

Lecture 2

Asymptotic Notation,
Worst-Case Analysis, and MergeSort

Announcements

- Please (continue to) send OAE letters to cs161-staff-win2324@cs.stanford.edu

161A (ACE)

- ACE is a School of Engineering's initiative to provide additional resources to students who enroll in the program
- CS 161ACE is a 1-unit supplementary section held **Wednesday 3:30-5:20pm PDT**
- Enrollment is limited and you can still apply for the course (link on website)
- Students will be notified whether they got accepted or not this weekend
- Section attendance is mandatory for students who get in, and enroll in the course (we will provide an enrollment code)
- For further questions you are welcome to email me at stpshrkv@stanford.edu

Homework!

- HW1 will be released **today** (Wednesday).
- It is due the next **Wednesday, 11:59pm** (in one week), on Gradescope. As a reminder, HW1, HW2, and HW3 are solo submissions only.
- Homework comes in two parts:
 - Exercises:
 - More straightforward.
 - Try to do them on your own.
 - Problems:
 - Less straightforward.
 - Try them on your own first, but then collaborate!
- See the website for guidelines on homework:
 - Collaboration + late day policy (in the “Policies” tab)
 - Best practices (in the “Resources” tab)
 - Example homework (in the “Resources” tab)
 - LaTeX help (in the “Resources” tab)

Office Hours and Sections

- Office hours calendar is on the course website.
 - (under "Staff / Office Hours")
- Sections have been scheduled.
 - See course website
 - One will be recorded (and put on Canvas)
 - Don't need to formally enroll in sections, just show up!

Huang basement



Links on Canvas

Course website: <https://stanford-cs161.github.io/winter2024/> ↗

Remote section Zoom link:

- Jeff (Thursdays 7:30pm-9:30pm) : [https://stanford.zoom.us/██](https://stanford.zoom.us/j/██) ↗

Remote office hours Zoom links:

- Thomas (Mondays 7PM-9PM): [https://stanford.zoom.us/██](https://stanford.zoom.us/j/██) ↗
- Samantha (Wednesdays 2PM-4PM, Sundays 7PM-9PM): [https://stanford.zoom.us/██](https://stanford.zoom.us/j/██) ↗
- Amol (Thursdays 9AM-11AM): [https://stanford.zoom.us/██](https://stanford.zoom.us/j/██) ↗
- Xinyi (Thursdays 8PM-10PM): [https://stanford.zoom.us/██](https://stanford.zoom.us/j/██) ↗
- Jeff (Saturdays 2PM-6PM): [https://stanford.zoom.us/██](https://stanford.zoom.us/j/██) ↗
- Kayla (Sundays 2PM-4PM, Mondays 4PM-6PM): [https://stanford.zoom.us/██](https://stanford.zoom.us/j/██) ↗

Queuestatus link: <https://queuestatus.com/████████████████████> ↗

End of announcements!

Last time

Philosophy

- Algorithms are awesome!
- Our motivating questions:
 - Does it work?
 - Is it fast?
 - Can I do better?

Technical content

- Divide-and-conquer
- Karatsuba integer multiplication
- Not-so-rigorous analysis

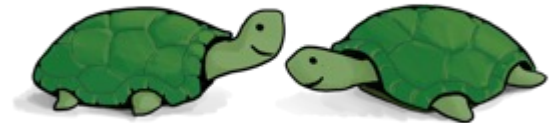
Cast



Plucky the pedantic penguin



Lucky the lackadaisical lemur



Think-Pair-Share Terrapins



Ollie the over-achieving ostrich



Siggi the studios stork

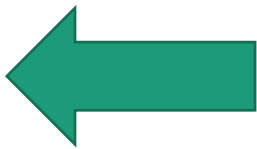
Sorting

- We are going to ask:
 - Does it work?
 - Is it fast?
- We'll start to see how to answer these by looking at some examples of sorting algorithms.
 - InsertionSort
 - MergeSort



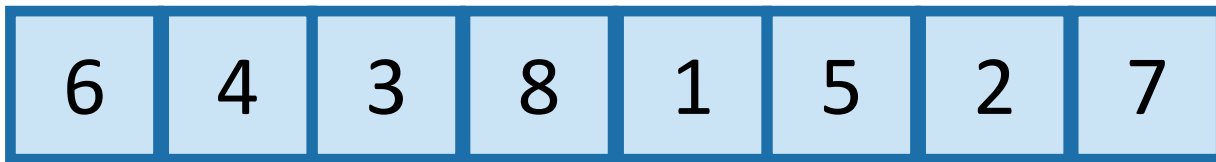
SortingHatSort not discussed

The Plan

- Sorting! 
- Worst-case analysis
 - InsertionSort: Does it work?
- Asymptotic Analysis
 - InsertionSort: Is it fast?
- MergeSort
 - Does it work?
 - Is it fast?

Sorting

- Important primitive
- For today, we'll pretend all elements are distinct.



Length of the list is n

Pre-lecture exercise:

What was the mystery sort algorithm?

1. MergeSort
2. QuickSort
3. InsertionSort
4. BogoSort

```
def mysteryAlgorithmOne(A):
    B = [None for i in range(len(A))]
    for x in A:
        for i in range(len(B)):
            if B[i] == None or B[i] > x:
                j = len(B)-1
                while j > i:
                    B[j] = B[j-1]
                    j -= 1
                B[i] = x
                break
    return B
```

```
def mysteryAlgorithmTwo(A):
    for i in range(1, len(A)):
        current = A[i]
        j = i-1
        while j >= 0 and A[j] > current:
            A[j+1] = A[j]
            j -= 1
        A[j+1] = current
```

Pre-lecture exercise:

What was the mystery sort algorithm?

1. MergeSort
2. QuickSort
3. InsertionSort
4. BogoSort

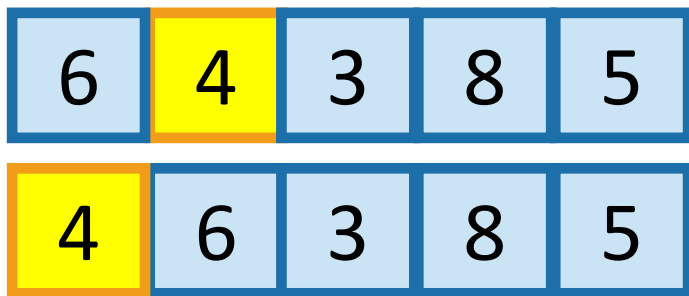
```
def mysteryAlgorithmOne(A):
    B = [None for i in range(len(A))]
    for x in A:
        for i in range(len(B)):
            if B[i] == None or B[i] > x:
                j = len(B)-1
                while j > i:
                    B[j] = B[j-1]
                    j -= 1
                B[i] = x
            break
    return B
```

```
def mysteryAlgorithmTwo(A):
    for i in range(1, len(A)):
        current = A[i]
        j = i-1
        while j >= 0 and A[j] > current:
            A[j+1] = A[j]
            j -= 1
        A[j+1] = current
```

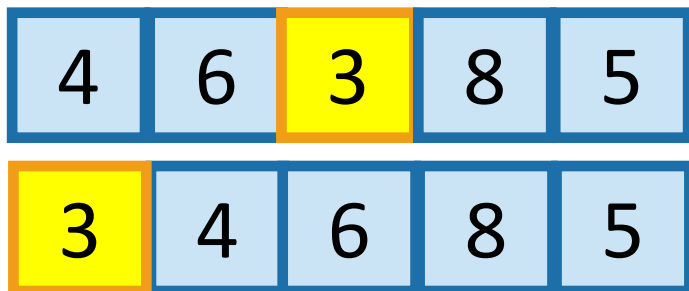
InsertionSort

example

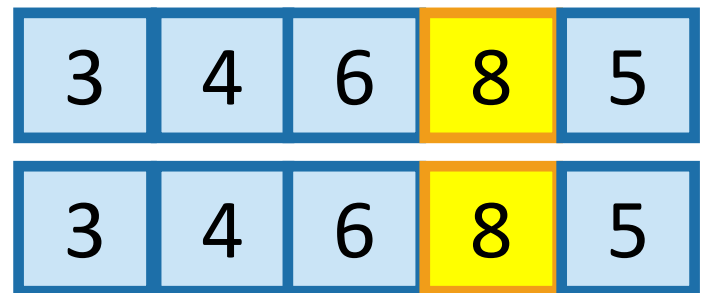
Start by moving $A[1]$ toward the beginning of the list until you find something smaller (or can't go any further):



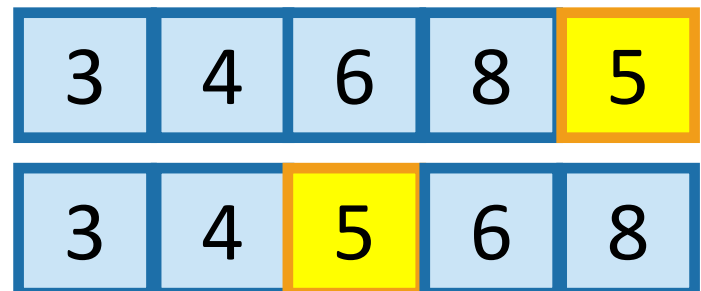
Then move $A[2]$:



Then move $A[3]$:



Then move $A[4]$:



Then we are done!



Insertion Sort


1. Does it work?
2. Is it fast?

What does that
mean???



Plucky the
Pedantic Penguin

The Plan

- InsertionSort recap
- Worst-case Analysis 
 - Back to InsertionSort: Does it work?
- Asymptotic Analysis
 - Back to InsertionSort: Is it fast?
- MergeSort
 - Does it work?
 - Is it fast?

Claim: InsertionSort “works”

- “Proof:” It just worked in this example:

6 4 3 8 5

6 4 3 8 5

4 6 3 8 5

4 6 3 8 5

3 4 6 8 5

3 4 6 8 5

3 4 6 8 5

3 4 6 8 5

3 4 5 6 8

Sorted!

What does it mean to “work”?

- Is it enough to be correct on only one input?
- Is it enough to be correct on most inputs?
- In this class, we will use **worst-case analysis**:
 - An algorithm must be correct on **all possible** inputs.
 - The running time of an algorithm is the worst possible running time over all inputs.

Worst-case analysis

Think of it like a game:



Here is my algorithm!

```
Algorithm:  
Do the thing  
Do the stuff  
Return the answer
```

Algorithm
designer

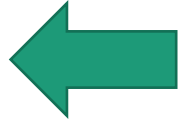
**HERE IS AN INPUT!
(WHICH I DESIGNED
TO BE TERRIBLE FOR
YOUR ALGORITHM!)**



- **Pros:** very strong guarantee
- **Cons:** very strong guarantee

Insertion Sort

1. Does it work?



2. Is it fast?



• Okay, so it's pretty obvious that it works.



• **HOWEVER!** In the future it won't be so obvious, so let's take some time now to see how we would prove this rigorously.

Why does this work?

- Say you have a sorted list,

3	4	6	8
---	---	---	---

, and another element

5

.

- Insert

5

 right after the largest thing that's still smaller than

5

. (Aka, right after

4

).

- Then you get a sorted list:

3	4	5	6	8
---	---	---	---	---

So just use this logic at every step.



The first element, [6], makes up a sorted list.

So correctly inserting 4 into the list [6] means that [4,6] becomes a sorted list.



The first two elements, [4,6], make up a sorted list.

So correctly inserting 3 into the list [4,6] means that [3,4,6] becomes a sorted list.



The first three elements, [3,4,6], make up a sorted list.

So correctly inserting 8 into the list [3,4,6] means that [3,4,6,8] becomes a sorted list.



The first four elements, [3,4,6,8], make up a sorted list.

So correctly inserting 5 into the list [3,4,6,8] means that [3,4,5,6,8] becomes a sorted list.



YAY WE ARE DONE!

This sounds like a job for...

**Proof By
Induction!**

The notes contain the details!

- See website!

2.1 Correctness of InsertionSort

Once you figure out what InsertionSort is doing (see the slides for the intuition on this), you may think that it's "obviously" correct. However, if you didn't know what it was doing and just got the above code, maybe this wouldn't be so obvious. Additionally, for algorithms

1

that we'll study in the future, it *won't* always be obvious that it works, and so we'll have to prove it. To warm us up for those proofs, let's carefully go through a proof of correctness of InsertionSort.

Outline of a proof by induction

Let A be a list of length n

- **Inductive Hypothesis:**

- A[:i+1] is sorted at the end of the i^{th} iteration (of the outer loop).

- **Base case (i=0):**

- A[:1] is sorted at the end of the 0'th iteration. ✓

- **Inductive step:**

- For any $0 < k < n$, if the inductive hypothesis holds for $i=k-1$, then it holds for $i=k$.
- Aka, if A[:k] is sorted at step k-1, then A[:k+1] is sorted at step k

- **Conclusion:**

- The inductive hypothesis holds for $i = 0, 1, \dots, n-1$.
- In particular, it holds for $i=n-1$.
- At the end of the $n-1^{\text{st}}$ iteration (aka, at the end of the algorithm), A[:n] = A is sorted.
- That's what we wanted! ✓

This logic
(see notes for details)



The first two elements, [4,6], make up a sorted list.



So correctly inserting 3 into the list [4,6] means that [3,4,6] becomes a sorted list.

This was
iteration $i=2$.

Aside: proofs by induction

- We're going to see/do/skip over a lot of them.
- I'm assuming you're comfortable with them from CS103.
 - When you assume...
- If that went by too fast and was confusing:
 - GO TO SECTION
 - **GO TO SECTION**
 - Notes
 - References
 - Office hours

Make sure you really understand the argument on the previous slide! Check out the notes for a more formal write-up and go to the sections for an overview of what we are looking for in proofs by induction.




