

PG4200: Algorithms And Data Structures

Lesson 03: Runtime Analysis and Sorting

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How Long?



- You want **fast** algorithms
- You could just run some “experiments”, and check how long your algorithm takes
- But what if algorithm will need to be run on a larger problem than I used in the experiments?
- If the problem is **twice as big**, will my algorithm take just **twice as long**???

```
public static int sum(int[] array) {  
  
    int sum = 0;  
    for(int i=0; i<array.length; i++) {  
        sum += array[i];  
    }  
    return sum;  
}
```

- “Cost” can be measured in number of executed statements
- Given size of array N, the loop will be taken N times
- There is some constant cost independent of N, eg creation of “*int sum*” variable
- If N doubles, would expect function will be *roughly* twice as slow

$$\text{instructions}(N) = 3N + 4$$

$$\text{instructions}(N=0)=4$$

```
1. int sum = 0;  
2. int i=0;  
3. i<array.length;  
4. return sum;
```

- Number of instructions depends on size N of the array, plus some constant cost
- Can be represented with a function, eg $f(N)=3N+4$
- For large N, constants are not important

$$\text{instructions}(N=3)=13$$

```
1. int sum = 0;  
2. int i=0;  
3. i<array.length;  
4. sum += array[i];  
5. i++;  
6. i<array.length;  
7. sum += array[i];  
8. i++;  
9. i<array.length;  
10. sum += array[i];  
11. i++;  
12. i<array.length;  
13. return sum;
```

```

public static int pairs(int[] array) {
    int pairs = 0;

    for(int i=0; i<array.length; i++){
        for(int j=0; j<array.length; j++){
            if(i!=j && array[i] == array[j]){
                pairs++;
            }
        }
    }
    return pairs;
}

```

/*

On my machine, repeated 100 times:

N=100	seconds=0.005
N=200	seconds=0.005
N=400	seconds=0.012
N=800	seconds=0.072
N=1600	seconds=0.211
N=3200	seconds=0.754
N=6400	seconds=2.829
N=12800	seconds=11.48

*/

- Two nested loops
- Inner loop executed once per each element in array
- So, $N * N = N^2$
- Twice as big is now $2 * 2 = 4$ times as slow!!! (roughly)

Scalability

- When analyzing algorithms, we will not look at the low level optimization details
- N as representation of the problem size (eg, length of array or number of elements in a container)
- How does the algorithm *scale* for larger sizes???
- Example: if my website works fine with a load of 100 users, what will happen with 2,000???. Will I just need 20 times the resources?

Wheat/Rice and Chessboard Problem



- 1 rice grain on first square
- Double at each square
- How many grains on the board?
- 18,446,744,073,709,551,615
- ie, 18 Quintillions

Analysis of Algorithms

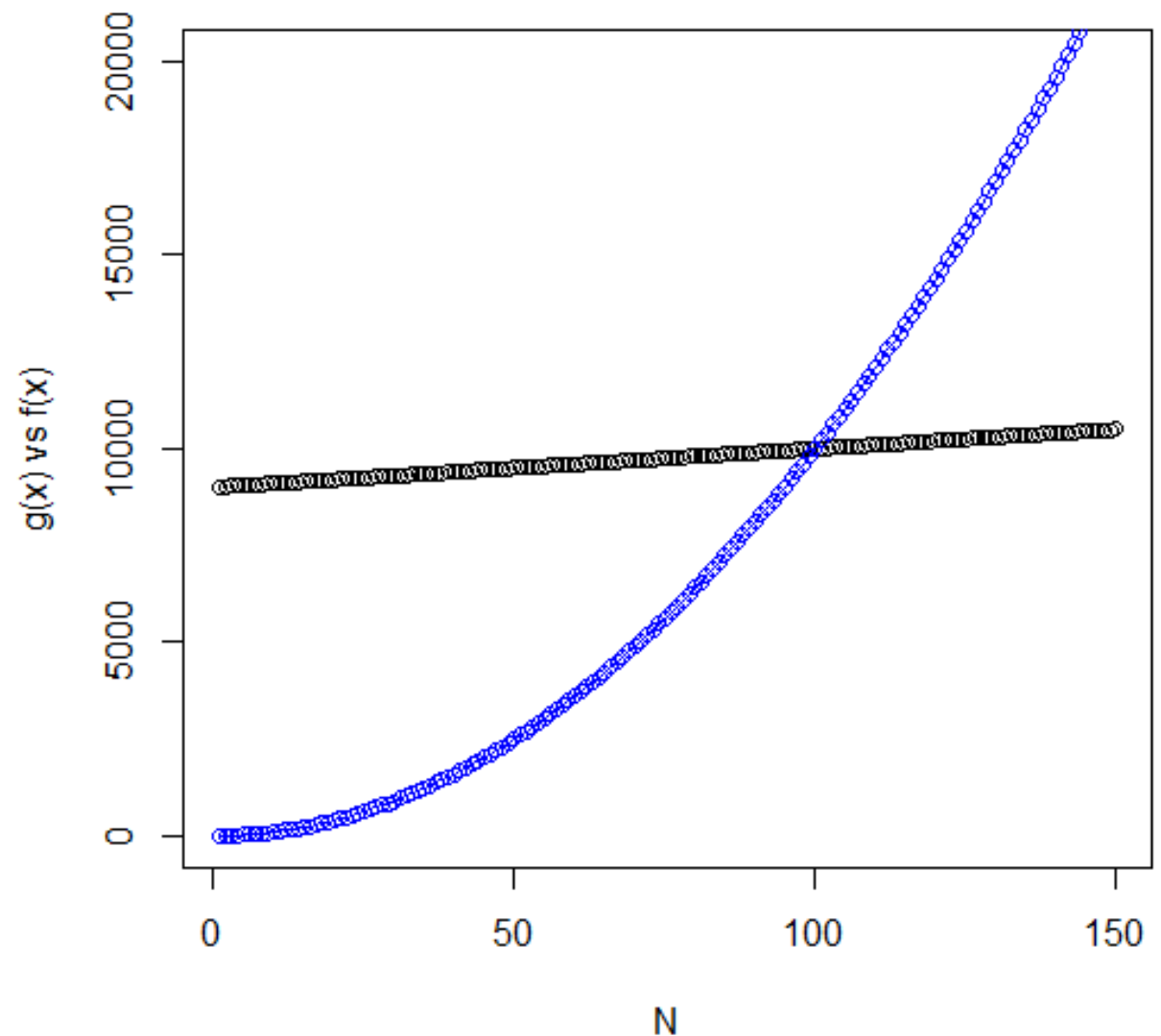
- Mathematically define the cost as a function of the input size
- *Precise* functions can be impractical, so we need approximations
- Usually, we are interested in *upper* and *lower* bounds

Example

- $f(n) = a N^2 + b N + c$
- Given an algorithm whose performance is described by the polynomial $f(n)$, finding the actual values for a, b, c might be too difficult
- However, can we say something about the **scalability**?
- YES!!! Regardless of $a = 5$ or $a = 400$, still doubling N would result in increase of at least 4 times (roughly...)

Which Is Better?

- $f(n) = n^2$
- $g(n) = 10n + 9000$
- For small values $f(n)$ is better, but it becomes worse from $n > 100$
- We will look at *large* n , so for us $g(n)$ is better



Large N???

- How do we define *large*?
 - 10? 50? 10000000000000000000000???
- We can't really say... however, things grow so fast... what we think is *large* today, is likely going to be considered *tiny* in few years...
- Today I know how fast my algorithms are, because I run them. But I want to know how they will *scale* to the larger problem instances of tomorrow.
 - Eg, when my apps get more users

FPS... large increase in number of polygons to render...



