A Lower Bound for Worst Case

**Theorem:** Any comparison sort algorithm requires $\Omega(n \lg n)$ comparisons in the worst case.

**Proof:**
- Suffices to determine the height of a decision tree.
- The number of leaves is at least $n!$ (# outputs)
- The number of internal nodes $\geq n! - 1$
- The height is at least $\log (n! - 1) = \Omega(n \lg n)$
Can we do better?

- Linear sorting algorithms
  - Counting Sort (special case of Bucket Sort)
  - Bucket Sort
  - Radix Sort
- Make certain assumptions about the data
- Linear sorts are NOT “comparison sorts”

Application: Constructing Histograms

- One common computation in data visualization and analysis is computing a histogram.
- For example, n students might be assigned integer scores in some range, such as 0 to 100, and are then placed into ranges or “buckets” based on these scores.

A histogram of scores from a recent Algorithms course taught by one of the authors (with extra credit included).
Application: An Algorithm for Constructing Histograms

- When we think about the algorithmic issues in constructing a histogram of n scores, it is easy to see that this is a type of sorting problem.
- But it is not the most general kind of sorting problem, since the keys being used to sort are simply integers in a given range.
- So a natural question to ask is whether we can sort these values faster than with a general comparison-based sorting algorithm.
- The answer is “yes.” In fact, we can sort them in $O(n)$ time.

Bucket-Sort

- Let be $S$ be a sequence of $n$ (key, element) items with keys in the range $[0, r - 1]$.
- Bucket-sort uses the keys as indices into an auxiliary array $B$ of sequences (buckets).
  - **Phase 1**: Empty sequence $S$ by moving each entry $(k, o)$ into its bucket $B[k]$.
  - **Phase 2**: For $i = 0, ..., r - 1$, move the entries of bucket $B[i]$ to the end of sequence $S$.
- Analysis:
  - Phase 1 takes $O(n)$ time.
  - Phase 2 takes $O(n + r)$ time.
- Bucket-sort takes $O(n + r)$ time.

Algorithm

bucketSort(S):

**Input:** Sequence S of entries with integer keys in the range $[0, r - 1]$

**Output:** Sequence S sorted in nondecreasing order of the keys.

for each entry e in S do
  k = the key of e
  remove e from S
  insert e at the end of bucket B[k]

for i = 0 to r - 1 do
  for each entry e in B[i] do
    remove e from B[i]
    insert e at the end of S
Example

- Key range $[0, 9]$ ($r = 10$)

Array-based Implementation: Counting Sort

- Assumptions:
  - $n$ integers which are in the range $[0 \ldots r-1]$
  - $r$ has the same growth rate as $n$, that is, $r = O(n)$

- Idea:
  - For each element $x$, find the number of occurrences of $x$ and store it in the counter
  - Place $x$ into its correct position in the output array using the counter.
Step 1
Find the number of times $A[i]$ appears in $A$ (i.e., frequencies)

```
Step 1
(i.e., frequencies)
```

(i = 0; i < n; i++)
```
for (i = 0; i < n; i++)
```
```
C[A[i]]++;
```

allocate C
```
allocate C
```
```
1 2 3 4 5 6
```
```
0 0 0 0 0 0
```
```
1 2 3 4 5 6
```
```
0 0 1 0 0 0
```
```
1 2 3 4 5 6
```
```
0 0 1 0 0 1
```
```
1 2 3 4 5 6
```
```
0 0 1 1 0 1
```
```
1 2 3 4 5 6
```
```
2 0 2 3 0 1
```
```
C[] = number of times element i appears in A
```

Step 2
```
Step 2
```
```
int index = 0
```
```
For i = 0 to r-1
```
```
For j = 1 to C[i]
```
```
A[index++] = i
```
```
// Copy value i into the array C[i] times
```

Example:
```
i: 0 1 2 3 4 5 6
C = [ 0 2 0 2 3 0 1 ]
A = [ 1 1 3 3 4 4 6 ]
```

Example:
```
i: 0 1 2 3 4 5 6
C = [ 0 2 0 2 3 0 1 ]
A = [ 1 1 3 3 4 4 6 ]
```
Properties and Extensions

- **Key-type Property**
  - The keys are used as indices into an array and cannot be arbitrary objects
  - No external comparator

- **Stable Sort Property**
  - The relative order of any two items with the same key is preserved after the execution of the algorithm

