CSCI 132:
Basic Data Structures and Algorithms

Growth Rates

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Spring 2023

Announcements

Program 2 due 3/10

Midterm Exam one week from today

No lab next week

As computer scientists, we write many **algorithms**

We want to be able to describe how well our algorithms perform on a variety of inputs

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We want to be able to describe how well our algorithms perform on a variety of inputs

Consider an algorithm that will **make a cake**

How could measure the effectiveness and performance of our cake making algorithm?

Consider an algorithm that will **make a cake**

What are some ways we could measure the performance and effectiveness of our algorithm ?

What is the **total time needed** to make the cake?

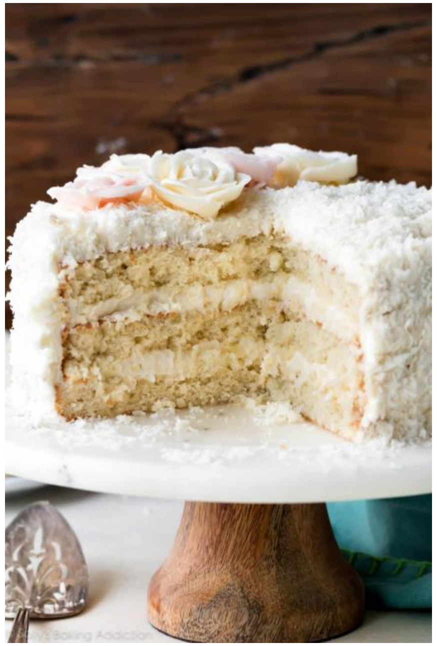
- Prep time
- Combining ingredients
- Baking
- Cooling
- Icing

The **time** an algorithm takes to finish is important. We generally want our algorithms to run as fast as possible

Consider an algorithm that will **make a cake**

What are some ways we could measure the performance and effectiveness of our algorithm ?

How well does our algorithm work on a variety of problems?



Suppose we needed to make different types of cake, How well would our algorithm do?

Generalizability and Reliability

Consider an algorithm that will **make a cake**

What are some ways we could measure the performance and effectiveness of our algorithm ?

How well does our cake taste?

We want our algorithm to output the best cake possible

Does our algorithm always yield the **optimal** result ?

Consider an algorithm that will **make a cake**

What are some ways we could measure the performance and effectiveness of our algorithm ?

Does our algorithm actually make a cake?

Does our algorithm *actually* do what we say it does?

Our algorithm needs to be **valid**

Consider an algorithm that will **make a cake**

What are some ways we could measure the performance and effectiveness of our algorithm ?

Suppose we needed to make a lot of the same cake

How well does our algorithm **scale**?

Consider an algorithm that will **make a cake**

What are some ways we could measure the performance and effectiveness of our algorithm ?

How much kitchen **space** is needed to make the cake?

What if the cake needed is really big?

Algorithm Analysis

Performance & Efficiency

1. Running time of Algorithm
2. Space needed to run the algorithm

Algorithm Correctness

- Validity
- Optimality
- Generalizability

Algorithm Analysis

Performance & Efficiency

1. Running time of Algorithm
2. Space needed to run the algorithm

Important: How well does the algorithm do as the problem gets bigger? (Scalability)

Algorithm Correctness

- Validity
- Optimality
- Generalizability

The **growth rate** of the algorithm looks at how much more resource an algorithm needs (time or space) as the input size increases

*(In this class, we will be focusing on **time**)*

Running time issues

The easiest way I could prove the running time of an algorithm is by starting a stopwatch when the algorithm starts, and stop when algorithm finishes

This is not a very good way to accurately show the running time because …

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This is not a very good way to accurately show the running time because …

What if this is my computer?

Running time issues

Issue: The time needed to run an algorithm varies depending on the hardware of computer that is running the algorithm


Running time issues

Issue: The time needed to run an algorithm varies depending on the <u>hardware of computer</u> that is running the algorithm

Instead of focusing on the actual time needed to run an algorithm (seconds), we will look at the **number of steps/instructions in the algorithm** that need be executed *as the input grows*!

The **growth rate** of the algorithm looks at how much more resource an algorithm needs (time or space) as the input size increases

???	???
???	???
???	???

We will look at 4 growth rates today

The remaining two will be covered later this semester

Algorithm #1: Finding the Maximum Value in an Array

```
public int find_max_value(int[] array) {
   int largest_so_far = -1;
   for(int i = 0; i < array.length; i++) {
       if ( array[i] > largest_so_far ) {
           largest_so_far = array[i];
       }
   }
   return largest_so_far;
}
```

This algorithm will find the largest value in some **N** sized array

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This code checks each spot in the array

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    }
    return largest_so_far;
}
```

This algorithm will find the largest value in some **N** sized array

This code checks each spot in the array

Let’s look at how many times this instruction is executed as the array size grows

Algorithm #1: Finding the Maximum Value in an Array

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public int find_max_value(int[] array) {
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        if ( array[i] > largest_so_far ) {
            largest_so_far = array[i];
        }
    }
    return largest_so_far;
}
```

Array Size	Number of Spots Checked
10	

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```

Array Size	Number of Spots Checked
10	10
100	

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    }
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```

Array Size	Number of Spots Checked
10	10
100	100
533	533

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        }
    }
    return largest_so_far;
}
```

Array Size	Number of Spots Checked
10	10
100	100
533	533
1000	1000

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Array Size	Number of Spots Checked
10	10
100	100
533	533
1000	1000
9999	

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Array Size	Number of Spots Checked
10	10
100	100
533	533
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}
```

Array Size	Number of Spots Checked
10	10
100	100
533	533
1000	1000
9999	9999
1	

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    }
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Array Size	Number of Spots Checked
10	10
100	100
533	533
1000	1000
9999	9999
1	1

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```

Array Size	Number of Spots Checked
10	10
100	100
533	533
1000	1000
9999	9999
1	1
1000000000	

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```

Array Size	Number of Spots Checked
10	10
100	100
533	533
1000	1000
9999	9999
1	1
1000000000	1000000000