Doom (1993)

Doom (2016)



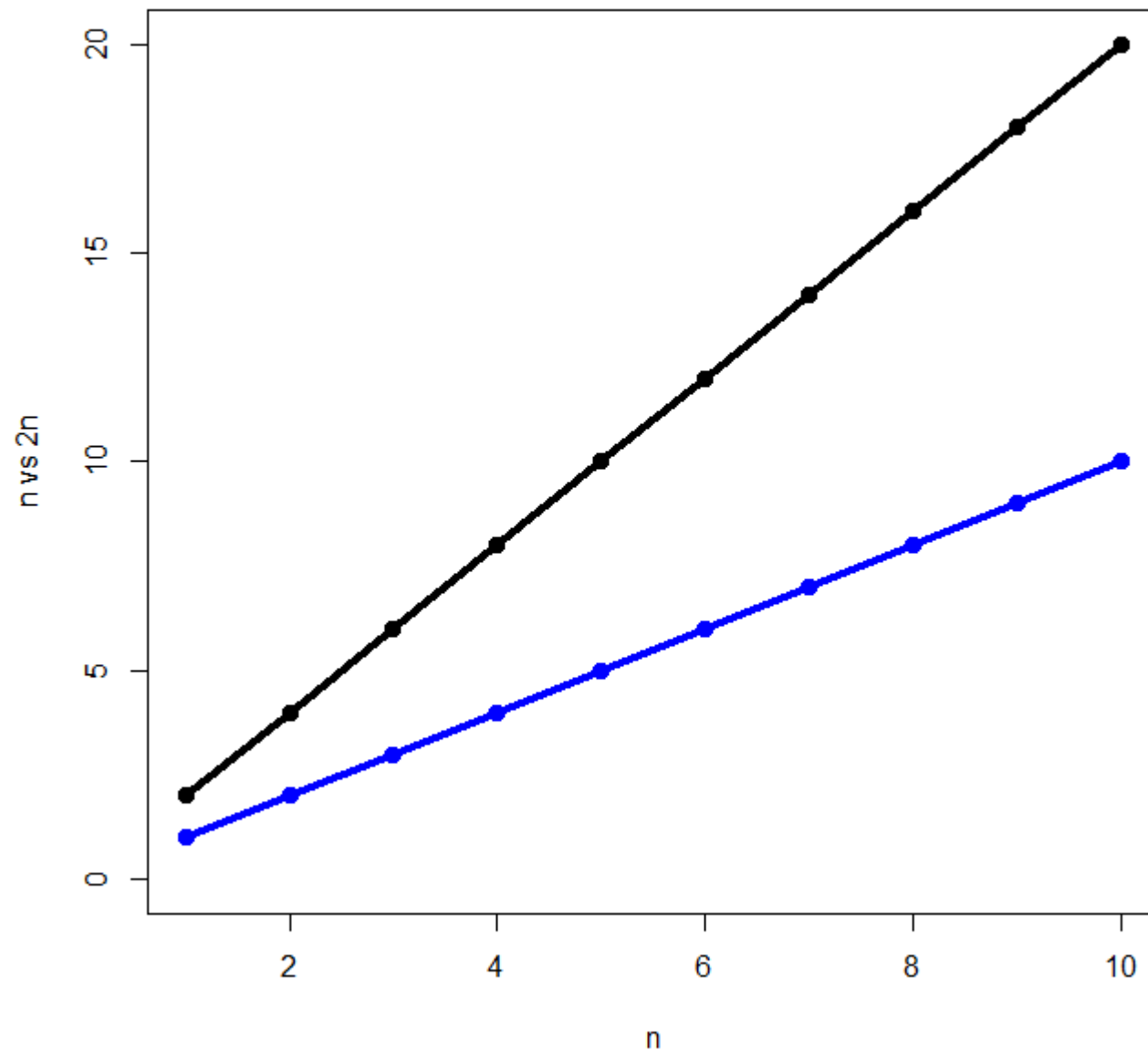
Scalability

- $f(n) = 5n + 100$
 - If I am interested in scalability, the constants 5 and 100 are *irrelevant*
- $g(n) = 2n^2 + 10n + 7$
 - The constants 2, 10 and 7 are irrelevant. But what about the n compared with n^2 ??? It is smaller, but maybe still important?

Big O Upper Bound

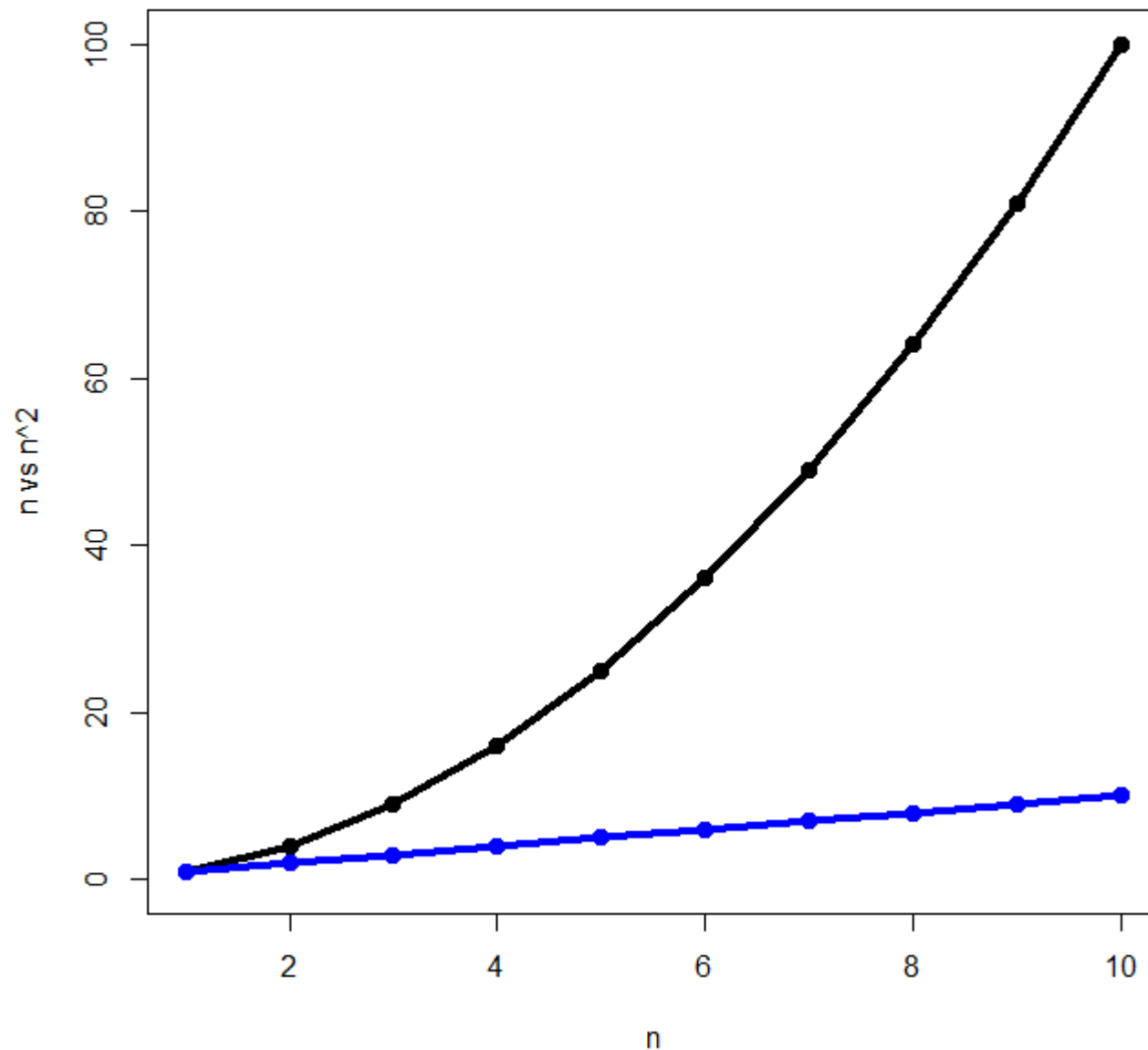
- $f(n) = O(g(n))$
- If there exists positive constants c and n' , such that $0 \leq f(n) \leq c * g(n)$ for all $n \geq n'$
- In other words, $c * g(n)$ is an upper bound for $f(n)$ for large values of n
- Useful to consider *worst case scenarios*

