Divide And Conquer Sorting

• Divide and Conquer:
  • Recursive algorithm design technique
  • Solve a large problem by breaking it up into smaller versions of the same problem
Divide and Conquer

• **Base Case:**
  • If the problem is “small” then solve directly and return

• **Divide:**
  • Break the problem into subproblem(s), each smaller instances

• **Conquer:**
  • Solve subproblem(s) recursively

• **Combine:**
  • Use solutions to subproblems to solve original problem
def my_DandC(problem):
    // Base Case
    if (problem.size() <= small_value):
        return solve(problem); // directly solve (e.g., brute force)
    
    // Divide
    List subproblems = divide(problem);

    // Conquer
    solutions = new List();
    for (sub : subproblems):
        subsolution = my_DandC(sub);
        solutions.add(subsolution);
    
    // Combine
    return combine(solutions);
Merge Sort

• **Base Case:**
  • If the list is of length 1 or 0, it’s already sorted, so just return it

• **Divide:**
  • Split the list into two “sublists” of (roughly) equal length

• **Conquer:**
  • Sort both lists recursively

• **Combine:**
  • **Merge** sorted sublists into one sorted list
Merge Sort In Action!

Sort between indices \( \text{low} \) and \( \text{high} \)

<table>
<thead>
<tr>
<th>5</th>
<th>8</th>
<th>2</th>
<th>9</th>
<th>4</th>
<th>1</th>
<th>3</th>
<th>7</th>
</tr>
</thead>
</table>

\( \text{low} \) \hspace{2cm} \text{high} \n
Base Case: if \( \text{low} == \text{high} \) then that range is already sorted!

Divide and Conquer: Otherwise call \text{mergesort} on ranges \((\text{low}, \frac{\text{low}+\text{high}}{2})\) and \((\frac{\text{low}+\text{high}}{2} + 1, \text{high})\)

<table>
<thead>
<tr>
<th>5</th>
<th>8</th>
<th>2</th>
<th>9</th>
<th>4</th>
<th>1</th>
<th>3</th>
<th>7</th>
</tr>
</thead>
</table>

\( \text{low} \) \hspace{2cm} \frac{\text{low}+\text{high}}{2} \hspace{2cm} \frac{\text{low}+\text{high}}{2} + 1 \hspace{2cm} \text{high} \n
After Recursion:

<table>
<thead>
<tr>
<th>2</th>
<th>5</th>
<th>8</th>
<th>9</th>
<th>1</th>
<th>3</th>
<th>4</th>
<th>7</th>
</tr>
</thead>
</table>

\( \text{low} \) \hspace{2cm} \text{high} \
Create a **new array to merge into**, and 3 pointers/indices:

- **L_next**: the smallest “unmerged” thing on the left
- **R_next**: the smallest “unmerged” thing on the right
- **M_next**: where the next smallest thing goes in the merged array

One-by-one: put the smallest of **L_next** and **R_next** into **M_next**, then advance both **M_next** and whichever of **L/R** was used.
Merge Sort Pseudocode

void mergesort(myArray){
    ms_helper(myArray, 0, myArray.length());
}

void ms_helper(myArray, low, high){
    if (low == high){return;} // Base Case
    mid = (low+high)/2;
    ms_helper(low, mid);
    ms_helper(mid+1, high);
    merge(myArray, low, mid, high);
}

void merge(myArray, low, mid, high){
    merged = new int[high-low+1]; // or whatever type is in myArray
    l_next = low;
    r_next = high;
    m_next = 0;
    while (l_next <= mid && r_next <= high){
        if (myArray[l_next] <= myArray[r_next]){
            merged[m_next++] = myArray[l_next++];
        }
        else{
            merged[m_next++] = myArray[r_next++];
        }
    }
    while (l_next <= mid){ merged[m_next++] = myArray[l_next++]; }  
    while (r_next <= high){ merged[m_next++] = myArray[r_next++]; }  
    for(i=0; i<=merged.length; i++){ myArray[i+low] = merged[i];}
}
Analyzing Merge Sort

1. Identify time required to Divide and Combine
2. Identify all subproblems and their sizes
3. Use recurrence relation to express recursive running time
4. Solve and express running time asymptotically

• **Divide**: 0 comparisons
• **Conquer**: recursively sort two lists of size \( \frac{n}{2} \)
• **Combine**: \( n \) comparisons
• **Recurrence**:

\[
T(n) = 0 + T\left(\frac{n}{2}\right) + T\left(\frac{n}{2}\right) + n
\]

\[
T(n) = 2T\left(\frac{n}{2}\right) + n
\]
Red box represents a problem instance

Blue value represents time spent at that level of recursion

\[ T(n) = 2T\left(\frac{n}{2}\right) + n \]

\[ T(n) = \sum_{i=1}^{\log_2 n} n = n \log_2 n \]
Properties of Merge Sort

• Worst Case Running time:
  • \( \Theta(n \log n) \)

• In-Place?
  • No!