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    }
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}
```

Array Size	Number of Spots Checked
10	10
100	100
533	533
1000	1000
9999	9999
1	1
1000000000	1000000000

What if we graphed these points?

(10,10) , (100,100), (533,533), (1000,100) ….

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    }
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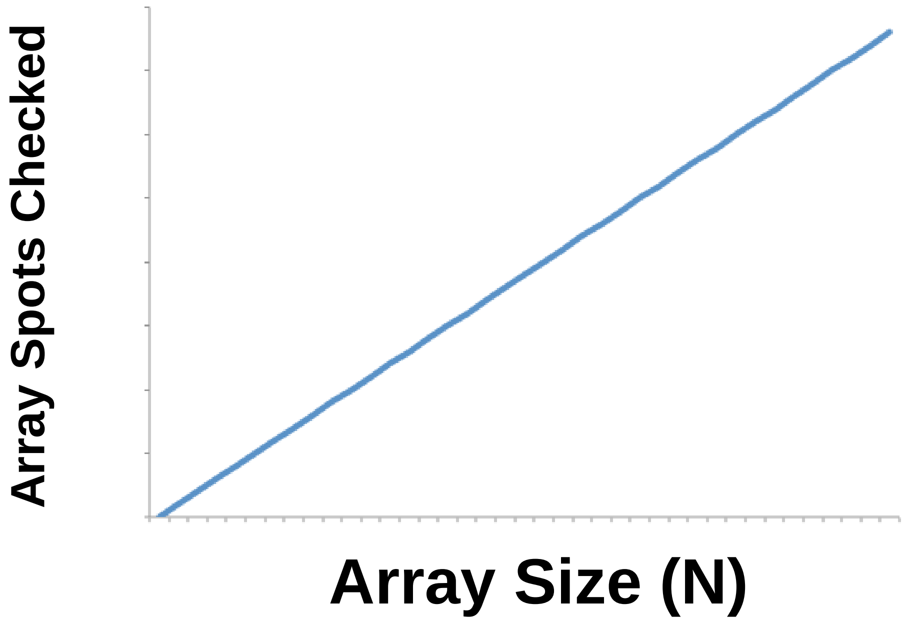
}
```

Array Size	Number of Spots Checked
10	10
100	100
533	533
1000	1000
9999	9999
1	1
1000000000	1000000000



Algorithm #1: Finding the Maximum Value in an Array

The growth rate of this algorithm is **linear**

A linear growth rate is a growth rate where the resource needs and the amount of data is directly proportional to each other.

```
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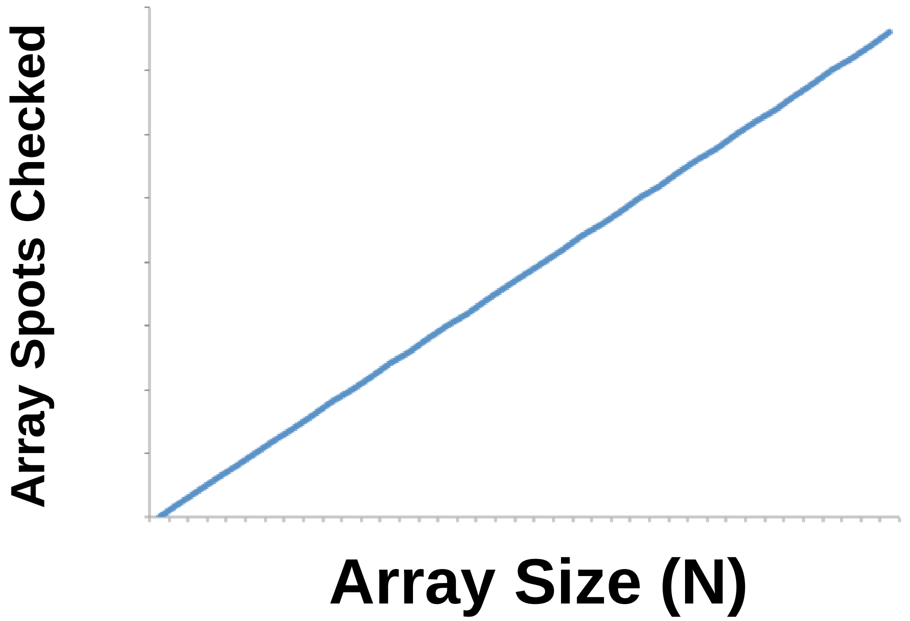
```



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   }
   return largest_so_far;
}
```

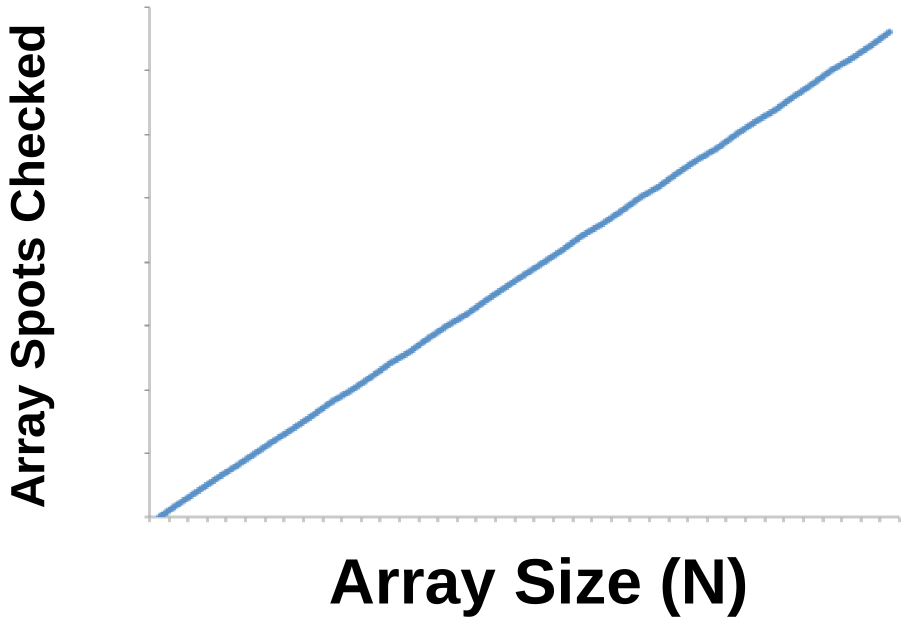
The growth rate of this algorithm is **linear**

A linear growth rate is a growth rate where the resource needs and the amount of data is directly proportional to each other.

The driving factor of this algorithm is the size of the array

As N increases, the number of steps executed in this algorithm linearly increases

F(x) = N



Algorithm #2: Printing out an N x N 2D Array

```
public void print2Darray(int[][] array) {
    for(int[] x: array) {
        for(int y: x) {
            System.out.print(y);
        }
    System.out.println();
    }
}
```

Given an N x N 2D array, print out its contents

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    System.out.println();
    }
}
```

Given an N x N 2D array, print out its contents

N = 3

```
000
000
000
```

N = 7

```
0000000
0000000
0000000
0000000
0000000
0000000
0000000
```

Algorithm #2: Printing out an N x N 2D Array

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        }
    System.out.println();
    }
}
```

Given an N x N 2D array, print out its contents

Let’s look at how many times this operation is executed as N increases

N = 3

