
Data Structures & Algorithms

4. Advanced Topics in Sorting

- complexity
- system sorts
- duplicate keys
- comparators



Slides are Reformatted From Lecture Note of Algorithms Course,
by Robert Sedgewick, Princeton University, Fall, 2008.

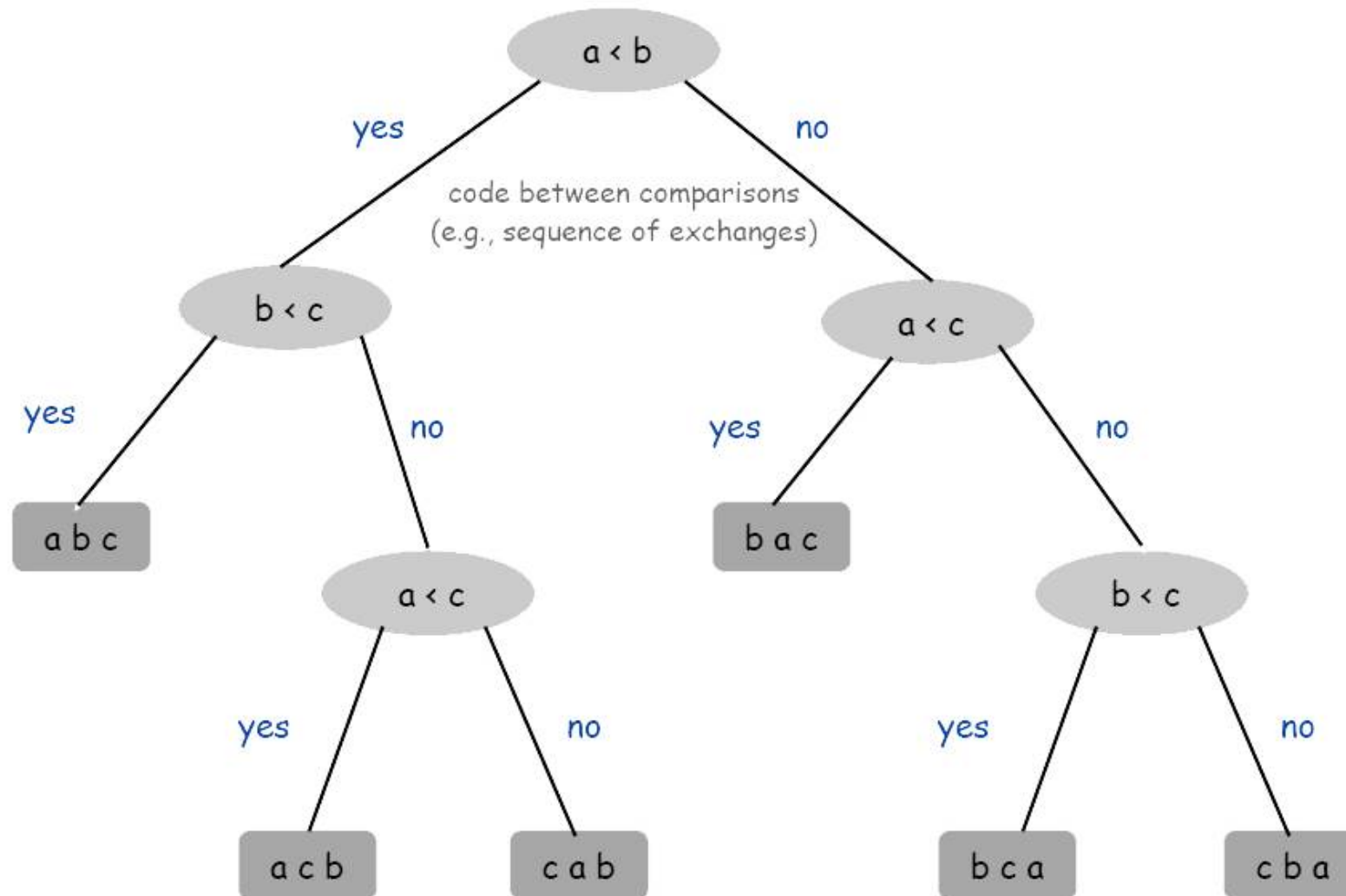
4. Advanced Topics in Sorting

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Complexity of Sorting

- ❑ **Computational complexity.** Framework to study efficiency of algorithms for solving a particular problem X.
 - ❑ **Machine model.** Focus on fundamental operations.
 - ❑ **Upper bound.** Cost guarantee **provided** by some algorithm for X.
 - ❑ **Lower bound.** **Proven** limit on cost guarantee of any algorithm for X.
 - ❑ **Optimal algorithm.** Algorithm with **best** cost guarantee for X.
 - ❑ **Example: sorting.**
 - ◆ Machine model = # comparisons
 - ◆ Upper bound = $N \lg N$ from mergesort.
 - ◆ Lower bound ?
- ↑
lower bound ~ upper bound
- ← access information only through compares

Decision Tree



Comparison-Based Lower Bound for Sorting

Theorem. Any comparison based sorting algorithm must use more than $N \lg N - 1.44 N$ comparisons in the worst-case.

□ Pf.