$$n = O(n)$$



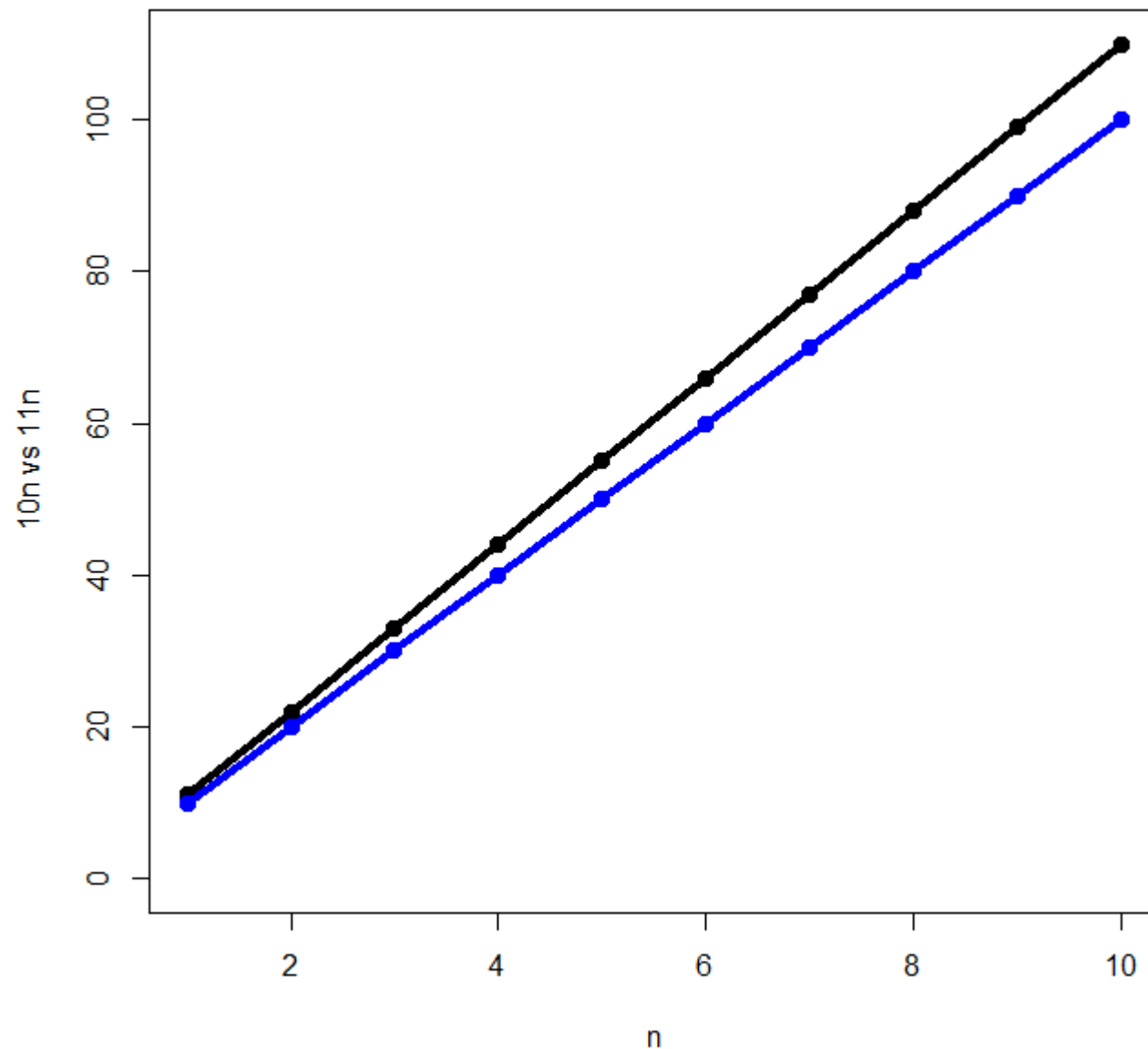
- $g(n) = n$
- Examples: $c = 2, n' = 1$
- $n < 2n$ for $n \geq 1$

$$n = O(n^2)$$



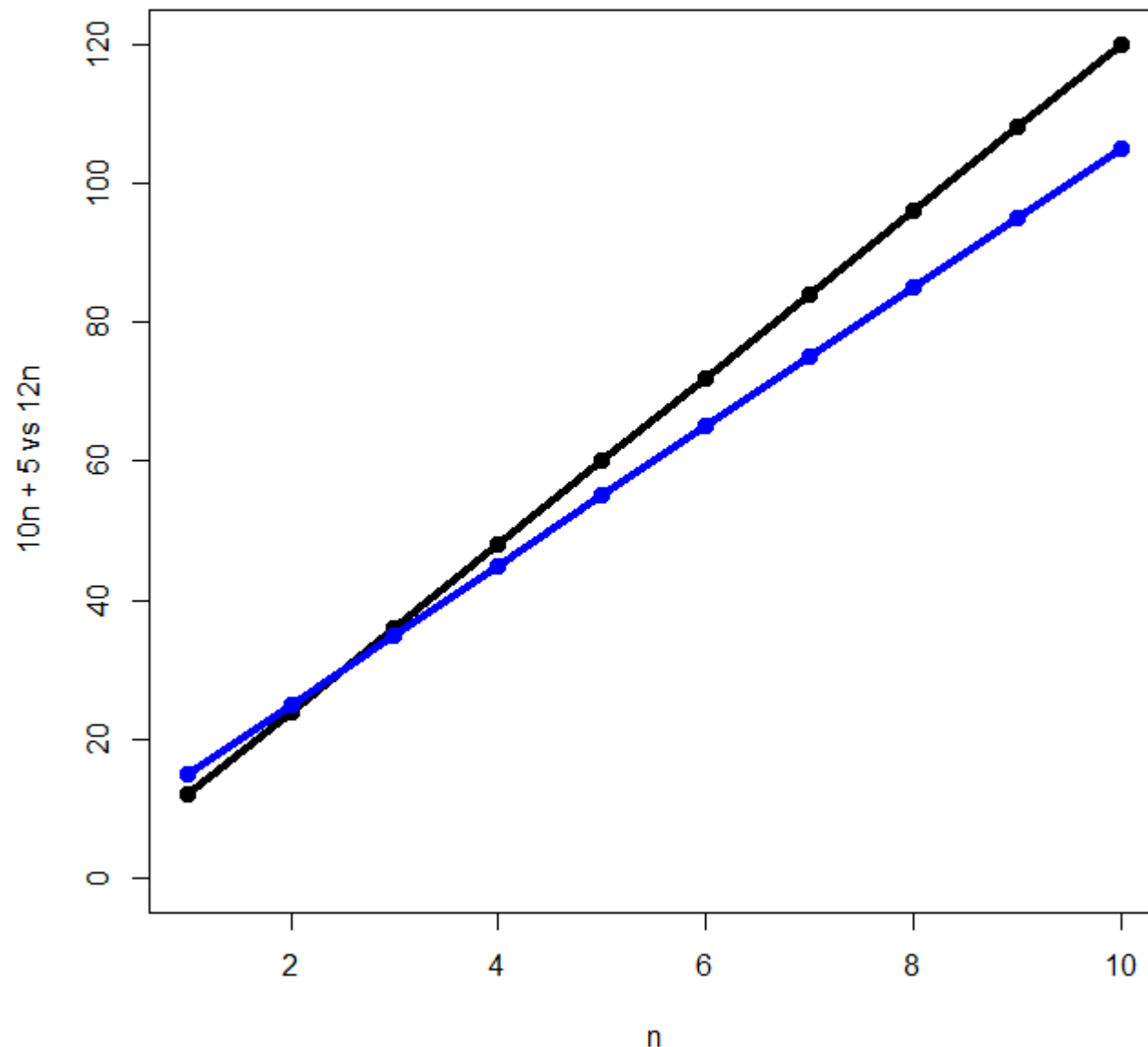
- $g(n) = n^2$
- Examples: $c = 1, n' = 2$
- $n < n^2$ for $n \geq 2$

$$10n = O(n)$$



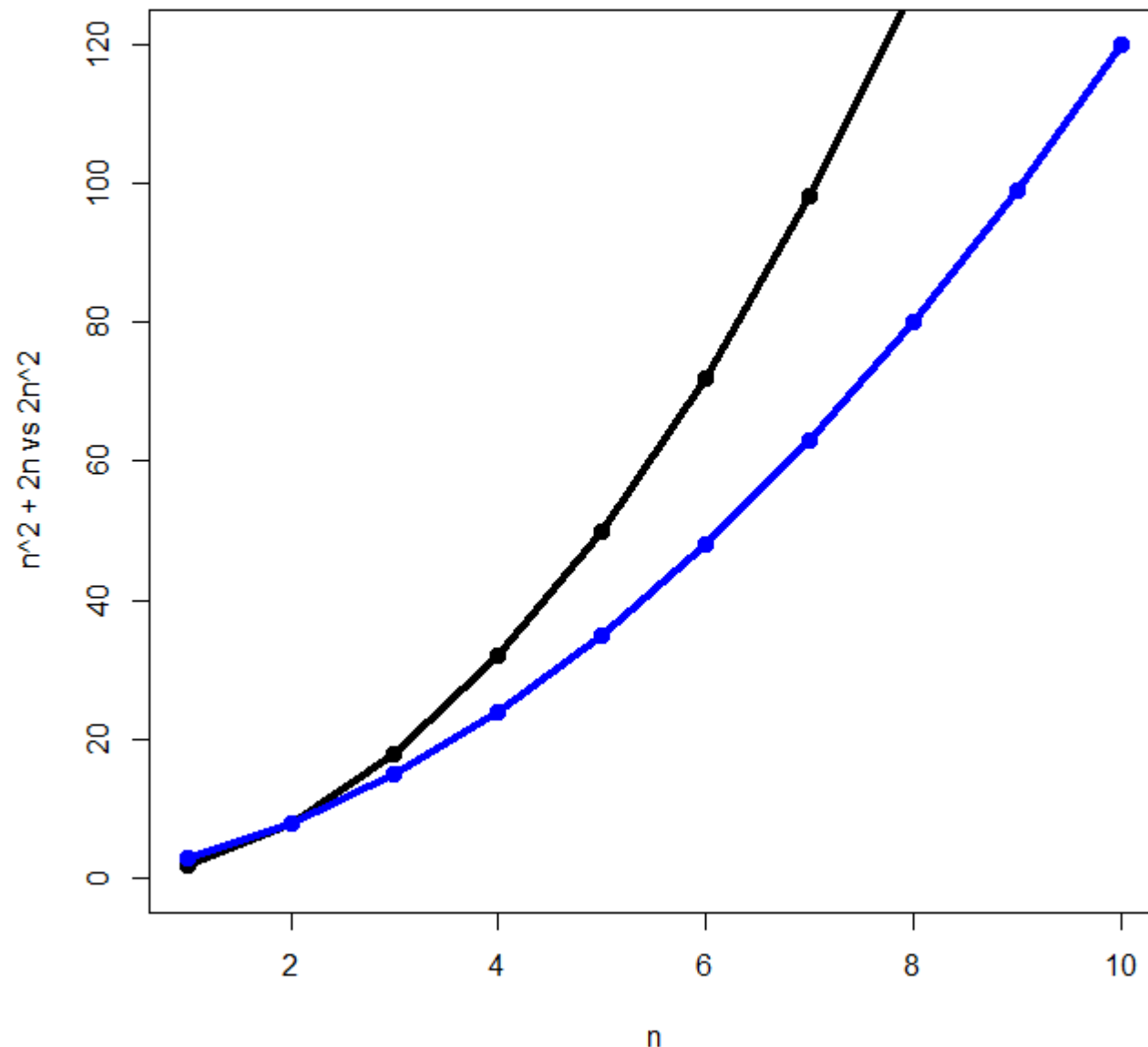
- $g(n) = n$
- Examples: $c = 11, n' = 1$
- $10n < 11n$ for $n \geq 1$

