Acknowledgement: The course slides are adapted from the slides prepared by R. Sedgewick and K. Wayne of Princeton University.
Mergesort

Basic plan.

• Divide array into two halves.
• **Recursively** sort each half.
• Merge two halves.

Mergesort overview

input: M E R G E S O R T E X A M P L E

sort left half: E E G M O R R S  T E X A M P L E

sort right half: E E G M O R R S  A E E L M P T X

merge results: A E E E E E G L M M O P R R S T X
Mergesort - Example
Goal. Given two sorted subarrays $a[lo]$ to $a[mid]$ and $a[mid+1]$ to $a[hi]$, replace with sorted subarray $a[lo]$ to $a[hi]$. 

\[ \begin{array}{cccccccc}
\text{lo} & \text{mid} & \text{mid+1} & \text{hi} \\
E & E & G & M & R & A & C & E & R & T \\
\end{array} \] 

sorted \hspace{1cm} \text{sorted}
**Goal.** Given two sorted subarrays $a[lo]$ to $a[mid]$ and $a[mid+1]$ to $a[hi]$, replace with sorted subarray $a[lo]$ to $a[hi]$.

<table>
<thead>
<tr>
<th>lo</th>
<th>mid</th>
<th>mid+1</th>
<th>hi</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>E</td>
<td>G</td>
<td>M R</td>
</tr>
<tr>
<td>A</td>
<td>C</td>
<td>E R</td>
<td>T</td>
</tr>
</tbody>
</table>

**copy to auxiliary array**

<table>
<thead>
<tr>
<th>aux[]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>
Abstract in-place merge

**Goal.** Given two sorted subarrays \(a[lo]\) to \(a[mid]\) and \(a[mid+1]\) to \(a[hi]\), replace with sorted subarray \(a[lo]\) to \(a[hi]\).
**Goal.** Given two sorted subarrays \(a[lo]\) to \(a[mid]\) and \(a[mid+1]\) to \(a[hi]\), replace with sorted subarray \(a[lo]\) to \(a[hi]\).

---

**compare minimum in each subarray**

```
  a[]    | E  | E  | G  | M  | R  | A  | C  | E  | R  | T
  -----------------------
  k
```

```
aux[]   | E  | E  | G  | M  | R  | A  | C  | E  | R  | T
  -----------------------
  i   j
```
**Goal.** Given two sorted subarrays $a[lo]$ to $a[mid]$ and $a[mid+1]$ to $a[hi]$, replace with sorted subarray $a[lo]$ to $a[hi]$.

### Abstract in-place merge

<table>
<thead>
<tr>
<th>a[]</th>
<th>E</th>
<th>G</th>
<th>M</th>
<th>R</th>
<th>A</th>
<th>C</th>
<th>E</th>
<th>R</th>
<th>T</th>
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</thead>
<tbody>
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<td></td>
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<td>k</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

**compare minimum in each subarray**

<table>
<thead>
<tr>
<th>aux[]</th>
<th>E</th>
<th>E</th>
<th>G</th>
<th>M</th>
<th>R</th>
<th>A</th>
<th>C</th>
<th>E</th>
<th>R</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td></td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

 aux[] | E | E | G | M | R | A | C | E | R | T |
Abstract in-place merge

**Goal.** Given two sorted subarrays $a[lo]$ to $a[mid]$ and $a[mid+1]$ to $a[hi]$, replace with sorted subarray $a[lo]$ to $a[hi]$.

```plaintext

<table>
<thead>
<tr>
<th>a[]</th>
<th>A</th>
<th>E</th>
<th>G</th>
<th>M</th>
<th>R</th>
<th>A</th>
<th>C</th>
<th>E</th>
<th>R</th>
<th>T</th>
</tr>
</thead>
</table>


k

```plaintext

**compare minimum in each subarray**

```plaintext

<table>
<thead>
<tr>
<th>aux[]</th>
<th>E</th>
<th>E</th>
<th>G</th>
<th>M</th>
<th>R</th>
<th>A</th>
<th>C</th>
<th>E</th>
<th>R</th>
<th>T</th>
</tr>
</thead>
</table>

```

i          j
**Goal.** Given two sorted subarrays \(a[lo] \) to \(a[mid]\) and \(a[mid+1] \) to \(a[hi]\), replace with sorted subarray \(a[lo]\) to \(a[hi]\).

