

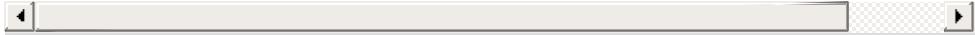
19.4 Binary Search

The **binary search algorithm** is more efficient than linear search, but it requires that the array be sorted. The first iteration of this algorithm tests the *middle* element in the array. If this matches the search key, the algorithm ends. Assuming the array is sorted in *ascending* order, then if the search key is *less than* the middle element, it cannot match any element in the second half of the array and the algorithm continues with only the first half of the array (i.e., the first element up to, but not including, the middle element). If the search key is *greater than* the middle element, it cannot match any element in the first half of the array and the algorithm continues with only the second half (i.e., the element *after* the middle element through the last element). Each iteration tests the middle value of the remaining portion of the array. If the search key does not match the element, the algorithm eliminates half of the remaining elements. The algorithm ends by either finding an element that matches the search key or reducing the subarray to zero size.

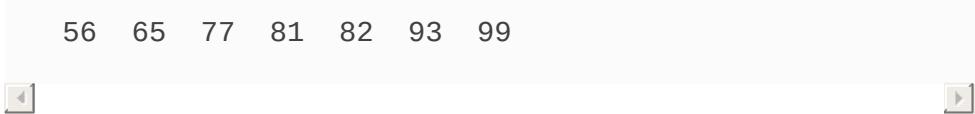
Example

As an example consider the sorted 15-element array

2 3 5 10 27 30 34 51 56 65 77 81 82 93



and a search key of 65. A program implementing the binary search algorithm would first check whether 51 is the search key (because 51 is the *middle* element of the array). The search key (65) is larger than 51, so 51 is ignored along with the first half of the array (all elements smaller than 51), leaving



Next, the algorithm checks whether 81 (the middle element of the remainder of the array) matches the search key. The search key (65) is smaller than 81, so 81 is discarded along with the elements larger than 81. After just two tests, the algorithm has narrowed the number of values to check to only three (56, 65 and 77). It then checks 65 (which indeed matches the search key) and returns the index of the array element containing 65. This algorithm required just three comparisons to determine whether the search key matched an element of the array. Using a linear search algorithm would have required 10 comparisons.

[*Note:* In this example, we've chosen to use an array with 15 elements so that there will always be an obvious middle element in the array. With an even number of elements, the middle of the array lies between two elements. We implement the algorithm to choose the higher of those two elements.]

19.4.1 Binary Search

Implementation

Class `BinarySearchTest` (Fig. 19.3) contains:

- `static` method `binarySearch` to search an `int` array for a specified key,
- `static` method `remainingElements` to display the remaining elements in the array being searched, and
- `main` to test method `binarySearch`.

8

The `main` method (lines 60–89) is nearly identical to `main` in Fig. 19.2. In this program, line 65 creates a 15-element stream (Java SE 8) of random values, sorts the values into ascending order, then converts the stream’s elements to an array of `ints`. Recall that the binary search algorithm will work only on a *sorted* array. The first line of output from this program shows the sorted array of `ints`. When the user instructs the program to search for `18`, the program first tests the middle element, which is `57` (as indicated by `*`) in our sample execution. The search key is less than `57`, so the program eliminates the second half of the array and tests the middle element from the first half. The search key is smaller than `36`, so the program eliminates the second half of the array, leaving only three elements. Finally, the program checks `18` (which matches the search key) and returns the index `1`.

```
1  // Fig. 19.3: BinarySearchTest.java
2  // Use binary search to locate an item in an arr
3  import java.security.SecureRandom;
```

```
4  import java.util.Arrays;
5  import java.util.Scanner;
6
7  public class BinarySearchTest {
8      // perform a binary search on the data
9      public static int binarySearch(int[] data, in
10         int low = 0; // low end of the search area
11         int high = data.length - 1; // high end of
12         int middle = (low + high + 1) / 2; // midd
13         int location = -1; // return value; -1 if
14
15         do { // loop to search for element
16             // print remaining elements of array
17             System.out.print(remainingElements(data
18
19             // output spaces for alignment
20             for (int i = 0; i < middle; i++) {
21                 System.out.print(" ");
22             }
23             System.out.println(" * "); // indicate
24
25             // if the element is found at the middl
26             if (key == data[middle]) {
27                 location = middle; // location is th
28             }
29             else if (key < data[middle]) { // middl
30                 high = middle - 1; // eliminate the
31             }
32             else { // middle element is too low
33                 low = middle + 1; // eliminate the l
34             }
35
36             middle = (low + high + 1) / 2; // recal
37         } while ((low <= high) && (location == -1)
38
39         return location; // return location of sea
40     }
41
42     // method to output certain values in array
43     private static String remainingElements(
```

```
44         int[] data, int low, int high) {  
45             StringBuilder temporary = new StringBuilder()  
46             46  
47                 // append spaces for alignment  
48                 for (int i = 0; i < low; i++) {  
49                     temporary.append(" ");  
50                 }  
51  
52                 // append elements left in array  
53                 for (int i = low; i <= high; i++) {  
54                     temporary.append(data[i] + " ");  
55                 }  
56  
57             return String.format("%s%n", temporary);  
58         }  
59  
60         public static void main(String[] args) {  
61             Scanner input = new Scanner(System.in);  
62             SecureRandom generator = new SecureRandom()  
63  
64             // create array of 15 random integers in s  
65             int[] data = generator.ints(15, 10, 91).so  
66             System.out.printf("%s%n%n", Arrays.toStrin  
67  
68                 // get input from user  
69                 System.out.print("Please enter an integer  
70                 int searchInt = input.nextInt();  
71  
72                 // repeatedly input an integer; -1 termina  
73                 while (searchInt != -1) {  
74                     // perform search  
75                     int location = binarySearch(data, searc  
76  
77                     if (location == -1) { // not found  
78                         System.out.printf("%d was not found%  
79                         }  
80                     else { // found  
81                         System.out.printf("%d was found in p  
82                                         searchInt, location);  
83                         }  
84  
85             }  
86  
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```

