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## 2.2 MERGESORT

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- ▶ *mergesort*
- ▶ *bottom-up mergesort*
- ▶ *sorting complexity*
- ▶ *divide-and-conquer*

# Two classic sorting algorithms: mergesort and quicksort

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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]



Quicksort. [next lecture]





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## 2.2 MERGESORT

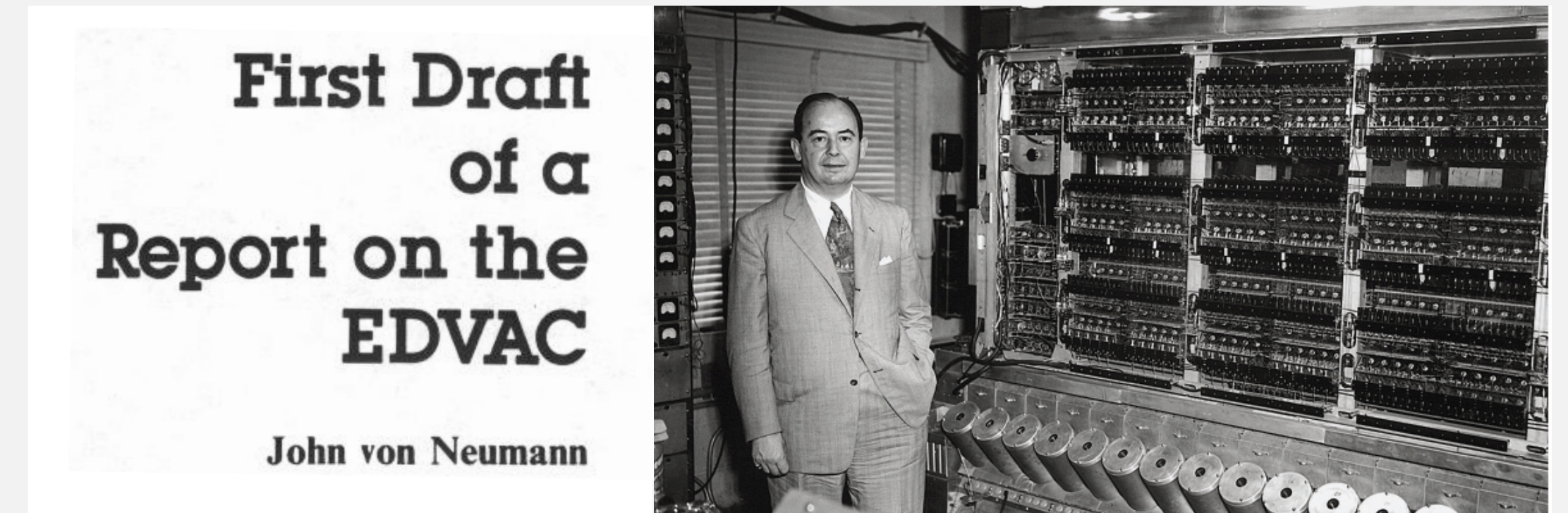
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- ▶ *mergesort*
- ▶ *bottom-up mergesort*
- ▶ *sorting complexity*
- ▶ *divide-and-conquer*

# Mergesort

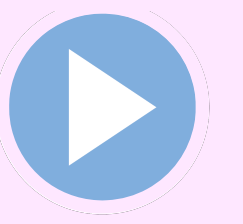
## Basic plan.

- Divide array into two halves.
- Recursively left half.
- Recursively sort right half.
- **Merge** two sorted halves.

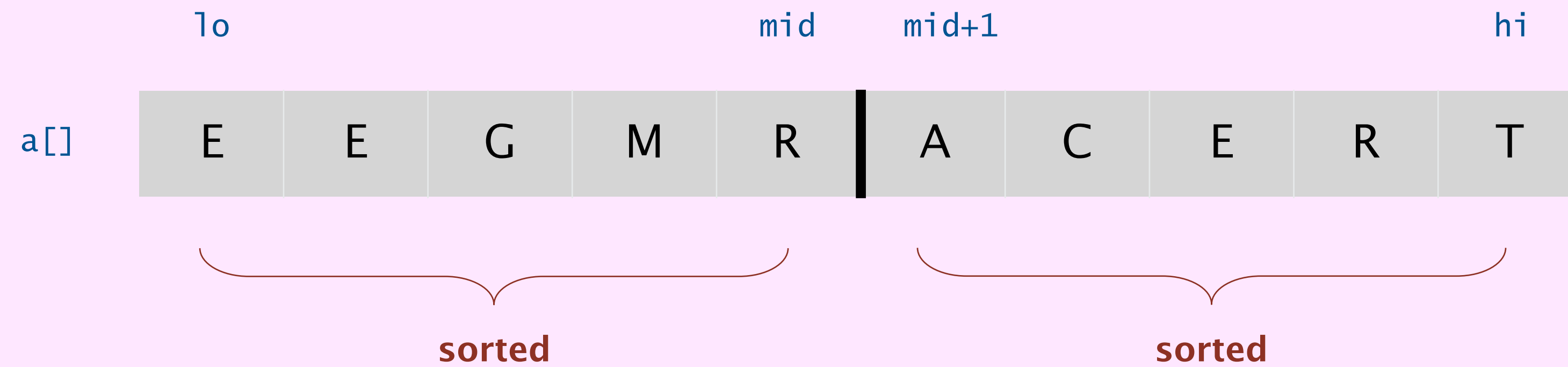


<b>input</b>	M	E	R	G	E	S	O	R	...	T	E	X	A	M	P	L	E
<b>sort left half</b>	E	E	G	M	O	R	R	S	...	T	E	X	A	M	P	L	E
<b>sort right half</b>	E	E	G	M	O	R	R	S	...	A	E	E	L	M	P	T	X
<b>merge results</b>	A	E	E	E	E	G	L	M	M	O	P	R	R	S	T	X	

