftIndex].compare(data->arr[rightIndex]) < 0) { // Compare the 2 elements from each half
            // Add the next element from the left half
            newSubArr[i] = data->arr[leftIndex];
            leftIndex++;

            // Increment the number of comparisons made
            if (comparisons != nullptr) {
                (*comparisons)++;
            }
        } else {
            // Add the next element from the right half
            newSubArr[i] = data->arr[rightIndex];
            rightIndex++;

            // Make sure to increment comparisons because a comparison was made in the last else-if condition
            if (comparisons != nullptr) {
                (*comparisons)++;
            }
        }
    }

```

```
    // Transfer the merged subarray to the actual array
    for (int j = 0; j < subArrLength; j++) {
        data->arr[start + j] = newSubArr[j];
    }
}
```

Listing 3: Merge Sort (C++)

5.5 Quicksort

```
void quickSort(StringArr* data, int* comparisons) {
    // Run the helper function for the entire array
    quickSortWithIndices(data, 0, data->length - 1, comparisons);
}

void quickSortWithIndices(StringArr* data, int start, int end, int* comparisons) {
    // Base case for arrays of size 1 or 0
    if (start >= end) {
        // No work is needed
        return;
    }

    // The variable used for the pivot index
    int pivotIndex;

    if (end - start < 3) {
        // Array of size 2 should take either element as it will need exactly 1 more divide
            regardless of the pivot
        pivotIndex = start;
    } else {
        // Initialize random seed
        srand(time(NULL));

        // Generate 3 random indices that are all unique to use to pick a pivot
        int pivotChoice1 = rand() % (end - start) + start;
        int pivotChoice2 = rand() % (end - start) + start;
        while (pivotChoice2 != pivotChoice1) {
            pivotChoice2 = rand() % (end - start) + start;
        }
        int pivotChoice3 = rand() % (end - start) + start;
        while (pivotChoice3 != pivotChoice1 && pivotChoice3 != pivotChoice2) {
            pivotChoice3 = rand() % (end - start) + start;
        }

        // Find the median of the 3 indices picked and set the pivot index appropriately
        // This will hopefully create balanced partitions regardless of the status of the
            array
        if (data->arr[pivotChoice1] <= data->arr[pivotChoice2] && data->arr[pivotChoice1] >=
             data->arr[pivotChoice3]) {
            pivotIndex = pivotChoice1;

            // We made 2 comparisons to choose the pivot
            if (comparisons != nullptr) {
                *comparisons += 2;
            }
        } else if (data->arr[pivotChoice1] <= data->arr[pivotChoice3] && data->arr[
            pivotChoice1] >= data->arr[pivotChoice2]) {
            pivotIndex = pivotChoice1;

            // Estimated 4 comparisons to choose the pivot
            if (comparisons != nullptr) {
                *comparisons += 4;
            }
        } else if (data->arr[pivotChoice2] <= data->arr[pivotChoice1] && data->arr[
            pivotChoice2] >= data->arr[pivotChoice3]) {
```

```
            pivotIndex = pivotChoice2;

            // Estimated 6 comparisons to choose the pivot
            if (comparisons != nullptr) {
                *comparisons += 6;
            }
        } else if (data->arr[pivotChoice2] >= data->arr[pivotChoice1] && data->arr[pivotChoice2] <= data->arr[pivotChoice3]) {
            pivotIndex = pivotChoice2;

            // Estimated 8 comparisons to choose the pivot
            if (comparisons != nullptr) {
                *comparisons += 8;
            }
        } else {
            pivotIndex = pivotChoice3;

            // Estimated 8 comparisons to choose the pivot
            if (comparisons != nullptr) {
                *comparisons += 8;
            }
        }
    }

    // Partition the data around the pivot
    int partitionOut = partition(data, start, end, pivotIndex, comparisons);

    // Sort each of the partitions
    quickSortWithIndices(data, start, partitionOut - 1, comparisons);
    quickSortWithIndices(data, partitionOut + 1, end, comparisons);
}

int partition(StringArr* data, int start, int end, int pivotIndex, int* comparisons) {
    // Move the pivot to the end of the subarray
    std::string pivot = data->arr[pivotIndex];
    data->arr[pivotIndex] = data->arr[end];
    data->arr[end] = pivot;

    // We initially do not have any items in the low partition, so make it less than the start
    int lastLowPartitonIndex = start - 1;

    // Iterate through the subarray, excluding the pivot
    for (int i = start; i <= end - 1; i++) {
        // Check if the element is less than the pivot
        if (data->arr[i].compare(pivot) < 0) {
            // We have an element for the low partition
            lastLowPartitonIndex++;

            // Move the element to the end of the low partition
            std::string temp = data->arr[i];
            data->arr[i] = data->arr[lastLowPartitonIndex];
            data->arr[lastLowPartitonIndex] = temp;
        }
        // Incement comparisons
        if (comparisons != nullptr) {
            (*comparisons)++;
        }
    }

    // Move the pivot into its appropriate place between the partitions
    data->arr[end] = data->arr[lastLowPartitonIndex + 1];
    data->arr[lastLowPartitonIndex + 1] = pivot;

    return lastLowPartitonIndex + 1;
```

```
}
```

Listing 4: Quicksort (C++)