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## 2.2 MERGESORT

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- ▶ *mergesort*
- ▶ *bottom-up mergesort*
- ▶ *sorting complexity*
- ▶ *comparators*
- ▶ *stability*

# Two classic sorting algorithms

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Critical components in the world's computational infrastructure.

- Full scientific understanding of their properties has enabled us to develop them into practical system sorts.
- Quicksort honored as one of top 10 algorithms of 20<sup>th</sup> century in science and engineering.

Mergesort. [this lecture]

- Java sort for objects.
- Perl, C++ stable sort, Python stable sort, Firefox JavaScript, ...

Quicksort. [next lecture]

- Java sort for primitive types.
- C qsort, Unix, Visual C++, Python, Matlab, Chrome JavaScript, ...

# Algorithms

ROBERT SEDGEWICK | KEVIN WAYNE

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# Mergesort

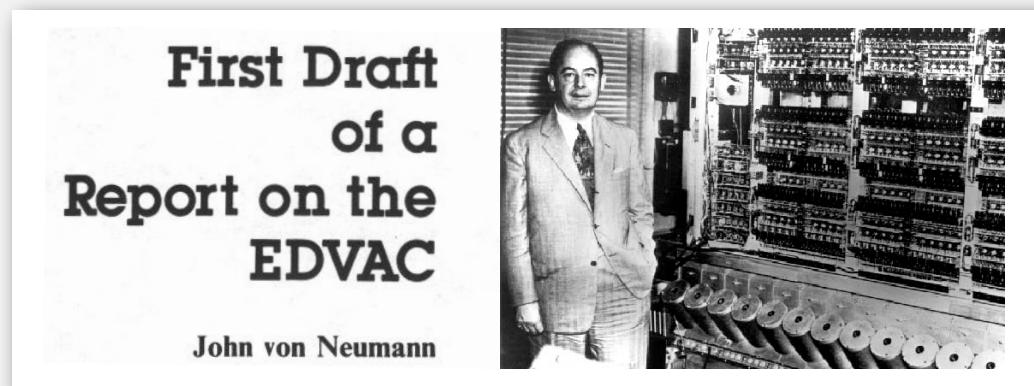
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## Basic plan.

- Divide array into two halves.
- Recursively sort each half.
- Merge two halves.

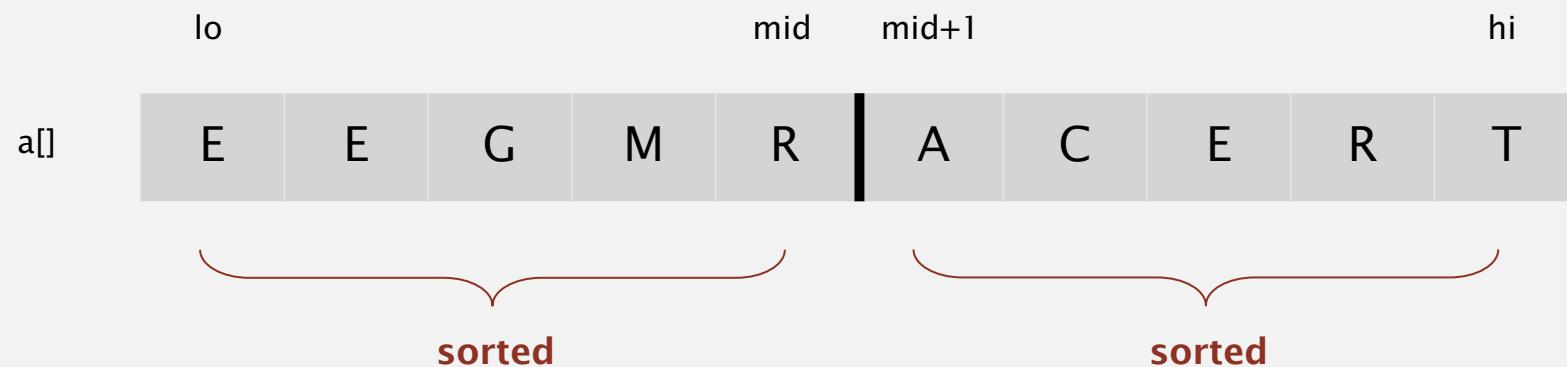
input	M	E	R	G	E	S	O	R	T	E	X	A	M	P	L	E	
sort left half	E	E	G	M	M	O	R	R	S	T	E	X	A	M	P	L	E
sort right half	E	E	G	M	M	O	R	R	S	A	E	E	L	M	P	T	X
merge results	A	E	E	E	E	E	G	L	M	M	O	P	R	R	S	T	X

Mergesort overview



# Abstract in-place merge demo

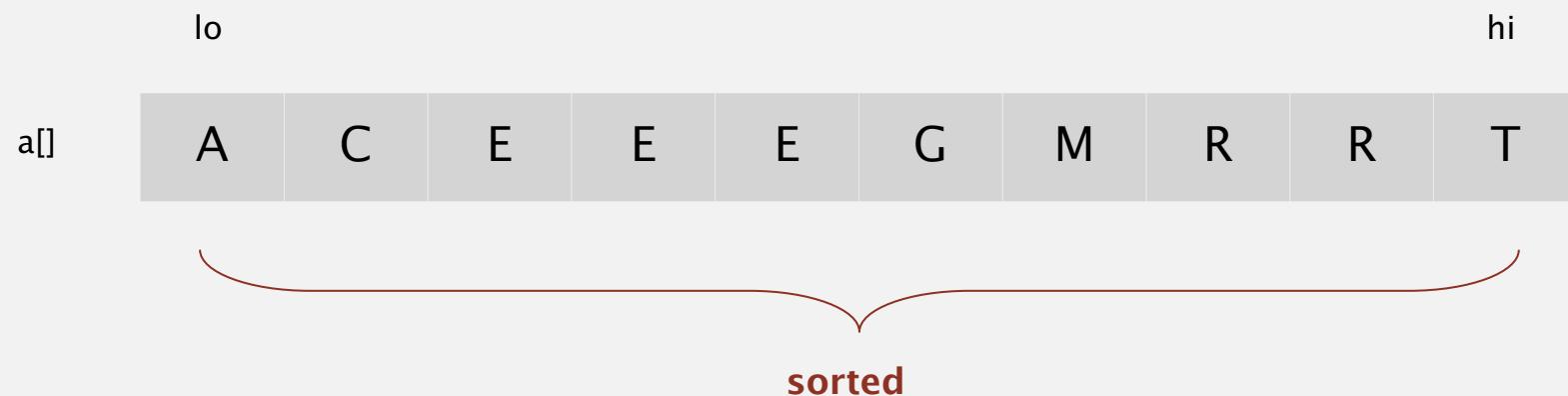
**Goal.** Given two sorted subarrays  $a[lo]$  to  $a[mid]$  and  $a[mid+1]$  to  $a[hi]$ , replace with sorted subarray  $a[lo]$  to  $a[hi]$ .



# Abstract in-place merge demo

---

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



# Merging: Java implementation

```
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++)                                copy
        aux[k] = a[k];

    int i = lo, j = mid+1;
    for (int k = lo; k <= hi; k++)                                merge
    {
        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
}
```



# Assertions

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**Assertion.** Statement to test assumptions about your program.

- Helps detect logic bugs.
- Documents code.

**Java assert statement.** Throws exception unless boolean condition is true.

```
assert isSorted(a, lo, hi);
```

**Can enable or disable at runtime.** ⇒ No cost in production code.

```
java -ea MyProgram    // enable assertions  
java -da MyProgram    // disable assertions (default)
```

**Best practices.** Use assertions to check internal invariants;  
assume assertions will be disabled in production code. ←

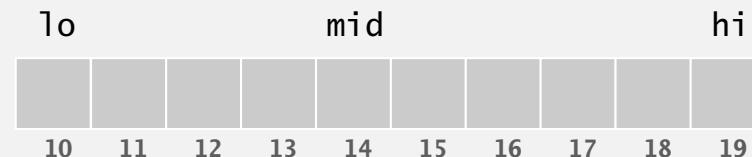
do not use for external  
argument checking