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

    int i = lo, j = mid+1;                 merge
    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++];
    }
}
```





How many calls does `merge()` make to `less()` in order to merge two sorted subarrays, each of length  $n/2$ , into a sorted array of length  $n$ ?

- A.  $\sim \frac{1}{4} n$  to  $\sim \frac{1}{2} n$
- B.  $\sim \frac{1}{2} n$
- C.  $\sim \frac{1}{2} n$  to  $\sim n$
- D.  $\sim n$

merging two sorted arrays, each of length  $n/2$

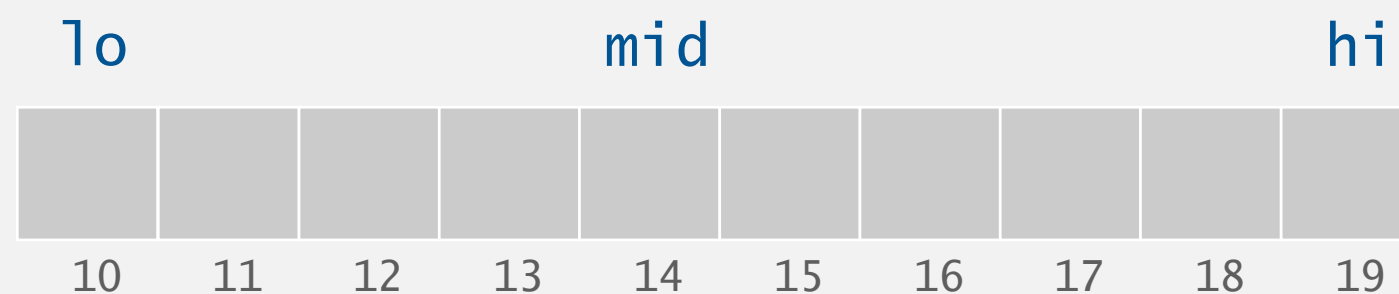


# Mergesort: Java implementation

