



Algorithm Efficiency & Sorting

- Algorithm efficiency
- Big-O notation
- Searching algorithms
- Sorting algorithms



Overview

- Writing programs to solve problem consists of a large number of decisions
 - how to represent aspects of the problem for solution
 - which of several approaches to a given solution component to use
- If several algorithms are available for solving a given problem, the developer must choose among them
- If several ADTs can be used to represent a given set of problem data
 - which ADT should be used?
 - how will ADT choice affect algorithm choice?



Overview – 2

- If a given ADT (i.e. stack or queue) is attractive as part of a solution
- How will the ADT implementation affect the program's:
 - correctness and performance?
- Several goals must be balanced by a developer in producing a solution to a problem
 - correctness, clarity, and efficient use of computer resources to produce the best performance
- How is solution performance best measured?
 - *time* and *space*



Overview – 3

- The order of importance is, generally,
 - correctness
 - efficiency
 - clarity
- Clarity of expression is qualitative and somewhat dependent on perception by the reader
 - developer salary costs dominate many software projects
 - time efficiency of understanding code written by others can thus have a significant monetary implication
- Focus of this chapter is *execution efficiency*
 - mostly, run-time (some times, memory space)



Measuring Algorithmic Efficiency

- Analysis of algorithms
 - provides tools for contrasting the efficiency of different methods of solution
- Comparison of algorithms
 - should focus on *significant* differences in efficiency
 - should not consider reductions in computing costs due to clever coding tricks
- Difficult to compare programs instead of algorithms
 - how are the algorithms coded?
 - what computer should you use?
 - what data should the programs use?



Analyzing Algorithmic Cost

- Viewed abstractly, an algorithm is a sequence of steps
 - Algorithm A { S1; S2; Sm1; Sm }
- The total cost of the algorithm will thus, obviously, be the total cost of the algorithm's m steps
 - assume we have a function giving cost of each statement

Cost (S_i) = execution cost of S_i , for-all i , $1 \leq i \leq m$

- Total cost of the algorithm's m steps would thus be:

$$Cost (A) = \sum_{i=1}^m Cost (S_i)$$



Analyzing Algorithmic Cost – 2

- However, an algorithm can be applied to a wide variety of problems and data sizes
 - so we want a cost function for the algorithm A that takes the data set size n into account
$$Cost(A, n) = \sum_1^n (\sum_1^m (Cost(S_i)))$$
- Several factors complicate things
 - conditional statements: cost of evaluating condition and branch taken
 - loops: cost is sum of each of its iterations
 - recursion: may require solving a recurrence equation



Analyzing Algorithmic Cost – 3

- Do not attempt to accumulate a precise prediction for program execution time, because
 - far too many complicating factors: compiler instructions output, variation with specific data sets, target hardware speed
- Provide an approximation, an *order of magnitude* estimate, that permits fair comparison of one algorithm's behavior against that of another



Analyzing Algorithmic Cost – 4

- Various behavior bounds are of interest
 - best case, average case, worst case
- Worst-case analysis
 - A determination of the maximum amount of time that an algorithm requires to solve problems of size n
- Average-case analysis
 - A determination of the average amount of time that an algorithm requires to solve problems of size n
- Best-case analysis
 - A determination of the minimum amount of time that an algorithm requires to solve problems of size n



Analyzing Algorithmic Cost – 5

- Complexity measures can be calculated in terms of
 - $T(n)$: time complexity and $S(n)$: space complexity
- Basic model of computation used
 - sequential computer (one statement at a time)
 - all data require same amount of storage in memory
 - each datum in memory can be accessed in constant time
 - each basic operation can be executed in constant time
- Note that all of these assumptions are incorrect!
 - good for this purpose
- Calculations we want are order of magnitude



Example – Linked List Traversal

- Assumptions

C_1 = cost of assign.

C_2 = cost of compare

C_3 = cost of write }

```
Node *cur = head;    // assignment op
while (cur != NULL) // comparisons op
    cout << cur->item
        << endl;      // write op
    cur->next;         // assignment op
```

- Consider the number of operations for n items

$$\begin{aligned} T(n) &= (n+1)C_1 + (n+1)C_2 + nC_3 \\ &= (C_1+C_2+C_3)n + (C_1+C_2) = K_1n + K_2 \end{aligned}$$

- Says, algorithm is of linear complexity
 - work done grows linearly with n but also involves constants



Example – Sequential Search

- Number of comparisons

$$T_B(n) = 1$$

$$T_w(n) = n$$

$$T_A(n) = (n+1)/2$$

- In general, what developers worry about the most is that this is $O(n)$ algorithm
 - more precise analysis is nice but rarely influences algorithmic decision

Seq_Search(A: array, key: integer);

 i = 1;

 while i ≤ n and A[i] ≠ key do

 i = i + 1

 endwhile;

 if i ≤ n

 then return(i)

 else return(0)

 endif;

end Seq_Search;



Bounding Functions

- To provide a guaranteed bound on how much work is involved in applying an algorithm **A** to **n** items
 - we find a bounding function $f(n)$ such that

$$T(n) \leq f(n), \forall n$$

- It is often easier to satisfy a less stringent constraint by finding an elementary function $f(n)$ such that

$$T(n) \leq k * f(n), \text{ for sufficiently large } n$$

- This is denoted by the asymptotic **big-O** notation
- Algorithm A is $O(n)$ says
 - that complexity of A is no worse than $k*n$ as n grows sufficiently large



