Analysis of Algorithms

Outline

Algorithmic Complexity

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Time complexity of a program is how long it will take to solve a problem

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Time complexity of a program is how long it will take to solve a problem

Space complexity of a program is how much memory it will need to solve a problem

Time Complexity

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Program: `ThreeSum.java`

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- Command-line input: a filename (String)

Time Complexity

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- Command-line input: a filename (String)
- Standard output: the number of unordered triples (x, y, z) in the file such that $x + y + z = 0$

Time Complexity

Program: `ThreeSum.java`

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```
>_ ~/workspace/dsaj/programs

$ _
```

Time Complexity

Program: `ThreeSum.java`

- Command-line input: a filename (String)
- Standard output: the number of unordered triples (x, y, z) in the file such that $x + y + z = 0$

```
>_ ~/workspace/dsaj/programs

$ cat ../data/1Kints.txt
```

Program: `ThreeSum.java`

- Command-line input: a filename (String)
- Standard output: the number of unordered triples (x, y, z) in the file such that $x + y + z = 0$

```
>_ ~/workspace/dsaj/programs

$ cat ../data/1Kints.txt
 324110
-442472
...
 745942
$ _
```

Time Complexity

Program: `ThreeSum.java`

- Command-line input: a filename (String)
- Standard output: the number of unordered triples (x, y, z) in the file such that $x + y + z = 0$

```
>_ ~/workspace/dsaj/programs

$ cat ../data/1Kints.txt
 324110
-442472
...
 745942
$ /usr/bin/time -f "%es" java ThreeSum ../data/1Kints.txt
```

Time Complexity

Program: `ThreeSum.java`

- Command-line input: a filename (String)
- Standard output: the number of unordered triples (x, y, z) in the file such that $x + y + z = 0$

>_ ~/workspace/dsaj/programs

```
$ cat ../data/1Kints.txt
 324110
-442472
...
 745942
$ /usr/bin/time -f "%es" java ThreeSum ../data/1Kints.txt
70
0.28s
$ _
```

Time Complexity

Program: `ThreeSum.java`

- Command-line input: a filename (String)
- Standard output: the number of unordered triples (x, y, z) in the file such that $x + y + z = 0$

```
>_ ~/workspace/dsaj/programs

$ cat ../data/1Kints.txt
 324110
-442472
...
 745942
$ /usr/bin/time -f "%es" java ThreeSum ../data/1Kints.txt
70
0.28s
$ /usr/bin/time -f "%es" java ThreeSum ../data/2Kints.txt
```

Time Complexity

Program: `ThreeSum.java`

- Command-line input: a filename (String)
- Standard output: the number of unordered triples (x, y, z) in the file such that $x + y + z = 0$

```
>_ ~/workspace/dsaj/programs

$ cat ../data/1Kints.txt
 324110
-442472
...
 745942
$ /usr/bin/time -f "%es" java ThreeSum ../data/1Kints.txt
70
0.28s
$ /usr/bin/time -f "%es" java ThreeSum ../data/2Kints.txt
528
1.80s
$ _
```

Time Complexity

Program: `ThreeSum.java`

- Command-line input: a filename (String)
- Standard output: the number of unordered triples (x, y, z) in the file such that $x + y + z = 0$

```
>_ ~/workspace/dsaj/programs

$ cat ../data/1Kints.txt
 324110
-442472
...
 745942
$ /usr/bin/time -f "%es" java ThreeSum ../data/1Kints.txt
70
0.28s
$ /usr/bin/time -f "%es" java ThreeSum ../data/2Kints.txt
528
1.80s
$ /usr/bin/time -f "%es" java ThreeSum ../data/4Kints.txt
```

Time Complexity

Program: `ThreeSum.java`

- Command-line input: a filename (String)
- Standard output: the number of unordered triples (x, y, z) in the file such that $x + y + z = 0$

```
>_ ~/workspace/dsaj/programs

$ cat ../data/1Kints.txt
 324110
-442472
...
 745942
$ /usr/bin/time -f "%es" java ThreeSum ../data/1Kints.txt
70
0.28s
$ /usr/bin/time -f "%es" java ThreeSum ../data/2Kints.txt
528
1.80s
$ /usr/bin/time -f "%es" java ThreeSum ../data/4Kints.txt
4039
14.06s
$ _
```

Time Complexity

Time Complexity

ThreeSum.java