Siggi the Studious Stork

What have we learned?

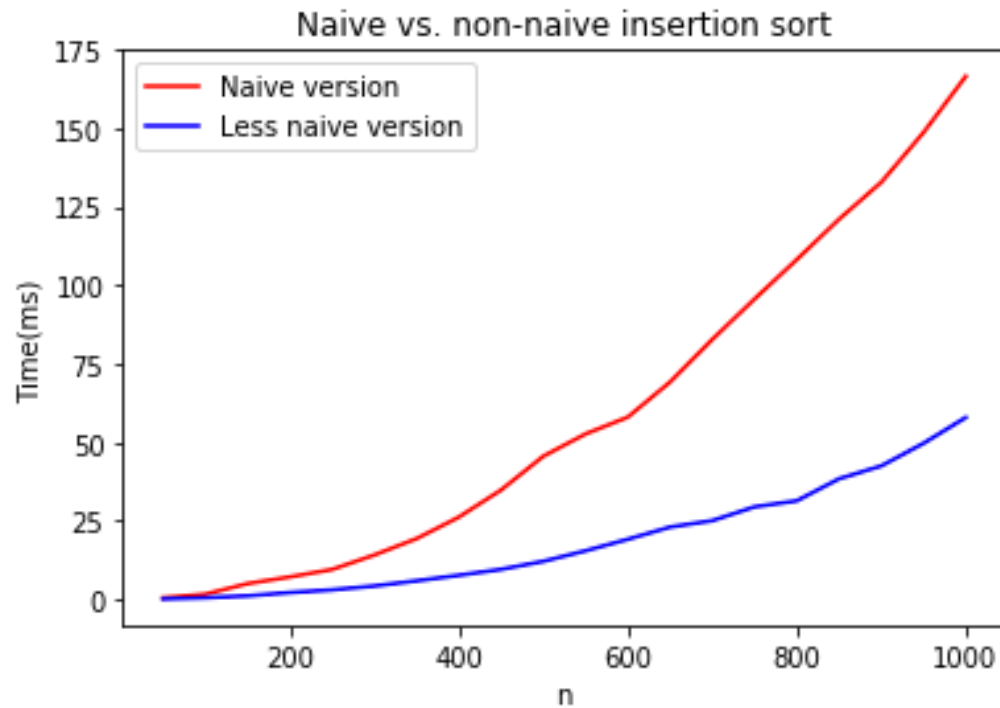
- In this class we will use worst-case analysis:
 - We assume that a “bad guy” produces a worst-case input for our algorithm, and we measure performance on that worst-case input.
- With this definition, InsertionSort “works”
 - Proof by induction!

The Plan

- InsertionSort recap
- Worst-case Analysis
 - Back to InsertionSort: Does it work?
- Asymptotic Analysis 
 - Back to InsertionSort: Is it fast?
- MergeSort
 - Does it work?
 - Is it fast?

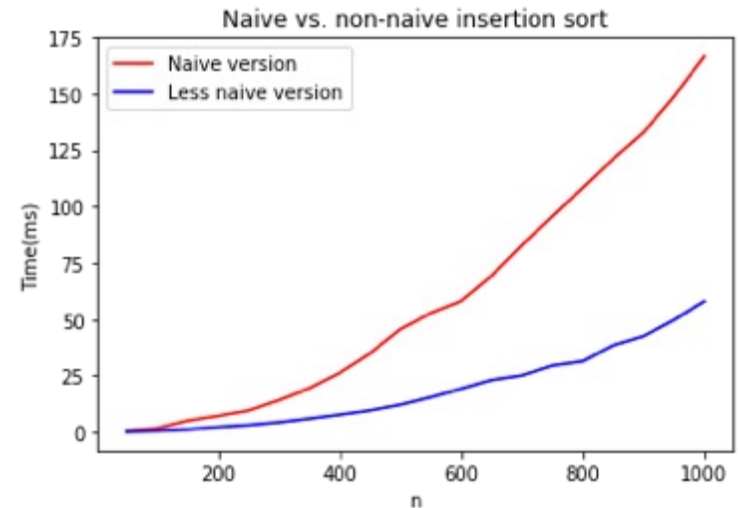
How fast is InsertionSort?

- This fast:



Issues with this answer?

- The “same” algorithm can be slower or faster depending on the implementations.
- It can also be slower or faster depending on the hardware that we run it on.



With this answer,
“running time” isn’t
even well-defined!



How fast is InsertionSort?



- Let's count the number of operations!

```
def InsertionSort(A):  
    for i in range(1, len(A)):  
        current = A[i]  
        j = i-1  
        while j >= 0 and A[j] > current:  
            A[j+1] = A[j]  
            j -= 1  
        A[j+1] = current
```

By my count*...

- $2n^2 - n - 1$ variable assignments
- $2n^2 - n - 1$ increments/decrements
- $2n^2 - 4n + 1$ comparisons
- ...

*Do not pay attention to these formulas, they do not matter.
Also not valid for bug bounty (good citizenship) points.

Issues with this answer?

- It's very tedious!
- In order to use this to understand running time, I need to know how long each operation takes, plus a whole bunch of other stuff...

```
def InsertionSort(A):  
    for i in range(1, len(A)):  
        current = A[i]  
        j = i-1  
        while j >= 0 and A[j] > current:  
            A[j+1] = A[j]  
            j -= 1  
        A[j+1] = current
```

Counting individual operations is a lot of work and doesn't seem very helpful!



Lucky the lackadaisical lemur

In this class we will use...

- **Big-Oh notation!**
- Gives us a meaningful way to talk about the running time of an algorithm, independent of programming language, computing platform, etc., without having to count all the operations.

Main idea:

Focus on how the runtime **scales** with n (the input size).

Some examples...

(Heuristically: only pay attention to the largest function of n that appears.)

Number of operations	Asymptotic Running Time
$\frac{1}{10} \cdot n^2 + 100$	$O(n^2)$
$0.063 \cdot n^2 - .5n + 12.7$	$O(n^2)$
$100 \cdot n^{1.5} - 10^{10000} \sqrt{n}$	$O(n^{1.5})$
$11 \cdot n \log(n) - 1$	$O(n \log(n))$

We say this algorithm is “asymptotically faster” than the others.

Why is this a good idea?

- Suppose the running time of an algorithm is:

$$T(n) = 10n^2 + 3n + 7 \text{ ms}$$

This constant factor of 10
depends a lot on my
computing platform...

These lower-order
terms don't really
matter as n gets large.

We're just left with the n^2 term!
That's what's meaningful.

Pros and Cons of Asymptotic Analysis

Pros:

- Abstracts away from hardware- and language-specific issues.
- Makes algorithm analysis much more tractable.
- Allows us to meaningfully compare how algorithms will perform on large inputs.

Cons:

- Only makes sense if n is large (compared to the constant factors).

1000000000 n
is “better” than n^2 !?!

pronounced “big-oh of ...” or sometimes “oh of ...”



Informal definition for $O(\dots)$

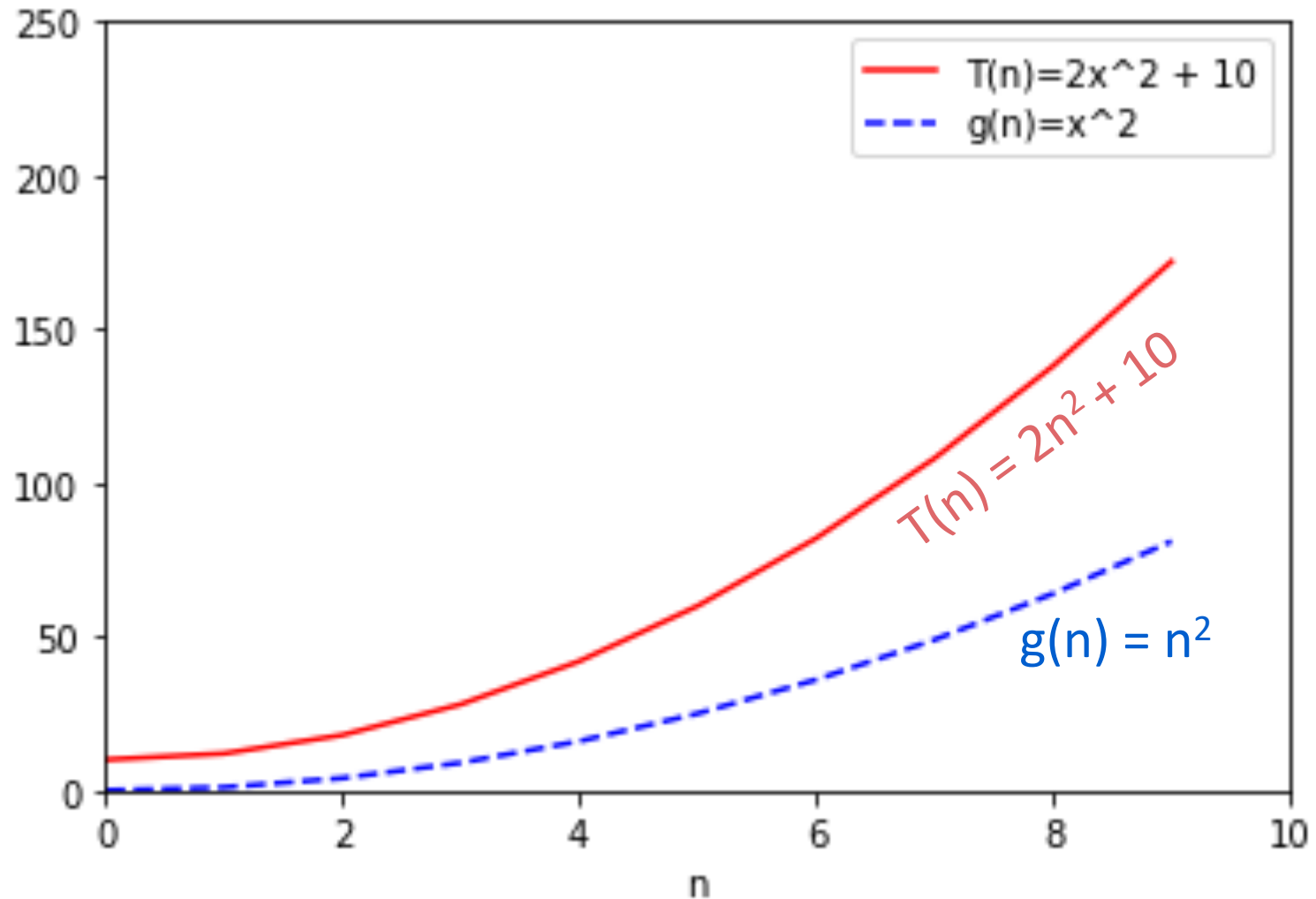
- Let $T(n)$, $g(n)$ be functions of positive integers.
 - Think of $T(n)$ as a runtime: positive and increasing in n .
- We say “ $T(n)$ is $O(g(n))$ ” if:
 - for all large enough n ,
 - $T(n)$ is at most some constant multiple of $g(n)$.

Here, “constant” means “some number that doesn’t depend on n .”

Example

$$2n^2 + 10 = O(n^2)$$

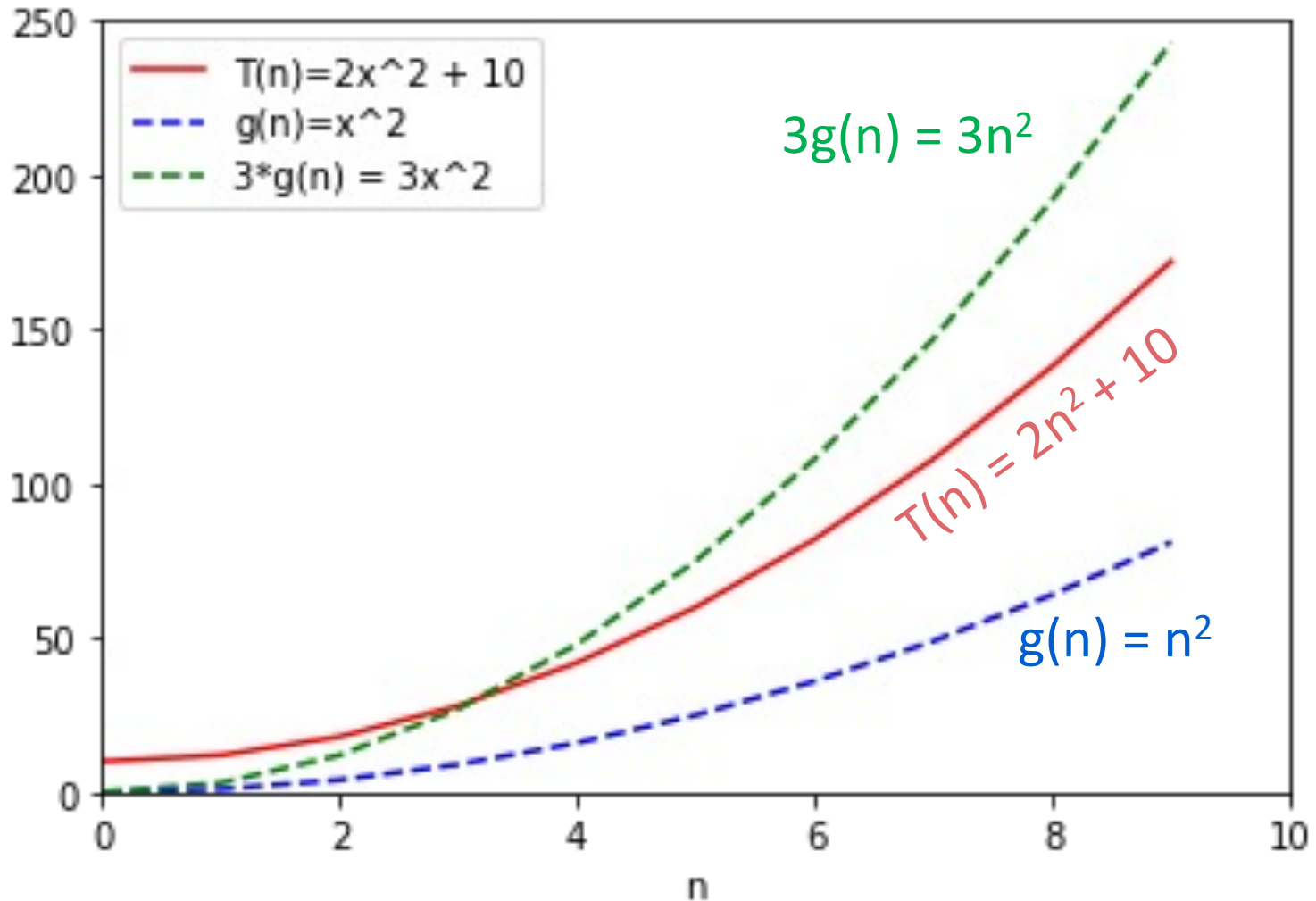
for large enough n ,
 $T(n)$ is at most some constant
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Example