### Extensions

- Integer keys in the range \([a, b]\)
  - Put entry \((k, o)\) into bucket \(B[k - a]\)
- Float numbers round to integers
- String keys from a set \(D\) of possible strings, where \(D\) has constant size (e.g., names of the 50 U.S. states)
  - Sort \(D\) and compute the rank \(r(k)\) of each string \(k\) of \(D\) in the sorted sequence
  - Put entry \((k, o)\) into bucket \(B[r(k)]\)

---

**Example - Bucket Sort**

\(R = [0..0.99]\)

<table>
<thead>
<tr>
<th>A</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>.78</td>
<td>.17</td>
<td>.39</td>
<td>.26</td>
<td>.72</td>
<td>.94</td>
<td>.21</td>
<td>.12</td>
<td>.68</td>
</tr>
</tbody>
</table>

Distribute Into buckets
Example - Bucket Sort

Sort within each bucket: because the mapping from keys to bucket is many-to-one.

Concatenate the lists from 0 to k – 1 together, in order.
Analysis of Extended Bucket Sort

**Alg.:** BUCKET-SORT(A, n)

```
for i ← 1 to n

for i ← 0 to r - 1
    do sort list B[i] with merge sort

concatenate lists B[0], B[1], , , B[r-1]
together in order

return the concatenated lists
```

Note: If the mapping from keys to buckets is 1-to-1, there is no need to sort each bucket, and the time is the worst case, not the average case.

Lexicographic Order

- A *d*-tuple is a sequence of *d* keys \((k_1, k_2, ...., k_d)\), where key \(k_i\) is said to be the *i*-th dimension of the tuple.
- Example:
  - The Cartesian coordinates of a point in 3D space are a 3-tuple.
  - The lexicographic order of two *d*-tuples is recursively defined as follows:
    \[(x_1, x_2, ...., x_d) <_{lex} (y_1, y_2, ..., y_d) \iff x_1 < y_1 \lor (x_1 = y_1 \land (x_2, ...., x_d) <_{lex} (y_2, ..., y_d))\]
    I.e., the tuples are compared by the first dimension, then by the second dimension, etc.
**Lexicographic-Sort**

- Let $C_i$ be the comparator that compares two tuples by their $i$-th dimension.
- Let $stableSort(S, C)$ be a stable sorting algorithm that uses comparator $C$.
- Lexicographic-sort sorts a sequence of $d$-tuples in lexicographic order by executing $d$ times algorithm $stableSort$, one per dimension.
- Lexicographic-sort runs in $O(dT(n))$ time, where $T(n)$ is the running time of $stableSort$.

**Algorithm** $lexicographicSort(S)$

```plaintext
Input sequence $S$ of $d$-tuples
Output sequence $S$ sorted in lexicographic order

for $i \leftarrow d$ downto 1
    $stableSort(S, C_i)$ // $C_i$ compares $i$-th dimension
```

**Example:**

$(7,4,6)$ $(5,1,5)$ $(2,1,4)$ $(3,2,4)$

$(2,1,4)$ $(3,2,4)$ $(5,1,5)$ $(7,4,6)$ $(2,4,6)$

$(2,1,4)$ $(2,4,6)$ $(3,2,4)$ $(5,1,5)$ $(7,4,6)$

**Correctness of Alg. $lexicographicSort(S)$**

**Theorem:** Alg. $lexicographicSort(S)$ sorts $S$ by lexicographic order.

**Proof:** Induction on $d$.

- Base case: $d=1$, $stableSort(S, C_1)$ will do the job.
- Induction hypothesis: Theorem is true for $d' < d$.
- Inductive case:
  - Suppose $(x_1, x_2, \ldots, x_d) \prec_{lex} (y_1, y_2, \ldots, y_d)$.
  - If $x_1 < y_1$, then the last round places $(x_1, x_2, \ldots, x_d)$ before $(y_1, y_2, \ldots, y_d)$.
  - If $x_1 = y_1$, then $(x_2, \ldots, x_d) \prec_{lex} (y_2, \ldots, y_d)$.
  - By induction hypothesis, the previous rounds will place $(x_2, \ldots, x_d)$ before $(y_2, \ldots, y_d)$. And we use a stable sort, so $(x_1, x_2, \ldots, x_d)$ goes before $(y_1, y_2, \ldots, y_d)$. 

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Radix-Sort

- Radix-sort is a specialization of lexicographic-sort that uses bucket-sort as the stable sorting algorithm in each dimension.
- Radix-sort is applicable to tuples where the keys in each dimension \( i \) are integers in the range \([0, r - 1]\)
- Radix-sort runs in time \( O(d(n + r)) \)
- If \( d \) is constant and \( r \) is \( O(n) \), then this is \( O(n) \).

