

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

4.2 ALGORITHMS

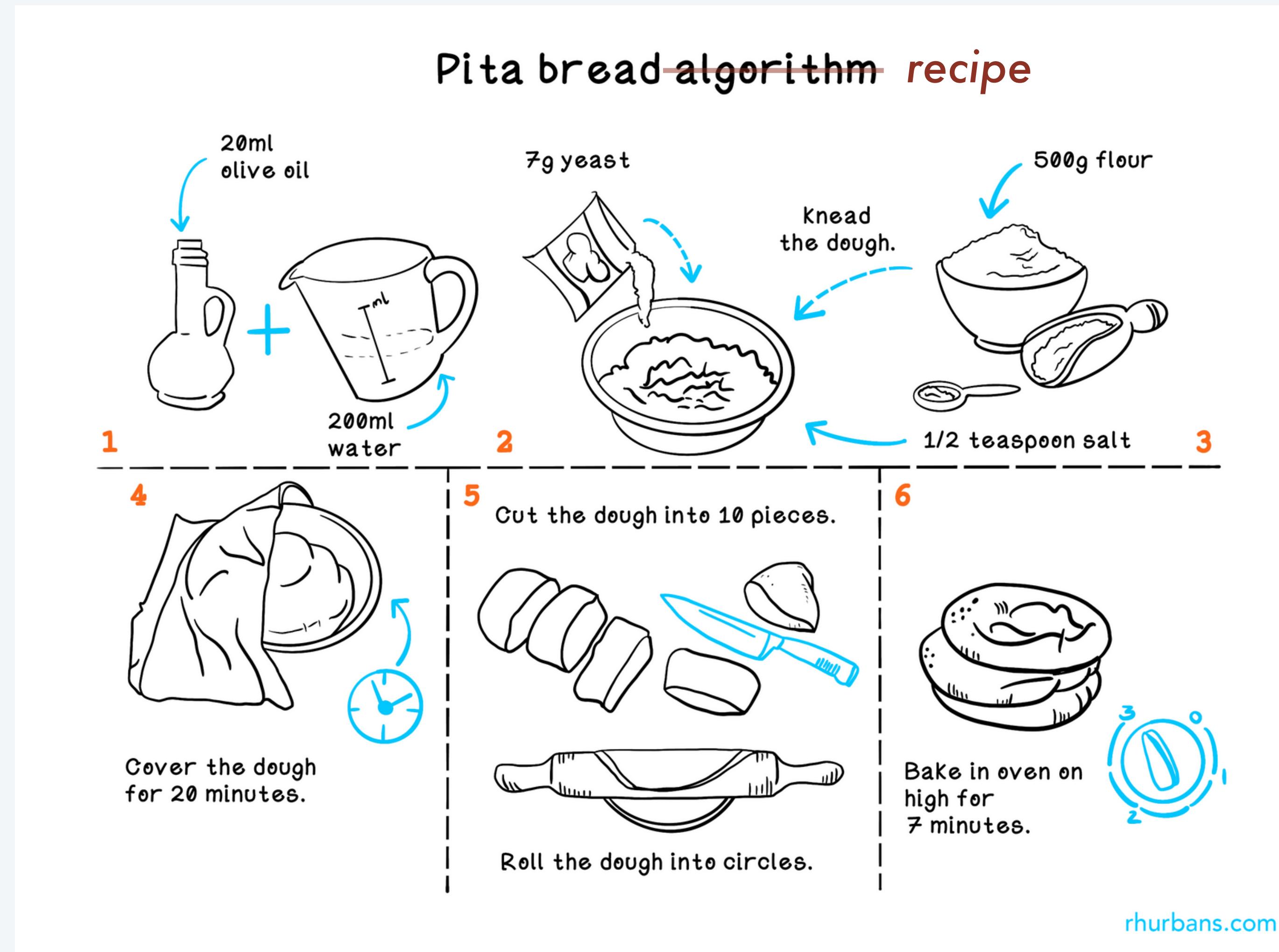
- ▶ *sequential search*
- ▶ *binary search*
- ▶ *insertion sort*
- ▶ *mergesort*



Algorithms



Intuition. An **algorithm** is like a recipe. ← *but unambiguous and mechanically executable*



Algorithms

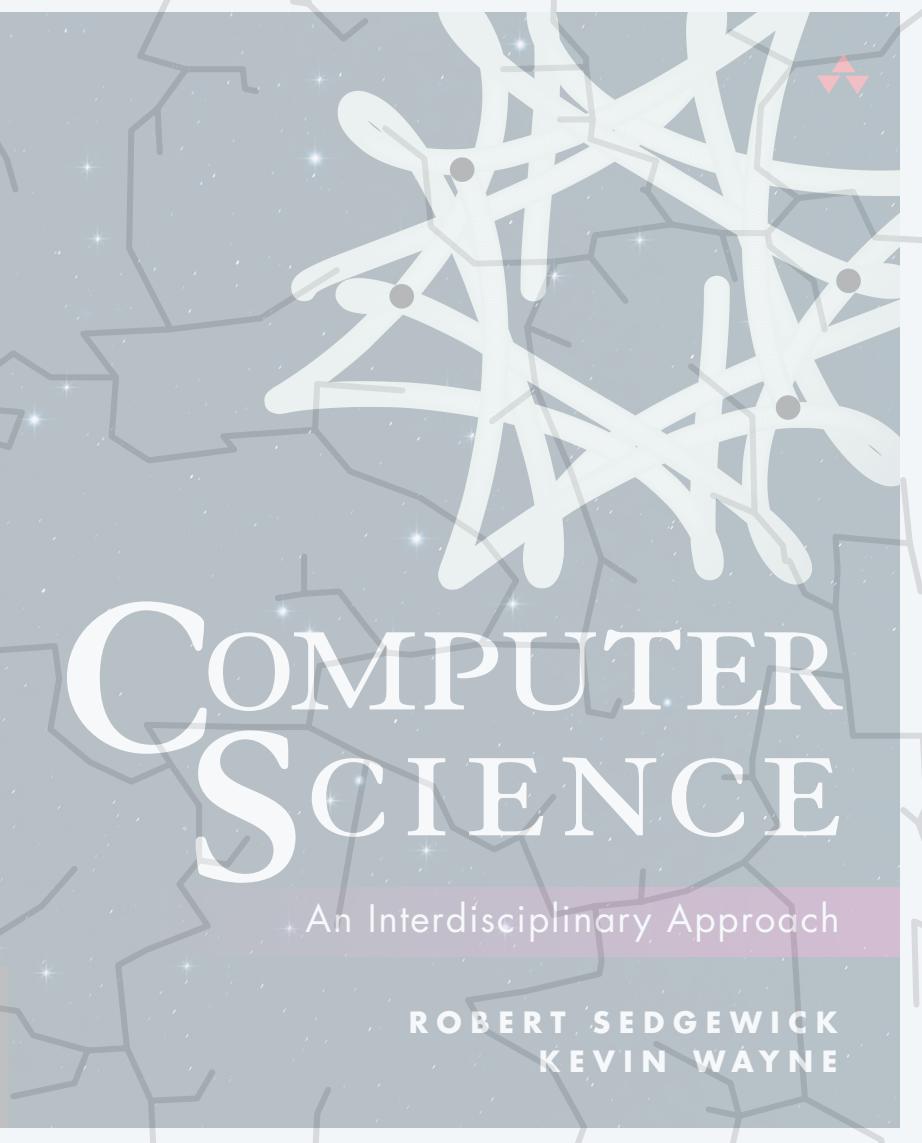


Algorithm. Step-by-step procedure for solving a problem.

- Takes input; produces output.
- Unambiguous and mechanically executable (e.g., in Java).

*formalized by
Turing machines
(stay tuned)*

category	famous algorithms
historic	<i>Euclid's gcd algorithm, gradient descent, Newton's method</i>
sorting and searching	<i>binary search, insertion sort, mergesort</i> ← <i>this lecture</i>
graphs	<i>DFS, BFS, Dijkstra, Kruskal, Ford–Fulkerson</i>
linear algebra	<i>Gaussian elimination, simplex method, QR method, PageRank</i>
scientific computing	<i>Smith–Waterman, Metropolis–Hastings, k-means, FFT</i>
machine learning	<i>A*-search, neural network, transformer, AlphaFold</i>



4.2 ALGORITHMS

- ▶ ***sequential search***
- ▶ ***binary search***
- ▶ ***insertion sort***
- ▶ ***mergesort***

Sequential search

Problem. Given an **array** of n elements and a **search key**, find index of search key in array.

Sequential search. Check each element in array until match is found.



```
public static int sequentialSearch(String[] a, String key) {  
    int n = a.length;  
    for (int i = 0; i < n; i++) {  
        if (a[i].equals(key)) return i;  
    }  
    return -1;  ← return -1 to indicate  
               key is not in array  
}
```

for now, we'll assume
String keys



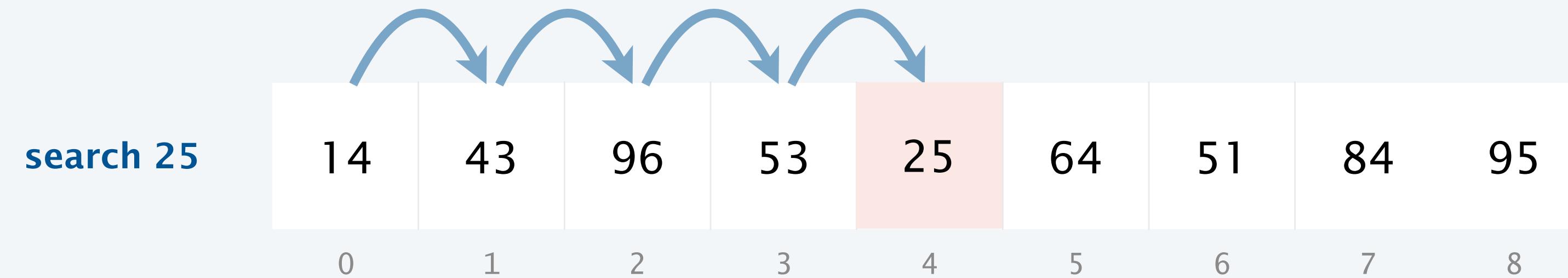
In the worst case, how many equality tests (or array accesses) does sequential search make to search for a key in an array of length n ?

- A.** $\Theta(1)$
- B.** $\Theta(\log n)$
- C.** $\Theta(n)$
- D.** $\Theta(n^2)$

Sequential search

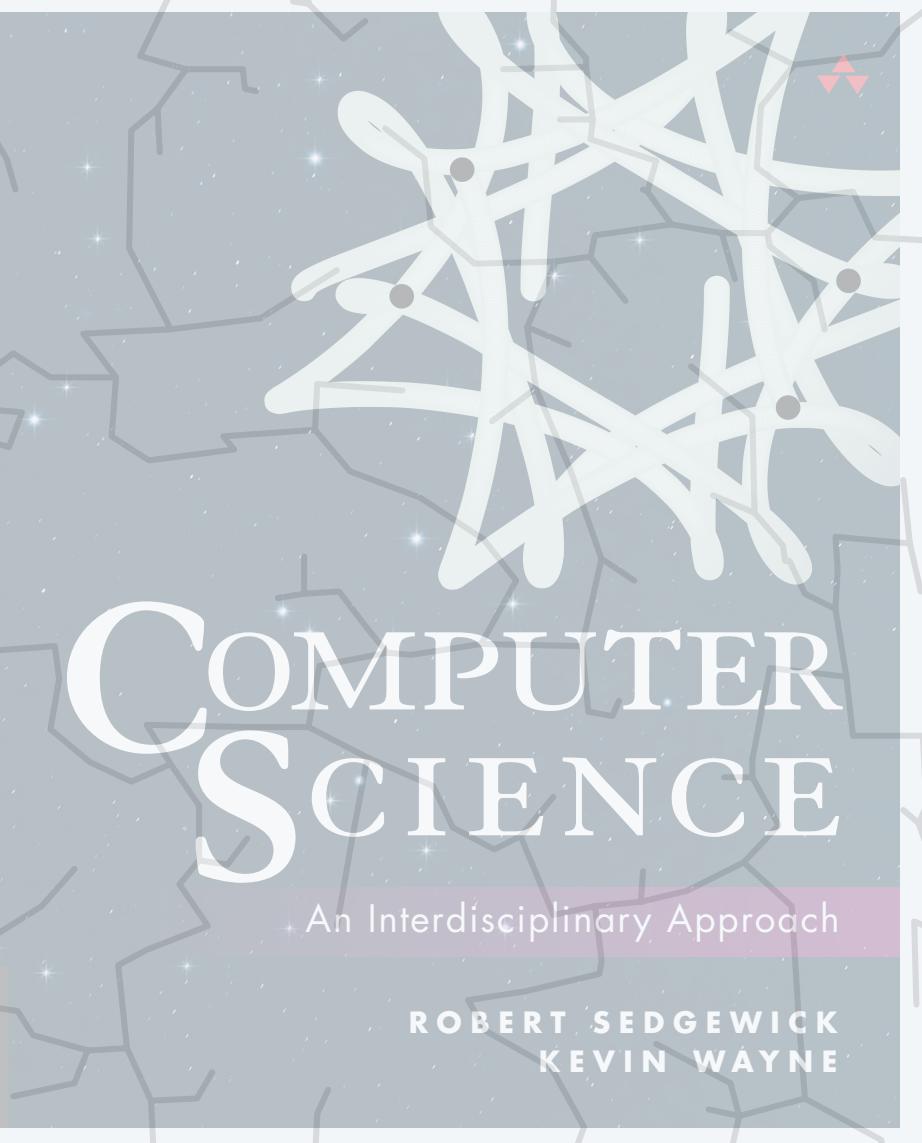
Problem. Given an array of n elements and a search key, find index of search key in array.

Sequential search (linear search). Check each element in array until match is found.



Cost model. Equality tests (or array accesses).

Performance. Sequential search solves the problem using $\leq n$ equality tests.



4.2 ALGORITHMS

- ▶ *sequential search*
- ▶ **binary search**
- ▶ *insertion sort*
- ▶ *mergesort*



Problem. Given a **sorted array** of n elements and a **search key**, find index of search key in array.

Binary search. Compare search key with middle element.

- Too small, go left.
- Too big, go right.
- Equal, found.

sorted array

10	13	14	25	33	43	51	53	64	72	84	93	95	96	97
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
↑														↑

lo

hi

Binary search demo

Problem. Given a sorted array and a search key, find index of the search key in the array.

Binary search. Compare search key with middle entry.

- Too small, go left.
- Too big, go right.
- Equal, found.

sorted array

10	13	14	25	33	43	51	53	64	72	84	93	95	96	97
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14

lo  *hi* 

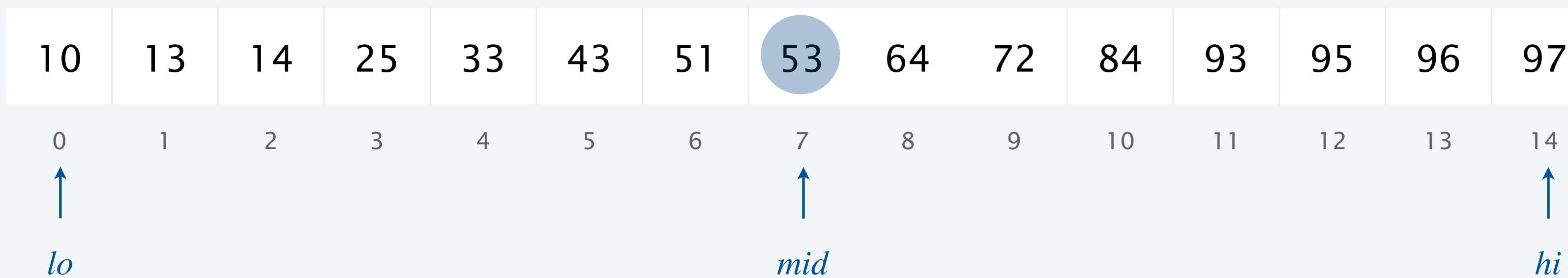
Binary search demo

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successful search for 33



Binary search demo

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Binary search demo

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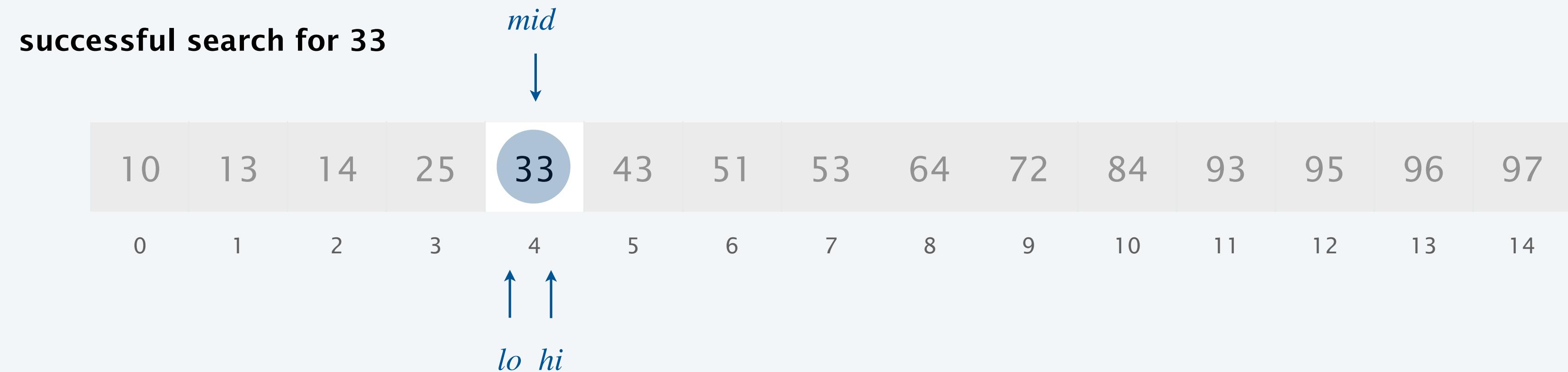


Binary search demo

Problem. Given a sorted array and a search key, find index of the search key in the array.

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- Equal, found.



return 4

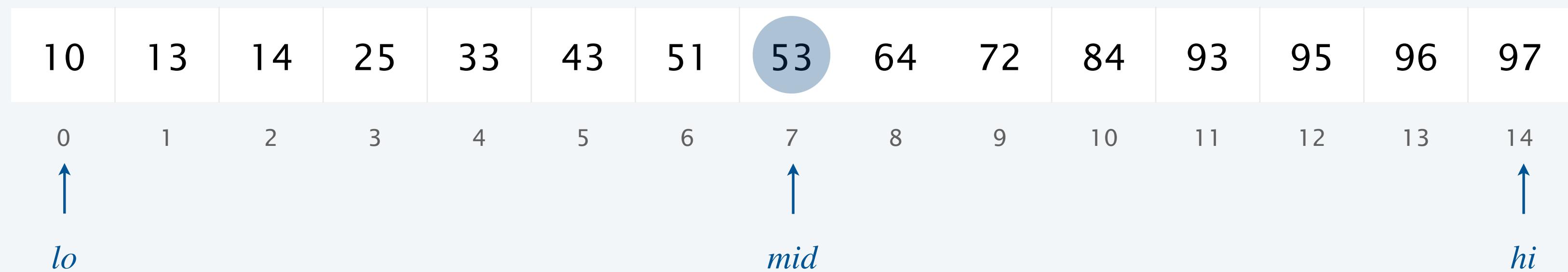
Binary search demo

Problem. Given a sorted array and a search key, find index of the search key in the array.

Binary search. Compare search key with middle entry.

- Too small, go left.
- Too big, go right.
- Equal, found.

unsuccessful search for 90



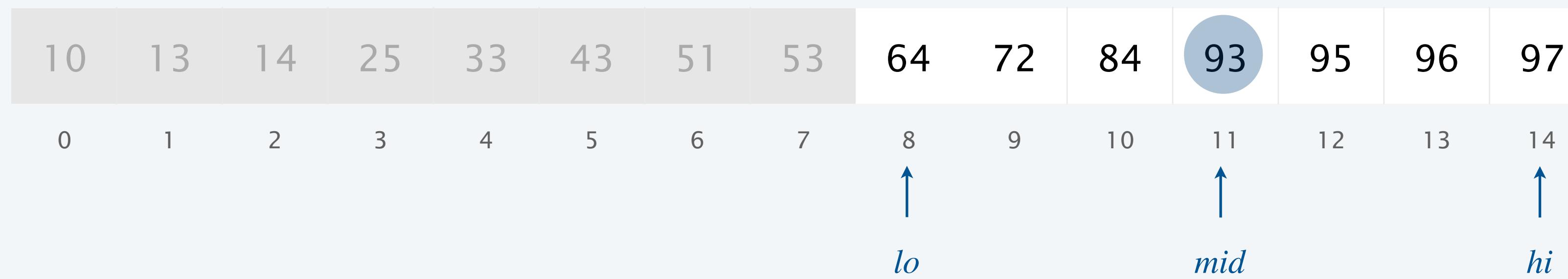
Binary search demo

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unsuccessful search for 90



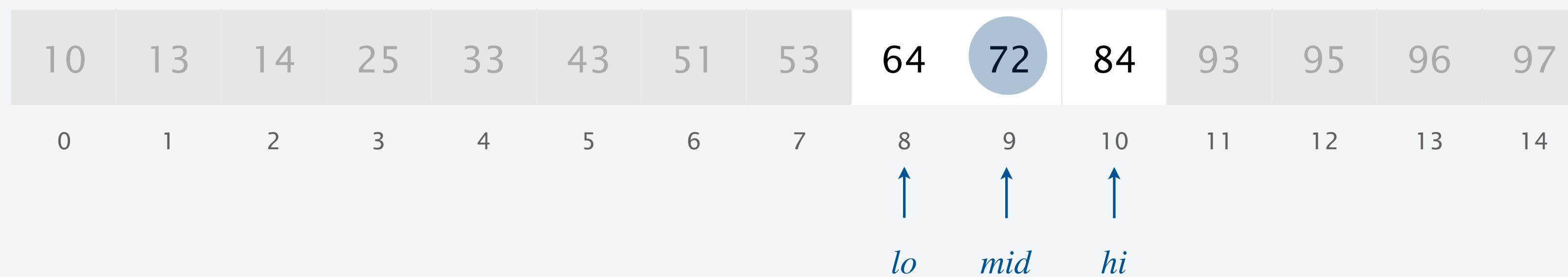
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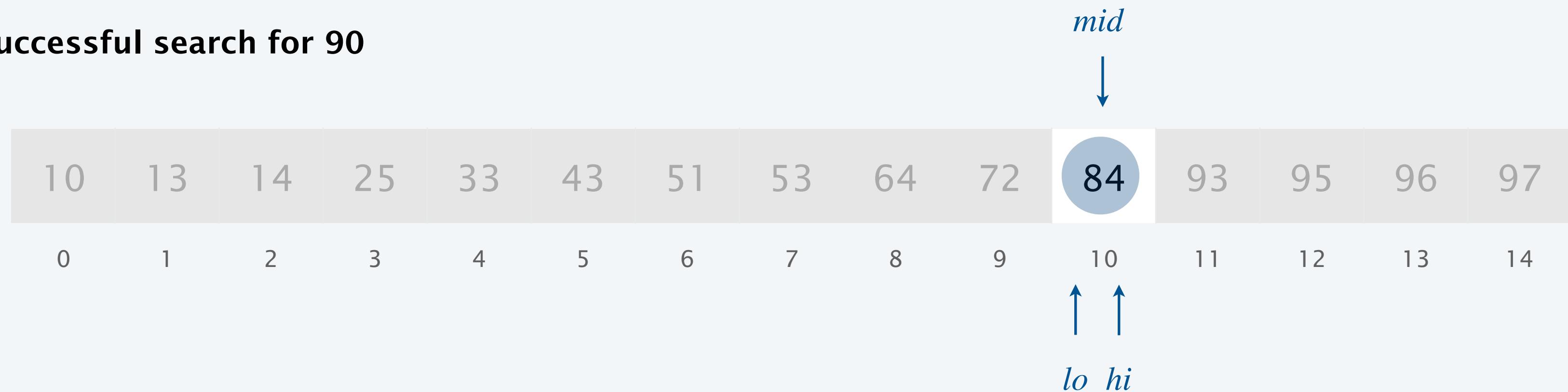
Binary search demo

Problem. Given a sorted array and a search key, find index of the search key in the array.

Binary search. Compare search key with middle entry.