```
000
000
000
```

N = 7

```
0000000
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```

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N	Number of Array Spots Printed out

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```

N	Number of Array Spots Printed out
1	

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        }
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    }
}
```

N	Number of Array Spots Printed out
1	1

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    System.out.println();
    }
}
```

N	Number of Array Spots Printed out
1	1
2	4

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N	Number of Array Spots Printed out
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```

N	Number of Array Spots Printed out
1	1
2	4
3	9

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N	Number of Array Spots Printed out
1	1
2	4
3	9
4	16

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        }
    System.out.println();
    }
}
```

N	Number of Array Spots Printed out
1	1
2	4
3	9
4	16
5	25

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    }
}
```

N	Number of Array Spots Printed out
1	1
2	4
3	9
4	16
5	25
…	…
100	10000

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N	Number of Array Spots Printed out
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2	4
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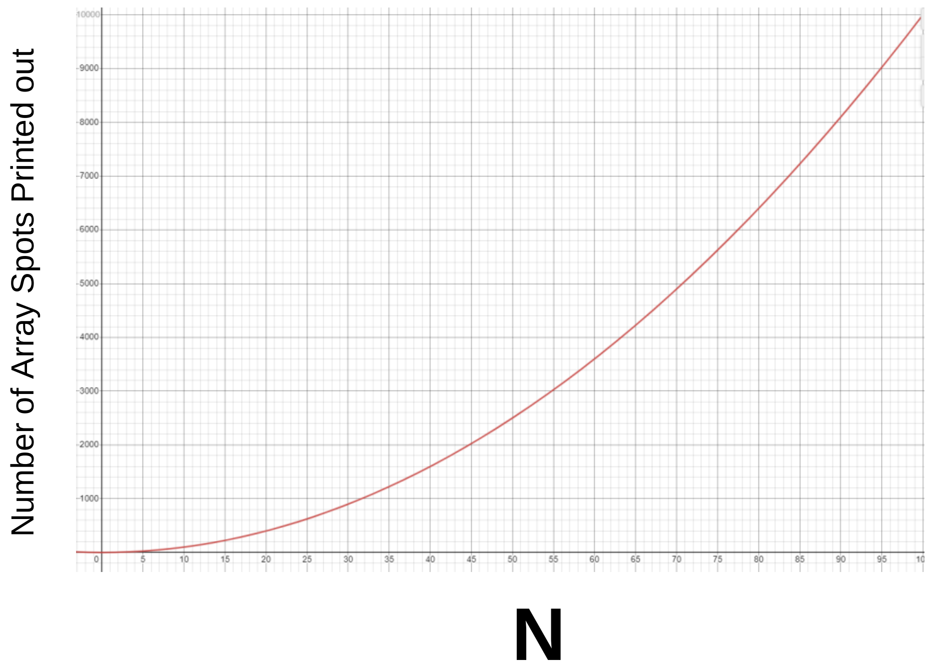
5	25
…	…
100	10000



Algorithm #2: Printing out an N x N 2D Array

The growth rate of this algorithm is **quadratic**

A quadratic growth rate is a growth rate where the resource needs and the amount of data is proportional to the *square* of a function

```java
public void print2Darray(int[][] array) {
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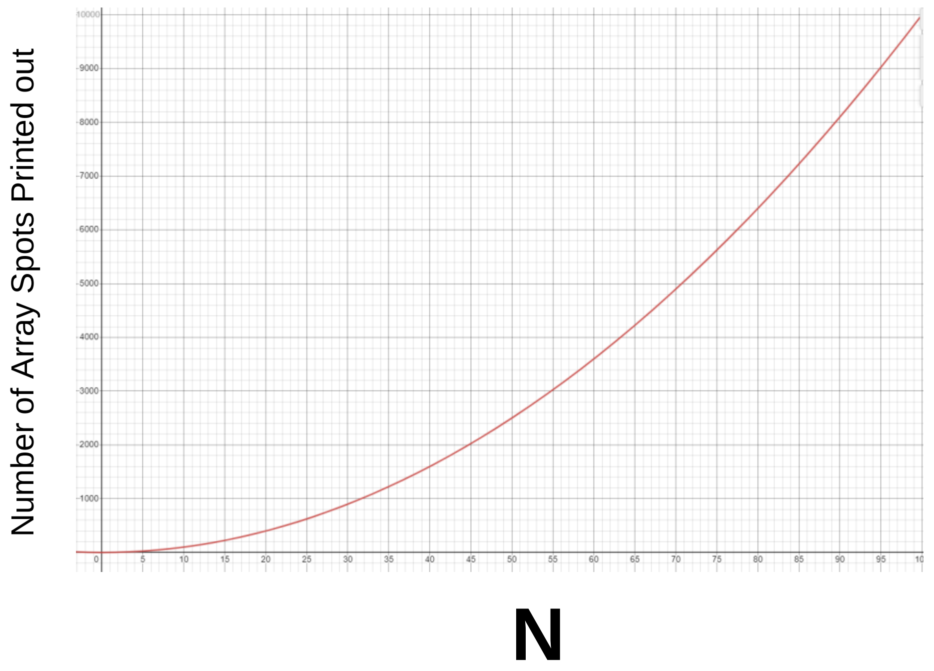

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		}
	System.out.println();
	}
}
```
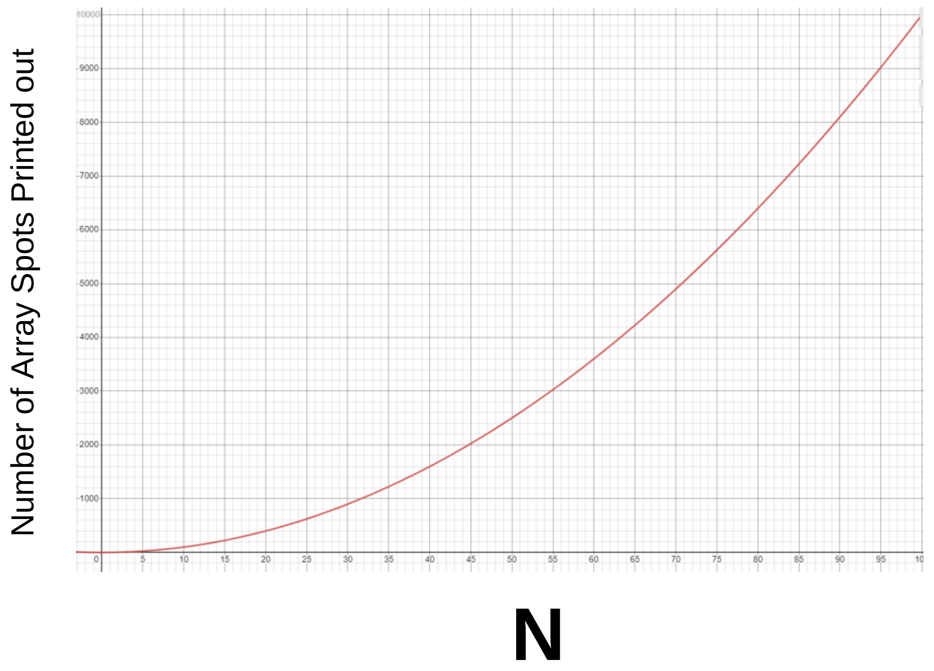