Algorithm \( \text{radixSort}(S, N) \)

- Input sequence \( S \) of \( d \)-tuples such that \((0, \ldots, 0) \leq (x_1, \ldots, x_d) \) and \((x_1, \ldots, x_d) \leq (N - 1, \ldots, N - 1) \) for each tuple \((x_1, \ldots, x_d) \) in \( S \)
- Output sequence \( S \) sorted in lexicographic order
- for \( i \leftarrow d \) downto 1
  - \( \text{bucketSort}(S, N) \)

Radix Sort Example

- Represents keys as \( d \)-digit numbers in some base-\( r \)
  \[ \text{key} = x_1x_2\ldots x_d \quad \text{where} \quad 0 \leq x_i \leq r - 1 \]
- Example: \( \text{key}=15 \)
  \[ \text{key}_{10} = 15, \quad d=2, \quad r=10 \quad \text{where} \quad 0 \leq x_i \leq 9 \]
Radix Sort Example

- Sorting looks at one column at a time
  - For a $d$ digit number, sort the least significant digit first
  - Continue sorting on the next least significant digit, until all digits have been sorted
  - Requires only $d$ passes through the list

RADIX-SORT

Alg.: RADIX-SORT(A, d)
for $i \leftarrow 1$ to $d$
do use a stable bucket sort of array $A$ on digit $i$
(stable sort: preserves order of identical elements)
Analysis of Radix Sort

- Given \( n \) numbers of \( d \) digits each, where each digit may take up to \( k \) possible values, RADIX-SORT correctly sorts the numbers in \( O(d(n+k)) \)
  - One pass of sorting per digit takes \( O(n+k) \) assuming that we use bucket sort
  - There are \( d \) passes (for each digit)

Summary: Beating the lower bound

- We can beat the lower bound if we don’t base our sort on comparisons:
  - Counting sort for keys in \([0..k]\), \( k = O(n) \)
  - Bucket sort for keys which can map to small range of integers (uniformly distributed)
  - Radix sort for keys with a fixed number of “digits”
Finding Medians

- A common data analysis tool is to compute a median, that is, a value taken from among \( n \) values such that there are at most \( n/2 \) values larger than this one and at most \( n/2 \) elements smaller.
- Of course, such a number can be found easily if we were to sort the scores, but it would be ideal if we could find medians in \( O(n) \) time without having to perform a sorting operation.

### Selection: Finding the Median and the \( k \)th Smallest Element

- The median of a sequence of \( n \) sorted numbers \( A[1...n] \) is the “middle” element.
- If \( n \) is odd, then the middle element is the \((n+1)/2\)th element in the sequence.
- If \( n \) is even, then there are two middle elements occurring at positions \( n/2 \) and \( n/2+1 \). In this case, we will choose the \( n/2 \)th smallest element.
- Thus, in both cases, the median is the \( \lceil n/2 \rceil \)th smallest element.
- The \( k \)th smallest element is a general case.
The Selection Problem

- Given an integer \( k \) and \( n \) elements \( x_1, x_2, \ldots, x_n \) taken from a total order, find the \( k \)-th smallest element in this set.
- Of course, we can sort the set in \( O(n \log n) \) time and then index the \( k \)-th element.

\[ k=3 \quad 7 \ 4 \ 9 \ 6 \ 2 \to 2 \ 4 \ 6 \ 7 \ 9 \]

- We want to solve the selection problem faster.

Quick-Select

Quick-select is a randomized selection algorithm based on the prune-and-search paradigm:

- **Prune**: pick a random element \( x \) (called pivot) and partition \( S \) into
  - \( L \): elements less than \( x \)
  - \( E \): elements equal \( x \)
  - \( G \): elements greater than \( x \)
- **Search**: depending on \( k \), either answer is in \( E \), or we need to recur in either \( L \) or \( G \)

\[
\begin{align*}
    &k \leq |L| \quad k > |L| + |E| \\
    &k' = k - |L| - |E|
\end{align*}
\]

\[ |L| < k \leq |L| + |E| \]

(done)
Pseudo-code

Algorithm quickSelect(S, k):

Input: Sequence S of n comparable elements, and an integer k ∈ [1, n]
Output: The kth smallest element of S

if n = 1 then
    return the (first) element of S

pick a random element x of S
remove all the elements from S and put them into three sequences:

• L, storing the elements in S less than x
• E, storing the elements in S equal to x
• G, storing the elements in S greater than x.

if k ≤ |L| then
    quickSelect(L, k)
else if k ≤ |L| + |E| then
    return x  // each element in E is equal to x
else
    quickSelect(G, k − |L| − |E|)

Note that partitioning takes $O(n)$ time.