- ◆ Assume input consists of N distinct values a_1 through a_N .
- ◆ Worst case dictated by tree height h .
- ◆ $N!$ different orderings.
- ◆ (At least) one leaf corresponds to each ordering.
- ◆ Binary tree with $N!$ leaves cannot have height less than $\lg(N!)$

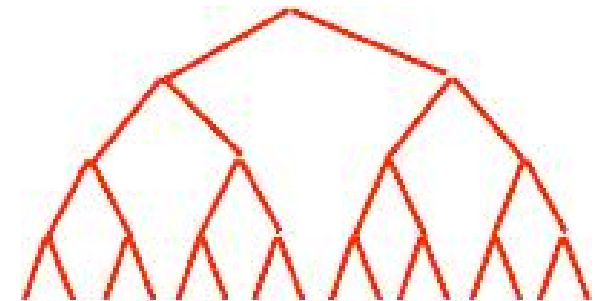
$$\checkmark h \geq \lg N!$$

$$\checkmark \geq \lg (N / e)^N$$

$$\checkmark = N \lg N - N \lg e$$

$$\checkmark \geq N \lg N - 1.44 N$$

← Stirling's
formula



Complexity of Sorting

- ❑ **Upper bound.** Cost *guarantee* provided by some algorithm for X.
- ❑ **Lower bound.** Proven limit on cost *guarantee* of any algorithm for X.
- ❑ **Optimal algorithm.** Algorithm with best cost guarantee for X.

- ❑ **Example: sorting.**
 - ◆ Machine model = # comparisons
 - ◆ Upper bound = $N \lg N$ (mergesort)
 - ◆ Lower bound = $N \lg N - 1.44 N$

Mergesort is **optimal** (to within a small additive factor)

↑
lower bound \approx upper bound

- ❑ First goal of algorithm design: optimal algorithms

Complexity Results in Context

❑ Other operations?

- ◆ statement is only about number of compares
- ◆ quicksort is faster than mergesort (lower use of other operations)

❑ Space?

- ◆ mergesort is not optimal with respect to space usage
- ◆ insertion sort, selection sort, shellsort, quicksort are space-optimal
- ◆ is there an algorithm that is both time- and space-optimal?

stay tuned for heapsort

❑ Nonoptimal algorithms may be better in practice

- ◆ statement is only about guaranteed worst-case performance
- ◆ quicksort's probabilistic guarantee is just as good in practice

Lessons

- use theory as a guide
- know your algorithms

don't try to design an algorithm that uses half as many compares as mergesort

use quicksort when time and space are critical

Example: Selection

□ Find the k th largest element.

- ◆ Max: $k = 1$.
- ◆ Min: $k = N$.
- ◆ **Median**: $k = N/2$.

□ Applications.

- ◆ Order statistics.
- ◆ Find the “top k ”

□ Use theory as a guide

- ◆ easy $O(N \log N)$ **upper bound**: sort, return $a[k]$
- ◆ easy $O(N)$ **upper bound** for some k : min, max
- ◆ easy $\Omega(N)$ **lower bound**: must examine every element

□ Which is true?

- ◆ $\Omega(N \log N)$ lower bound? [is selection as hard as sorting?]
- ◆ $O(N)$ upper bound? [linear algorithm for all k]

Complexity Results in Context (Cont'd)

- ❑ Lower bound may not hold if the algorithm has information about
 - ◆ the key values
 - ◆ their initial arrangement

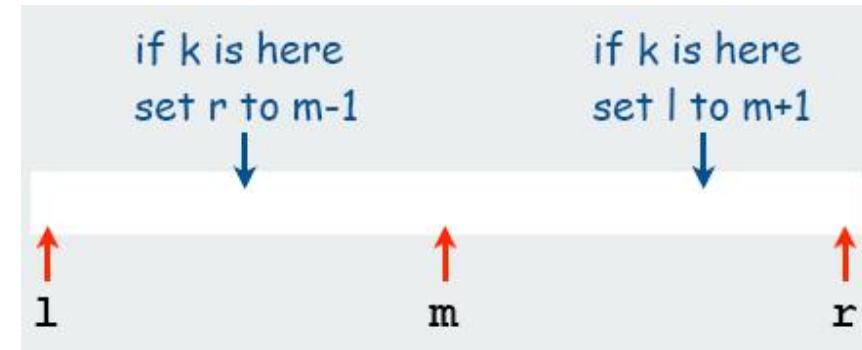
- ❑ **Partially ordered** arrays. Depending on the initial order of the input, we may not need $N \lg N$ compares.
 - ↖ insertion sort requires $O(N)$ compares on an already sorted array

- ❑ **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 comparisons** instead of key comparisons for numbers and strings.
 - ↖ stay tuned for radix sorts

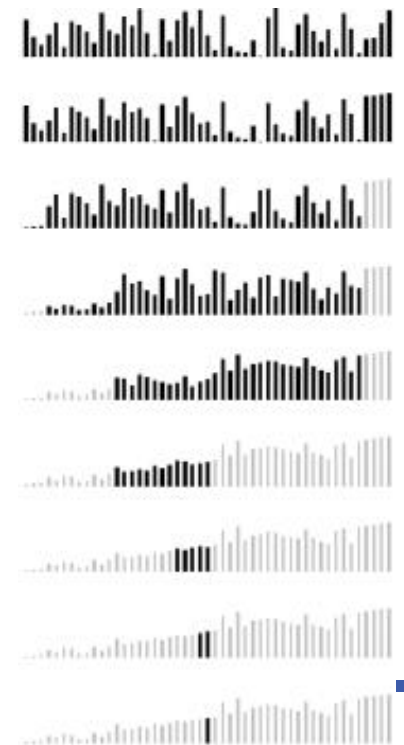
Selection: quick-select Algorithm

- Partition array so that:
 - ◆ element $a[m]$ is in place
 - ◆ no larger element to the left of m
 - ◆ no smaller element to the right of m
- Repeat in **one** subarray, depending on m .