Asymptotic Upper Bound

- Defn: A function f is positive if $f(n) > 0, \forall n > 0$
- Defn: Given a positive function $f(n)$, then

$$f(n) = O(g(n))$$

iff there exist constants $k > 0$ and $n_0 > 0$ such that

$$f(n) \leq k * g(n), \forall n > n_0$$

- Thus, $g(n)$ is an asymptotic bounding function for the work done by the algorithm
- k and n_0 can be *any* constants
 - can lead to unsatisfactory conclusions if they are very large and a developer's data set is relatively small



Asymptotic Upper Bound – 2

- Example: show that: $2n^2 - 3n + 10 = O(n^2)$
- Observe that
$$2n^2 - 3n + 10 \leq 2n^2 + 10, n > 1$$
$$2n^2 - 3n + 10 \leq 2n^2 + 10, n^2 n > 1$$
$$2n^2 - 3n + 10 \leq 12n^2, n > 1$$
- Thus, expression is $O(n^2)$ for $k = 12$ and $n_0 > 1$ (also $k = 3$ and $n_0 > 1$, BTW)
 - algorithm efficiency is typically a concern for large problems only
- Then, $O(f(n))$ information helps choose a set of final candidates and direct measurement helps final choice

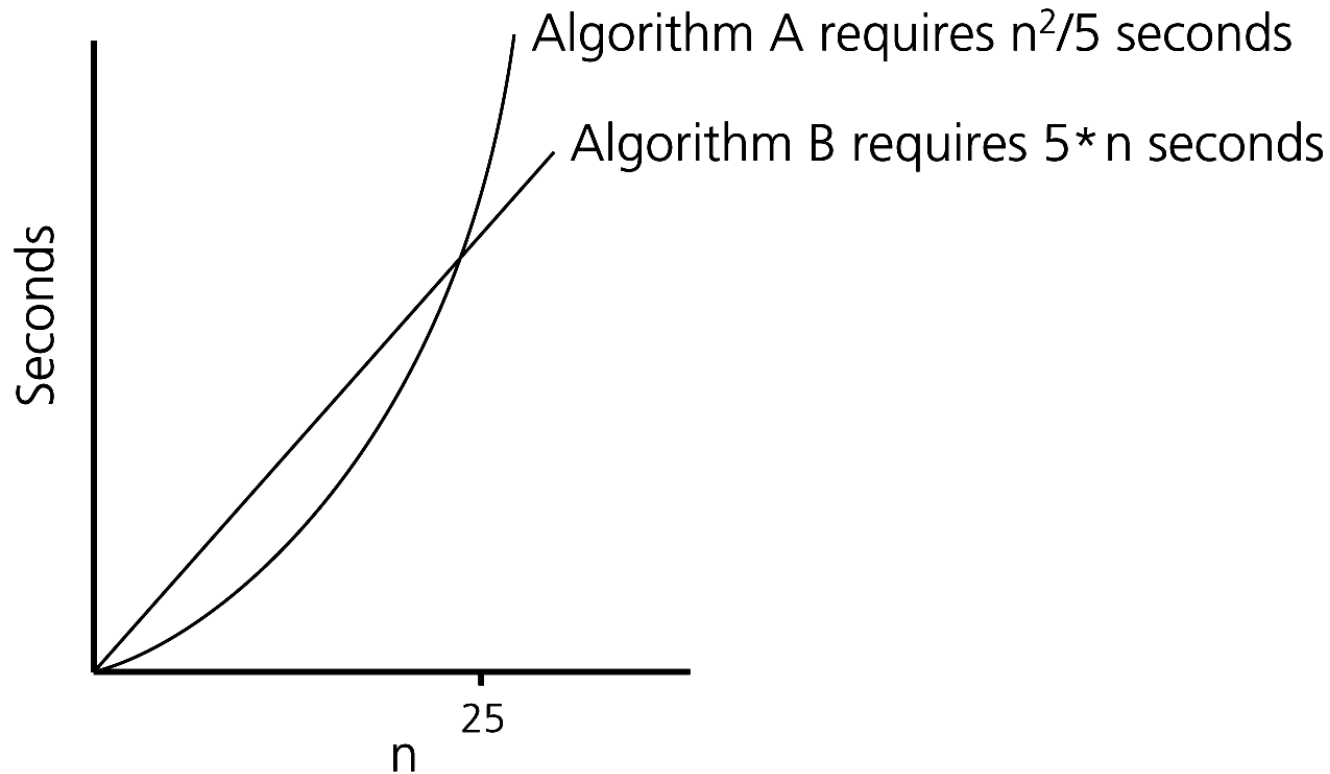


Algorithm Growth Rates

- An algorithm's time requirements can be measured as a function of the problem size
 - Number of nodes in a linked list
 - Size of an array
 - Number of items in a stack
 - Number of disks in the Towers of Hanoi problem



Algorithm Growth Rates – 2



- Algorithm A requires time proportional to n^2
- Algorithm B requires time proportional to n



Algorithm Growth Rates – 3

- An algorithm's growth rate enables comparison of one algorithm with another
- Example
 - if, algorithm A requires time proportional to n^2 , and algorithm B requires time proportional to n
 - algorithm B is faster than algorithm A
 - n^2 and n are growth-rate functions
 - Algorithm A is $O(n^2)$ - order n^2
 - Algorithm B is $O(n)$ - order n
- Growth-rate function $f(n)$
 - mathematical function used to specify an algorithm's order in terms of the size of the problem