Quick-Select Visualization

An execution of quick-select can be visualized by a recursion path:

- Each node represents a recursive call of quick-select, and stores k and the remaining sequence

```
5
k=1, S=(7 6 5)

k=2, S=(7 6 5)

k=2, S=(7 4 6 5)

k=2, S=(7 4 9 6 5)

k=2, S=(7 4 9 3 2 6 5 1 8)
```

Note that partitioning takes $O(n)$ time.
Expected Running Time

- Consider a recursive call of quick-select on a sequence of size $s$
  - **Good call:** the sizes of $L$ and $G$ are each less than $3s/4$
  - **Bad call:** one of $L$ and $G$ has size greater than $3s/4$

  - A call is **good** with probability $1/2$
    - $1/2$ of the possible pivots cause good calls:
      - Good call
      - Bad call

  7 2 9 4 3 7 6 1
  2 4 3 1
  7 9 7

  7 2 9 4 3 7 6 4
  1
  7 2 9 4 3 7 6

- **Expected Running Time, Part 2**
  - **Probabilistic Fact:** The expected number of coin tosses required in order to get $k$ heads is $2^k$
  - For a node of depth $i$, we expect
    - $i/2$ ancestors are good calls
    - The size of the input sequence for the current call is at most $(3/4)^{i/2}n$

  - Therefore, we have
    - For a node of depth $2\log_{4/3}n$, the expected input size is one
    - The expected height of the quick-sort tree is $O(\log n)$

  - The amount or work done at the nodes of the same depth is $O((3/4)^{i/2}n)$
  - Thus, the expected running time of quick-sort is $O(n)$
Expected Running Time

- Let $T(n)$ denote the expected running time of quick-select.
- By Fact #2,
  - $T(n) \leq T(3n/4) + bn^*(\text{expected # of calls before a good call})$
- By Fact #1,
  - $T(n) \leq T(3n/4) + 2bn$
- That is, $T(n)$ is a geometric series:
  - $T(n) \leq 2bn + 2b(3/4)n + 2b(3/4)^2n + 2b(3/4)^3n + ...$
- So $T(n)$ is $O(n)$.
- We can solve the selection problem in $O(n)$ expected time.

Linear Time Selection Algorithm

- Also called Median Finding Algorithm.
- Find $k^{th}$ smallest element in $O(n)$ time in worst case.
- Uses Divide and Conquer strategy.
- Uses elimination in order to cut down the running time substantially.
Deterministic Selection

- If we select an element $m$ among $A$, then $A$ can be divided into 3 parts:
  - $L = \{ a \mid a \text{ is in } A, a < m \}$
  - $E = \{ a \mid a \text{ is in } A, a = m \}$
  - $G = \{ a \mid a \text{ is in } A, a > m \}$

- According to the number elements in $L$, $E$, $G$, there are following three cases. In each case, where is the $k$-th smallest element?
  - Case 1: $|L| \geq k$  The $k$-th element is in $L$
  - Case 2: $|L| + |E| > k > |L|$  The $k$-th element is in $E$
  - Case 3: $|L| + |E| < k$  The $k$-th element is in $G$

Deterministic Selection

- We can do selection in $O(n)$ worst-case time.
- Main idea: recursively use the selection algorithm itself to find a good pivot for quick-select:
  - Divide $S$ into $n/5$ groups of 5 each
  - Find a median in each group
  - Recursively find the median of the “baby” medians.
Steps to solve the problem

- Step 1: If \( n \) is small, for example \( n < 45 \), just sort and return the \( k^{th} \) smallest number in constant time i.e; \( O(1) \) time.
- Step 2: Group the given numbers in subsets of 5 in \( O(n) \) time.
- Step 3: Sort each of the group in \( O(n) \) time. Find median of each group.

Example:

- Given a set
  (.........2,6,8,19,24,54,5,87,9,10,44,32,21,13,3,4,
  18,26,36,30,25,39,47,56,71,91,61,44,28........) having \( n \) elements.
Arrange the numbers in groups of five

Sort each group of 5 from top to bottom

Each group of 5 is sorted
Step 4: Find median of \( n/5 \) group medians recursively

There are \( s = n/5 \) groups, there are \( s/2 \) groups on the left of \( m \) and \( s/2 \) groups on the right of \( m \).