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unsuccessful search for 90



return -1

Binary search: Java implementation

Invariant. If key appears in array $a[]$, then $a[lo] \leq \text{key} \leq a[hi]$.

```
public static int binarySearch(String[] a, String key) {  
    int lo = 0, hi = a.length - 1;  
    while (lo <= hi) {  
        int mid = lo + (hi - lo) / 2; ←  
        int compare = key.compareTo(a[mid]); ←  
        if (compare < 0) hi = mid - 1;  
        else if (compare > 0) lo = mid + 1;  
        else return mid;  
    }  
    return -1;  
}
```

*essentially equivalent to
 $mid = (lo + hi) / 2$
(but avoids arithmetic overflow)*

*return zero (if equal),
negative integer (if less),
positive integer (if greater)*



In the worst case, how many compares (or array accesses) does binary search make to search for a key in a sorted array of length n ?

- A.** $\Theta(1)$
- B.** $\Theta(\log n)$
- C.** $\Theta(n)$
- D.** $\Theta(n^2)$

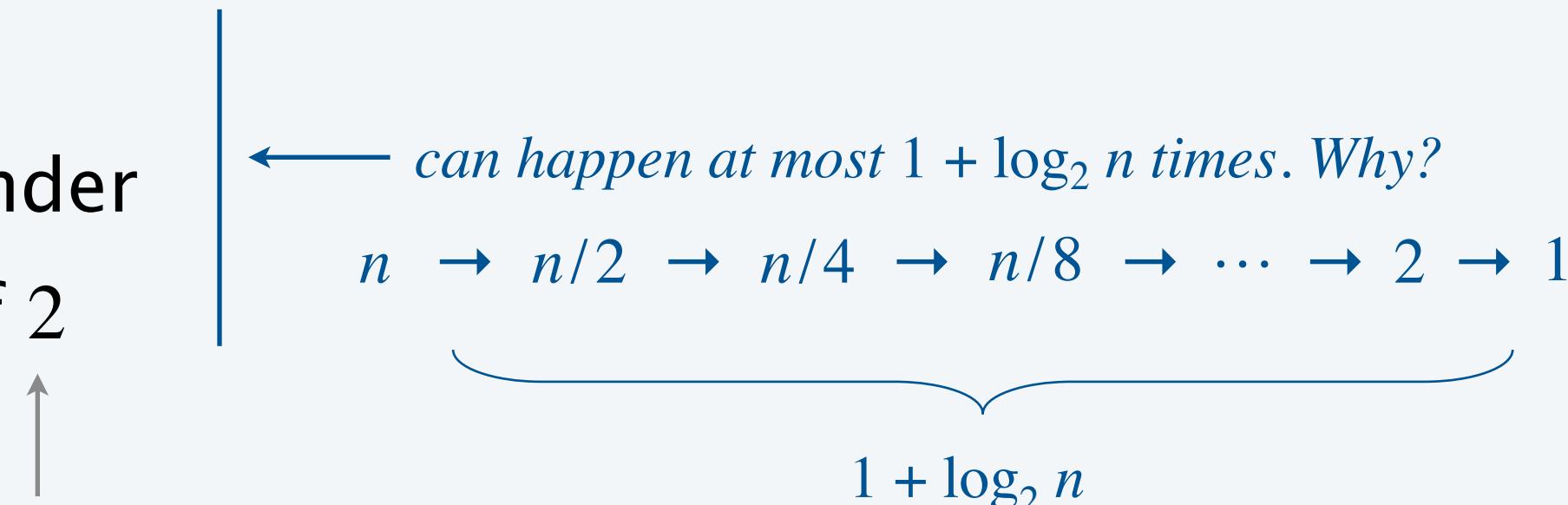
Binary search: analysis

Problem. Given a **sorted array** of n elements and a **search key**, find index of search key in array.

Proposition. Binary search solves problem using $\leq 1 + \log_2 n$ compares.

Pf.

- Each iteration of `while` loop:
 - calls `compareTo()` once
 - decreases the length of subarray under consideration by at least a factor of 2



*slightly better than 2x,
due to elimination of `a[mid]` from subarray
(or early termination of `while` loop)*

Sequential search vs. binary search: empirical analysis

Running time and energy estimates (approximate):

- CPU core executes 10^8 compares/second.
- CPU core consumes 18 watts power.

Resources required. [on array of length $n = 10^9$]

queries/hour	CPU cores	power
thousand	2.78	50 watts
million	2.78 thousand	50 kilowatts
billion	2.78 million	50 megawatts

sequential search $\Theta(n)$

queries/hour	CPU cores	power
million	—	—
billion	0.083	1.5 watts
trillion	83	1.5 kilowatts

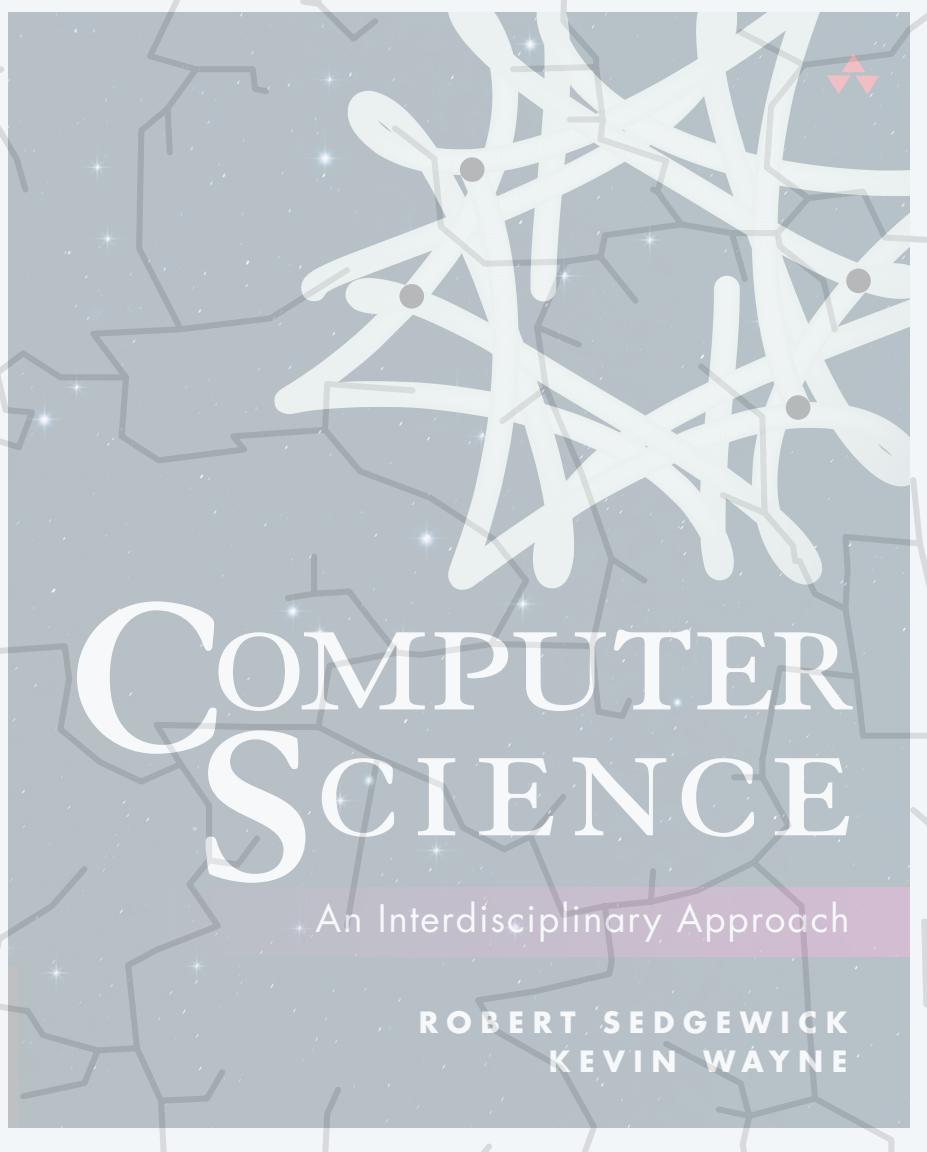
binary search $\Theta(\log n)$

Bottom line. Great algorithms can replace server farms. ←

500K ChatGPT
queries per hour
(≈ 1 gigawatt)



about 33M times more efficient
(10^9 vs. $\log_2 10^9$) ←



4.2 ALGORITHMS

- ▶ *sequential search*
- ▶ *binary search*
- ▶ ***insertion sort***
- ▶ *mergesort*

Sorting problem

Problem. Given an array of n elements, rearrange in ascending order by key.

element →

Last	First	House	Year
Longbottom	Neville	Gryffindor	1998
Weasley	Ron	Gryffindor	1998
Abbott	Hannah	Hufflepuff	1998
Potter	Harry	Gryffindor	1998
Chang	Cho	Ravenclaw	1997
Granger	Hermione	Gryffindor	1998
Malfoy	Draco	Slytherin	1998
Diggory	Cedric	Hufflepuff	1996
Weasley	Ginny	Gryffindor	1999
Parkinson	Pansy	Slytherin	1998

key →



sorting hat

Sorting problem

Problem. Given an array of n elements, rearrange in ascending order by key.

Last	First	House	Year
Abbott	Hannah	Hufflepuff	1998
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Parkinson	Pansy	Slytherin	1998
Potter	Harry	Gryffindor	1998
Weasley	Ron	Gryffindor	1998
Weasley	Ginny	Gryffindor	1999

key →

element →

sorted by key



sorting hat

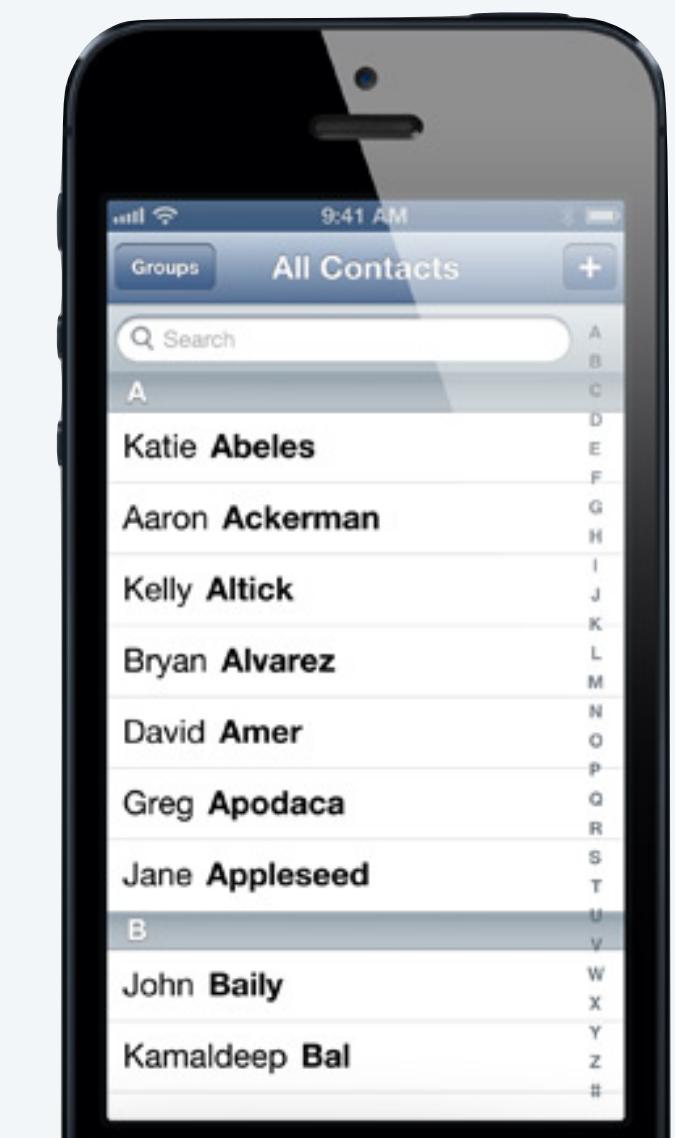
Sorting applications

International Departures				
Flight No	Destination	Time	Gate	Remarks
CX7183	Berlin	7:50	A-11	Gate closing
QF3474	London	7:50	A-12	Gate closing
BA372	Paris	7:55	B-10	Boarding
AY6554	New York	8:00	C-33	Boarding
KL3160	San Francisco	8:00	F-15	Boarding
BA8903	Manchester	8:05	B-12	Gate lounge open
BA710	Los Angeles	8:10	C-12	Check-in open
QF3371	Hong Kong	8:15	F-10	Check-in open
MA4866	Barcelona	8:15	F-12	Check-in at kiosks
CX7221	Copenhagen	8:20	G-32	Check-in at kiosks

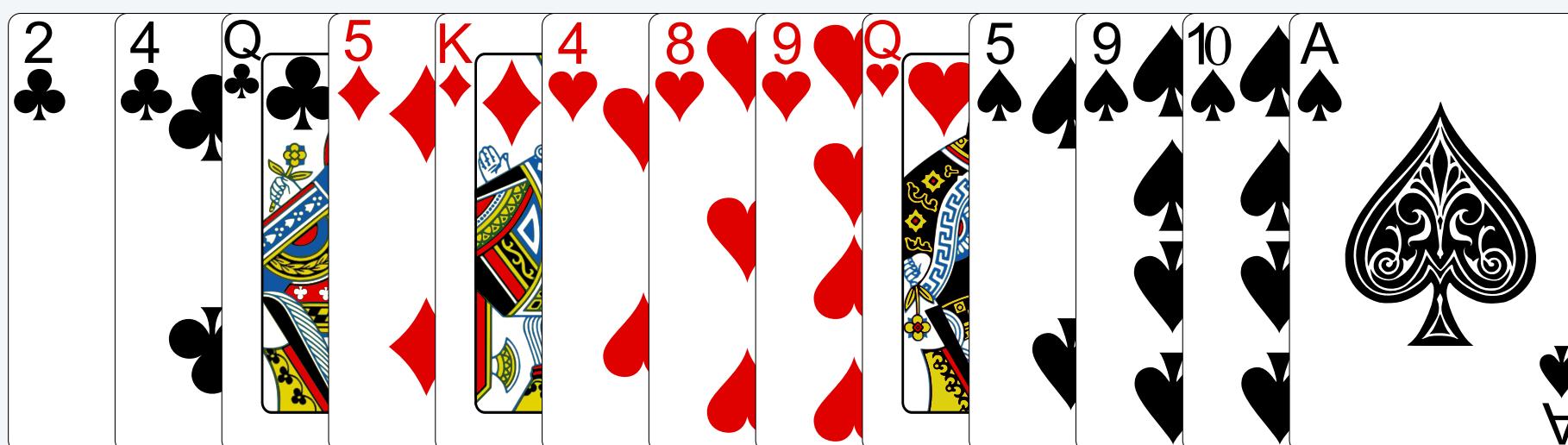
chronological order

No. ↴	Video name	Views (billions) ▼
1.	"Baby Shark Dance" ^[3]	10.15
2.	"Despacito" ^[6]	7.73
3.	"Johny Johny Yes Papa" ^[12]	6.15
4.	"Shape of You" ^[13]	5.61
5.	"See You Again" ^[15]	5.41

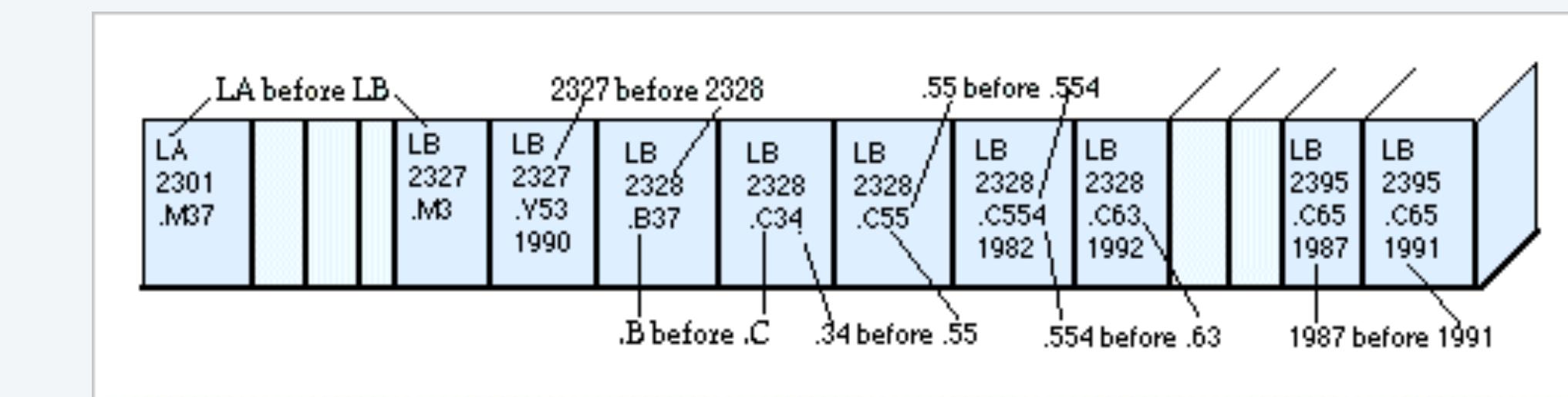
numerical order (descending)



alphabetical order



suit and rank order

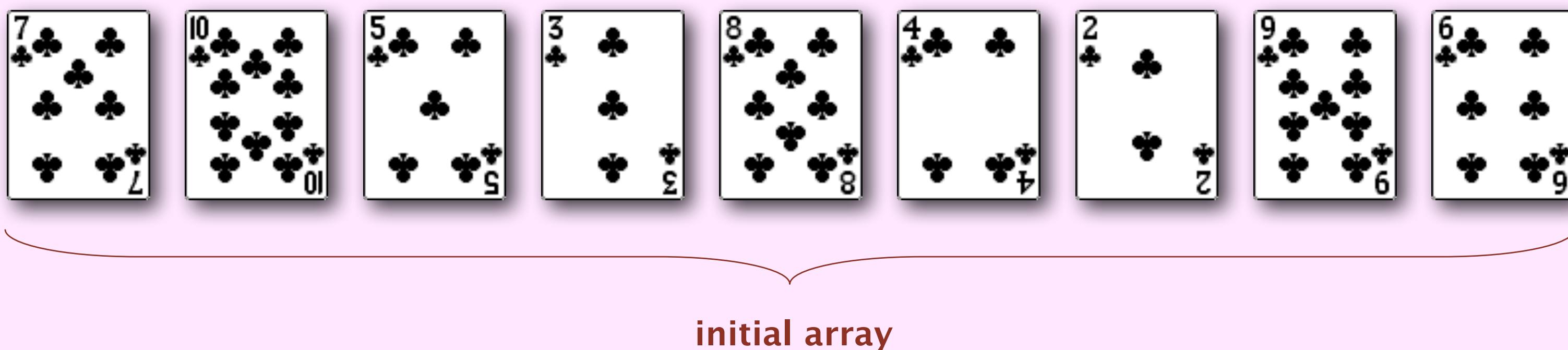


Library of Congress order



Algorithm. For each index $i = 0$ to $n - 1$:

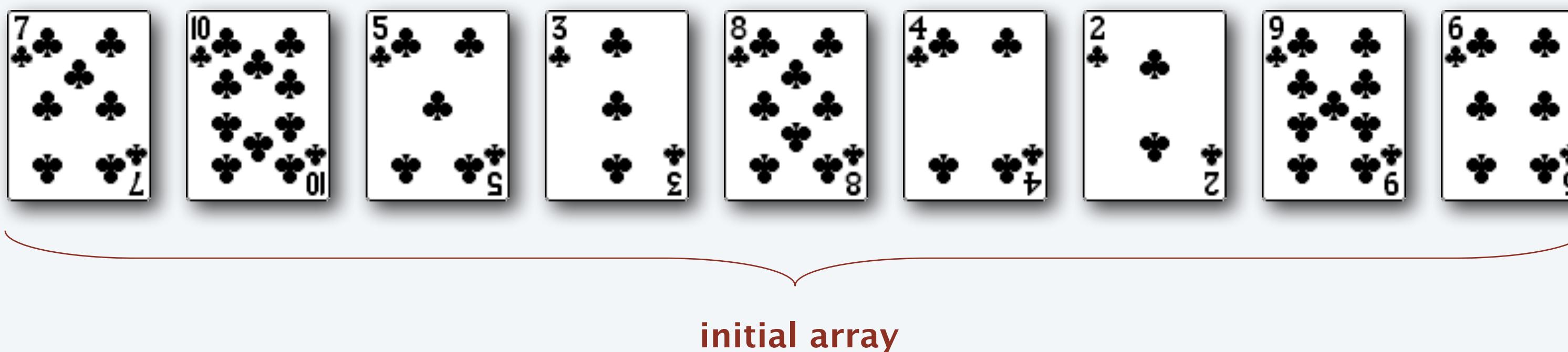
- Let x be the element at index i .
- Repeatedly exchange x with each larger element to its immediate left.



Insertion sort demo

Algorithm. For each index $i = 0$ to $n - 1$:

