

## 2.3 QUICKSORT

- ▶ *quicksort*
- ▶ *selection*
- ▶ *duplicate keys*
- ▶ *system sorts*

## Two classic sorting algorithms: mergesort and quicksort

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.

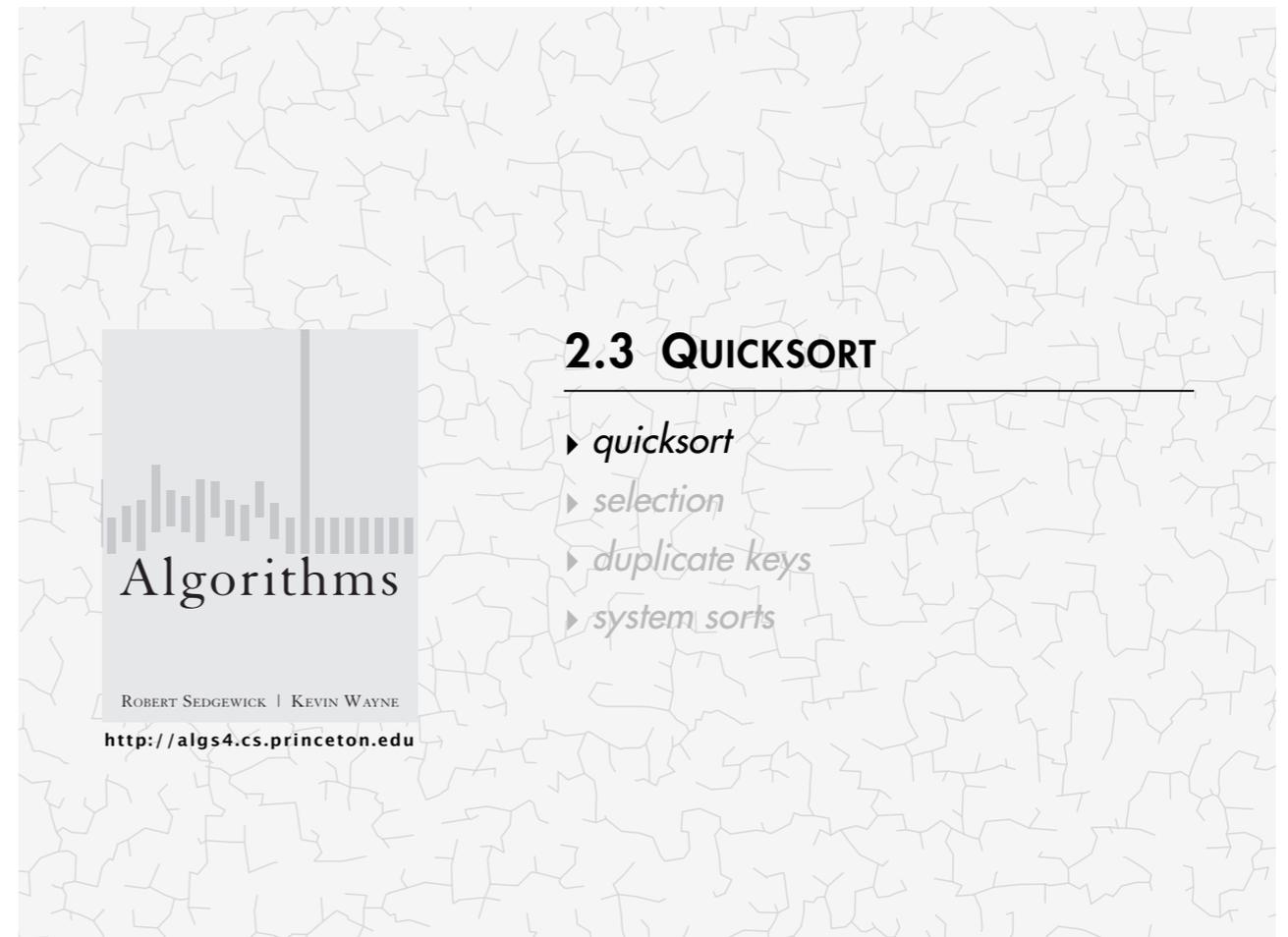
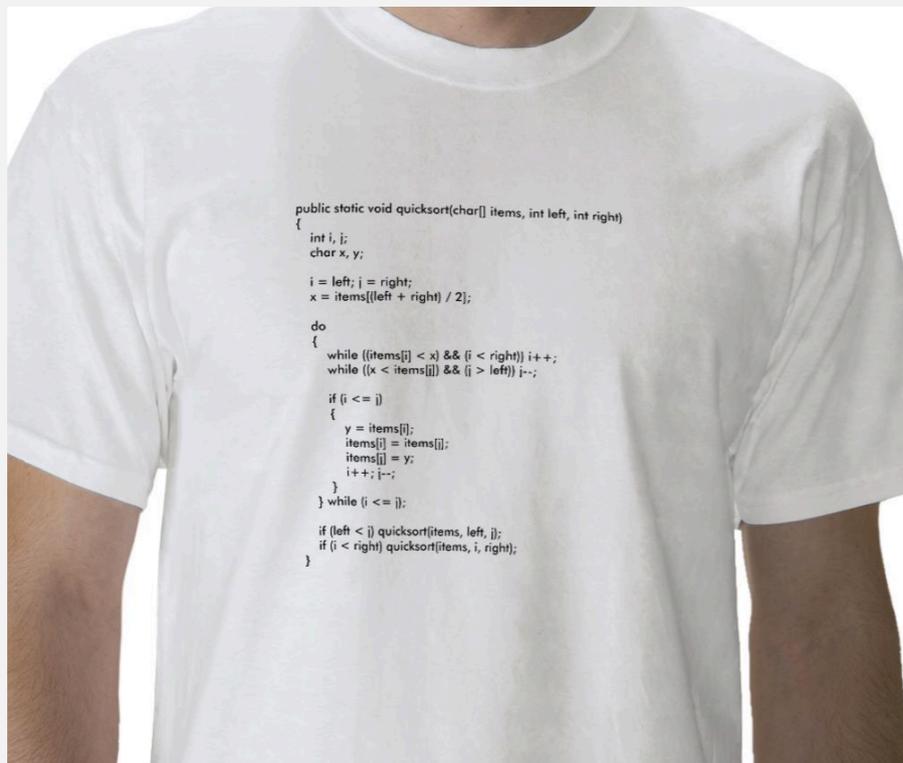
Mergesort. [last lecture]



Quicksort. [this lecture]



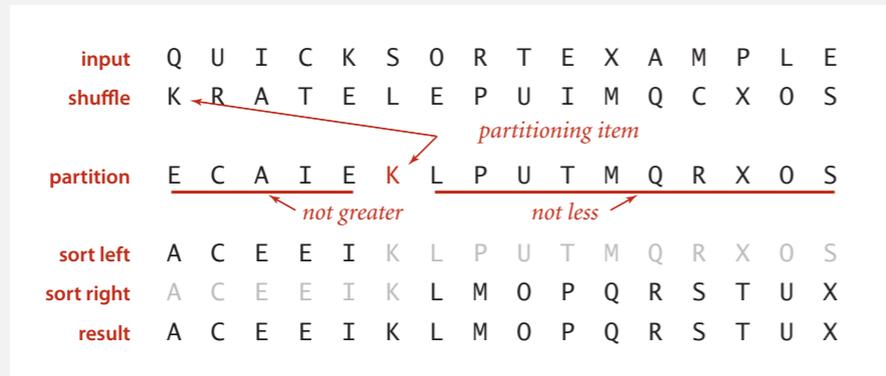
## Quicksort t-shirt



## Quicksort

### Basic plan.

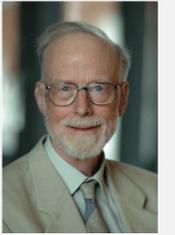
- **Shuffle** the array.
- **Partition** so that, for some  $j$ 
  - entry  $a[j]$  is in place
  - no larger entry to the left of  $j$
  - no smaller entry to the right of  $j$
- **Sort** each subarray recursively.