```
import stdlib.In;
import stdlib.StdOut;

public class ThreeSum {
    public static void main(String[] args) {
        In in = new In(args[0]);
        int[] a = in.readAllInts();
        StdOut.println(count(a));
    }

    private static int count(int[] a) {
        int n = a.length;
        int count = 0;
        for (int i = 0; i < n; i++) {
            for (int j = i + 1; j < n; j++) {
                for (int k = j + 1; k < n; k++) {
                    if (a[i] + a[j] + a[k] == 0) {
                        count++;
                    }
                }
            }
        }
        return count;
    }
}
```

Time Complexity

Experimental analysis

n	$f(n)$
1K	0.28s
2K	1.8s
4K	14.06s
8K	111.83s
16K	892.19s

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n	$f(n)$
1K	0.28s
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4K	14.06s
8K	111.83s
16K	892.19s

$$f(n) = 0.2273121n^3 + 0.007625303n^2 + 0.006868505n + 0.01817256$$

Time Complexity

The function $g(n)$ is called the tilde approximation of the function $f(n)$ if

$$\lim_{n \to \infty} \frac{g(n)}{f(n)} = 1$$

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We refer to the function $T(n) = n^b(\log n)^c$ as the running time

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We refer to the function $T(n) = n^b(\log n)^c$ as the running time

For example, if $g(n) = 31n^2$, then $T(n) = n^2$

For the Three Sum problem, $T(n) = n^3$

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1. The cost of executing each statement (property of the computer)

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Mathematically, we compute a function $f(n)$ from:

1. The cost of executing each statement (property of the computer)
2. The frequency of execution of each statement (property of the program and the input)

Time Complexity

Time Complexity

```
private static int count(int[] a) {
    int n = a.length;                                [A]
    int count = 0;
    for (int i = 0; i < n; i++) {                    [B]
        for (int j = i + 1; j < n; j++) {            [C]
            for (int k = j + 1; k < n; k++) {        [D]
                if (a[i] + a[j] + a[k] == 0) {
                    count++;                         [E]
                }
            }
        }
    }
    return count;
}
```

Time Complexity

```
private static int count(int[] a) {
    int n = a.length;                              [A]
    int count = 0;
    for (int i = 0; i < n; i++) {                  [B]
        for (int j = i + 1; j < n; j++) {          [C]
            for (int k = j + 1; k < n; k++) {      [D]
                if (a[i] + a[j] + a[k] == 0) {
                    count++;                       [E]
                }
            }
        }
    }
    return count;
}
```

Statement Block	Time	Frequency	Total Time
$[A]$	t_4	1	t_4
$[B]$	t_3	n	$t_3 n$
$[C]$	t_2	$\binom{n}{2} = n^2/2 - n/2$	$t_2(n^2/2 - n/2)$
$[D]$	t_1	$\binom{n}{3} = n^3/6 - n^2/2 + n/3$	$t_1(n^3/6 - n^2/2 + n/3)$
$[E]$	t_0	x (depends on input)	$t_0 x$

Time Complexity

```
private static int count(int[] a) {
    int n = a.length;                                   [A]
    int count = 0;
    for (int i = 0; i < n; i++) {                       [B]
        for (int j = i + 1; j < n; j++) {               [C]
            for (int k = j + 1; k < n; k++) {           [D]
                if (a[i] + a[j] + a[k] == 0) {
                    count++;                            [E]
                }
            }
        }
    }
    return count;
}
```

Statement Block	Time	Frequency	Total Time
$[A]$	t_4	1	t_4
$[B]$	t_3	n	$t_3 n$
$[C]$	t_2	$\binom{n}{2} = n^2/2 - n/2$	$t_2(n^2/2 - n/2)$
$[D]$	t_1	$\binom{n}{3} = n^3/6 - n^2/2 + n/3$	$t_1(n^3/6 - n^2/2 + n/3)$
$[E]$	t_0	x (depends on input)	$t_0 x$

$$f(n) = (t_1/6)n^3 + (t_2/2 - t_1/2)n^2 + (t_1/3 - t_2/2 + t_3)n + t_4 + t_0 x$$

Time Complexity