So there are \( 3/2s - 1 = 3n/10 - 1 \) numbers less than \( m \) and \( 3n/10 - 1 \) numbers greater than \( m \).
Step 5: Find the sets $L$, $E$, and $G$

- Compare each $(n-1)$ elements in the top-right and bottom-left regions with the median $m$ and find three sets $L$, $E$, and $G$ such that every element in $L$ is smaller than $m$, every element in $E$ is equal to $m$, and every element in $G$ is greater than $m$.

\[
\frac{3n}{10} - |E| \leq |L| \leq \frac{7n}{10} - |E|
\]

($|L|$ is the size or cardinality of $L$)

\[
\frac{3n}{10} - |E| \leq |G| \leq \frac{7n}{10} - |E|
\]

Pseudo code: Finding the $k$-th Smallest Element

- **Input:** An array $A[1...n]$ of $n$ elements and an integer $k$, $1 \leq k \leq n$;
- **Output:** The $k$th smallest element in $A$;
- 1. $select(A, n, k)$;
Pseudo code: Finding the $k$-th Smallest Element

- $select(A, n, k)$
- 2. if $n < 45$ then sort $A$ and return ($A[k]$);
- 3. Let $q = \lceil n/5 \rceil$. Divide $A$ into $q$ groups of 5 elements each.
  - If 5 does not divide $n$, then add max element;
- 4. Sort each of the $q$ groups individually and extract its median.
- Let the set of medians be $M$.
- 5. $m \leftarrow select(M, q, \lceil q/2 \rceil)$;
- 6. Partition $A$ into three arrays:
  - $L = \{a \mid a < m\}$, $E = \{a \mid a = m\}$, $G = \{a \mid a > m\}$;
- 7. case
  - $|L| \geq k$: return $select(L, |L|, k)$;
  - $|L| + |E| \geq k$: return $m$;
  - $|L| + |E| < k$: return $select(G, |G|, k-|L|-|E|)$;
- 8. end case;

Complexity: Finding the $k$-th Smallest Element (Bound time: $T(n)$)

- $select(A, n, k)$
- 2. if $n < 45$ then sort $A$ and return ($A[k]$); $O(1)$
- 3. Let $q = \lceil n/5 \rceil$. Divide $A$ into $q$ groups of 5 elements each. $O(n)$
  - If 5 does not divide $n$, then add max element;
- 4. Sort each of the $q$ groups individually and extract its median. $O(n)$
- Let the set of medians be $M$.
- 5. $m \leftarrow select(M, q, \lceil q/2 \rceil)$; $T(n/5)$
- 6. Partition $A$ into three arrays:
  - $L = \{a \mid a < m\}$, $E = \{a \mid a = m\}$, $G = \{a \mid a > m\}$; $O(n)$
- 7. case
  - $|L| \geq k$: return $select(L, |L|, k)$; $T(7n/10)$
  - $|L| + |E| \geq k$: return $m$; $O(1)$
  - $|L| + |E| < k$: return $select(G, |G|, k-|L|-|E|)$; $T(7n/10)$
- 8. end case;

Summary: $T(n) = T(n/5) + T(7n/10) + a*n$
Analysis: Finding the *k*-th Smallest Element

- What is the best case time complexity of this algorithm?
- \(O(n)\) when \(|L| < k \leq |L| + |E|\)

- \(T(n)\): the worst case time complexity of select\((A, n, k)\)
  \[T(n) = T(n/5) + T(7n/10) + a*n\]

- The *k*-th smallest element in a set of *n* elements drawn from a linearly ordered set can be found in \(\Theta(n)\) time.

Recursive formula

\[T(n) = T(n/5) + T(7n/10) + a*n\]

We will solve this equation in order to get the complexity.

We guess that \(T(n) \leq Cn\) for a constant, and then by induction on \(n\).

The base case when \(n < 45\) is trivial.

\[
T(n) = T(n/5) + T(7n/10) + a*n
\leq C*n/5 + C*7*n/10 + a*n \quad \text{(by induction hypothesis)}
= ((2C + 7C)/10 + a)n
= (9C/10 + a)n
\leq Cn \quad \text{if} \quad C \geq 9C/10 + a, \text{or} \quad C/10 \geq a, \text{or} \quad C \geq 10a
\]

So we let \(C = 10a\).

Then \(T(n) \leq Cn\).

So \(T(n) = O(n)\).
Why group of 5??

- If we divide elements into groups of 3 then we will have 
  \[ T(n) = a*n + T(n/3) + T(2n/3) \]
  so \( T(n) \) cannot be \( O(n) \).....

- If we divide elements into groups of more than 5, finding the median of each group will be more, so grouping elements into 5 is the optimal situation.