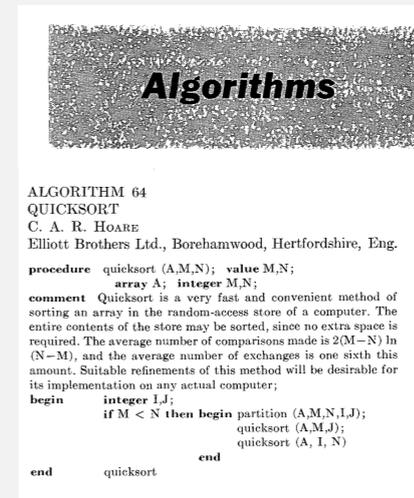
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## Tony Hoare

- Invented quicksort to translate Russian into English.  
[ but couldn't explain his algorithm or implement it! ]
- Learned Algol 60 (and recursion).
- Implemented quicksort.



Tony Hoare  
1980 Turing Award



Communications of the ACM (July 1961)

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Tony Hoare  
1980 Turing Award

“ There are two ways of constructing a software design: One way is to make it so simple that there are obviously no deficiencies, and the other way is to make it so complicated that there are no obvious deficiencies. The first method is far more difficult. ”

“ I call it my billion-dollar mistake. It was the invention of the null reference in 1965... This has led to innumerable errors, vulnerabilities, and system crashes, which have probably caused a billion dollars of pain and damage in the last forty years. ”

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## Bob Sedgewick

- Refined and popularized quicksort.
- Analyzed many versions of quicksort.



Bob Sedgewick



This paper is a practical study of how to implement the Quicksort sorting algorithm and its best variants on real computers, including how to apply various code optimization techniques. A detailed implementation combining the most effective improvements to Quicksort is given, along with a discussion of how to implement it in assembly language. Analytic results describing the performance of the programs are summarized. A variety of special situations are considered from a practical standpoint to illustrate Quicksort's wide applicability as an internal sorting method which requires negligible extra storage.

Key Words and Phrases: Quicksort, analysis of algorithms, code optimization, sorting  
CR Categories: 4.0, 4.6, 5.25, 5.31, 5.5

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### The Analysis of Quicksort Programs\*

Robert Sedgewick

Received January 19, 1976

**Summary.** The Quicksort sorting algorithm and its best variants are presented and analyzed. Results are derived which make it possible to obtain exact formulas describing the total expected running time of particular implementations on real computers of Quicksort and an improvement called the median-of-three modification. Detailed analysis of the effect of an implementation technique called loop unwrapping is presented. The paper is intended not only to present results of direct practical utility, but also to illustrate the intriguing mathematics which arises in the complete analysis of this important algorithm.

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## Quicksort quiz 1

Q. How many compares (in the worst case) to partition an array of length  $N$ ?

- A.  $\sim \frac{1}{4} N$
- B.  $\sim \frac{1}{2} N$
- C.  $\sim N$
- D.  $\sim N \lg N$
- E. *I don't know.*

