

CMSC 132: Object-Oriented Programming II



Algorithmic Complexity I

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Algorithm Efficiency

■ Efficiency

- Amount of resources used by algorithm

 - Time, space

■ Measuring efficiency

- Benchmarking

- Asymptotic analysis

Benchmarking

■ Approach

- Pick some desired inputs
- Actually run implementation of algorithm
- Measure time & space needed

■ Industry benchmarks

- SPEC – CPU performance
- MySQL – Database applications
- WinStone – Windows PC applications
- MediaBench – Multimedia applications
- Linpack – Numerical scientific applications

Benchmarking

■ Advantages

- Precise information for given configuration
 - Implementation, hardware, inputs

■ Disadvantages

- Affected by configuration
 - Data sets (often too small)
 - a dataset that was the right size 3 years ago is likely too small now
 - Hardware
 - Software
- Affected by special cases (biased inputs)
- Does not measure **intrinsic** efficiency

Asymptotic Analysis

■ Approach

- Mathematically analyze efficiency
- Calculate time as function of input size n
 - $T \approx O(f(n))$
 - T is on the order of $f(n)$
 - “Big O” notation

■ Advantages

- Measures intrinsic efficiency
- Dominates efficiency for large input sizes
- Programming language, compiler, processor irrelevant

Search Example

- **Number guessing game**
 - **Pick a number between $1 \dots n$**
 - **Guess a number**
 - **Answer “correct”, “too high”, “too low”**
 - **Repeat guesses until correct number guessed**

Linear Search Algorithm

■ Algorithm

- Guess number = 1
- If incorrect, increment guess by 1
- Repeat until correct

■ Example

- Given number between 1...100
- Pick 20
- Guess sequence = 1, 2, 3, 4 ... 20
- Required 20 guesses

Linear Search Algorithm

- **Analysis of # of guesses needed for 1...n**
 - If number = 1, requires 1 guess
 - If number = n, requires n guesses
 - On average, needs $n/2$ guesses
 - Time = $O(n)$ = **Linear** time

Binary Search Algorithm

■ Algorithm

- Set low and high to be lowest and highest possible value
- Guess middle = $(\text{low} + \text{high}) / 2$
- If too large, set high = middle - 1
- If too small, set low = middle + 1
- Repeat until guess correct

Binary Search Algorithm

■ Example

- Given number between 1...100

- secret number we are trying to find is 20

- Guesses

- low = 1, high = 100, guess 50, Answer = too large

- low = 1, high = 49, guess 25, Answer = too large

- low = 1, high = 24, guess 12, Answer = too small

- low = 13, high = 24, guess 18, Answer = too small

- low = 19, high = 24, guess 21, Answer = too large

- low = 19, high = 20, guess 19, Answer = too small

- low = 20, high = 20, guess 20, Answer = correct

- Required 7 guesses

Binary Search Algorithm

- **Analysis of # of guesses needed for 1...n**
 - If number = $n/2$, requires 1 guess
 - If number = 1, requires $\log_2(n)$ guesses
 - If number = n , requires $\log_2(n)$ guesses
 - On average, needs $\log_2(n)$ guesses
 - Time = $O(\log_2(n)) = O(\log(n)) = \text{Log time}$

Search Comparison

- For number between 1...100
 - Simple algorithm = 50 steps
 - Binary search algorithm = $\log_2(n) = 7$ steps
- For number between 1...100,000
 - Simple algorithm = 50,000 steps
 - Binary search algorithm = $\log_2(n)$ (about 17 steps)
- Binary search is **much** more efficient!

Asymptotic Complexity

■ Comparing two linear functions

Size	Running Time	
	$n/2$	$4n+3$
64	32	259
128	64	515
256	128	1027
512	256	2051

Asymptotic Complexity

- **Comparing two functions**
 - $n/2$ and $4n+3$ behave similarly
 - Run time roughly doubles as input size doubles
 - Run time increases **linearly** with input size
- **For large values of n**
 - $\text{Time}(2n) / \text{Time}(n)$ approaches exactly 2
- Both are $O(n)$ programs

Asymptotic Complexity

■ Comparing two log functions

Size	Running Time	
	$\log_2(n)$	$5 * \log_2(n) + 3$
64	6	33
128	7	38
256	8	43
512	9	48

Asymptotic Complexity

- Comparing two functions
 - $\log_2(n)$ and $5 * \log_2(n) + 3$ behave similarly
 - Run time roughly increases by constant as input size doubles
 - Run time increases **logarithmically** with input size
- For large values of n
 - $\text{Time}(2n) - \text{Time}(n)$ approaches constant
 - Base of logarithm does not matter
 - Simply a multiplicative factor
$$\log_a N = (\log_b N) / (\log_b a)$$
- Both are $O(\log(n))$ programs