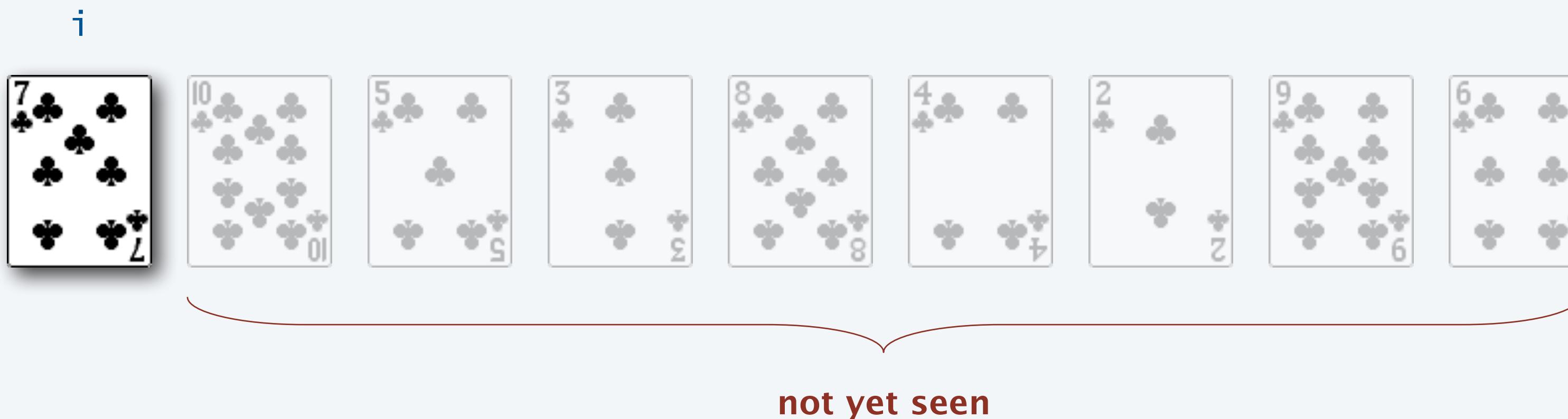
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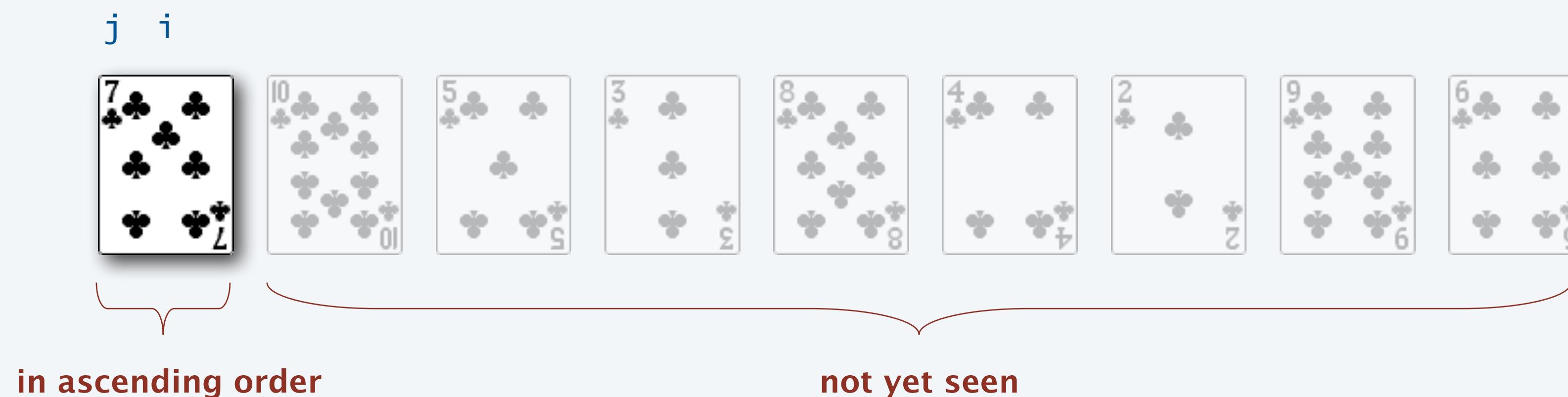
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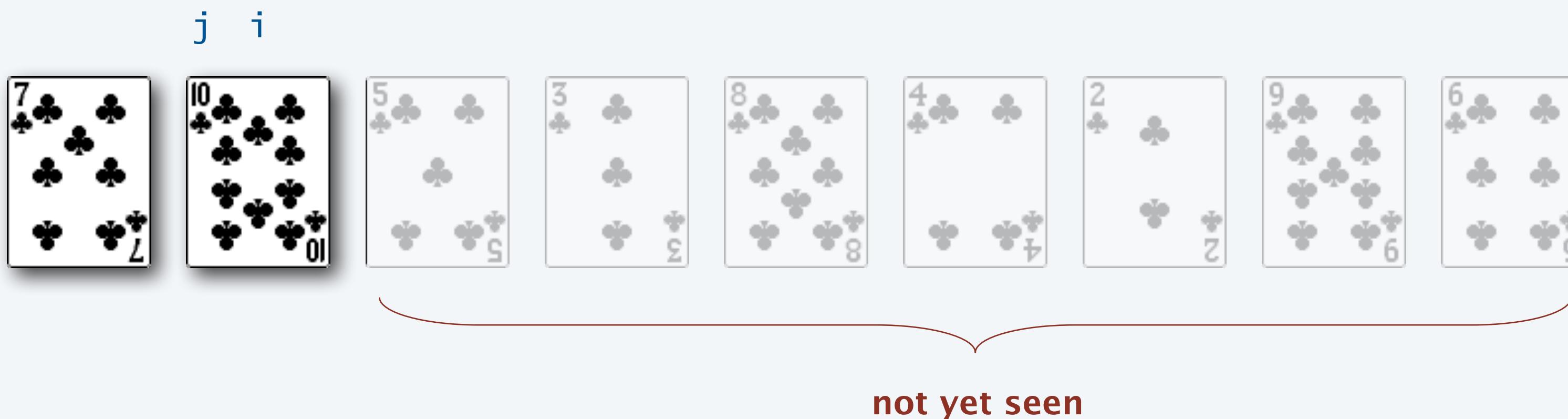
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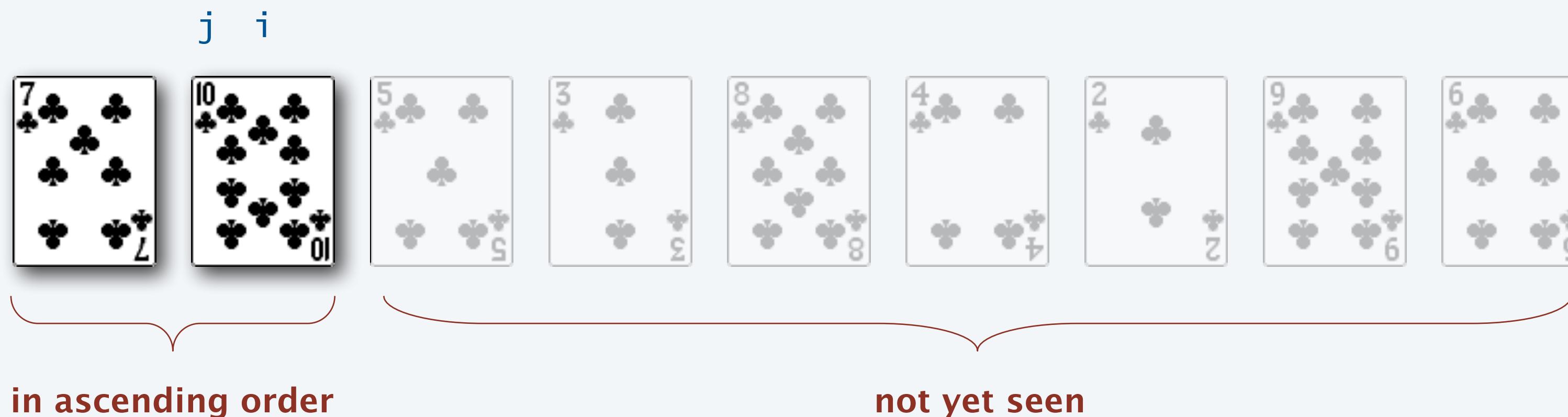
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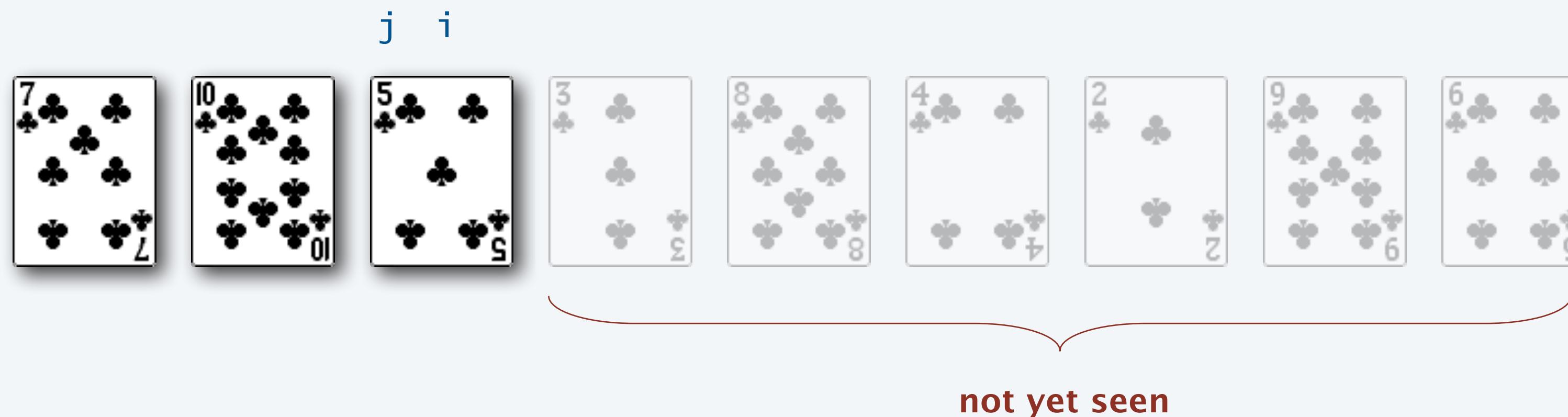
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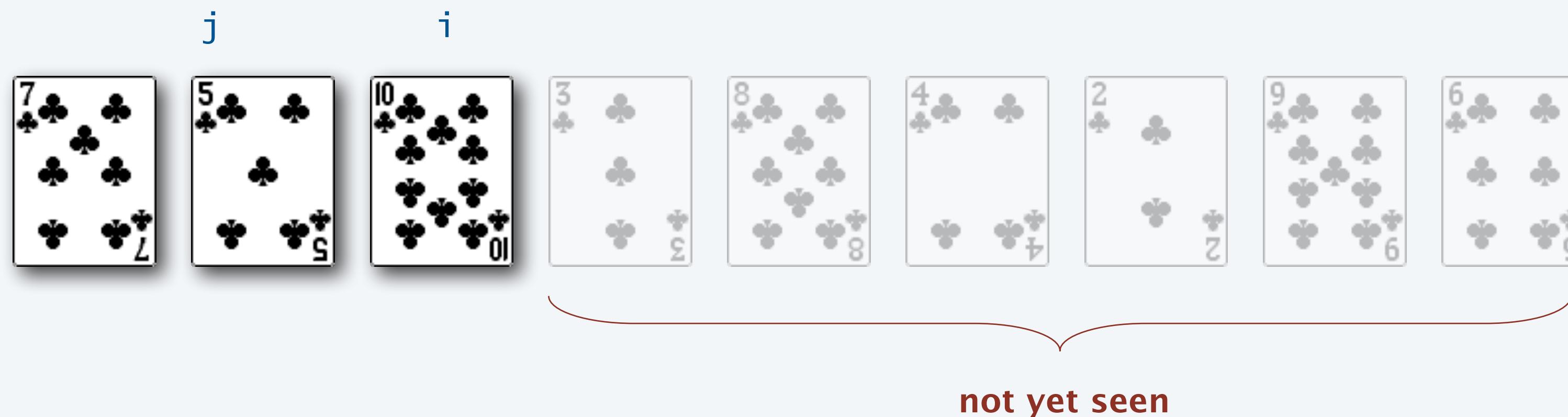
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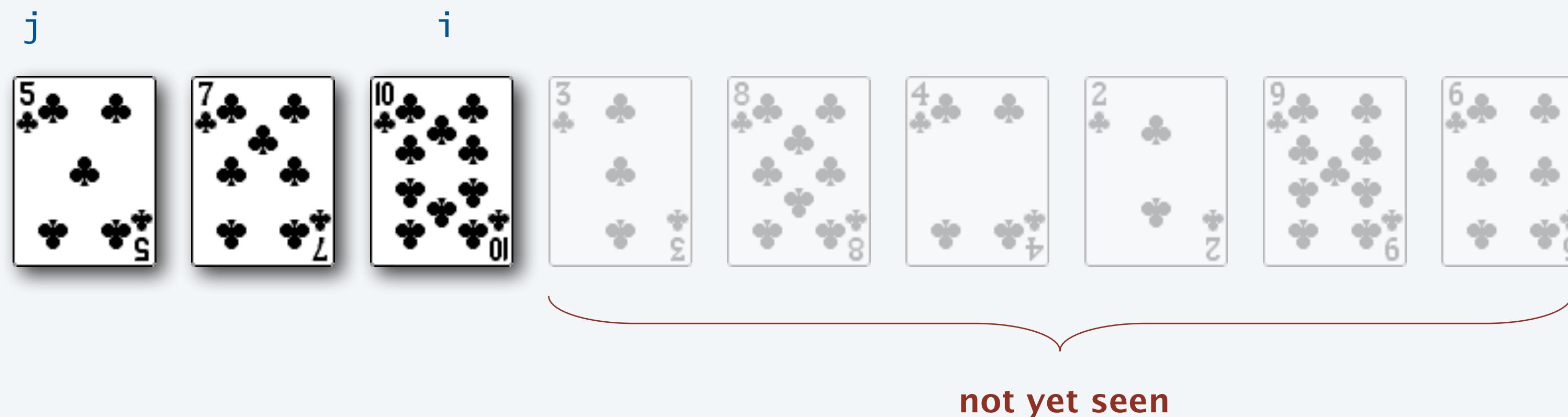
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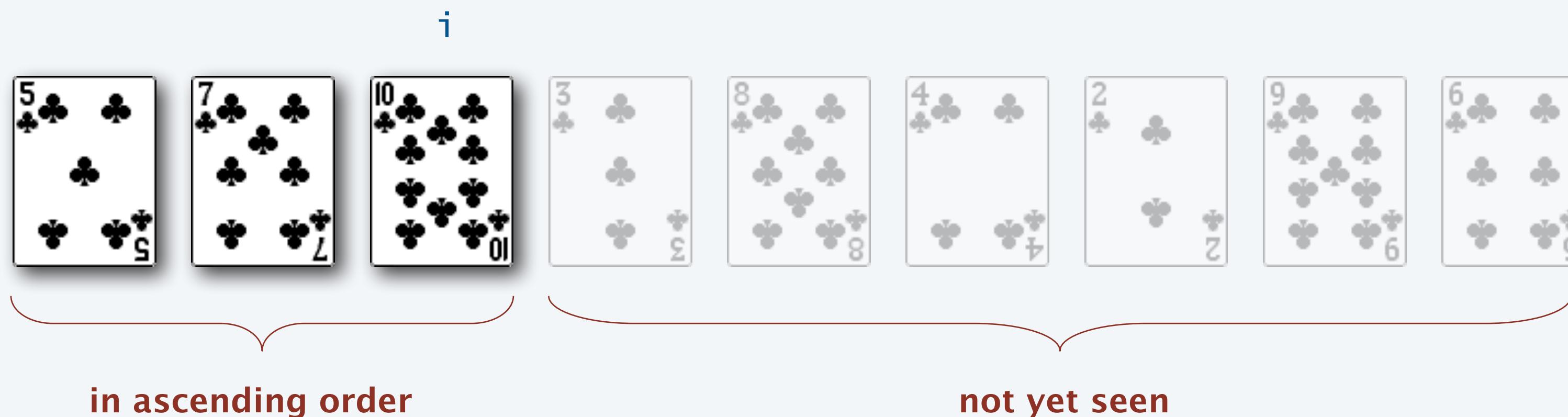
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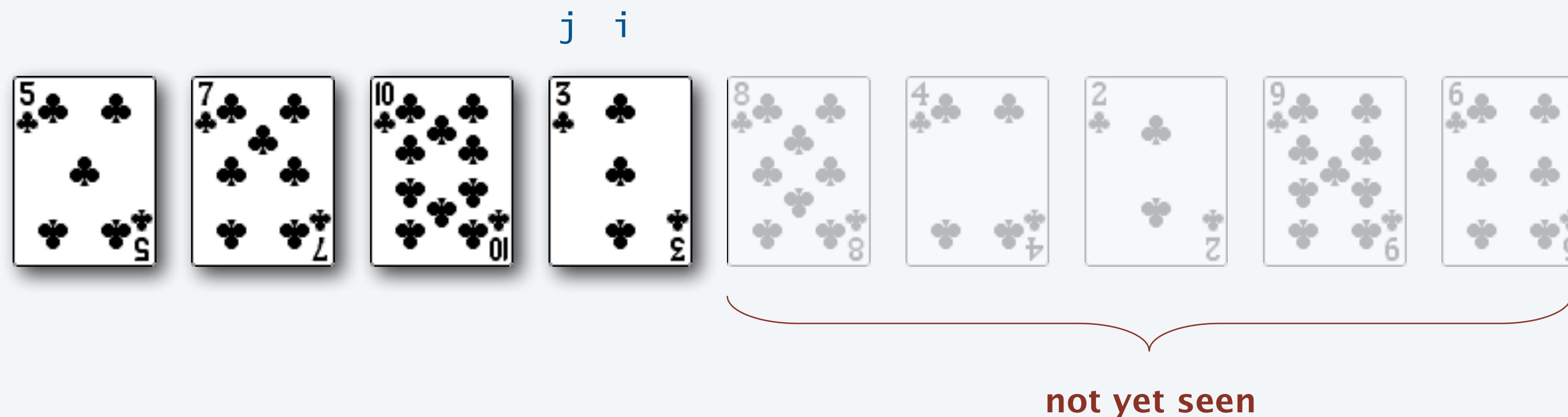
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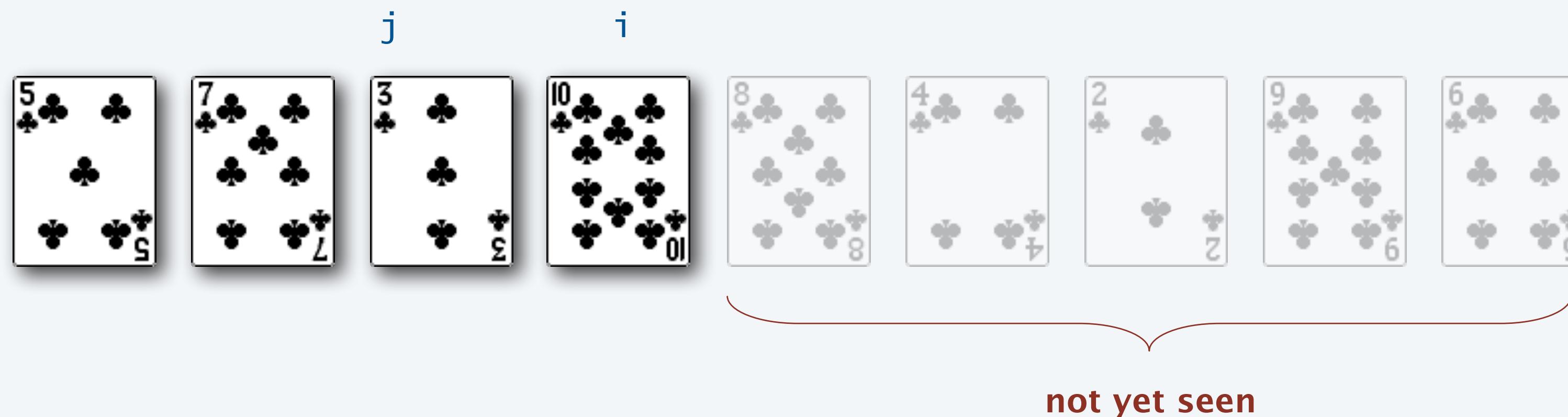
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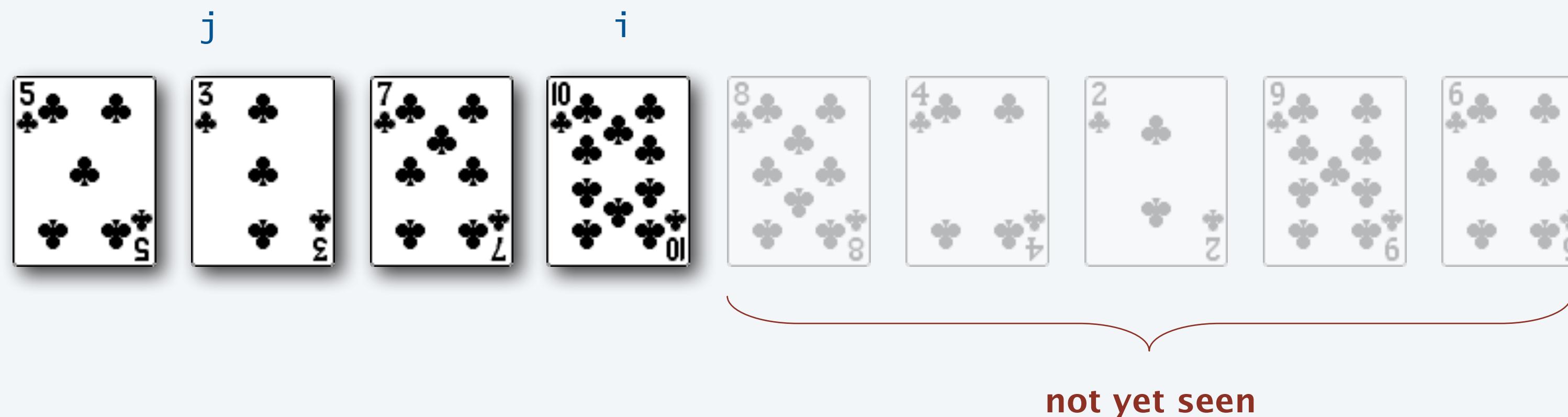
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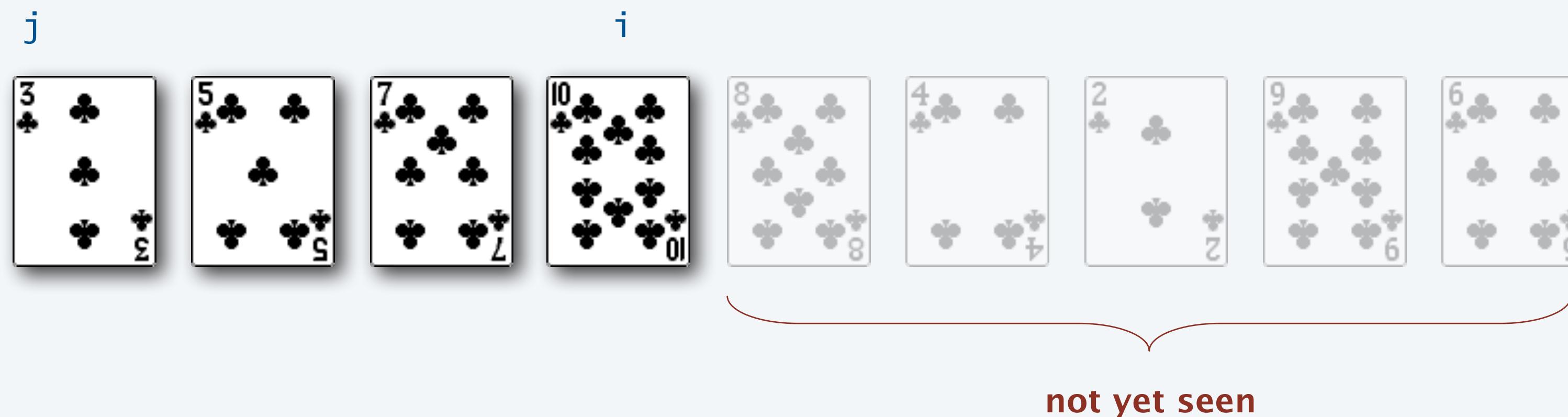
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Insertion sort demo