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## Quicksort: Java implementation

```
public class Quick
{
    private static int partition(Comparable[] a, int lo, int hi)
    { /* see previous slide */ }

    public static void sort(Comparable[] a)
    {
        StdRandom.shuffle(a);
        sort(a, 0, a.length - 1);
    }

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

shuffle needed for performance guarantee (stay tuned)

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## Quicksort trace

	lo	j	hi	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
initial values				Q	U	I	C	K	S	O	R	T	E	X	A	M	P	L	E
random shuffle				K	R	A	T	E	L	E	P	U	I	M	Q	C	X	O	S
	0	5	15	E	C	A	I	E	K	L	P	U	T	M	Q	R	X	O	S
	0	3	4	E	C	A	E	I	K	L	P	U	T	M	Q	R	X	O	S
	0	2	2	A	C	E	E	I	K	L	P	U	T	M	Q	R	X	O	S
	0	0	1	A	C	E	E	I	K	L	P	U	T	M	Q	R	X	O	S
	1		1	A	C	E	E	I	K	L	P	U	T	M	Q	R	X	O	S
	4		4	A	C	E	E	I	K	L	P	U	T	M	Q	R	X	O	S
	6	6	15	A	C	E	E	I	K	L	P	U	T	M	Q	R	X	O	S
	7	9	15	A	C	E	E	I	K	L	M	O	P	T	Q	R	X	U	S
	7	7	8	A	C	E	E	I	K	L	M	O	P	T	Q	R	X	U	S
	8		8	A	C	E	E	I	K	L	M	O	P	T	Q	R	X	U	S
	10	13	15	A	C	E	E	I	K	L	M	O	P	S	Q	R	T	U	X
	10	12	12	A	C	E	E	I	K	L	M	O	P	R	Q	S	T	U	X
	10	11	11	A	C	E	E	I	K	L	M	O	P	Q	R	S	T	U	X
	10		10	A	C	E	E	I	K	L	M	O	P	Q	R	S	T	U	X
	14	14	15	A	C	E	E	I	K	L	M	O	P	Q	R	S	T	U	X
	15		15	A	C	E	E	I	K	L	M	O	P	Q	R	S	T	U	X
result				A	C	E	E	I	K	L	M	O	P	Q	R	S	T	U	X

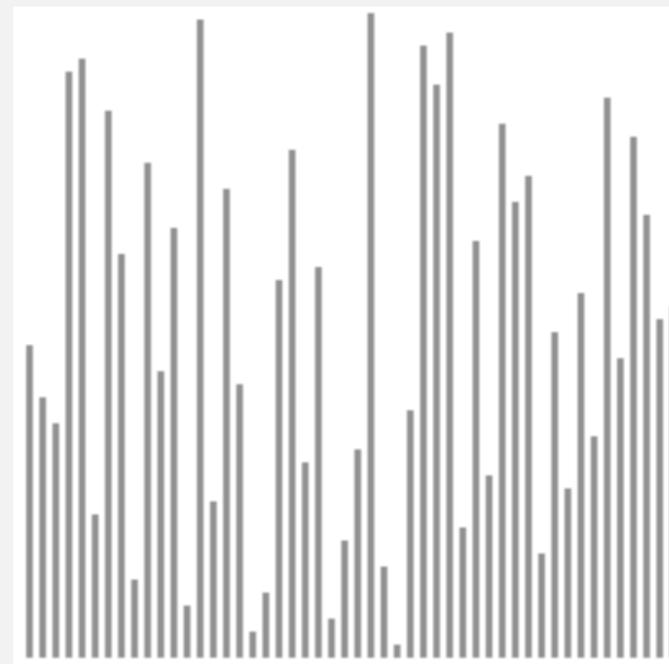
no partition for subarrays of size 1

Quicksort trace (array contents after each partition)

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## Quicksort animation

50 random items



▲ algorithm position  
 in order  
 current subarray  
 not in order

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

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## Quicksort: implementation details

**Partitioning in-place.** Using an extra array makes partitioning easier (and stable), but is not worth the cost.

**Terminating the loop.** Testing whether the pointers cross is trickier than it might seem.

**Equal keys.** When duplicates are present, it is (counter-intuitively) better to stop scans on keys equal to the partitioning item's key. ← stay tuned

**Preserving randomness.** Shuffling is needed for performance guarantee.  
**Equivalent alternative.** Pick a random partitioning item in each subarray.

## Quicksort: empirical analysis (1961)

**Running time estimates:**

- Algol 60 implementation.
- National-Elliott 405 computer.

**Table 1**

NUMBER OF ITEMS	MERGE SORT	QUICKSORT
500	2 min 8 sec	1 min 21 sec
1,000	4 min 48 sec	3 min 8 sec
1,500	8 min 15 sec*	5 min 6 sec
2,000	11 min 0 sec*	6 min 47 sec

\* These figures were computed by formula, since they cannot be achieved on the 405 owing to limited store size.

sorting N 6-word items with 1-word keys



Elliott 405 magnetic disc (16K words)

## Quicksort: empirical analysis

**Running time estimates:**

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

computer	insertion sort ( $N^2$ )			mergesort ( $N \log N$ )			quicksort ( $N \log N$ )		
	thousand	million	billion	thousand	million	billion	thousand	million	billion
home	instant	2.8 hours	317 years	instant	1 second	18 min	instant	0.6 sec	12 min
super	instant	1 second	1 week	instant	instant	instant	instant	instant	instant

**Lesson 1.** Good algorithms are better than supercomputers.

**Lesson 2.** Great algorithms are better than good ones.

## Quicksort: best-case analysis

**Best case.** Number of compares is  $\sim N \lg N$ .

lo	j	hi	a[]														
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
			H	A	C	B	F	E	G	D	L	I	K	J	N	M	O
			H	A	C	B	F	E	G	D	L	I	K	J	N	M	O
0	7	14	D	A	C	B	F	E	G	H	L	I	K	J	N	M	O
0	3	6	B	A	C	D	F	E	G	H	L	I	K	J	N	M	O
0	1	2	A	B	C	D	F	E	G	H	L	I	K	J	N	M	O
0		0	A	B	C	D	F	E	G	H	L	I	K	J	N	M	O
2		2	A	B	C	D	F	E	G	H	L	I	K	J	N	M	O
4	5	6	A	B	C	D	E	F	G	H	L	I	K	J	N	M	O
4		4	A	B	C	D	E	F	G	H	L	I	K	J	N	M	O
6		6	A	B	C	D	E	F	G	H	L	I	K	J	N	M	O
8	11	14	A	B	C	D	E	F	G	H	J	I	K	L	N	M	O
8	9	10	A	B	C	D	E	F	G	H	I	J	K	L	N	M	O
8		8	A	B	C	D	E	F	G	H	I	J	K	L	N	M	O
10		10	A	B	C	D	E	F	G	H	I	J	K	L	N	M	O
12	13	14	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
12		12	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
14		14	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
			A	B	C	D	E	F	G	H	I	J	K	L	M	N	O

## Quicksort: worst-case analysis

**Worst case.** Number of compares is  $\sim \frac{1}{2} N^2$ .

		a[]															
lo	j	hi	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
initial values			A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
random shuffle			A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	0	14	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	1	14	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
2	2	14	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
3	3	14	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
4	4	14	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
5	5	14	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
6	6	14	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
7	7	14	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
8	8	14	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
9	9	14	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
10	10	14	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
11	11	14	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
12	12	14	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
13	13	14	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
14	14	14	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O

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## Quicksort: average-case analysis

**Proposition.** The average number of compares  $C_N$  to quicksort an array of  $N$  distinct keys is  $\sim 2N \ln N$  (and the number of exchanges is  $\sim \frac{1}{3} N \ln N$ ).

**Pf.**  $C_N$  satisfies the recurrence  $C_0 = C_1 = 0$  and for  $N \geq 2$ :

$$C_N = (N+1) + \left( \frac{C_0 + C_{N-1}}{N} \right) + \left( \frac{C_1 + C_{N-2}}{N} \right) + \dots + \left( \frac{C_{N-1} + C_0}{N} \right)$$

- Multiply both sides by  $N$  and collect terms: partitioning probability

$$NC_N = N(N+1) + 2(C_0 + C_1 + \dots + C_{N-1})$$

- Subtract from this equation the same equation for  $N-1$ :

$$NC_N - (N-1)C_{N-1} = 2N + 2C_{N-1}$$

- Rearrange terms and divide by  $N(N+1)$ :

$$\frac{C_N}{N+1} = \frac{C_{N-1}}{N} + \frac{2}{N+1}$$

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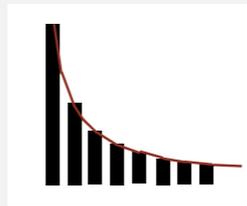
## Quicksort: average-case analysis

- Repeatedly apply previous equation:

$$\begin{aligned} \frac{C_N}{N+1} &= \frac{C_{N-1}}{N} + \frac{2}{N+1} \\ &= \frac{C_{N-2}}{N-1} + \frac{2}{N} + \frac{2}{N+1} \quad \leftarrow \text{substitute previous equation} \\ &= \frac{C_{N-3}}{N-2} + \frac{2}{N-1} + \frac{2}{N} + \frac{2}{N+1} \\ &= \frac{2}{3} + \frac{2}{4} + \frac{2}{5} + \dots + \frac{2}{N+1} \end{aligned}$$

- Approximate sum by an integral:

$$\begin{aligned} C_N &= 2(N+1) \left( \frac{1}{3} + \frac{1}{4} + \frac{1}{5} + \dots + \frac{1}{N+1} \right) \\ &\sim 2(N+1) \int_3^{N+1} \frac{1}{x} dx \end{aligned}$$



- Finally, the desired result:

$$C_N \sim 2(N+1) \ln N \approx 1.39N \lg N$$

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## Quicksort: summary of performance characteristics

Quicksort is a (Las Vegas) **randomized algorithm**.

- Guaranteed to be correct.
- Running time depends on random shuffle.

**Average case.** Expected number of compares is  $\sim 1.39 N \lg N$ .

- 39% more compares than mergesort.
- Faster than mergesort in practice because of less data movement.

**Best case.** Number of compares is  $\sim N \lg N$ .

**Worst case.** Number of compares is  $\sim \frac{1}{2} N^2$ .

[ but more likely that lightning bolt strikes computer during execution ]



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## Quicksort properties

**Proposition.** Quicksort is an **in-place** sorting algorithm.

**Pf.**

- Partitioning: constant extra space.
- Depth of recursion: logarithmic extra space (with high probability).

can guarantee logarithmic depth by recurring on smaller subarray before larger subarray (requires using an explicit stack)

**Proposition.** Quicksort is **not stable**.

**Pf.** [ by counterexample ]

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

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## Quicksort: practical improvements

**Insertion sort small subarrays.**

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

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

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## Quicksort: practical improvements

**Median of sample.**

- Best choice of pivot item = median.
- Estimate true median by taking median of sample.
- Median-of-3 (random) items.

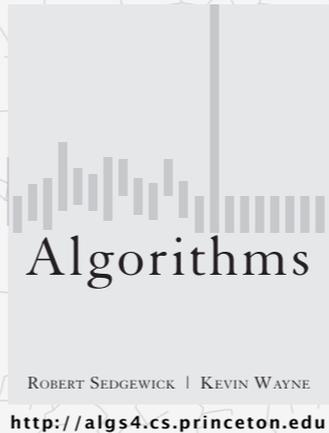
$\sim 12/7 N \ln N$  compares (14% fewer)  
 $\sim 12/35 N \ln N$  exchanges (3% more)