**Abstract in-place merge**

- **a[]**
  
<table>
<thead>
<tr>
<th>A</th>
<th>C</th>
<th>G</th>
<th>M</th>
<th>R</th>
<th>A</th>
<th>C</th>
<th>E</th>
<th>R</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **aux[]**
  
<table>
<thead>
<tr>
<th>E</th>
<th>E</th>
<th>G</th>
<th>M</th>
<th>R</th>
<th>A</th>
<th>C</th>
<th>E</th>
<th>R</th>
<th>T</th>
</tr>
</thead>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**compare minimum in each subarray**

- \(k\)
  
  |   |   |   |   |   |   |   |   |   |   |

- \(i\) and \(j\)
Goal. Given two sorted subarrays \(a[lo]\) to \(a[mid]\) and \(a[mid+1]\) to \(a[hi]\), replace with sorted subarray \(a[lo]\) to \(a[hi]\).

```
<table>
<thead>
<tr>
<th>a[]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>G</td>
</tr>
<tr>
<td>M</td>
</tr>
<tr>
<td>R</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>E</td>
</tr>
<tr>
<td>R</td>
</tr>
<tr>
<td>T</td>
</tr>
</tbody>
</table>
```

\[ k \]

compare minimum in each subarray

```
<table>
<thead>
<tr>
<th>aux[]</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
</tr>
<tr>
<td>E</td>
</tr>
<tr>
<td>G</td>
</tr>
<tr>
<td>M</td>
</tr>
<tr>
<td>R</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>E</td>
</tr>
<tr>
<td>R</td>
</tr>
<tr>
<td>T</td>
</tr>
</tbody>
</table>
```

\[ i \]

\[ j \]
**Goal.** Given two sorted subarrays $a[lo]$ to $a[mid]$ and $a[mid+1]$ to $a[hi]$, replace with sorted subarray $a[lo]$ to $a[hi]$.

**Abstract in-place merge**

- **a[]**
  - $A$  $C$  $E$  $M$  $R$  $A$  $C$  $E$  $R$  $T$

  - $k$

- **aux[]**
  - $E$  $E$  $G$  $M$  $R$  $A$  $C$  $E$  $R$  $T$

  - $i$

  - $j$

**compare minimum in each subarray**
Abstract in-place merge

**Goal.** Given two sorted subarrays \( a[lo] \) to \( a[mid] \) and \( a[mid+1] \) to \( a[hi] \), replace with sorted subarray \( a[lo] \) to \( a[hi] \).

![Diagram showing the in-place merge algorithm](image)

**compare minimum in each subarray**

<table>
<thead>
<tr>
<th>( a[] )</th>
<th>A</th>
<th>C</th>
<th>E</th>
<th>M</th>
<th>R</th>
<th>A</th>
<th>C</th>
<th>E</th>
<th>R</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( aux[] )</th>
<th>E</th>
<th>E</th>
<th>G</th>
<th>M</th>
<th>R</th>
<th>A</th>
<th>C</th>
<th>E</th>
<th>R</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>( i )</td>
<td>( j )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Goal. Given two sorted subarrays $a[lo]$ to $a[mid]$ and $a[mid+1]$ to $a[hi]$, replace with sorted subarray $a[lo]$ to $a[hi]$.
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**Abstract in-place merge**

**compare minimum in each subarray**
Abstract in-place merge

Goal. Given two sorted subarrays $a[lo]$ to $a[mid]$ and $a[mid+1]$ to $a[hi]$, replace with sorted subarray $a[lo]$ to $a[hi]$. 

<table>
<thead>
<tr>
<th>a[]</th>
<th>A</th>
<th>C</th>
<th>E</th>
<th>E</th>
<th>E</th>
<th>A</th>
<th>C</th>
<th>E</th>
<th>R</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>k</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

compare minimum in each subarray

<table>
<thead>
<tr>
<th>aux[]</th>
<th>E</th>
<th>E</th>
<th>G</th>
<th>M</th>
<th>R</th>
<th>A</th>
<th>C</th>
<th>E</th>
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<tbody>
<tr>
<td></td>
<td>i</td>
<td>j</td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>
**Abstract in-place merge**

**Goal.** Given two sorted subarrays \(a[lo]\) to \(a[mid]\) and \(a[mid+1]\) to \(a[hi]\), replace with sorted subarray \(a[lo]\) to \(a[hi]\).