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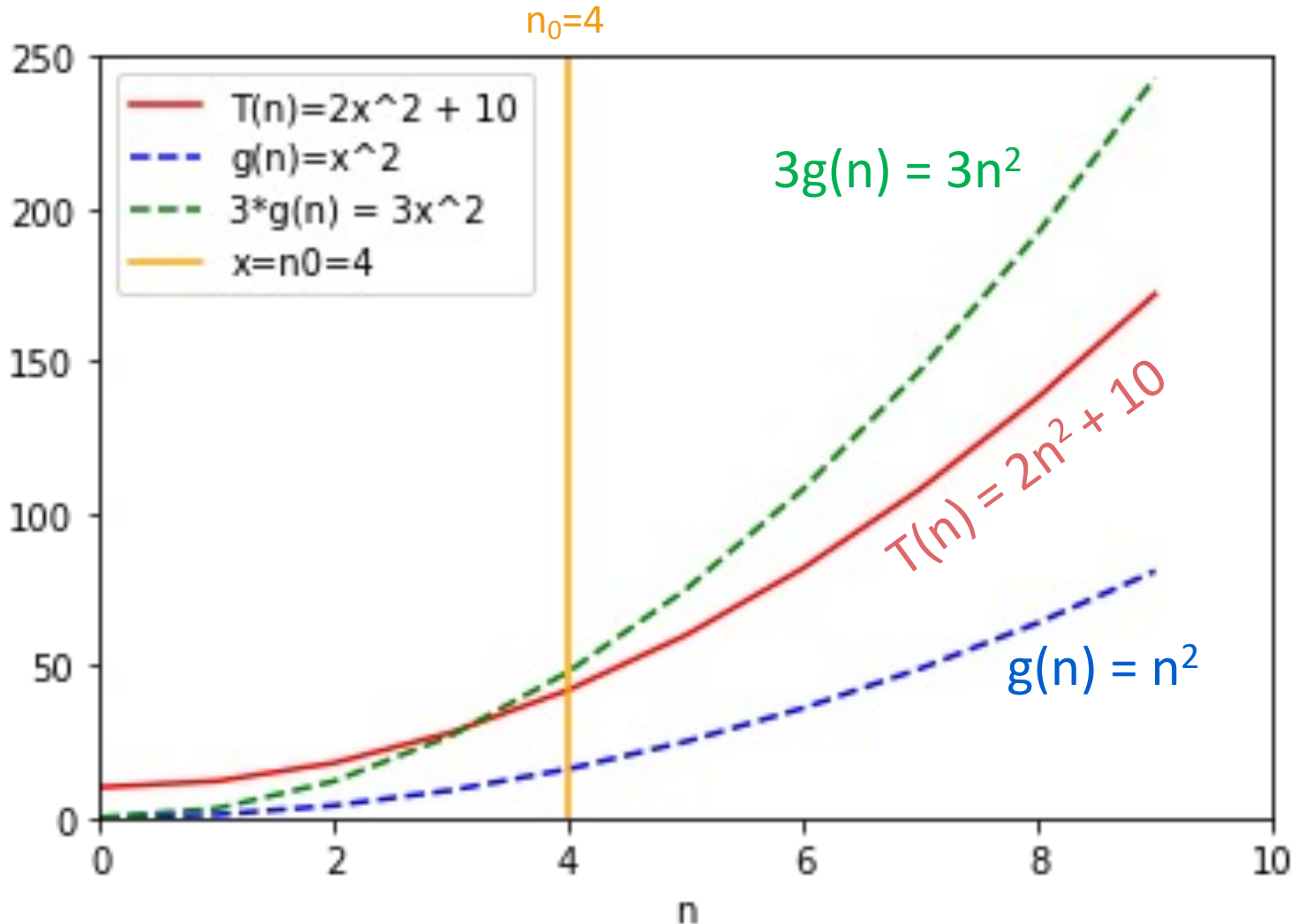
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Example

$$2n^2 + 10 = O(n^2)$$

for large enough n ,
 $T(n)$ is at most some constant
multiple of $g(n)$.



Formal definition of $O(\dots)$



- Let $T(n)$, $g(n)$ be functions of positive integers.
 - Think of $T(n)$ as a runtime: positive and increasing in n .
- Formally,

$$T(n) = O(g(n))$$

“If and only if”



“For all”

$\forall n \geq n_0,$

$\exists c > 0, n_0$ s. t.

$$T(n) \leq c \cdot g(n)$$

“There exists”

“such that”

Example

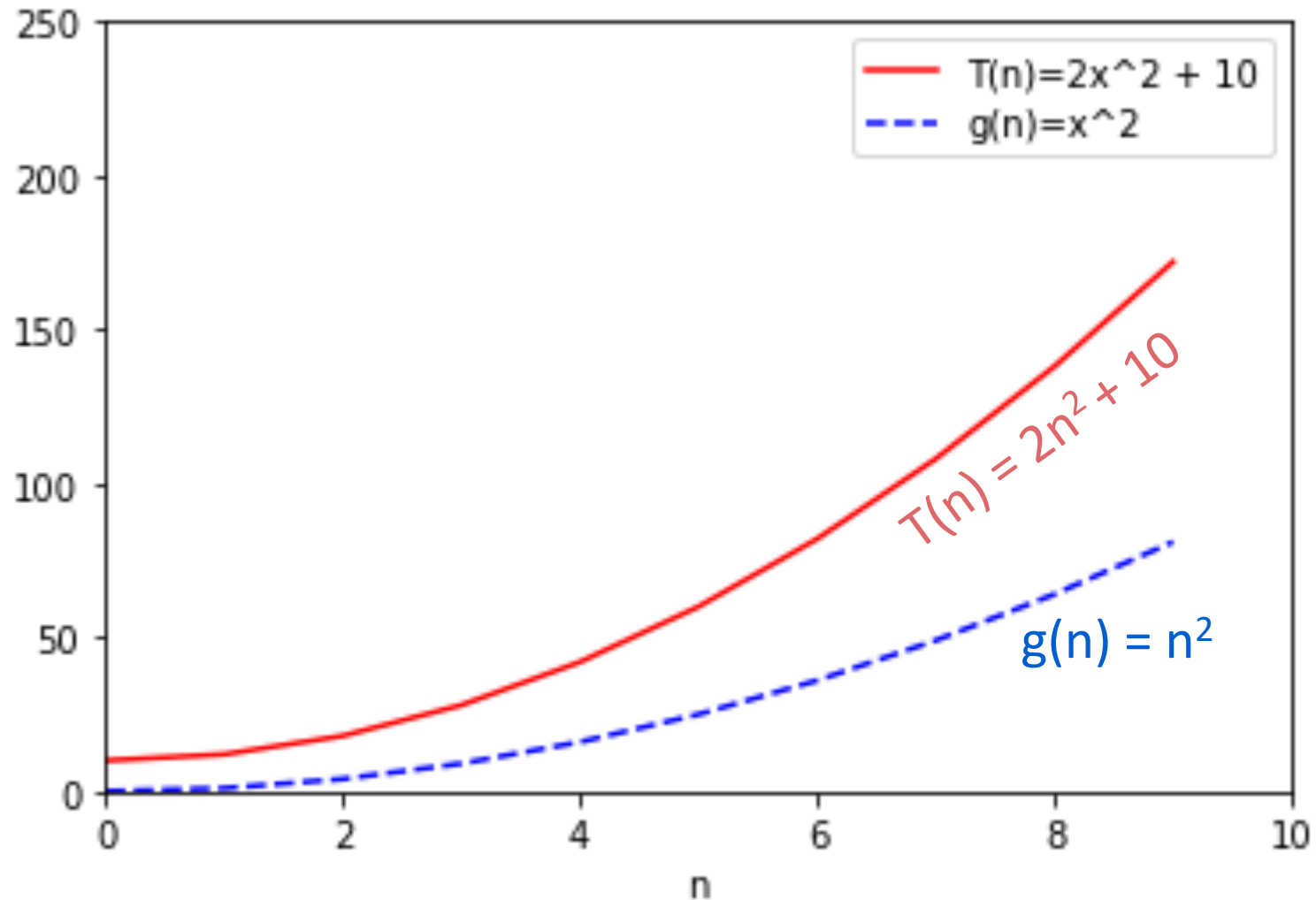
$$2n^2 + 10 = O(n^2)$$

$$T(n) = O(g(n))$$

\Leftrightarrow

$$\exists c > 0, n_0 \text{ s.t. } \forall n \geq n_0,$$

$$T(n) \leq c \cdot g(n)$$



Example

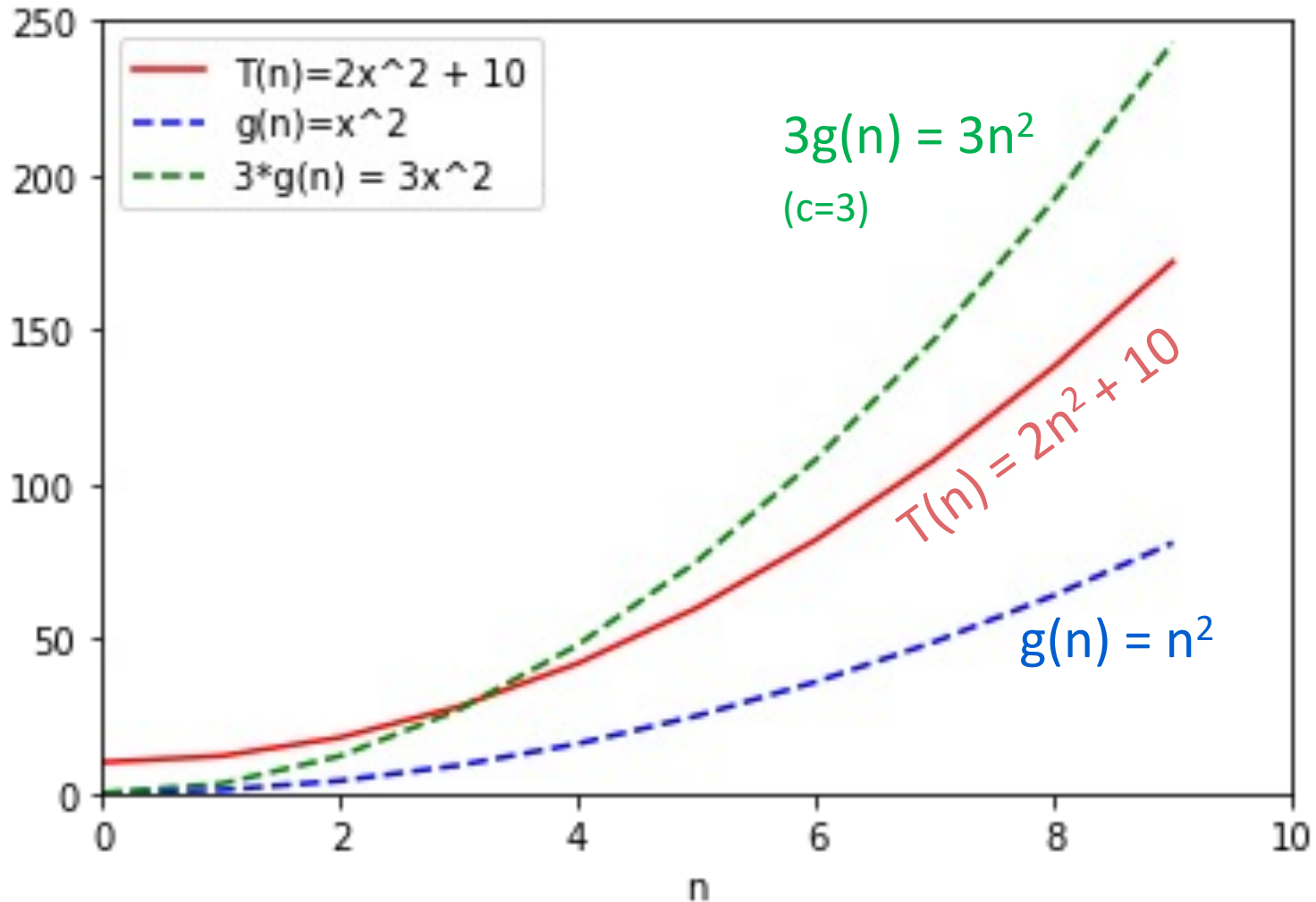
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$$T(n) = O(g(n))$$