```
private static void sort(Comparable[] a, int lo, int hi)
{
    if (hi <= lo) return;

    int median = medianOf3(a, lo, lo + (hi - lo)/2, hi);
    swap(a, lo, median);

    int j = partition(a, lo, hi);
    sort(a, lo, j-1);
    sort(a, j+1, hi);
}
```

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### 2.3 QUICKSORT

- ▶ quicksort
- ▶ selection
- ▶ duplicate keys
- ▶ system sorts

ROBERT SEDGEWICK | KEVIN WAYNE  
<http://algs4.cs.princeton.edu>

## Selection

**Goal.** Given an array of  $N$  items, find the  $k^{\text{th}}$  smallest item.

**Ex.** Min ( $k=0$ ), max ( $k=N-1$ ), median ( $k=N/2$ ).

### Applications.

- Order statistics.
- Find the "top  $k$ ."

### Use theory as a guide.

- Easy  $N \log N$  upper bound. How?
- Easy  $N$  upper bound for  $k=1, 2, 3$ . How?
- Easy  $N$  lower bound. Why?

### Which is true?

- $N \log N$  lower bound? ← is selection as hard as sorting?
- $N$  upper bound? ← is there a linear-time algorithm?

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## Quick-select

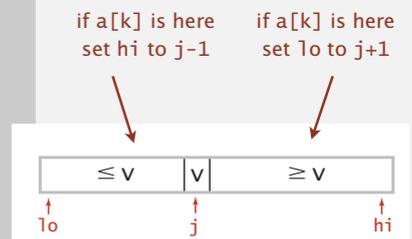
### Partition array so that:

- Entry  $a[j]$  is in place.
- No larger entry to the left of  $j$ .
- No smaller entry to the right of  $j$ .



**Repeat** in **one** subarray, depending on  $j$ ; finished when  $j$  equals  $k$ .

```
public static Comparable select(Comparable[] a, int k)
{
    StdRandom.shuffle(a);
    int lo = 0, hi = a.length - 1;
    while (hi > lo)
    {
        int j = partition(a, lo, hi);
        if (j < k) lo = j + 1;
        else if (j > k) hi = j - 1;
        else return a[k];
    }
    return a[k];
}
```



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## Quick-select: mathematical analysis

**Proposition.** Quick-select takes **linear** time on average.

### Pf sketch.

- Intuitively, each partitioning step splits array approximately in half:  
 $N + N/2 + N/4 + \dots + 1 \sim 2N$  compares.
- Formal analysis similar to quicksort analysis yields:

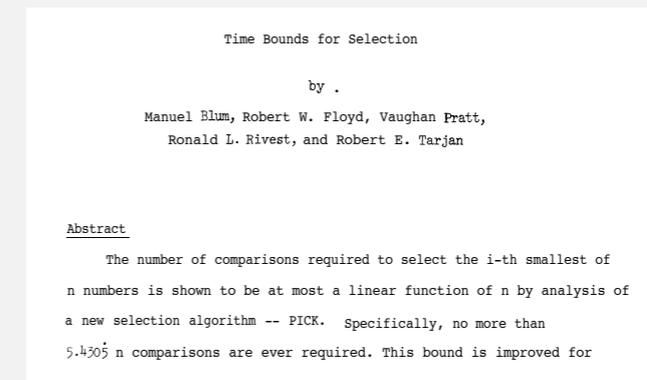
$$C_N = 2N + 2k \ln(N/k) + 2(N-k) \ln(N/(N-k))$$

- **Ex:**  $(2 + 2 \ln 2)N \approx 3.38N$  compares to find median  $k = N/2$ .

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## Theoretical context for selection

**Proposition.** [Blum, Floyd, Pratt, Rivest, Tarjan, 1973] Compare-based selection algorithm whose worst-case running time is linear.

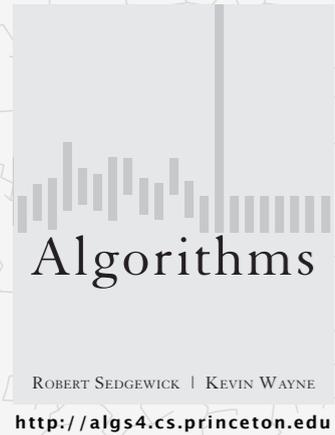


**Remark.** Constants are high  $\Rightarrow$  not used in practice.

### Use theory as a guide.

- Still worthwhile to seek **practical** linear-time (worst-case) algorithm.
- Until one is discovered, use quick-select if you don't need a full sort.

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## 2.3 QUICKSORT

- ▶ quicksort
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- ▶ system sorts

## Duplicate keys

Often, purpose of sort is to bring items with equal keys together.

- Sort population by age.
- Remove duplicates from mailing list.
- Sort job applicants by college attended.

Typical characteristics of such applications.

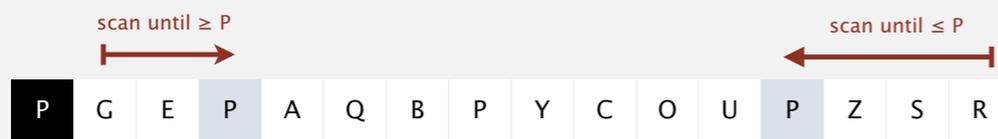
- Huge array.
- Small number of key values.