The growth rate of this algorithm is **quadratic**

A quadratic growth rate is a growth rate where the resource needs and the amount of data is proportional to the *square* of a function

$$F(x) = X \wedge 2$$

We have a for loop inside of a for loop, so as N increases, the number of times the inside for loop executes = N * N



Algorithm #3: Adding a node to front of linked list

```
public void addToFront(Node newNode) {
     newNode.setNext(this.head);
     this.head = newNode;
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Given a singly linked list (with at least one node), this algorithm adds a new node to the front of the LL

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```

Given a singly linked list (with at least one node), this algorithm adds a new node to the front of the LL

This algorithm consists of two operations. Let’s look at how many times these operations are executed as the Linked List size increases

Algorithm #3: Adding a node to front of linked list

```
public void addToFront(Node newNode) {
     newNode.setNext(this.head);
     this.head = newNode;
}
```

N	# of operations executed

N= # of nodes in LL

Algorithm #3: Adding a node to front of linked list

```
public void addToFront(Node newNode) {
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}
```

N	# of operations executed
1	

N= # of nodes in LL

Algorithm #3: Adding a node to front of linked list

```
public void addToFront(Node newNode) {
     newNode.setNext(this.head);
     this.head = newNode;
}
```

N	# of operations executed
1	2

N= # of nodes in LL

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```
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     newNode.setNext(this.head);
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}
```

N	# of operations executed
1	2
2	

N= # of nodes in LL

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```
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     newNode.setNext(this.head);
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}
```

N	# of operations executed
1	2
2	2

N= # of nodes in LL

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```

N	# of operations executed
1	2
2	2
3	

N= # of nodes in LL

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1	2
2	2
3	2

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```

N	# of operations executed
1	2
2	2
3	2
4	

N= # of nodes in LL

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```java
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     newNode.setNext(this.head);
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}
```

N	# of operations executed
1	2
2	2
3	2
4	2

N= # of nodes in LL

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```
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```

N	# of operations executed
1	2
2	2
3	2
4	2
100	

N= # of nodes in LL

Algorithm #3: Adding a node to front of linked list

```
public void addToFront(Node newNode) {
     newNode.setNext(this.head);
     this.head = newNode;
}
```

N	# of operations executed
1	2
2	2
3	2
4	2
100	2

N= # of nodes in LL

Algorithm #3: Adding a node to front of linked list

```
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     newNode.setNext(this.head);
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```

N	# of operations executed
1	2
2	2
3	2
4	2
100	2
777	

N= # of nodes in LL

Algorithm #3: Adding a node to front of linked list

```
public void addToFront(Node newNode) {
     newNode.setNext(this.head);
     this.head = newNode;
}
```

N	# of operations executed
1	2
2	2
3	2
4	2
100	2
777	2

N= # of nodes in LL

Algorithm #3: Adding a node to front of linked list

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    newNode.setNext(this.head);
    this.head = newNode;
}
```

N	**# of operations executed**
1	2
2	2
3	2
4	2
100	2
777	2
1000000000	

N= # of nodes in LL

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N= # of nodes in LL

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```

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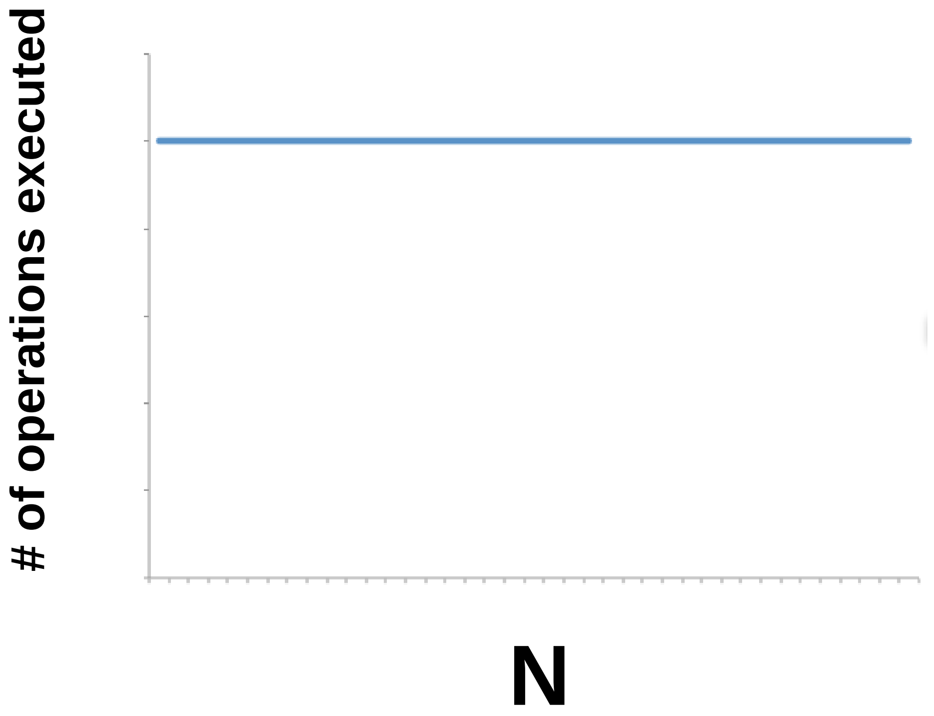
2	2
3	2
4	2
100	2
777	2
1000000000	2



N= # of nodes in LL

Algorithm #3: Adding a node to front of linked list

```
public void addToFront(Node newNode) {
      newNode.setNext(this.head);
      this.head = newNode;
}
```