$$10n + 5 = O(n)$$



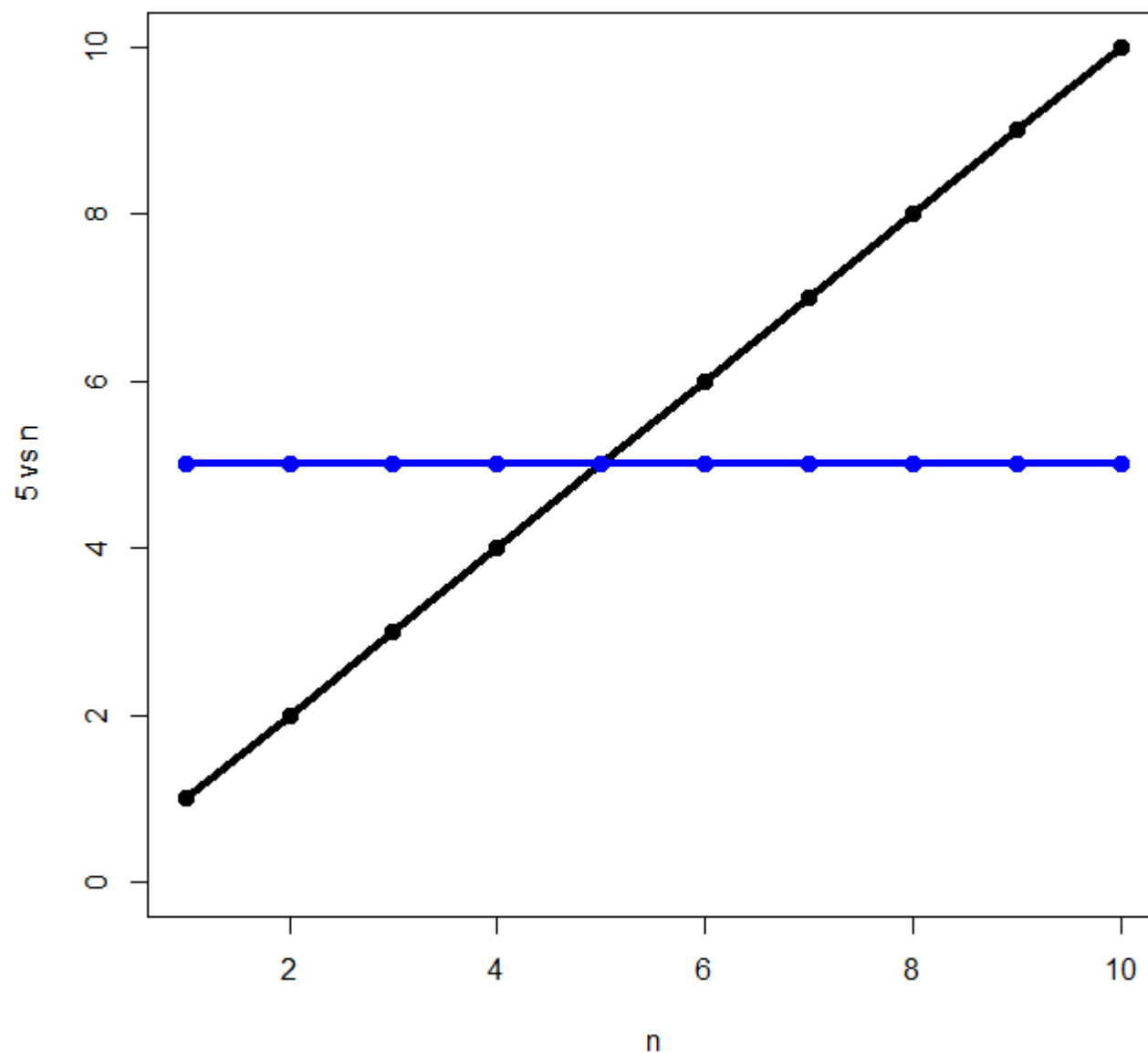
- $g(n) = n$
- Examples: $c = 12, n' = 3$
- $10n + 5 < 12n$ for $n \geq 3$
- Eg: $n=3 \rightarrow f(n)=35, g(n)=36$
- Note: for $n \leq 2$, $f(n)$ is actually larger

$$n^2 + 2n = O(n^2)$$



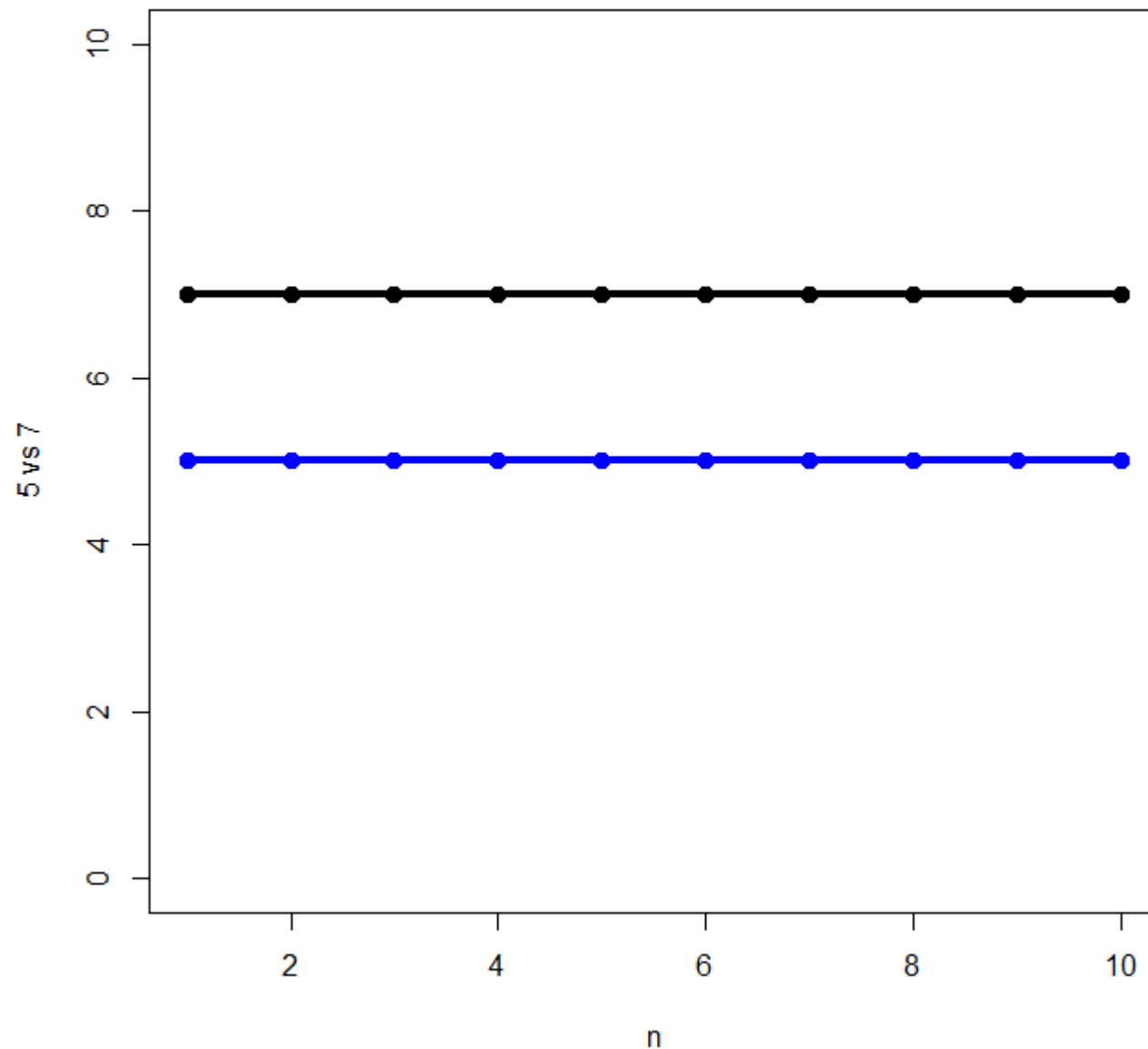
- $g(n) = n^2$
- Examples: $c = 2, n' = 3$
- $n^2 + 2n < 2n^2$ for $n \geq 3$
- Eg: $n=3 \rightarrow f(n)=15, g(n)=18$