- Finished when $m = k$ ← $a[k]$ is in place, no larger element to the left, no smaller element to the right

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



Quick-Select Analysis

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

□ Pf.

- ◆ Intuitively, each partitioning step roughly splits array in half.
- ◆ $N + N/2 + N/4 + \dots + 1 \approx 2N$ comparisons.
- ◆ Formal analysis similar to quicksort analysis:

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

Ex: $(2 + 2 \ln 2)N$ comparisons to find the median

Note. Might use $\sim N^2/2$ comparisons, but as with quicksort, the **random shuffle** provides a probabilistic guarantee.

□ **Theorem.** [Blum, Floyd, Pratt, Rivest, Tarjan, 1973] There exists a selection algorithm that take **linear** time in the worst case.

Note. Algorithm is far too complicated to be useful 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

4. Advanced Topics in Sorting

- complexity
- **system sorts**
- duplicate keys
- comparators

Sorting Challenge 1

- ❑ Problem: sort a file of huge records with tiny keys.
- ❑ Ex: reorganizing your MP3 files.
- ❑ Which sorting method to use?
 1. merge sort
 2. insertion sort
 3. selection sort

file →

record →

key →

Fox	1	A	243-456-9091	101 Brown
Quilici	1	C	343-987-5642	32 McCosh
Chen	2	A	884-232-5341	11 Dickinson
Furia	3	A	766-093-9873	22 Brown
Kanaga	3	B	898-122-9643	343 Forbes
Andrews	3	A	874-088-1212	121 Whitman
Rohde	3	A	232-343-5555	115 Holder
Battle	4	C	991-878-4944	308 Blair
Aaron	4	A	664-480-0023	097 Little
Gazsi	4	B	665-303-0266	113 Walker

Sorting Challenge 1

- ❑ **Problem:** sort a file of huge records with tiny keys.
- ❑ **Ex:** reorganizing your MP3 files.

- ❑ **Which sorting method to use?**
 1. merge sort probably no, selection sort simpler and faster
 2. insertion sort no, too many exchanges
 3. selection sort **YES**, linear time under reasonable assumptions

- ❑ **Ex: 5,000 records, each 2 million bytes with 100-byte keys.**
 - ◆ Cost of comparisons: $100 \times 5000^2 / 2 = 1.25$ billion
 - ◆ Cost of exchanges: $2,000,000 \times 5,000 = 10$ trillion
 - ◆ Merge sort might be a factor of $\log(5000)$ slower.

Sorting Challenge 2

- ❑ **Problem:** sort a huge randomly-ordered file of small records.
- ❑ **Ex:** process transaction records for a phone company.
- ❑ Which sorting method to use?
 1. quick sort
 2. insertion sort
 3. selection sort

file →

record →

key →

Fox	1	A	243-456-9091	101 Brown
Quillici	1	C	343-987-5642	32 McCosh
Chen	2	A	884-232-5341	11 Dickinson
Furia	3	A	766-093-9873	22 Brown
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Sorting Challenge 2

- ❑ **Problem:** sort a huge randomly-ordered file of small records.
- ❑ **Ex:** process transaction records for a phone company.

- ❑ **Which sorting method to use?**

- | | |
|-------------------|---|
| 1. quick sort | YES, it's designed for this problem |
| 2. insertion sort | no, quadratic time for randomly-ordered files |
| 3. selection sort | no, always takes quadratic time |

Sorting Challenge 3

- ❑ **Problem:** sort a huge number of tiny files (each file is independent)
- ❑ **Ex:** daily customer transaction records.
- ❑ **Which sorting method to use?**
 1. quick sort
 2. insertion sort
 3. selection sort

file →

record →

key →

Fox	1	A	243-456-9091	101 Brown
Quilici	1	C	343-987-5642	32 McCosh
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Sorting Challenge 3

- ❑ **Problem:** sort a huge number of tiny files (each file is independent)
- ❑ **Ex:** daily customer transaction records.

- ❑ **Which sorting method to use?**
 1. quick sort no, too much overhead
 2. insertion sort YES, much less overhead than system sort
 3. selection sort YES, much less overhead than system sort

- ❑ **Ex: 4 record file.**
 - ◆ $4 N \log N + 35 = 70$
 - ◆ $2N^2 = 32$

Sorting Challenge 4

- ❑ Problem: sort a huge file that is already almost in order.
- ❑ Ex: re-sort a huge database after a few changes.
- ❑ Which sorting method to use?
 1. quick sort
 2. insertion sort
 3. selection sort

file →

record →

key →

Fox	1	A	243-456-9091	101 Brown
Quilici	1	C	343-987-5642	32 McCosh
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Sorting Challenge 4

- ❑ **Problem:** sort a huge file that is already almost in order.
- ❑ **Ex:** re-sort a huge database after a few changes.

- ❑ **Which sorting method to use?**
 1. quick sort probably no, insertion simpler and faster
 2. insertion sort **YES**, linear time for most definitions of "in order"
 3. selection sort no, always takes quadratic time

- ❑ **Ex:**

```
A B C D E F H I J G P K L M N O Q R S T U V W X Y Z
Z A B C D E F G H I J K L M N O P Q R S T U V W X Y
```

Sorting Applications

□ Sorting algorithms are essential in a broad variety of applications

- ◆ Sort a list of names.
- ◆ Organize an MP3 library.
- ◆ Display Google PageRank results.
- ◆ List RSS (Really Simple Syndication) news items in reverse chronological order.

obvious applications

- ◆ Find the median.
- ◆ Find the closest pair.
- ◆ Binary search in a database.
- ◆ Identify statistical outliers.
- ◆ Find duplicates in a mailing list.

problems become easy once
items are in sorted order

- ◆ Data compression.
- ◆ Computer graphics.
- ◆ Computational biology.
- ◆ Supply chain management.
- ◆ Load balancing on a parallel computer.

non-obvious applications

Every system needs (and has) a system sort!