Order-of-Magnitude Analysis and Big O Notation

(a)

Function	n					
	10	100	1,000	10,000	100,000	1,000,000
1	1	1	1	1	1	1
$\log_2 n$	3	6	9	13	16	19
n	10	10^2	10^3	10^4	10^5	10^6
$n * \log_2 n$	30	664	9,965	10^5	10^6	10^7
n^2	10^2	10^4	10^6	10^8	10^{10}	10^{12}
n^3	10^3	10^6	10^9	10^{12}	10^{15}	10^{18}
2^n	10^3	10^{30}	10^{301}	$10^{3,010}$	$10^{30,103}$	$10^{301,030}$

Figure 9-3a A comparison of growth-rate functions: (a) in tabular form



Order-of-Magnitude Analysis and Big O Notation

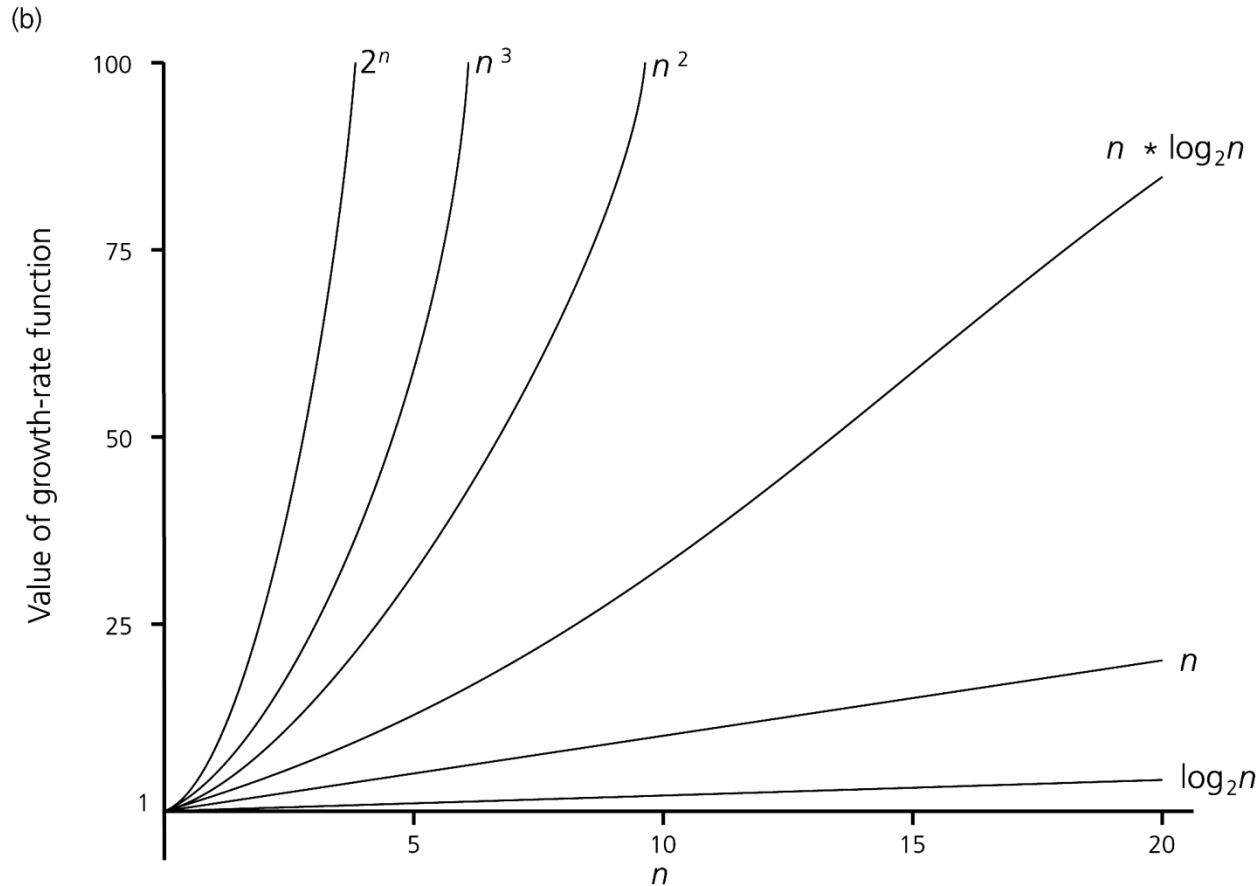


Figure 9-3b A comparison of growth-rate functions: (b) in graphical form



Order-of-Magnitude Analysis and Big O Notation

- Order of growth of some common functions
 - $O(C) < O(\log(n)) < O(n) < O(n * \log(n)) < O(n^2) < O(n^3) < O(2^n) < O(3^n) < O(n!) < O(n^n)$
- Properties of growth-rate functions
 - $O(n^3 + 3n)$ is $O(n^3)$: ignore low-order terms
 - $O(5 f(n)) = O(f(n))$: ignore multiplicative constant in the high-order term
 - $O(f(n)) + O(g(n)) = O(f(n) + g(n))$



Keeping Your Perspective

- Only significant differences in efficiency are interesting
- Frequency of operations
 - when choosing an ADT's implementation, consider how frequently particular ADT operations occur in a given application
 - however, some seldom-used but critical operations must be efficient