$$5 = O(n)$$



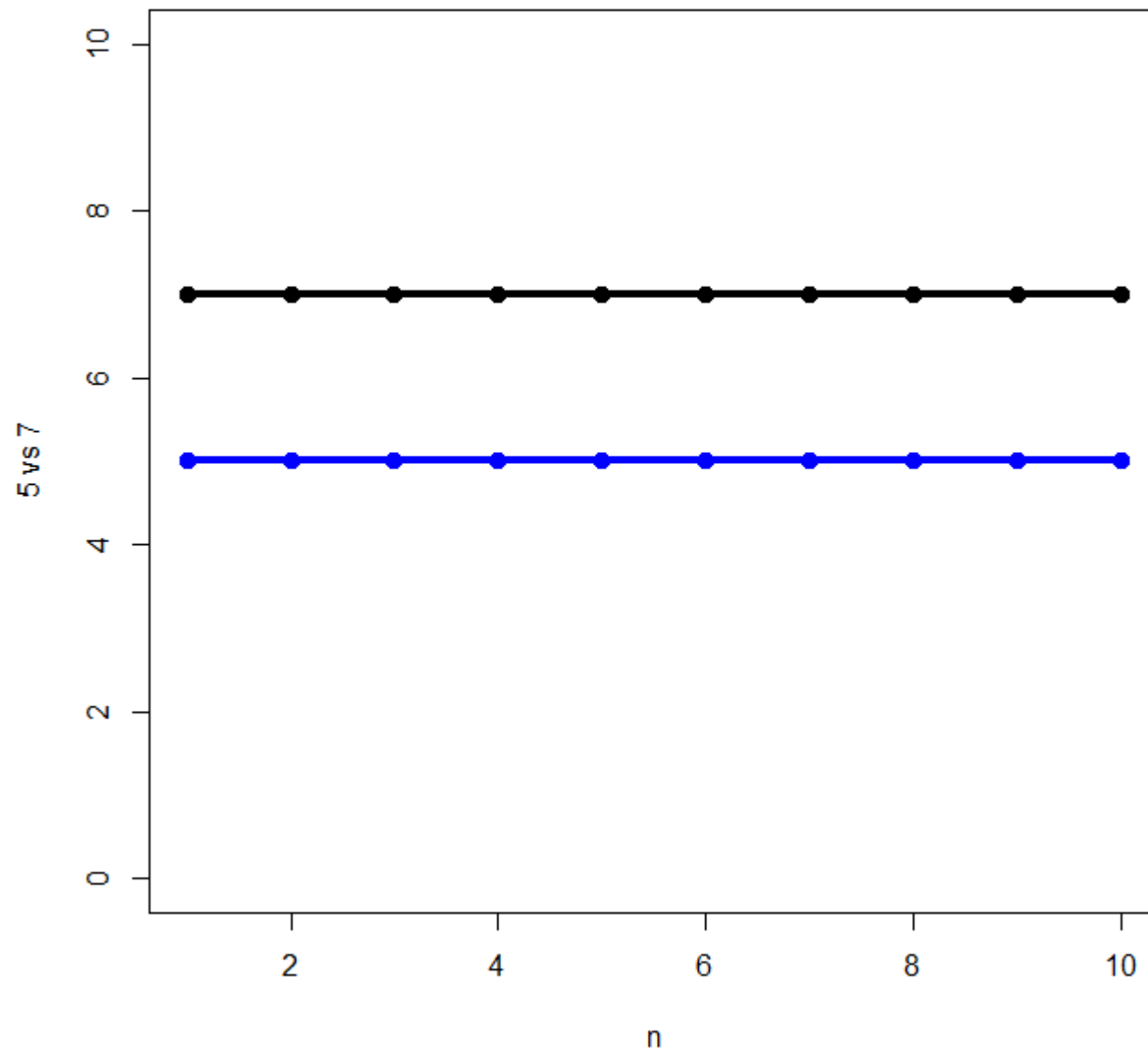
- $g(n) = n$
- Examples: $c = 1, n' = 6$
- $5 < n$ for $n \geq 6$

$$5 = O(7)$$



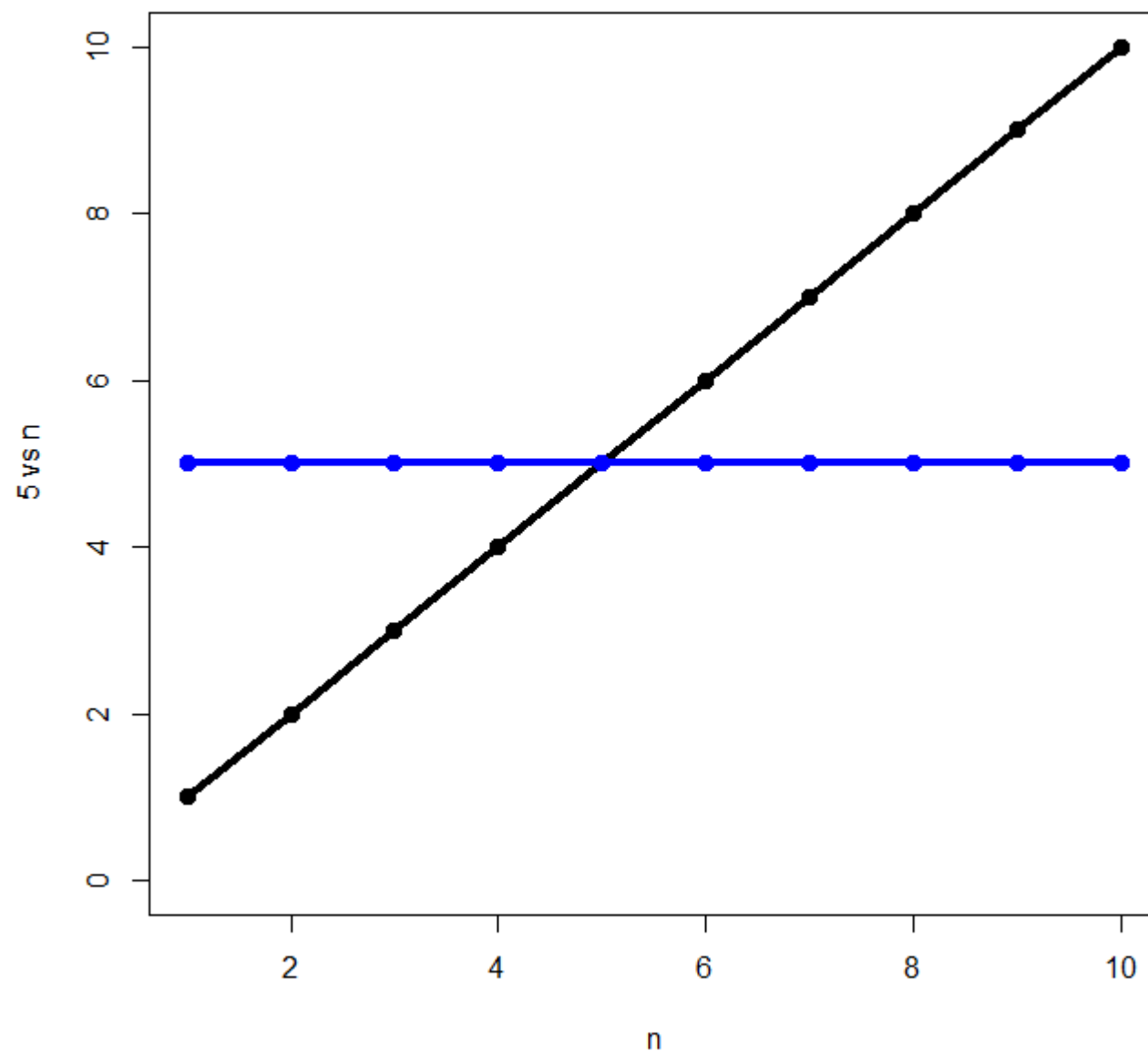
- $g(n) = 7$
- Examples: $c = 1, n' = 1$
- $5 < 7$ for regardless of n