```
public class Merge
{
    private static void merge(...)
    { /* 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)
    {
        Comparable[] aux = new Comparable[a.length]; ← avoid array allocation
        sort(a, aux, 0, a.length - 1);                in inner loop
    }
}
```

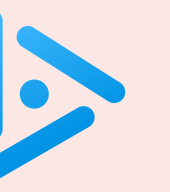




# Mergesort: trace

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

← result after recursive call



Which subarray lengths will arise when mergesorting an array of length 12?

**A.** { 1, 2, 3, 4, 6, 8, 12 }

**B.** { 1, 2, 3, 6, 12 }

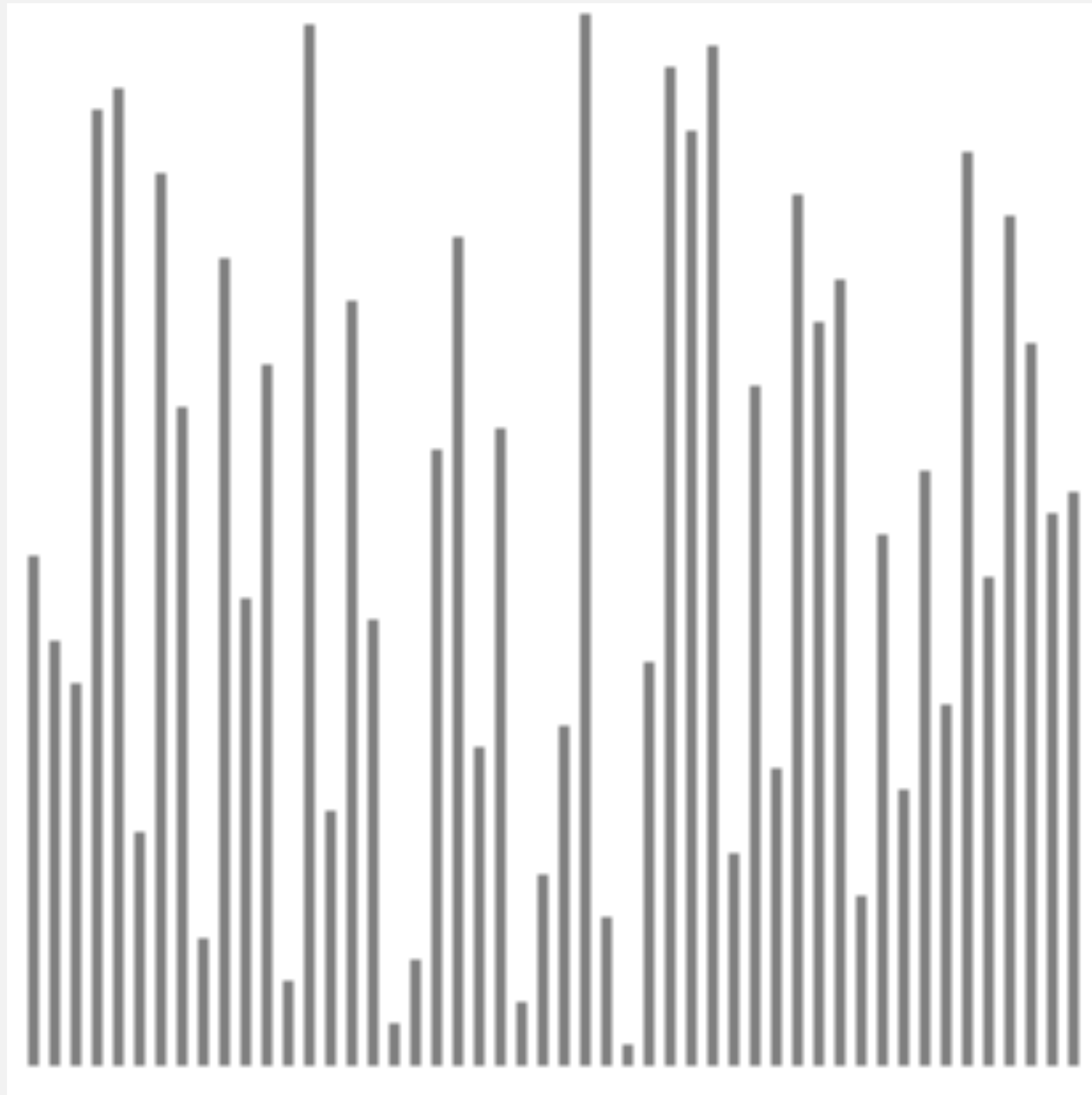
**C.** { 1, 2, 4, 8, 12 }

**D.** { 1, 3, 6, 9, 12 }

# Mergesort: animation

---

50 random items



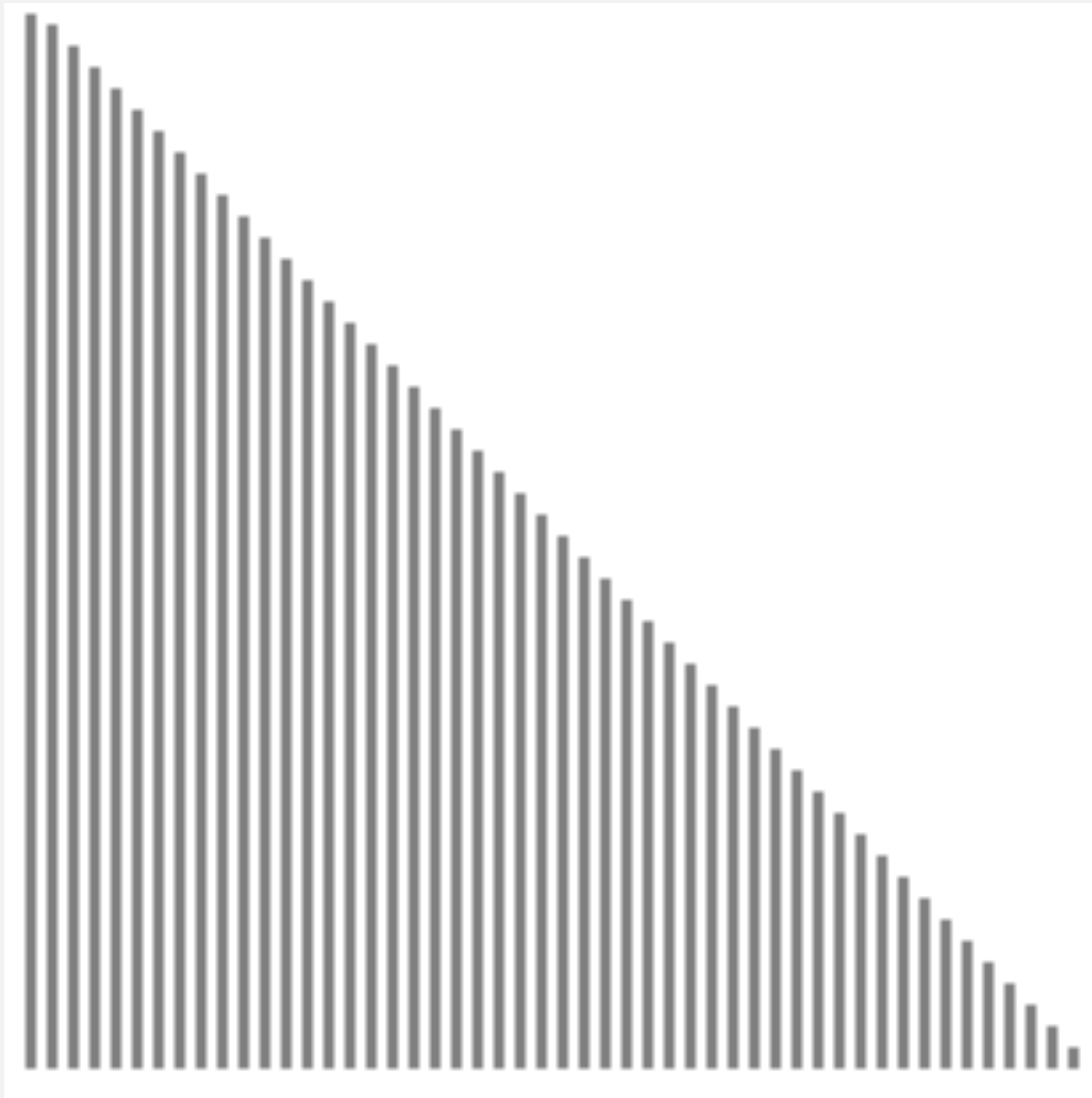
<http://www.sorting-algorithms.com/merge-sort>

- ▲ 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.

	insertion sort ( $n^2$ )			mergesort ( $n \log n$ )		
computer	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 analysis: number of compares

---

**Proposition.** Mergesort uses  $\leq n \log_2 n$  compares to sort any array of length  $n$ .

**Pf sketch.** The number of compares  $C(n)$  to mergesort any array of length  $n$  satisfies the **recurrence**:

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

$\uparrow$                      $\uparrow$                      $\uparrow$   
sort                    sort                    merge  
left half              right half

**For simplicity:** Assume  $n$  is a power of 2 and solve this recurrence:

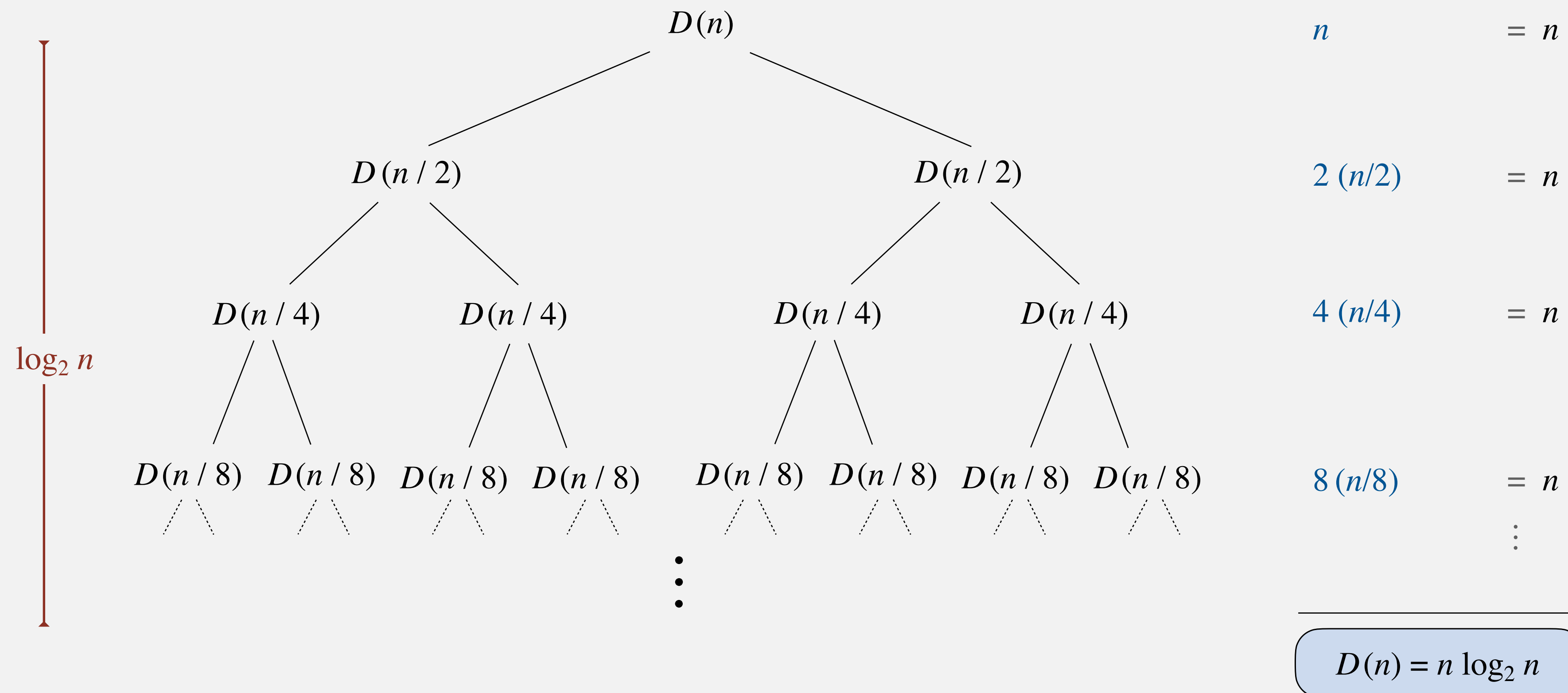
proposition holds even when  $n$  is not a power of 2  
(but analysis cleaner in this case)

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

# Divide-and-conquer recurrence

**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 by picture.** [assuming  $n$  is a power of 2]



## Mergesort analysis: number of array accesses

---

**Proposition.** Mergesort makes  $\Theta(n \log n)$  array accesses.

**Pf sketch.** The number of array accesses  $A(n)$  satisfies the recurrence:

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

**Key point.** Any algorithm with the following structure takes  $\Theta(n \log n)$  time:

```
public static void f(int n)
{
    if (n == 0) return;
    f(n/2);      ← solve two problems
    f(n/2);      ← of half the size
    linear(n);   ← do  $\Theta(n)$  work
}
```

**Famous examples.** FFT and convolution, hidden-line removal, Kendall-tau distance, ...



# Mergesort analysis: memory

---

**Proposition.** Mergesort uses  $\Theta(n)$  extra space.

**Pf.** The array `aux[]` needs to be of length  $n$  for the last merge.

two sorted subarrays

A C D G H I M N U V

B E F J O P Q R S T

merged result

A B C D E F G H I J M N O P Q R S T U V

essentially negligible

**Def.** A sorting algorithm is **in-place** if it uses  $\leq c \log_2 n$  extra space.

**Ex.** Insertion sort and selection sort.

**Challenge 1 (not hard).** Use `aux[]` array of length  $\sim \frac{1}{2}n$  instead of  $n$ .

**Challenge 2 (very hard).** In-place merge. [Kronrod 1969]



Consider the following **modified** version of mergesort.

How much total memory is allocated over all recursive calls?

- A.  $\Theta(n)$
- B.  $\Theta(n \log n)$
- C.  $\Theta(n^2)$
- D.  $\Theta(2^n)$

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

# Mergesort: practical improvement

---

Use insertion sort for small subarrays.

- Mergesort has too much overhead for tiny subarrays.
- Cutoff to insertion sort for  $\approx 10$  items.

```
private static void sort(...)
```

```
{
```

```
    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);
```

```
}
```

← makes mergesort  
about 20% faster



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## 2.2 MERGESORT

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- ▶ *mergesort*
- ▶ *bottom-up mergesort*
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# Bottom-up mergesort

## Basic plan.

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

		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	G	L	M	M	O	P	R	R	S	T	X
	merge(a, aux, 0, 7, 15)	A	E	E	E	E	G	L	M	M	O	P	R	R	S	T	X

# Bottom-up mergesort: Java implementation

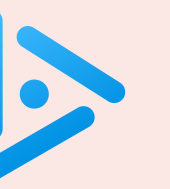
---