# Mergesort: Java implementation

```
public class Merge
{
    private static void merge(...)

    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

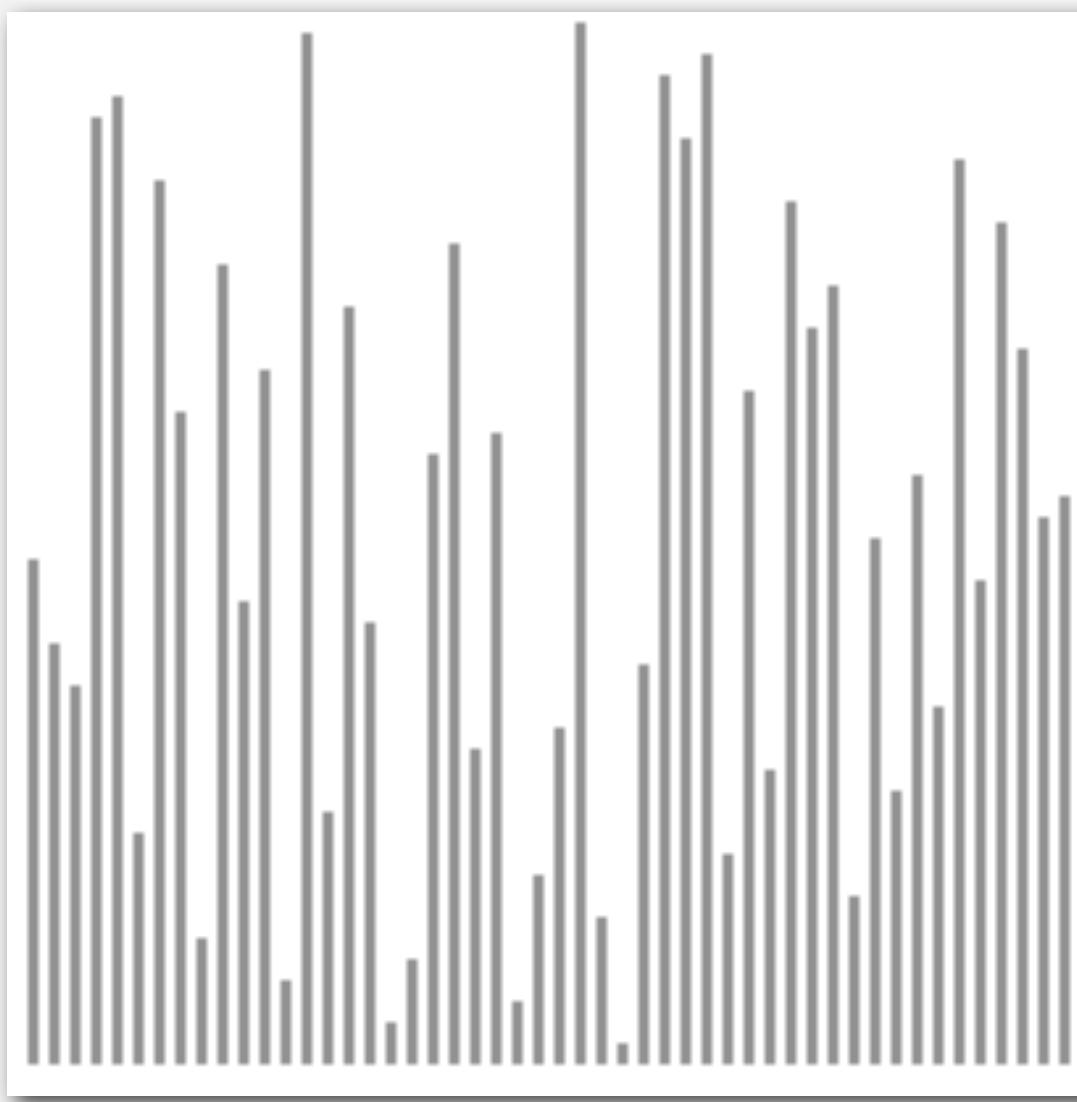
---

	a[]																
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
lo	M	E	R	G	E	S	O	R	T	E	X	A	M	P	L	E	
hi	E	M	R	G	E	S	O	R	T	E	X	A	M	P	L	E	
merge(a, aux, 0, 0, 1)	E	M	G	R	E	S	O	R	T	E	X	A	M	P	L	E	
merge(a, aux, 2, 2, 3)	E	G	M	R	E	S	O	R	T	E	X	A	M	P	L	E	
merge(a, aux, 0, 1, 3)	E	G	M	R	E	S	O	R	T	E	X	A	M	P	L	E	
merge(a, aux, 4, 4, 5)	E	G	M	R	E	S	O	R	T	E	X	A	M	P	L	E	
merge(a, aux, 6, 6, 7)	E	G	M	R	E	S	O	R	T	E	X	A	M	P	L	E	
merge(a, aux, 4, 5, 7)	E	G	M	R	E	O	R	S	T	E	X	A	M	P	L	E	
merge(a, aux, 0, 3, 7)	E	E	G	M	O	R	R	S	T	E	X	A	M	P	L	E	
merge(a, aux, 8, 8, 9)	E	E	G	M	O	R	R	S	E	T	X	A	M	P	L	E	
merge(a, aux, 10, 10, 11)	E	E	G	M	O	R	R	S	E	T	A	X	M	P	L	E	
merge(a, aux, 8, 9, 11)	E	E	G	M	O	R	R	S	A	E	T	X	M	P	L	E	
merge(a, aux, 12, 12, 13)	E	E	G	M	O	R	R	S	A	E	T	X	M	P	L	E	
merge(a, aux, 14, 14, 15)	E	E	G	M	O	R	R	S	A	E	T	X	M	P	E	L	
merge(a, aux, 12, 13, 15)	E	E	G	M	O	R	R	S	A	E	T	X	E	L	M	P	
merge(a, aux, 8, 11, 15)	E	E	G	M	O	R	R	S	A	E	E	L	M	P	T	X	
merge(a, aux, 0, 7, 15)	A	E	E	E	E	E	G	L	M	M	O	P	R	R	S	T	X

result after recursive call

# Mergesort: animation

## 50 random items

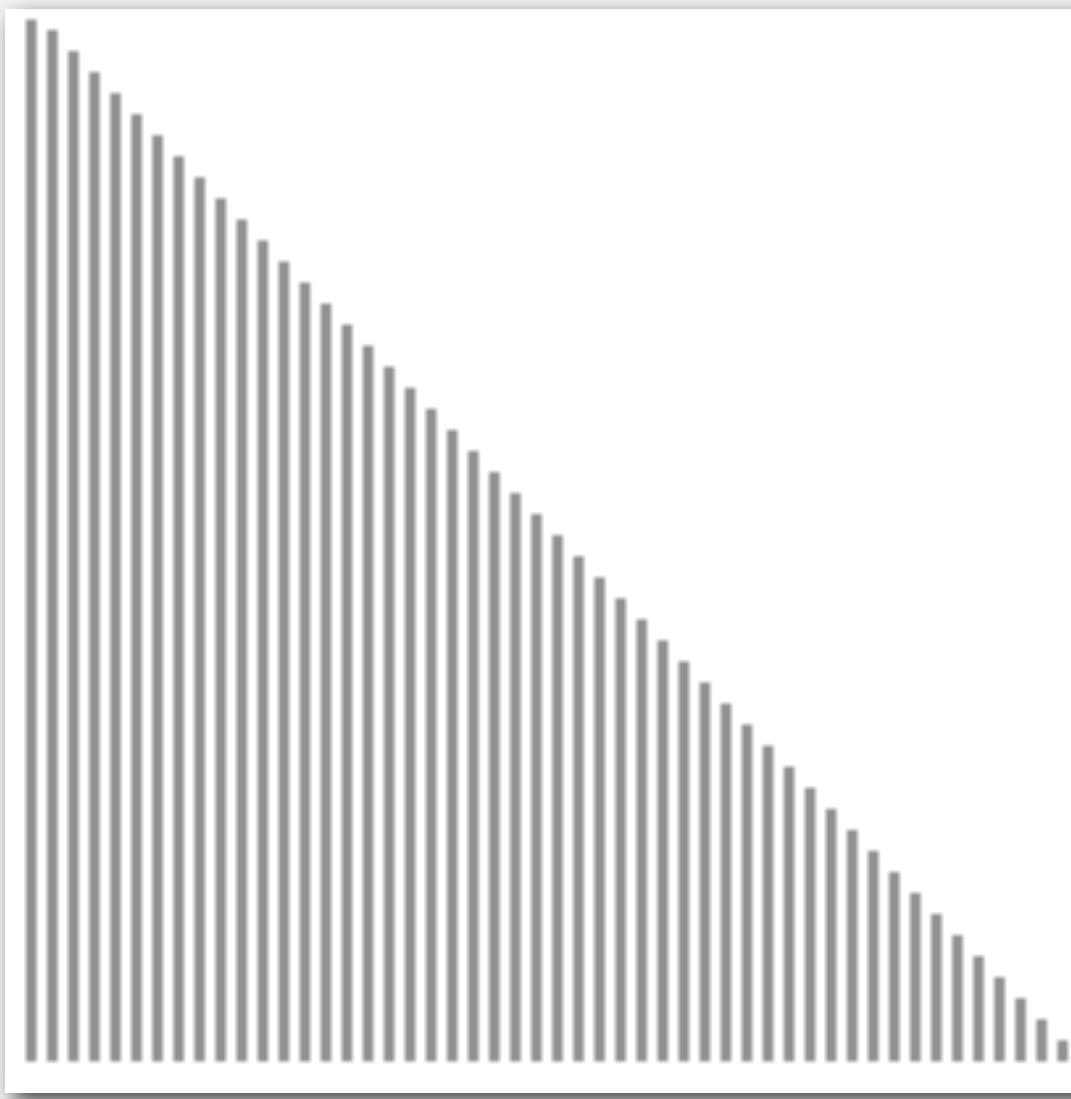


<http://www.sorting-algorithms.com/merge-sort>

- ▲ algorithm position
- █ in order
- ▒ current subarray
- ░ not in order

# Mergesort: animation

## 50 reverse-sorted items



<http://www.sorting-algorithms.com/merge-sort>

- ▲ algorithm position
  - █ in order
  - █ current subarray
  - █ not in order

# Mergesort: empirical analysis

---

## Running time estimates:

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

computer	insertion sort ( $N^2$ )			mergesort ( $N \log N$ )		
	thousand	million	billion	thousand	million	billion
home	instant	2.8 hours	317 years	instant	1 second	18 min
super	instant	1 second	1 week	instant	instant	instant

Bottom line. Good algorithms are better than supercomputers.

## Mergesort: number of compares and array accesses

---