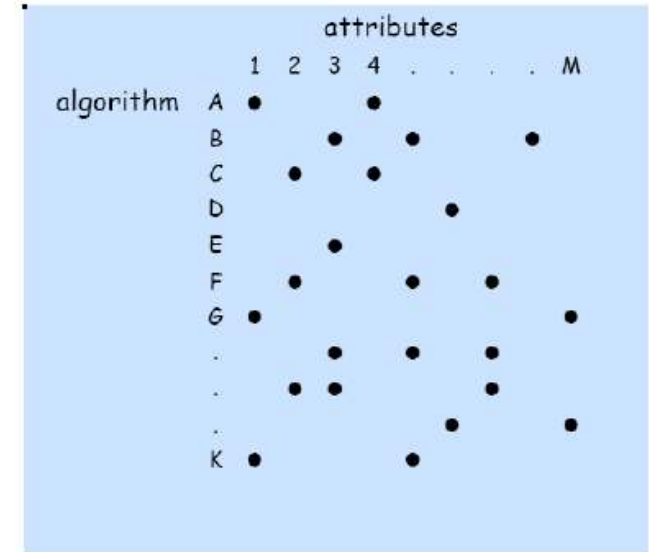
System Sort: Which Algorithm to Use?

- ❑ Many sorting algorithms to choose from
- ❑ internal sorts.
 - ◆ insertion sort, selection sort, bubblesort, shaker sort.
 - ◆ quicksort, mergesort, heapsort, samplesort, shellsort.
 - ◆ solitaire sort, red-black sort, splay sort, Dobosiewicz sort, psort, ...
- ❑ external sorts. Poly-phase mergesort, cascade-merge, oscillating sort.
- ❑ radix sorts.
 - ◆ Distribution, MSD, LSD.
 - ◆ 3-way radix quicksort.
- ❑ parallel sorts.
 - ◆ bitonic sort, Batchers even-odd sort.
 - ◆ smooth sort, cube sort, column sort.
 - ◆ GPU sort.

System Sort: Which Algorithm to Use?

□ Applications have diverse attributes

- ◆ Stable?
- ◆ Multiple keys?
- ◆ Deterministic?
- ◆ Keys all distinct?
- ◆ Multiple key types?
- ◆ Linked list or arrays?
- ◆ Large or small records?
- ◆ Is your file randomly ordered?
- ◆ Need guaranteed performance?



many more combinations of attributes than algorithms

□ Elementary sort may be method of choice for some combination.

□ Cannot cover **all** combinations of attributes.

□ **Q.** Is the system sort good enough?

□ **A.** Maybe (no matter which algorithm it uses).

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Duplicate Keys

- Often, purpose of sort is to bring records with duplicate keys together.
 - ◆ Sort population by age.
 - ◆ Finding collinear points.
 - ◆ Remove duplicates from mailing list.
 - ◆ Sort job applicants by college attended.

Typical characteristics of such applications.

- Huge file.
- Small number of key values.

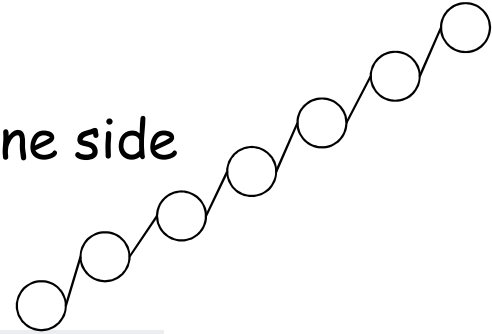
- Mergesort with duplicate keys: always $\sim N \lg N$ compares

- Quicksort with duplicate keys

- ◆ algorithm goes **quadratic** unless partitioning stops on equal keys!
- ◆ [many textbook and system implementations have this problem]
- ◆ 1990s Unix user found this problem in `qsort()`

Duplicate Keys: the Problem

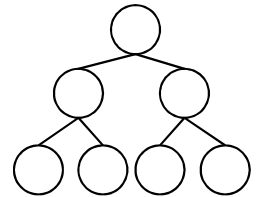
- ❑ Assume all keys are **equal**.
- ❑ Recursive code guarantees that case will predominate!
- ❑ **Mistake:** Put all keys equal to the partitioning element on one side
 - ◆ easy to code
 - ◆ guarantees N^2 running time when all keys equal



B A A B A B B B C C C

A A A A A A A A A A A

- ❑ **Recommended:** Stop scans on keys equal to the partitioning element
 - ◆ easy to code
 - ◆ guarantees $N \lg N$ compares when all keys equal