```
private static int count(int[] a) {
    int n = a.length;                                   [A]
    int count = 0;
    for (int i = 0; i < n; i++) {                       [B]
        for (int j = i + 1; j < n; j++) {               [C]
            for (int k = j + 1; k < n; k++) {           [D]
                if (a[i] + a[j] + a[k] == 0) {
                    count++;                            [E]
                }
            }
        }
    }
    return count;
}
```

Statement Block	Time	Frequency	Total Time
$[A]$	t_4	1	t_4
$[B]$	t_3	n	$t_3 n$
$[C]$	t_2	$\binom{n}{2} = n^2/2 - n/2$	$t_2(n^2/2 - n/2)$
$[D]$	t_1	$\binom{n}{3} = n^3/6 - n^2/2 + n/3$	$t_1(n^3/6 - n^2/2 + n/3)$
$[E]$	t_0	x (depends on input)	$t_0 x$

$$f(n) = (t_1/6)n^3 + (t_2/2 - t_1/2)n^2 + (t_1/3 - t_2/2 + t_3)n + t_4 + t_0 x$$

$$g(n) = (t_1/6)n^3$$

Time Complexity

```
private static int count(int[] a) {
    int n = a.length;                                   [A]
    int count = 0;
    for (int i = 0; i < n; i++) {                       [B]
        for (int j = i + 1; j < n; j++) {               [C]
            for (int k = j + 1; k < n; k++) {           [D]
                if (a[i] + a[j] + a[k] == 0) {
                    count++;                            [E]
                }
            }
        }
    }
    return count;
}
```

Statement Block	Time	Frequency	Total Time
$[A]$	t_4	1	t_4
$[B]$	t_3	n	$t_3 n$
$[C]$	t_2	$\binom{n}{2} = n^2/2 - n/2$	$t_2(n^2/2 - n/2)$
$[D]$	t_1	$\binom{n}{3} = n^3/6 - n^2/2 + n/3$	$t_1(n^3/6 - n^2/2 + n/3)$
$[E]$	t_0	x (depends on input)	$t_0 x$

$$f(n) = (t_1/6)n^3 + (t_2/2 - t_1/2)n^2 + (t_1/3 - t_2/2 + t_3)n + t_4 + t_0 x$$

$$g(n) = (t_1/6)n^3$$

$$T(n) = n^3$$

Time Complexity

Time Complexity

Running time classifications

Name	$T(n)$	Code Description	Example
constant	1	statement	increment the ith element in an array
logarithmic	$\log n$	divide and discard	binary search
linear	n	loop	find the maximum
linearithmic	$n \log n$	divide and conquer	merge sort
quadratic	n^2	double loop	check all ordered pairs
cubic	n^3	triple loop	check all ordered triples
exponential	2^n	exhaustive search	check all subsets

Time Complexity

Time Complexity

dsa.LinearSearch	
`static int indexOf(Object[] a, Object key)`	returns the index of `key` in the array `a`, or -1
`static int indexOf(int[] a, int key)`	returns the index of `key` in the array `a`, or -1
`static int indexOf(double[] a, double key)`	returns the index of `key` in the array `a`, or -1

Time Complexity

Time Complexity

Program: `LinearSearch.java`

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- Command-line input: a filename (String)

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- Command-line input: a filename (String)
- Standard input: a sequence of integers

Program: `LinearSearch.java`

- Command-line input: a filename (String)
- Standard input: a sequence of integers
- Standard output: the integers from standard input that are not in the file

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- Command-line input: a filename (String)
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- Standard output: the integers from standard input that are not in the file

```
>_ ~/workspace/dsaj/programs
$ _
```

Program: `LinearSearch.java`

- Command-line input: a filename (String)
- Standard input: a sequence of integers
- Standard output: the integers from standard input that are not in the file

```
>_ ~/workspace/dsaj/programs
$ cat ../data/tinyW.txt
```

Program: `LinearSearch.java`

- Command-line input: a filename (String)
- Standard input: a sequence of integers
- Standard output: the integers from standard input that are not in the file

```
>_ ~/workspace/dsaj/programs

$ cat ../data/tinyW.txt
84
48
...
29
$ _
```

Program: `LinearSearch.java`

- Command-line input: a filename (String)
- Standard input: a sequence of integers
- Standard output: the integers from standard input that are not in the file