$$5 = O(1)$$



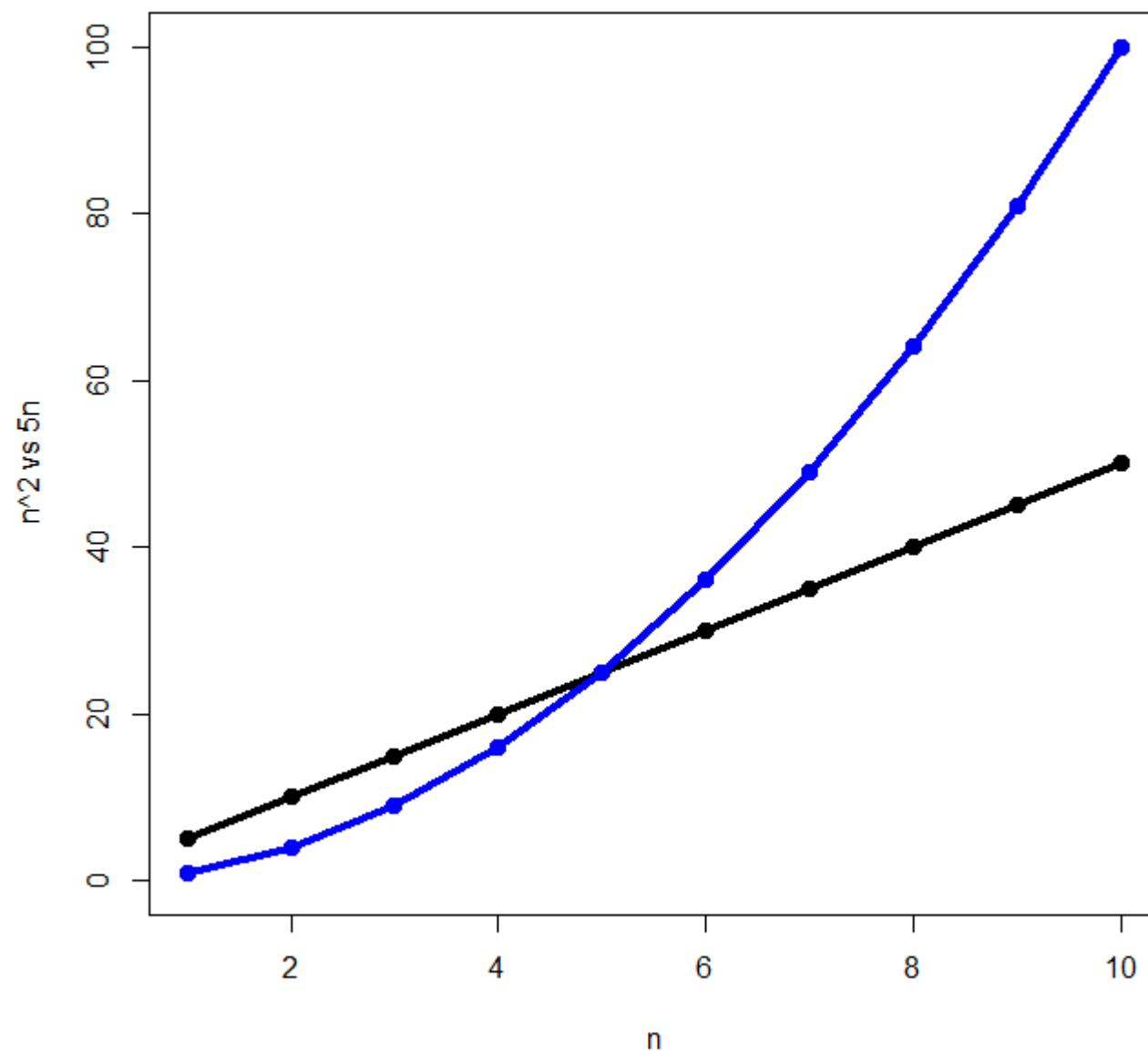
- $g(n) = 1$
- Examples: $c = 7, n' = 1$
- $5 < 7$ for regardless of n

$$n \neq O(1)$$



- $g(n) = 1$
- Whatever c I use (eg 5), $f(n) < c$ will not hold for $n' > c$, eg $n' = c + 1$

$$n^2 \neq O(n)$$



- $g(n) = n$
- Whatever c I use (eg 5), $f(n) < cn$ will not hold for $n' > c$, eg $n' = c + 1$

Big O Examples

- $n = O(n)$
- $n = O(n^2)$
- $10n = O(n)$
- $10n + 5 = O(n)$
- $n^2 + 2n = O(n^2)$
- $5 = O(n)$
- $5 = O(7)$
- $5 = O(1)$
- $n \neq O(1)$
- $n^2 \neq O(n)$

Big O Rules of Thumb

- When you have a polynomial, for upper bound just look at the highest exponent
- $an^3 + bn^2 + cn + d = O(n^3)$
- This means that, when analyzing an algorithm, you can ignore the parts with less impact
- When representing constants independent from the problem size, just use 1 by convention, eg $O(1)$

Notation

- $O(g(n)) = \{ f(n) : \text{there exists positive constants } c \text{ and } n', \text{ such that } 0 \leq f(n) \leq c * g(n) \text{ for all } n \geq n' \}$
- $O(g(n))$ is actually a *set* of functions
- $f(n) = O(g(n))$ is not fully correct as notation, as we use it to represent the fact that $f(n)$ is one member of the set $O(g(n))$
- $f(n) \in O(g(n))$ would be more precise, but often for simplicity you will see “=” instead of “ \in ”

Big Ω Lower Bound

- $f(n) = \Omega(g(n))$
- If there exists positive constants c and n' , such that $0 \leq c * g(n) \leq f(n)$ for all $n \geq n'$
- In other words, $g(n)$ is a *lower bound*
- Useful to consider *how expensive* algorithm is even in the *best possible scenario*
- $\Omega(1)$ is a trivial lower bound valid for all functions

Big Θ Tight Bound

- $f(n) = \Theta(g(n))$
- If there exists positive constants c, d and n' , such that $0 \leq c * g(n) \leq f(n) \leq d * g(n)$ for all $n \geq n'$
- In other words, this happens when the lower and upper bounds are asymptotically the same (and just differ by the constant)

```
public static int sum(int[] array) {  
    int sum = 0;  
    for(int i=0; i<array.length; i++) {  
        sum += array[i];  
    }  
    return sum;  
}
```

- In this case, the actual cost in number of instructions is $f(n) = 3n + 4$
- Asymptotically, we can say that $3n+4 = \Theta(n)$
- As the number of instructions does not depend on the content of the array, the *best case* and *worst case* for the runtime are the *same*

Order Of Growth Classification

- 1: constant (best you can have)
- $\log(N)$: logarithmic (very, very efficient)
- N : linear (OK for most cases)
- $N \log(N)$: linearithmic (OK for most cases)
- N^2 : quadratic (bearable, but things start to get expensive)
- N^3 : cubic (becoming painful)
- 2^N : exponential (*completely hopeless*, time to cry in a corner)

Which Scales Best?

- $f(n) = O(n)$
- $g(n) = \Omega(n)$
- $t(n) = \Omega(n \log(n))$
- $k(n) = O(n^2)$
- $z(n) = \Theta(n)$

The **only** thing that I can say for sure is that $f(n)$ and $z(n)$ are better than $t(n)$. Why???

Purple represents possible actual runtimes for those bounds

	1	$\log n$	n	$n \log n$	n^2	n^3	2^n
$O(n)$							
$\Omega(n)$							
$\Omega(n \log(n))$							
$O(n^2)$							
$\Theta(n)$							

In Practice

- Proving tight bounds is often infeasible
- Usually, from practical standpoint, the *worst case scenario* is what matters, so most discussions are about $O(g(n))$
- Often, lower bound is not so interesting, as in happy-day scenario you get $\Omega(1)$

A Big Mistake

- **BIG MISTAKE:** assuming that an upper bound is tight, eg claiming $f(n) = O(n)$ is necessarily better than $g(n) = O(n^2)$
 - Although you might still want to prefer $f(n)$ if you do not have any other information
- Even if a lower upper bound O exists, it might be too difficult to formally prove it, so $O(n^2)$ might just be the best approximation we currently have
- However, it is also important to consider that worst case scenario is different from the average one, but proving averages is much more difficult

```
public static void doSomething(int[] array) {  
    for(int i=0; i<array.length; i++) {  
        for(int j=i; j<array.length; j++) {  
            //... something  
        }  
    }  
}
```

- Note the “int j=i”. What can we say about that function?
- Without digging into the math, we can say that, even in best case, first loop is taken at least once, so $\Omega(n)$
- In worst case, not worse than assuming “int j=0”, so $O(n^2)$
 - In other words, we can mentally consider a more expensive algorithm which does more iterations, but that is easier then to analyze
- Is the true complexity closer to the lower or to the upper bound? Maybe $\Theta(n \log n)$???