• Adaptive?
  • No!

• Stable?
  • Yes!
  • As long as in a tie you always pick \( l_{\text{next}} \)
Quicksort

• Like Mergesort:
  • Divide and conquer
  • $O(n \log n)$ run time (kind of...)

• Unlike Mergesort:
  • Divide step is the “hard” part
  • *Typically* faster than Mergesort
Quicksort

Idea: pick a pivot element, recursively sort two sublists around that element

• **Divide:** select pivot element $p$, $\text{Partition}(p)$
• **Conquer:** recursively sort left and right sublists
• **Combine:** Nothing!
Partition (Divide step)

Given: a list, a pivot $p$

Start: unordered list

| 8 | 5 | 7 | 3 | 12 | 10 | 1 | 2 | 4 | 9 | 6 | 11 |

Goal: All elements $< p$ on left, all $> p$ on right

| 5 | 7 | 3 | 1 | 2 | 4 | 6 | 8 | 12 | 10 | 9 | 11 |
Partition, Procedure

If **Begin** value < *p*, move **Begin** right
Else swap **Begin** value with **End** value, move **End** Left
Done when **Begin** = **End**

![Diagram of the partitioning process with numbers 8 5 7 3 12 10 1 2 4 9 6 11 arranged and moved accordingly.](image-url)
Partition, Procedure

If $\text{Begin}$ value $< p$, move $\text{Begin}$ right
Else swap $\text{Begin}$ value with $\text{End}$ value, move $\text{End}$ Left
Done when $\text{Begin} = \text{End}$
Partition, Procedure

If Begin value < \( p \), move Begin right
Else swap Begin value with End value, move End Left
Done when Begin = End

Case 1: meet at element < \( p \)
Swap \( p \) with pointer position (2 in this case)
Partition, Procedure

If \textbf{Begin} value $< p$, move \textbf{Begin} right

Else swap \textbf{Begin} value with \textbf{End} value, move \textbf{End} Left

Done when \textbf{Begin} = \textbf{End}

\begin{center}
\begin{tabular}{cccccccccccc}
  & 8 & 5 & 7 & 3 & 6 & 4 & 1 & 2 & 10 & 9 & 11 & 12
\end{tabular}
\end{center}

Case 2: meet at element $> p$

Swap $p$ with value to the left (2 in this case)

\begin{center}
\begin{tabular}{cccccccccccc}
  2 & 5 & 7 & 3 & 6 & 4 & 1 & 8 & 10 & 9 & 11 & 12
\end{tabular}
\end{center}
Partition Summary

1. Put $p$ at beginning of list
2. Put a pointer (Begin) just after $p$, and a pointer (End) at the end of the list
3. While Begin < End:
   1. If Begin value < $p$, move Begin right
   2. Else swap Begin value with End value, move End Left
4. If pointers meet at element < $p$: Swap $p$ with pointer position
5. Else If pointers meet at element > $p$: Swap $p$ with value to the left

Run time? $O(n)$
Conquer

All elements $< p$

Exactly where it belongs!

All elements $> p$

Recursively sort Left and Right sublists
Quicksort Run Time (Best)

If the **pivot** is always the median:

\[
T(n) = 2T\left(\frac{n}{2}\right) + n
\]

\[
T(n) = O(n \log n)
\]

Then we divide in half each time
Quicksort Run Time (Worst)

If the pivot is always at the extreme:

Then we shorten by 1 each time

\[ T(n) = T(n - 1) + n \]

\[ T(n) = O(n^2) \]
Quicksort Run Time (Worst)

\[ T(n) = T(n - 1) + n \]

\[ T(n) = 1 + 2 + 3 + \cdots + n \]

\[ T(n) = \frac{n(n + 1)}{2} \]

\[ T(n) = O(n^2) \]
Quicksort on a (nearly) Sorted List

First element always yields unbalanced pivot

So we shorten by 1 each time

\[ T(n) = T(n - 1) + n \]

\[ T(n) = O(n^2) \]
Good Pivot

• What makes a good Pivot?
  • Roughly even split between left and right
  • Ideally: median

• There are ways to find the median in linear time, but it’s complicated and slow and you’re better off using mergesort

• In Practice:
  • Pick a random value as a pivot
  • Pick the middle of 3 random values as the pivot
Properties of Quick Sort

• Worst Case Running time:
  • $\Theta(n^2)$
  • But $\Theta(n \log n)$ average! And typically faster than mergesort!