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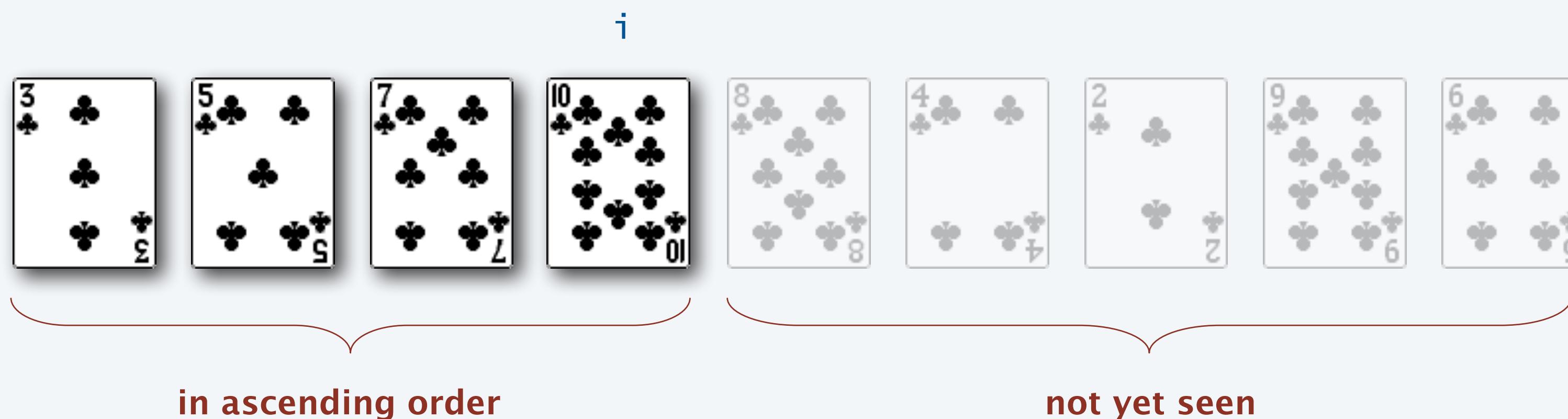
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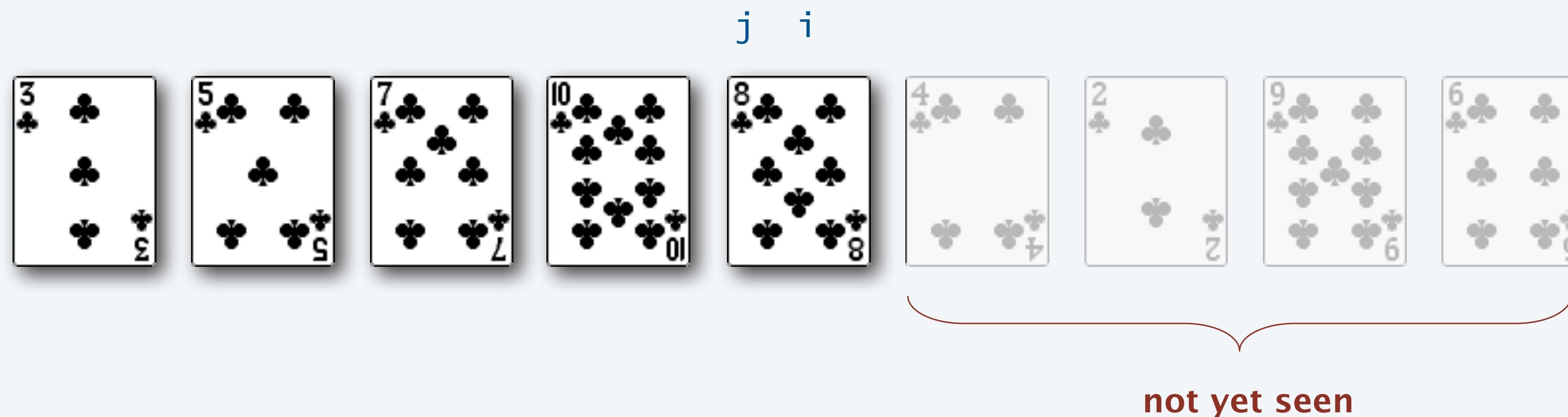
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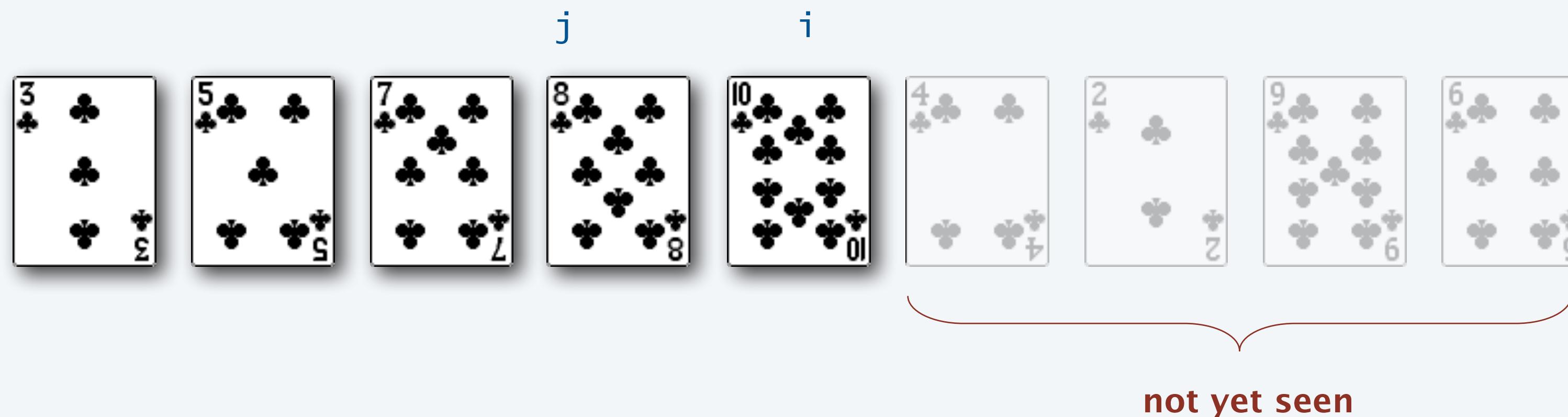
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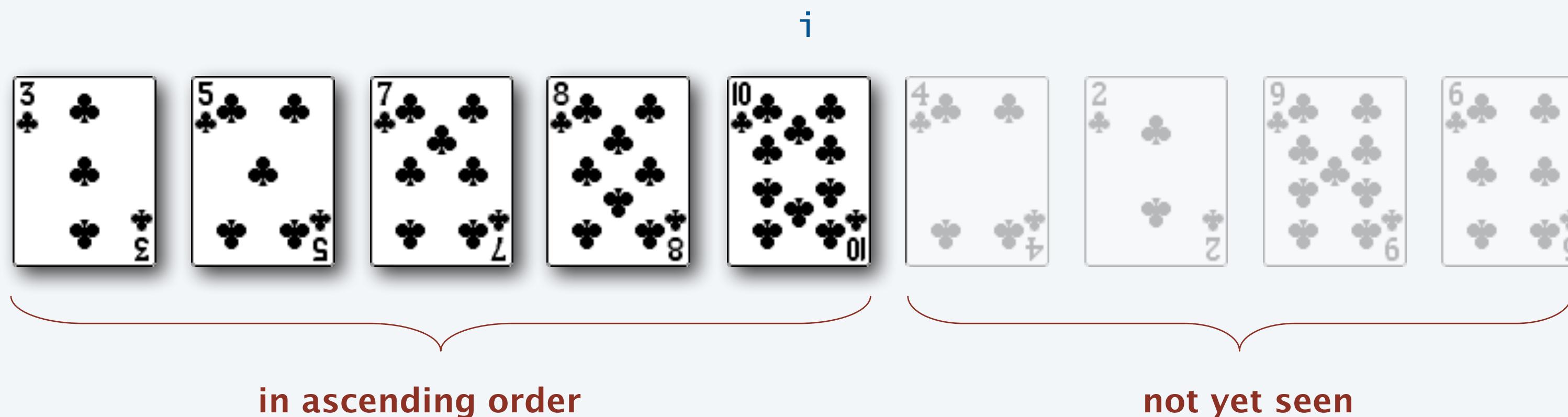
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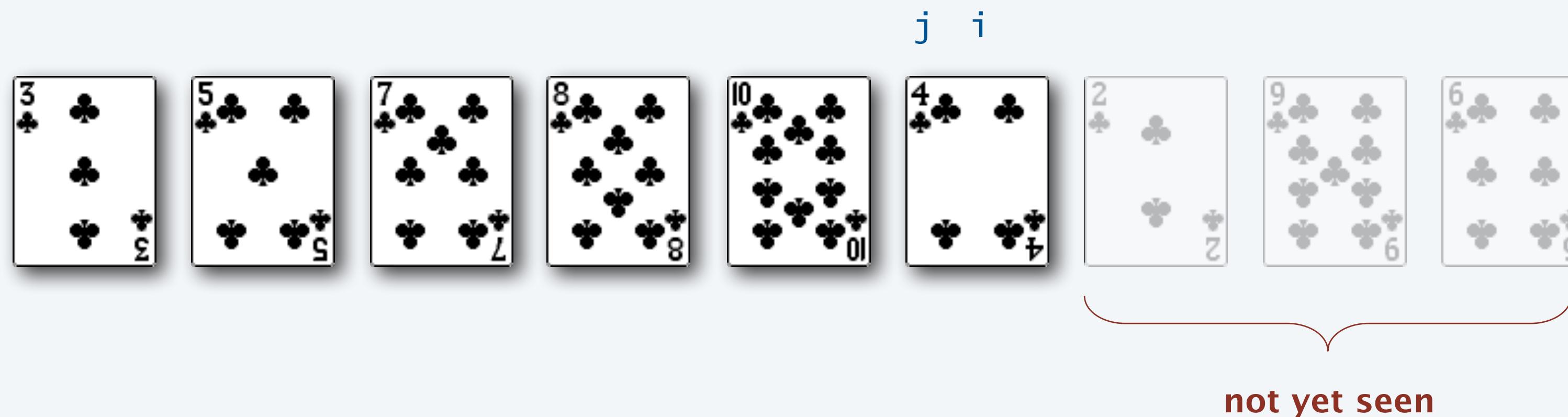
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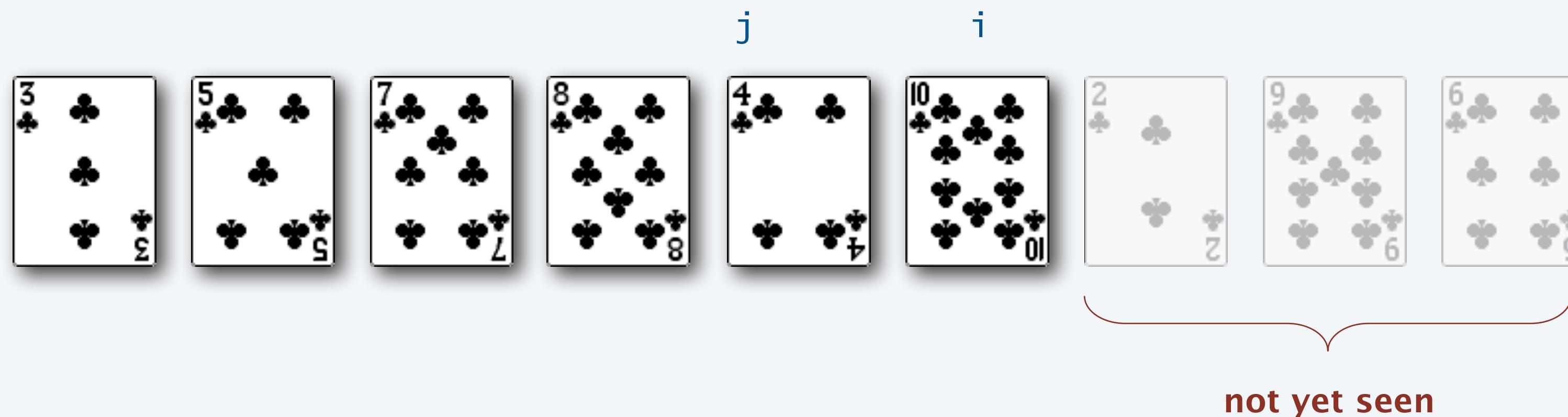
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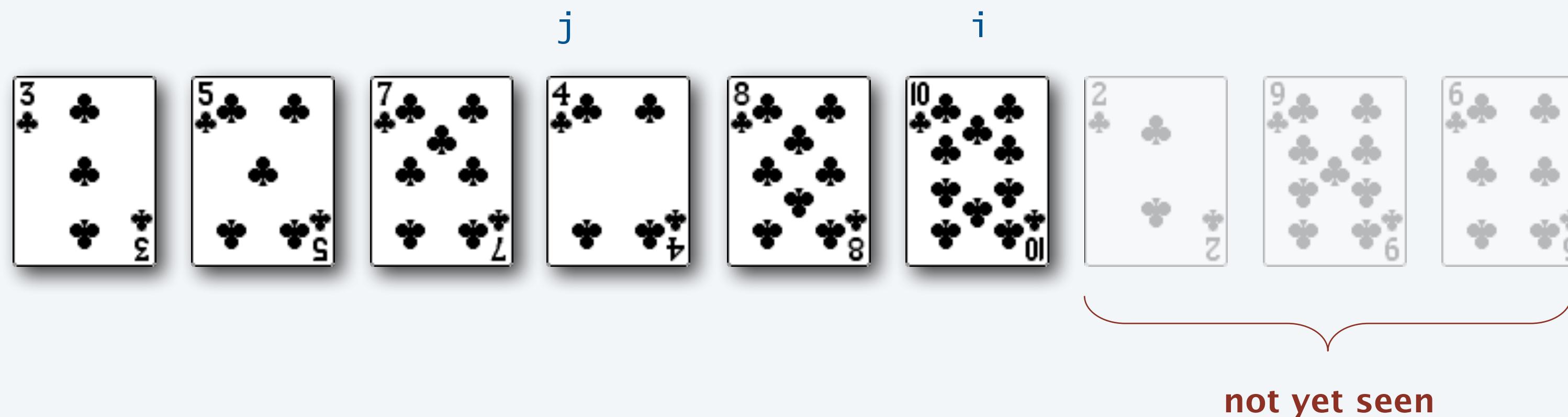
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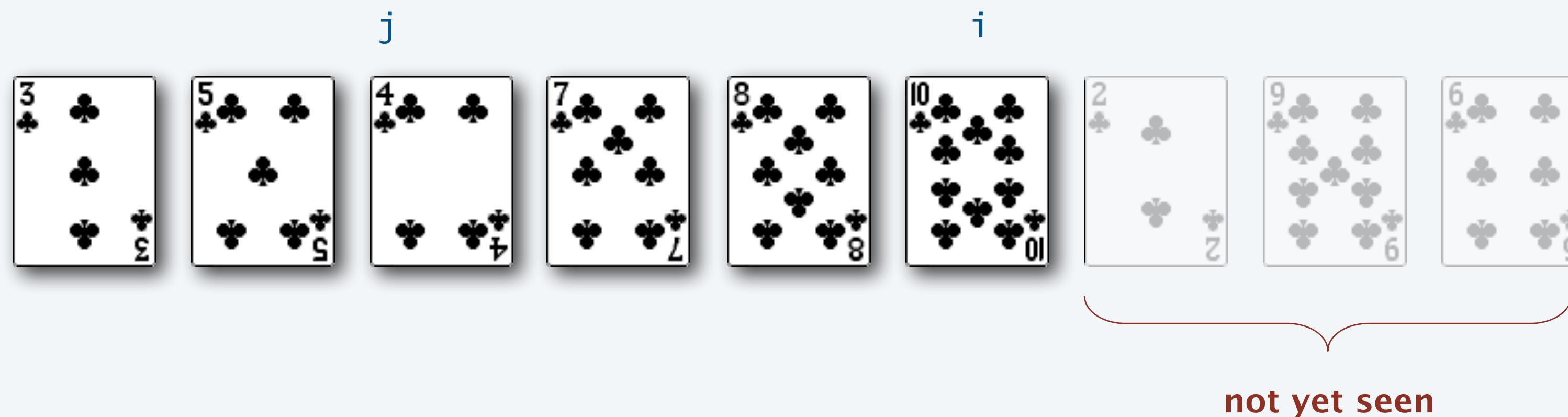
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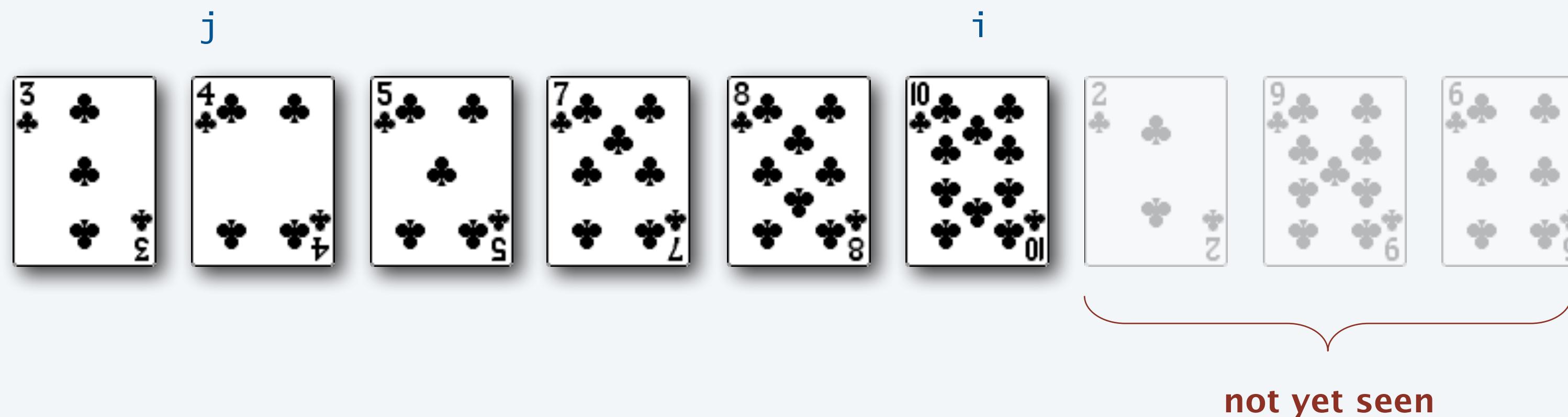
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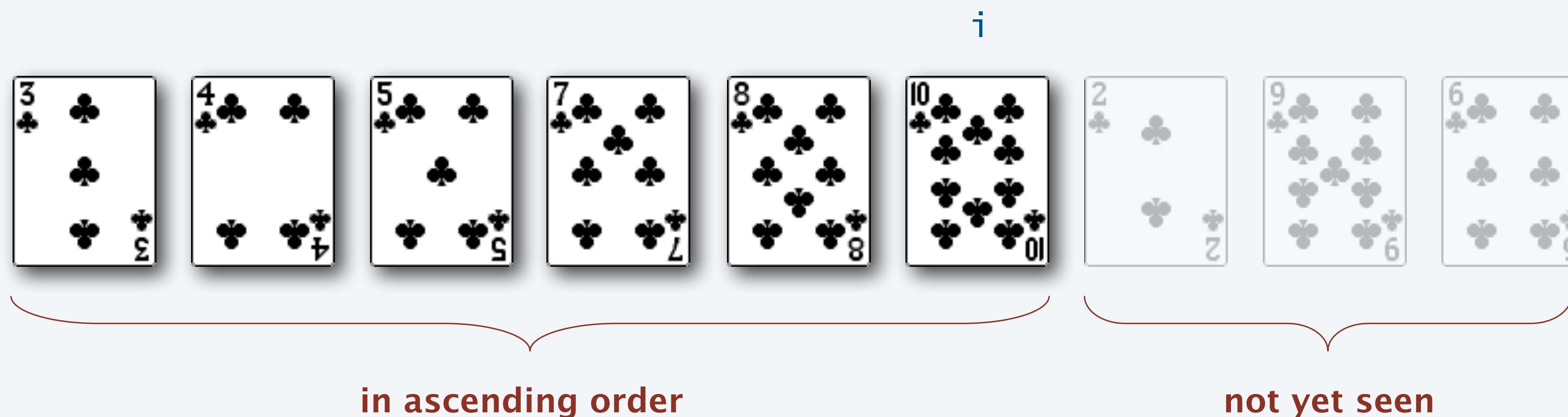
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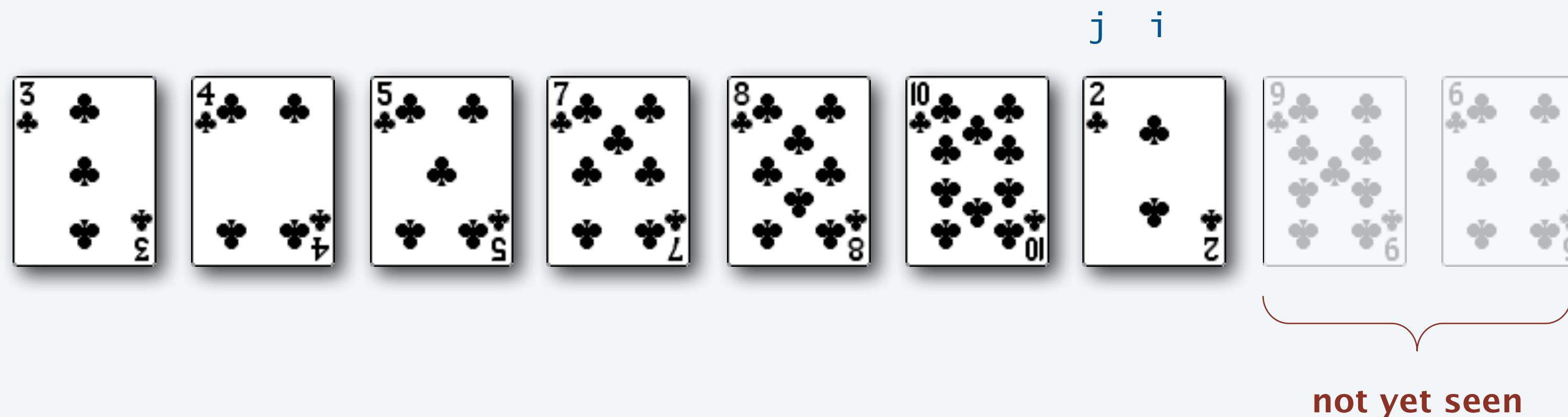
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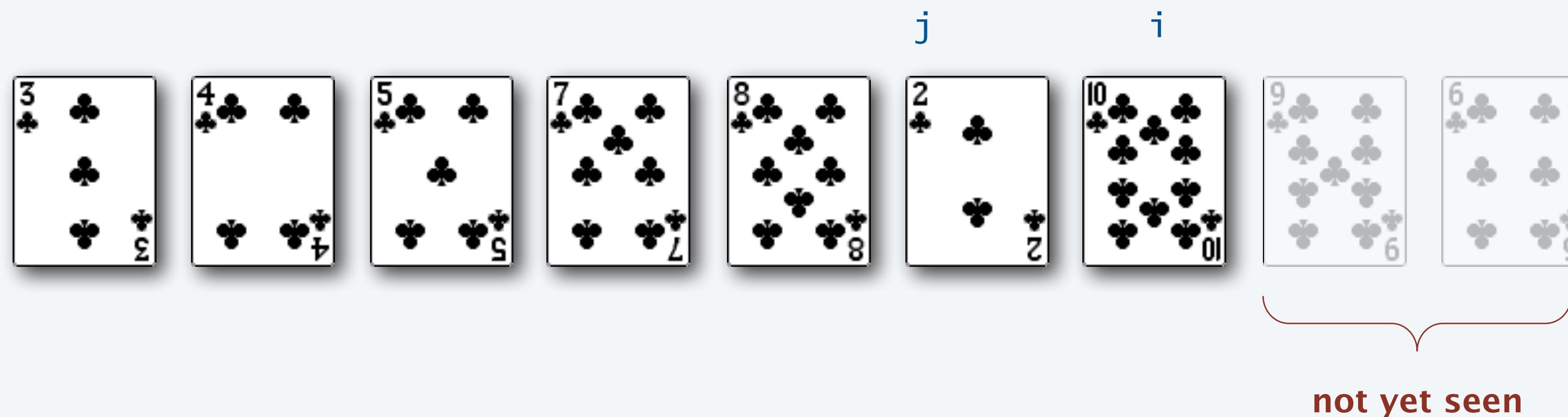
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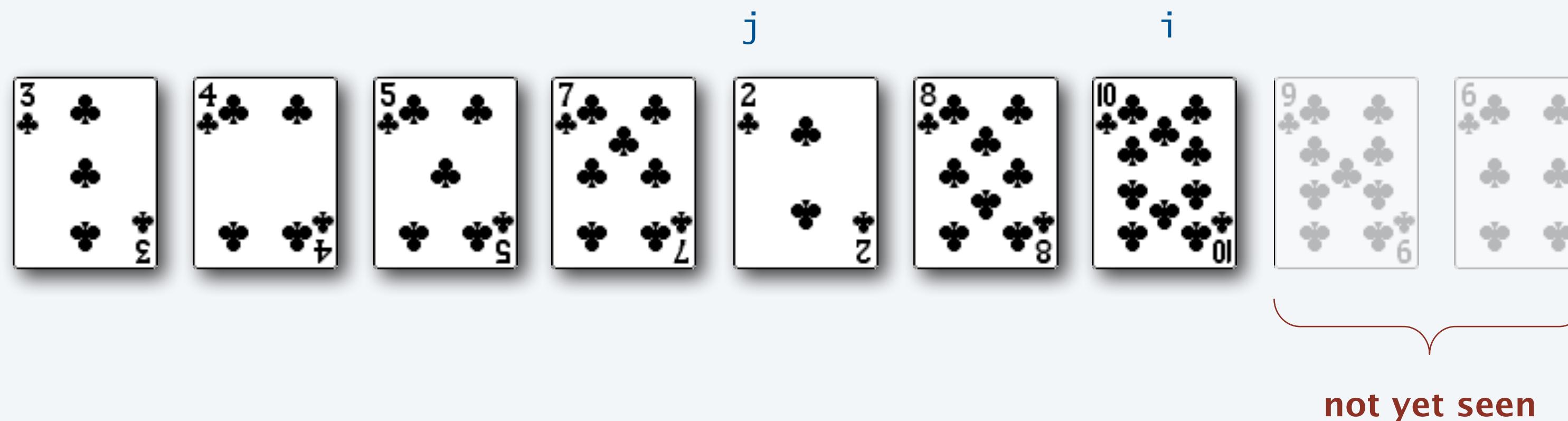
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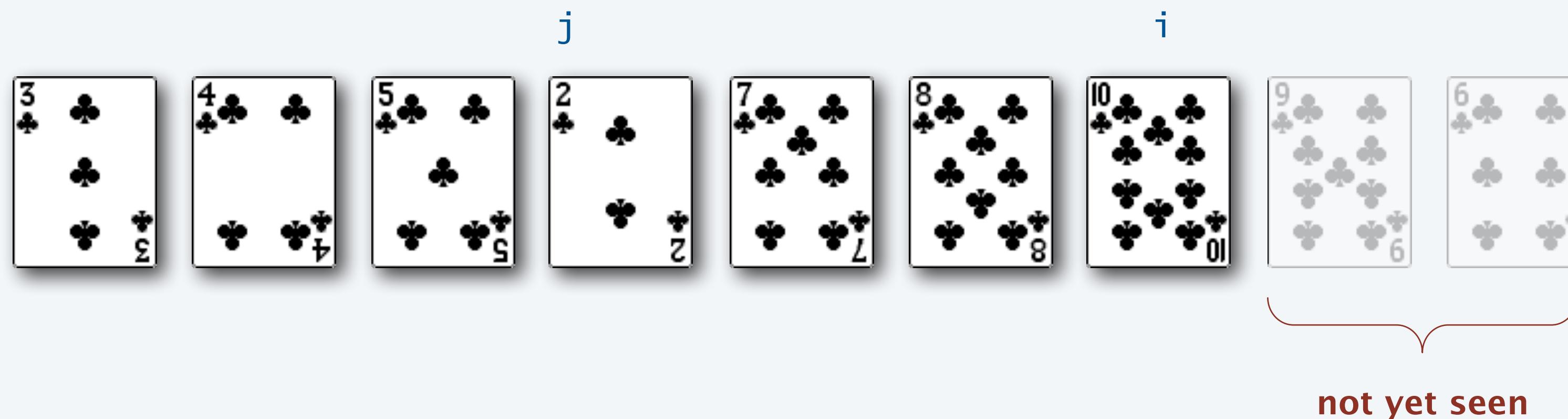
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Insertion sort demo

Algorithm. For each index $i = 0$ to $n - 1$:

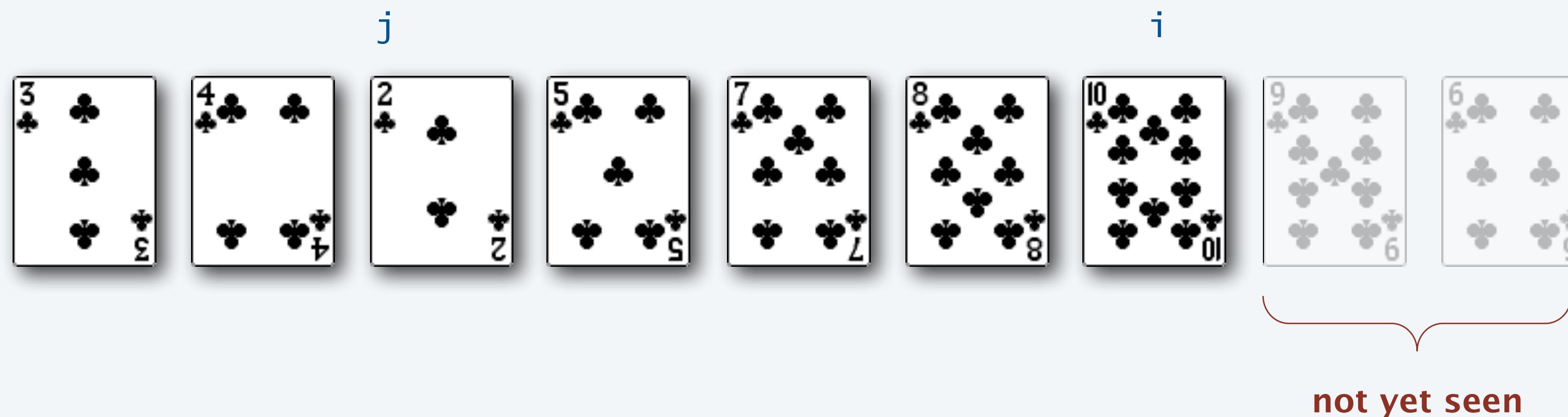
- Let x be the element at index i .
- Repeatedly exchange x with each larger element to its immediate left.