**compare minimum in each subarray**
**Abstract in-place merge**

**Goal.** Given two sorted subarrays $a[lo]$ to $a[mid]$ and $a[mid+1]$ to $a[hi]$, replace with sorted subarray $a[lo]$ to $a[hi]$.

```
a[]
A C E E E G C E R T

k
```

**compare minimum in each subarray**

```
aux[]
E E G M R A C E R T

i j
```
Goal. Given two sorted subarrays a[lo] to a[mid] and a[mid+1] to a[hi], replace with sorted subarray a[lo] to a[hi].

**Abstract in-place merge**

<table>
<thead>
<tr>
<th>a[]</th>
<th>A</th>
<th>C</th>
<th>E</th>
<th>E</th>
<th>E</th>
<th>G</th>
<th>C</th>
<th>E</th>
<th>R</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>aux[]</td>
<td>E</td>
<td>E</td>
<td>G</td>
<td>M</td>
<td>R</td>
<td>A</td>
<td>C</td>
<td>E</td>
<td>R</td>
<td>T</td>
</tr>
</tbody>
</table>

compare minimum in each subarray
Abstract in-place merge

**Goal.** Given two sorted subarrays `a[lo]` to `a[mid]` and `a[mid+1]` to `a[hi]`, replace with sorted subarray `a[lo]` to `a[hi].`
**Goal.** Given two sorted subarrays $a[lo]$ to $a[mid]$ and $a[mid+1]$ to $a[hi]$, replace with sorted subarray $a[lo]$ to $a[hi]$.

**Abstract in-place merge**

- **a[]**
  - A
  - C
  - E
  - E
  - E
  - G
  - M
  - E
  - R
  - T
  - k

- **aux[]**
  - E
  - E
  - G
  - M
  - R
  - A
  - C
  - E
  - R
  - T
  - i
  - j
Goal. Given two sorted subarrays \(a[lo] \) to \(a[mid] \) and \(a[mid+1] \) to \(a[hi] \), replace with sorted subarray \(a[lo] \) to \(a[hi] \).

```

<table>
<thead>
<tr>
<th>a[]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A C E E E G M R R T</td>
</tr>
</tbody>
</table>

\(k\)

```

cmpare minimum in each subarray

```

<table>
<thead>
<tr>
<th>aux[]</th>
</tr>
</thead>
<tbody>
<tr>
<td>E E G M R</td>
</tr>
</tbody>
</table>

\(i\)

\(j\)
**Goal.** Given two sorted subarrays \(a[lo]\) to \(a[mid]\) and \(a[mid+1]\) to \(a[hi]\), replace with sorted subarray \(a[lo]\) to \(a[hi]\).

**Abstract in-place merge**

<table>
<thead>
<tr>
<th>(a[])</th>
<th>A</th>
<th>C</th>
<th>E</th>
<th>E</th>
<th>E</th>
<th>G</th>
<th>M</th>
<th>R</th>
<th>R</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>(k)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**one subarray exhausted, take from other**

<table>
<thead>
<tr>
<th>(aux[])</th>
<th>E</th>
<th>E</th>
<th>G</th>
<th>M</th>
<th>R</th>
<th>A</th>
<th>C</th>
<th>E</th>
<th>R</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i)</td>
<td>(j)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Goal.** Given two sorted subarrays \( a[lo] \) to \( a[mid] \) and \( a[mid+1] \) to \( a[hi] \), replace with sorted subarray \( a[lo] \) to \( a[hi] \).

---

**Abstract in-place merge**

- **a[]**
  - \( A \) \( C \) \( E \) \( E \) \( E \) \( G \) \( M \) \( R \) \( R \) \( T \)
  - \( k \)

- **aux[]**
  - \( E \) \( E \) \( G \) \( M \) \( R \) \( A \) \( C \) \( E \) \( R \) \( T \)
  - \( i \) \( j \)
Abstract in-place merge

**Goal.** Given two sorted subarrays \(a[lo] \) to \(a[mid]\) and \(a[mid+1] \) to \(a[hi]\), replace with sorted subarray \(a[lo] \) to \(a[hi]\).

---

**one subarray exhausted, take from other**

```plaintext
<table>
<thead>
<tr>
<th>a[]</th>
<th>A</th>
<th>C</th>
<th>E</th>
<th>E</th>
<th>E</th>
<th>G</th>
<th>M</th>
<th>R</th>
<th>R</th>
<th>T</th>
</tr>
</thead>
</table>
```