• In-Place?
  • ....Debatable

• Adaptive?
  • No!

• Stable?
  • No!
Improving Running time

• Recall our definition of the sorting problem:
  • Input:
    • An array $A$ of items
    • A comparison function for these items
      • Given two items $x$ and $y$, we can determine whether $x < y$, $x > y$, or $x = y$
  • Output:
    • A permutation of $A$ such that if $i \leq j$ then $A[i] \leq A[j]$

• Under this definition, it is impossible to write an algorithm faster than $n \log n$ asymptotically.

• Observation:
  • Sometimes there might be ways to determine the position of values without comparisons!
“Linear Time” Sorting Algorithms

• Useable when you are able to make additional assumptions about the contents of your list (beyond the ability to compare)
  • Examples:
    • The list contains only positive integers less than $k$
    • The number of distinct values in the list is much smaller than the length of the list

• The running time expression will always have a term other than the list’s length to account for this assumption
  • Examples:
    • Running time might be $\Theta(k \cdot n)$ where $k$ is the range/count of values
BucketSort

• Assumes the array contains integers between 0 and $k - 1$ (or some other small range)

• Idea:
  • Use each value as an index into an array of size $k$
  • Add the item into the “bucket” at that index (e.g. linked list)
  • Get sorted array by “appending” all the buckets
BucketSort Running Time

• Create array of $k$ buckets
  • Either $\Theta(k)$ or $\Theta(1)$ depending on some things...
• Insert all $n$ things into buckets
  • $\Theta(n)$
• Empty buckets into an array
  • $\Theta(n + k)$
• Overall:
  • $\Theta(n + k)$
• When is this better than mergesort?
Properties of BucketSort

• In-Place?
  • No

• Adaptive?
  • No

• Stable?
  • Yes!
RadixSort

• Radix: The base of a number system
  • We’ll use base 10, most implementations will use larger bases

• Idea:
  • BucketSort by each digit, one at a time, from least significant to most significant

<table>
<thead>
<tr>
<th>103</th>
<th>801</th>
<th>401</th>
<th>323</th>
<th>255</th>
<th>823</th>
<th>999</th>
<th>101</th>
<th>113</th>
<th>901</th>
<th>555</th>
<th>512</th>
<th>245</th>
<th>800</th>
<th>018</th>
<th>121</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
</tr>
</tbody>
</table>

Place each element into a “bucket” according to its 1’s place

<table>
<thead>
<tr>
<th>800</th>
<th>801</th>
<th>401</th>
<th>101</th>
<th>901</th>
<th>121</th>
<th>512</th>
<th>103</th>
<th>323</th>
<th>823</th>
<th>113</th>
<th>255</th>
<th>555</th>
<th>245</th>
<th>018</th>
<th>999</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
</tr>
</tbody>
</table>
RadixSort

• Radix: The base of a number system
  • We’ll use base 10, most implementations will use larger bases

• Idea:
  • BucketSort by each digit, one at a time, from least significant to most significant

<table>
<thead>
<tr>
<th>800</th>
<th>801</th>
<th>401</th>
<th>101</th>
<th>901</th>
<th>121</th>
<th>512</th>
<th>323</th>
<th>052</th>
<th>555</th>
<th>245</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

Place each element into a “bucket” according to its 10’s place
RadixSort

• **Radix**: The base of a number system
  • We’ll use base 10, most implementations will use larger bases

• **Idea:**
  • BucketSort by each digit, one at a time, from least significant to most significant

Place each element into a “bucket” according to its 100’s place
RadixSort

• Radix: The base of a number system
  • We’ll use base 10, most implementations will use larger bases

• Idea:
  • BucketSort by each digit, one at a time, from least significant to most significant

<table>
<thead>
<tr>
<th>018</th>
<th>101</th>
<th>103</th>
<th>113</th>
<th>121</th>
<th>245</th>
<th>255</th>
<th>323</th>
<th>401</th>
<th>512</th>
<th>555</th>
<th>800</th>
<th>801</th>
<th>823</th>
<th>901</th>
<th>999</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Convert back into an array