B A A B A B C C B C B

A A A A A A A A A A A

- ❑ **Desirable:** Put all keys equal to the partitioning element in place

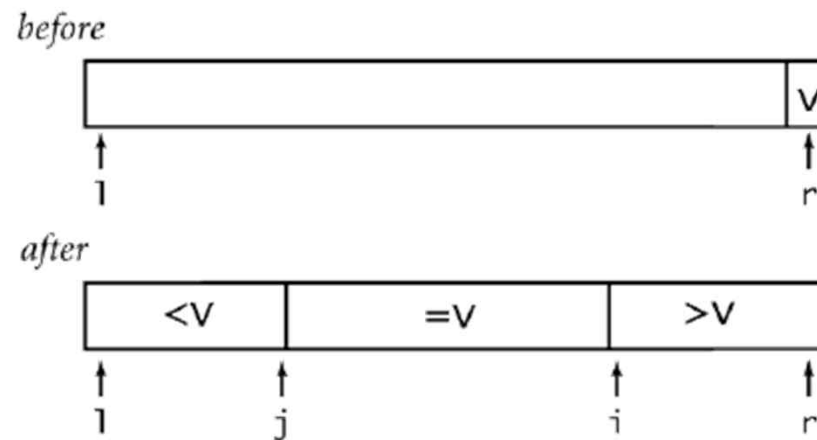
A A A B B B B B C C C

A A A A A A A A A A A

- ❑ Common wisdom to 1990s: not worth adding code to inner loop

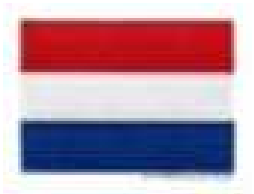
3-Way Partitioning

- 3-Way Partitioning. Partition elements into 3 parts:
 - ◆ Elements **between i and j** equal to partition element v.
 - ◆ No larger elements to **left of j**.
 - ◆ No smaller elements to **right of i**.



- Dutch National Flag Problem.

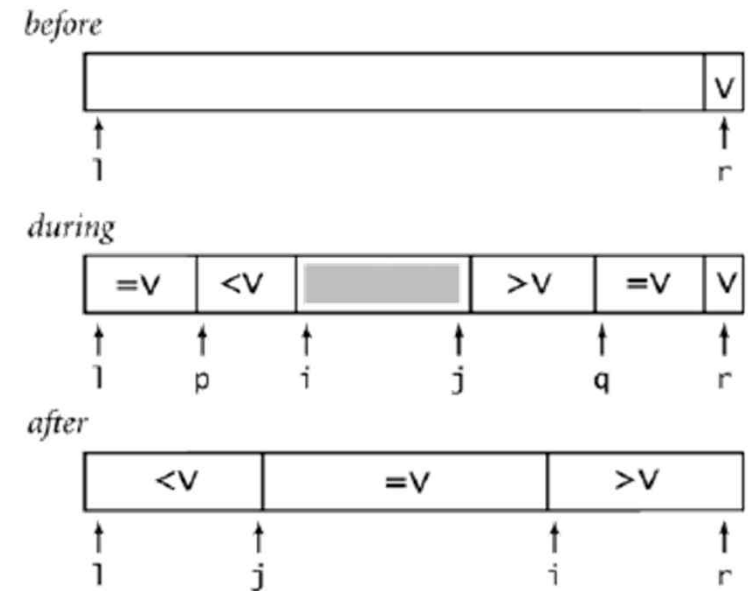
- ◆ not done in practical sorts before mid-1990s.
- ◆ new approach discovered when fixing mistake in Unix `qsort()`
- ◆ now incorporated into Java system sort



Solution to Dutch National Flag Problem.

□ 3-way partitioning (Bentley-McIlroy).

- ◆ Partition elements into 4 parts:
 - ✓ no larger elements to **left of i**
 - ✓ no smaller elements to **right of j**
 - ✓ equal elements to **left of p**
 - ✓ equal elements to **right of q**
- ◆ Afterwards, swap equal keys into center.



□ All the right properties.

- ◆ in-place.
- ◆ not much code.
- ◆ linear if keys are all equal.
- ◆ small overhead if no equal keys.