Insertion sort demo

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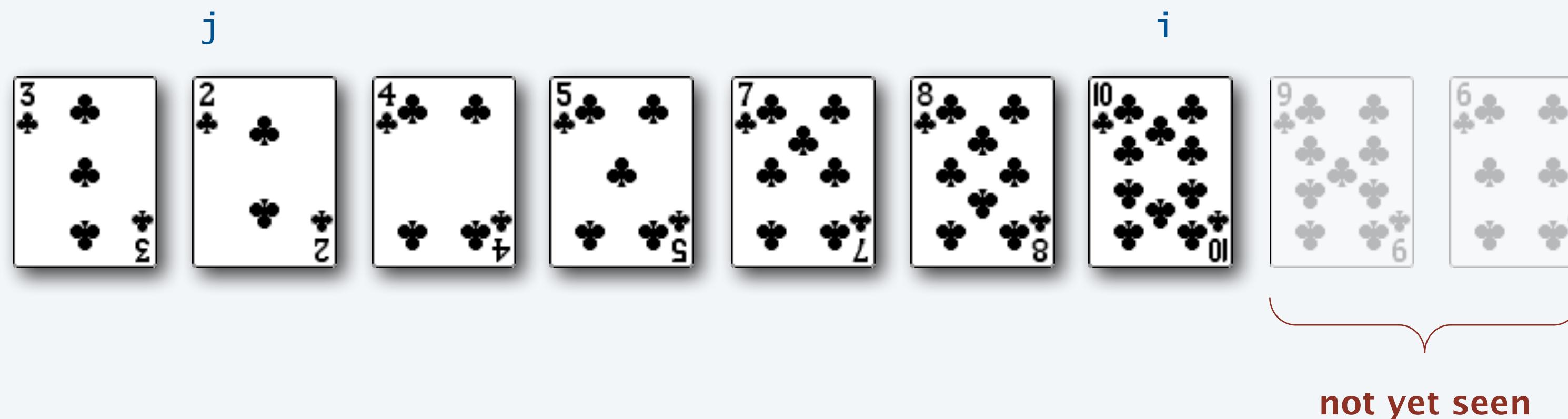
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Insertion sort demo

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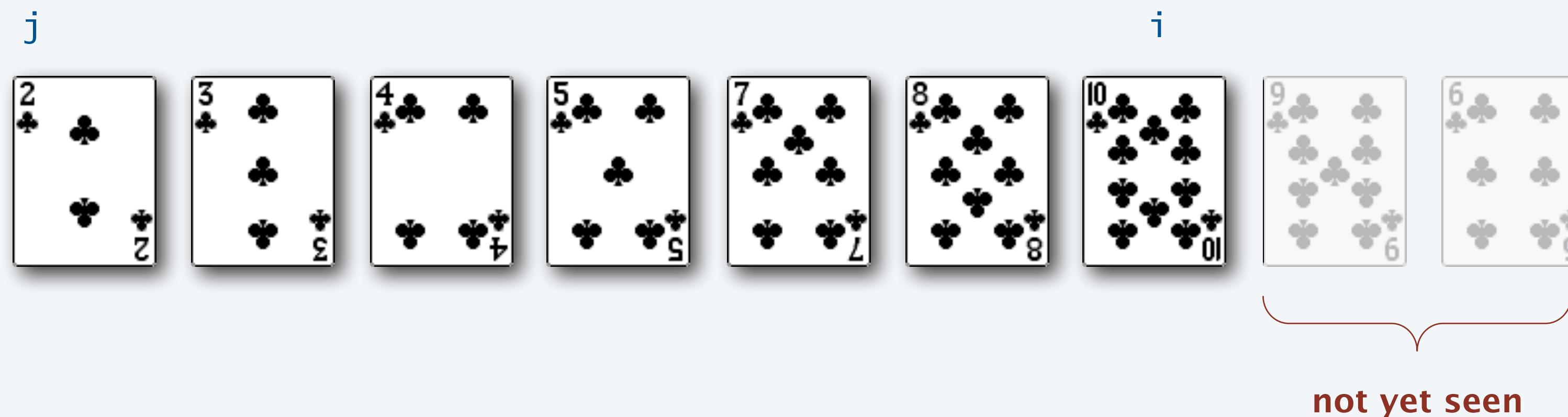
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Insertion sort demo

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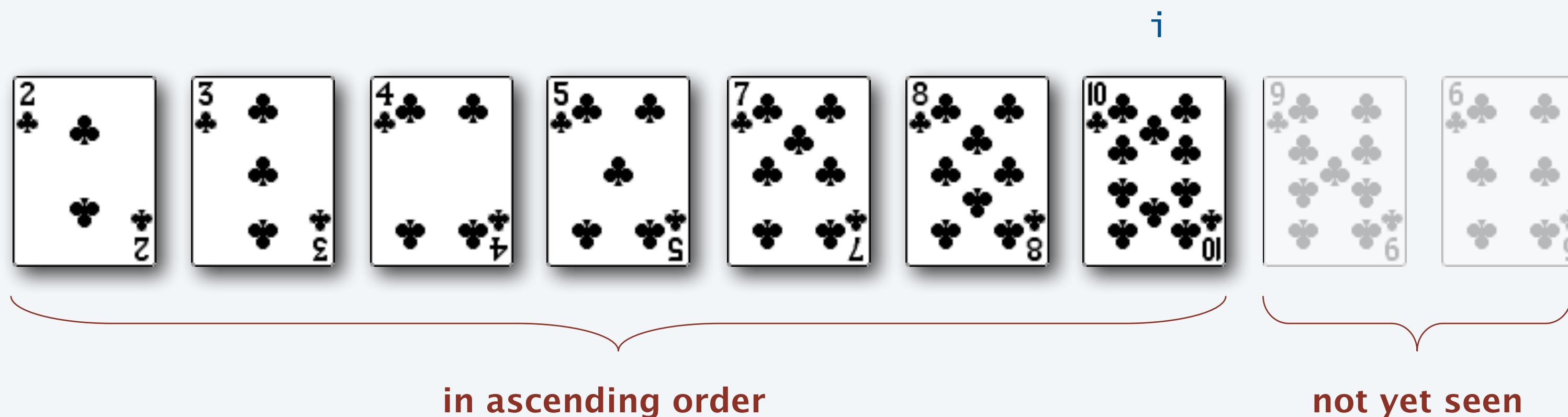
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Insertion sort demo

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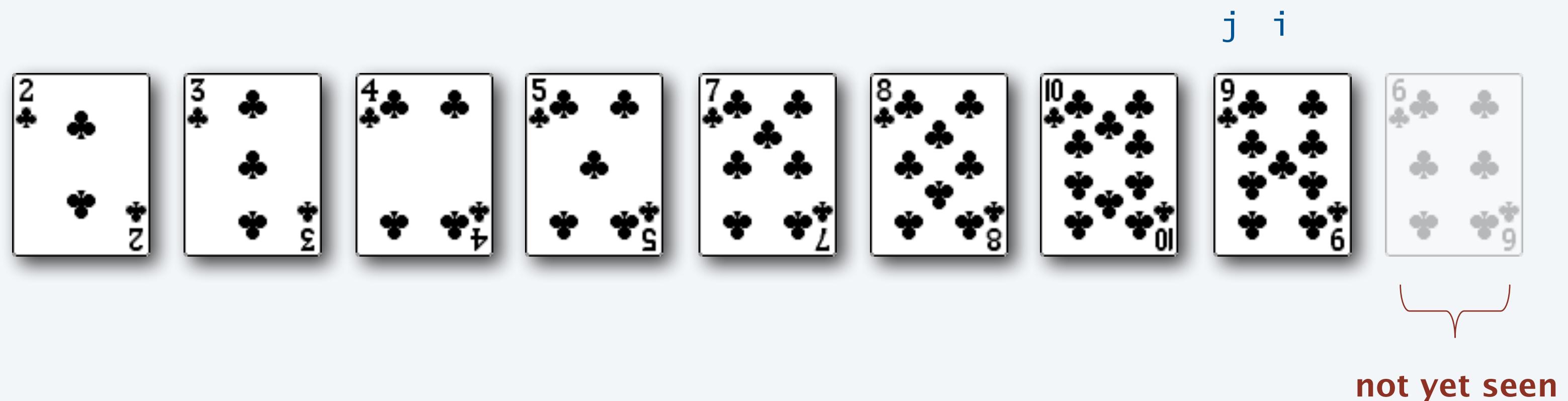
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Insertion sort demo

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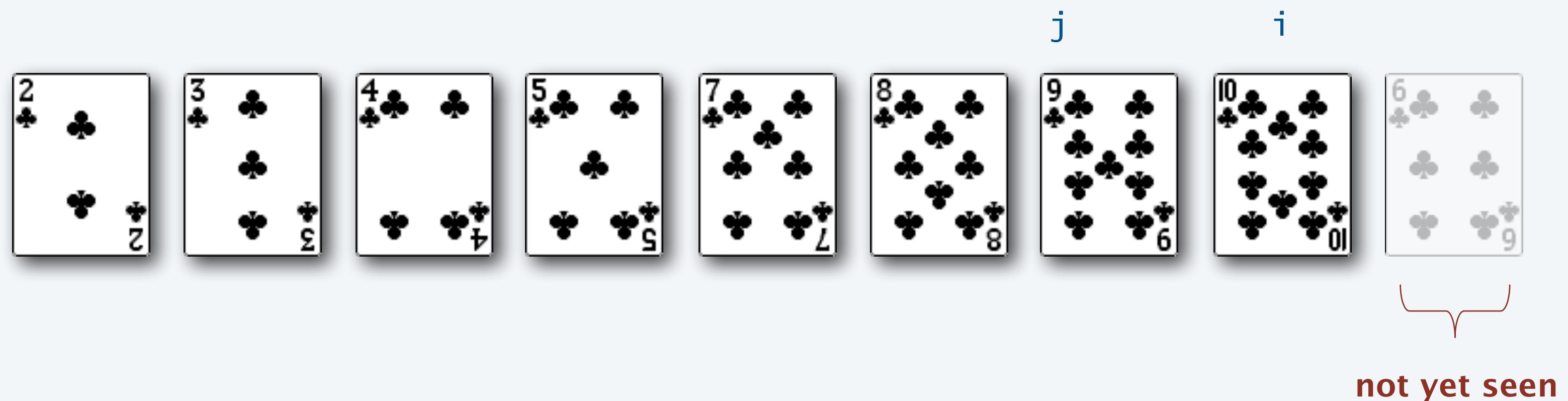
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Insertion sort demo

Algorithm. For each index $i = 0$ to $n - 1$:

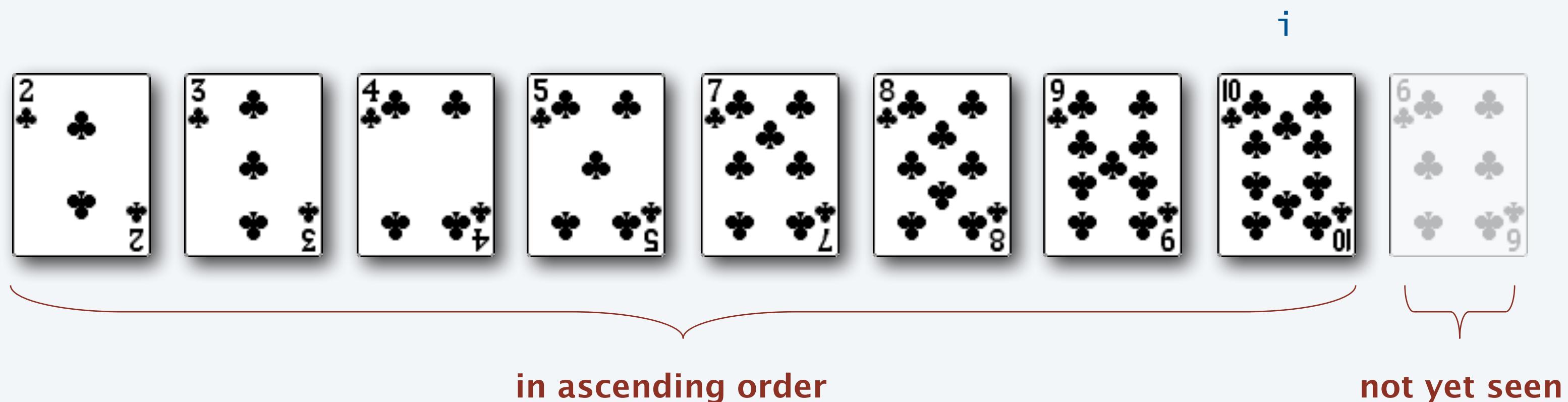
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Insertion sort demo

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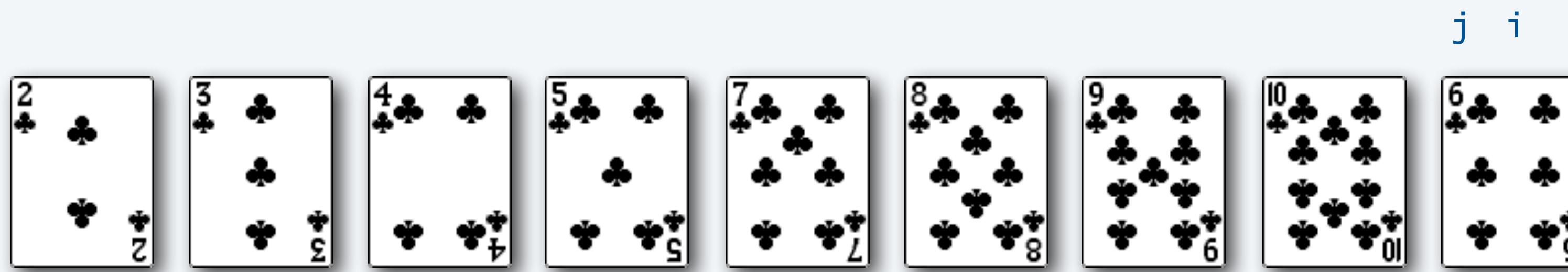
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Insertion sort demo

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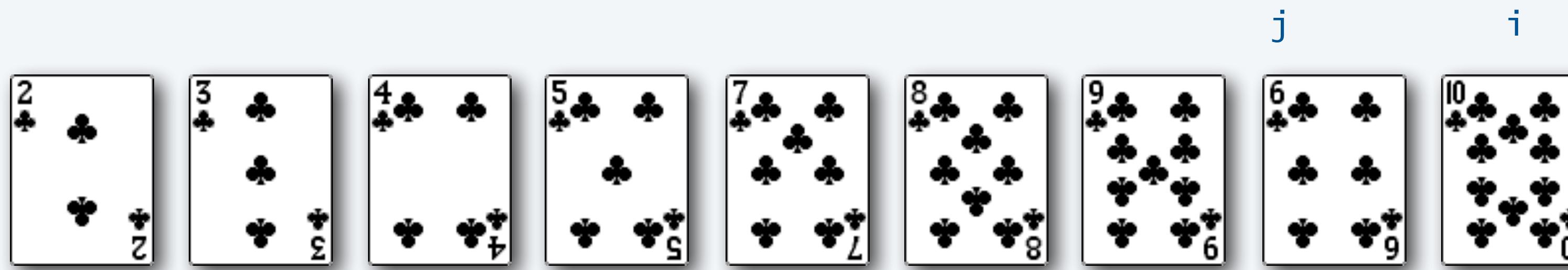
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Insertion sort demo

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Insertion sort demo

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Insertion sort demo

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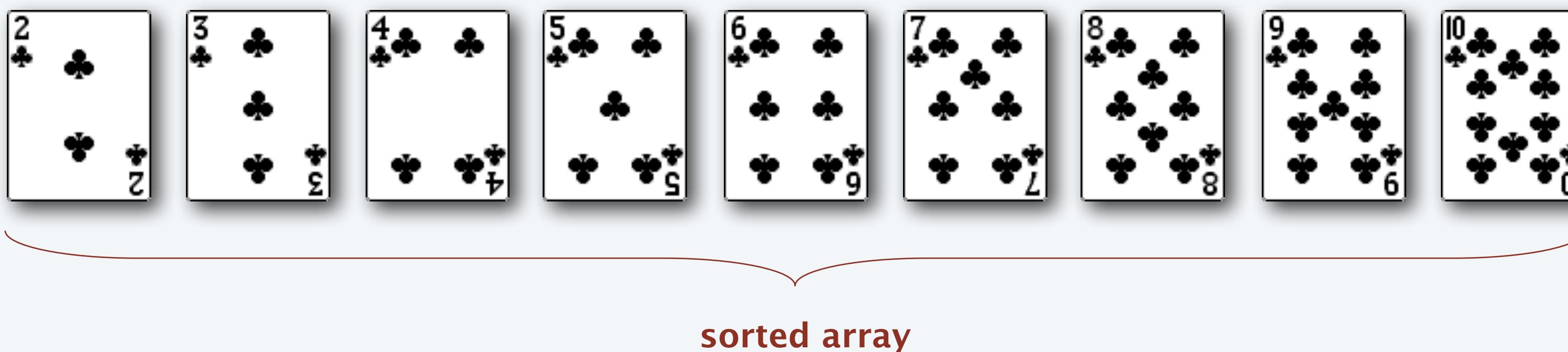
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Insertion sort demo

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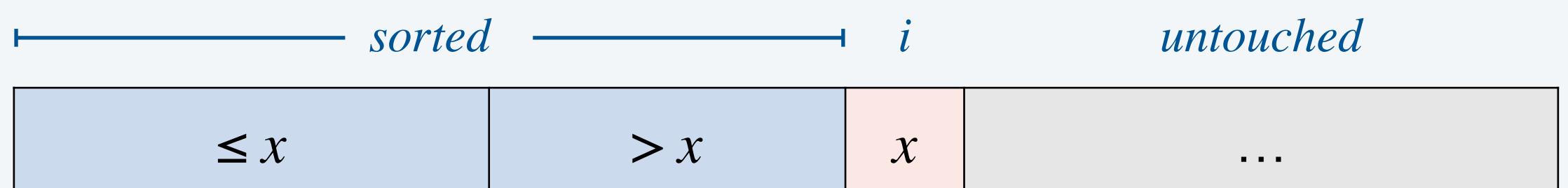
Insertion sort

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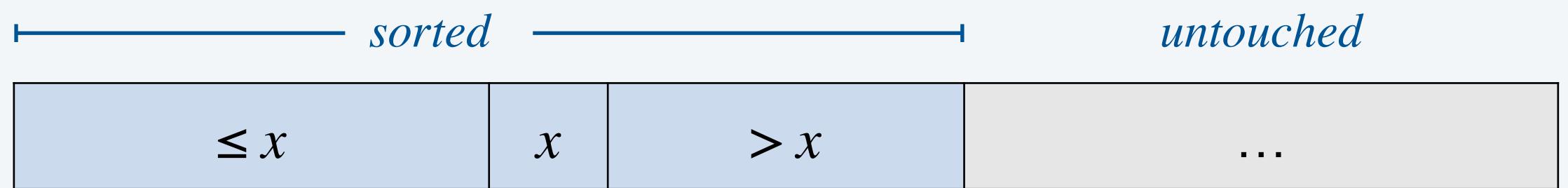
- Let x be the element at index i .
- Repeatedly exchange x with each larger element to its left.

Invariants.

before iteration i



after iteration i



Insertion sort: Java implementation

```
public class Insertion {  
  
    public static void sort(String[] 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; ← breaks out of  
innermost loop  
    }  
  
    private static boolean less(String v, String w) {  
        return v.compareTo(w) < 0; ←  
    }  
  
    private static void exch(String[] a, int i, int j) {  
        String temp = a[i];  
        a[i] = a[j];  
        a[j] = temp;  
    }  
}
```

*return zero (if equal),
negative integer (if less),
positive integer (if greater)*



How many compares does insertion sort make to sort an array of n distinct keys in reverse order?

- A. $\Theta(1)$
- B. $\Theta(\log n)$
- C. $\Theta(n)$
- D. $\Theta(n^2)$

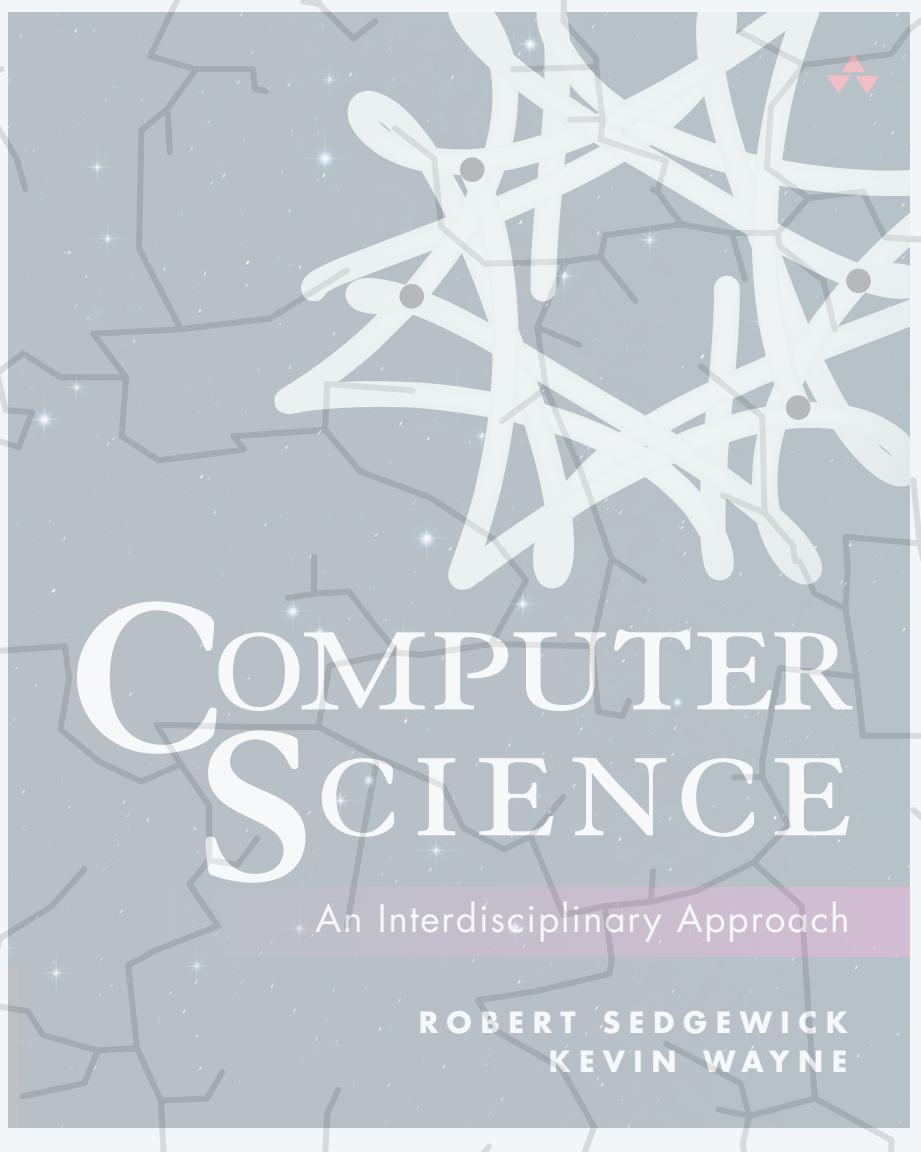
Insertion sort: analysis

Sorting cost model. Number of compares (or array accesses).