<table>
<thead>
<tr>
<th>018</th>
<th>811</th>
<th>103</th>
<th>113</th>
<th>121</th>
<th>245</th>
<th>255</th>
<th>323</th>
<th>401</th>
<th>512</th>
<th>555</th>
<th>800</th>
<th>801</th>
<th>823</th>
<th>901</th>
<th>999</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
</tr>
</tbody>
</table>
RadixSort Running Time

- Suppose largest value is \( m \)
- Choose a radix (base of representation) \( b \)
- BucketSort all \( n \) things using \( b \) buckets
  - \( \Theta(n + k) \)
- Repeat once per each digit
  - \( \log_b m \) iterations
- Overall:
  - \( \Theta(n \log_b m + b \log_b m) \)
- In practice, you can select the value of \( b \) to optimize running time
- When is this better than mergesort?
ARPANET
Undirected Graphs

Definition: $G = (V, E)$

Vertices/Nodes

$V = \{1, 2, 3, 4, 5, 6, 7, 8, 9\}$

Edges

$E = \{(1, 2), (2, 3), (1, 3), \ldots\}$
Directed Graphs

Definition: $G = (V, E)$

Vertices/Nodes

$V = \{1, 2, 3, 4, 5, 6, 7, 8, 9\}$

Edges

$E = \{(1, 2), (2, 3), (1, 3), \ldots\}$
Some graphs may have duplicate edges (e.g. here we have the edge (1,2) twice). Some may also have self-edges (e.g. here there is an edge from 1 to 1). Graph with Neither self-edges nor duplicate edges are called simple graphs.
Weighted Graphs

Definition: \( G = (V, E) \)

\[ w(e) = \text{weight of edge } e \]

Vertices/Nodes

\[ V = \{1, 2, 3, 4, 5, 6, 7, 8, 9\} \]

Edges

\[ E = \{(1, 2), (2, 3), (1, 3), \ldots\} \]
Graph Applications

• For each application below, consider:
  • What are the nodes, what are the edges?
  • Is the graph directed?
  • Is the graph simple?
  • Is the graph weighted?

• Facebook friends
• Twitter followers
• Java inheritance
• Airline Routes
Some Graph Terms

• **Adjacent/Neighbors**
  • Nodes are adjacent/neighbors if they share an edge

• **Degree**
  • Number of “neighbors” of a vertex

• **Indegree**
  • Number of incoming neighbors

• **Outdegree**
  • Number of outgoing neighbors
Graph Operations

• To represent a Graph (i.e. build a data structure) we need:
  • Add Edge
  • Remove Edge
  • Check if Edge Exists
  • Get Neighbors (incoming)
  • Get Neighbors (outgoing)
**Adjacency List**

- **Time/Space Tradeoffs**
  - Space to represent: $\Theta(n + m)$
  - Add Edge: $\Theta(1)$
  - Remove Edge: $\Theta(1)$
  - Check if Edge Exists: $\Theta(n)$
  - Get Neighbors (incoming): $\Theta(n + m)$
  - Get Neighbors (outgoing): $\Theta(\text{deg}(v))$

\[ |V| = n \]
\[ |E| = m \]
Adjacency List (Weighted)

Time/Space Tradeoffs
Space to represent: $\Theta(n + m)$
Add Edge: $\Theta(1)$
Remove Edge: $\Theta(1)$
Check if Edge Exists: $\Theta(n)$
Get Neighbors (incoming): $\Theta(?)$
Get Neighbors (outgoing): $\Theta(?)$

\[ |V| = n \]
\[ |E| = m \]
Adjacency Matrix

Time/Space Tradeoffs
Space to represent: $\Theta(\cdot)$
Add Edge: $\Theta(\cdot)$
Remove Edge: $\Theta(\cdot)$
Check if Edge Exists: $\Theta(\cdot)$
Get Neighbors (incoming): $\Theta(\cdot)$
Get Neighbors (outgoing): $\Theta(\cdot)$

$|V| = n$
$|E| = m$
**Adjacency Matrix (weighted)**

### Time/Space Tradeoffs

- **Space to represent:** $\Theta(n^2)$
- **Add Edge:** $\Theta(1)$
- **Remove Edge:** $\Theta(1)$
- **Check if Edge Exists:** $\Theta(1)$
- **Get Neighbors (incoming):** $\Theta(n)$
- **Get Neighbors (outgoing):** $\Theta(n)$

\[
|V| = n \\
|E| = m
\]

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>E</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>F</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>G</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>H</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>I</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Aside

• Almost always, adjacency lists are the better choice
• Most graphs are missing most of their edges, so the adjacency list is much more space efficient and the slower operations aren’t that bad