```
>_ ~/workspace/dsaj/programs

$ cat ../data/tinyW.txt
84
48
...
29
$ cat ../data/tinyT.txt
```

Program: `LinearSearch.java`

- Command-line input: a filename (String)
- Standard input: a sequence of integers
- Standard output: the integers from standard input that are not in the file

```
>_ ~/workspace/dsaj/programs

$ cat ../data/tinyW.txt
84
48
...
29
$ cat ../data/tinyT.txt
23
50
...
68
$ _
```

Program: `LinearSearch.java`

- Command-line input: a filename (String)
- Standard input: a sequence of integers
- Standard output: the integers from standard input that are not in the file

```
>_ ~/workspace/dsaj/programs

$ cat ../data/tinyW.txt
84
48
...
29
$ cat ../data/tinyT.txt
23
50
...
68
$ java dsa.LinearSearch ../data/tinyW.txt < ../data/tinyT.txt
```

Program: `LinearSearch.java`

- Command-line input: a filename (String)
- Standard input: a sequence of integers
- Standard output: the integers from standard input that are not in the file

```
>_ ~/workspace/dsaj/programs

$ cat ../data/tinyW.txt
84
48
...
29
$ cat ../data/tinyT.txt
23
50
...
68
$ java dsa.LinearSearch ../data/tinyW.txt < ../data/tinyT.txt
50
99
13
$ _
```

Time Complexity

Time Complexity

LinearSearch.java

```
package dsa;

import stdlib.In;
import stdlib.StdIn;
import stdlib.StdOut;

public class LinearSearch {
    public static int indexOf(Object[] a, Object key) {
        for (int i = 0; i < a.length; i++) {
            if (a[i].equals(key)) {
                return i;
            }
        }
        return -1;
    }

    public static int indexOf(int[] a, int key) {
        for (int i = 0; i < a.length; i++) {
            if (a[i] == key) {
                return i;
            }
        }
        return -1;
    }

    public static int indexOf(double[] a, double key) {
        for (int i = 0; i < a.length; i++) {
            if (a[i] == key) {
                return i;
            }
        }
        return -1;
    }

    public static void main(String[] args) {
```

Time Complexity

LinearSearch.java

```
        In inStream = new In(args[0]);
        int[] whiteList = inStream.readAllInts();
        while (!StdIn.isEmpty()) {
            int key = StdIn.readInt();
            if (indexOf(whiteList, key) == -1) {
                StdOut.println(key);
            }
        }
    }
}
```

Time Complexity

Time Complexity

dsa.BinarySearch

`static int indexOf(Comparable[] a, Comparable key)`	returns the index of `key` in the sorted array `a`, or -1
`static int indexOf(int[] a, int key)`	returns the index of `key` in the sorted array `a`, or -1
`static int indexOf(double[] a, double key)`	returns the index of `key` in the sorted array `a`, or -1

Time Complexity

Time Complexity

Program: `BinarySearch.java`

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- Command-line input: a filename (String)

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- Command-line input: a filename (String)
- Standard input: a sequence of integers

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- Standard input: a sequence of integers
- Standard output: the integers from standard input that are not in the file

Program: `BinarySearch.java`

- Command-line input: a filename (String)
- Standard input: a sequence of integers
- Standard output: the integers from standard input that are not in the file

```
>_ ~/workspace/dsaj/programs
$ _
```

Program: `BinarySearch.java`

- Command-line input: a filename (String)
- Standard input: a sequence of integers
- Standard output: the integers from standard input that are not in the file

```
>_ ~/workspace/dsaj/programs
$ cat ../data/tinyW.txt
```

Program: `BinarySearch.java`

- Command-line input: a filename (String)
- Standard input: a sequence of integers
- Standard output: the integers from standard input that are not in the file

```
>_ ~/workspace/dsaj/programs

$ cat ../data/tinyW.txt
84
48
...
29
$ _
```

Program: `BinarySearch.java`

- Command-line input: a filename (String)
- Standard input: a sequence of integers
- Standard output: the integers from standard input that are not in the file

```
>_ ~/workspace/dsaj/programs

$ cat ../data/tinyW.txt
84
48
...
29
$ cat ../data/tinyT.txt
```

Program: `BinarySearch.java`

- Command-line input: a filename (String)
- Standard input: a sequence of integers
- Standard output: the integers from standard input that are not in the file