```
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));
    }
}
```

**Proposition.** At most  $n \log_2 n$  compares;  $\Theta(n)$  extra space.

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



Which is faster in practice for  $n = 2^{20}$ , top-down mergesort or bottom-up mergesort?

- A. Top-down (recursive) mergesort.
- B. Bottom-up (non-recursive) mergesort.
- C. No difference.
- D. *I don't know.*

# Natural mergesort

---

**Idea.** Exploit pre-existing order by identifying naturally occurring runs.

**input**

1	5	10	16	3	4	23	9	13	2	7	8	12	14
---	---	----	----	---	---	----	---	----	---	---	---	----	----



**first run**

1	5	10	16	3	4	23	9	13	2	7	8	12	14
---	---	----	----	---	---	----	---	----	---	---	---	----	----

**second run**

1	5	10	16	3	4	23	9	13	2	7	8	12	14
---	---	----	----	---	---	----	---	----	---	---	---	----	----

**merge two runs**

1	3	4	5	10	16	23	9	13	2	7	8	12	14
---	---	---	---	----	----	----	---	----	---	---	---	----	----

**Tradeoff.** Fewer passes vs. extra compares per pass to identify runs.



# Timsort (2002)

---

- Natural mergesort.
- Use binary insertion sort to make initial runs (if needed).
- A few more clever optimizations.

Intro

-----

This describes an adaptive, stable, natural mergesort, modestly called timsort (hey, I earned it <wink>). It has supernatural performance on many kinds of partially ordered arrays (less than  $\lg(n!)$  comparisons needed, and as few as  $n-1$ ), yet as fast as Python's previous highly tuned samplesort hybrid on random arrays.

In a nutshell, the main routine marches over the array once, left to right, alternately identifying the next run, then merging it into the previous runs "intelligently". Everything else is complication for speed, and some hard-won measure of memory efficiency.

...



**Tim Peters**

**Consequence.** Linear time on many arrays with pre-existing order.

**Now widely used.** Python, Java 7–11, GNU Octave, Android, ....



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## Proving that Android's, Java's and Python's sorting algorithm is broken (and showing how to fix it)

🕒 February 24, 2015   📁 Envisage   ✍️ Written by Stijn de Gouw. 👤 \$s