\Leftrightarrow

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$$T(n) \leq c \cdot g(n)$$



Example

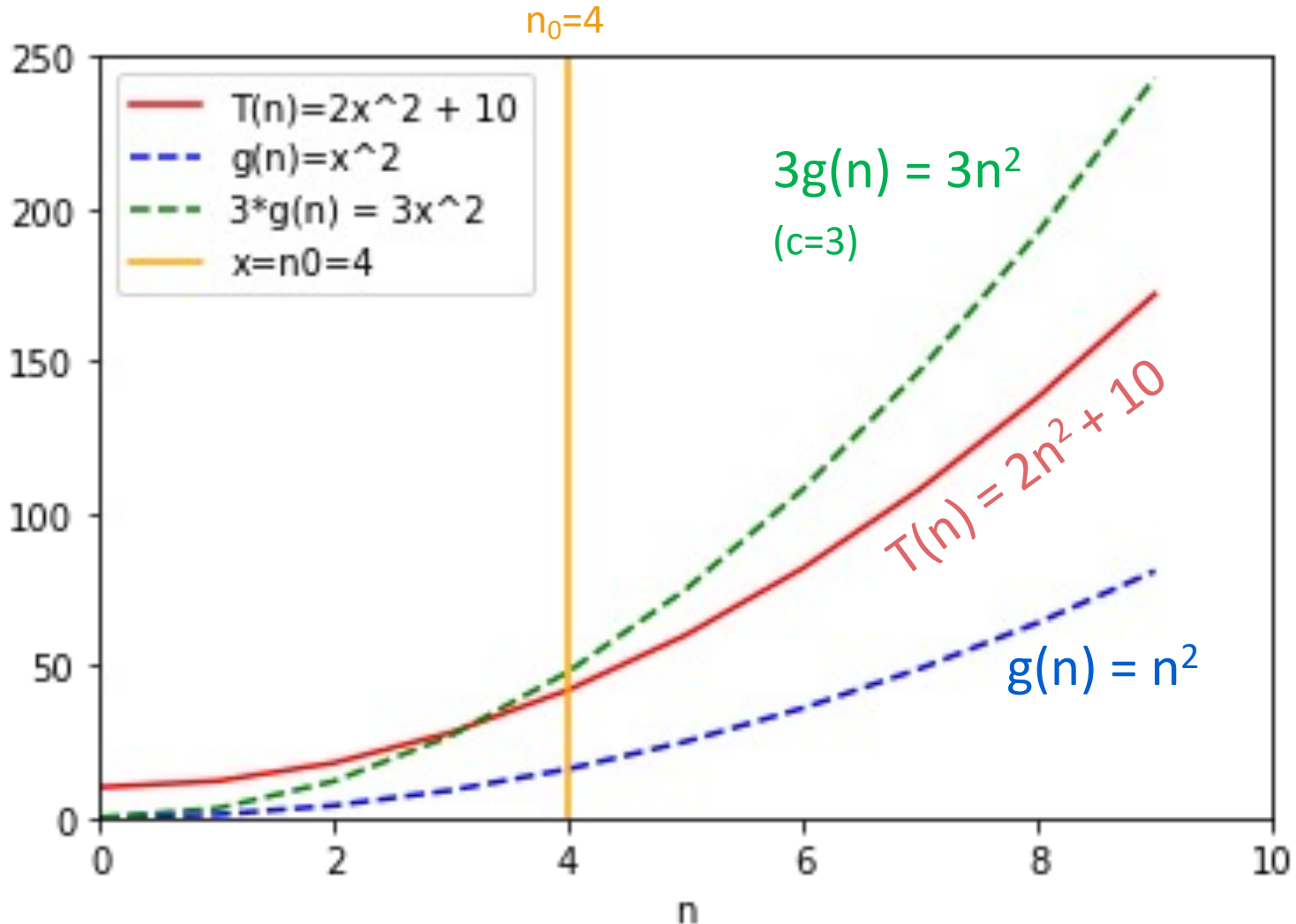
$$2n^2 + 10 = O(n^2)$$

$$T(n) = O(g(n))$$

\Leftrightarrow

$$\exists c > 0, n_0 \text{ s.t. } \forall n \geq n_0,$$

$$T(n) \leq c \cdot g(n)$$



Example

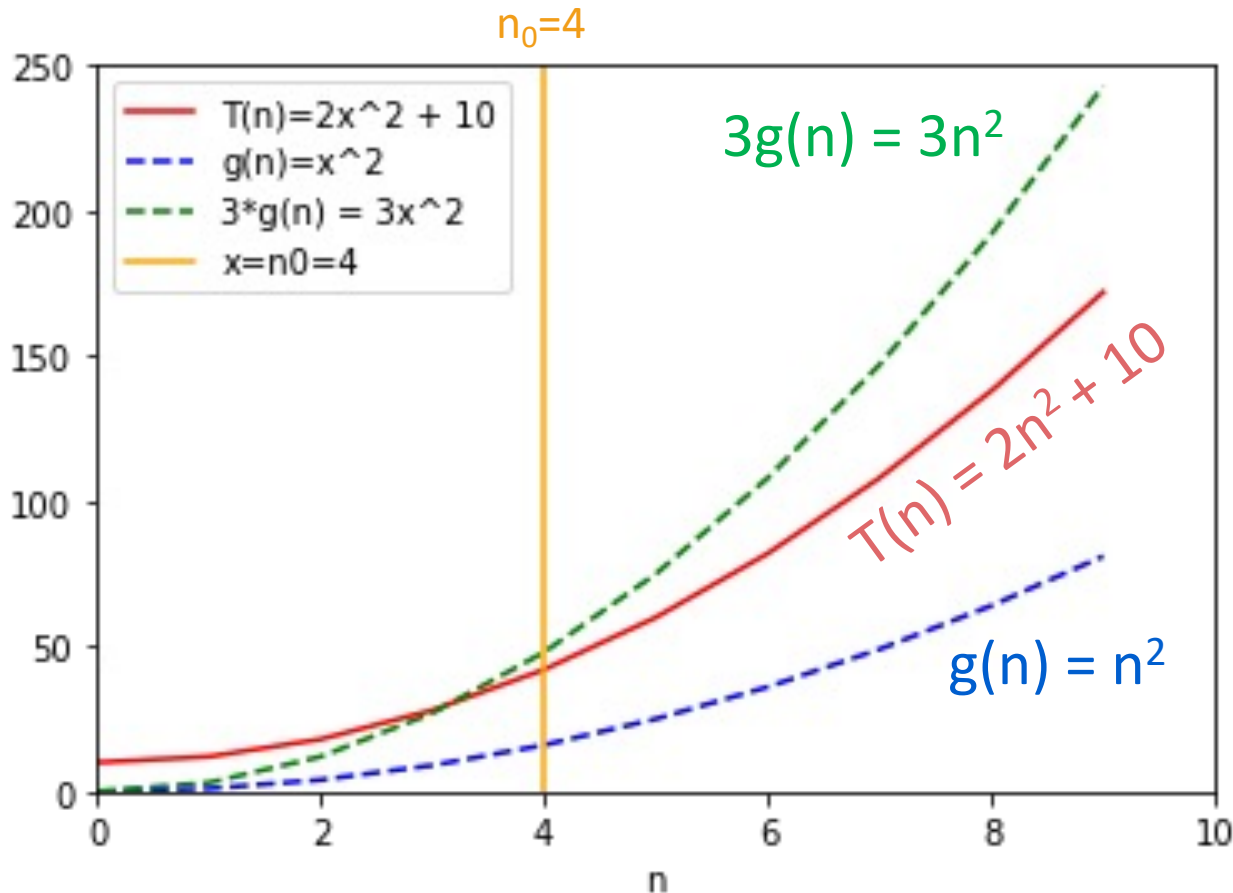
$$2n^2 + 10 = O(n^2)$$

$$T(n) = O(g(n))$$

\Leftrightarrow

$$\exists c > 0, n_0 \text{ s.t. } \forall n \geq n_0,$$

$$T(n) \leq c \cdot g(n)$$



Formally:

- Choose $c = 3$
- Choose $n_0 = 4$
- Then:

$$\forall n \geq 4,$$

$$2n^2 + 10 \leq 3 \cdot n^2$$

Same example

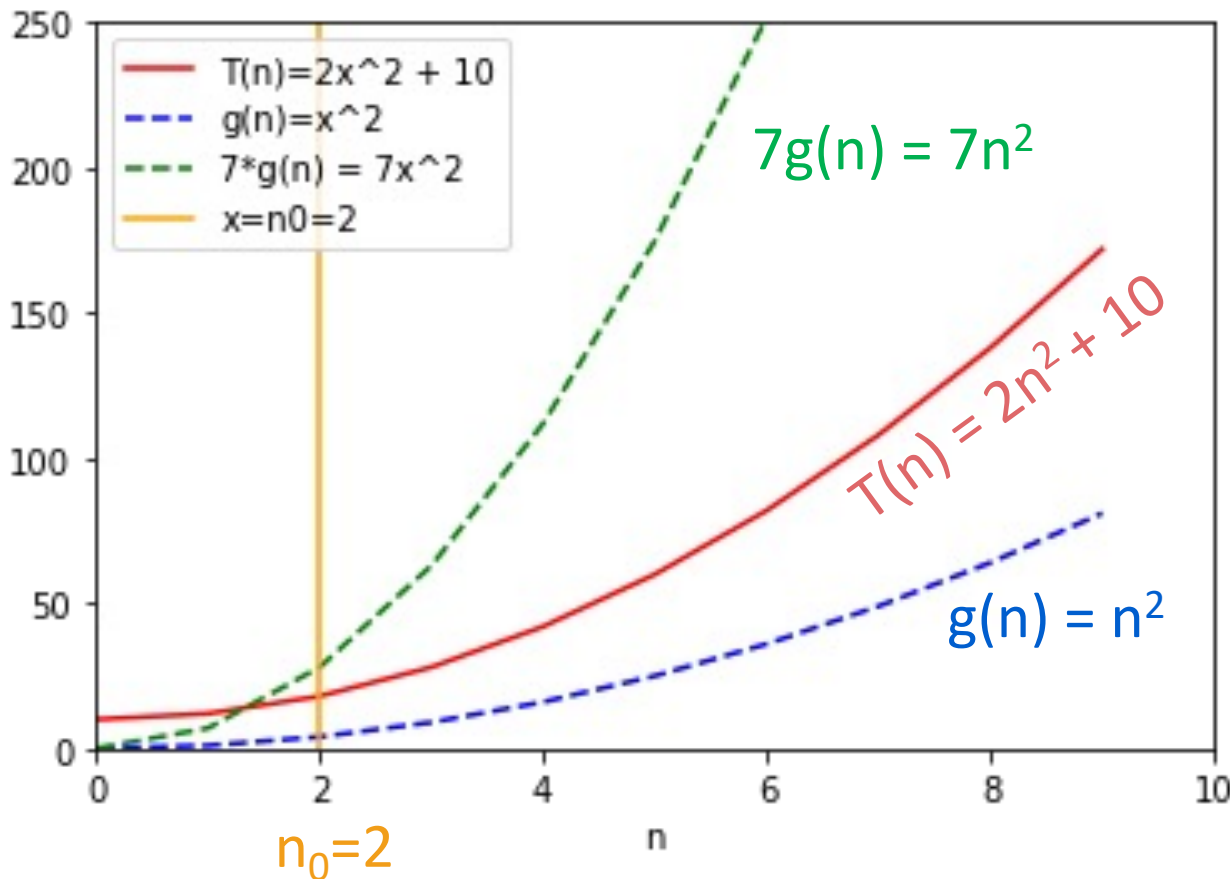
$2n^2 + 10 = O(n^2)$

$$T(n) = O(g(n))$$

\Leftrightarrow

$$\exists c > 0, n_0 \text{ s.t. } \forall n \geq n_0,$$

$$T(n) \leq c \cdot g(n)$$



Formally:

- Choose $c = 7$
- Choose $n_0 = 2$
- Then:

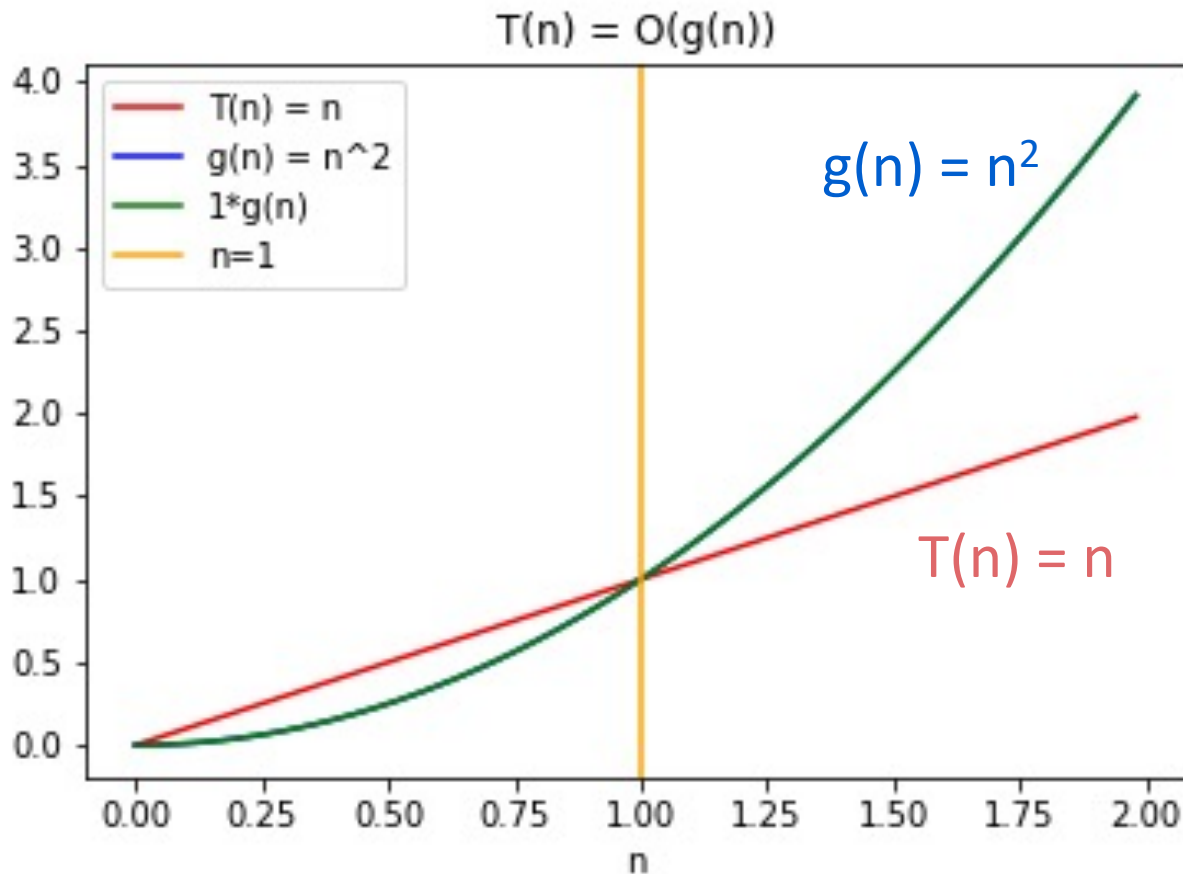
$$\forall n \geq 2,$$

$$2n^2 + 10 \leq 7 \cdot n^2$$

There is not a
"correct" choice
of c and n_0

$O(\dots)$ is an upper bound:
 $n = O(n^2)$

$$T(n) = O(g(n)) \Leftrightarrow \exists c > 0, n_0 \text{ s.t. } \forall n \geq n_0, T(n) \leq c \cdot g(n)$$



- Choose $c = 1$
- Choose $n_0 = 1$
- Then

$$\forall n \geq 1, n \leq n^2$$

$\Omega(\dots)$ means a lower bound

- We say “ $T(n)$ is $\Omega(g(n))$ ” if, for large enough n , $T(n)$ is at least as big as a constant multiple of $g(n)$.
- Formally,

$$T(n) = \Omega(g(n))$$

\Leftrightarrow

$$\exists c > 0, n_0 \text{ s.t. } \forall n \geq n_0,$$

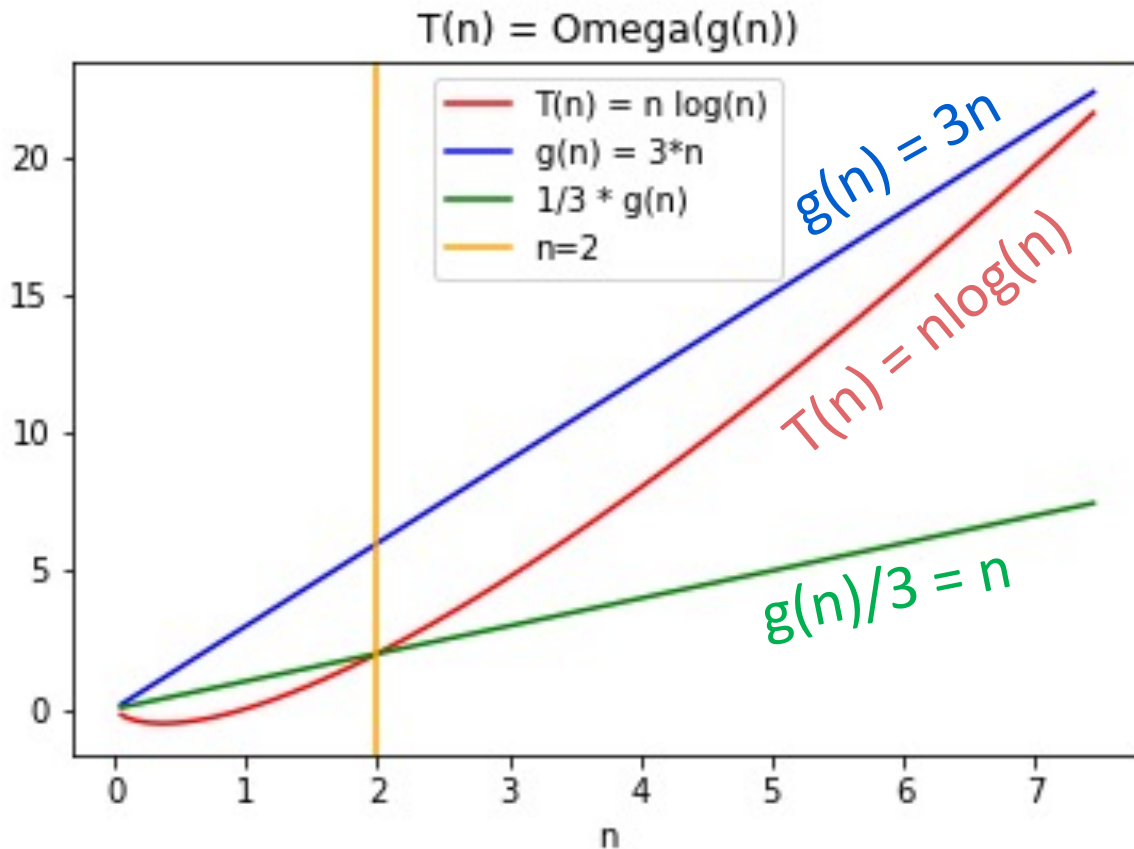
$$c \cdot g(n) \leq T(n)$$

Switched these!!

Example

$n \log_2(n) = \Omega(3n)$

$$T(n) = \Omega(g(n))$$
$$\Leftrightarrow$$
$$\exists c > 0, n_0 \text{ s.t. } \forall n \geq n_0,$$
$$c \cdot g(n) \leq T(n)$$



- Choose $c = 1/3$
- Choose $n_0 = 2$
- Then

$$\forall n \geq 2,$$

$$\frac{3n}{3} \leq n \log_2(n)$$

$\Theta(\dots)$ means both!

- We say “ $T(n)$ is $\Theta(g(n))$ ” iff both:

$$T(n) = O(g(n))$$

and

$$T(n) = \Omega(g(n))$$

Non-Example: n^2 is not $O(n)$

$$T(n) = O(g(n)) \\ \Leftrightarrow \\ \exists c > 0, n_0 \text{ s.t. } \forall n \geq n_0, \\ T(n) \leq c \cdot g(n)$$

- Proof by contradiction:
- Suppose that $n^2 = O(n)$.
- Then there is some positive c and n_0 so that:

$$\forall n \geq n_0, \quad n^2 \leq c \cdot n$$

- Divide both sides by n :

$$\forall n \geq n_0, \quad n \leq c$$

- That's not true!!! What about $\max(n_0, c + 1)$?
 - Then $n \geq n_0$, but $n > c$.
- Contradiction!

Take-away from examples

- To prove $T(n) = O(g(n))$, you have to come up with c and n_0 so that the definition is satisfied.
- To prove $T(n)$ is **NOT** $O(g(n))$, one way is **proof by contradiction**:
 - Suppose (to get a contradiction) that someone gives you a c and an n_0 so that the definition *is* satisfied.
 - Show that this someone must be lying to you by deriving a contradiction.

Another example: polynomials

- Say $p(n) = a_k n^k + a_{k-1} n^{k-1} + \dots + a_1 n + a_0$ is a polynomial of degree $k \geq 1$ and $a_k > 0$.

- Then:

1. $p(n) = O(n^k)$
2. $p(n)$ is **not** $O(n^{k-1})$

- See the notes/references for a proof.

Try to prove it
yourself first!



Siggi the Studios Stork

More examples

- $n^3 + 3n = O(n^3 - n^2)$
- $n^3 + 3n = \Omega(n^3 - n^2)$
- $n^3 + 3n = \Theta(n^3 - n^2)$

- 3^n is **NOT** $O(2^n)$
- $\log_2(n) = \Omega(\ln(n))$
- $\log_2(n) = \Theta(2^{\log\log(n)})$

Work through these
on your own! Also
look at the examples
in the reading!



Siggi the Studious Stork

Brain teaser

- Are there functions f, g so that **NEITHER** $f = O(g)$ nor $f = \Omega(g)$?



Ollie the Over-achieving Ostrich

Recap: Asymptotic Notation

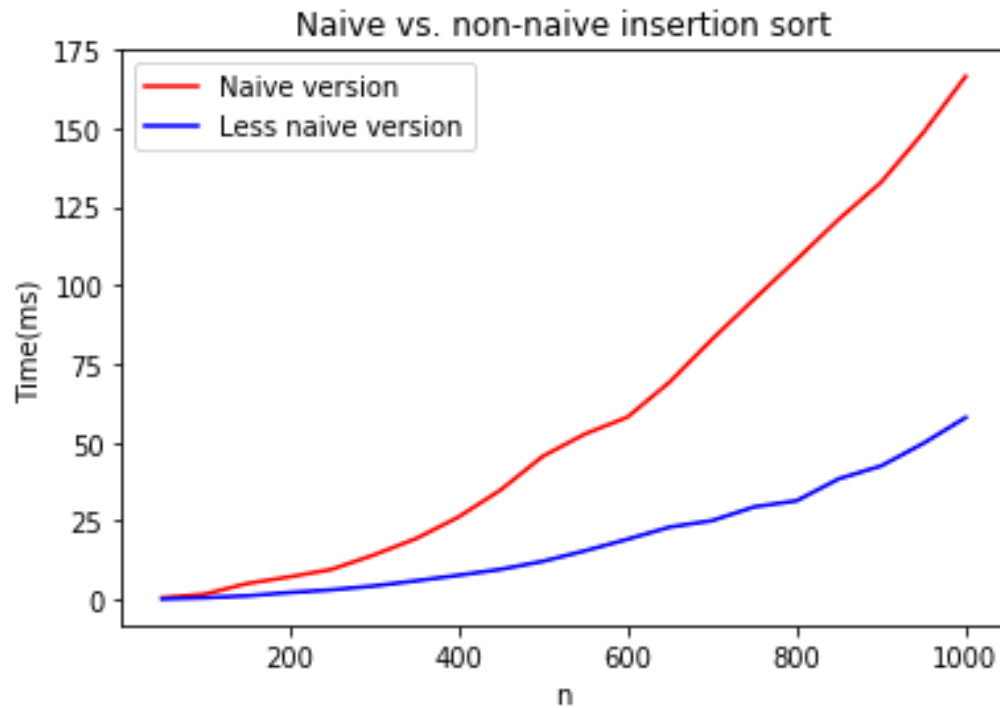
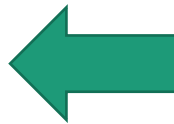
- This makes both Plucky and Lucky happy.
 - **Plucky the Pedantic Penguin** is happy because there is a precise definition.
 - **Lucky the Lackadaisical Lemur** is happy because we don't have to pay close attention to all those pesky constant factors.
- But we should always be careful not to abuse it.
- In the course, (almost) every algorithm we see will be practical, without needing to take $n \geq n_0 = 2^{100000000}$.



Back to Insertion Sort

1. Does it work?

2. Is it fast?

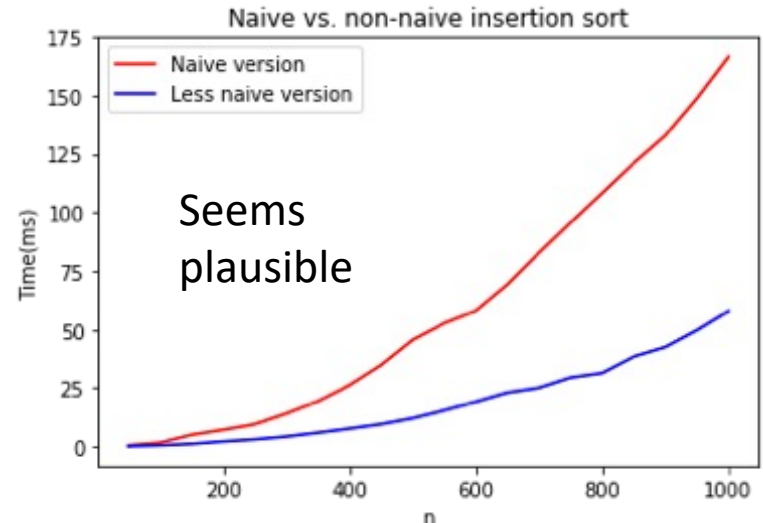


Insertion Sort: running time

- Operation count was:
 - $2n^2 - n - 1$ variable assignments
 - $2n^2 - n - 1$ increments/decrements
 - $2n^2 - 4n + 1$ comparisons
 - ...
- The running time is $O(n^2)$



Go back to the pseudocode
and convince yourself of this!




What have we learned?

InsertionSort is an algorithm that correctly sorts an arbitrary n -element array in time $O(n^2)$.

Can we do better?