Proposition. Insertion sort never makes more than $\sim \frac{1}{2} n^2$ compares to sort an array of length n .

Pf.

- The worst case is a reverse-sorted array of n distinct keys.
- In iteration i , insertion sort makes i compares.
- Total number of compares = $0 + 1 + 2 + \dots + (n-1) = \frac{1}{2} n(n-1)$.



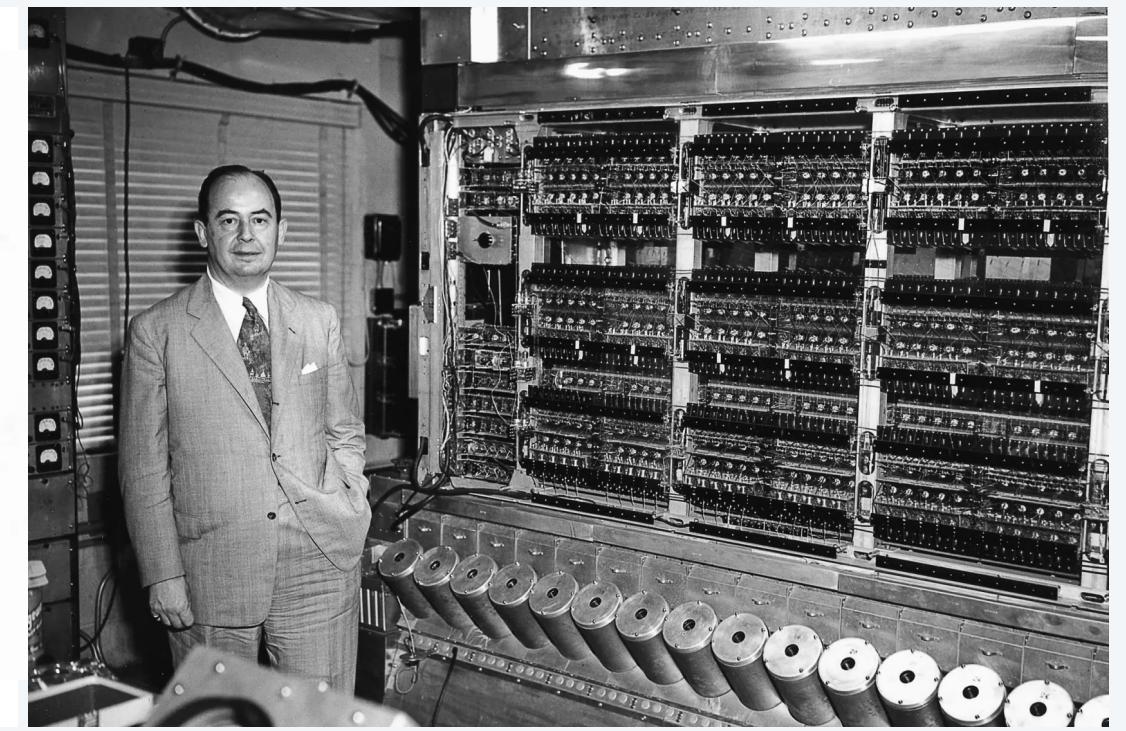
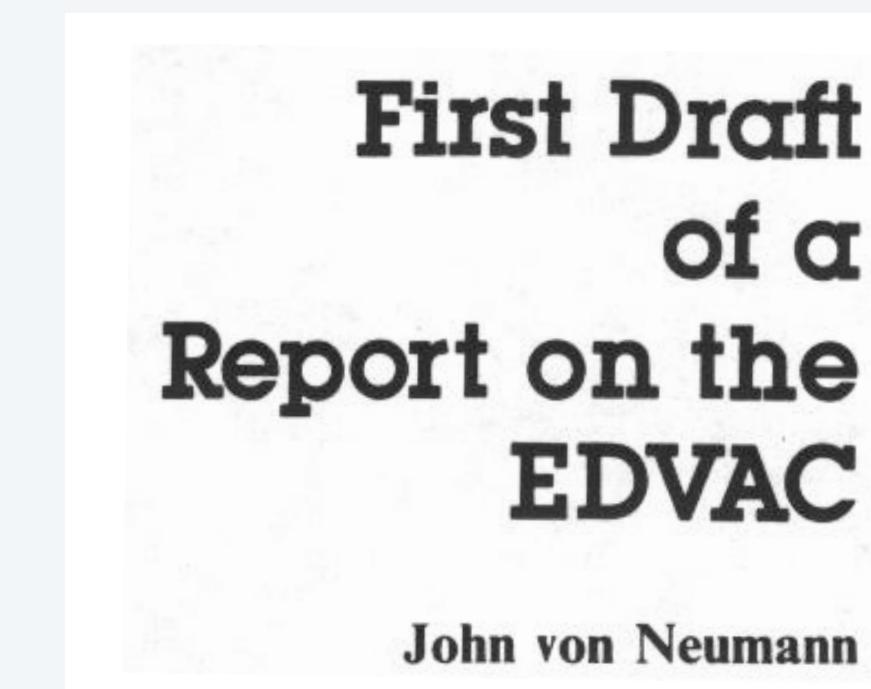
4.2 ALGORITHMS

- ▶ *sequential search*
- ▶ *binary search*
- ▶ *insertion sort*
- ▶ ***mergesort***

Mergesort overview

Basic plan.

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

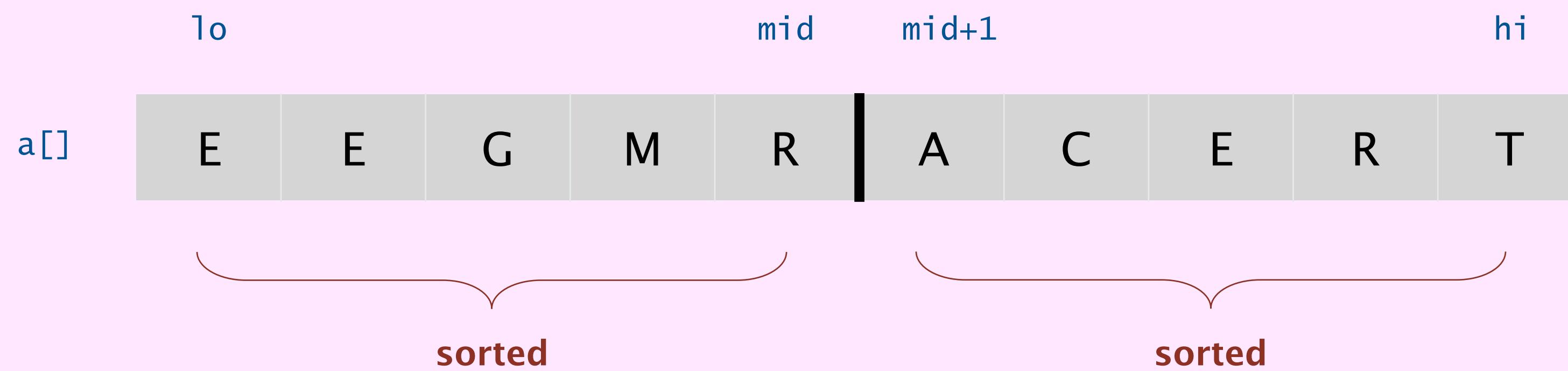


input	M	E	R	G	E	S	O	R		T	E	X	A	M	P	L	E
sort left half	E	E	G	M	O	R	R	S		T	E	X	A	M	P	L	E
sort right half	E	E	G	M	O	R	R	S		A	E	E	L	M	P	T	X
merge results	A	E	E	E	E	G	L	M	M	O	P	R	R	S	T	X	

Abstract in-place merge demo

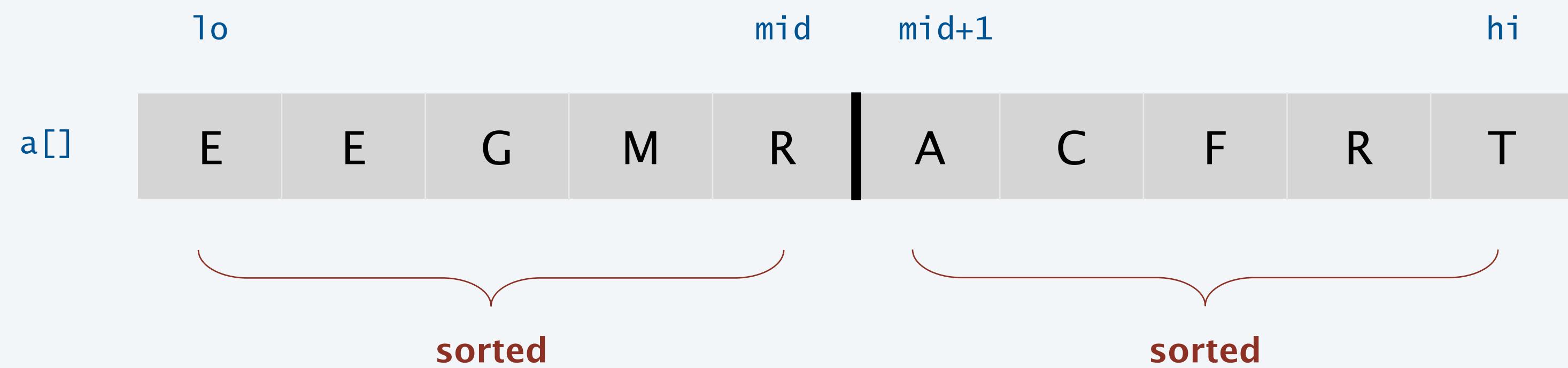


Goal. Given two sorted subarrays $a[lo]$ to $a[mid]$ and $a[mid+1]$ to $a[hi]$,
replace with sorted subarray $a[lo]$ to $a[hi]$.



Merging demo

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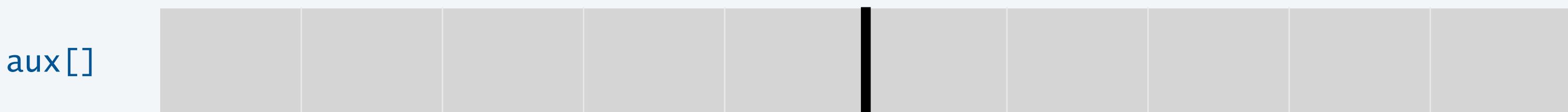


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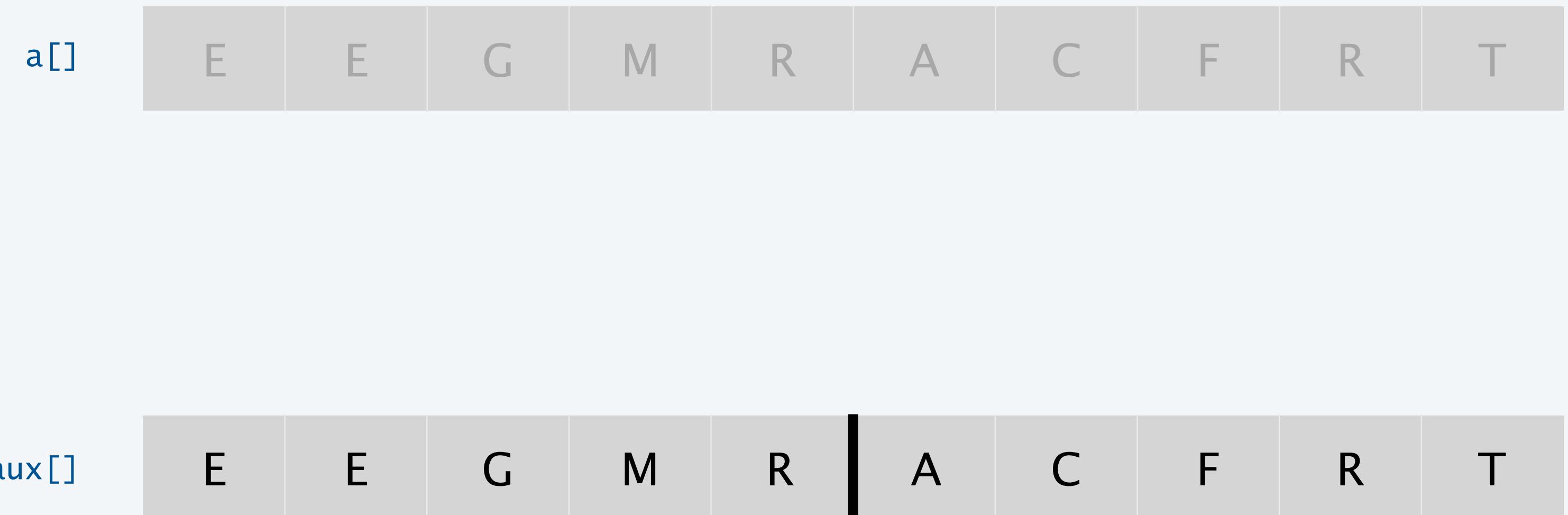


copy to auxiliary array



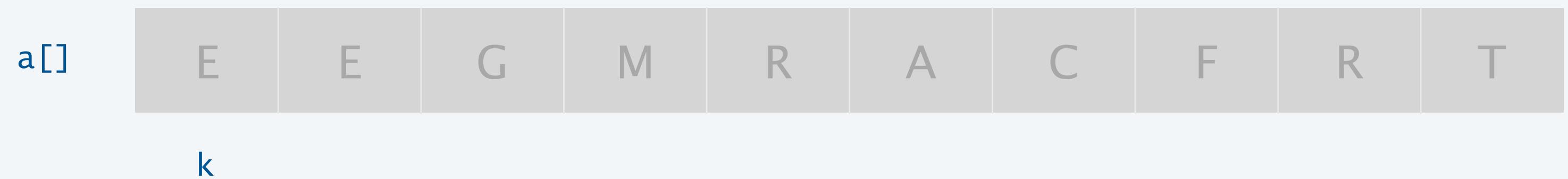
Merging demo

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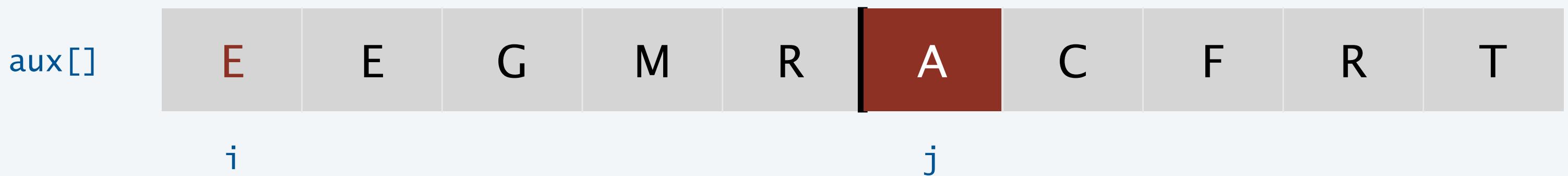


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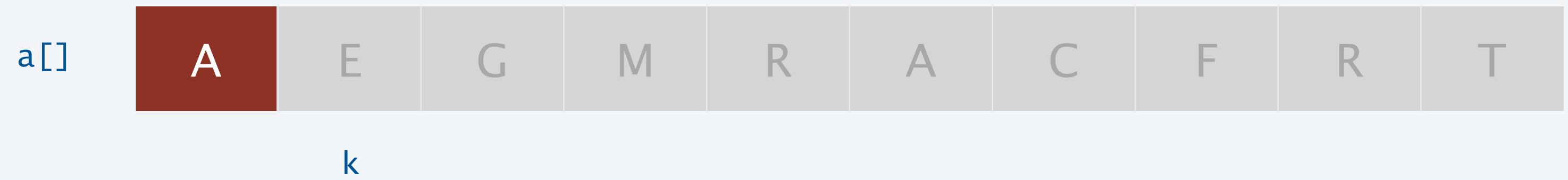


compare minimum in each subarray



Merging demo

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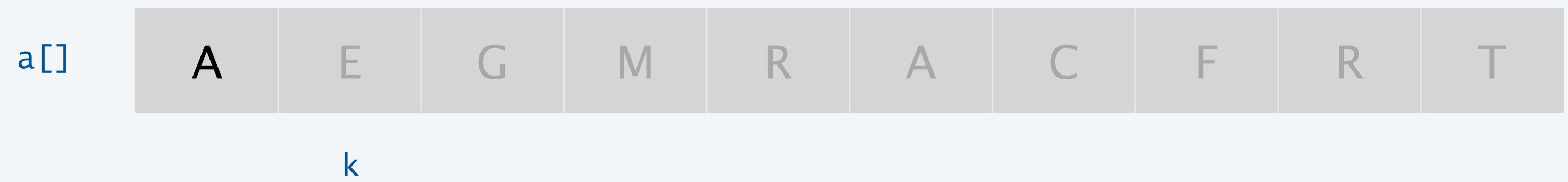


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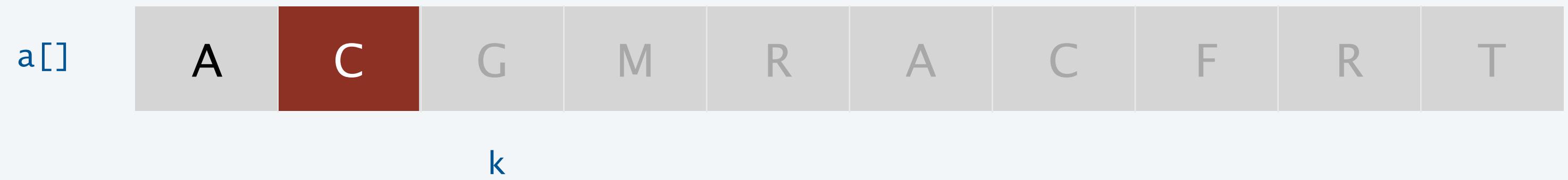


compare minimum in each subarray



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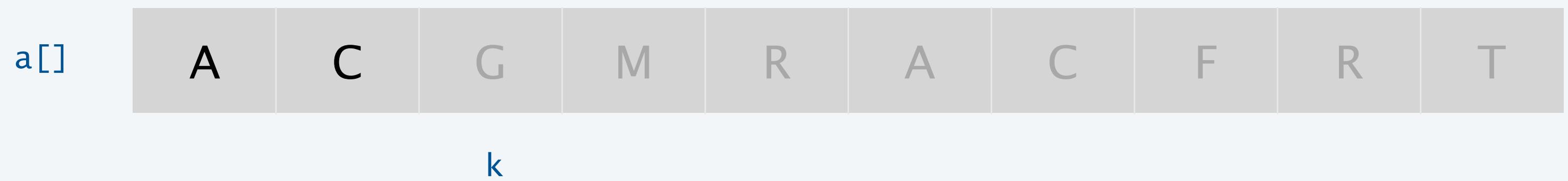


compare minimum in each subarray

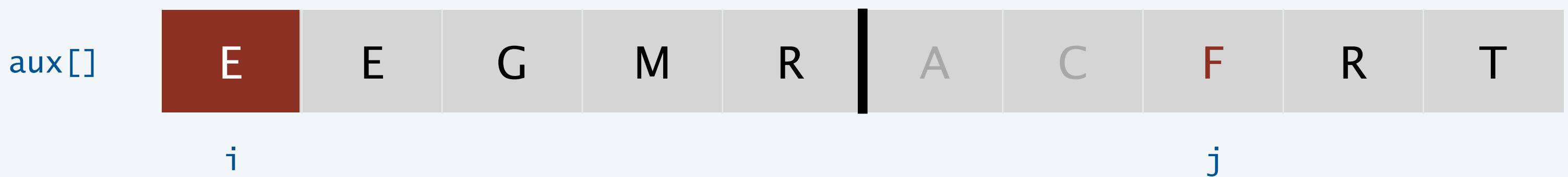


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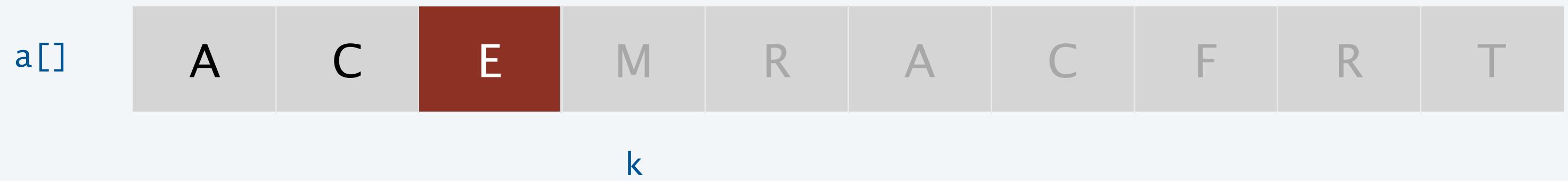


compare minimum in each subarray



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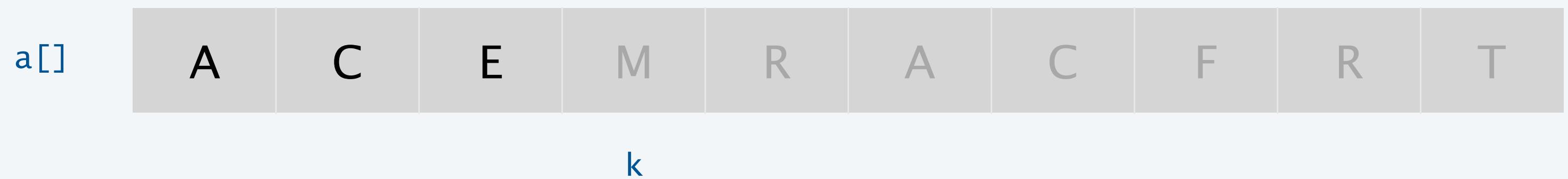


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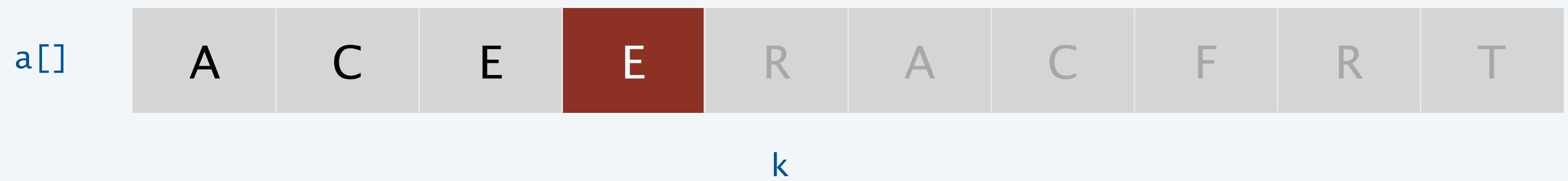


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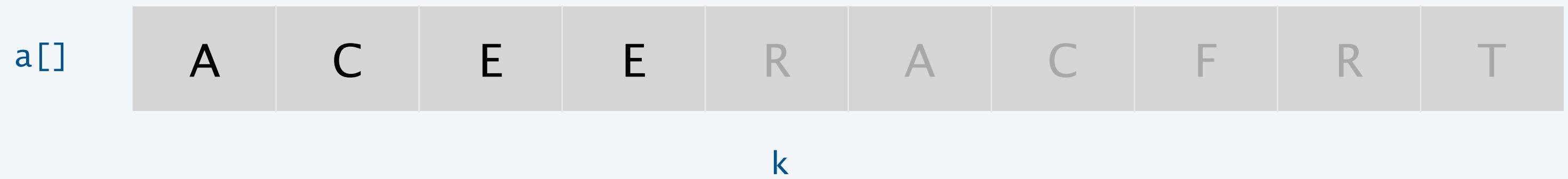