**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:

$$C(N) \leq C(\lceil N/2 \rceil) + C(\lfloor N/2 \rfloor) + N \text{ for } N > 1, \text{ with } C(1) = 0.$$



$$A(N) \leq A(\lceil N/2 \rceil) + A(\lfloor N/2 \rfloor) + 6N \text{ for } N > 1, \text{ with } A(1) = 0.$$

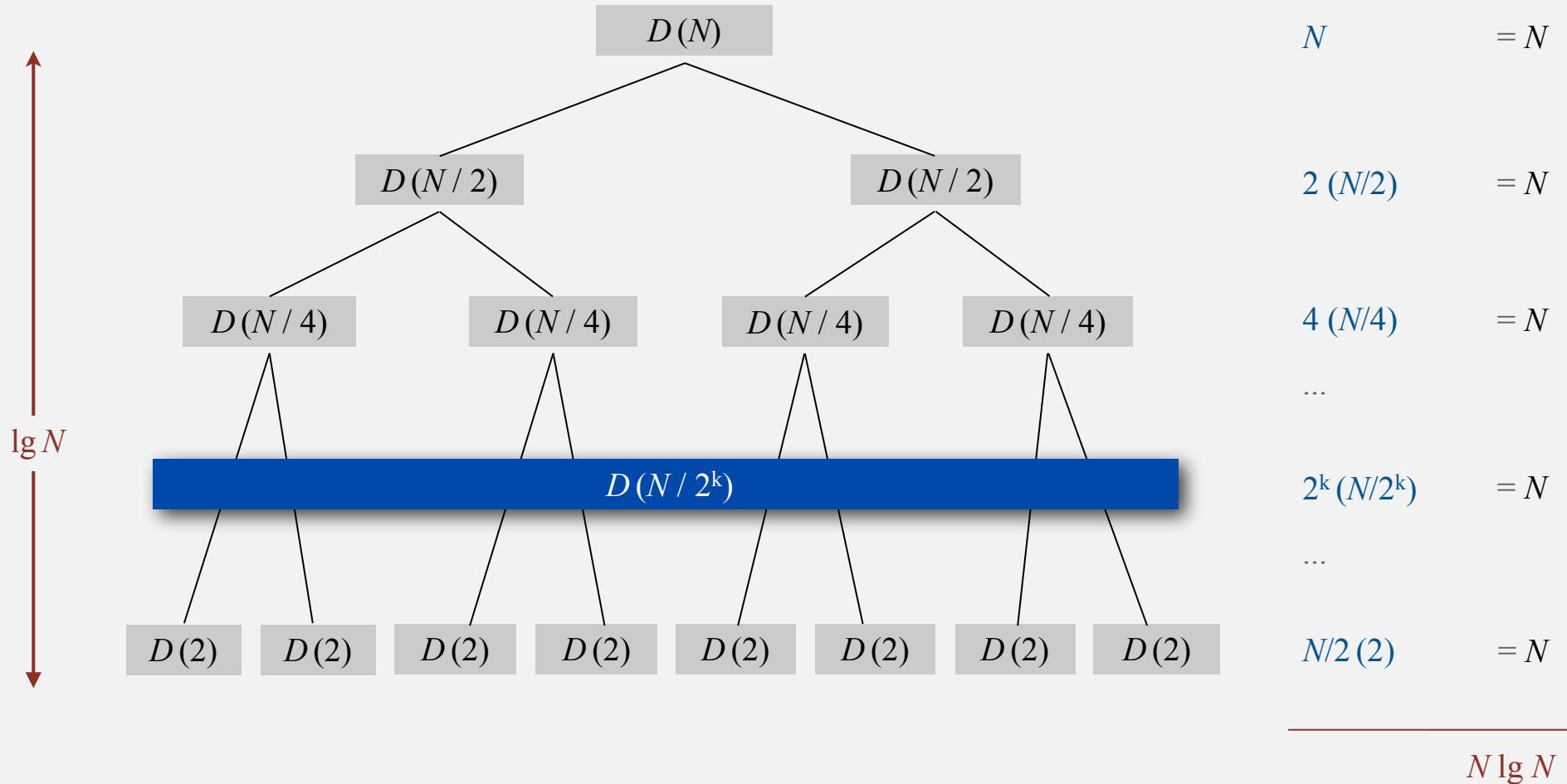
We solve the recurrence when  $N$  is a power of 2. ← result holds for all  $N$

$$D(N) = 2D(N/2) + N, \text{ for } N > 1, \text{ with } D(1) = 0.$$

# Divide-and-conquer recurrence: proof by picture

**Proposition.** If  $D(N)$  satisfies  $D(N) = 2 D(N / 2) + N$  for  $N > 1$ , with  $D(1) = 0$ , then  $D(N) = N \lg N$ .

**Pf 1.** [assuming  $N$  is a power of 2]



$$N \lg N$$

## Divide-and-conquer recurrence: proof by expansion

**Proposition.** If  $D(N)$  satisfies  $D(N) = 2D(N/2) + N$  for  $N > 1$ , with  $D(1) = 0$ , then  $D(N) = N \lg N$ .

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

$$D(N) = 2D(N/2) + N$$

given

$$D(N)/N = 2D(N/2)/N + 1$$

divide both sides by  $N$

$$= D(N/2)/(N/2) + 1$$

algebra

$$= D(N/4)/(N/4) + 1 + 1$$

apply to first term

$$= D(N/8)/(N/8) + 1 + 1 + 1$$

apply to first term again

...

$$= D(N/N)/(N/N) + 1 + 1 + \dots + 1$$

stop applying,  $D(1) = 0$

$$= \lg N$$

## Divide-and-conquer recurrence: proof by induction

---

**Proposition.** If  $D(N)$  satisfies  $D(N) = 2 D(N / 2) + N$  for  $N > 1$ , with  $D(1) = 0$ , then  $D(N) = N \lg N$ .

**Pf 3.** [assuming  $N$  is a power of 2]

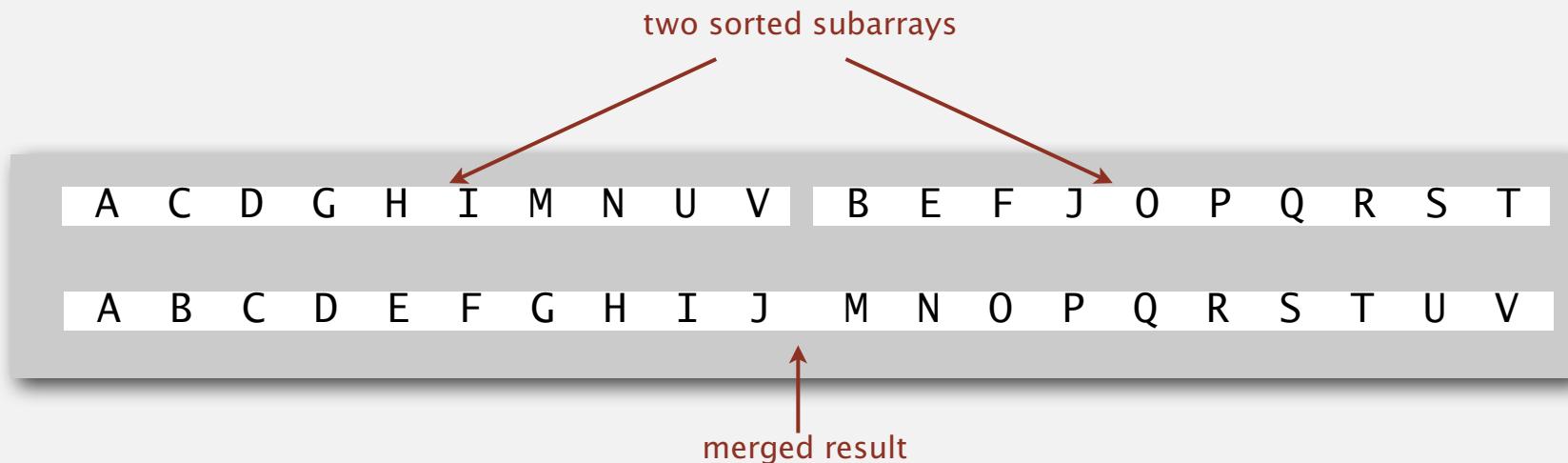
- Base case:  $N = 1$ .
- Inductive hypothesis:  $D(N) = N \lg N$ .
- Goal: show that  $D(2N) = (2N) \lg (2N)$ .

$$\begin{aligned} D(2N) &= 2 D(N) + 2N && \text{given} \\ &= 2 N \lg N + 2N && \text{inductive hypothesis} \\ &= 2 N (\lg (2N) - 1) + 2N && \text{algebra} \\ &= 2 N \lg (2N) && \text{QED} \end{aligned}$$

## Mergesort analysis: memory

**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

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Use insertion sort for small subarrays.

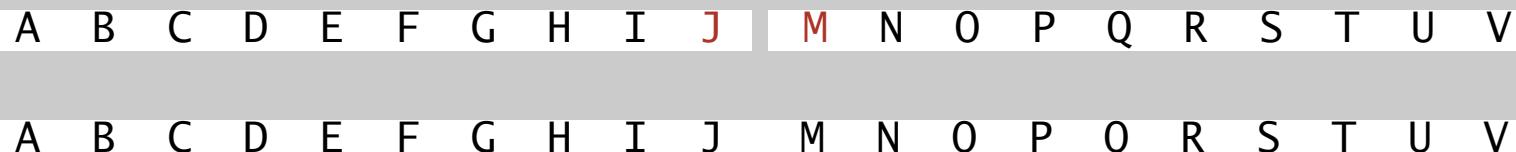
- Mergesort has too much overhead for tiny subarrays.
- Cutoff to insertion sort for  $\approx 7$  items.