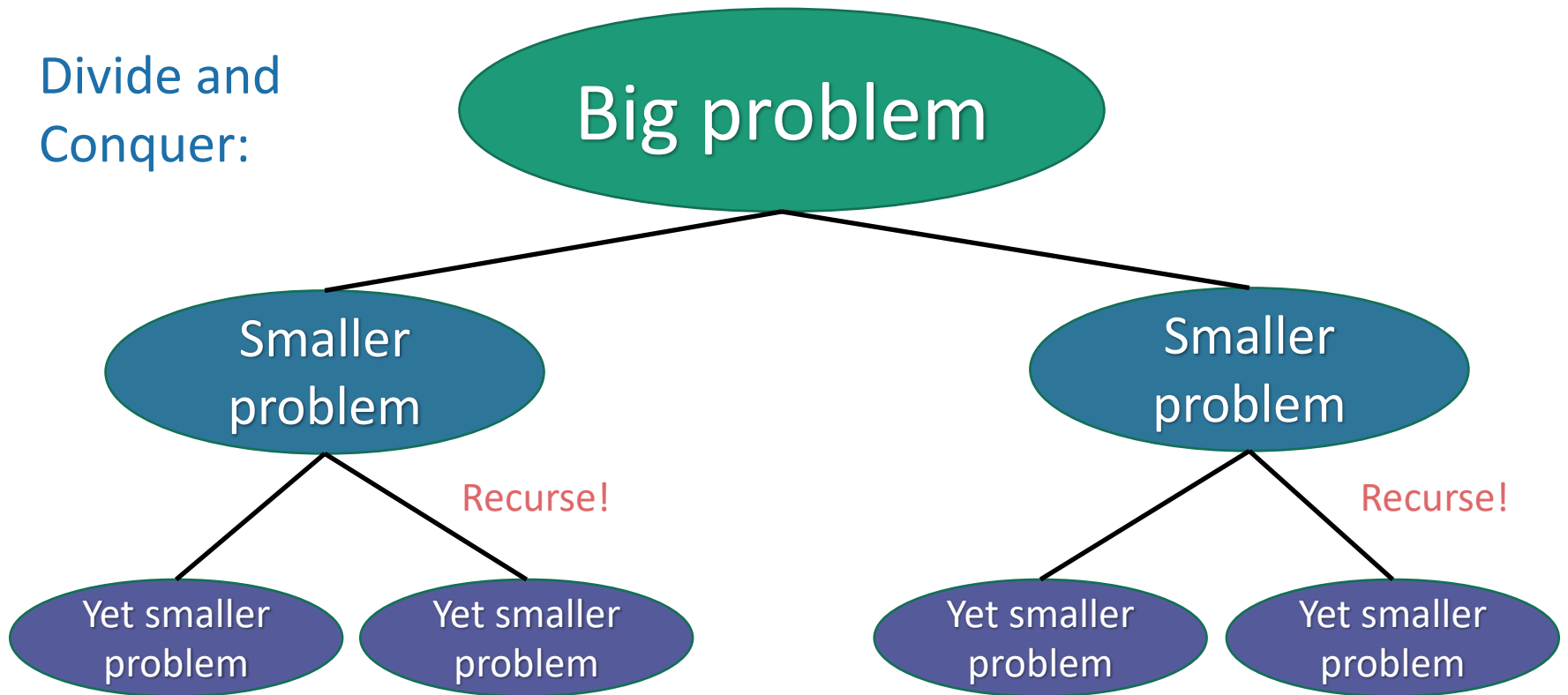
The Plan

- InsertionSort recap
- Worst-case analysis
 - Back to InsertionSort: Does it work?
- Asymptotic Analysis
 - Back to InsertionSort: Is it fast?
- MergeSort 
 - Does it work?
 - Is it fast?

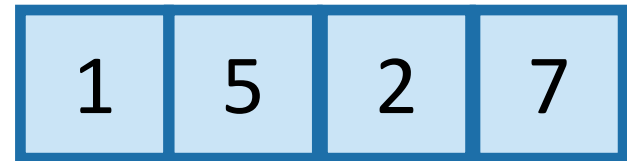
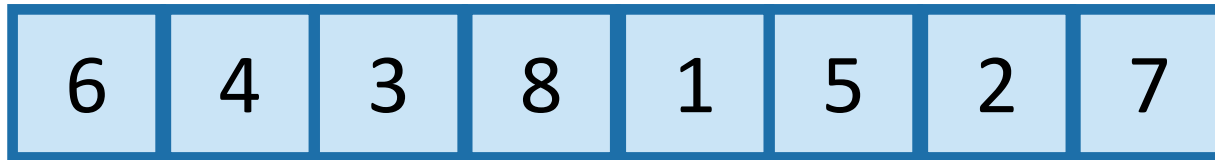
Can we do better?

- MergeSort: a **divide-and-conquer** approach
- Recall:

Divide and
Conquer:

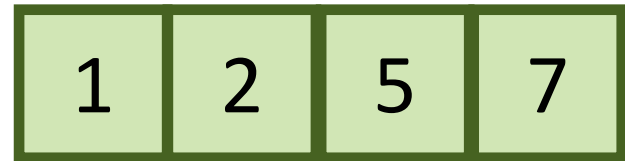
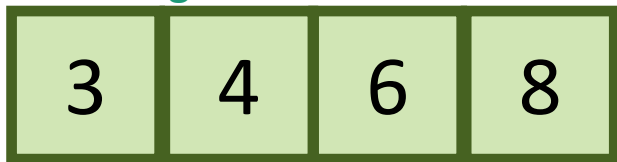


MergeSort



Recursive magic!

Recursive magic!



MERGE!



How would you do this in-place?

Code for the **MERGE** step is given in the Lecture2 IPython notebook, or the notes

Ollie the over-achieving Ostrich



MergeSort Pseudocode

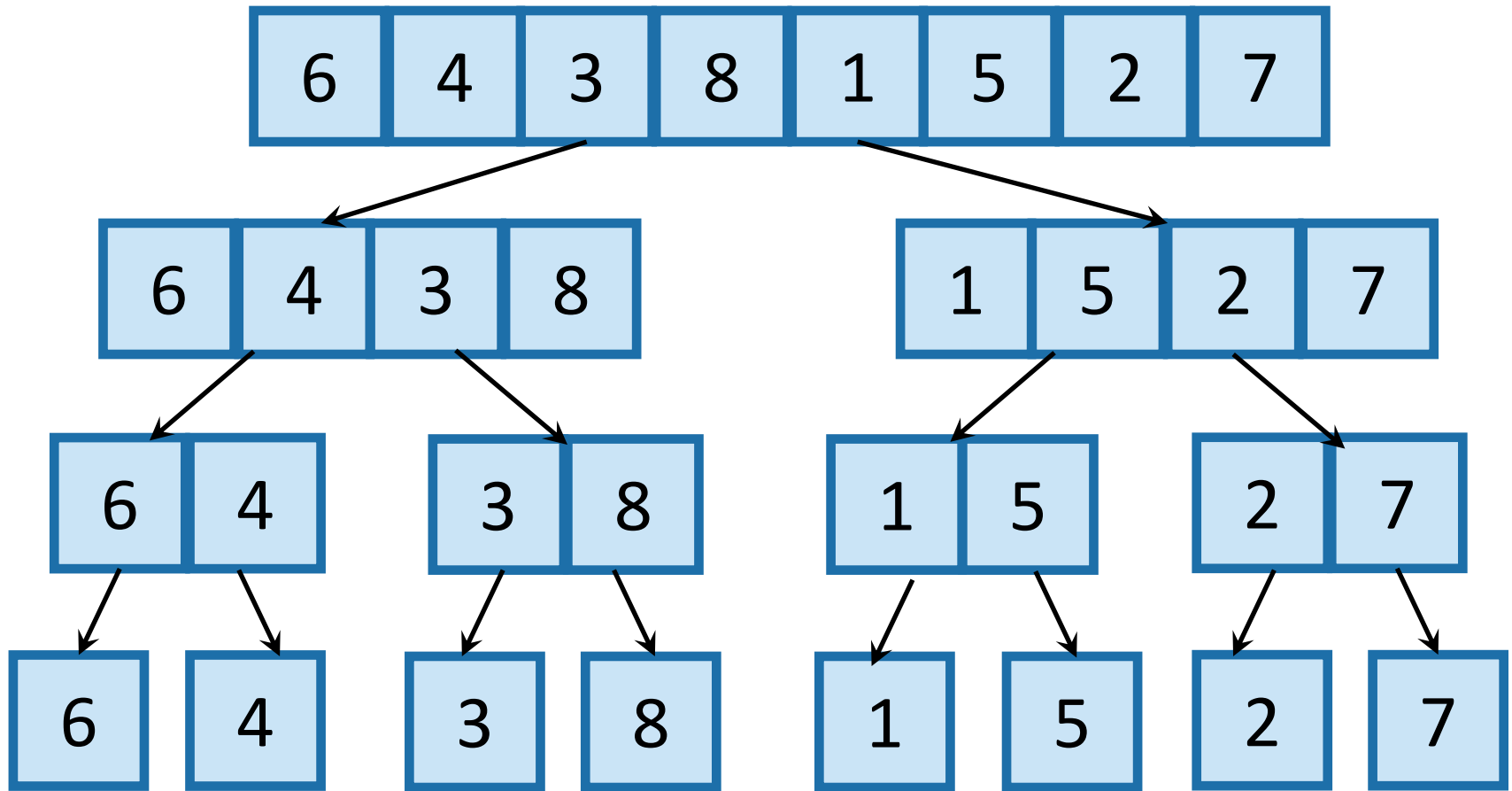
MERGESORT(A):

- $n = \text{length}(A)$
- **if** $n \leq 1$:
 - **return** A

If A has length 1,
It is already sorted!
- $L = \text{MERGESORT}(A[0 : n/2])$ Sort the left half
- $R = \text{MERGESORT}(A[n/2 : n])$ Sort the right half
- **return** **MERGE**(L, R) Merge the two halves

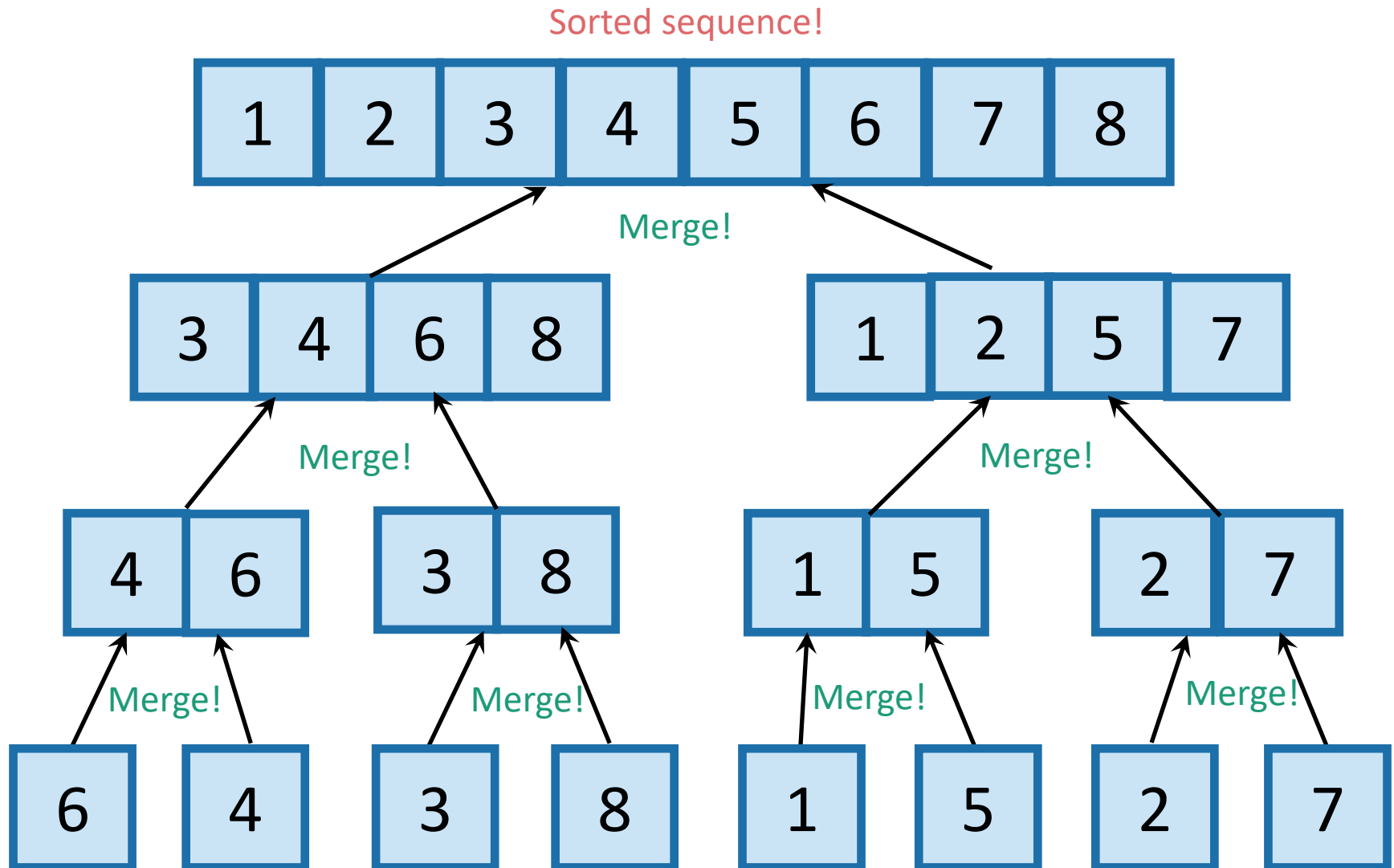
What actually happens?

First, recursively break up the array all the way down to the base cases



This array of length 1 is sorted!

