Better than $N \lg N$?

- Can prove that if all you can do to keys is compare them then sorting must take $\Omega(N \lg N)$.
- Basic idea: there are $N!$ possible ways the input data could be scrambled.
- Therefore, your program must be prepared to do $N!$ different combinations of move operations.
- Therefore, there must be $N!$ possible combinations of outcomes of all the if tests in your program (we're assuming that comparisons are 2-way).

\[
\begin{array}{c}
T \\
\quad \quad a < b \\
\quad \quad b < c \\
F \\
\quad \quad a < c \\
\quad \quad b < c
\end{array}
\]

\begin{align*}
\text{Height} & \propto \text{Sorting time} \\
abc & \quad a < c \\
acb & \quad b < c \\
\text{bac} & \quad a < c \\
\text{acb} & \quad b < c \\
\text{bca} & \quad b < c \\
\text{cba} & \quad a < c
\end{align*}

Beyond Comparison: Distribution

- But suppose can do more than compare keys?
- For example, how can we sort a set of $N$ integer keys whose values range from 0 to $kN$, for some small constant $k$?
- One technique: put the integers into $N$ buckets, with an integer $p$ going to bucket $p/k$.
- At most $k$ keys per bucket, so catenate and use insertion sort, which will now be fast.
- E.g., $k = 2, N = 10$:

```
Start:
14 3 10 13 4 2 19 17 0 9
In buckets:
| 0 | 3 | 2 | 4 | | 9 | 10 | 13 | 14 | 17 | 19 |
```

\[
\begin{align*}
\text{Now insertion sort is fast. For fixed } k, \Theta(N).
\end{align*}
\]
Distribution Counting

- Another technique: count the number of items < 1, < 2, etc.
- If \( M_p = \) #items with value < \( p \), then in sorted order, the \( j \)th item with value \( p \) must be \( \#M_p + j \).
- Gives linear-time algorithm.

Distribution Counting Example

- Suppose all items are between 0 and 9 as in this example:

\[
\begin{array}{cccccccccccccccc}
0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\end{array}
\]

\[
\begin{array}{cccccccccccccccc}
3 & 3 & 1 & 2 & 2 & 1 & 1 & 3 & 0 & 3 \\
3 & 3 & 1 & 2 & 2 & 1 & 1 & 3 & 0 & 3 \\
\end{array}
\]

- "Counts" line gives # occurrences of each key.
- "Running sum" gives cumulative count of keys \( \leq \) each value...
- ...which tells us where to put each key:
- The first instance of key \( k \) goes into slot \( m \), where \( m \) is the number of key instances that are < \( k \).

Radix Sort

Idea: Sort keys one character at a time.
- Can use distribution counting for each digit.
- Can work either right to left (LSD radix sort) or left to right (MSD radix sort).
- LSD radix sort is venerable: used for punched cards.

Initial: set, cat, cad, con, bat, can, be, let, bet

Pass 1 (by char #2)

be, cad, can, set, cat, bat, let, bet

Pass 2 (by char #1)

cad, can, cat, be, set, let, bet, con

Pass 3 (by char #0)

bet, cad, let, set

bat, be, bet, cat, can, con, set, cat, bat, let, bet

cad, can, cat, bat, be, set, let, bet, con

bat, be, bet, cat, can, con, set, cat, bat, let, bet

cad, can, cat, bat, be, set, let, bet, con

MSD Radix Sort

- A bit more complicated: must keep lists from each step separate
- But, can stop processing 1-element lists
Performance of Radix Sort

• Radix sort takes $\Theta(B)$ time where $B$ is total size of the key data.
• Have measured other sorts as function of # records.
• How to compare?
• To have $N$ different records, must have keys at least $\Theta(\lg N)$ long [why?]
• Furthermore, comparison actually takes time $\Theta(K)$ where $K$ is size of key in worst case [why?]
• So $N \lg N$ comparisons really means $N(\lg N)^2$ operations.
• While radix sort takes $B = N \lg N$ time.
• On the other hand, must work to get good constant factors with radix sort.

And Don’t Forget Search Trees

Idea: A search tree is in sorted order, when read in inorder.

• Need balance to really use for sorting [next topic].
• Given balance, same performance as heapsort: $N$ insertions in time $\lg N$ each, plus $\Theta(N)$ to traverse, gives $\Theta(N + N \lg N) = \Theta(N \lg N)$

Summary

• Insertion sort: $\Theta(Nk)$ comparisons and moves, where $k$ is maximum amount data is displaced from final position.
  - Good for small datasets or almost ordered data sets.
• Quicksort: $\Theta(N \lg N)$ with good constant factor if data is not pathological. Worst case $O(N^2)$.
• Merge sort: $\Theta(N \lg N)$ guaranteed. Good for external sorting.
• Heapsort, treesort with guaranteed balance: $\Theta(N \lg N)$ guaranteed.
• Radix sort, distribution sort: $\Theta(B)$ (number of bytes). Also good for external sorting.