```
private static void sort(Comparable[] a, Comparable[] aux, int lo, int hi)
{
    if (hi <= lo + CUTOFF - 1)
    {
        Insertion.sort(a, lo, hi);
        return;
    }
    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.



```
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.

```
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++]; ← merge from a[] to aux[]
        else                   aux[k] = a[i++];
    }
}

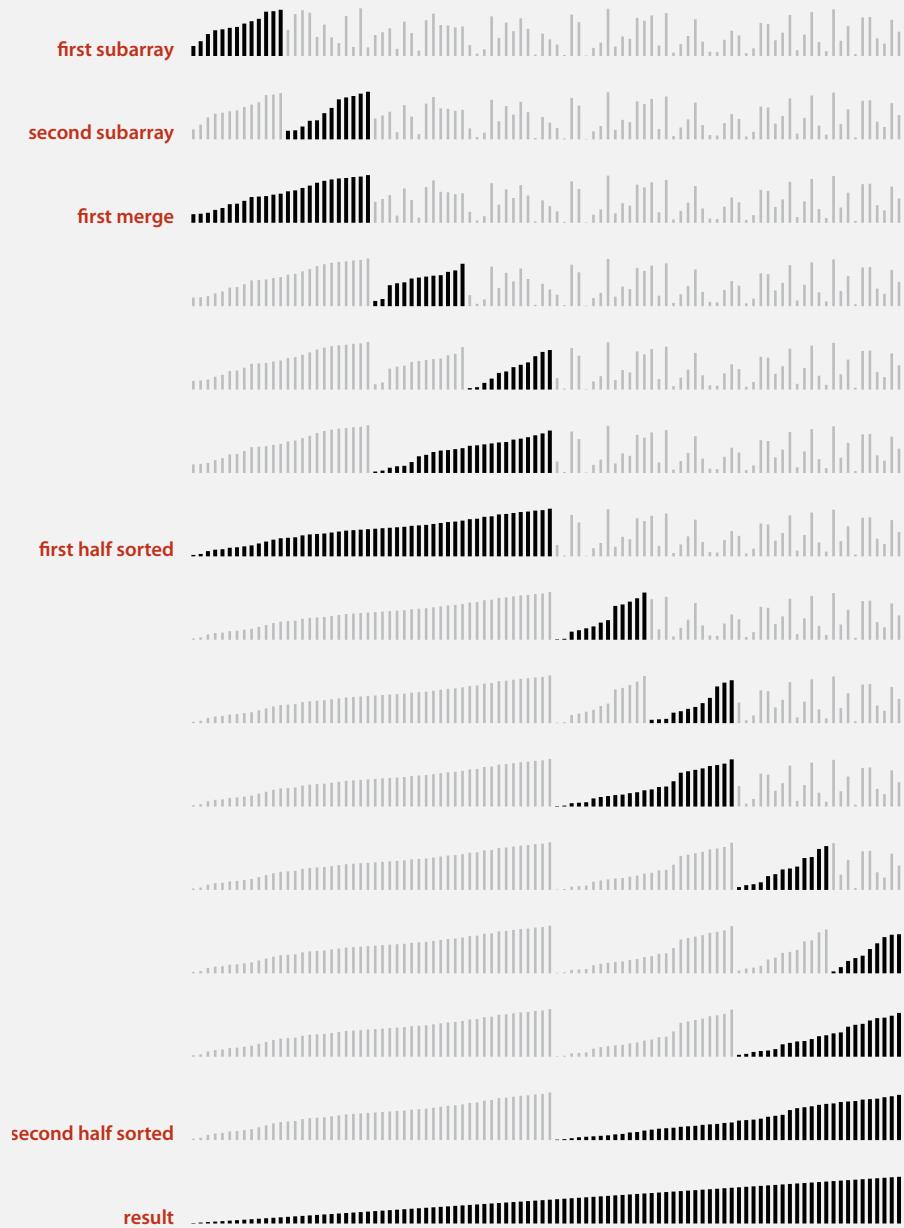
private static void sort(Comparable[] a, Comparable[] aux, int lo, int hi)
{
```

```
    if (hi <= lo) return;
    int mid = lo + (hi - lo) / 2;
    sort (aux, a, lo, mid);
    sort (aux, a, mid+1, hi);      Note: sort(a) initializes aux[] and sets
    merge(a, aux, lo, mid, hi);    aux[i] = a[i] for each i.
}
```

switch roles of aux[] and a[]

# Mergesort: visualization

---



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# Bottom-up mergesort

---

Basic plan.

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

	a[i]																
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
<b>sz = 1</b>	M	E	R	G	E	S	O	R	T	E	X	A	M	P	L	E	
merge(a, aux, 0, 0, 1)	E	M	R	G	E	S	O	R	T	E	X	A	M	P	L	E	
merge(a, aux, 2, 2, 3)	E	M	G	R	E	S	O	R	T	E	X	A	M	P	L	E	
merge(a, aux, 4, 4, 5)	E	M	G	R	E	S	O	R	T	E	X	A	M	P	L	E	
merge(a, aux, 6, 6, 7)	E	M	G	R	E	S	O	R	T	E	X	A	M	P	L	E	
merge(a, aux, 8, 8, 9)	E	M	G	R	E	S	O	R	E	T	X	A	M	P	L	E	
merge(a, aux, 10, 10, 11)	E	M	G	R	E	S	O	R	E	T	A	X	M	P	L	E	
merge(a, aux, 12, 12, 13)	E	M	G	R	E	S	O	R	E	T	A	X	M	P	L	E	
merge(a, aux, 14, 14, 15)	E	M	G	R	E	S	O	R	E	T	A	X	M	P	E	L	
<b>sz = 2</b>	E	G	M	R	E	S	O	R	E	T	A	X	M	P	E	L	
merge(a, aux, 0, 1, 3)	E	G	M	R	E	O	R	S	E	T	A	X	M	P	E	L	
merge(a, aux, 4, 5, 7)	E	G	M	R	E	O	R	S	A	E	T	X	M	P	E	L	
merge(a, aux, 8, 9, 11)	E	G	M	R	E	O	R	S	A	E	T	X	M	P	E	L	
merge(a, aux, 12, 13, 15)	E	G	M	R	E	O	R	S	A	E	T	X	E	L	M	P	
<b>sz = 4</b>	E	E	G	M	O	R	R	S	A	E	T	X	E	L	M	P	
merge(a, aux, 0, 3, 7)	E	E	G	M	O	R	R	S	A	E	E	L	M	P	T	X	
merge(a, aux, 8, 11, 15)	E	E	G	M	O	R	R	S	A	E	E	L	M	P	T	X	
<b>sz = 8</b>	A	E	E	E	E	E	G	L	M	M	O	P	R	R	S	T	X
merge(a, aux, 0, 7, 15)	A	E	E	E	E	E	G	L	M	M	O	P	R	R	S	T	X

## Bottom-up mergesort: Java implementation