Tim Peters developed the **Timsort hybrid sorting algorithm** in 2002. It is a clever combination of ideas from merge sort and insertion sort, and designed to perform well on real world data. TimSort was first developed for Python, but later ported to Java (where it appears as `java.util.Collections.sort` and `java.util.Arrays.sort`) by **Joshua Bloch** (the designer of Java Collections who also pointed out that **most binary search algorithms were broken**). TimSort is today used as the default sorting algorithm for Android SDK, Sun's JDK and OpenJDK. Given the popularity of these platforms this means that the number of computers, cloud services and mobile phones that use TimSort for sorting is well into the billions.

# Timsort bug (May 2018)

---



JDK / [JDK-8203864](#)

## Execution error in Java's Timsort

### Details

Type:	Bug
Status:	<b>RESOLVED</b>
Priority:	P3
Resolution:	Fixed
Affects Version/s:	None
Fix Version/s:	11
Component/s:	<a href="#">core-libs</a>
Labels:	None
Subcomponent:	<a href="#">java.util:collections</a>
Introduced In Version:	6
Resolved In Build:	b20

### Description

Carine Pivoteau wrote:

While working on a proper complexity analysis of the algorithm, we realised that there was an error in the last paper reporting such a bug (<http://envisage-project.eu/wp-content/uploads/2015/02/sorting.pdf>).

This implies that the correction implemented in the Java source code (changing Timsort stack size) is wrong and that it is still possible to make it break.

This is explained in full details in our analysis: <https://arxiv.org/pdf/1805.08612.pdf>.

We understand that coming upon data that actually causes this error is very unlikely, but we thought you'd still like to know and do something about it. As the authors of the previous article advocated for, we strongly believe that you should consider modifying the algorithm as explained in their article (and as was done in Python) rather than trying to fix the stack size.

<https://bugs.openjdk.java.net/browse/JDK-8203864>

# Sorting summary

	in-place?	stable?	best	average	worst	remarks
selection	✓		$\frac{1}{2} n^2$	$\frac{1}{2} n^2$	$\frac{1}{2} n^2$	$n$ exchanges
insertion	✓	✓	$n$	$\frac{1}{4} n^2$	$\frac{1}{2} n^2$	use for small $n$ or partially sorted
merge		✓	$\frac{1}{2} n \log_2 n$	$n \log_2 n$	$n \log_2 n$	$\Theta(n \log n)$ guarantee; stable
timsort		✓	$n$	$n \log_2 n$	$n \log_2 n$	improves mergesort when pre-existing order
?	✓	✓	$n$	$n \log_2 n$	$n \log_2 n$	holy sorting grail

number of compares to sort an array of  $n$  elements

stated but not proved until a decade  
after widespread adoption (!)



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## 2.2 MERGESORT

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# Computational complexity

---

A framework to study efficiency of algorithms for solving a particular problem  $X$ .