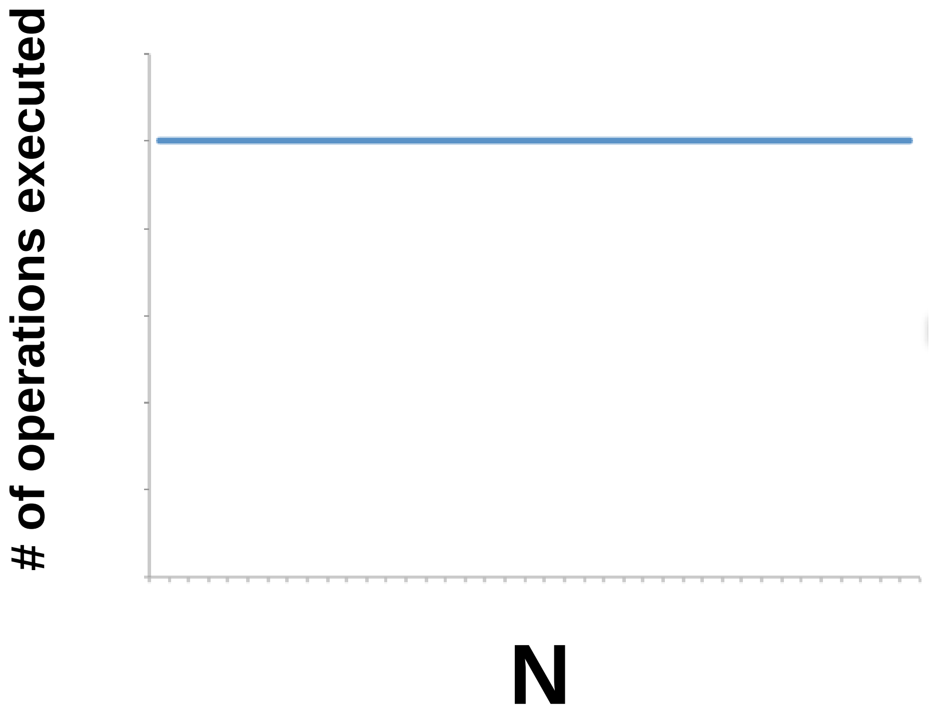
The growth rate of this algorithm is **constant**

A **constant growth rate** is one where the resource need does not grow as N increases.

F(x) = 1

The number of instructions executed for adding something to LL of size 1 is the same as adding to a LL of size 100000000000

ie. As N increases, the number of steps our algorithm performs is constant



Algorithm #4: Generating all possible binary combinations of length N

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```
Input: 2
Output:
0 0
0 1
1 0
1 1
```

Algorithm #4: Generating all possible binary combinations of length N

```
Input: 2
Output:
0 0
0 1
1 0
1 1
```

```
Input: 3
Output:
0 0 0
0 0 1
0 1 0
0 1 1
1 0 0
1 0 1
1 1 0
1 1 1
```

Algorithm #4: Generating all possible binary combinations of length N

```
Input: 2
Output:
0 0
0 1
1 0
1 1
```

```
Input: 3
Output:
0 0 0
0 0 1
0 1 0
0 1 1
1 0 0
1 0 1
1 1 0
1 1 1
```

Input: 4

Output

0000
0001
0010
0011
0100
0101
0110
0111
…
1111

Algorithm #4: Generating all possible binary combinations of length N

```
static void generateAllBinaryStrings(int n, int arr[], int i) {
        if (i == n) {
            printTheArray(arr, n);
            return;
        }
        arr[i] = 0;
        generateAllBinaryStrings(n, arr, i + 1);

        arr[i] = 1;
        generateAllBinaryStrings(n, arr, i + 1);
}
```

Don’t worry too much about the specifics of the algorithm. Let’s look at the amount a string that get generated as N increases

Algorithm #4: Generating all possible binary combinations of length N

```
static void generateAllBinaryStrings(int n, int arr[], int i) {
                if (i == n) {
                        printTheArray(arr, n);
            return;
        }
        arr[i] = 0;
        generateAllBinaryStrings(n, arr, i + 1);

        arr[i] = 1;
        generateAllBinaryStrings(n, arr, i + 1);
}
```

N	**# Of binary digits generated**
1	

N = length of binary digits

Algorithm #4: Generating all possible binary combinations of length N

```
static void generateAllBinaryStrings(int n, int arr[], int i) {
                if (i == n) {
                    printTheArray(arr, n);
            return;
        }
        arr[i] = 0;
        generateAllBinaryStrings(n, arr, i + 1);

        arr[i] = 1;
        generateAllBinaryStrings(n, arr, i + 1);
}
```

N	# Of binary digits generated
1	2

N = length of binary digits

Algorithm #4: Generating all possible binary combinations of length N

```
static void generateAllBinaryStrings(int n, int arr[], int i) {
                if (i == n) {
                        printTheArray(arr, n);
                return;
        }
        arr[i] = 0;
        generateAllBinaryStrings(n, arr, i + 1);

        arr[i] = 1;
        generateAllBinaryStrings(n, arr, i + 1);
}
```

N	# Of binary digits generated
1	2
2	

N = length of binary digits

Algorithm #4: Generating all possible binary combinations of length N

```
static void generateAllBinaryStrings(int n, int arr[], int i) {
        if (i == n) {
            printTheArray(arr, n);
        return;
    }
    arr[i] = 0;
    generateAllBinaryStrings(n, arr, i + 1);

    arr[i] = 1;
    generateAllBinaryStrings(n, arr, i + 1);
}
```

N	# Of binary digits generated
1	2
2	4

N = length of binary digits

Algorithm #4: Generating all possible binary combinations of length N

```
static void generateAllBinaryStrings(int n, int arr[], int i) {
                if (i == n) {
                        printTheArray(arr, n);
            return;
        }
        arr[i] = 0;
        generateAllBinaryStrings(n, arr, i + 1);

        arr[i] = 1;
        generateAllBinaryStrings(n, arr, i + 1);
}
```

N	# Of binary digits generated
1	2
2	4
3	

N = length of binary digits

Algorithm #4: Generating all possible binary combinations of length N

```
static void generateAllBinaryStrings(int n, int arr[], int i) {
                if (i == n) {
                    printTheArray(arr, n);
            return;
        }
        arr[i] = 0;
        generateAllBinaryStrings(n, arr, i + 1);

        arr[i] = 1;
        generateAllBinaryStrings(n, arr, i + 1);
}
```

N	**# Of binary digits generated**
1	2
2	4
3	8

N = length of binary digits

Algorithm #4: Generating all possible binary combinations of length N

```
static void generateAllBinaryStrings(int n, int arr[], int i) {
                if (i == n) {
                    printTheArray(arr, n);
            return;
        }
        arr[i] = 0;
        generateAllBinaryStrings(n, arr, i + 1);

        arr[i] = 1;
        generateAllBinaryStrings(n, arr, i + 1);
}
```

N	# Of binary digits generated
1	2
2	4
3	8
4	

N = length of binary digits

Algorithm #4: Generating all possible binary combinations of length N