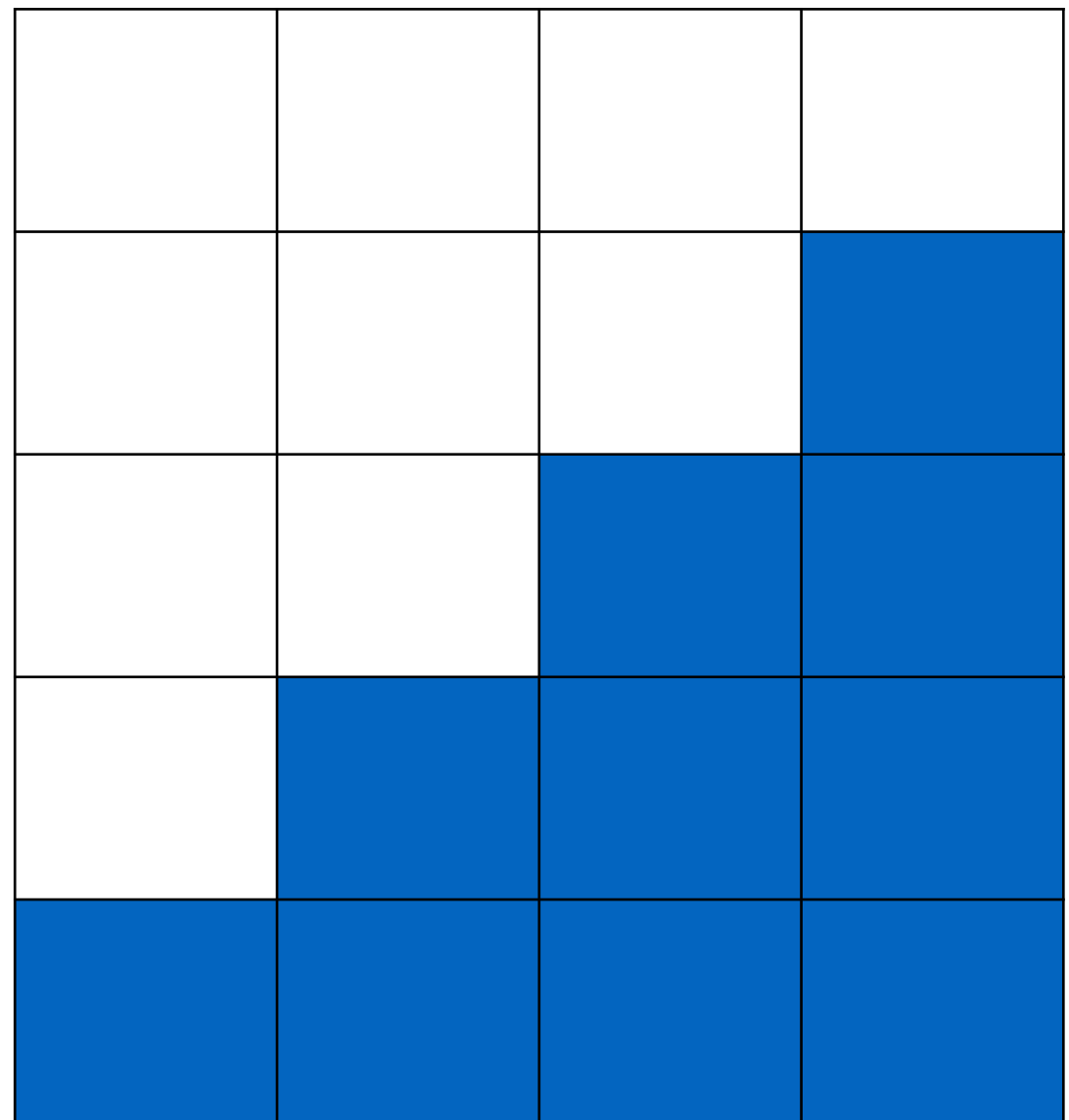
Let's Dig Into the Math...

```
public static void doSomething(int[] array) {  
    for(int i=0; i<array.length; i++) {  
        for(int j=i; j<array.length; j++) {  
            //... something  
        }  
    }  
}
```

- Outer loop is taken N times
- Inner loop is shorter by 1 at each iteration
- $N + (N - 1) + (N - 2) + \dots + 1 = \sum_{i=0}^N i = \frac{1}{2}N(N + 1) = \frac{1}{2}(N^2 + N) = \Theta(N^2)$

$$\sum_{i=0}^N i = \frac{1}{2}N(N+1)$$

- Think about a rectangle with sides N and $N+1$
- Its area is $N * (N+1)$
- But we are interested only in the colored area, so divide by 2
- $1+2+3+4 = 4 * 5 / 2 = 10$



Sorting

Consider a Playlist

...

Browse

Radio

YOUR LIBRARY

Recently Played

Songs

Albums

Artists

Stations

Local Files

Podcasts




PLAYLISTS

While marking exams

< > Q Search

UPGRADE

Andrea



PLAYLIST

While marking exams

Created by Andrea • 6 songs, 25 min

PLAY

...
















FOLLOWERS 0

Download

Filter

	TITLE	ARTIST	ALBUM		
+	Paranoid - 2009 Remastered Version	Black Sabbath	Paranoid (2009 Remastered Version)	2 minutes ago	2:47
+	Iron Man - 2009 Remastered Version	Black Sabbath	Paranoid (2009 Remastered Version)	2 minutes ago	5:54
+	Square Hammer	Ghost	Meliora (Redux)	a minute ago	3:58
+	The Number Of The Beast - 1998 Remastered Version	Iron Maiden	The Number Of The Beast (1998 R...	2 minutes ago	4:51
+	Run to the Hills - 1998 Remastered Version	Iron Maiden	The Number Of The Beast (1998 R...	2 minutes ago	3:54
+	Toxicity	System Of A Down	Toxicity	a minute ago	3:39

Consider a Playlist

#	TITLE	ALBUM	DATE ADDED		
17	 Gloria Judicator	Let There Be Nothing	1 hour ago		5:45
18	 Run to the Hills - 2015 Remaster Iron Maiden	The Number of the Beast (2015 Remaster)	1 hour ago		3:54
19	 Cliffs of Gallipoli Sabaton	Cliffs of Gallipoli	1 hour ago		5:41
20	 Painkiller Judas Priest	Playlist: The Very Best of Judas Priest	1 hour ago		6:05
21	 Worth Fighting For Judas Priest	Collections	1 hour ago	♥	4:19
22	 Holst: The Planets, Op. 32: I. Mars, the Bringer of War (Allegro) Gustav Holst, Philharmonia Orchestra, Sir Simon Rattle	Holst: The Planets	1 hour ago	♥	7:15
23	 The Trooper - 2015 Remaster Iron Maiden	Piece of Mind (2015 Remaster)	1 hour ago		4:13
24	 Resist and Bite Sabaton	Heroes	1 hour ago	♥	3:27
25	 Mozart: Requiem in D Minor, K. 626: III. Dies irae Nikolaus Harnoncourt, Vienna State Opera Chorus	Mozart : Requiem (Elatus)	1 hour ago		1:51
26	 Orff: Carmina Burana, Introduction, Fortuna Imperatrix Mundi... Carl Orff, Michel Plasson, Orfeon Donostiarra, Orchestre National Du ...	Carmina Burana	1 hour ago		2:39
27	 Peer Gynt - In The Hall Of The Mountain King Edvard Grieg	Classical Wedding Album	1 hour ago		2:35
28	 Walk E Pantera	Vulgar Display of Power	1 hour ago		5:15
29	 Ace of Spades Motörhead	Ace of Spades (Expanded Edition)	1 hour ago		2:47
30	 The Writing On The Wall Iron Maiden	The Writing On The Wall	1 hour ago		6:14
31	 Pavel Chinezu, Leat 1479	Muaur De Fluier	1 hour ago		6:13

Sort by Title or Artist, Ascending or Descending

The image shows a Spotify interface with a playlist titled "While marking exams" created by Andrea. The playlist contains 6 songs and has a duration of 25 minutes. The interface includes a sidebar with navigation options like Browse, Radio, Your Library, Recently Played, Songs, Albums, Artists, Stations, Local Files, Podcasts, and Playlists. The main area displays the playlist cover art and a list of songs. Two purple arrows point to the sort headers "ARTIST" and "TITLE" in the song list.