```
public class MergeBU
{
    private static void merge(...)
    { /* as before */ }

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

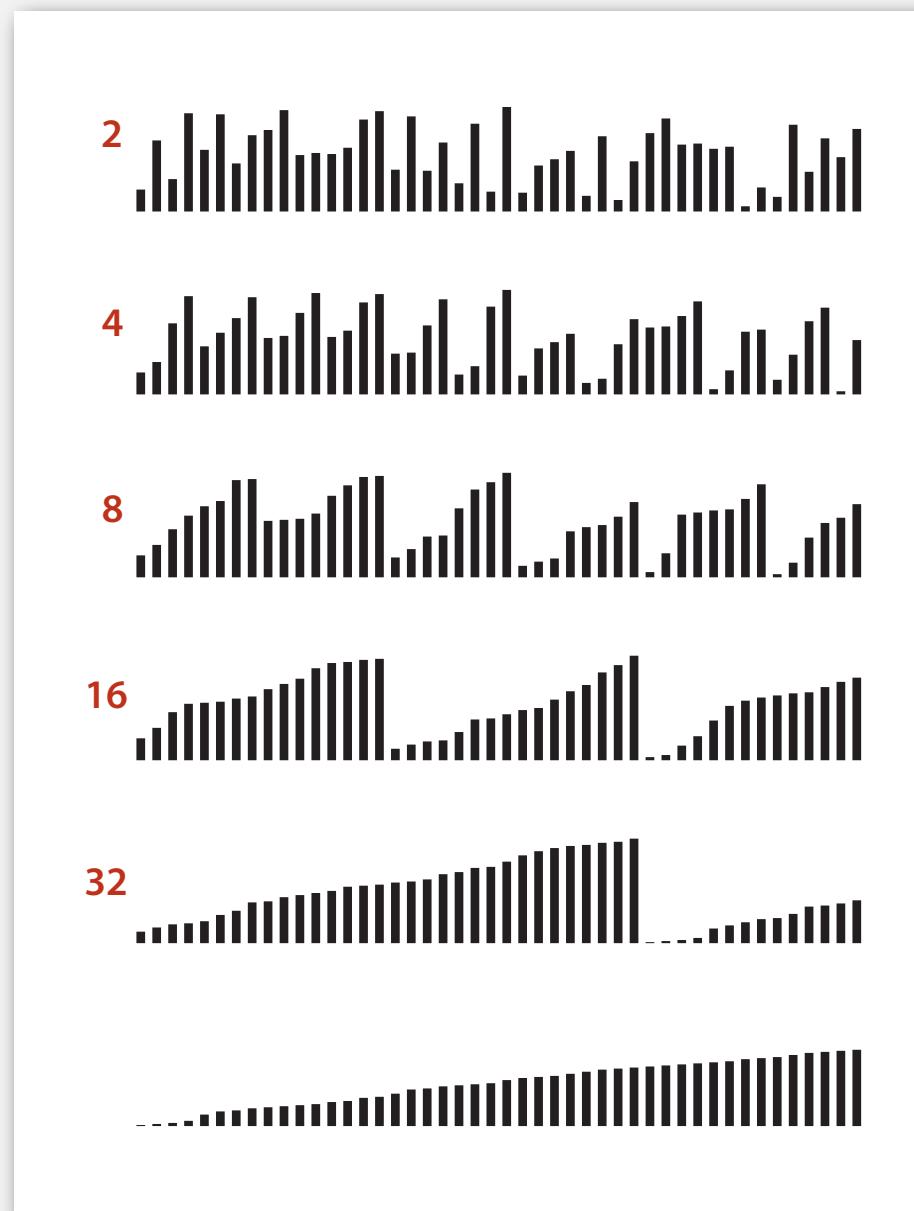
but about 10% slower than recursive,  
top-down mergesort on typical systems

Bottom line. Simple and non-recursive version of mergesort.



## Bottom-up mergesort: visual trace

---



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# 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  $X$ .

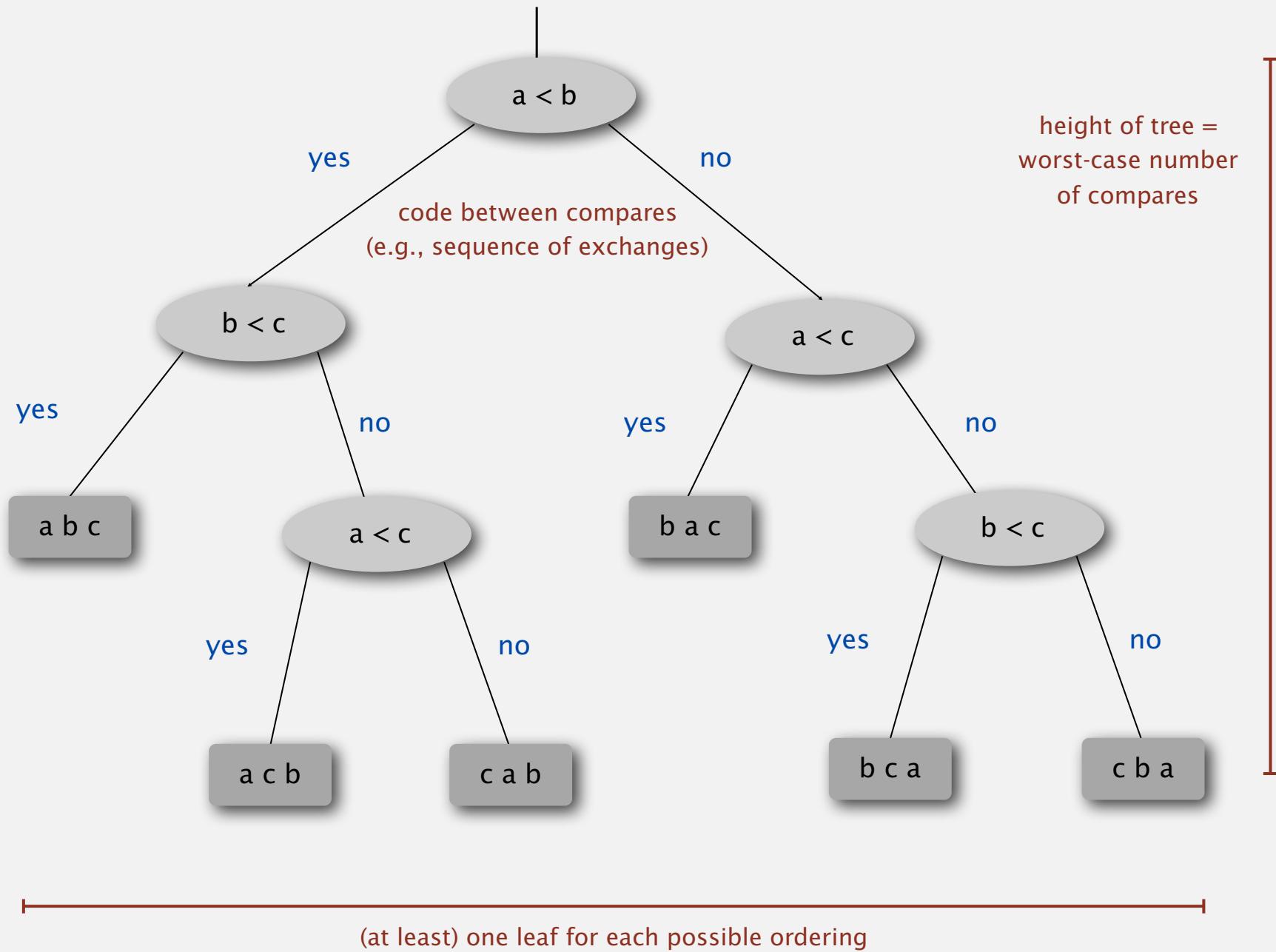
**Optimal algorithm.** Algorithm with best possible cost guarantee for  $X$ .