```
static void generateAllBinaryStrings(int n, int arr[], int i) {
                if (i == n) {
                    printTheArray(arr, n);
            return;
        }
        arr[i] = 0;
        generateAllBinaryStrings(n, arr, i + 1);

        arr[i] = 1;
        generateAllBinaryStrings(n, arr, i + 1);
}
```

N	# Of binary digits generated
1	2
2	4
3	8
4	16

N = length of binary digits

Algorithm #4: Generating all possible binary combinations of length N

```
static void generateAllBinaryStrings(int n, int arr[], int i) {
                if (i == n) {
                    printTheArray(arr, n);
            return;
        }
        arr[i] = 0;
        generateAllBinaryStrings(n, arr, i + 1);

        arr[i] = 1;
        generateAllBinaryStrings(n, arr, i + 1);
}
```

N	# Of binary digits generated
1	2
2	4
3	8
4	16
5	

N = length of binary digits

Algorithm #4: Generating all possible binary combinations of length N

```
static void generateAllBinaryStrings(int n, int arr[], int i) {
		if (i == n) {
			printTheArray(arr, n);
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	arr[i] = 1;
	generateAllBinaryStrings(n, arr, i + 1);
}
```

N	# Of binary digits generated
1	2
2	4
3	8
4	16
5	32

N = length of binary digits

Algorithm #4: Generating all possible binary combinations of length N

```
static void generateAllBinaryStrings(int n, int arr[], int i) {
                if (i == n) {
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        arr[i] = 1;
        generateAllBinaryStrings(n, arr, i + 1);
}
```

N	# Of binary digits generated
1	2
2	4
3	8
4	16
5	32
8	256

N = length of binary digits

Algorithm #4: Generating all possible binary combinations of length N

```
static void generateAllBinaryStrings(int n, int arr[], int i) {
                if (i == n) {
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       arr[i] = 0;
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       arr[i] = 1;
       generateAllBinaryStrings(n, arr, i + 1);
}
```

N	**# Of binary digits generated**
1	2
2	4
3	8
4	16
5	32
8	256
16	65536

N = length of binary digits

Algorithm #4: Generating all possible binary combinations of length N

```
static void generateAllBinaryStrings(int n, int arr[], int i) {
		if (i == n) {
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		return;
	}
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	generateAllBinaryStrings(n, arr, i + 1);

	arr[i] = 1;
	generateAllBinaryStrings(n, arr, i + 1);
}
```
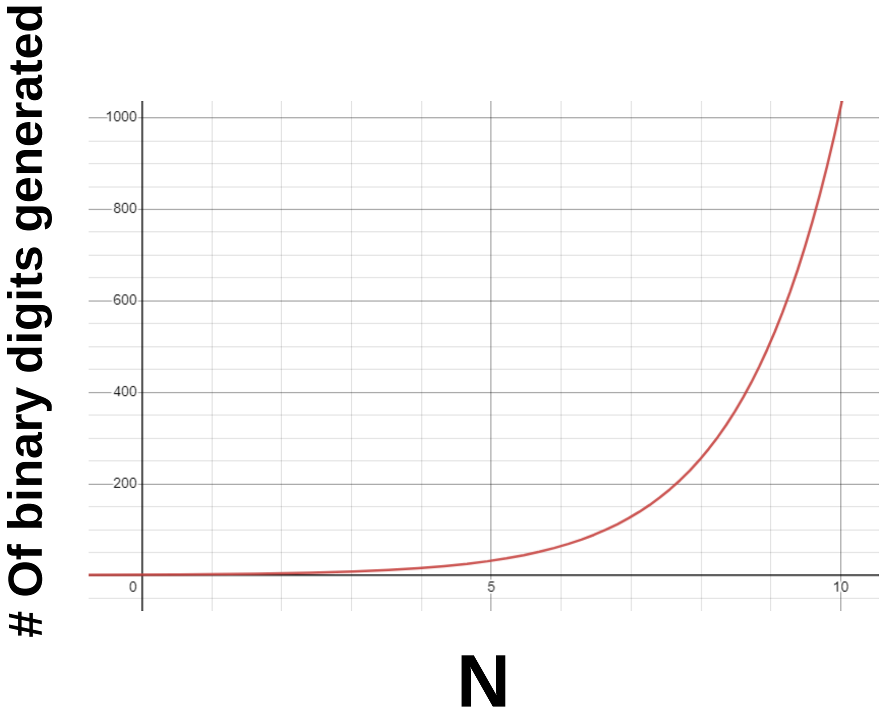

N	# Of binary digits generated
1	2
2	4
3	8
4	16
5	32
8	256
16	65536



N = length of binary digits

Algorithm #4: Generating all possible binary combinations of length N

```
static void generateAllBinaryStrings(int n, int arr[], int i) {
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}
```
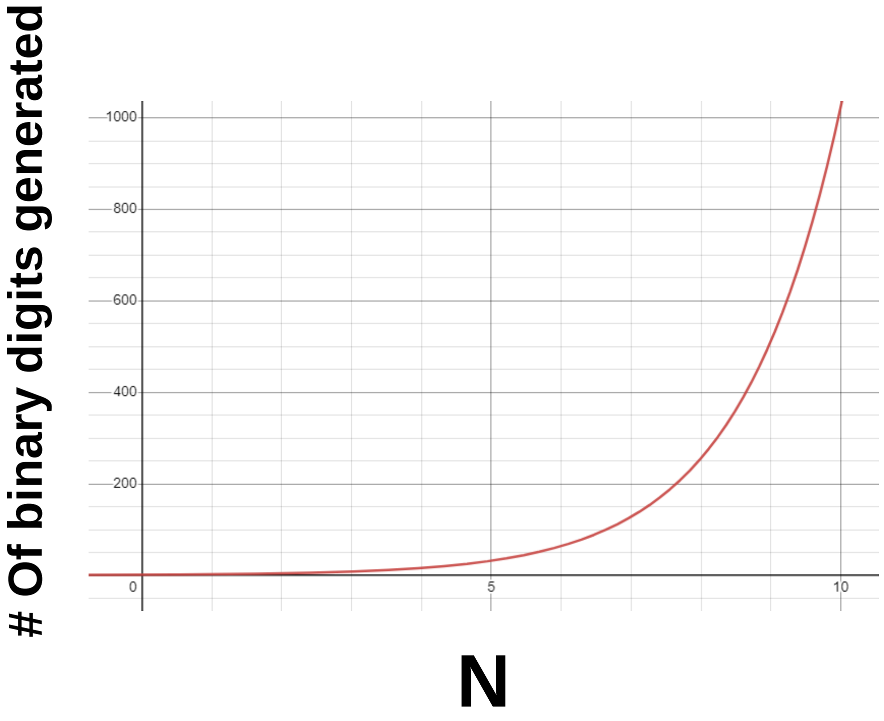

The growth rate of this algorithm is **exponential**

An **exponential growth rate** is one where the resource needed begins to double or increase very drastically as N increases

F(x) = B ^ x



Algorithm #4: Generating all possible binary combinations of length N