PLAYLIST
While marking exams
Created by Andrea • 6 songs, 25 min

PLAY **...**

Filter

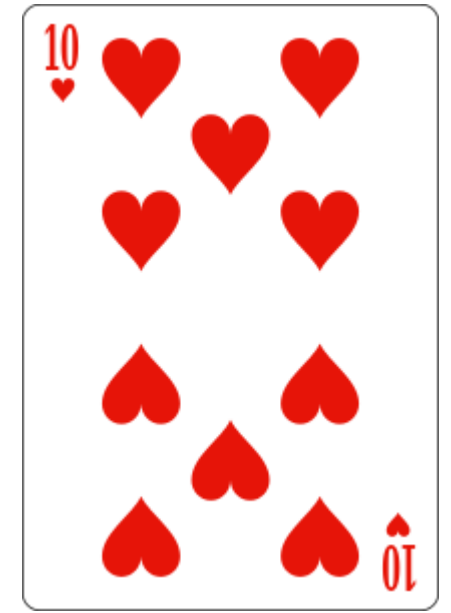
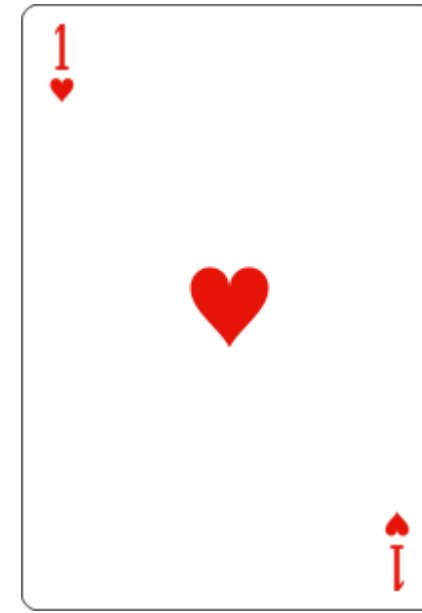
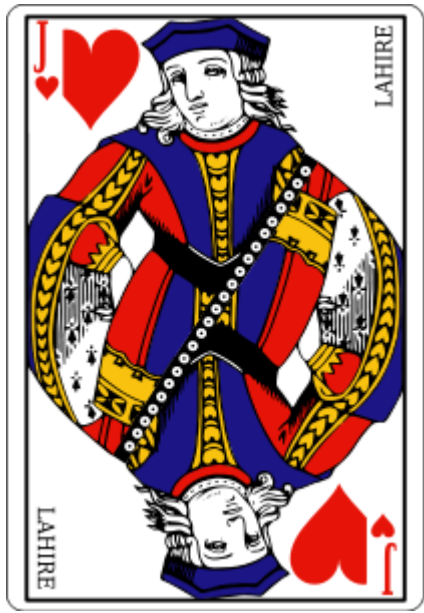
	TITLE	ARTIST	ALBUM		
+	Paranoid - 2009 Remastered Version	Black Sabbath	Paranoid (2009 Remastered Version)	2 minutes ago	2:47
+	Iron Man - 2009 Remastered Version	Black Sabbath	Paranoid (2009 Remastered Version)	4 minutes ago	5:54
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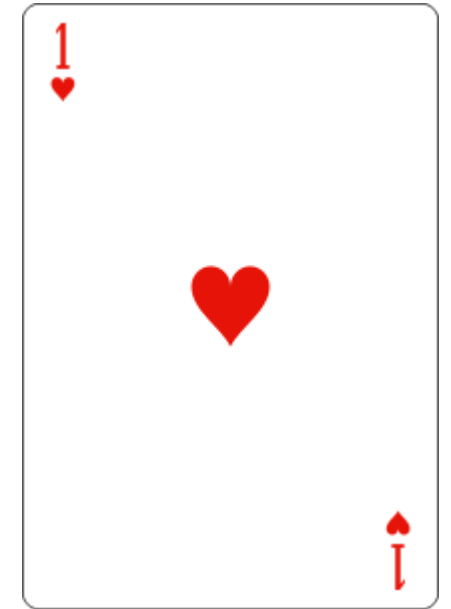
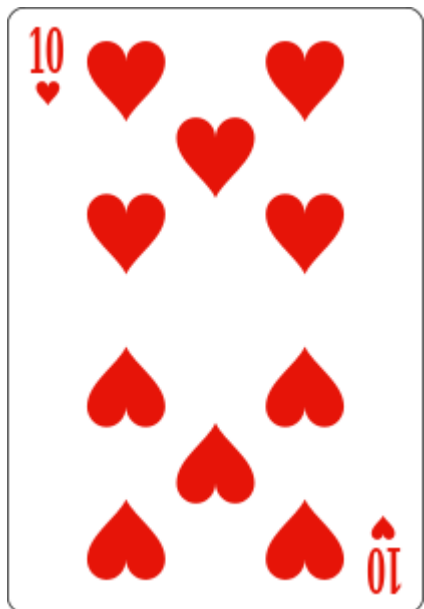
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How do you sort when
playing cards?



Sorting Algorithms

- Many different sorting algorithms, with different properties
- Given two items A and B , just need a *comparator* that can state which one is greater or equal
 - easy to say that 5 greater than 2, but what does it mean that song A is greater than song B ? e.g., could look at alphabetic ordering of titles or artist names
- Most language APIs provides good defaults
 - Unless very large data, default will be fine 99% of the cases
- Sorting is very popular in programming
 - Important to understand how it works under the hood
- Tractable mathematically
 - So good example to show how to analyze algorithms

Sorting Algorithms

- Bubble Sort
- Insertion Sort
- Merge Sort (next class)
- Quick Sort (next class)
- There are more, but those are the most famous that you need to know
- Good way to see a problem been solved in many different ways

Bubble Sort

- *Easiest* sorting algorithms
- From left to right
- Look at adjacent cards, and swap them if not in order
- Repeat from left to right till no more swap



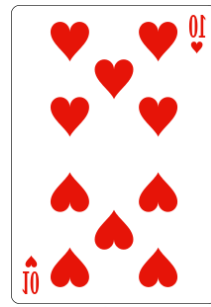
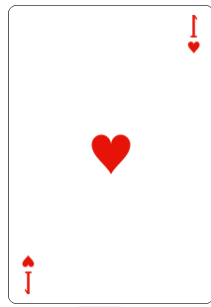
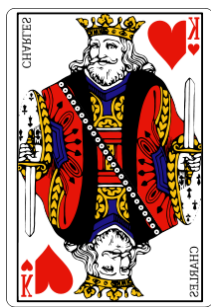
No swap, they are in order



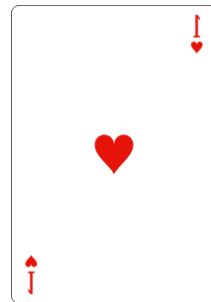
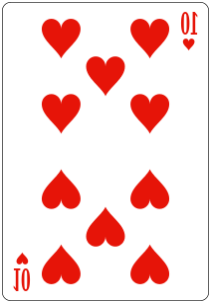
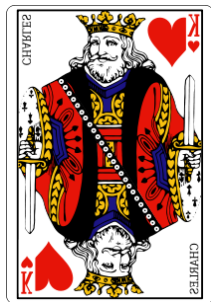
Swap



No swap, they are in order



Swap



- Restart from beginning.
- At each iteration, at least one card will be in right position, as it *bubbles up* to the top.

Runtime of Bubble Sort

- To sort N cards, need *at most* N iterations, in which you check *at most* $N-1$ pairs
- Even if already sorted, need to check each of $N-1$ pairs at least once, to see if indeed sorted
- $\Omega(N)$ and $O(N^2)$ pair comparisons

Insertion Sort

- An array of size 0 or 1 is always considered sorted
- From left to right, till length N
- K -leftmost values are sorted
- Position $K+1$ is not sorted, insert it in the first K
 - by swapping adjacent elements, like in Bubble Sort

4	5	1	3	2	6
---	---	---	---	---	---

 $K=0$

4	5	1	3	2	6
---	---	---	---	---	---

 $K=1$

4	5	1	3	2	6
---	---	---	---	---	---

 $K=2$

4	5	1	3	2	6
---	---	---	---	---	---

 $K=3$

4	1	5	3	2	6
---	---	---	---	---	---

 swap

1	4	5	3	2	6
---	---	---	---	---	---

 swap

Cont.

1	4	5	3	2	6
---	---	---	---	---	---

K=4

1	4	3	5	2	6
---	---	---	---	---	---

swap

1	3	4	5	2	6
---	---	---	---	---	---

swap

1	3	4	5	2	6
---	---	---	---	---	---

K=5

1	3	4	2	5	6
---	---	---	---	---	---

swap

1	3	2	4	5	6
---	---	---	---	---	---

swap

1	2	3	4	5	6
---	---	---	---	---	---

swap

1	2	3	4	5	6
---	---	---	---	---	---

K=6

- Best case: already sorted, e.g., 1-2-3-4-5-6, need to do $N-1$ comparisons, so $\Omega(N)$
- Worst case: opposite order, e.g., 6-5-4-3-2-1, each element needs to be compared and swapped with all previous K ones, so $O(N^2)$

Best vs. Worst Case

- “Best case” is not when $N=0$
- Runtime might not only depend on size N , but also on the **content** of the input
 - an array already sorted will likely take less time to sort than a shuffled one
 - on the other hand, summing all integers in an array will likely have no difference between Best and Worst case, ie $\Theta(N)$
- Considering all possible inputs in a mathematical formula would not be viable
 - that is why we talk about BEST and WORST cases in relation to N

Homework

- Study Book Chapter 1.4 and 2.1
 - Note: in the book, the authors use the \sim notation instead of the standard O , Ω and Θ . They explain their reason in the Q&A for such weird choice, but I do disagree
- Study code in the *org.pg4200.les03* package
- Do exercises in *exercises/ex03*
- Extra: do exercises in the book