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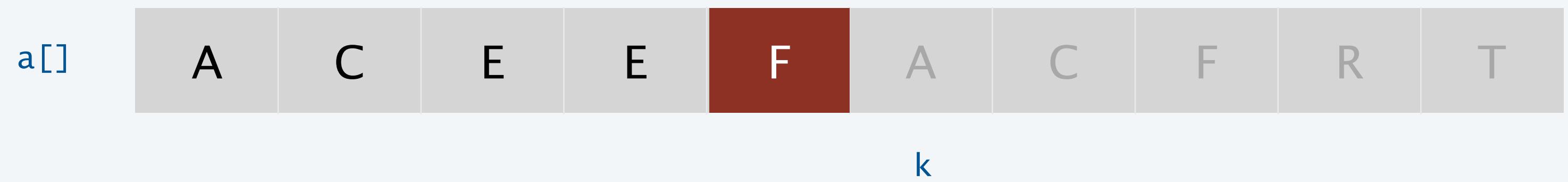


compare minimum in each subarray



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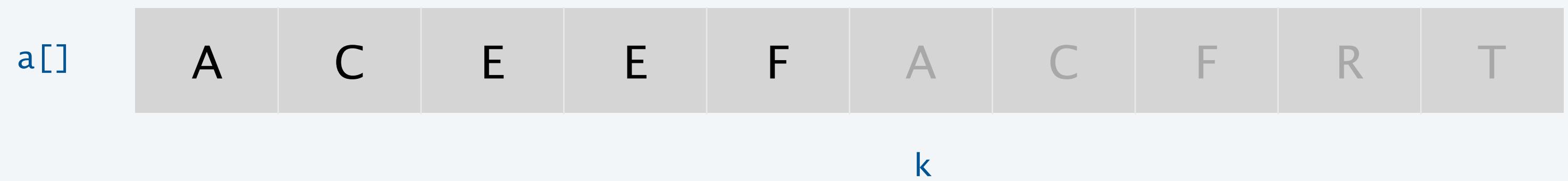


compare minimum in each subarray



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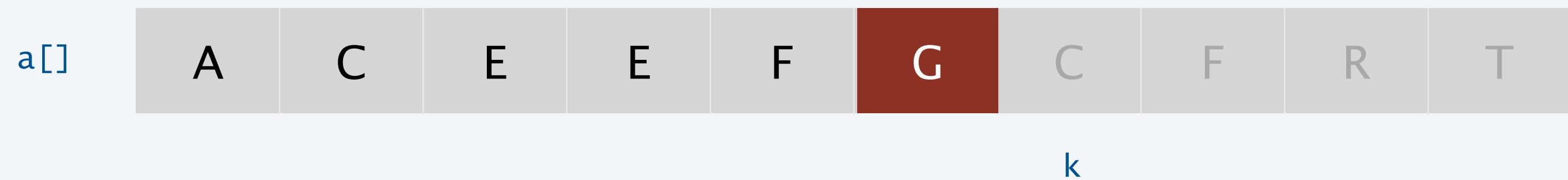


compare minimum in each subarray

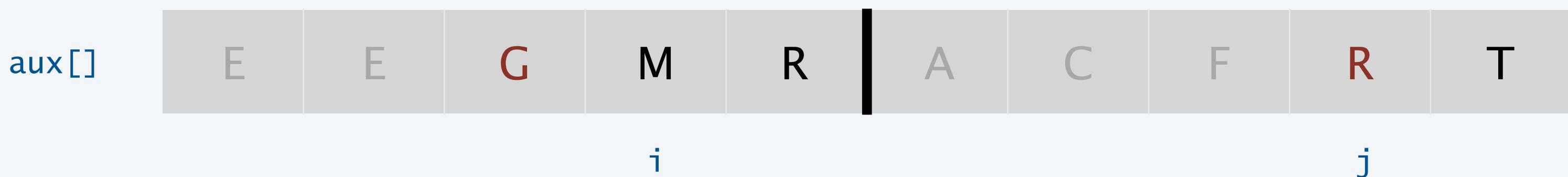


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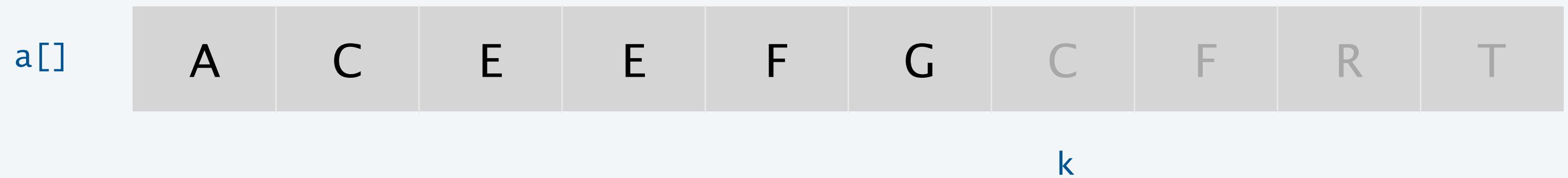


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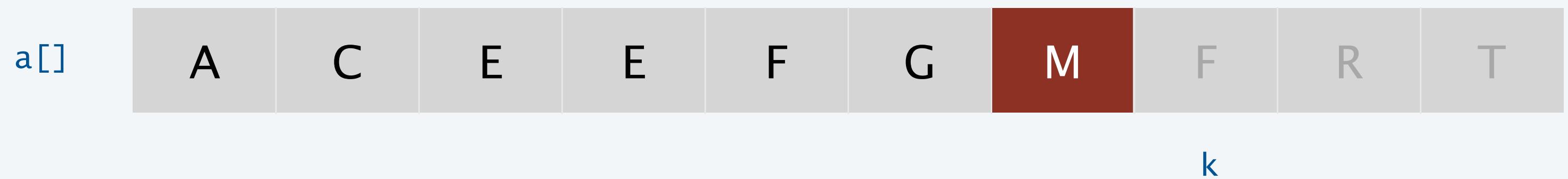


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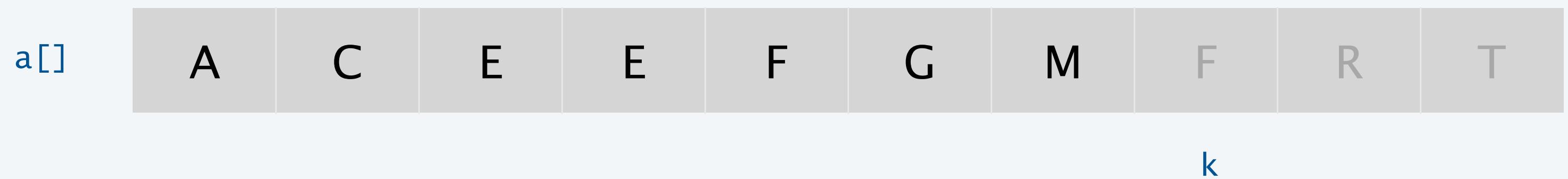


compare minimum in each subarray

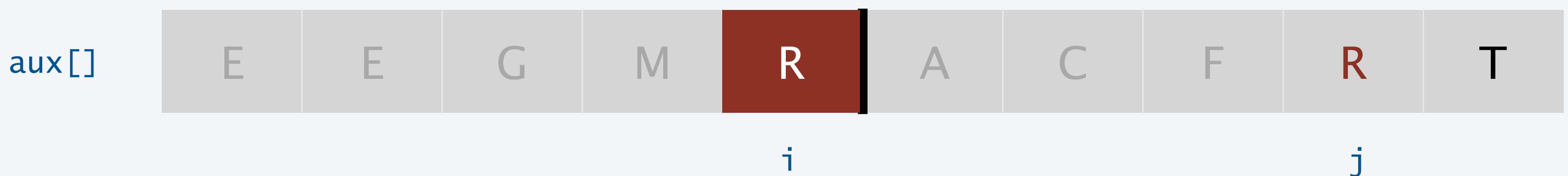


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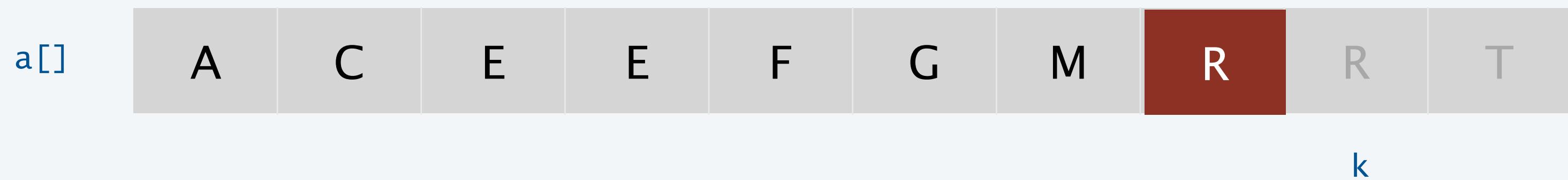


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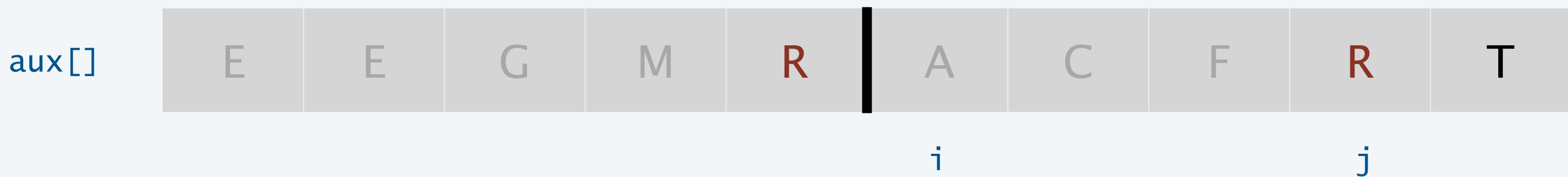


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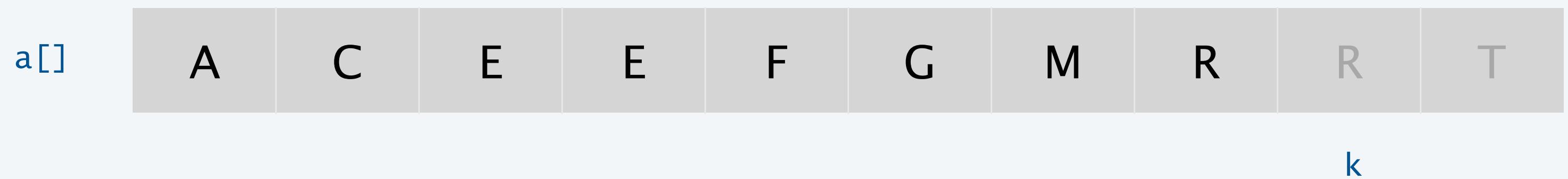


compare minimum in each subarray

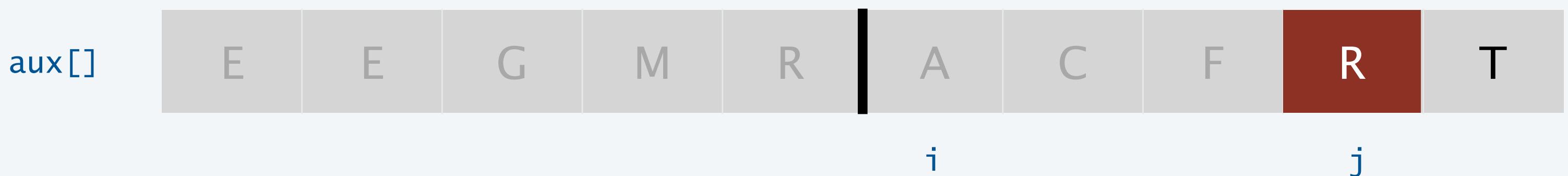


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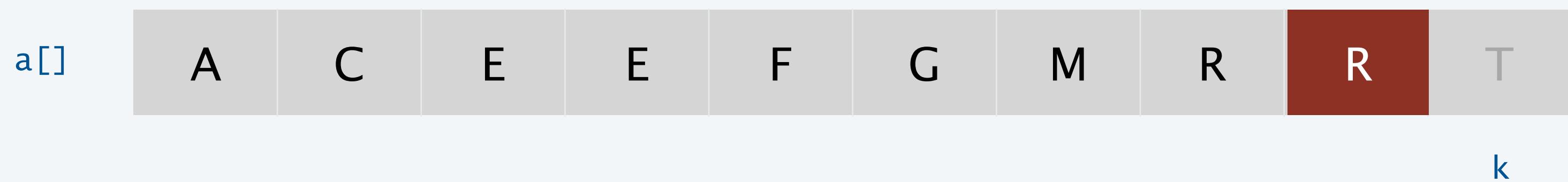


one subarray exhausted, take from other

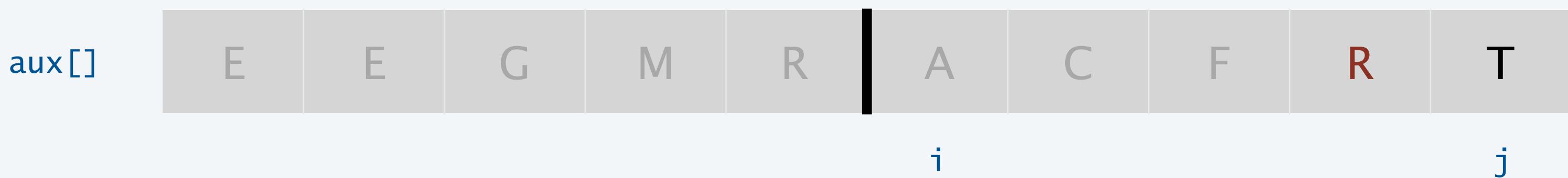


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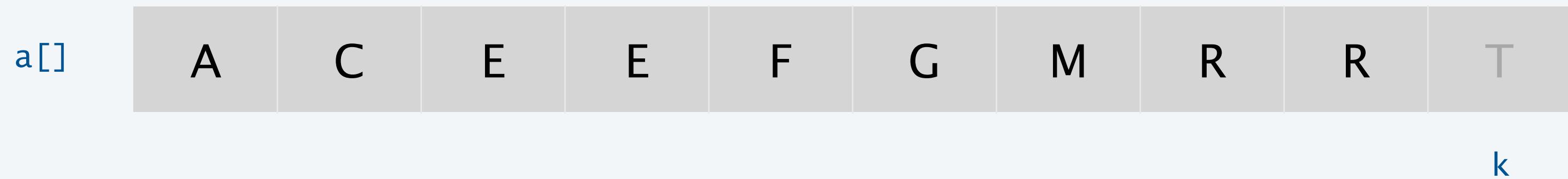


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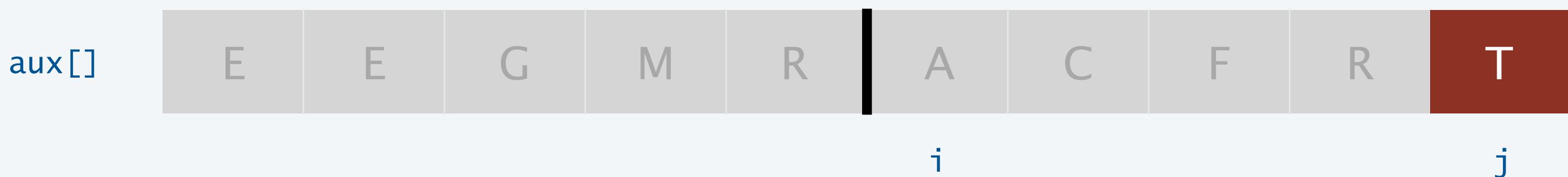


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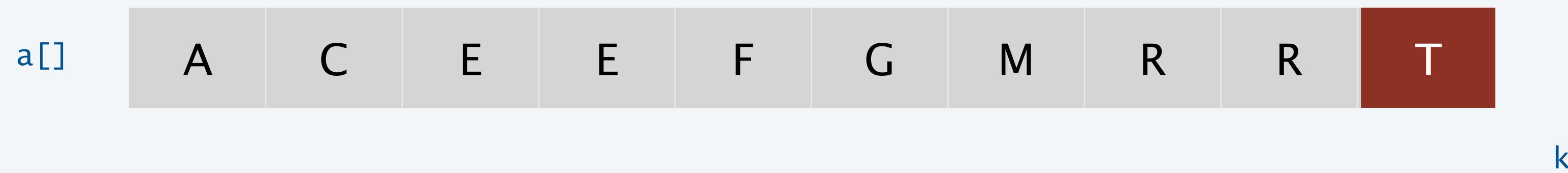


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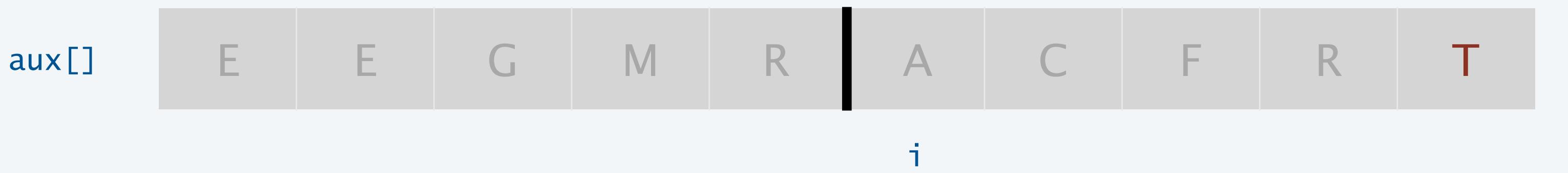


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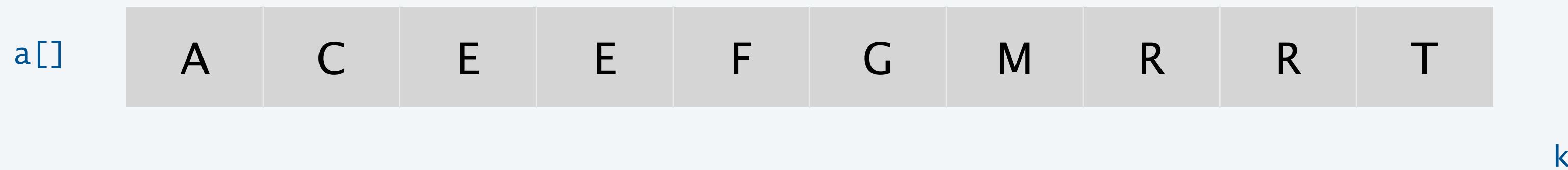


one subarray exhausted, take from other

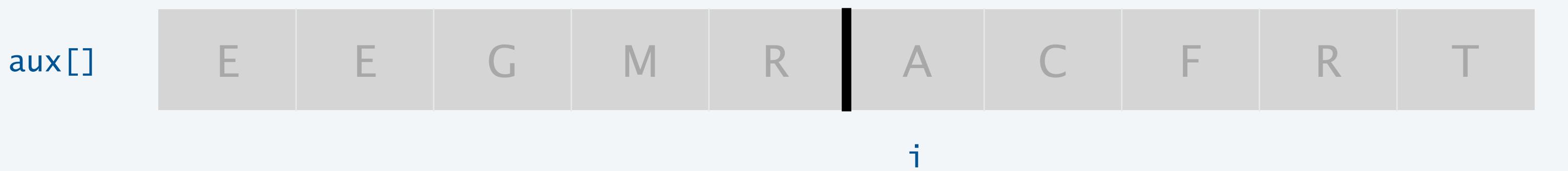


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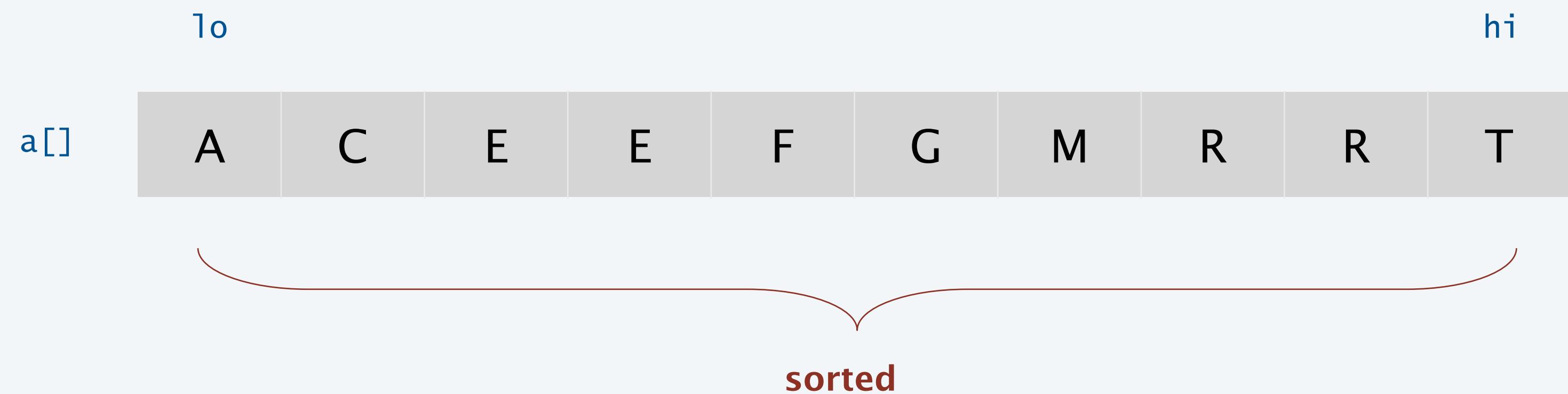


both subarrays exhausted, done



Merging demo

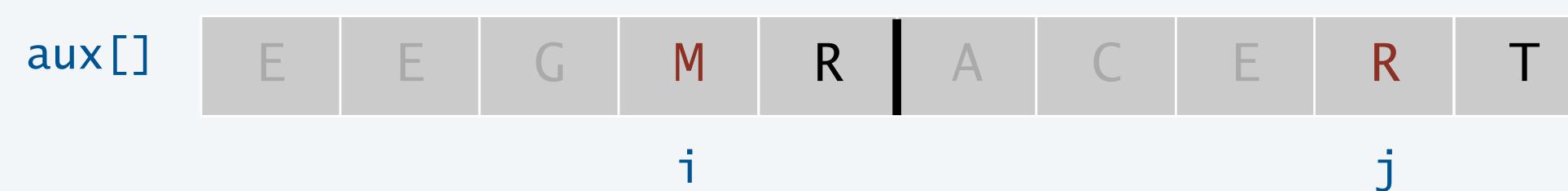
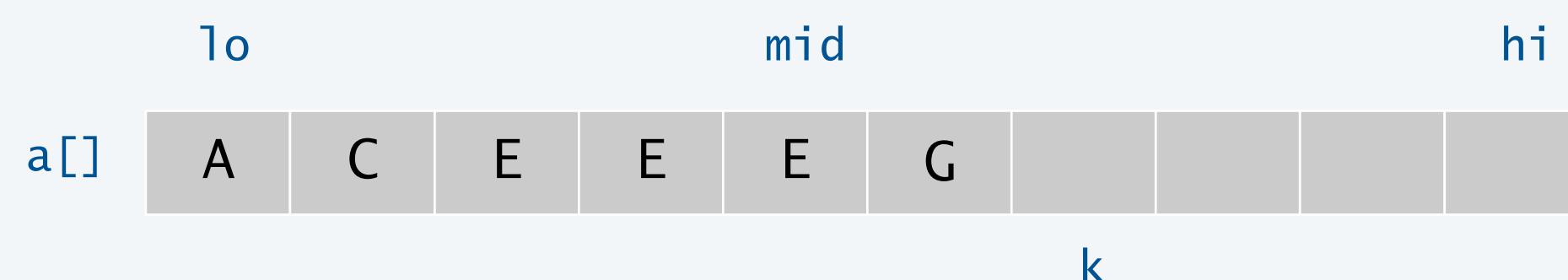
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Merging: Java implementation

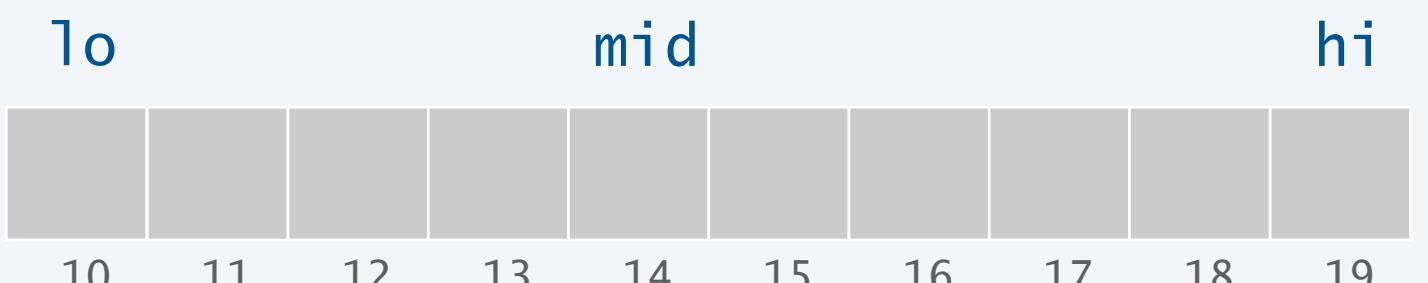
```
private static void merge(String[] a, String[] aux, int lo, int mid, int hi) {  
    for (int k = lo; k <= hi; k++)    copy  
        aux[k] = a[k];
```

```
int i = lo, j = mid+1;                                merge  
for (int k = lo; k <= hi; k++) {  
    if      (i > mid)          a[k] = aux[j++]; increments variable after  
    else if (j > hi)           a[k] = aux[i++]; using it to index array  
    else if (less(aux[j], aux[i])) a[k] = aux[j++];  
    else                         a[k] = aux[i++];  
}  
}
```



Mergesort: Java implementation

```
public class Merge {  
    private static void merge(...) {  
        /* as before */  
    }  
  
    private static void sort(String[] a, String[] 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(String[] a) {  
        String[] aux = new String[a.length]; create (and reuse)  
        sort(a, aux, 0, a.length - 1); auxiliary array  
    }  
}
```



Mergesort: trace

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

←———— result after recursive call

Insertion sort vs. mergesort: empirical analysis

Running time estimates (approximate):

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

n	laptop	super	n	laptop	super
thousand	<i>instant</i>	<i>instant</i>	thousand	<i>instant</i>	<i>instant</i>
million	<i>2.8 hours</i>	<i>1 second</i>	million	<i>1 second</i>	<i>instant</i>
billion	<i>317 years</i>	<i>1 week</i>	billion	<i>18 minutes</i>	<i>instant</i>

insertion sort

mergesort

Bottom line. Great algorithms are better than supercomputers.