```
>_ ~/workspace/dsaj/programs

$ cat ../data/tinyW.txt
84
48
...
29
$ cat ../data/tinyT.txt
23
50
...
68
$ _
```

Program: `BinarySearch.java`

- Command-line input: a filename (String)
- Standard input: a sequence of integers
- Standard output: the integers from standard input that are not in the file

```
>_ ~/workspace/dsaj/programs

$ cat ../data/tinyW.txt
84
48
...
29
$ cat ../data/tinyT.txt
23
50
...
68
$ java dsa.BinarySearch ../data/tinyW.txt < ../data/tinyT.txt
```

Time Complexity

Program: `BinarySearch.java`

- Command-line input: a filename (String)
- Standard input: a sequence of integers
- Standard output: the integers from standard input that are not in the file

```
>_ ~/workspace/dsaj/programs

$ cat ../data/tinyW.txt
84
48
...
29
$ cat ../data/tinyT.txt
23
50
...
68
$ java dsa.BinarySearch ../data/tinyW.txt < ../data/tinyT.txt
50
99
13
$ _
```

Time Complexity

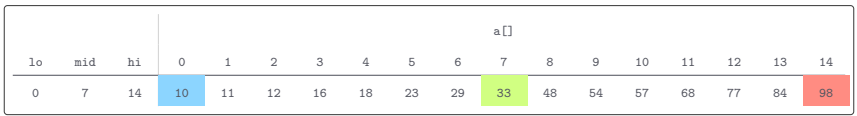
Time Complexity

Successful binary search for the key 23 (returns 5)

			a[]													
lo	mid	hi	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
			10	11	12	16	18	23	29	33	48	54	57	68	77	84	98

Time Complexity

Successful binary search for the key 23 (returns 5)



Time Complexity

Successful binary search for the key 23 (returns 5)

			a[]														
lo	mid	hi	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
0	3	6	10	11	12	16	18	23	29	33	48	54	57	68	77	84	98

Time Complexity

Successful binary search for the key 23 (returns 5)

			a[]													
lo	mid	hi	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
4	5	6	10	11	12	16	18	23	29	33	48	54	57	68	77	84	98

Time Complexity

Successful binary search for the key 23 (returns 5)

			a[]													
lo	mid	hi	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
4	5	6	10	11	12	16	18	23	29	33	48	54	57	68	77	84	98

Time Complexity

Time Complexity

Unsuccessful binary search for the key 50 (returns -1)

			a[]													
lo	mid	hi	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
			10	11	12	16	18	23	29	33	48	54	57	68	77	84	98

Time Complexity

Unsuccessful binary search for the key 50 (returns -1)

			a[]													
lo	mid	hi	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
0	7	14	10	11	12	16	18	23	29	33	48	54	57	68	77	84	98

Time Complexity

Unsuccessful binary search for the key 50 (returns -1)

			a[]													
lo	mid	hi	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
8	11	14	10	11	12	16	18	23	29	33	48	54	57	68	77	84	98

Time Complexity

Unsuccessful binary search for the key 50 (returns -1)

			a[]													
lo	mid	hi	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
8	9	10	10	11	12	16	18	23	29	33	48	54	57	68	77	84	98

Time Complexity

Unsuccessful binary search for the key 50 (returns -1)

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Time Complexity

Time Complexity

BinarySearch.java

```
package dsa;

import java.util.Arrays;

import stdlib.In;
import stdlib.StdIn;
import stdlib.StdOut;

public class BinarySearch {
    public static int indexOf(Comparable[] a, Comparable key) {
        int lo = 0;
        int hi = a.length - 1;
        while (lo <= hi) {
            int mid = lo + (hi - lo) / 2;
            int cmp = key.compareTo(a[mid]);
            if (cmp < 0) {
                hi = mid - 1;
            } else if (cmp > 0) {
                lo = mid + 1;
            } else {
                return mid;
            }
        }
        return -1;
    }

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

Time Complexity

BinarySearch.java

```
            } else {
                return mid;
            }
        }
        return -1;
    }

    public static int indexOf(double[] a, double key) {
        int lo = 0;
        int hi = a.length - 1;
        while (lo <= hi) {
            int mid = lo + (hi - lo) / 2;
            if (key < a[mid]) {
                hi = mid - 1;
            } else if (key > a[mid]) {
                lo = mid + 1;
            } else {
                return mid;
            }
        }
        return -1;
    }

    public static void main(String[] args) {
        In inStream = new In(args[0]);
        int[] whiteList = inStream.readAllInts();
        Arrays.sort(whiteList);
        while (!StdIn.isEmpty()) {
            Integer key = StdIn.readInt();
            if (indexOf(whiteList, key) == -1) {
                StdOut.println(key);
            }
        }
    }
}
```