Keeping Your Perspective

- If the problem size is always small, you can probably ignore an algorithm's efficiency
 - order-of-magnitude analysis focuses on large problems
- Weigh the trade-offs between an algorithm's time requirements and its memory requirements
- Compare algorithms for both style and efficiency



Sequential Search

- Sequential search
 - look at each item in the data collection in turn
 - stop when the desired item is found, or the end of the data is reached

```
int search(const int a[ ], int number_used, int target) {  
    int index = 0; bool found = false;  
    while ((!found) && (index < number_used)) {  
        if (target == a[index])  
            found = true;  
        else  
            index++;  
    }  
    if (found) return index;  
    else return -1;  
}
```




Efficiency of Sequential Search

- Worst case: $O(n)$
 - key value not present, we search the entire list to prove failure
- Average case: $O(n)$
 - all positions for the key being equally likely
- Best case: $O(1)$
 - key value happens to be first



The Efficiency of Searching Algorithms

- Binary search of a sorted array
 - Strategy
 - Repeatedly divide the array in half
 - Determine which half could contain the item, and discard the other half
 - Efficiency
 - Worst case: $O(\log_2 n)$
 - For large arrays, the binary search has an enormous advantage over a sequential search
 - At most 20 comparisons to search an array of one million items



Sorting Algorithms and Their Efficiency

- Sorting
 - A process that organizes a collection of data into either ascending or descending order
 - The sort key is the data item that we consider when sorting a data collection
- Sorting algorithm types
 - comparison based
 - bubble sort, insertion sort, quick sort, etc.
 - address calculation
 - radix sort



Sorting Algorithms and Their Efficiency

- Categories of sorting algorithms
 - An internal sort
 - Requires that the collection of data fit entirely in the computer's main memory
 - An external sort
 - The collection of data will not fit in the computer's main memory all at once, but must reside in secondary storage



Selection Sort

- Strategy
 - Place the largest (or smallest) item in its correct place
 - Place the next largest (or next smallest) item in its correct place, and so on
- Algorithm

```
for index=0 to size-2 {  
    select min/max element from among A[index], ..., A[size-1];  
    swap(A[index], min);  
}
```
- Analysis
 - worst case: $O(n^2)$, average case: $O(n^2)$
 - does not depend on the initial arrangement of the data



Selection Sort

Shaded elements are selected;
boldface elements are in order.

Initial array:

29	10	14	37	13
----	----	----	----	----

After 1st swap:

29	10	14	13	37
----	----	----	----	-----------

After 2nd swap:

13	10	14	29	37
----	----	----	-----------	-----------

After 3rd swap:

13	10	14	29	37
----	----	-----------	-----------	-----------

After 4th swap:

10	13	14	29	37
-----------	-----------	-----------	-----------	-----------



Bubble Sort

- Strategy
 - compare adjacent elements and exchange them if they are out of order
 - moves the largest (or smallest) elements to the end of the array
 - repeat this process
 - eventually sorts the array into ascending (or descending) order
- Analysis: worst case: $O(n^2)$, best case: $O(n)$



Bubble Sort – algorithm

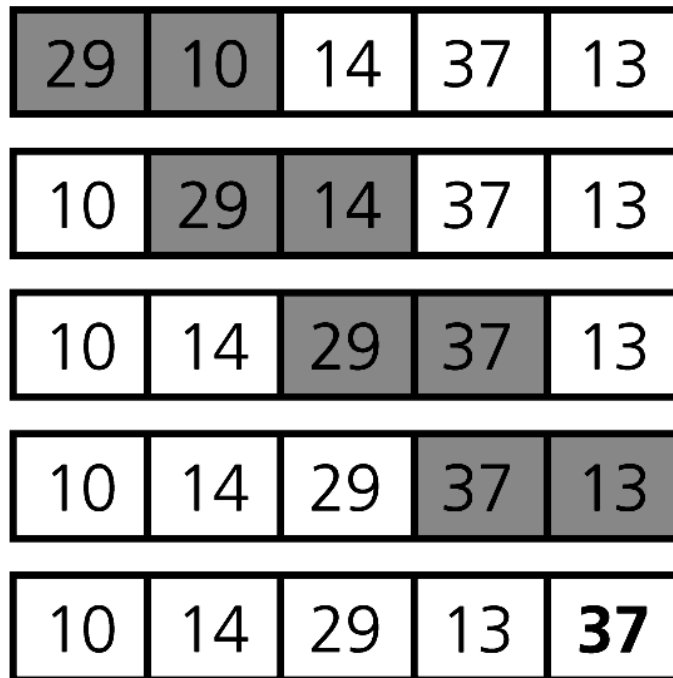
```
for i = 1 to size - 1 do
  for index = 1 to size - i do
    if A[index] < A[index-1]
      swap(A[index], A[index-1]);
    endfor;
  endfor;
```




Bubble Sort

(a) Pass 1

Initial array:



(b) Pass 2

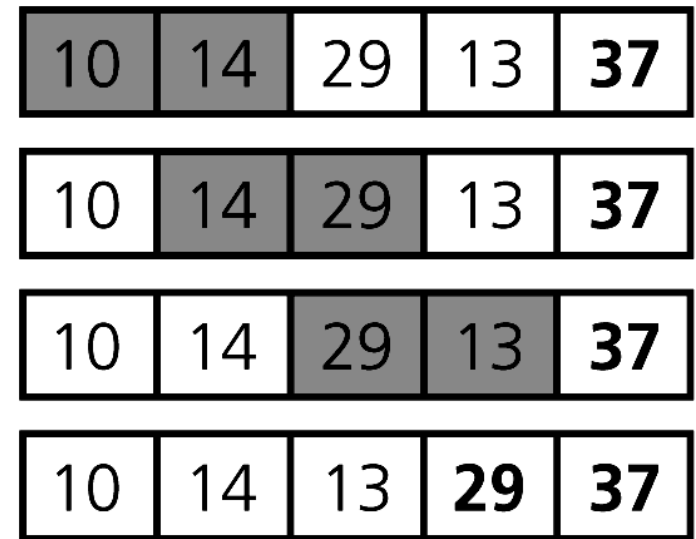


Figure 9-5

The first two passes of a bubble sort of an array of five integers: (a) pass 1; (b) pass 2



Insertion Sort

- Strategy
 - Partition array in two regions: sorted and unsorted
 - initially, entire array is in unsorted region
 - take each item from the unsorted region and insert it into its correct position in the sorted region
 - each *pass* shrinks unsorted region by 1 and grows sorted region by 1
- Analysis
 - Worst case: $O(n^2)$
 - Appropriate for small arrays due to its simplicity
 - Prohibitively inefficient for large arrays

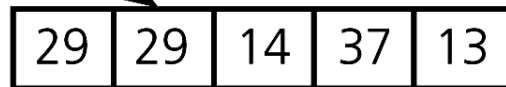


Insertion Sort

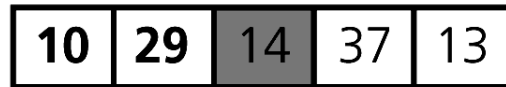
Initial array:



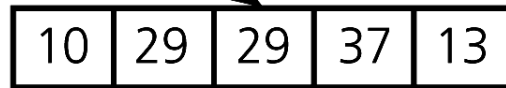
Copy 10



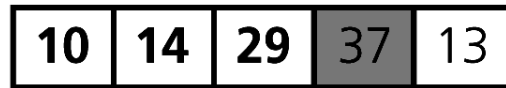
Shift 29



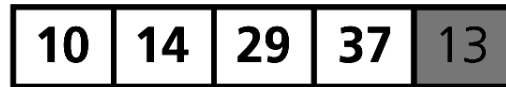
Insert 10; copy 14



Shift 29



Insert 14; copy 37, insert 37 on top of itself



Copy 13



Shift 37, 29, 14

Sorted array:



Insert 13

Figure 9-7 An insertion sort of an array of five integers.



Mergesort

- A recursive sorting algorithm
- Performance is independent of the initial order of the array items
- Strategy
 - divide an array into halves
 - sort each half
 - merge the sorted halves into one sorted array
 - divide-and-conquer approach



Mergesort – Algorithm

```
mergeSort(A,first,last) {  
    if (first < last) {  
        mid = (first + last)/2;  
        mergeSort(A, first, mid);  
        mergeSort(A, mid+1, last);  
        merge(A, first, mid, last)  
    }  
}
```



Mergesort

theArray:

8	1	4	3	2
---	---	---	---	---

Divide the array in half

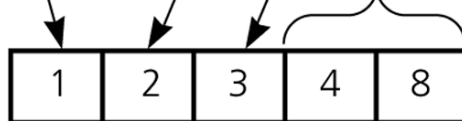


Sort the halves

Merge the halves:

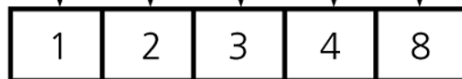
- a. $1 < 2$, so move 1 from left half to **tempArray**
- b. $4 > 2$, so move 2 from right half to **tempArray**
- c. $4 > 3$, so move 3 from right half to **tempArray**
- d. Right half is finished, so move rest of left half to **tempArray**

Temporary array
tempArray:



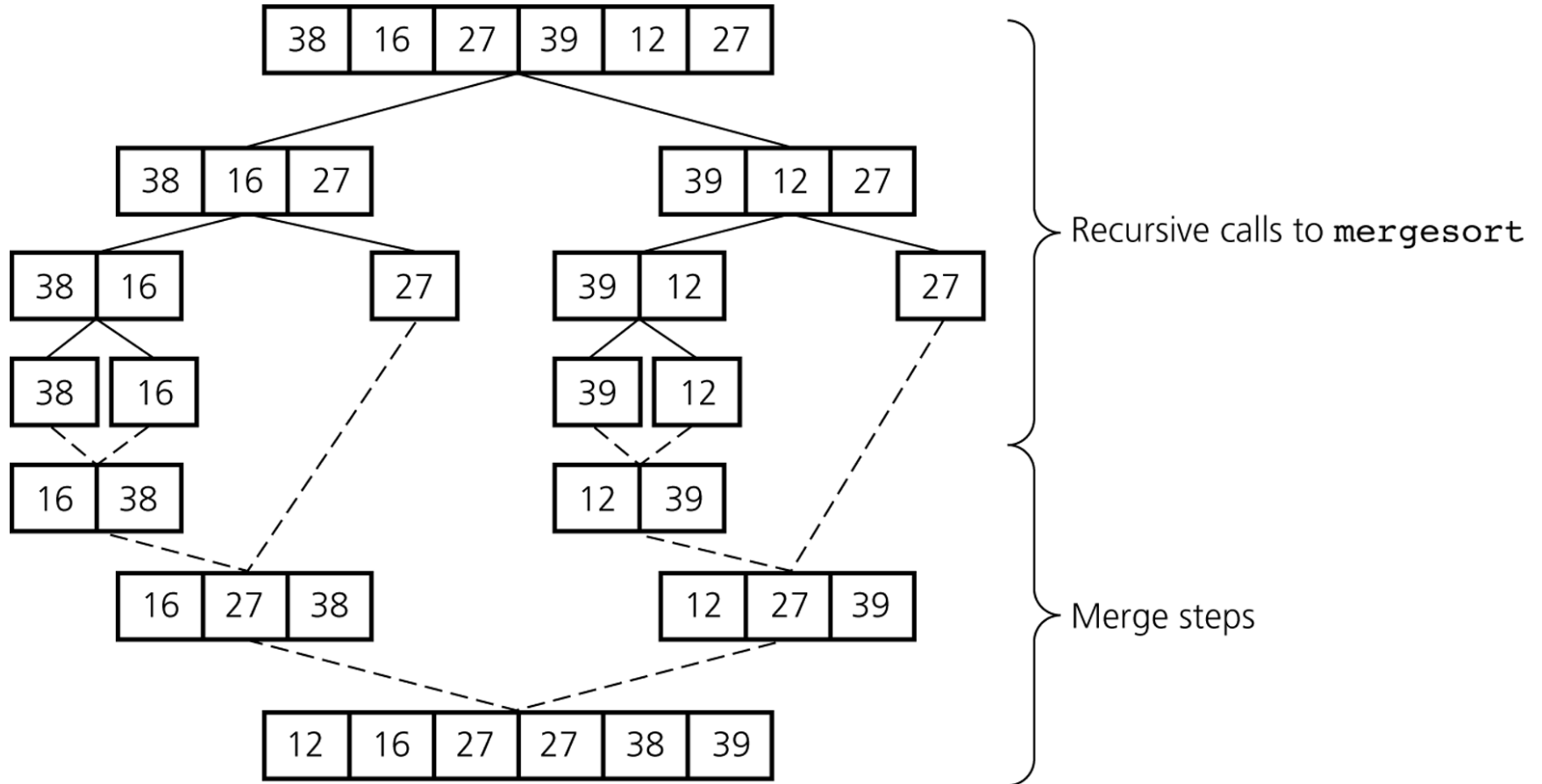
Copy temporary array back into
original array

theArray:





Mergesort





Mergesort – Properties

- Needs a temporary array into which to copy elements during merging
 - doubles space requirement
- Mergesort is *stable*
 - items with equal key values appear in the same order in the output array as in the input
- Advantage
 - mergesort is an extremely fast algorithm
- Analysis: worst / average case: $O(n * \log_2 n)$



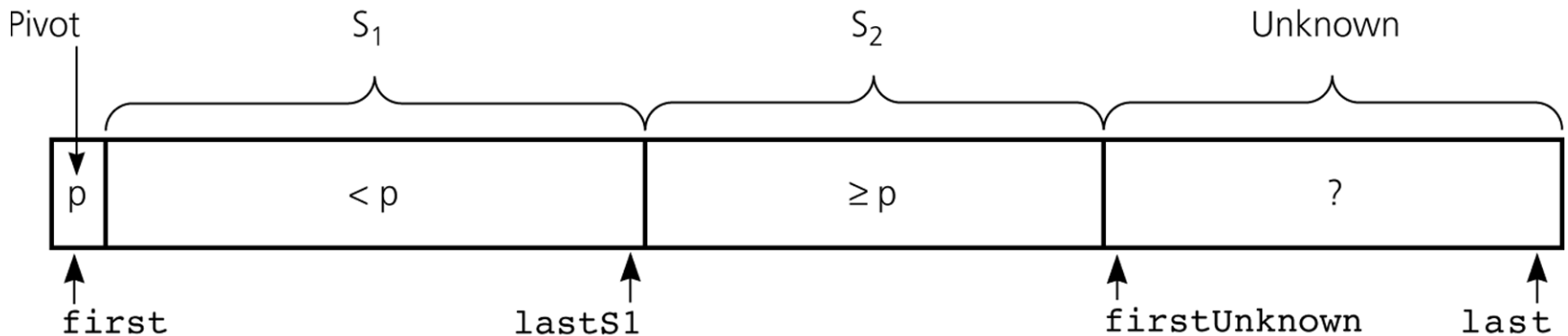
Quicksort

- A recursive divide-and-conquer algorithm
 - given a linear data structure A with n records
 - divide A into sub-structures S_1 and S_2
 - sort S_1 and S_2 recursively
- Algorithm
 - Base case: if $|S| == 1$, S is already sorted
 - Recursive case:
 - divide A around a pivot value P into S_1 and S_2 , such that all elements of $S_1 \leq P$ and all elements of $S_2 \geq P$
 - recursively sort S_1 and S_2 in place



Quicksort

- Partition()
 - (a) scans array, (b) chooses a pivot, (c) divides A around pivot, (d) returns pivot index
 - Invariant: items in S_1 are all less than pivot, and items in S_2 are all greater than or equal to pivot
- Quicksort()
 - partitions A, sorts S_1 and S_2 recursively





Quicksort – Pivot Partitioning

- Pivot selection and array partition are fundamental work of algorithm
- Pivot selection
 - perfect value: median of $A[]$
 - sort required to determine median (oops!)
 - approximation: If $|A| > N$, $N==3$ or $N==5$, use median of N
 - Heuristic approaches used instead
 - Choose $A[\text{first}]$ OR $A[\text{last}]$ OR $A[\text{mid}]$ ($\text{mid} = (\text{first} + \text{last}) / 2$) OR Random element
 - heuristics equivalent if contents of $A[]$ randomly arranged