**Model of computation.** Allowable operations.

**Cost model.** Operation counts.

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

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

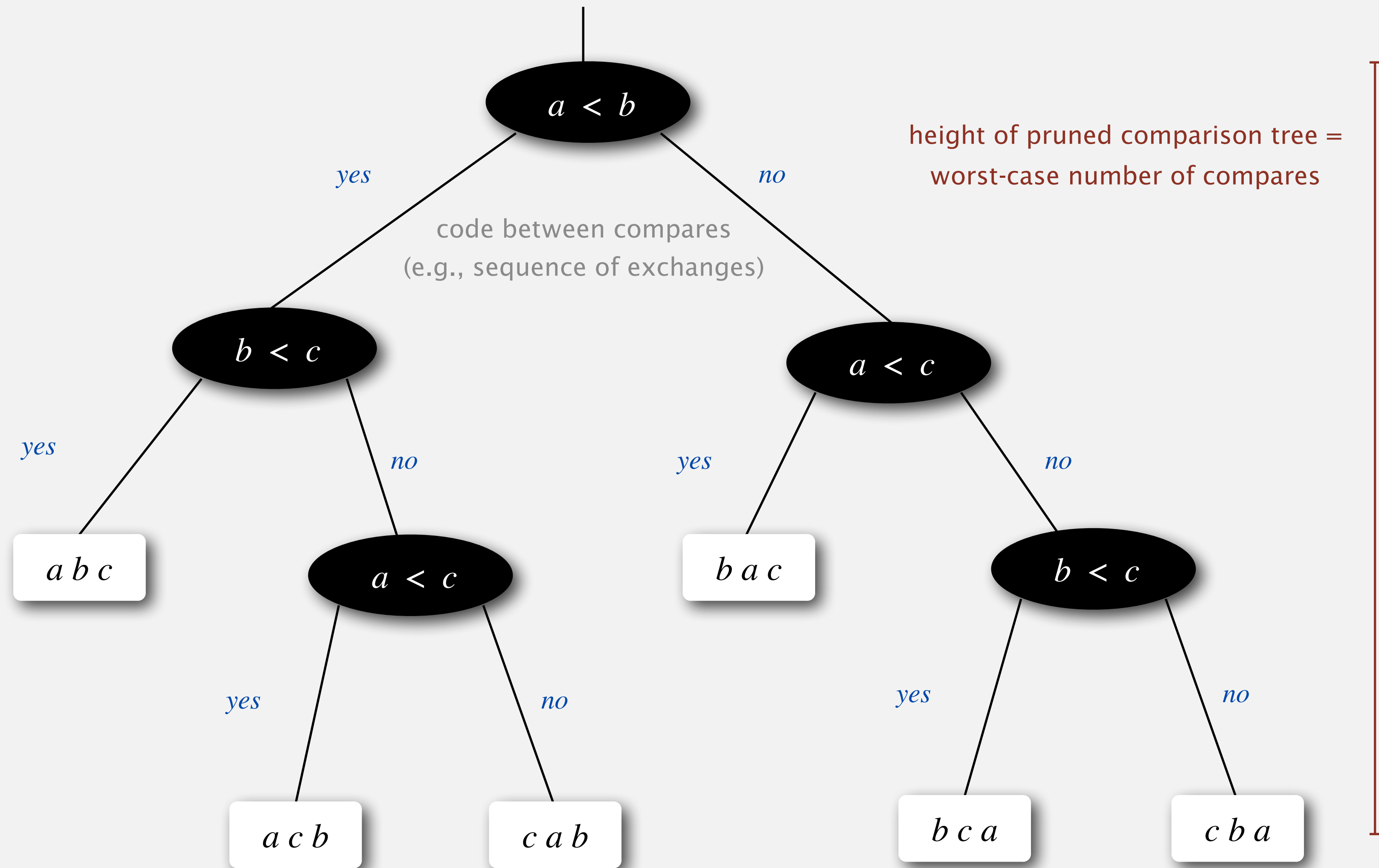
**Optimal algorithm.** Algorithm with best possible cost guarantee for  $X$ .

← lower bound ~ upper bound

<b>model of computation</b>	<i>comparison tree</i>	← can gain knowledge about input only through compares (e.g., Java Comparable framework)
<b>cost model</b>	<i># compares</i>	
<b>upper bound</b>	$\sim n \log_2 n$	← from mergesort
<b>lower bound</b>	?	
<b>optimal algorithm</b>	?	

computational complexity of sorting

# Comparison tree (for 3 distinct keys a, b, and c)

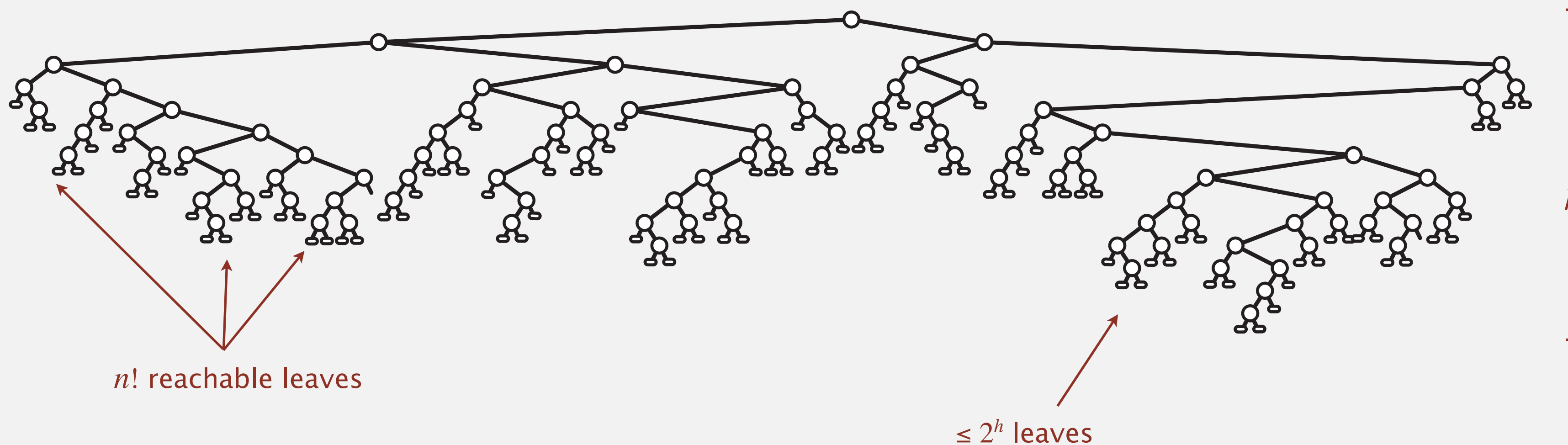


# Compare-based lower bound for sorting

**Proposition.** In the worst case, any compare-based sorting algorithm must make at least  $\log_2(n!) \sim n \log_2 n$  compares.

**Pf.**

- Assume array consists of  $n$  distinct values  $a_1$  through  $a_n$ .
- $n!$  different orderings  $\Rightarrow n!$  reachable leaves.
- Worst-case number of compares = height  $h$  of pruned comparison tree.
- Binary tree of height  $h$  has  $\leq 2^h$  leaves.





# Compare-based lower bound for sorting

---

**Proposition.** In the worst case, any compare-based sorting algorithm must make at least  $\log_2(n!) \sim n \log_2 n$  compares.

**Pf.**

- Assume array consists of  $n$  distinct values  $a_1$  through  $a_n$ .
- $n!$  different orderings  $\Rightarrow n!$  reachable leaves.
- Worst-case number of compares = height  $h$  of pruned comparison tree.
- Binary tree of height  $h$  has  $\leq 2^h$  leaves.

$$2^h \geq \# \text{ reachable leaves} = n!$$

$$\Rightarrow h \geq \log_2(n!)$$

$$\sim n \log_2 n$$



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  $X$ .

<b>model of computation</b>	<i>comparison tree</i>	
<b>cost model</b>	<i># compares</i>	
<b>upper bound</b>	$\sim n \log_2 n$	← from mergesort
<b>lower bound</b>	$\sim n \log_2 n$	← comparison tree
<b>optimal algorithm</b>	<i>mergesort</i>	

complexity of sorting

**First goal of algorithm design:** optimal algorithms.

# Complexity results in context

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Compares? Mergesort is **optimal** with respect to number compares.

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



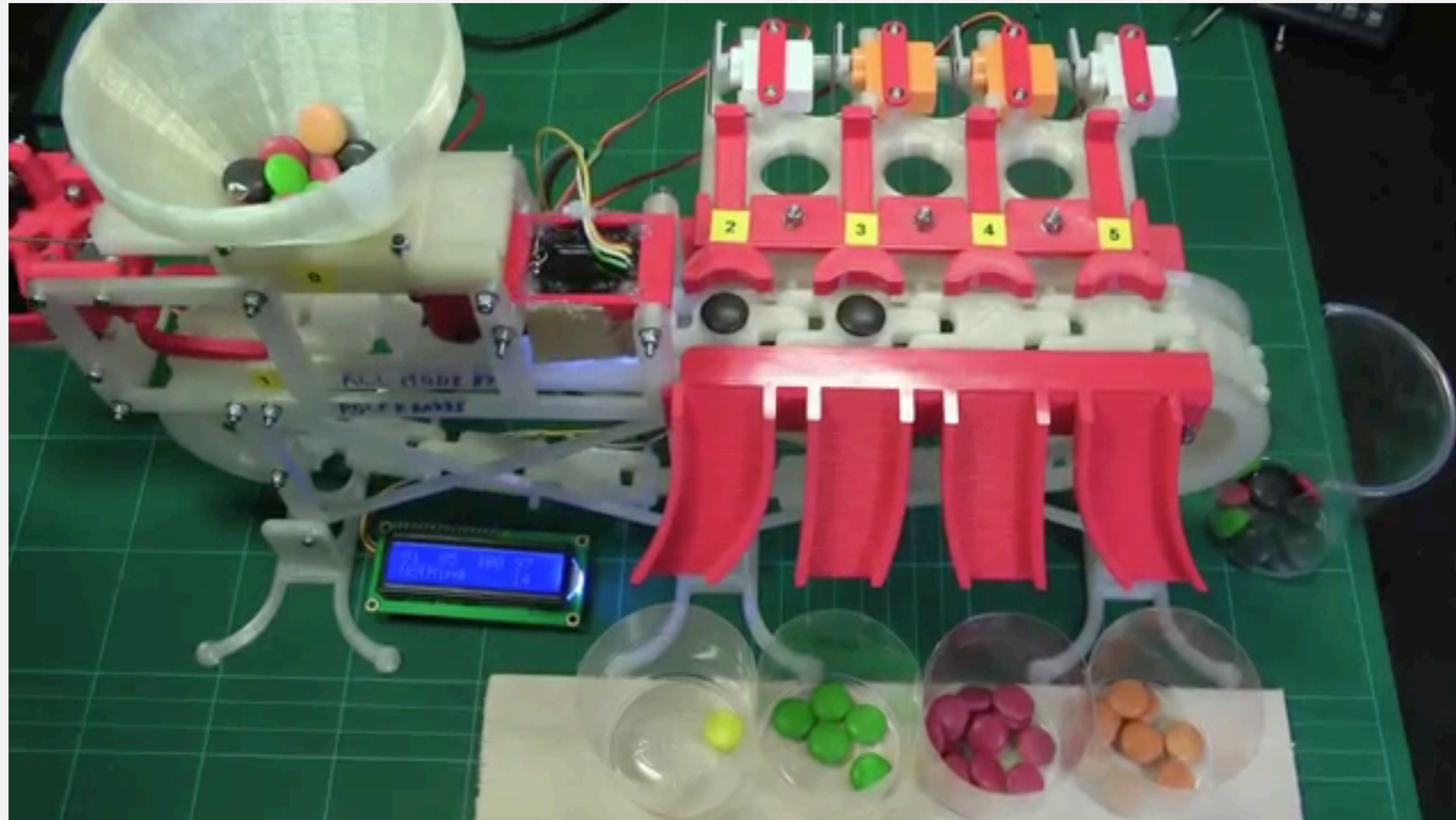
Lessons. Use theory as a guide.