```java
static void generateAllBinaryStrings(int n, int arr[], int i) {
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}
```
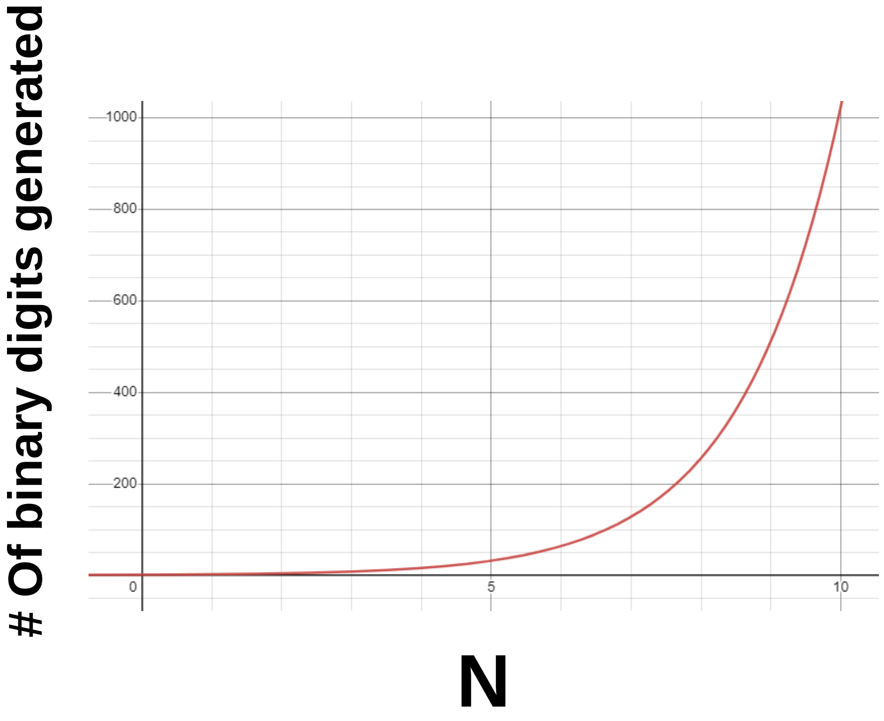

The growth rate of this algorithm is **exponential**

An **exponential growth rate** is one where the resource needed begins to double or increase very drastically as N increases

$$F(x) = B \wedge x$$

An algorithm that has an exponential growth rate is generally perceived as **inefficient**. When N gets big, sometimes the algorithm won't finish for years

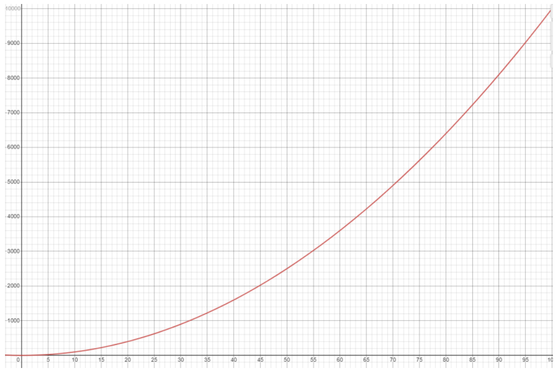