```plaintext
<table>
<thead>
<tr>
<th>aux[]</th>
<th>E</th>
<th>E</th>
<th>G</th>
<th>M</th>
<th>R</th>
<th>A</th>
<th>C</th>
<th>E</th>
<th>R</th>
<th>T</th>
</tr>
</thead>
</table>
```

\(i\) \hspace{1cm} \(j\) \hspace{1cm} \(k\)
Abstract in-place merge

**Goal.** Given two sorted subarrays \( a[lo] \) to \( a[mid] \) and \( a[mid+1] \) to \( a[hi] \), replace with sorted subarray \( a[lo] \) to \( a[hi] \).

\[
\begin{array}{cccccccc}
A & C & E & E & E & G & M & R & R & T \\
\end{array}
\]

**one subarray exhausted, take from other**

\[
\begin{array}{ccccccccc}
E & E & G & M & R & \text{|} & A & C & E & R & T \\
\end{array}
\]

\( i \)

\( j \)

\( k \)
Abstract in-place merge

**Goal.** Given two sorted subarrays $a[lo]$ to $a[mid]$ and $a[mid+1]$ to $a[hi]$, replace with sorted subarray $a[lo]$ to $a[hi]$.

- $a[]$:
  
<p>| | | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>C</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>G</td>
<td>M</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>T</td>
</tr>
</tbody>
</table>

- $aux[]$:

<p>| | | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>E</td>
<td>G</td>
<td>M</td>
<td>R</td>
<td>A</td>
<td>C</td>
<td>E</td>
<td>R</td>
<td>T</td>
<td></td>
</tr>
</tbody>
</table>

  Both subarrays exhausted, done

  i | j | k
Abstract in-place merge

**Goal.** Given two sorted subarrays \(a[lo]\) to \(a[mid]\) and \(a[mid+1]\) to \(a[hi]\), replace with sorted subarray \(a[lo]\) to \(a[hi]\).
Q. How to combine two sorted subarrays into a sorted whole.
A. Use an auxiliary array.

Abstract in-place merge trace
private static void merge(Comparable[] a, Comparable[] aux, int lo, int mid, int hi) {
    assert isSorted(a, lo, mid); // precondition: a[lo..mid] sorted
    assert isSorted(a, mid+1, hi); // precondition: a[mid+1..hi] sorted

    for (int k = lo; k <= hi; k++)
        aux[k] = a[k];

    int i = lo, j = mid+1;
    for (int k = lo; k <= hi; k++)
    {
        if      (i > mid)              a[k] = aux[j++];
        else if (j > hi)               a[k] = aux[i++];
        else if (less(aux[j], aux[i])) a[k] = aux[j++];
        else                           a[k] = aux[i++];
    }

    assert isSorted(a, lo, hi); // postcondition: a[lo..hi] sorted
}
public class Merge {
    private static void merge(Comparable[] a, Comparable[] aux, int lo, int mid, int hi) {
        /* as before */
    }
    private static void sort(Comparable[] a, Comparable[] aux, int lo, int hi) {
        if (hi <= lo) return;
        int mid = lo + (hi - lo) / 2;
        sort (a, aux, lo, mid);
        sort (a, aux, mid+1, hi);
        merge(a, aux, lo, mid, hi);
    }
    public static void sort(Comparable[] a) {
        aux = new Comparable[a.length];
        sort(a, aux, 0, a.length - 1);
    }
}
Mergesort: trace

Trace of merge results for top-down mergesort

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</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>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>E</td>
<td>R</td>
<td>G</td>
<td>E</td>
<td>S</td>
<td>O</td>
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Mergesort: animation

http://www.sorting-algorithms.com/merge-sort
Mergesort: animation

50 reverse-sorted items

http://www.sorting-algorithms.com/merge-sort
Mergesort: empirical analysis

Running time estimates:

- Laptop executes $10^8$ compares/second.
- Supercomputer executes $10^{12}$ compares/second.

<table>
<thead>
<tr>
<th></th>
<th>insertion sort ($N^2$)</th>
<th>mergesort ($N \log N$)</th>
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<tbody>
<tr>
<td></td>
<td>computer</td>
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</tr>
<tr>
<td>home</td>
<td>instant</td>
<td>2.8 hours</td>
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<td>super</td>
<td>instant</td>
<td>1 second</td>
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</table>

**Bottom line.** Good algorithms are better than supercomputers.
Proposition. Mergesort uses at most $N \lg N$ compares and $6N \lg N$ array accesses to sort any array of size $N$.

Pf sketch. The number of compares $C(N)$ and array accesses $A(N)$ to mergesort an array of size $N$ satisfy the recurrences:

\[
C(N) \leq C([N/2]) + C([N/2]) + N \quad \text{for } N > 1, \text{ with } C(1) = 0.
\]

\[
A(N) \leq A([N/2]) + A([N/2]) + 6N \quad \text{for } N > 1, \text{ with } A(1) = 0.
\]

We solve the recurrence when $N$ is a power of 2.

\[
D(N) = 2D(N/2) + N, \text{ for } N > 1, \text{ with } D(1) = 0.
\]
private static void merge(Comparable[] a, Comparable[] aux, int lo, int mid, int hi) {
    assert isSorted(a, lo, mid);  // precondition: a[lo..mid] sorted
    assert isSorted(a, mid+1, hi);  // precondition: a[mid+1..hi] sorted
    for (int k = lo; k <= hi; k++)
        aux[k] = a[k];               // copy
    int i = lo, j = mid+1;
    for (int k = lo; k <= hi; k++)
    {
        if      (i > mid)              a[k] = aux[j++];          // merge
        else if (j > hi)               a[k] = aux[i++];
        else if (less(aux[j], aux[i])) a[k] = aux[j++];
        else                           a[k] = aux[i++];
    }
    assert isSorted(a, lo, hi);    // postcondition: a[lo..hi] sorted
}
Proposition. If $D(N)$ satisfies $D(N) = 2D(N/2) + N$ for $N > 1$, with $D(1) = 0$, then $D(N) = N \log N$.

Pf 1. [assuming $N$ is a power of 2]
Proposition. If $D(N)$ satisfies $D(N) = 2D(N/2) + N$ for $N > 1$, with $D(1) = 0$, then $D(N) = N \log N$.

Pf 2. [assuming $N$ is a power of 2]

\[
\begin{align*}
D(N) &= 2D(N/2) + N \\
\frac{D(N)}{N} &= 2\frac{D(N/2)}{N} + 1 \\
&= \frac{D(N/2)}{(N/2)} + 1 \\
&= \frac{D(N/4)}{(N/4)} + 1 + 1 \\
&= \frac{D(N/8)}{(N/8)} + 1 + 1 + 1 \\
& \vdots \\
&= \frac{D(N/N)}{(N/N)} + 1 + 1 + \ldots + 1 \\
&= \log N
\end{align*}
\]
Proposition. If \( D(N) \) satisfies \( D(N) = 2D(N/2) + N \) for \( N > 1 \),
with \( D(1) = 0 \),
then \( D(N) = N \log_2 N \).

Pf 3. [assuming \( N \) is a power of 2]

- Base case: \( N = 1 \).
- Inductive hypothesis: \( D(N) = N \log_2 N \).
- Goal: show that \( D(2N) = (2N) \log_2 (2N) \).

\[
D(2N) = 2D(N) + 2N
\]

\[
= 2N \log_2 N + 2N
\]

\[
= 2N (\log_2 (2N) - 1) + 2N
\]

\[
= 2N \log_2 (2N)
\]

QED
**Proposition.** Mergesort uses extra space proportional to $N$.

**Pf.** The array $\text{aux}[]$ needs to be of size $N$ for the last merge.

---

**Def.** A sorting algorithm is **in-place** if it uses $\leq c \log N$ extra memory.

**Ex.** Insertion sort, selection sort, shellsort.

---

**Challenge for the bored.** In-place merge. [Kronrod, 1969]
Mergesort: practical improvements

Use insertion sort for small subarrays.

- Mergesort has too much overhead for tiny subarrays.
- Cutoff to insertion sort for ≈ 7 items.