In the worst case, how many compares are needed to merge two sorted subarrays of length $n/2$ to produce a sorted array of length n ?

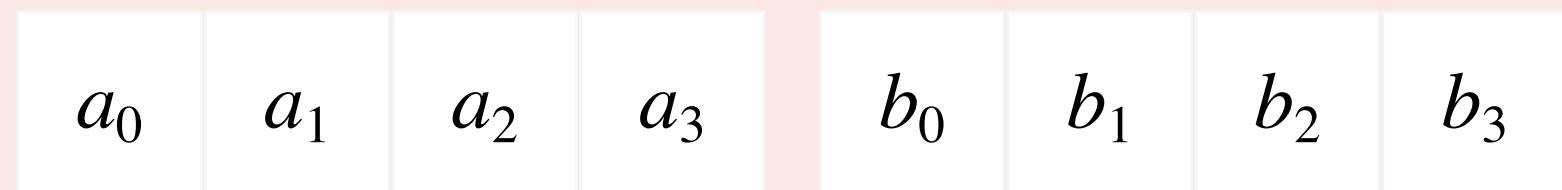
A. $n/2$

B. $n - 1$

C. $\Theta(n \log n)$

D. $\Theta(n^2)$

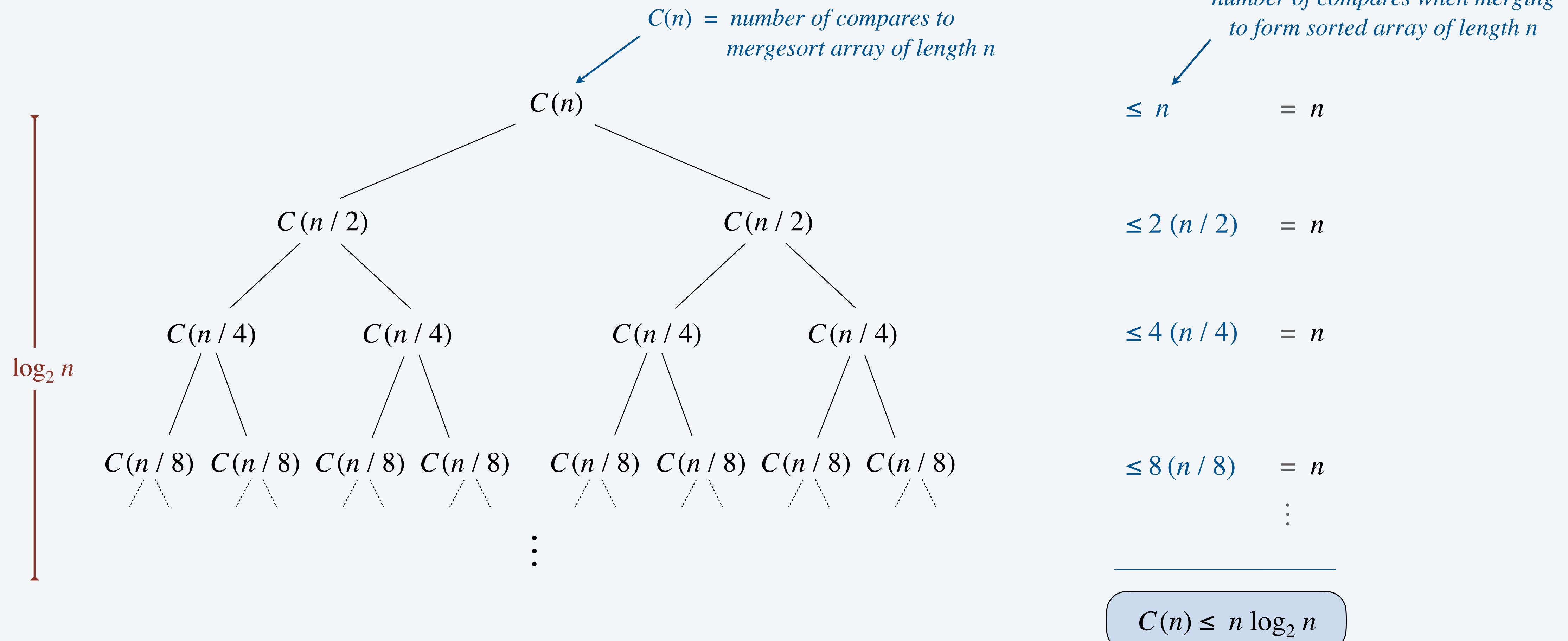
merging two sorted arrays, each of length $n/2$

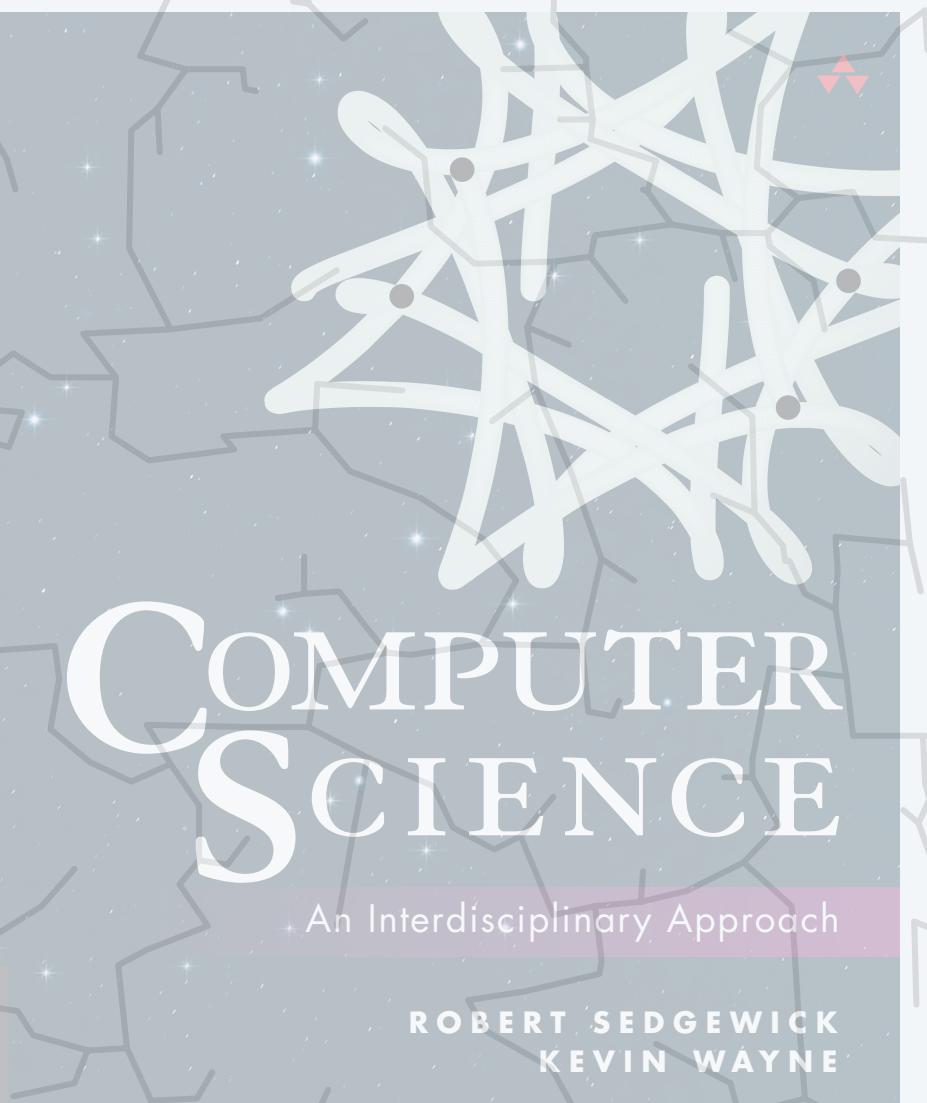


Mergesort analysis

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

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





4.2 ALGORITHMS

- ▶ *sequential search*
- ▶ *binary search*
- ▶ *insertion sort*
- ▶ *mergesort*
- ▶ ***system libraries***

`java.util.Arrays` contains static methods for manipulating arrays. ← *sorting, searching, comparing, ...*

Module `java.base`

Package `java.util`

Class Arrays

`java.lang.Object`
 `java.util.Arrays`

```
public class Arrays
extends Object
```

This class contains various methods for manipulating arrays (such as sorting and searching). This class also contains a static factory that allows arrays to be viewed as lists.

The methods in this class all throw a `NullPointerException`, if the specified array reference is null, except where noted.

The documentation for the methods contained in this class includes brief descriptions of the *implementations*. Such descriptions should be regarded as *implementation notes*, rather than parts of the *specification*. Implementors should feel free to substitute other algorithms, so long as the specification itself is adhered to. (For example, the algorithm used by `sort(Object[])` does not have to be a MergeSort, but it does have to be *stable*.)

System sort and binary search

`Arrays.sort()` and `Arrays.binarySearch()` each refer to several overloaded methods.

- For primitive types.
- For reference types. ← *must be Comparable
(such as `String`, stay tuned)*
- For subarrays.

```
import java.util.Arrays;  
  
public class TestSort {  
    public static void main(String[] args) {  
        Arrays.sort(args);  
        StdOut.println(Arrays.toString(args));  
    }  
}
```

*to access methods defined
in `java.util.Arrays`*



*useful function to print elements in an array
(separated by commas, enclosed in square braces)*

```
~/cos126/algorithms> java-introcs TestSort S O R T M E  
[E, M, O, R, S, T]
```

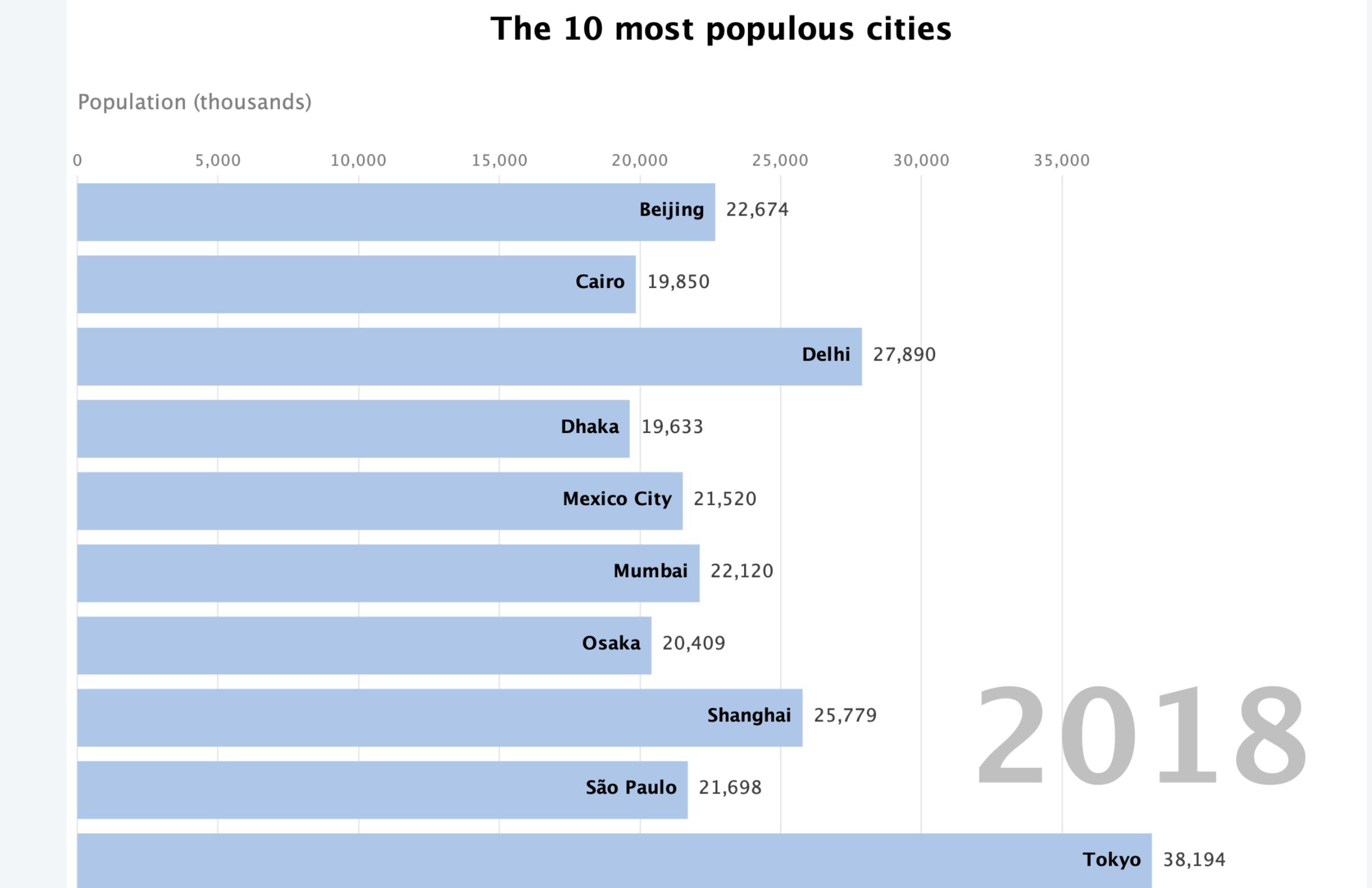
Bar charts

BarChart is a data type (with simple API) to draw bar charts.

```
// create the bar chart
String title = "The 10 most populous cities";
String xLabel = "Population (thousands)";
String source = "Source: United Nations";
BarChart chart = new BarChart(title, xLabel, source);

// add the bars and caption to the bar chart
chart.add("Beijing", 22674, "East Asia");
chart.add("Cairo", 19850, "Middle East");
chart.add("Delhi", 27890, "South Asia");
chart.add("Dhaka", 19633, "South Asia");
chart.add("Mexico City", 21520, "Latin America");
chart.add("Mumbai", 22120, "South Asia");
chart.add("Osaka", 20409, "East Asia");
chart.add("Shanghai", 25779, "East Asia");
chart.add("São Paulo", 21698, "Latin America");
chart.add("Tokyo", 38194, "East Asia");
chart.setCaption("2018");

// draw the bar chart
chart.draw();
```

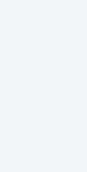


Sorted bar chart

Sort the bars in descending order by value (e.g., population).

Color the bars by category (e.g., region).

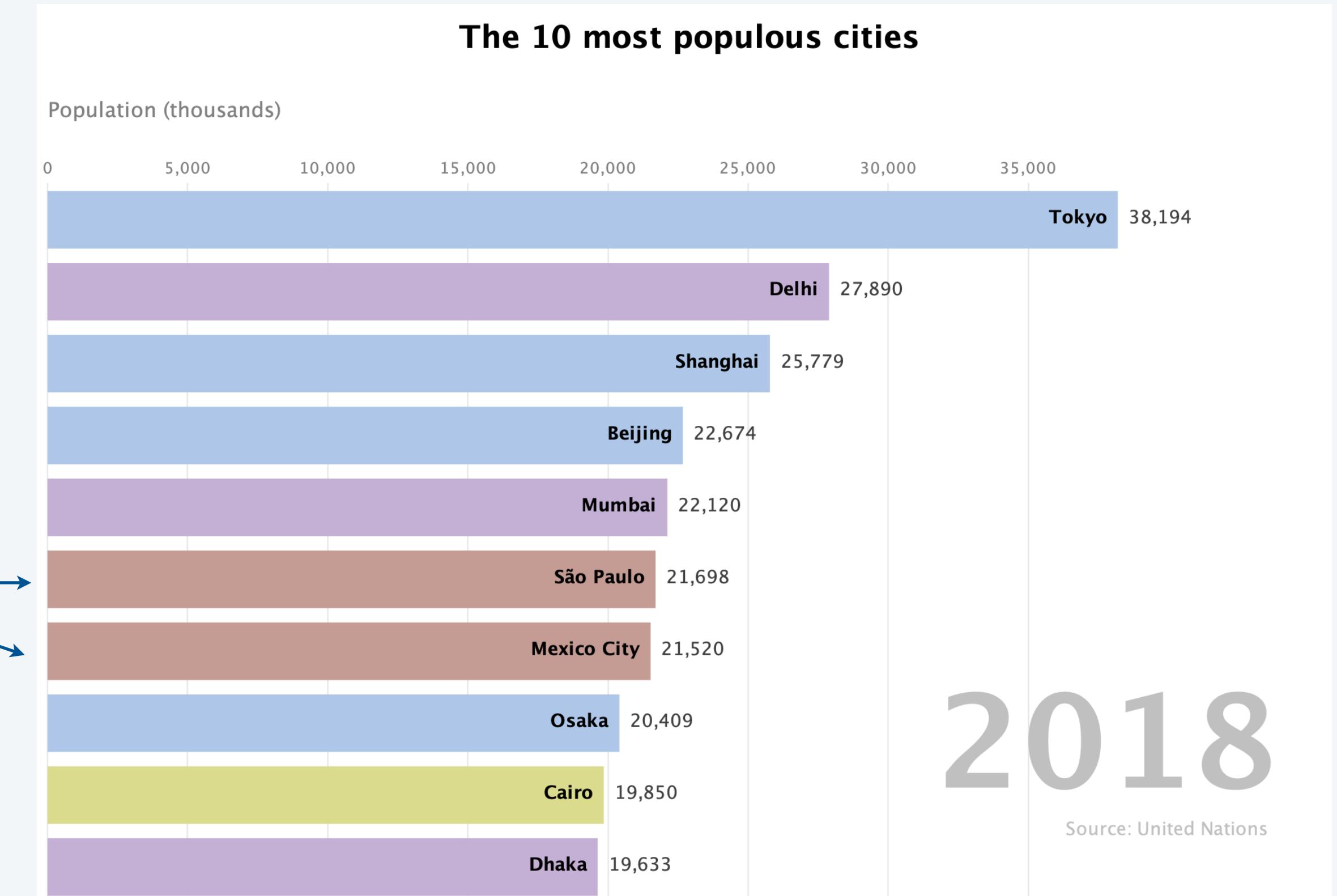
name and region



Challenge. Maintain auxiliary info when sorting.

Solution. Define helper [Bar](#) data type.

Latin America



bars appear in descending order by population

Bar data type

To create a user-defined data type for use with `Arrays.sort()`:

- Declare the data type to be Comparable.
- Include a `compareTo()` method that compares two objects.

```
public class Bar implements Comparable<Bar> {
    private final String name;
    private final int value;
    private final String category;

    public Bar(String name, int value, String category) {
        this.name = name;
        this.value = value;
        this.category = category;
    }

    public int compareTo(Bar that) {
        if (this.value < that.value) return -1;
        if (this.value > that.value) return +1;
        return 0;
    }
    ...
}
```

```
Bar[] bars = new Bar[10];
...
Arrays.sort(bars);
```

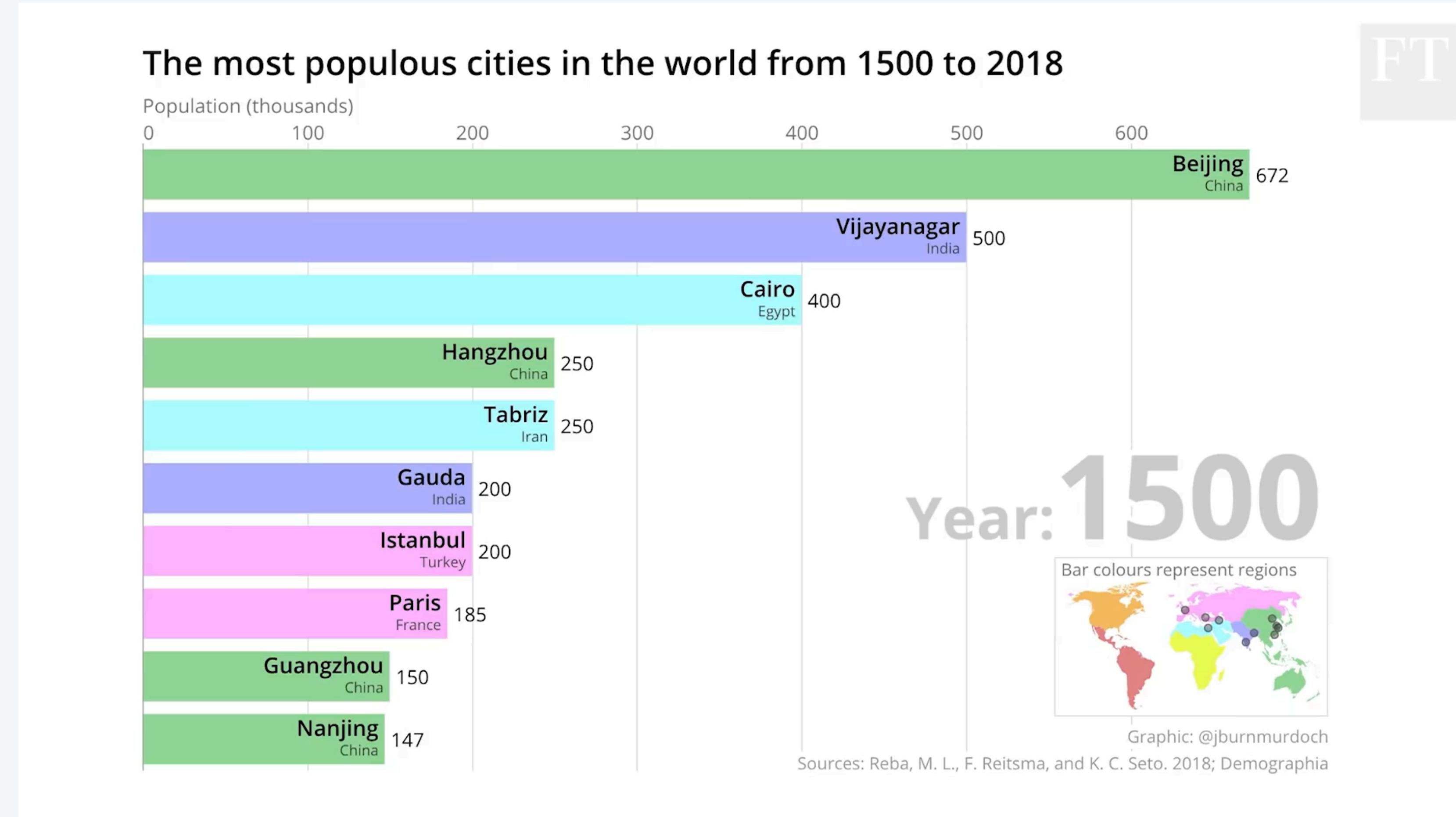
sort bars in ascending order by value

*return a negative integer (smaller),
positive integer (larger), or zero (equal)*



Bar chart race

Animated bar chart. Draw sorted bar chart (largest $k = 10$) for each year.



<https://www.youtube.com/watch?v=pMs5xapBewM>

Credits

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<i>java.util.Arrays API</i>	Oracle	
<i>Most Populous Cities</i>	John Burn-Murdoch	