lower bound  $\sim$  upper bound

**Example: sorting.**

- Model of computation: decision tree. ← can access information only through compares  
(e.g., Java Comparable framework)
- 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)

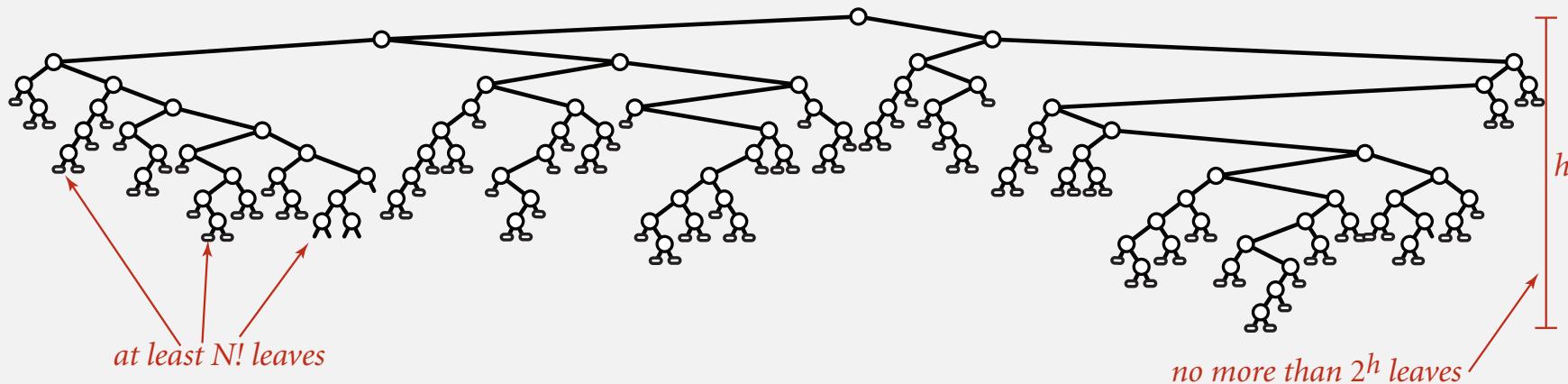


## Compare-based lower bound for sorting

**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.



## Compare-based lower bound for sorting

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- Binary tree of height  $h$  has at most  $2^h$  leaves.
- $N!$  different orderings  $\Rightarrow$  at least  $N!$  leaves.

$$\begin{aligned} 2^h &\geq \# \text{leaves} \geq N! \\ \Rightarrow h &\geq \lg(N!) \sim N \lg N \end{aligned}$$

↑  
Stirling's formula

# Complexity of sorting

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**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.

## Complexity results in context

---

Compares? Mergesort **is** optimal with respect to number compares.  
Space? Mergesort **is not** optimal with respect to space usage.



Lessons. Use theory as a guide.

- Ex. Design sorting algorithm that guarantees  $\frac{1}{2} N \lg N$  compares?
- Ex. Design sorting algorithm that is both time- and space-optimal?

## Complexity results in context (continued)

---

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  $N \lg N$  compares.

insertion sort requires only  $N-1$   
compares if input array is sorted

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

stay tuned for 3-way quicksort

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

stay tuned for radix sorts

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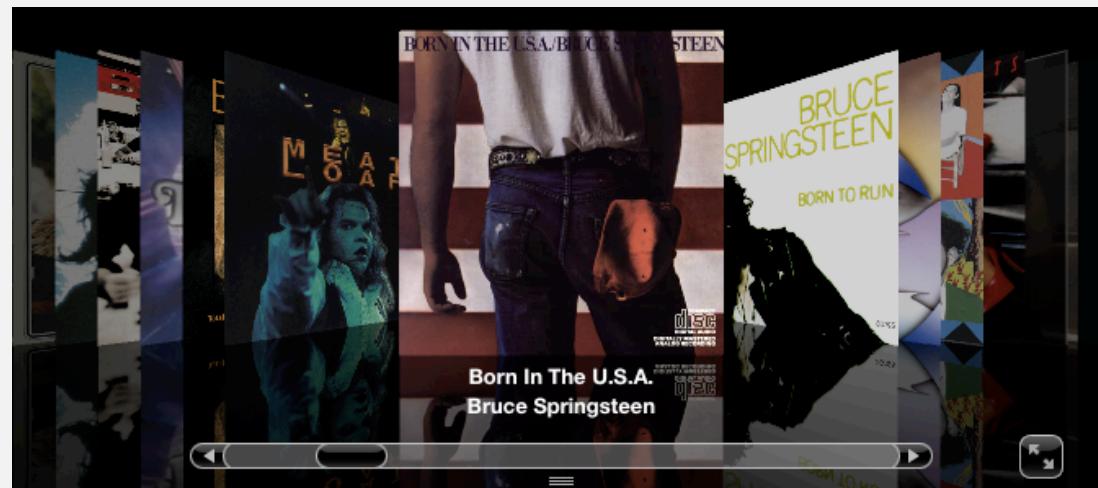
## 2.2 MERGESORT

---

- ▶ *mergesort*
- ▶ *bottom-up mergesort*
- ▶ *sorting complexity*
- ▶ **comparators**
- ▶ *stability*

# Sort music library by artist name

---



	Name	Artist	Time	Album
12	<input checked="" type="checkbox"/> Let It Be	The Beatles	4:03	Let It Be
13	<input checked="" type="checkbox"/> Take My Breath Away	BERLIN	4:13	Top Gun – Soundtrack
14	<input checked="" type="checkbox"/> Circle Of Friends	Better Than Ezra	3:27	Empire Records
15	<input checked="" type="checkbox"/> Dancing With Myself	Billy Idol	4:43	Don't Stop
16	<input checked="" type="checkbox"/> Rebel Yell	Billy Idol	4:49	Rebel Yell
17	<input checked="" type="checkbox"/> Piano Man	Billy Joel	5:36	Greatest Hits Vol. 1
18	<input checked="" type="checkbox"/> Pressure	Billy Joel	3:16	Greatest Hits, Vol. II (1978 – 1985) (Disc 2)
19	<input checked="" type="checkbox"/> The Longest Time	Billy Joel	3:36	Greatest Hits, Vol. II (1978 – 1985) (Disc 2)
20	<input checked="" type="checkbox"/> Atomic	Blondie	3:50	Atomic: The Very Best Of Blondie
21	<input checked="" type="checkbox"/> Sunday Girl	Blondie	3:15	Atomic: The Very Best Of Blondie
22	<input checked="" type="checkbox"/> Call Me	Blondie	3:33	Atomic: The Very Best Of Blondie
23	<input checked="" type="checkbox"/> Dreaming	Blondie	3:06	Atomic: The Very Best Of Blondie
24	<input checked="" type="checkbox"/> Hurricane	Bob Dylan	8:32	Desire
25	<input checked="" type="checkbox"/> The Times They Are A-Changin'	Bob Dylan	3:17	Greatest Hits
26	<input checked="" type="checkbox"/> Livin' On A Prayer	Bon Jovi	4:11	Cross Road
27	<input checked="" type="checkbox"/> Beds Of Roses	Bon Jovi	6:35	Cross Road
28	<input checked="" type="checkbox"/> Runaway	Bon Jovi	3:53	Cross Road
29	<input checked="" type="checkbox"/> Rasputin (Extended Mix)	Boney M	5:50	Greatest Hits
30	<input checked="" type="checkbox"/> Have You Ever Seen The Rain	Bonnie Tyler	4:10	Faster Than The Speed Of Night
31	<input checked="" type="checkbox"/> Total Eclipse Of The Heart	Bonnie Tyler	7:02	Faster Than The Speed Of Night
32	<input checked="" type="checkbox"/> Straight From The Heart	Bonnie Tyler	3:41	Faster Than The Speed Of Night
33	<input checked="" type="checkbox"/> Holding Out For A Hero	Bonny Tyler	5:49	Meat Loaf And Friends
34	<input checked="" type="checkbox"/> Dancing In The Dark	Bruce Springsteen	4:05	Born In The U.S.A.
35	<input checked="" type="checkbox"/> Thunder Road	Bruce Springsteen	4:51	Born To Run
36	<input checked="" type="checkbox"/> Born To Run	Bruce Springsteen	4:30	Born To Run
37	<input checked="" type="checkbox"/> Jungleland	Bruce Springsteen	9:34	Born To Run
38	<input checked="" type="checkbox"/> Tug! Tug! Tug! (To Everything)	The Rude	3:57	Forrest Gump The Soundtrack (Disc 2)