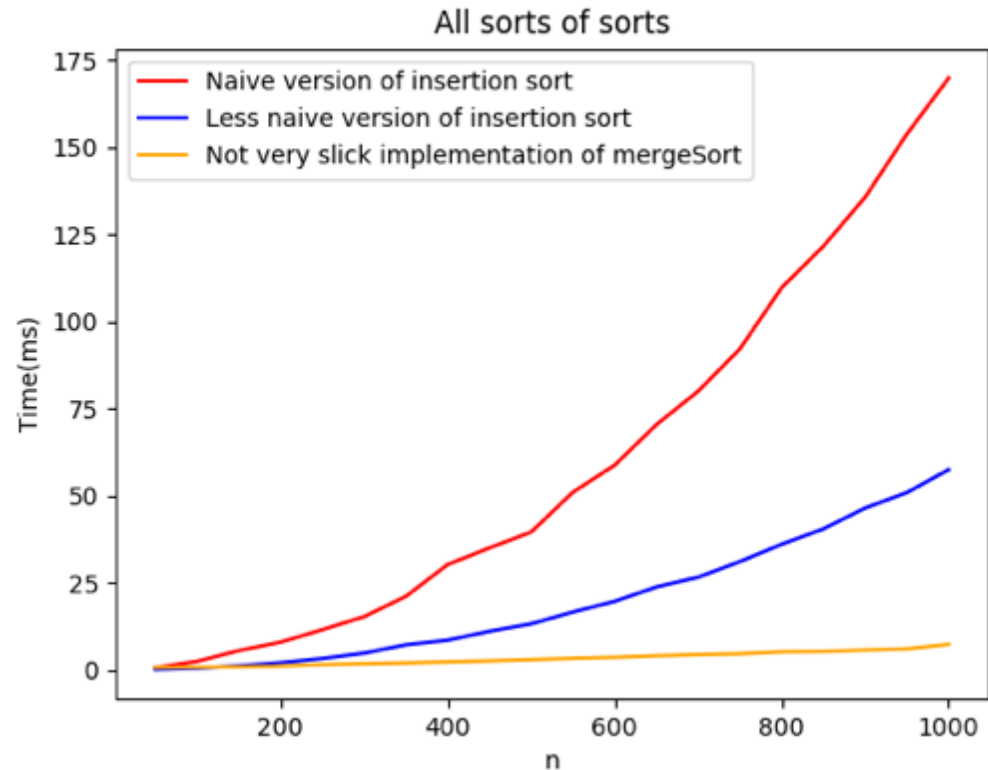
Then, merge them all back up!



Two questions

1. Does this work?
2. Is it fast?

I Python notebook says...



Empirically:

1. Seems to work.
2. Seems fast.

It works

- Yet another job for...

Proof By Induction!

Work this out! There's a skipped slide
with an outline to help you get started.



Assume that n is a power of 2
for convenience.

It's fast

CLAIM:

MergeSort runs in time $O(n \log(n))$

- Proof coming soon.
- But first, how does this compare to InsertionSort?
 - Recall InsertionSort ran in time $O(n^2)$.

$O(n \log(n))$ vs. $O(n^2)$?

All logarithms in this course are base 2

Aside:



Quick log refresher

- **Def:** $\log(n)$ is the number so that $2^{\log(n)} = n$.
- **Intuition:** $\log(n)$ is how many times you need to divide n by 2 in order to get down to 1.

$$32, \underbrace{16, 8, 4, 2, 1}_{\text{Halve 5 times}} \Rightarrow \log(32) = 5$$

$$64, \underbrace{32, 16, 8, 4, 2, 1}_{\text{Halve 6 times}} \Rightarrow \log(64) = 6$$

$$\log(128) = 7$$

$$\log(256) = 8$$

$$\log(512) = 9$$

....

$$\log(\# \text{ particles in the universe}) < 280$$

- $\log(n)$ grows very slowly!

$O(n \log n)$ vs. $O(n^2)$?

- $\log(n)$ grows much more slowly than n
- $n \log(n)$ grows much more slowly than n^2

Punchline: A running time of $O(n \log n)$ is a lot better than $O(n^2)$!

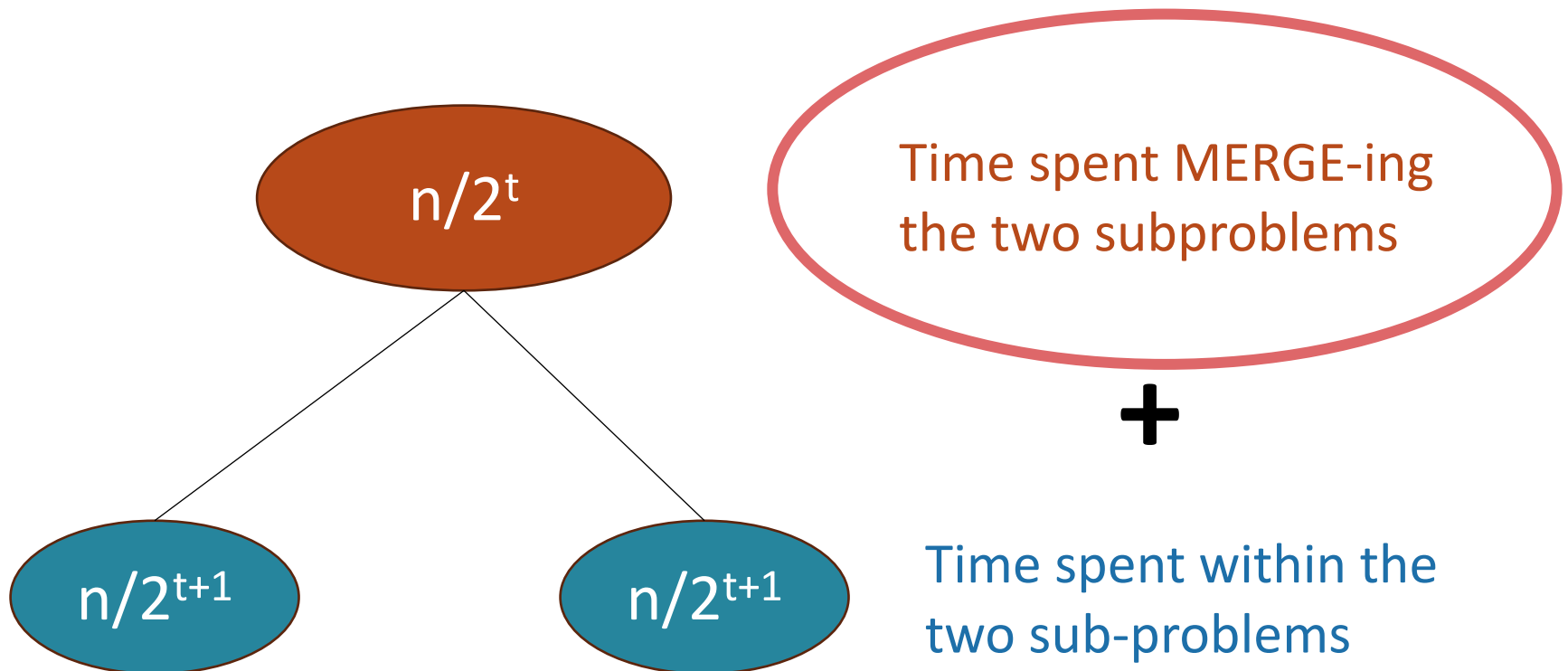
Assume that n is a power of 2
for convenience.

Now let's prove the claim

CLAIM:

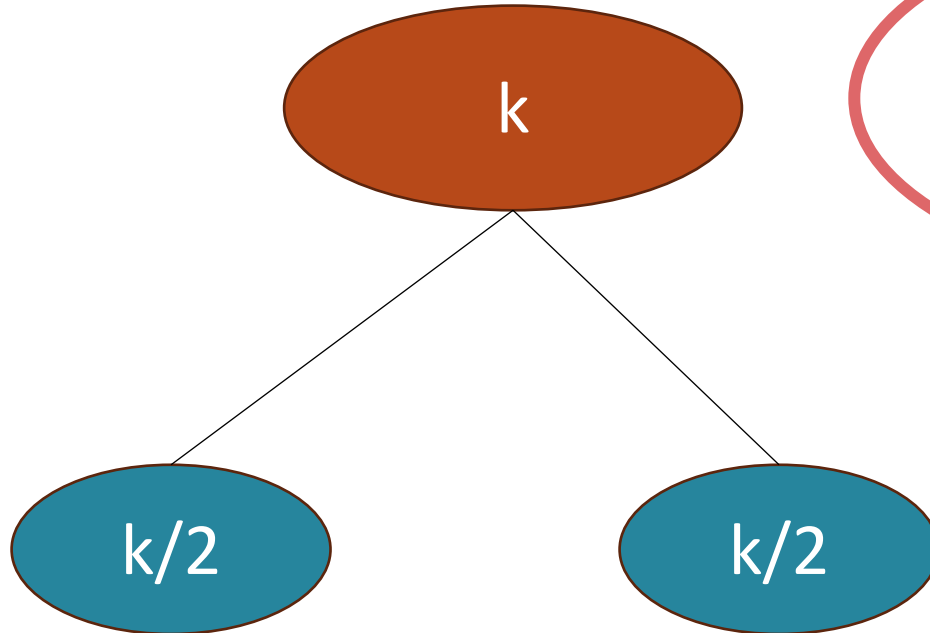
MergeSort runs in time $O(n \log(n))$

How much work in this sub-problem?



How much work in this sub-problem?

Let $k=n/2^t$...

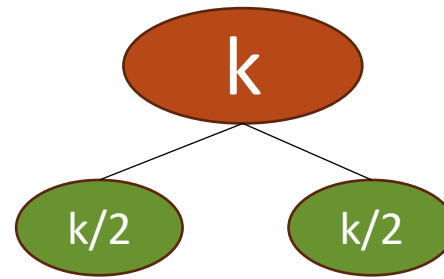


Time spent MERGE-ing
the two subproblems

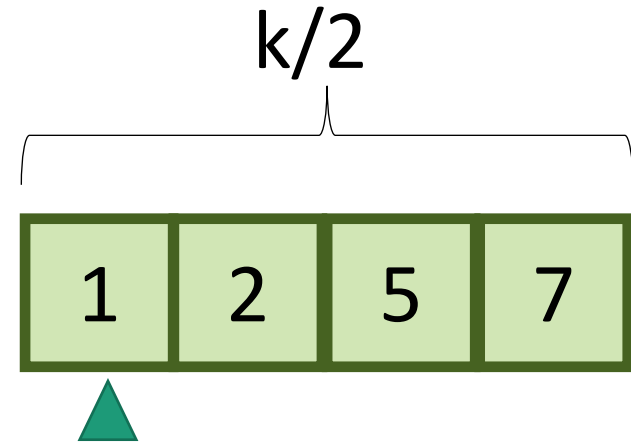
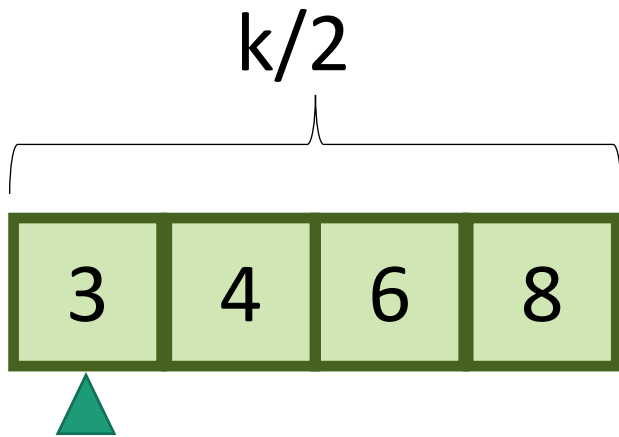
+

Time spent within the
two sub-problems

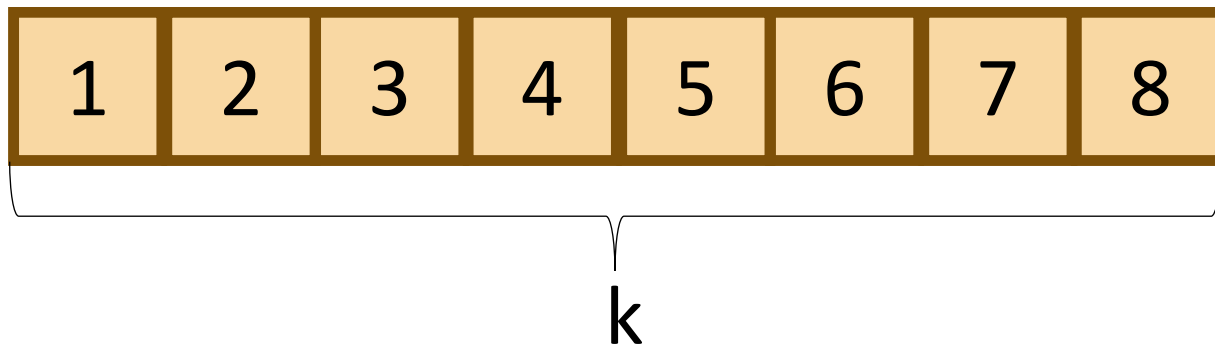
How long does it take to MERGE?



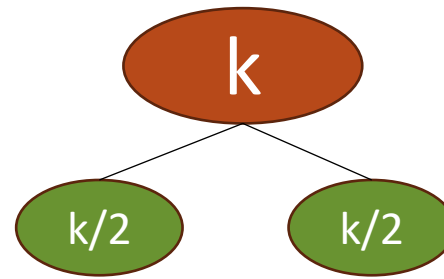
Code for the **MERGE** step is given in the Lecture2 notebook.



MERGE!