```java
private static void sort(Comparable[] a, Comparable[] aux, int lo, int hi)
{
    if (hi <= lo + CUTOFF - 1) Insertion.sort(a, lo, hi);
    int mid = lo + (hi - lo) / 2;
    sort (a, aux, lo, mid);
    sort (a, aux, mid+1, hi);
    merge(a, aux, lo, mid, hi);
}
```
Mergesort: practical improvements

Stop if already sorted.
- Is biggest item in first half $\leq$ smallest item in second half?
- Helps for partially-ordered arrays.

```java
private static void sort(Comparable[] a, Comparable[] aux, int lo, int hi)
{
    if (hi <= lo) return;
    int mid = lo + (hi - lo) / 2;
    sort (a, aux, lo, mid);
    sort (a, aux, mid+1, hi);
    if (!less(a[mid+1], a[mid])) return;
    merge(a, aux, lo, mid, hi);
}
```
Mergesort: practical improvements

Eliminate the copy to the auxiliary array. Save time (but not space) by switching the role of the input and auxiliary array in each recursive call.

```java
private static void merge(Comparable[] a, Comparable[] aux, int lo, int mid, int hi)
{
    int i = lo, j = mid+1;
    for (int k = lo; k <= hi; k++)
    {
        if      (i > mid) aux[k] = a[j++];
        else if (j > hi) aux[k] = a[i++];
        else if (less(a[j], a[i])) aux[k] = a[j++];
        else aux[k] = a[i++];
    }
}

private static void sort(Comparable[] a, Comparable[] aux, int lo, int hi)
{
    if (hi <= lo) return;
    int mid = lo + (hi - lo) / 2;
    sort (aux, a, lo, mid);
    sort (aux, a, mid+1, hi);
    merge(aux, a, lo, mid, hi);
}
```

---

merge from a[] to aux[]

switch roles of aux[] and a[]
Mergesort: visualization

- first subarray
- second subarray
- first merge
- first half sorted
- second half sorted
- result
Bottom-up mergesort

Basic plan.

- Pass through array, merging subarrays of size 1.
- Repeat for subarrays of size 2, 4, 8, 16, ....

Bottom line. No recursion needed!
Bottom-up mergesort: Java implementation

```java
public class MergeBU {
    private static Comparable[] aux;

    private static void merge(Comparable[] a, int lo, int mid, int hi)
    {
        /* as before */
    }

    public static void sort(Comparable[] a)
    {
        int N = a.length;
        aux = new Comparable[N];
        for (int sz = 1; sz < N; sz = sz+sz)
            for (int lo = 0; lo < N-sz; lo += sz+sz)
                merge(a, lo, lo+sz-1, Math.min(lo+sz+sz-1, N-1));
    }
}
```

Bottom line. Concise industrial-strength code, if you have the space.
Bottom-up mergesort: visual trace
Bottom-up mergesort: visual trace

http://bl.ocks.org/mbostock/39566aca95eb03ddd526
Bottom-up mergesort: visual trace

http://bl.ocks.org/mbostock/e65d9895da07c57e94bd
Complexity of sorting

Computational complexity. Framework to study efficiency of algorithms for solving a particular problem $X$.

Model of computation. Allowable operations.

Cost model. Operation count(s).

Upper bound. Cost guarantee provided by some algorithm for $X$.

Lower bound. Proven limit on cost guarantee of all algorithms for $X$.

Optimal algorithm. Algorithm with best possible cost guarantee for $X$.

Example: sorting.

- Model of computation: decision tree.
- Cost model: $\#$ compares.
- Upper bound: $\sim N \lg N$ from mergesort.
- Lower bound: ?
- Optimal algorithm: ?
Decision tree (for 3 distinct items a, b, and c)

- **a < b**
  - yes
  - no

- **b < c**
  - yes
  - no

- **a < c**
  - yes
  - no

- **b a c**
- **b c a**

- **a b c**
- **c b a**

**height of tree = worst-case number of a < b**

code between compares (e.g., sequence of exchanges)

(at least) one leaf for each possible ordering
Proposition. Any compare-based sorting algorithm must use at least \( \lg (N!) \sim N \lg N \) compares in the worst-case.

Pf.
• Assume array consists of \( N \) distinct values \( a_1 \) through \( a_N \).
• Worst case dictated by height \( h \) of decision tree.
• Binary tree of height \( h \) has at most \( 2^h \) leaves.
• \( N! \) different orderings \(\Rightarrow\) at least \( N! \) leaves.
Proposition. Any compare-based sorting algorithm must use at least $\lg (N!) \sim N \lg N$ compares in the worst-case.

Pf.

• Assume array consists of $N$ distinct values $a_1$ through $a_N$.
• Worst case dictated by height $h$ of decision tree.
• Binary tree of height $h$ has at most $2^h$ leaves.
• $N!$ different orderings $\Rightarrow$ at least $N!$ leaves.

\[ 2^h \geq \# \text{ leaves} \geq N! \]
\[ \Rightarrow h \geq \lg (N!) \sim N \lg N \]

Stirling's formula
Complexity of sorting

Model of computation. Allowable operations.
Cost model. Operation count(s).
Upper bound. Cost guarantee provided by some algorithm for $X$.
Lower bound. Proven limit on cost guarantee of all algorithms for $X$.
Optimal algorithm. Algorithm with best possible cost guarantee for $X$.

Example: sorting.
• Model of computation: decision tree.
• Cost model: $\#$ compares.
• Upper bound: $\sim N \lg N$ from mergesort.
• Lower bound: $\sim N \lg N$.
• Optimal algorithm = mergesort.

First goal of algorithm design: optimal algorithms.
Other operations? Mergesort is optimal with respect to number of compares (e.g., but not with respect to number of array accesses).

Space?
- Mergesort is not optimal with respect to space usage.
- Insertion sort, selection sort, and shellsort are space-optimal.

Challenge. Find an algorithm that is both time- and space-optimal.
[stay tuned]

Lessons. Use theory as a guide.
Ex. Don't try to design sorting algorithm that guarantees $\frac{1}{2} N \lg N$ compares.
Lower bound may not hold if the algorithm has information about:

- The initial order of the input.
- The distribution of key values.
- The representation of the keys.

**Partially-ordered arrays.** Depending on the initial order of the input, we may not need $N \log N$ compares.

**Duplicate keys.** Depending on the input distribution of duplicates, we may not need $N \log N$ compares.

**Digital properties of keys.** We can use digit/character compares instead of key compares for numbers and strings.
Comparable interface: review

Comparable interface: sort using a type's natural order.