# Sort music library by song name

---

	Name	Artist	Time	Album
1	Alive	Pearl Jam	5:41	Ten
2	All Over The World	Pixies	5:27	Bossanova
3	All Through The Night	Cyndi Lauper	4:30	She's So Unusual
4	Allison Road	Gin Blossoms	3:19	New Miserable Experience
5	Ama, Ama, Ama Y Ensancha El ...	Extremoduro	2:34	Deltoya (1992)
6	And We Danced	Hooters	3:50	Nervous Night
7	As I Lay Me Down	Sophie B. Hawkins	4:09	Whaler
8	Atomic	Blondie	3:50	Atomic: The Very Best Of Blondie
9	Automatic Lover	Jay-Jay Johanson	4:19	Antenna
10	Baba O'Riley	The Who	5:01	Who's Better, Who's Best
11	Beautiful Life	Ace Of Base	3:40	The Bridge
12	<b>Beds Of Roses</b>	<b>Bon Jovi</b>	<b>6:35</b>	<b>Cross Road</b>
13	Black	Pearl Jam	5:44	Ten
14	Bleed American	Jimmy Eat World	3:04	Bleed American
15	Borderline	Madonna	4:00	The Immaculate Collection
16	Born To Run	Bruce Springsteen	4:30	Born To Run
17	Both Sides Of The Story	Phil Collins	6:43	Both Sides
18	Bouncing Around The Room	Phish	4:09	A Live One (Disc 1)
19	Boys Don't Cry	The Cure	2:35	Staring At The Sea: The Singles 1979–1985
20	Brat	Green Day	1:43	Insomniac
21	Breakdown	Deerheart	3:40	Deerheart
22	Bring Me To Life (Kevin Roen Mix)	Evanescence Vs. Pa...	9:48	
23	Californication	Red Hot Chili Pepp...	1:40	
24	Call Me	Blondie	3:33	Atomic: The Very Best Of Blondie
25	Can't Get You Out Of My Head	Kylie Minogue	3:50	Fever
26	Celebration	Kool & The Gang	3:45	Time Life Music Sounds Of The Seventies – C
27	Chaiwa Chaiwa	Sukhwinder Singh	5:11	Bombay Dreams

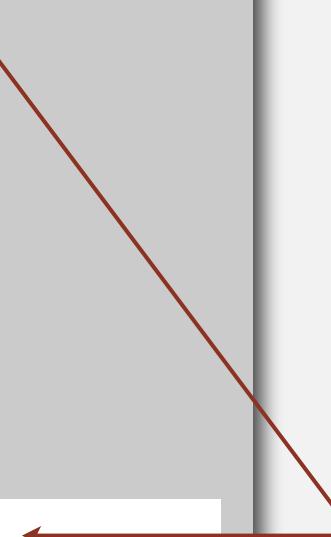
## Comparable interface: review

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;
    }
}
```



natural order

# Comparator interface

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 pre-1994 order for digraphs ch and ll and rr
- Case insensitive. is Now the time ↓
- Spanish. café cafetero cuarto churro nube ñoño
- 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().

```
String[] a;           uses natural order
...
Arrays.sort(a);      uses alternate order defined by
...
Arrays.sort(a, String.CASE_INSENSITIVE_ORDER);    Comparator<String> object
...
Arrays.sort(a, Collator.getInstance(new Locale("es")));
...
Arrays.sort(a, new BritishPhoneBookOrder());
...
```

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

```
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; }
```

# Comparator interface: implementing

To implement a comparator:

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

```
public 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; }
    }
}
```

one Comparator for the class

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.

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

Andrews	3	A	664-480-0023	097 Little
Battle	4	C	874-088-1212	121 Whitman
Chen	3	A	991-878-4944	308 Blair
Fox	3	A	884-232-5341	11 Dickinson
Furia	1	A	766-093-9873	101 Brown
Gazsi	4	B	766-093-9873	101 Brown
Kanaga	3	B	898-122-9643	22 Brown
Rohde	2	A	232-343-5555	343 Forbes

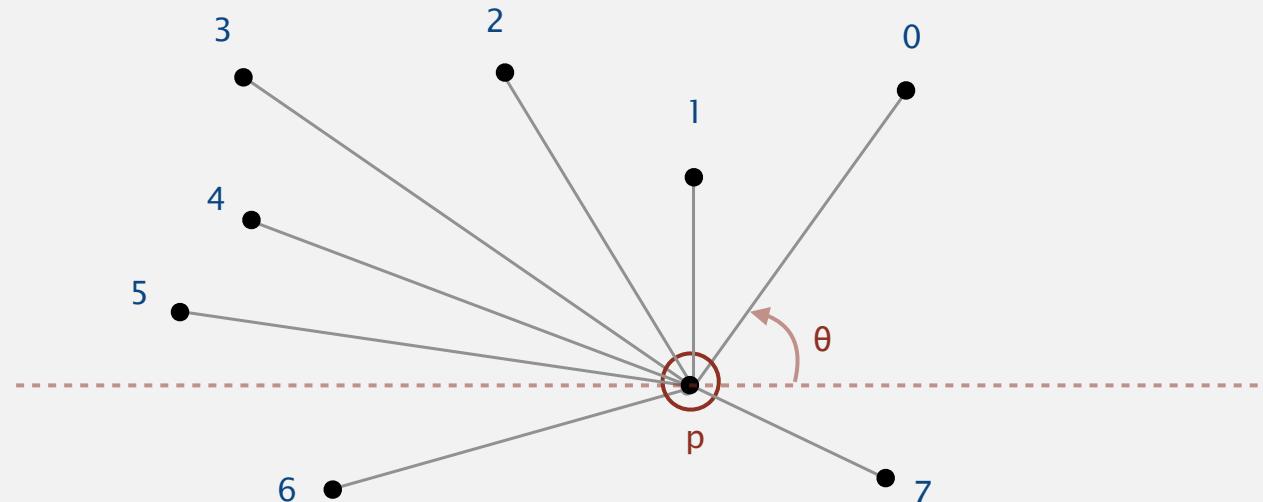
`Arrays.sort(a, Student.BY_SECTION);`

Furia	1	A	766-093-9873	101 Brown
Rohde	2	A	232-343-5555	343 Forbes
Andrews	3	A	664-480-0023	097 Little
Chen	3	A	991-878-4944	308 Blair
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Gazsi	4	B	766-093-9873	101 Brown

## Polar order

---

Polar order. Given a point  $p$ , order points by polar angle they make with  $p$ .



```
Arrays.sort(points, p.POLAR_ORDER);
```

Application. Graham scan algorithm for convex hull. [see previous lecture]

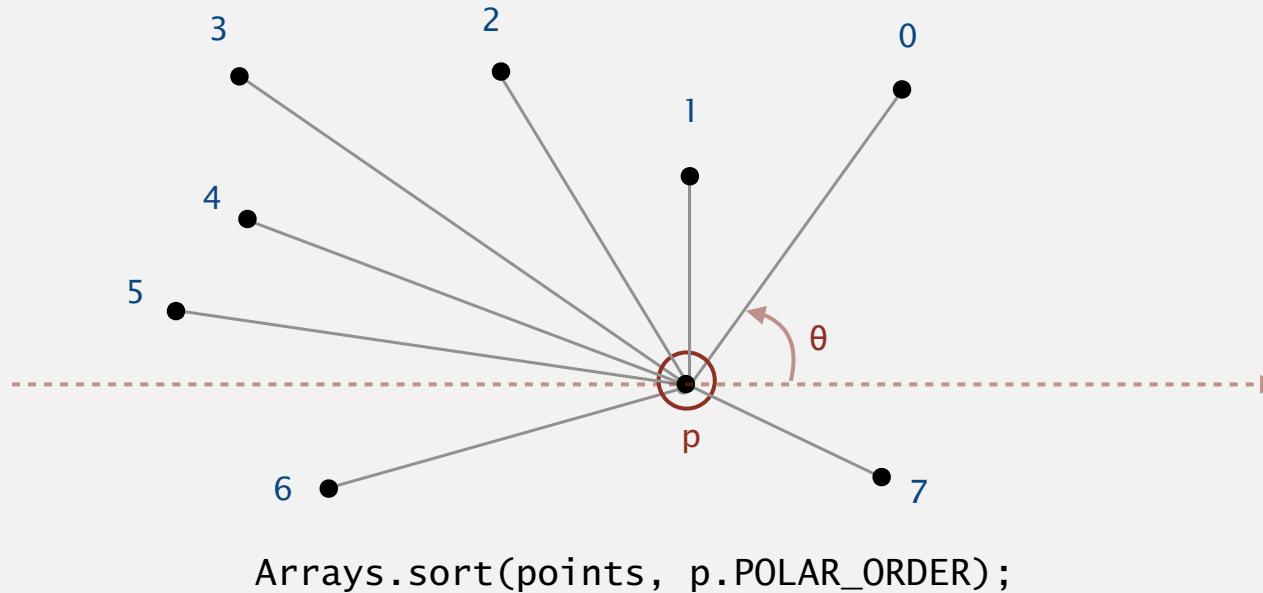
High-school trig solution. Compute polar angle  $\theta$  w.r.t.  $p$  using `atan2()`.

Drawback. Evaluating a trigonometric function is expensive.

## Polar order

---

Polar order. Given a point  $p$ , order points by polar angle they make with  $p$ .



A ccw-based solution.

- If  $q_1$  is above  $p$  and  $q_2$  is below  $p$ , then  $q_1$  makes smaller polar angle.
- If  $q_1$  is below  $p$  and  $q_2$  is above  $p$ , then  $q_1$  makes larger polar angle.
- Otherwise,  $ccw(p, q_1, q_2)$  identifies which of  $q_1$  or  $q_2$  makes larger angle.

## Comparator interface: polar order