```
Chicago 09:25:52
Chicago 09:03:13
Chicago 09:21:05
Chicago 09:19:46
Chicago 09:19:32
Chicago 09:00:00
Chicago 09:35:21
Chicago 09:00:59
Houston 09:01:10
Houston 09:00:13
Phoenix 09:37:44
Phoenix 09:00:03
Phoenix 09:14:25
Seattle 09:10:25
Seattle 09:36:14
Seattle 09:22:43
Seattle 09:10:11
Seattle 09:22:54
```

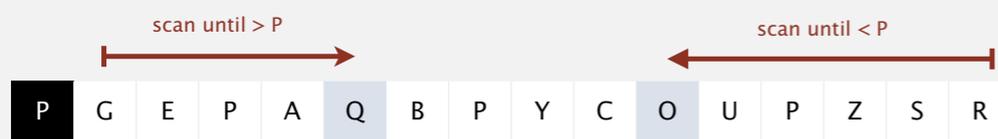
↑  
key

## Duplicate keys: stop on equal keys

Our partitioning subroutine stops both scans on equal keys.

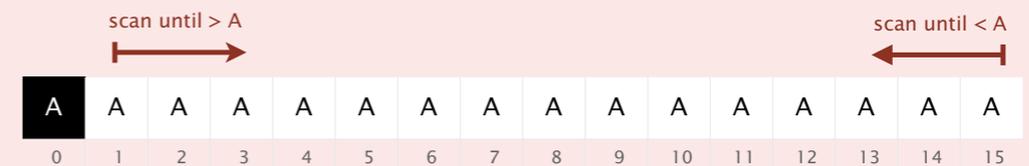


Q. Why not continue scans on equal keys?



## Quicksort quiz 2

What is the result of partitioning the following array (skip over equal keys)?



A.

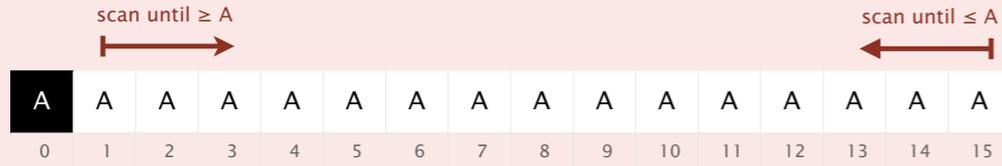
B.

C.

D. *I don't know.*

## Quicksort quiz 3

What is the result of partitioning the following array (stop on equal keys)?



- A. 

A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
- B. 

A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
- C. 

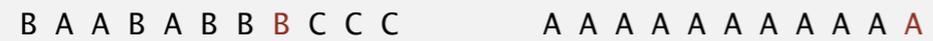
A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
- D. *I don't know.*

## Partitioning an array with all equal keys

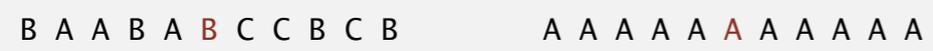
		a[ ]															
i	j	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
1	15	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
1	15	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
2	14	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
3	13	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
3	13	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
4	12	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
4	12	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
5	11	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
5	11	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
6	10	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
6	10	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
7	9	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
7	9	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
8	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
8	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A

## Duplicate keys: partitioning strategies

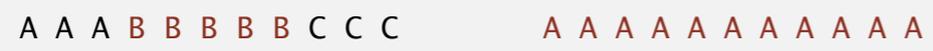
**Bad.** Don't stop scans on equal keys.  
[  $\sim \frac{1}{2} N^2$  compares when all keys equal ]



**Good.** Stop scans on equal keys.  
[  $\sim N \lg N$  compares when all keys equal ]

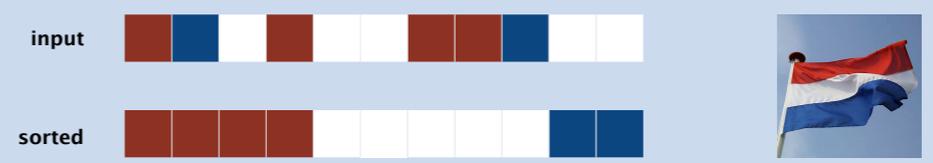


**Better.** Put all equal keys in place. How?  
[  $\sim N$  compares when all keys equal ]



## DUTCH NATIONAL FLAG PROBLEM

**Problem.** [Edsger Dijkstra] Given an array of  $N$  buckets, each containing a red, white, or blue pebble, sort them by color.



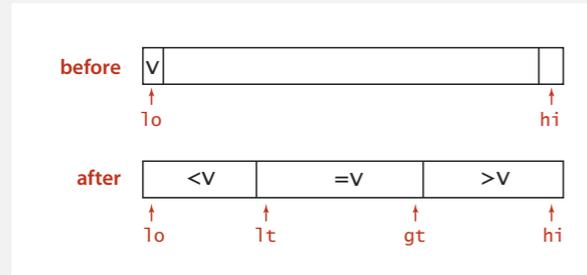
- Operations allowed.**
- $swap(i, j)$ : swap the pebble in bucket  $i$  with the pebble in bucket  $j$ .
  - $color(i)$ : color of pebble in bucket  $i$ .

- Requirements.**
- Exactly  $N$  calls to  $color()$ .
  - At most  $N$  calls to  $swap()$ .
  - Constant extra space.

## 3-way partitioning

**Goal.** Partition array into **three** parts so that:

- Entries between  $lt$  and  $gt$  equal to the partition item.
- No larger entries to left of  $lt$ .
- No smaller entries to right of  $gt$ .



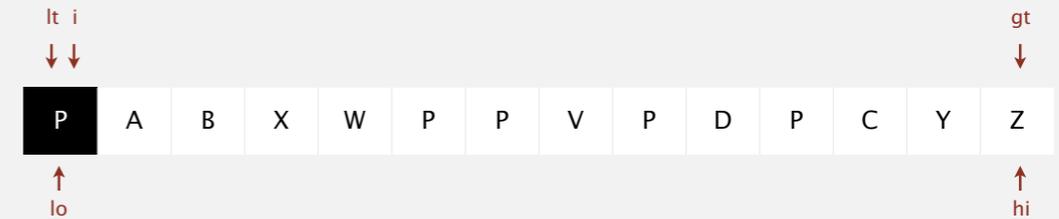
**Dutch national flag problem.** [Edsger Dijkstra]

- Conventional wisdom until mid 1990s: not worth doing.
- Now incorporated into C library `qsort()` and Java 6 system sort.

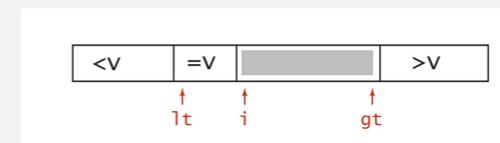
41

## Dijkstra 3-way partitioning demo

- Let  $v$  be partitioning item  $a[lo]$ .
- Scan  $i$  from left to right.
  - ( $a[i] < v$ ): exchange  $a[lt]$  with  $a[i]$ ; increment both  $lt$  and  $i$
  - ( $a[i] > v$ ): exchange  $a[gt]$  with  $a[i]$ ; decrement  $gt$
  - ( $a[i] == v$ ): increment  $i$



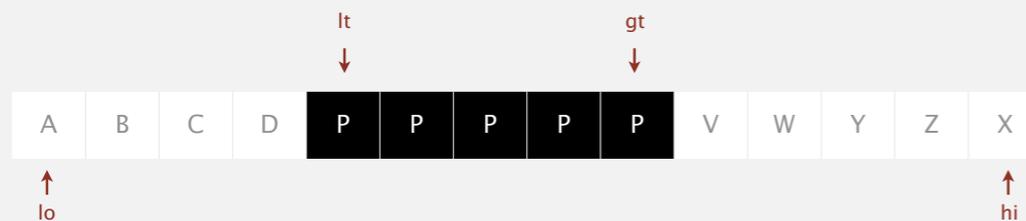
invariant



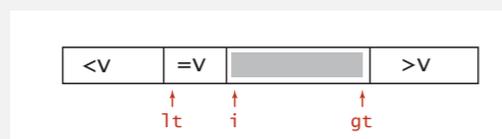
42

## Dijkstra 3-way partitioning demo

- Let  $v$  be partitioning item  $a[lo]$ .
- Scan  $i$  from left to right.
  - ( $a[i] < v$ ): exchange  $a[lt]$  with  $a[i]$ ; increment both  $lt$  and  $i$
  - ( $a[i] > v$ ): exchange  $a[gt]$  with  $a[i]$ ; decrement  $gt$
  - ( $a[i] == v$ ): increment  $i$



invariant



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## Dijkstra's 3-way partitioning: trace

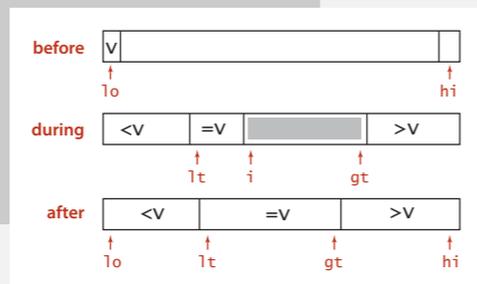
$lt$	$i$	$gt$	$a[]$												
			0	1	2	3	4	5	6	7	8	9	10	11	
0	0	11	R	B	W	W	R	W	B	R	R	W	B	R	
0	1	11	R	B	W	W	R	W	B	R	R	W	B	R	
1	2	11	B	R	W	W	R	W	B	R	R	W	B	R	
1	2	10	B	R	R	W	R	W	B	R	R	W	B	W	
1	3	10	B	R	R	W	R	W	B	R	R	W	B	W	
1	3	9	B	R	R	B	R	W	B	R	R	W	W	W	
2	4	9	B	B	R	R	R	W	B	R	R	W	W	W	
2	5	9	B	B	R	R	R	W	B	R	R	W	W	W	
2	5	8	B	B	R	R	R	W	B	R	R	W	W	W	
2	5	7	B	B	R	R	R	R	B	R	W	W	W	W	
2	6	7	B	B	R	R	R	R	B	R	W	W	W	W	
3	7	7	B	B	B	R	R	R	R	R	W	W	W	W	
3	8	7	B	B	B	R	R	R	R	R	W	W	W	W	
3	8	7	B	B	B	R	R	R	R	R	W	W	W	W	

3-way partitioning trace (array contents after each loop iteration)

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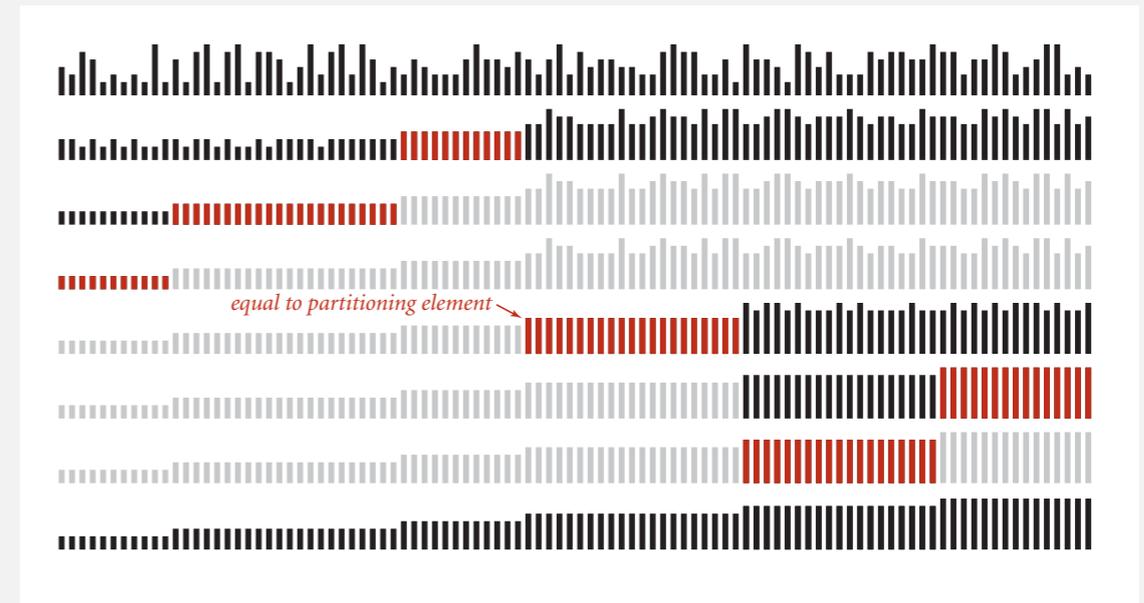
## 3-way quicksort: Java implementation