Quicksort – Pivot Partitioning Example

- $A = [5, 8, 3, 7, 4, 2, 1, 6]$, $\text{first} = 0$, $\text{last} = 7$
- $A[\text{first}]$: pivot = 5, $A[\text{last}]$: pivot = 6,
- $A[\text{mid}]$: $\text{mid} = (0+7)/2=3$, pivot = 7
- $A[\text{random}()]$: any key might be chosen
- $A[\text{medianof3}]$: $\text{median}(A[\text{first}], A[\text{mid}], A[\text{last}])$ is $\text{median}(5, 7, 6) = 6$
 - a sort of a fixed number of items is only $O(1)$
- Good pivot selection
 - computed in $O(1)$ time and partitions A into roughly equal parts $S1$ and $S2$



Quicksort – Pivot Partitioning

- Middle element is pivot
- lastS1: index of last element of S1 partition
- firstUnknown: first element needing classification
 - if $< p$, then add to first partition by incrementing last S1 and swapping
 - incrementing firstUnknown expands partitioned sets either way
- Partitioning is an $O(n)$ operation over $A[]$

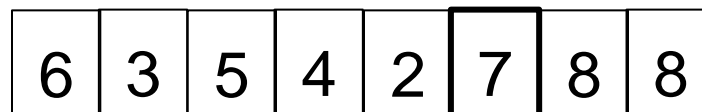
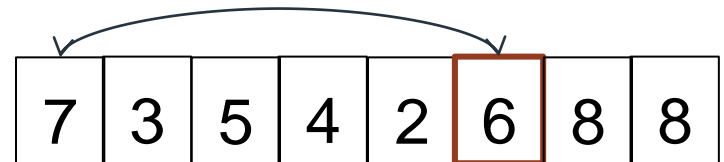
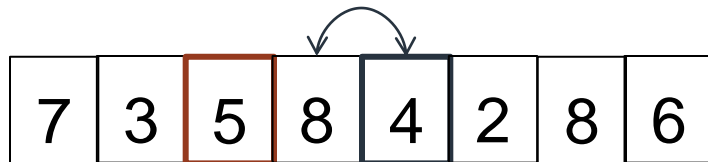
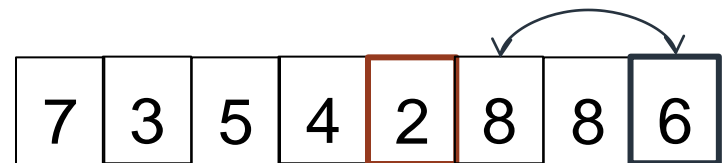
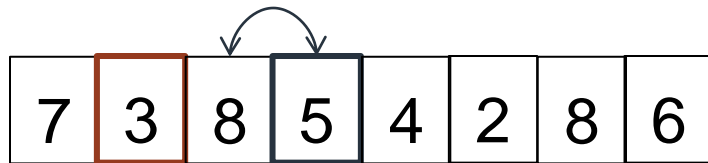
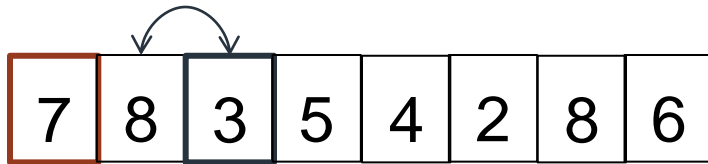
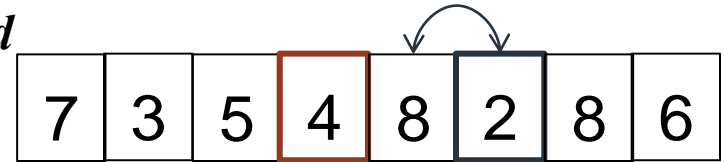
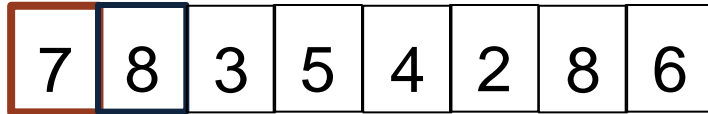
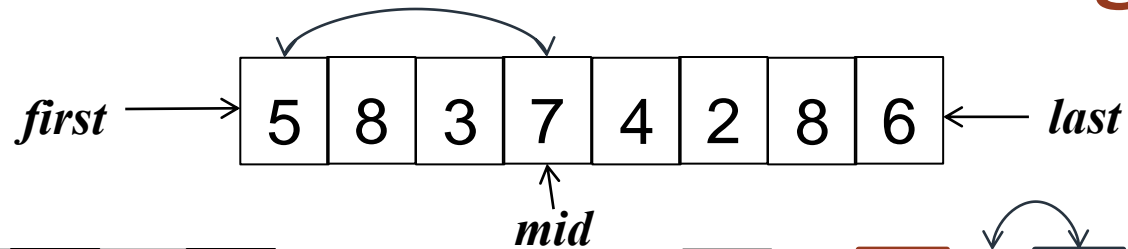
```
int partition(A,first,last) {  
    middle = (first+last)/2;  
    pivot = A[middle];  
    swap(A[middle],A[first]);  
    lastS1 = first;  
    firstUnknown = first+1;  
    while( firstUnknown <= last ) {  
        if (A[firstUnknown] < pivot) {  
            lastS1++;  
            swap(A[firstUnknown],A[lastS1]);  
        }  
        firstUnknown++;  
    }  
    swap(A[first],A[lastS1]);  
    pivotIndex = lastS1;  
    return(pivotIndex);  
}
```