```
public class Point2D
{
    public final Comparator<Point2D> POLAR_ORDER = new PolarOrder();
    private final double x, y;
    ...
    private static int ccw(Point2D a, Point2D b, Point2D c)
    { /* as in previous lecture */ }

    private class PolarOrder implements Comparator<Point2D>
    {
        public int compare(Point2D q1, Point2D q2)
        {
            double dy1 = q1.y - y;
            double dy2 = q2.y - y;

            if (dy1 == 0 && dy2 == 0) { ... }
            else if (dy1 >= 0 && dy2 < 0) return -1;
            else if (dy2 >= 0 && dy1 < 0) return +1;
            else return -ccw(Point2D.this, q1, q2);
        }
    }
}
```

one Comparator for each point (not static)

p, q1, q2 horizontal

q1 above p; q2 below p

q1 below p; q2 above p

both above or below p

to access invoking point from within inner class

# Algorithms

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## 2.2 MERGESORT

---

- ▶ *mergesort*
- ▶ *bottom-up mergesort*
- ▶ *sorting complexity*
- ▶ **comparators**
- ▶ *stability*

# Algorithms

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## 2.2 MERGESORT

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- ▶ *comparators*
- ▶ ***stability***

# Stability

---

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

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

Andrews	3	A	664-480-0023	097 Little
Battle	4	C	874-088-1212	121 Whitman
Chen	3	A	991-878-4944	308 Blair
Fox	3	A	884-232-5341	11 Dickinson
Furia	1	A	766-093-9873	101 Brown
Gazsi	4	B	766-093-9873	101 Brown
Kanaga	3	B	898-122-9643	22 Brown
Rohde	2	A	232-343-5555	343 Forbes

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

Furia	1	A	766-093-9873	101 Brown
Rohde	2	A	232-343-5555	343 Forbes
Chen	3	A	991-878-4944	308 Blair
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Gazsi	4	B	766-093-9873	101 Brown
Battle	4	C	874-088-1212	121 Whitman

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

A **stable** sort preserves the relative order of items with equal keys.

# Stability

---

Q. Which sorts are stable?

A. Insertion sort and mergesort (but not selection sort or shellsort).

sorted by time	sorted by location (not stable)	sorted by location (stable)
Chicago 09:00:00	Chicago 09:25:52	Chicago 09:00:00
Phoenix 09:00:03	Chicago 09:03:13	Chicago 09:00:59
Houston 09:00:13	Chicago 09:21:05	Chicago 09:03:13
Chicago 09:00:59	Chicago 09:19:46	Chicago 09:19:32
Houston 09:01:10	Chicago 09:19:32	Chicago 09:19:46
Chicago 09:03:13	Chicago 09:00:00	Chicago 09:21:05
Seattle 09:10:11	Chicago 09:35:21	Chicago 09:25:52
Seattle 09:10:25	Chicago 09:00:59	Chicago 09:35:21
Phoenix 09:14:25	Houston 09:01:10	Houston 09:00:13
Chicago 09:19:32	Houston 09:00:13	Houston 09:01:10
Chicago 09:19:46	Phoenix 09:37:44	Phoenix 09:00:03
Chicago 09:21:05	Phoenix 09:00:03	Phoenix 09:14:25
Seattle 09:22:43	Phoenix 09:14:25	Phoenix 09:37:44
Seattle 09:22:54	Seattle 09:10:25	Seattle 09:10:11
Chicago 09:25:52	Seattle 09:36:14	Seattle 09:10:25
Chicago 09:35:21	Seattle 09:22:43	Seattle 09:22:43
Seattle 09:36:14	Seattle 09:10:11	Seattle 09:22:54
Phoenix 09:37:44	Seattle 09:22:54	Seattle 09:36:14

Note. Need to carefully check code ("less than" vs. "less than or equal to").

## Stability: insertion sort

Proposition. Insertion sort is **stable**.

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

i	j	0	1	2	3	4
0	0	B <sub>1</sub>	A <sub>1</sub>	A <sub>2</sub>	A <sub>3</sub>	B <sub>2</sub>
1	0	A <sub>1</sub>	B <sub>1</sub>	A <sub>2</sub>	A <sub>3</sub>	B <sub>2</sub>
2	1	A <sub>1</sub>	A <sub>2</sub>	B <sub>1</sub>	A <sub>3</sub>	B <sub>2</sub>
3	2	A <sub>1</sub>	A <sub>2</sub>	A <sub>3</sub>	B <sub>1</sub>	B <sub>2</sub>
4	4	A <sub>1</sub>	A <sub>2</sub>	A <sub>3</sub>	B <sub>1</sub>	B <sub>2</sub>
		A <sub>1</sub>	A <sub>2</sub>	A <sub>3</sub>	B <sub>1</sub>	B <sub>2</sub>

Pf. Equal items never move past each other.

## Stability: selection sort

Proposition. Selection sort is **not** stable.

```
public class Selection
{
    public static void sort(Comparable[] a)
    {
        int N = a.length;
        for (int i = 0; i < N; i++)
        {
            int min = i;
            for (int j = i+1; j < N; j++)
                if (less(a[j], a[min]))
                    min = j;
            exch(a, i, min);
        }
    }
}
```

i	min	0	1	2
0	2	B <sub>1</sub>	B <sub>2</sub>	A
1	1	A	B <sub>2</sub>	B <sub>1</sub>
2	2	A	B <sub>2</sub>	B <sub>1</sub>

Pf by counterexample. Long-distance exchange might move an item past some equal item.

## Stability: shellsort

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;
        }
    }
}
```

h	0	1	2	3	4
	B <sub>1</sub>	B <sub>2</sub>	B <sub>3</sub>	B <sub>4</sub>	A <sub>1</sub>
4	A <sub>1</sub>	B <sub>2</sub>	B <sub>3</sub>	B <sub>4</sub>	B <sub>1</sub>
1	A <sub>1</sub>	B <sub>2</sub>	B <sub>3</sub>	B <sub>4</sub>	B <sub>1</sub>

Pf by counterexample. Long-distance exchanges.

## Stability: mergesort

---

Proposition. Mergesort is **stable**.

```
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.

## Stability: mergesort

Proposition. Merge operation is stable.

```
private static void merge(...)  
{  
    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++];  
    }  
}
```

0	1	2	3	4	5	6	7	8	9	10
A <sub>1</sub>	A <sub>2</sub>	A <sub>3</sub>	B	D	A <sub>4</sub>	A <sub>5</sub>	C	E	F	G

Pf. Takes from left subarray if equal keys.

# Algorithms

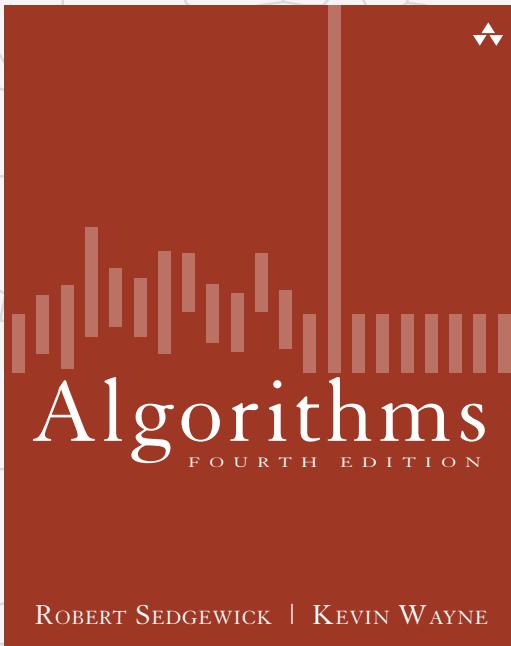
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