3-Way Quicksort: Java Implementation

```
private static void sort(Comparable[] a, int l, int r)
{
    if (r <= l) return;
    int i = l-1, j = r;
    int p = l-1, q = r;

    while(true)
    {
        while (less(a[++i], a[r])) ;
        while (less(a[r], a[--j])) if (j == l) break;
        if (i >= j) break;
        exch(a, i, j);
        if (eq(a[i], a[r])) exch(a, ++p, i);    swap equal keys to left or right
        if (eq(a[j], a[r])) exch(a, --q, j);
    }
    exch(a, i, r);

    j = i - 1;
    i = i + 1;
    for (int k = l ; k <= p; k++) exch(a, k, j--);
    for (int k = r-1; k >= q; k--) exch(a, k, i++);

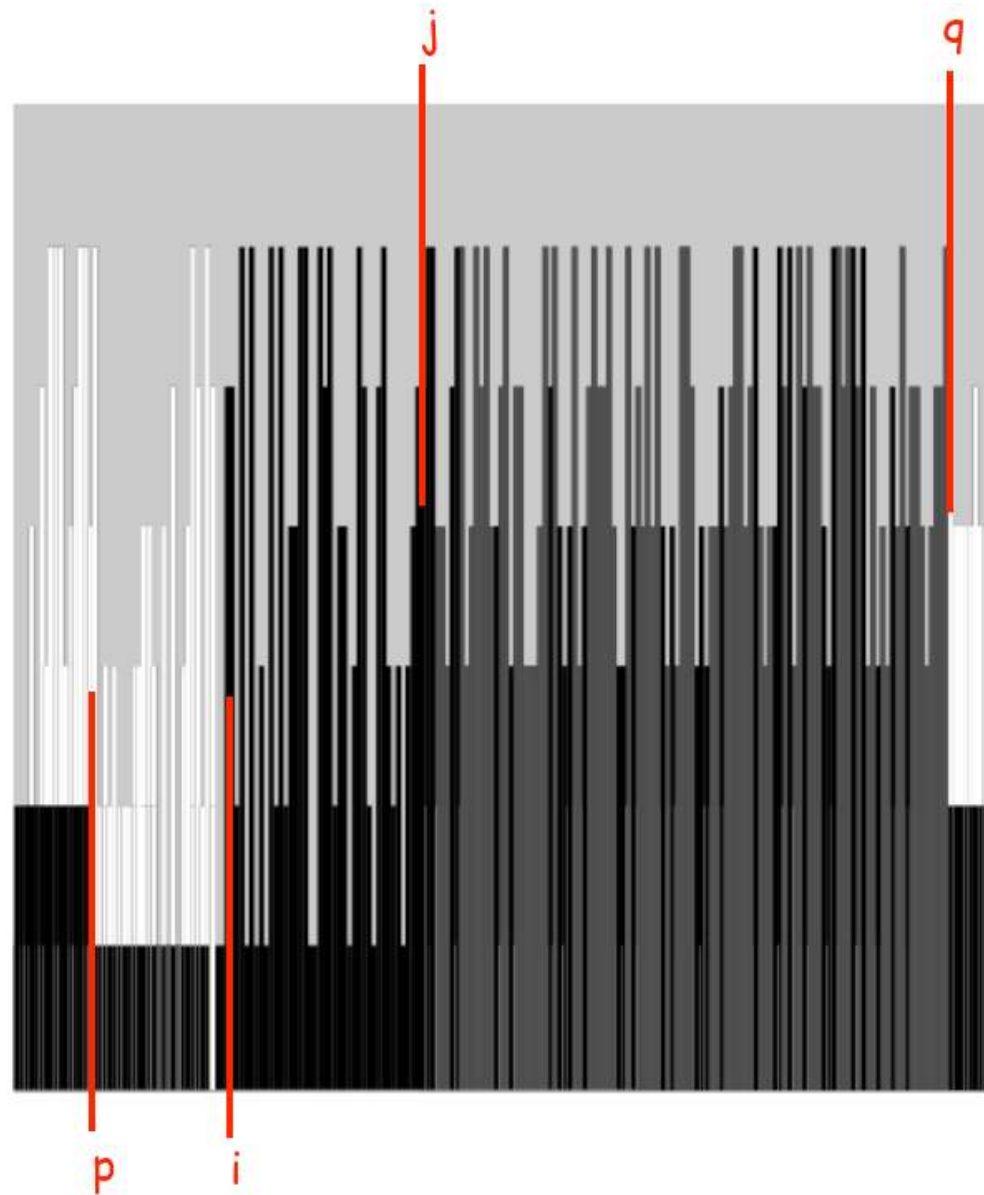
    sort(a, l, j);
    sort(a, i, r);
}
```

Duplicate Keys: Lower Bound

- Theorem. [Sedgewick-Bentley] Quicksort with 3-way partitioning is **optimal** for random keys with duplicates.
- Proof (beyond scope of the course).
 - ◆ generalize decision tree
 - ◆ tie cost to entropy
 - ◆ note: cost is **linear** when number of key values is $O(1)$

Bottom line: Randomized Quicksort with 3-way partitioning reduces cost from **linearithmic** to **linear** (!) in broad class of applications

3-Way Partitioning Animation



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Generalized Compare

- ❑ Comparable interface: sort uses type's compareTo() function:

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

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

    public int compareTo(Date b)
    {
        Date a = this;
        if (a.year < b.year ) return -1;
        if (a.year > b.year ) return +1;
        if (a.month < b.month) return -1;
        if (a.month > b.month) return +1;
        if (a.day < b.day ) return -1;
        if (a.day > b.day ) return +1;
        return 0;
    }
}
```

Generalized Compare

- ❑ Comparable interface: sort uses type's compareTo() function:

Problem 1: Not type-safe

Problem 2: May want to use a different order.

Problem 3: Some types may have no "natural" order.

- ❑ Ex. Sort strings by:

- ◆ Natural order.
- ◆ Case insensitive.
- ◆ French.
- ◆ Spanish.

Now is the time

is Now the time

real réal rico

café cuidado champiñón dulce

ch and rr are single letters

```
String[] a;  
...  
Arrays.sort(a);  
Arrays.sort(a, String.CASE_INSENSITIVE_ORDER);  
Arrays.sort(a, Collator.getInstance(Locale.FRENCH));  
Arrays.sort(a, Collator.getInstance(Locale.SPANISH));
```

import java.text.Collator;

Generalized Compare

- ❑ Comparable interface: sort uses type's compareTo() function:

Problem 1: Not type-safe

Problem 2: May want to use a different order.

Problem 3: Some types may have no "natural" order.

- ❑ A bad client

autoboxed to Integer

autoboxed to Double

```
public class BadClient
{
    public static void main(String[] args)
    {
        int N = Integer.parseInt(args[0]);
        Comparable[] a = new Comparable[N];
        ...
        a[i] = 1;
        ...
        a[j] = 2.0;
        ...
        Insertion.sort(a);
    }
}
```

Exception ... java.lang.ClassCastException: java.lang.Double
at java.lang.Integer.compareTo(Integer.java:35)

Generalized Compare

- Comparable interface: sort uses type's compareTo() function:

Problem 1: Not type-safe

Problem 2: May want to use a different order.

Problem 3: Some types may have no "natural" order.

- General key

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

Client can sort array of any Comparable type: Double[], File[], Date[], ...

Necessary in system library code; not in this course (for brevity)

Generalized Compare

- ❑ **Comparable interface:** sort uses type's `compareTo()` function:

Problem 1: Not type-safe

Problem 2: May want to use a different order.

Problem 3: Some types may have no "natural" order.

Solution: Use `Comparator` interface

- ❑ **Comparator interface.** Require a method `compare()` so that `compare(v, w)` is a total order that behaves like `compareTo()`.
- ❑ **Advantage.** Separates the definition of the data type from definition of what it means to compare two objects of that type.
 - ◆ add **any number of new orders** to a data type.
 - ◆ add an order to a library data type with no natural order.

Generalized Compare

- ❑ Comparable interface: sort uses type's compareTo() function:


Problem 2: May want to use a different order.

Problem 3: Some types may have no "natural" order.

- ❑ Solution: Use Comparator interface

- ❑ Example:

```
public class ReverseOrder implements Comparator<String>
{
    public int compare(String a, String b)
    {   return - a.compareTo(b);   }
}
```

 reverse sense of comparison

```
...
Arrays.sort(a, new ReverseOrder());
...
```

Generalized Compare

- Easy modification to support comparators in our sort implementations
 - ◆ pass comparator to `sort()`, `less()`
 - ◆ use it in `less()`
- Example: (insertion sort)

```
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; j--)
            if (less(comparator, a[j], a[j-1]))
                exch(a, j, j-1);
            else break;
}

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 t = a[i]; a[i] = a[j]; a[j] = t; }
```


Generalized Compare

- ❑ Comparators enable multiple sorts of single file (different keys)
- ❑ **Example.** Enable sorting students by name or by section.

```
Arrays.sort(students, Student.BY_NAME);  
Arrays.sort(students, Student.BY_SECT);
```

sort by name



Andrews	3	A	664-480-0023	097 Little
Battle	4	C	874-088-1212	121 Whitman
Chen	2	A	991-878-4944	308 Blair
Fox	1	A	884-232-5341	11 Dickinson
Furia	3	A	766-093-9873	101 Brown
Gazsi	4	B	665-303-0266	22 Brown
Kanaga	3	B	898-122-9643	22 Brown
Rohde	3	A	232-343-5555	343 Forbes

then sort by section



Fox	1	A	884-232-5341	11 Dickinson
Chen	2	A	991-878-4944	308 Blair
Andrews	3	A	664-480-0023	097 Little
Furia	3	A	766-093-9873	101 Brown
Kanaga	3	B	898-122-9643	22 Brown
Rohde	3	A	232-343-5555	343 Forbes
Battle	4	C	874-088-1212	121 Whitman
Gazsi	4	B	665-303-0266	22 Brown

Generalized Compare

- ❑ Comparators enable multiple sorts of single file (different keys)
- ❑ **Example.** Enable sorting students by name or by section.

```
public class Student
{
    public static final Comparator<Student> BY_NAME = new ByName();
    public static final Comparator<Student> BY_SECT = new BySect();

    private String name;
    private int section;
    ...

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

    private static class BySect implements Comparator<Student>
    {
        public int compare(Student a, Student b)
        { return a.section - b.section; }
    }
}
```

only use this trick if no danger of overflow

Generalized Compare problem

□ A typical application

- ◆ first, sort by name
- ◆ then, sort by section

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



Andrews	3	A	664-480-0023	097 Little
Battle	4	C	874-088-1212	121 Whitman
Chen	2	A	991-878-4944	308 Blair
Fox	1	A	884-232-5341	11 Dickinson
Furia	3	A	766-093-9873	101 Brown
Gazsi	4	B	665-303-0266	22 Brown
Kanaga	3	B	898-122-9643	22 Brown
Rohde	3	A	232-343-5555	343 Forbes

```
Arrays.sort(students, Student.BY_SECT);
```



Fox	1	A	884-232-5341	11 Dickinson
Chen	2	A	991-878-4944	308 Blair
Kanaga	3	B	898-122-9643	22 Brown
Andrews	3	A	664-480-0023	097 Little
Furia	3	A	766-093-9873	101 Brown
Rohde	3	A	232-343-5555	343 Forbes
Battle	4	C	874-088-1212	121 Whitman
Gazsi	4	B	665-303-0266	22 Brown

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

□ A **stable** sort preserves the relative order of records with equal keys.
Is the system sort stable?

Stability

□ Q. Which sorts are stable?

- ◆ Selection sort?
- ◆ Insertion sort?
- ◆ Shellsort?
- ◆ Quicksort?
- ◆ Mergesort?

□ A. Careful look at code required.

□ Annoying fact. Many useful sorting algorithms are unstable.

□ Easy solutions.

- ◆ add an **integer rank** to the key
- ◆ careful implementation of mergesort

Open: Stable, inplace, optimal, practical sort??

Java System Sorts

- ❑ **Use theory as a guide:** Java uses both mergesort and quicksort.
 - ◆ Can sort array of type Comparable or any primitive type.
 - ◆ Uses **quicksort** for **primitive types**.
 - ◆ Uses **mergesort** for **objects**.