```
private static void sort(Comparable[] a, int lo, int hi)
{
    if (hi <= lo) return;
    int lt = lo, gt = hi;
    Comparable v = a[lo];
    int i = lo;
    while (i <= gt)
    {
        int cmp = a[i].compareTo(v);
        if (cmp < 0) exch(a, lt++, i);
        else if (cmp > 0) exch(a, i, gt--);
        else i++;
    }
    sort(a, lo, lt - 1);
    sort(a, gt + 1, hi);
}
```



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## 3-way quicksort: visual trace



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## Duplicate keys: lower bound

**Sorting lower bound.** If there are  $n$  distinct keys and the  $i^{\text{th}}$  one occurs  $x_i$  times, any compare-based sorting algorithm must use at least

$$\lg \left( \frac{N!}{x_1! x_2! \cdots x_n!} \right) \sim - \sum_{i=1}^n x_i \lg \frac{x_i}{N}$$

*N lg N* when all distinct;  
linear when only a constant number of distinct keys

compares in the worst case.

**Proposition.** [Sedgewick-Bentley 1997]

Quicksort with 3-way partitioning is **entropy-optimal**.

**Pf.** [beyond scope of course]

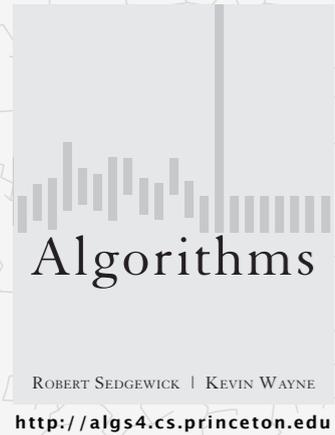
**Bottom line.** Quicksort with 3-way partitioning reduces running time from linearithmic to linear in broad class of applications.

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## Sorting summary

	inplace?	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 ordered
shell	✓		$N \log_3 N$	?	$c N^{3/2}$	tight code; subquadratic
merge		✓	$\frac{1}{2} N \lg N$	$N \lg N$	$N \lg N$	$N \log N$ guarantee; stable
timsort		✓	$N$	$N \lg N$	$N \lg N$	improves mergesort when preexisting order
quick	✓		$N \lg N$	$2 N \ln N$	$\frac{1}{2} N^2$	$N \log N$ probabilistic guarantee; fastest in practice
3-way quick	✓		$N$	$2 N \ln N$	$\frac{1}{2} N^2$	improves quicksort when duplicate keys
?	✓	✓	$N$	$N \lg N$	$N \lg N$	holy sorting grail

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## 2.3 QUICKSORT

- ▶ quicksort
- ▶ selection
- ▶ duplicate keys
- ▶ system sorts

## Sorting applications

Sorting algorithms are essential in a broad variety of applications:

- Sort a list of names.
- Organize an MP3 library. obvious applications
- Display Google PageRank results.
- List RSS feed in reverse chronological order.
  
- Find the median.
- Identify statistical outliers. problems become easy once items are in sorted order
- Binary search in a database.
- Find duplicates in a mailing list.
  
- Data compression.
- Computer graphics. non-obvious applications
- Computational biology.
- Load balancing on a parallel computer.
- ...

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## War story (system sort in C)

A beautiful bug report. [Allan Wilks and Rick Becker, 1991]

We found that qsort is unbearably slow on "organ-pipe" inputs like "01233210":

```
main (int argc, char**argv) {
    int n = atoi(argv[1]), i, x[100000];
    for (i = 0; i < n; i++)
        x[i] = i;
    for (; i < 2*n; i++)
        x[i] = 2*n-i-1;
    qsort(x, 2*n, sizeof(int), intcmp);
}
```

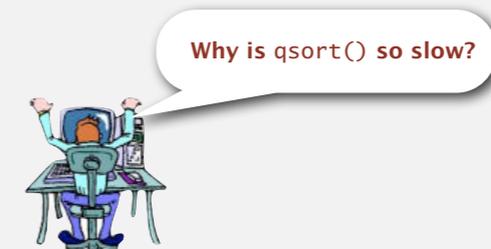
Here are the timings on our machine:

```
$ time a.out 2000
real    5.85s
$time a.out 4000
real   21.64s
$time a.out 8000
real   85.11s
```

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## War story (system sort in C)

Bug. A qsort() call that should have taken seconds was taking minutes.



At the time, almost all qsort() implementations based on those in:

- Version 7 Unix (1979): quadratic time to sort organ-pipe arrays.
- BSD Unix (1983): quadratic time to sort random arrays of 0s and 1s.

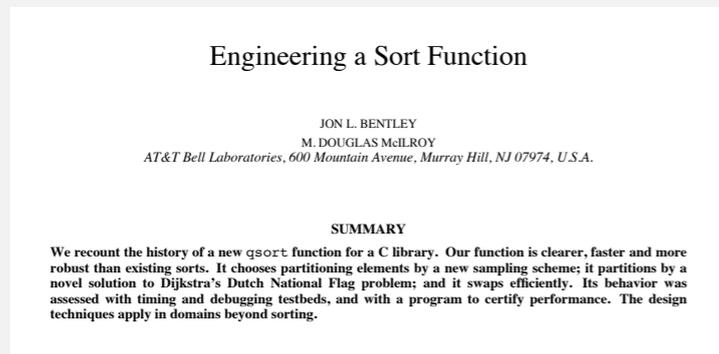


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## Engineering a system sort (in 1993)

### Bentley-McIlroy quicksort.

- Cutoff to insertion sort for small subarrays.
- Partitioning item: median of 3 or Tukey's ninther. ↑ samples 9 items
- Partitioning scheme: Bentley-McIlroy 3-way partitioning. ↑ similar to Dijkstra 3-way partitioning (but fewer exchanges when not many equal keys)



Very widely used. C, C++, Java 6, ....

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## A beautiful mailing list post (Yaroslavskiy, September 2009)

### Replacement of quicksort in java.util.Arrays with new dual-pivot quicksort

Hello All,

I'd like to share with you new **Dual-Pivot Quicksort** which is faster than the known implementations (theoretically and experimental). I'd like to propose to replace the JDK's Quicksort implementation by new one.

...

The new Dual-Pivot Quicksort uses *\*two\** pivots elements in this manner:

1. Pick an elements  $P_1$ ,  $P_2$ , called pivots from the array.
2. Assume that  $P_1 \leq P_2$ , otherwise swap it.
3. Reorder the array into three parts: those less than the smaller pivot, those larger than the larger pivot, and in between are those elements between (or equal to) the two pivots.
4. Recursively sort the sub-arrays.

The invariant of the Dual-Pivot Quicksort is:

[ <  $P_1$  |  $P_1 \leq$  &  $\leq P_2$  } >  $P_2$  ]

...

<http://mail.openjdk.java.net/pipermail/core-libs-dev/2009-September/002630.html>

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## A beautiful mailing list post (Yaroslavskiy-Bloch-Bentley, October 2009)

### Replacement of quicksort in java.util.Arrays with new dual-pivot quicksort

Date: Thu, 29 Oct 2009 11:19:39 +0000  
Subject: Replace quicksort in java.util.Arrays with dual-pivot implementation

Changeset: b05abb410c52  
Author: alanb  
Date: 2009-10-29 11:18 +0000  
URL: <http://hg.openjdk.java.net/jdk7/t1/jdk/rev/b05abb410c52>

6880672: Replace quicksort in java.util.Arrays with dual-pivot implementation  
Reviewed-by: jjb  
Contributed-by: vladimir.yaroslavskiy at sun.com, joshua.bloch at google.com, jrbentley at avaya.com

```
! make/java/java/FILES_java.gmk
! src/share/classes/java/util/Arrays.java
+ src/share/classes/java/util/DualPivotQuicksort.java
```

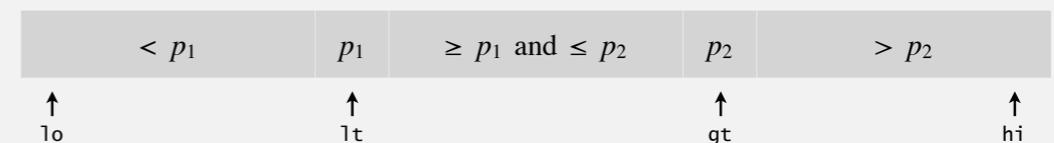
<http://mail.openjdk.java.net/pipermail/compiler-dev/2009-October.txt>

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## Dual-pivot quicksort

Use **two** partitioning items  $p_1$  and  $p_2$  and partition into three subarrays:

- Keys less than  $p_1$ .
- Keys between  $p_1$  and  $p_2$ .
- Keys greater than  $p_2$ .



Recursively sort three subarrays.

**Note.** Skip middle subarray if  $p_1 = p_2$ .

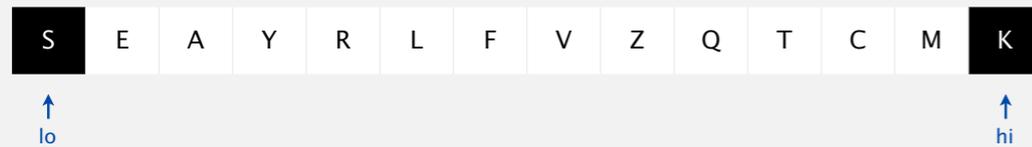
↑ degenerates to Dijkstra's 3-way partitioning

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## Dual-pivot partitioning demo

### Initialization.

- Choose  $a[lo]$  and  $a[hi]$  as partitioning items.
- Exchange if necessary to ensure  $a[lo] \leq a[hi]$ .

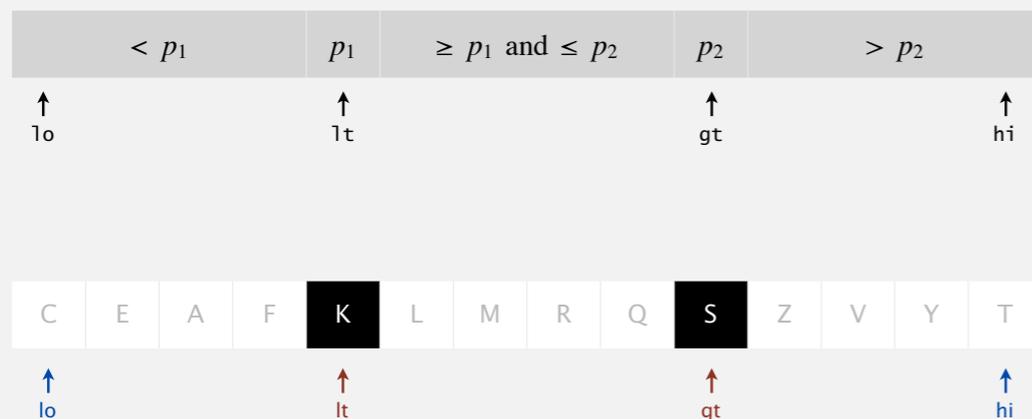


exchange  $a[lo]$  and  $a[hi]$

## Dual-pivot partitioning demo

### Finalize.

- Exchange  $a[lo]$  with  $a[--lt]$ .
- Exchange  $a[hi]$  with  $a[++gt]$ .

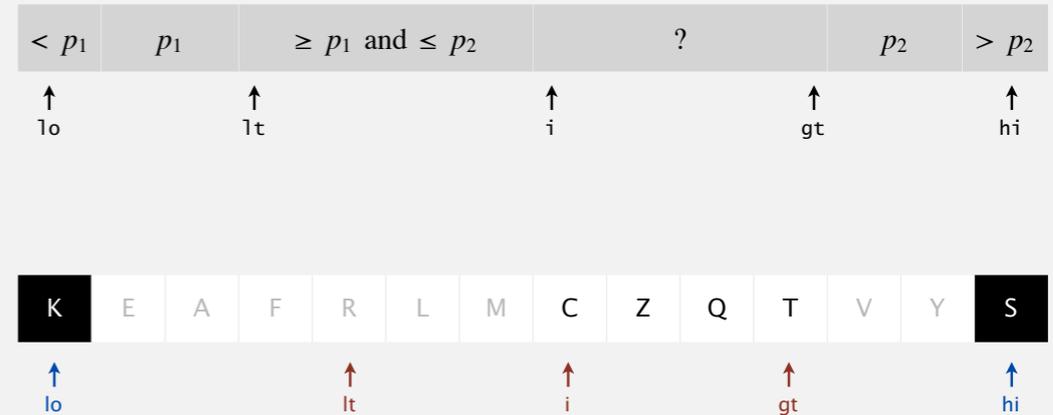


3-way partitioned

## Dual-pivot partitioning demo

### Main loop. Repeat until $i$ and $gt$ pointers cross.

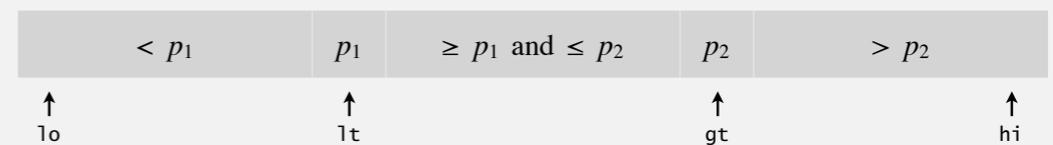
- If  $(a[i] < a[lo])$ , exchange  $a[i]$  with  $a[lt]$  and increment  $lt$  and  $i$ .
- Else if  $(a[i] > a[hi])$ , exchange  $a[i]$  with  $a[gt]$  and decrement  $gt$ .
- Else, increment  $i$ .



## Dual-pivot quicksort

Use **two** partitioning items  $p_1$  and  $p_2$  and partition into three subarrays:

- Keys less than  $p_1$ .
- Keys between  $p_1$  and  $p_2$ .
- Keys greater than  $p_2$ .



Now widely used. Java 7, Python unstable sort, Android, ...

## Three-pivot quicksort

Use **three** partitioning items  $p_1$ ,  $p_2$ , and  $p_3$  and partition into four subarrays:

- Keys less than  $p_1$ .
- Keys between  $p_1$  and  $p_2$ .
- Keys between  $p_2$  and  $p_3$ .
- Keys greater than  $p_3$ .

$< p_1$	$p_1$	$\geq p_1$ and $\leq p_2$	$p_2$	$\geq p_2$ and $\leq p_3$	$p_3$	$> p_3$
↑ lo	↑ a1		↑ a2		↑ a3	↑ hi

### Multi-Pivot Quicksort: Theory and Experiments

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## Quicksort quiz 4

Why do 2-pivot (and 3-pivot) quicksort perform better than 1-pivot?

- A. Fewer compares.
- B. Fewer exchanges.
- C. Fewer cache misses.
- D. *I don't know.*

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## Quicksort quiz 4

Why do 2-pivot (and 3-pivot) quicksort perform better than 1-pivot?

- A. Fewer compares.
- B. Fewer exchanges.
- C. Fewer cache misses.

# entries scanned is a good proxy for cache performance when comparing quicksort variants

partitioning	compares	exchanges	entries scanned
1-pivot	$2 N \ln N$	$0.333 N \ln N$	$2 N \ln N$
median-of-3	$1.714 N \ln N$	$0.343 N \ln N$	$1.714 N \ln N$
2-pivot	$1.9 N \ln N$	$0.6 N \ln N$	$1.6 N \ln N$
3-pivot	$1.846 N \ln N$	$0.616 N \ln N$	$1.385 N \ln N$

Reference: Analysis of Pivot Sampling in Dual-Pivot Quicksort by Wild-Nebel-Martinez

Bottom line. Caching can have a significant impact on performance.

beyond scope of this course

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## Which sorting algorithm to use?

Many sorting algorithms to choose from:

sorts	algorithms
elementary sorts	insertion sort, selection sort, bubblesort, shaker sort, ...
subquadratic sorts	quicksort, mergesort, heapsort, shellsort, samplesort, ...
system sorts	dual-pivot quicksort, timsort, introsort, ...
external sorts	Poly-phase mergesort, cascade-merge, psort, ....
radix sorts	MSD, LSD, 3-way radix quicksort, ...
parallel sorts	bitonic sort, odd-even sort, smooth sort, GPU sort, ...

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## Which sorting algorithm to use?

Applications have diverse attributes.

- Stable?
- Parallel?
- In-place?
- Deterministic?
- Duplicate keys?
- Multiple key types?
- Linked list or arrays?
- Large or small items?
- Randomly-ordered array?
- Guaranteed performance?

		attributes					
		1	2	3	4	...	M
algorithm	A	•		•			
	B		•		•		•
	C	•		•			
	D					•	
	E		•				
	F	•			•		•
	G	•					•
	.		•	•		•	•
	.					•	
	.						•
	K	•			•		

many more combinations of attributes than algorithms

Q. Is the system sort good enough?

A. Usually.

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## System sort in Java 7

`Arrays.sort()`.

- Has method for objects that are Comparable.
- Has overloaded method for each primitive type.
- Has overloaded method for use with a Comparator.
- Has overloaded methods for sorting subarrays.



Algorithms.

- Dual-pivot quicksort for primitive types.
- Timsort for reference types.

Q. Why use different algorithms for primitive and reference types?

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## Ineffective sorts

### INEFFECTIVE SORTS