Quicksort – Pivot Partitioning

 lastS1

 firstUnknown



pivotIndex = 5

S1 = *A*[0..4]

S2 = *A*[6..7]



Quicksort – Analysis

- Best case
 - perfect partition at each level, $\log_2 n$ levels
 - $O(n \log n)$ total
- Average case
 - roughly equal partition
 - $O(n \log n)$
- Worst case
 - S1 or S2 always empty
 - When the array is already sorted and the smallest item is chosen as the pivot
 - $O(n^2)$, n levels, rare as long as input is in random order



Quicksort – Analysis

- Partitioning and recursive call overhead is such that for $|A| < 10$ or so it is faster to simply use insertion sort
 - precise tipping point will vary with architecture
 - but, Quicksort is usually extremely fast in practice
- Not stable like Mergesort, but sorts in place
- Even if the worst case occurs, quicksort's performance is acceptable for moderately large arrays



Radix Sort

- Radix sort is a special kind of distribution sort that can efficiently sort data items using integer or other t element keys $(a_t a_{t-1} \dots a_0)_m$ in a given radix (base) m
 - character string keys work as well; total order of all characters required
- Strategy
 - Treats each data element as a character string
 - Repeatedly organizes the data into groups according to the i^{th} character in each element



Radix Sort

- Basic idea
 - each key consists of t places, each holding one of m possible values
 - use m buckets and iterate the basic algorithm t times, each time using a different element of the key for sorting
 - iterate from least significant to most significant key position
 - 12345 – Five digit key, iterated over $10^0, 10^1, 10^2, 10^3, 10^4$ using buckets 0-9 each time
 - FRED – Four character keys using capital letters, iterated from right to left using 26 buckets A-Z each time
- Analysis: Radix sort is $O(n)$



Radix Sort

0123, 2154, 0222, 0004, 0283, 1560, 1061, 2150	Original integers
(156 0 , 215 0) (106 1) (022 2) (012 3 , 028 3) (215 4 , 000 4)	Grouped by fourth digit
1560, 2150, 1061, 0222, 0123, 0283, 2154, 0004	Combined
(000 4) (022 2 , 012 3) (215 0 , 215 4) (156 0 , 106 1) (028 3)	Grouped by third digit
0004, 0222, 0123, 2150, 2154, 1560, 1061, 0283	Combined
(000 4 , 106 1) (012 3 , 215 0 , 215 4) (022 2 , 028 3) (156 0)	Grouped by second digit
0004, 1061, 0123, 2150, 2154, 0222, 0283, 1560	Combined
(000 4 , 012 3 , 022 2 , 028 3) (106 1 , 156 0) (215 0 , 215 4)	Grouped by first digit
0004, 0123, 0222, 0283, 1061, 1560, 2150, 2154	Combined (sorted)

Figure 9-21 A radix sort of eight integers



A Comparison of Sorting Algorithms

	<u>Worst case</u>	<u>Average case</u>
Selection sort	n^2	n^2
Bubble sort	n^2	n^2
Insertion sort	n^2	n^2
Mergesort	$n * \log n$	$n * \log n$
Quicksort	n^2	$n * \log n$
Radix sort	n	n
Treesort	n^2	$n * \log n$
Heapsort	$n * \log n$	$n * \log n$

Figure 9-22 Approximate growth rates of time required for eight sorting algorithms



Summary

- Order-of-magnitude analysis and Big O notation measure an algorithm's time requirement as a function of the problem size by using a growth-rate function
- To compare the efficiency of algorithms
 - examine growth-rate functions when problems are large
 - consider only significant differences in growth-rate functions



Summary

- Worst-case and average-case analyses
 - worst-case analysis considers the maximum amount of work an algorithm will require on a problem of a given size
 - average-case analysis considers the expected amount of work that an algorithm will require on a problem of a given size



Summary

- Worst case complexity of sorting algorithms

	Input in Sorted Order	Input in Reverse Sorted Order
Bubble Sort	$O(n)$	$O(n^2)$
Insertion Sort	$O(n)$	$O(n^2)$
Selection Sort	$O(n^2)$	$O(n^2)$
Merge Sort	$O(n \log n)$	$O(n \log n)$
Quick Sort	$O(n^2)$	$O(n^2)$
Radix Sort	$O(n)$	$O(n)$



Summary

- Complexity of sorting algorithms for random data, most common case

	TB(n)	TW(n)	TA(n)
Bubble	$O(n)$	$O(n^2)$	$O(n^2)$
Insertion	$O(n)$	$O(n^2)$	$O(n^2)$
Selection	$O(n^2)$	$O(n^2)$	$O(n^2)$
Merge	$O(n \log n)$	$O(n \log n)$	$O(n \log n)$
Quicksort	$O(n \log n)$	$O(n^2)$	$O(n \log n)$
Radix	$O(n)$	$O(n)$	$O(n)$



Summary

- Stability of sorting algorithms
 - stable sort preserves the input order of data items with identical keys
 - Thus, if input items x and y have identical keys, and x precedes y in the input data set, x will precede y in the output sorted data set
 - bubble, insertion, selection, merge, and radix are stable sorting algorithms