```
import java.util.Arrays;
public class IntegerSort
{
    public static void main(String[] args)
    {
        int N = Integer.parseInt(args[0]);
        int[] a = new int[N];
        for (int i = 0; i < N; i++)
            a[i] = StdIn.readInt();
        Arrays.sort(a);
        for (int i = 0; i < N; i++)
            System.out.println(a[i]);
    }
}
```

Q. Why use two different sorts?

A. Use of primitive types indicates time and space are critical

A. Use of objects indicates time and space not so critical

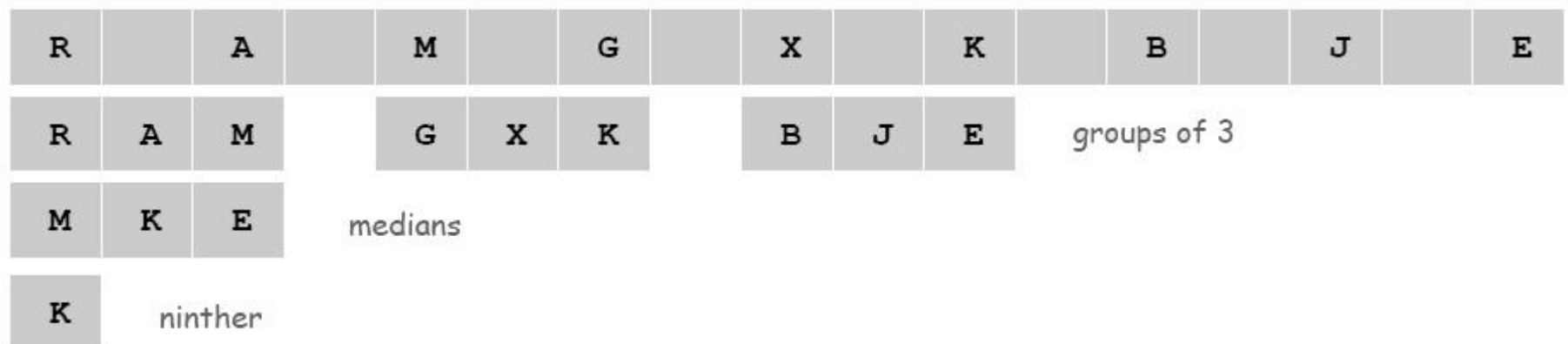
Arrays.sort() for Primitive Types

□ Bentley-McIlroy. [Engineering a Sort Function]

- ◆ Original motivation: improve qsort() function in C.
- ◆ Basic algorithm = 3-way quicksort with cutoff to insertion sort.
- ◆ Partition on Tukey's ninther: median-of-3 elements, each of which is a median-of-3 elements.

← approximate median-of-9

nine evenly spaced elements



□ Why use ninther?

- ◆ better partitioning than sampling
- ◆ quick and easy to implement with macros
- ◆ less costly than random ← Good idea? Stay tuned.

Achilles Heel in Bentley-McIlroy Implementation (Java System Sort)

- ❑ Based on all this research, Java's system sort is solid, **right**?
- ❑ **McIlroy's devious idea.** [A Killer Adversary for Quicksort]
 - ◆ Construct malicious input **while** running system quicksort, in response to elements compared.
 - ◆ If p is pivot, commit to $(x < p)$ and $(y < p)$, but don't commit to $(x < y)$ or $(x > y)$ until x and y are compared.
- ❑ **Consequences.**
 - ◆ Confirms theoretical possibility.
 - ◆ Algorithmic complexity attack: you enter linear amount of data; server performs quadratic amount of work.

Achilles Heel in Bentley-McIlroy Implementation (Java System Sort)

□ A killer input:

- ◆ blows function call stack in Java and crashes program
- ◆ would take quadratic time if it didn't crash first

more disastrous possibilities in C



```
% more 250000.txt
0
218750
222662
11
166672
247070
83339
156253
...
```

250,000 integers between
0 and 250,000

```
% java IntegerSort < 250000.txt
Exception in thread "main" java.lang.StackOverflowError
  at java.util.Arrays.sort1 (Arrays.java:562)
  at java.util.Arrays.sort1 (Arrays.java:606)
  at java.util.Arrays.sort1 (Arrays.java:608)
  at java.util.Arrays.sort1 (Arrays.java:608)
  at java.util.Arrays.sort1 (Arrays.java:608)
  . . .
```

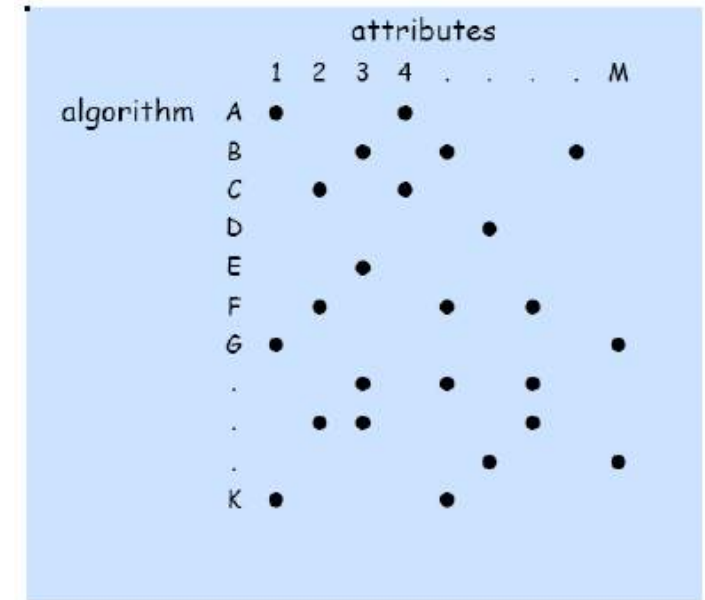
Java's sorting library crashes, even if
you give it as much stack space as Windows allows.

Attack is **not** effective if file is randomly ordered before sort

System Sort: Which Algorithm to Use?

□ Applications have diverse attributes

- ◆ Stable?
- ◆ Multiple keys?
- ◆ Deterministic?
- ◆ Keys all distinct?
- ◆ Multiple key types?
- ◆ Linked list or arrays?
- ◆ Large or small records?
- ◆ Is your file randomly ordered?
- ◆ Need guaranteed performance?



many more combinations of attributes than algorithms

□ Elementary sort may be method of choice for some combination. Cannot cover all combinations of attributes.

Q. Is the system sort good enough?

A. Maybe (no matter which algorithm it uses).