```
DEFINE HALFHEARTEDMERGESORT(LIST):
  IF LENGTH(LIST) < 2:
    RETURN LIST
  PIVOT = INT(LENGTH(LIST) / 2)
  A = HALFHEARTEDMERGESORT(LIST[:PIVOT])
  B = HALFHEARTEDMERGESORT(LIST[PIVOT:])
  // UMMMMMM
  RETURN [A, B] // HERE. SORRY.
```

```
DEFINE FASTBOGOSORT(LIST):
  // AN OPTIMIZED BOGOSORT
  // RUNS IN O(N*LOGN)
  FOR N FROM 1 TO LOG(LENGTH(LIST)):
    SHUFFLE(LIST):
    IF ISSORTED(LIST):
      RETURN LIST
  RETURN "KERNEL PAGE FAULT (ERROR CODE: 2)"
```

```
DEFINE JOBININTERVIEWQUICKSORT(LIST):
  OK SO YOU CHOOSE A PIVOT
  THEN DIVIDE THE LIST IN HALF
  FOR EACH HALF:
    CHECK TO SEE IF IT'S SORTED
    NO, WAIT, IT DOESN'T MATTER
    COMPARE EACH ELEMENT TO THE PIVOT
    THE BIGGER ONES GO IN A NEW LIST
    THE EQUAL ONES GO INTO, UH
    THE SECOND LIST FROM BEFORE
  HANG ON, LET ME NAME THE LISTS
  THIS IS LIST A
  THE NEW ONE IS LIST B
  PUT THE BIG ONES INTO LIST B
  NOW TAKE THE SECOND LIST
  CALL IT LIST, UH, A2
  WHICH ONE WAS THE PIVOT IN?
  SCRATCH ALL THAT
  IT JUST RECURSIVELY CALLS ITSELF
  UNTIL BOTH LISTS ARE EMPTY
  RIGHT?
  NOT EMPTY, BUT YOU KNOW WHAT I MEAN
  AM I ALLOWED TO USE THE STANDARD LIBRARIES?
```

```
DEFINE PANICSORT(LIST):
  IF ISSORTED(LIST):
    RETURN LIST
  FOR N FROM 1 TO 10000:
    PIVOT = RANDOM(0, LENGTH(LIST))
    LIST = LIST[:PIVOT] + LIST[PIVOT:]
    IF ISSORTED(LIST):
      RETURN LIST
  IF ISSORTED(LIST): // THIS CAN'T BE HAPPENING
    RETURN LIST
  IF ISSORTED(LIST): // COME ON COME ON
    RETURN LIST
  // OH JEEZ
  // I'M GONNA BE IN SO MUCH TROUBLE
  LIST = []
  SYSTEM("SHUTDOWN -H +5")
  SYSTEM("RM -RF /")
  SYSTEM("RM -RF ~/*")
  SYSTEM("RM -RF /")
  SYSTEM("RD /5 /Q C:\*") // PORTABILITY
  RETURN [1, 2, 3, 4, 5]
```

<http://xkcd.com/1185>

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