```java
generic Comparable interface: sort using a type's natural order.

public class Date implements Comparable<Date> {
    private final int month, day, year;

    public Date(int m, int d, int y) {
        month = m;
        day   = d;
        year  = y;
    }

    public int compareTo(Date that) {
        if (this.year < that.year) return -1;
        if (this.year > that.year) return +1;
        if (this.month < that.month) return -1;
        if (this.month > that.month) return +1;
        if (this.day < that.day) return -1;
        if (this.day > that.day) return +1;
        return 0;
    }
}
```
Comparator interface: sort using an alternate order.

```
public interface Comparator<Key>

    int compare(Key v, Key w)  // compare keys v and w
```

Required property. Must be a total order.

Ex. Sort strings by:
- Natural order.  
  - Now is the time
  - is Now the time
- Case insensitive.
  - café cafetero cuarto churro nube niño
- Spanish.
  - café cafetero cuarto churro nube niño
- British phone book.
  - McKinley Mackintosh
- ...
Comparator interface: system sort

To use with Java system sort:

- Create `Comparator` object.
- Pass as second argument to `Arrays.sort()`.

Bottom line. Decouples the definition of the data type from the definition of what it means to compare two objects of that type.
Comparator interface: using with our sorting libraries

To support comparators in our sort implementations:

- Use `Object` instead of `Comparable`.
- Pass `Comparator` to `sort()` and `less()` and use it in `less()`.

insertion sort using a Comparator

```java
public static void sort(Object[] a, Comparator comparator)
{
    int N = a.length;
    for (int i = 0; i < N; i++)
        for (int j = i; j > 0 && less(comparator, a[j], a[j-1]); j--)
            exch(a, j, j-1);
}

private static boolean less(Comparator c, Object v, Object w)
{  return c.compare(v, w) < 0;   }

private static void exch(Object[] a, int i, int j)
{  Object swap = a[i]; a[i] = a[j]; a[j] = swap;  }
```
To implement a comparator:

- Define a (nested) class that implements the `Comparator` interface.
- Implement the `compare()` method.

```java
class Student {
    public static final Comparator<Student> BY_NAME = new ByName();
    public static final Comparator<Student> BY_SECTION = new BySection();
    private final String name;
    private final int section;
    ...

    private static class ByName implements Comparator<Student> {
        public int compare(Student v, Student w) {
            return v.name.compareTo(w.name);
        }
    }

    private static class BySection implements Comparator<Student> {
        public int compare(Student v, Student w) {
            return v.section - w.section;
        }
    }
}
```

This technique works here since no danger of overflow.
Comparator interface: implementing

To implement a comparator:

- Define a (nested) class that implements the `Comparator` interface.
- Implement the `compare()` method.