```
84
85          // get input from user
86      System.out.print("Please enter an integ
87          searchInt = input.nextInt();
88          }
89          }
90      }
```

[◀ ▶]

```
[13, 18, 29, 36, 42, 47, 56, 57, 63, 68, 80, 81, 82,
Please enter an integer value (-1 to quit): 18
13 18 29 36 42 47 56 57 63 68 80 81 82 88 88
*
13 18 29 36 42 47 56
*
13 18 29
*
18 was found in position 1
```

[◀ ▶]

```
Please enter an integer value (-1 to quit): 82
13 18 29 36 42 47 56 57 63 68 80 81 82 88 88
*
63 68 80 81 82 88 88
*
82 88 88
*
82
*
82 was found in position 12
```

```
Please enter an integer value (-1 to quit): 69
13 18 29 36 42 47 56 57 63 68 80 81 82 88 88
*
63 68 80 81 82 88 88
*
63 68 80
*
```

```
80
*
69 was not found

Please enter an integer value (-1 to quit): -1
```

Fig. 19.3

Use binary search to locate an item in an array (the * in the output marks the middle element).

Lines 9–40 declare method **binarySearch**, which receives as parameters the array to search (**data**) and the search key (**key**). Lines 10–12 calculate the **low** end index, **high** end index and **middle** index of the portion of the array that the program is currently searching. At the beginning of the method, the **low** end is **0**, the **high** end is the length of the array minus **1** and the **middle** is the average of these two values. Line 13 initializes the **location** of the element to **-1** —the value that will be returned if the **key** is not found. Lines 15–37 loop until **low** is greater than **high** (this occurs when the **key** is not found) or **location** does not equal **-1** (indicating that the **key** was found). Line 26 tests whether the value in the **middle** element is equal to the **key**. If so, line 27 assigns **middle** to **location**, the loop terminates and **location** is returned to the caller. Each iteration of the loop tests a single value (line 26) and *eliminates half of the remaining values in the array* (lines 29–31 or 32–34) if the value is not the **key**.

19.4.2 Efficiency of the Binary Search

In the worst-case scenario, searching a *sorted* array of 1023 elements takes *only 10 comparisons* when using a binary search. Repeatedly dividing 1023 by 2 (because after each comparison we can eliminate half the array) and rounding down (because we also remove the middle element) yields the values 511, 255, 127, 63, 31, 15, 7, 3, 1 and 0. The number 1023 ($2^{10} - 1$) is divided by 2 only 10 times to get the value 0, which indicates that there are no more elements to test.

Dividing by 2 is equivalent to one comparison in the binary search algorithm. Thus, an array of 1,048,575 ($2^{20} - 1$) elements takes a *maximum of 20 comparisons* to find the key, and an array of over one billion elements takes a *maximum of 30 comparisons* to find the key. This is a tremendous improvement in performance over the linear search. For a one-billion-element array, this is a difference between an average of 500 million comparisons for the linear search and a maximum of only 30 comparisons for the binary search! The maximum number of comparisons needed for the binary search of any sorted array is the exponent of the first power of 2 greater than the number of elements in the array, which is represented as $\log_2 n$. All logarithms grow at roughly the same rate, so in big O notation the base can be omitted. This results in a big O of $O(\log n)$ for a binary search, which is also known as **logarithmic run time** and pronounced as “order log n.”