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```
>_ ~/workspace/dsaj/programs

$ _
```

Time Complexity

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```
>_ ~/workspace/dsaj/programs

$ /usr/bin/time -f "%es" java ThreeSumFast ../data/1Kints.txt
```

Time Complexity

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- Command-line input: a filename (String)
- Standard output: the number of unordered triples (x, y, z) in the file such that $x + y + z = 0$

```
>_ ~/workspace/dsaj/programs

$ /usr/bin/time -f "%es" java ThreeSumFast ../data/1Kints.txt
70
0.10s
$ _
```

Time Complexity

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$ /usr/bin/time -f "%es" java ThreeSumFast ../data/1Kints.txt
70
0.10s
$ /usr/bin/time -f "%es" java ThreeSumFast ../data/2Kints.txt
```

Time Complexity

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- Command-line input: a filename (String)
- Standard output: the number of unordered triples (x, y, z) in the file such that $x + y + z = 0$

```
>_ ~/workspace/dsaj/programs

$ /usr/bin/time -f "%es" java ThreeSumFast ../data/1Kints.txt
70
0.10s
$ /usr/bin/time -f "%es" java ThreeSumFast ../data/2Kints.txt
528
0.17s
$ _
```

Time Complexity

Program: `ThreeSumFast.java`

- Command-line input: a filename (String)
- Standard output: the number of unordered triples (x, y, z) in the file such that $x + y + z = 0$

```
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$ /usr/bin/time -f "%es" java ThreeSumFast ../data/1Kints.txt
70
0.10s
$ /usr/bin/time -f "%es" java ThreeSumFast ../data/2Kints.txt
528
0.17s
$ /usr/bin/time -f "%es" java ThreeSumFast ../data/4Kints.txt
```

Time Complexity

Program: `ThreeSumFast.java`

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- Standard output: the number of unordered triples (x, y, z) in the file such that $x + y + z = 0$

```
>_ ~/workspace/dsaj/programs

$ /usr/bin/time -f "%es" java ThreeSumFast ../data/1Kints.txt
70
0.10s
$ /usr/bin/time -f "%es" java ThreeSumFast ../data/2Kints.txt
528
0.17s
$ /usr/bin/time -f "%es" java ThreeSumFast ../data/4Kints.txt
4039
0.47s
$ _
```

Time Complexity

Time Complexity

ThreeSumFast.java

```
import java.util.Arrays;

import dsa.BinarySearch;
import stdlib.In;
import stdlib.StdOut;

public class ThreeSumFast {
    public static void main(String[] args) {
        In in = new In(args[0]);
        int[] a = in.readAllInts();
        StdOut.println(count(a));
    }

    private static int count(int[] a) {
        int n = a.length;
        Arrays.sort(a);
        int count = 0;
        for (int i = 0; i < n; i++) {
            for (int j = i + 1; j < n; j++) {
                int k = BinarySearch.indexOf(a, -(a[i] + a[j]));
                if (k > j) {
                    count++;
                }
            }
        }
        return count;
    }
}
```

Time Complexity

Time Complexity

n	Three Sum $T(n)$	Fast Three Sum $T(n)$
1K	0.28s	0.1s
2K	1.8s	0.17s
4K	14.06s	0.47s
8K	111.83s	1.58s
16K	892.19s	6.09s

Space Complexity

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Memory requirements for primitive types

Type	Bytes
`boolean`	1
`byte`	1
`char`	2
`short`	2
`int`	4
`float`	4
`long`	8
`double`	8

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`double`	8

To determine the memory usage of an object, we add the amount of memory used by each instance variable

For example, a `Counter` object uses 12 bytes: 8 bytes for `id` (a reference) and 4 bytes for `count`

Space Complexity

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A 2D array is an array of arrays (each array is an object)

For example, an $m \times n$ array of `double` values uses $8m$ bytes for references plus 8 bytes for each of the mn `double` values, for a grand total of $8mn + 8m$ bytes

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A `String` of length n uses $2n$ bytes