Ex. ~~Design sorting algorithm that makes  $\sim \frac{1}{2} n \log_2 n$  compares in worst case?~~

Ex. Design sorting algorithm that makes  $\Theta(n \log n)$  compares and uses  $\Theta(1)$  extra space.



Q. Why doesn't this Skittles sorter violate the sorting lower bound?



## Complexity results in context (continued)

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Lower bound may not hold if the algorithm can take advantage of:

- The initial order of the input array.

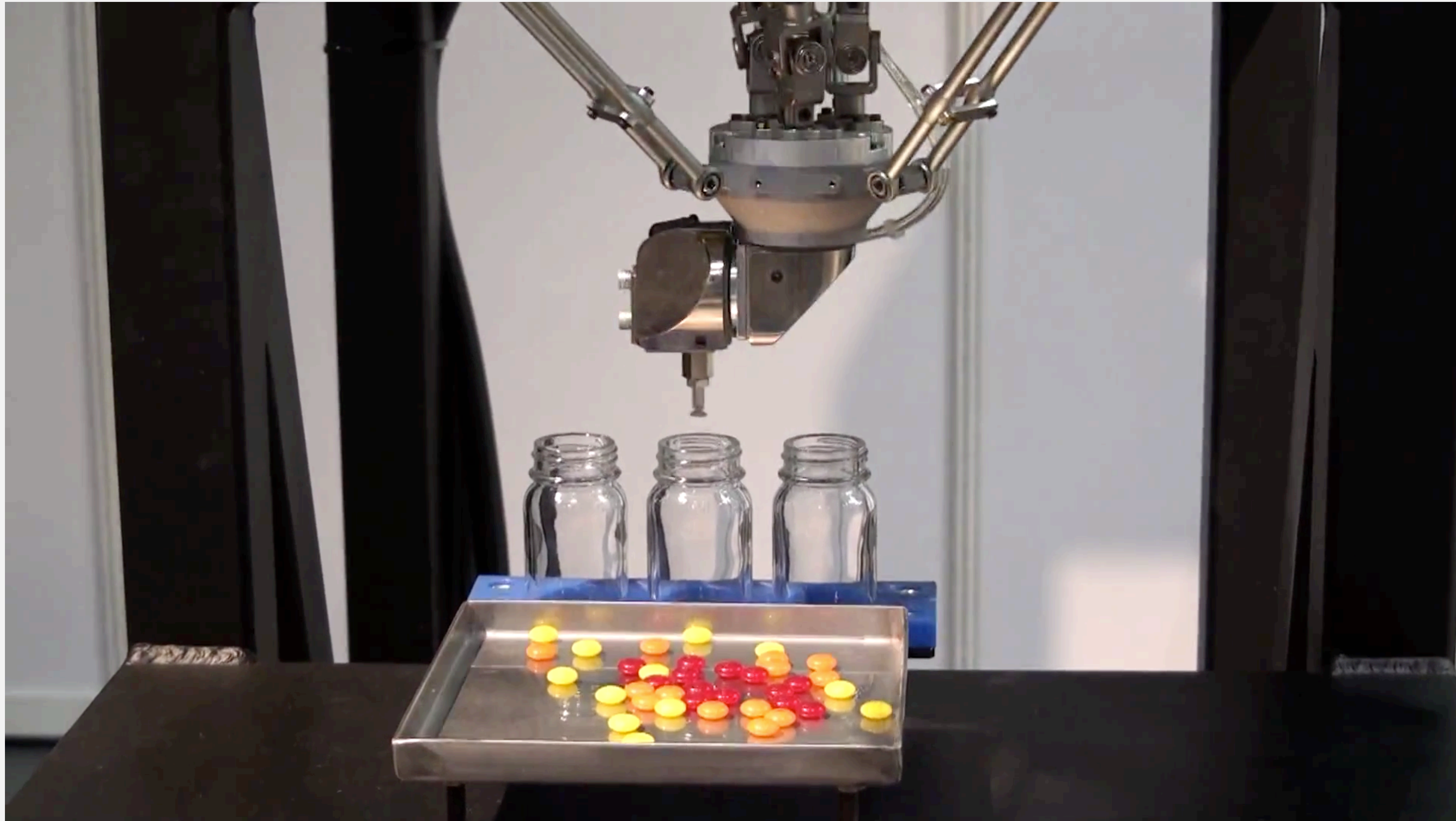
Ex: insertion sort makes only  $\Theta(n)$  compares on partially sorted arrays.

- The distribution of key values.

Ex: 3-way quicksort makes only  $\Theta(n)$  compares on arrays with a small number of distinct keys. [stay tuned]

- The representation of the keys.

Ex: radix sorts do not make any key compares; they access the data via character/digit compares. [stay tuned]



[https://www.youtube.com/watch?v=-\\_JdQZTQuTI#ws](https://www.youtube.com/watch?v=-_JdQZTQuTI#ws)

# Asymptotic notations

**Warning: many programmers abuse big O to mean  $\Theta$ .**

notation	provides	example	shorthand for
<b>tilde</b> $(\sim)$	<i>leading term</i>	$\sim \frac{1}{2} n^2$	$\frac{1}{2} n^2$ $\frac{1}{2} n^2 + 3n + 22$ ← ignore lower-order terms $\frac{1}{2} n^2 + n \log_2 n$
<b>big Theta</b> $(\Theta)$	<i>order of growth</i>	$\Theta(n^2)$	$\frac{1}{2} n^2$ $7n^2 + n^{\frac{1}{2}}$ ← also ignore leading coefficient $5n^2 - 3n$
<b>big O</b> $(O)$	<i>upper bound</i>	$O(n^2)$	$10n^2$ $22n$ ← $\Theta(n^2)$ or smaller $\log_2 n$
<b>big Omega</b> $(\Omega)$	<i>lower bound</i>	$\Omega(n^2)$	$\frac{1}{2} n^2$ $n^3 + 3n$ ← $\Theta(n^2)$ or larger $2^n$

# SORTING LOWER BOUND



**Interviewer.** Give a formal description of the sorting lower bound for sorting arrays of  $n$  elements.







<https://algs4.cs.princeton.edu>

## 2.2 MERGESORT

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- ▶ *mergesort*
- ▶ *bottom-up mergesort*
- ▶ *sorting complexity*
- ▶ *divide-and-conquer*

# SORTING A LINKED LIST



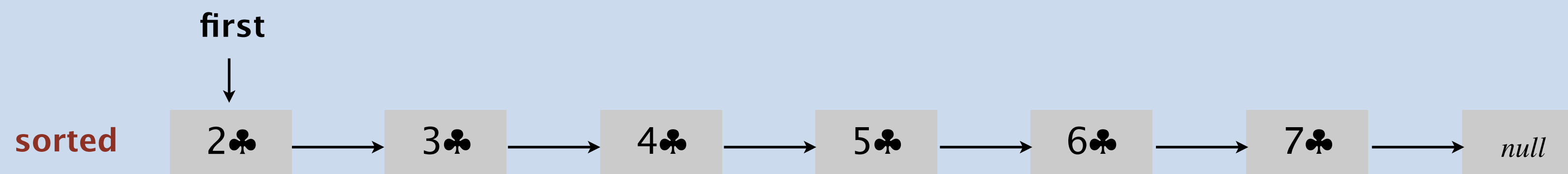
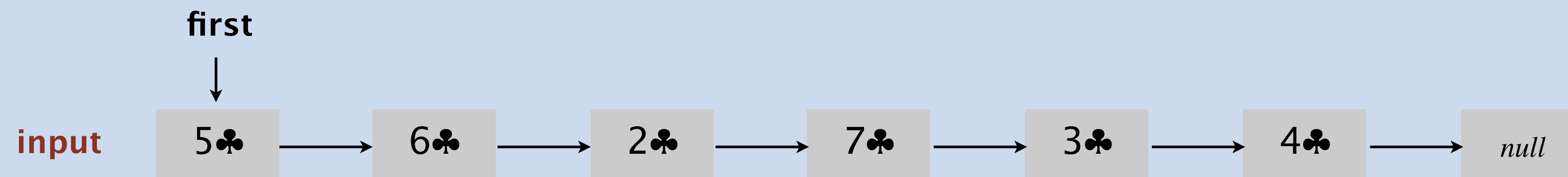
**Problem.** Given a singly linked list, rearrange its nodes in sorted order.

**Application.** Sort list of inodes to garbage collect in Linux kernel.

**Version 0.**  $\Theta(n \log n)$  time,  $\Theta(n)$  extra space.

**Version 1.**  $\Theta(n \log n)$  time,  $\Theta(\log n)$  extra space.

**Version 2.**  $\Theta(n \log n)$  time,  $\Theta(1)$  extra space.



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