The **growth rate** of the algorithm looks at how much more resource an algorithm needs (time or space) as the input size increases

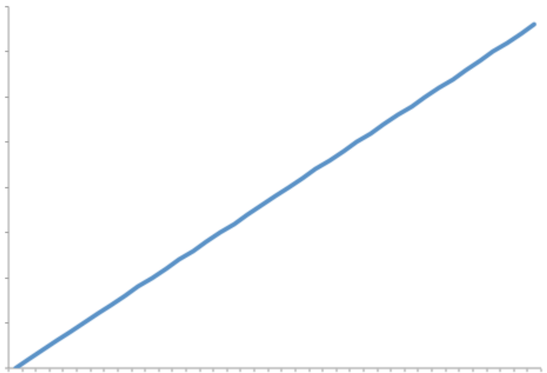
Constant	???
???	Quadratic
Linear	Exponential

Constant

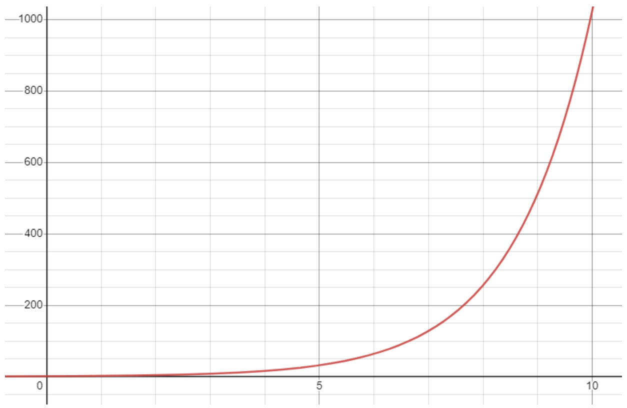
Quadratic

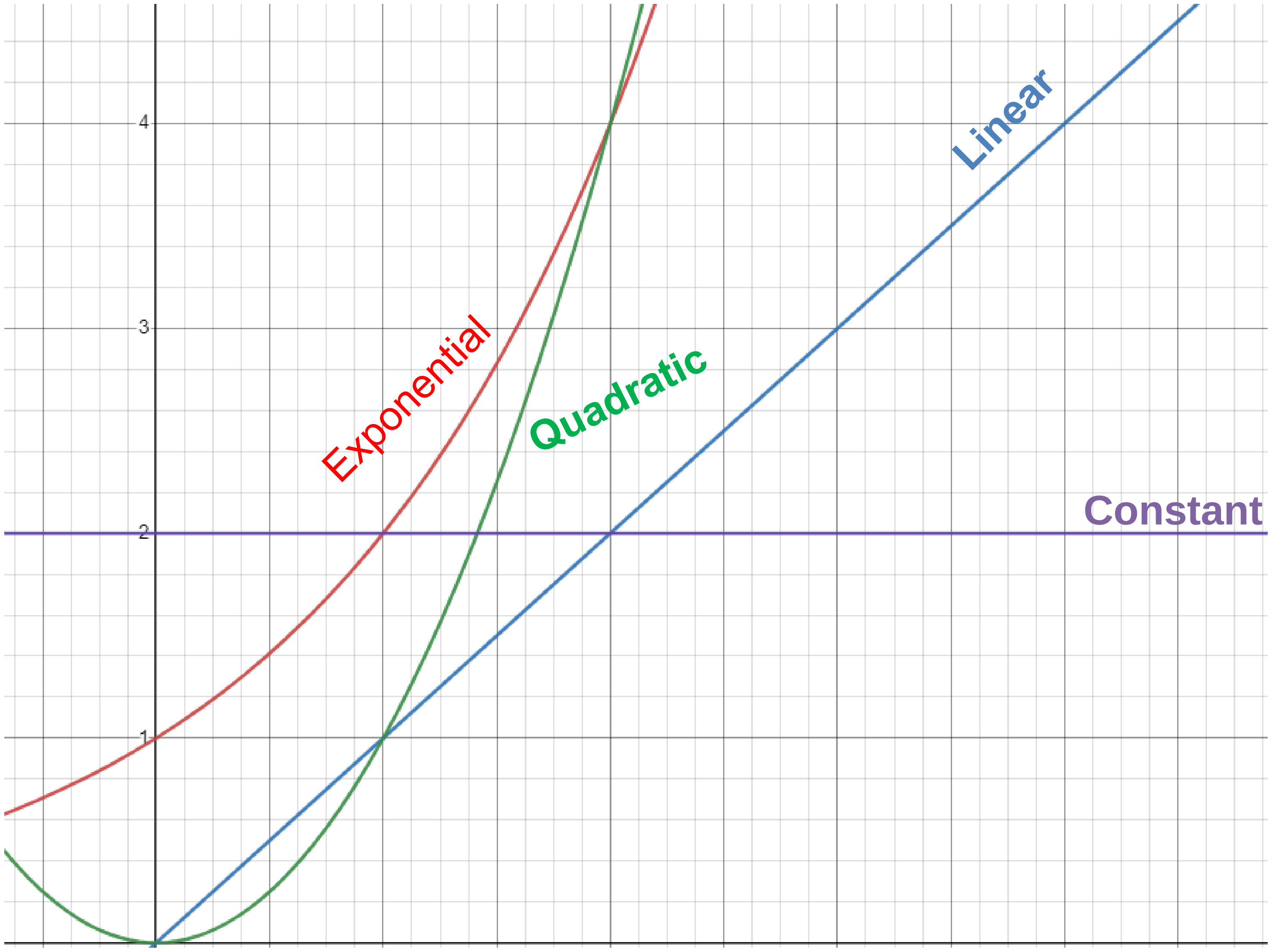


Linear

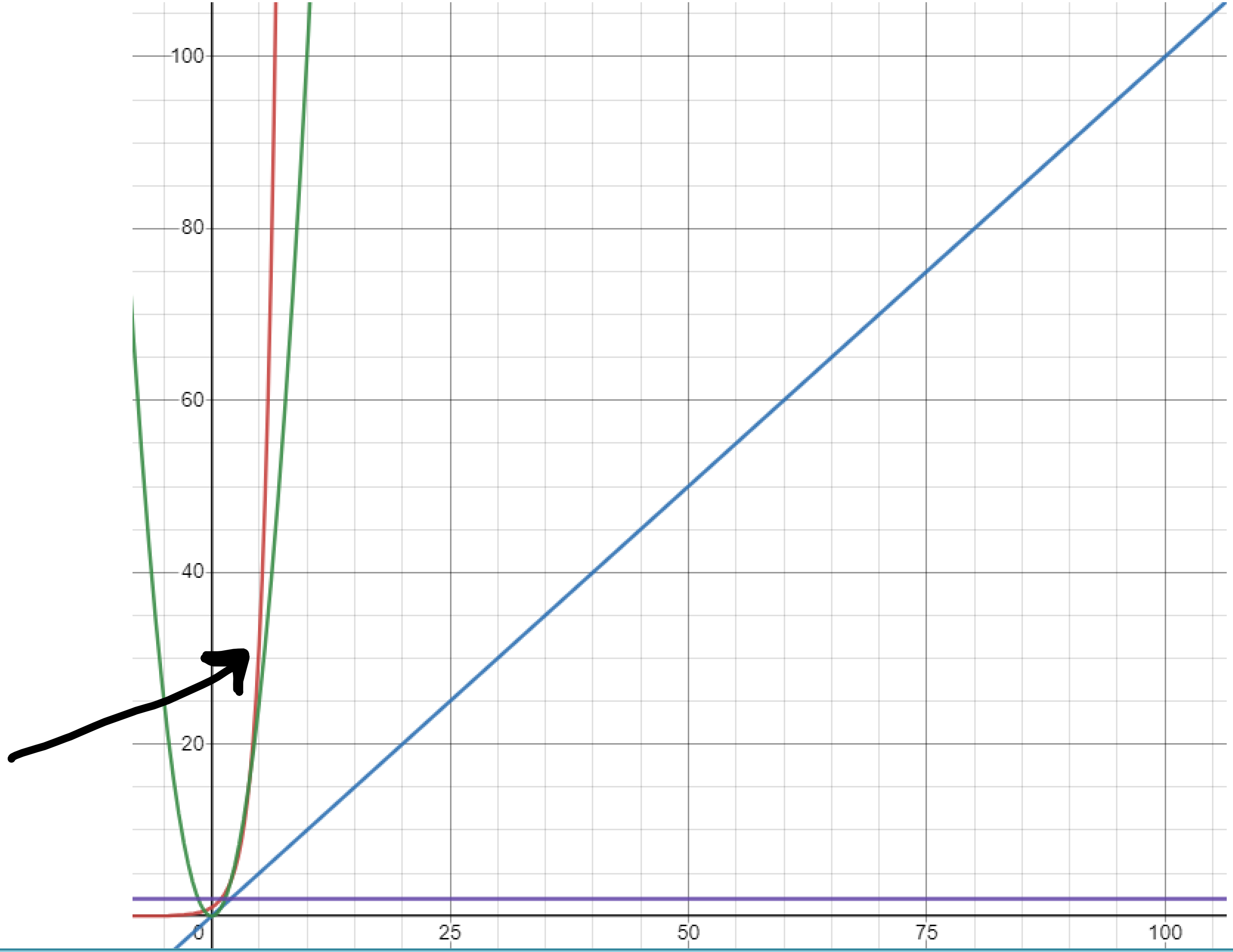


Exponential





4
3
2
1
Exponential
Quadratic
Linear
Constant



After a certain point, exponential growth rates goes crazy and beings to grow much faster than the other growth rates