```java
Arrays.sort(a, Student.BY_NAME);
Arrays.sort(a, Student.BY_SECTION);
```

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<th>Type</th>
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<td>22 Brown</td>
</tr>
<tr>
<td>Battle</td>
<td>4</td>
<td>874-088-1212</td>
<td>121 Whitman</td>
</tr>
<tr>
<td>Gazsi</td>
<td>4</td>
<td>766-093-9873</td>
<td>101 Brown</td>
</tr>
</tbody>
</table>
Stability

A typical application. First, sort by name; then sort by section.

```java
Selection.sort(a, Student.BY_NAME);
```

<table>
<thead>
<tr>
<th>Name</th>
<th>Section</th>
<th>Number</th>
<th>Phone</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andrews</td>
<td>3</td>
<td>A</td>
<td>664-480-0023</td>
<td>097 Little</td>
</tr>
<tr>
<td>Battle</td>
<td>4</td>
<td>C</td>
<td>874-088-1212</td>
<td>121 Whitman</td>
</tr>
<tr>
<td>Chen</td>
<td>3</td>
<td>A</td>
<td>991-878-4944</td>
<td>308 Blair</td>
</tr>
<tr>
<td>Fox</td>
<td>3</td>
<td>A</td>
<td>884-232-5341</td>
<td>11 Dickinson</td>
</tr>
<tr>
<td>Furia</td>
<td>1</td>
<td>A</td>
<td>766-093-9873</td>
<td>101 Brown</td>
</tr>
<tr>
<td>Gazsi</td>
<td>4</td>
<td>B</td>
<td>766-093-9873</td>
<td>101 Brown</td>
</tr>
<tr>
<td>Kanaga</td>
<td>3</td>
<td>B</td>
<td>898-122-9643</td>
<td>22 Brown</td>
</tr>
<tr>
<td>Rohde</td>
<td>2</td>
<td>A</td>
<td>232-343-5555</td>
<td>343 Forbes</td>
</tr>
</tbody>
</table>

```java
Selection.sort(a, Student.BY_SECTION);
```

<table>
<thead>
<tr>
<th>Name</th>
<th>Section</th>
<th>Number</th>
<th>Phone</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furia</td>
<td>1</td>
<td>A</td>
<td>766-093-9873</td>
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</tbody>
</table>

@#%&@! Students in section 3 no longer sorted by name.

A stable sort preserves the relative order of items with equal keys.
Q. Which sorts are stable?
A. Insertion sort and mergesort (but not selection sort or shellsort).

Note. Need to carefully check code ("less than" vs "less than or equal to").
Proposition. Insertion sort is stable.

Pf. Equal items never move past each other.
Proposition. Selection sort is not stable.

Pf by counterexample. Long-distance exchange might move an item past some equal item.
Proposition. Shellsort sort is not stable.

```
public class Shell {
    public static void sort(Comparable[] a) {
        int N = a.length;
        int h = 1;
        while (h < N/3) h = 3*h + 1;
        while (h >= 1) {
            for (int i = h; i < N; i++) {
                for (int j = i; j > h && less(a[j], a[j-h]); j -= h)
                    exch(a, j, j-h);
            }
            h = h/3;
        }
    }
}
```

Pf by counterexample. Long-distance exchanges.
**Stability: mergesort**

**Proposition.** Mergesort is **stable**.

```java
public class Merge {
    private static Comparable[] aux;
    private static void merge(Comparable[] a, int lo, int mid, int hi) {
        /* as before */
    }

    private static void sort(Comparable[] a, int lo, int hi) {
        if (hi <= lo) return;
        int mid = lo + (hi - lo) / 2;
        sort(a, lo, mid);
        sort(a, mid + 1, hi);
        merge(a, lo, mid, hi);
    }

    public static void sort(Comparable[] a) {
        /* as before */
    }
}
```

**Pf.** Suffices to verify that merge operation is stable.
Proposition. Merge operation is stable.

```
private static void merge(Comparable[] a, int lo, int mid, int hi)
{  
    for (int k = lo; k <= hi; k++)
        aux[k] = a[k];

    int i = lo, j = mid+1;
    for (int k = lo; k <= hi; k++)
    {
        if      (i > mid)              a[k] = aux[j++];
        else if (j > hi)               a[k] = aux[i++];
        else if (less(aux[j], aux[i])) a[k] = aux[j++];
        else                           a[k] = aux[i++];
    }
}
```

Pf. Takes from left subarray if equal keys.