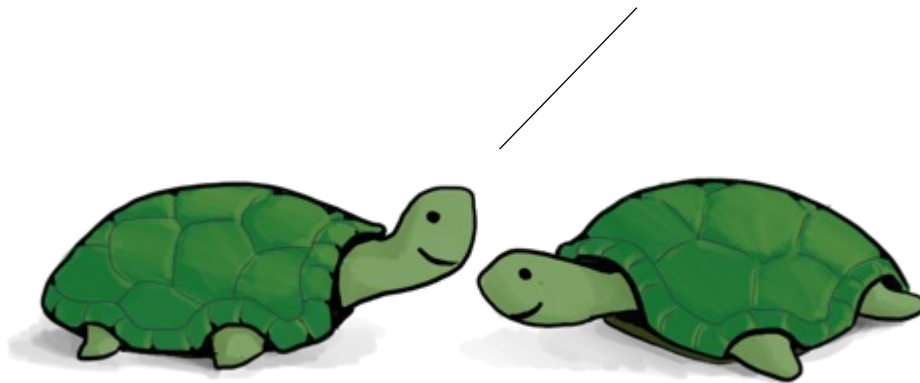


How long does it take to MERGE?



Code for the **MERGE** step is given in the Lecture2 notebook.

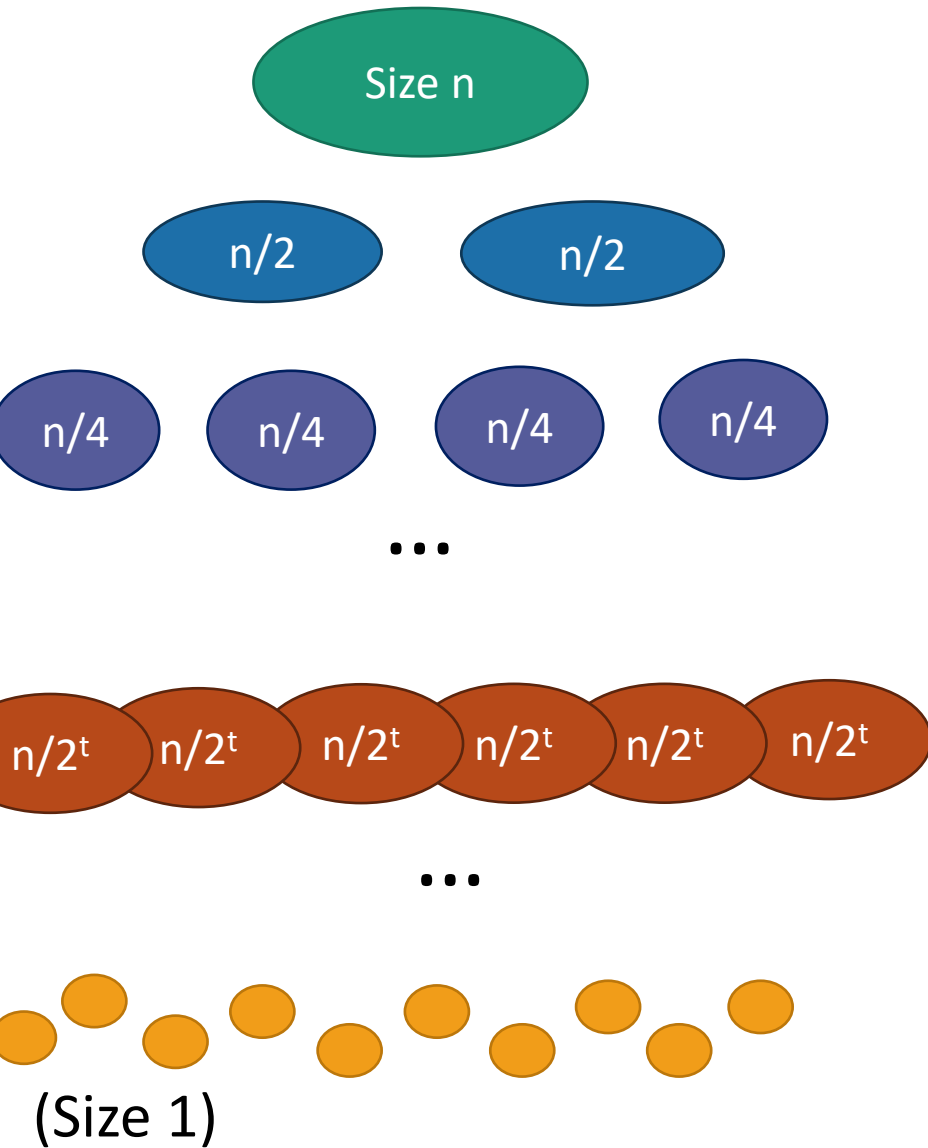
How long does it take to run MERGE on two lists of size $k/2$?



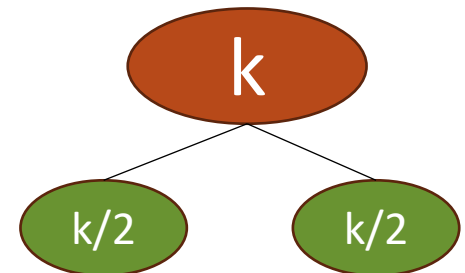
Think-Pair-Share Terrapins (if time)

Answer: It takes time $O(k)$, since we just walk across the list once.

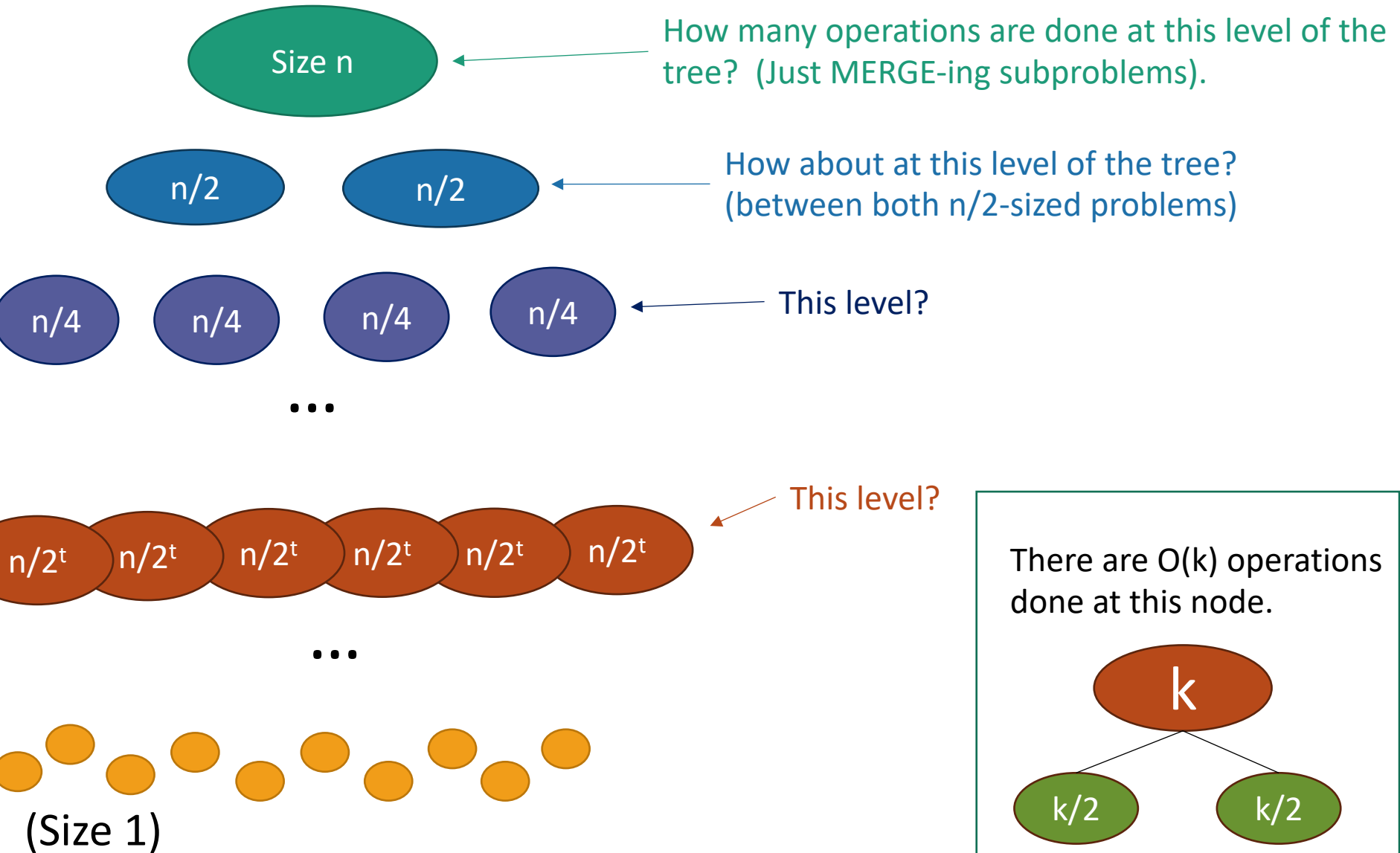
Recursion tree



There are $O(k)$ operations done at this node.

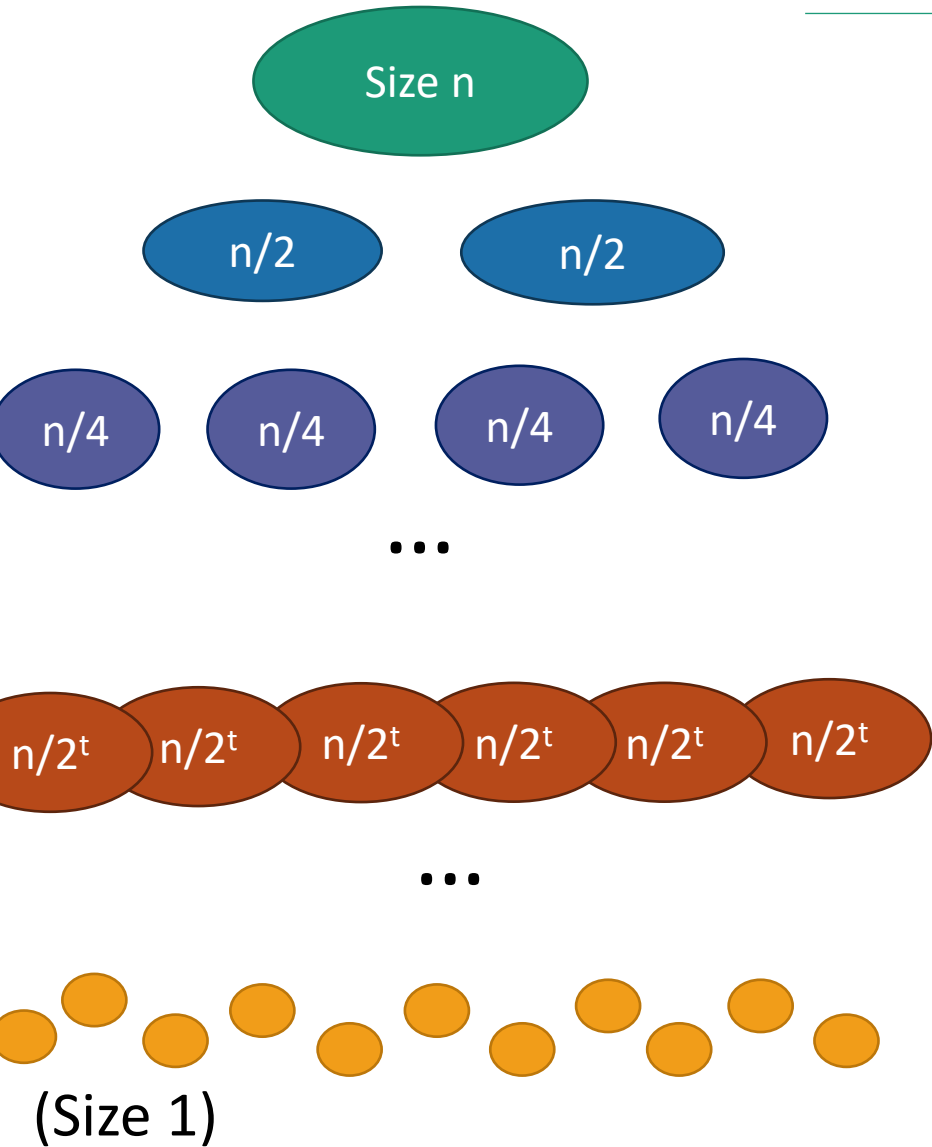


Recursion tree



Work this out yourself!

Recursion tree



Level	# problems	Size of each problem	Amount of work at this level
0	1	n	O(n)
1	2	n/2	O(n)
2	4	n/4	O(n)
...
t	2 ^t	n/2 ^t	O(n)
...
log(n)	n	1	O(n)

Total runtime...

- $O(n)$ steps per level, at every level
- $\log(n) + 1$ levels
- $O(n \log(n))$ total!

That was the claim!

What have we learned?

- MergeSort correctly sorts a list of n integers in time $O(n \log(n))$.
- That's (asymptotically) better than InsertionSort!

The Plan

- InsertionSort recap
- Worst-case analysis
 - Back to InsertionSort: Does it work?
- Asymptotic Analysis
 - Back to InsertionSort: Is it fast?
- MergeSort
 - Does it work?
 - Is it fast?

Wrap-Up



Recap

- InsertionSort runs in time $O(n^2)$
- MergeSort is a divide-and-conquer algorithm that runs in time $O(n \log(n))$
- How do we show an algorithm is correct?
 - Today, we did it by induction
- How do we measure the runtime of an algorithm?
 - Worst-case analysis
 - Asymptotic analysis
- How do we analyze the running time of a recursive algorithm?
 - One way is to draw a recursion tree.

Next time

- A more systematic approach to analyzing the runtime of recursive algorithms.

Before next time

- Pre-lecture Exercise:
 - A few recurrence relations (see website)