Asymptotic Complexity

■ Comparing two quadratic functions

Size	Running Time	
	n^2	$2n^2 + 8$
2	4	16
4	16	40
8	64	132
16	256	520

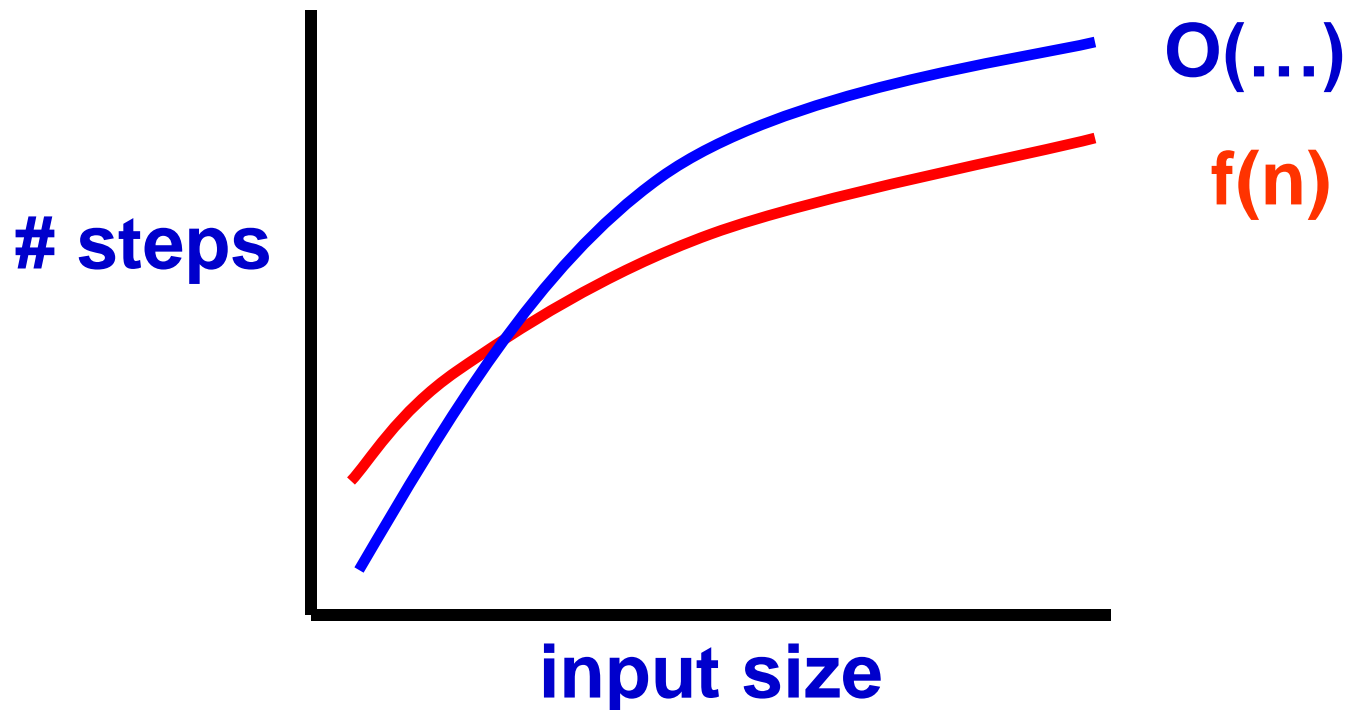
Asymptotic Complexity

- **Comparing two functions**
 - n^2 and $2n^2 + 8$ behave similarly
 - Run time roughly increases by 4 as input size doubles
 - Run time increases **quadratically** with input size
- **For large values of n**
 - $\text{Time}(2n) / \text{Time}(n)$ approaches 4
- Both are $O(n^2)$ programs

Big-O Notation

■ Represents

- Upper bound on number of steps in algorithm
 - For sufficiently large input size
- Intrinsic efficiency of algorithm for large inputs



Formal Definition of Big-O

- **Function $f(n)$ is $O(g(n))$ if**
 - For some positive constants M, N_0
 - $M \times g(n) \geq f(n)$, for all $n \geq N_0$
- **Intuitively**
 - For some coefficient M & all data sizes $\geq N_0$
 - $M \times g(n)$ is always greater than $f(n)$

Big-O Examples

- $5n + 1000 \Rightarrow O(n)$
 - Select $M = 6$, $N_0 = 1000$
 - For $n \geq 1000$
 - $6n \geq 5n+1000$ is always true
 - Example \Rightarrow for $n = 1000$
 - $6000 \geq 5000 + 1000$

Big-O Examples

■ $2n^2 + 10n + 1000 \Rightarrow O(n^2)$

■ Select $M = 4$, $N_0 = 100$

■ For $n \geq 100$

■ $4n^2 \geq 2n^2 + 10n + 1000$ is always true

■ Example \Rightarrow for $n = 100$

■ $40000 \geq 20000 + 1000 + 1000$

Observations

- **For large values of n**
 - **Any $O(\log(n))$ algorithm is faster than $O(n)$**
 - **Any $O(n)$ algorithm is faster than $O(n^2)$**
- **Asymptotic complexity is fundamental measure of efficiency**

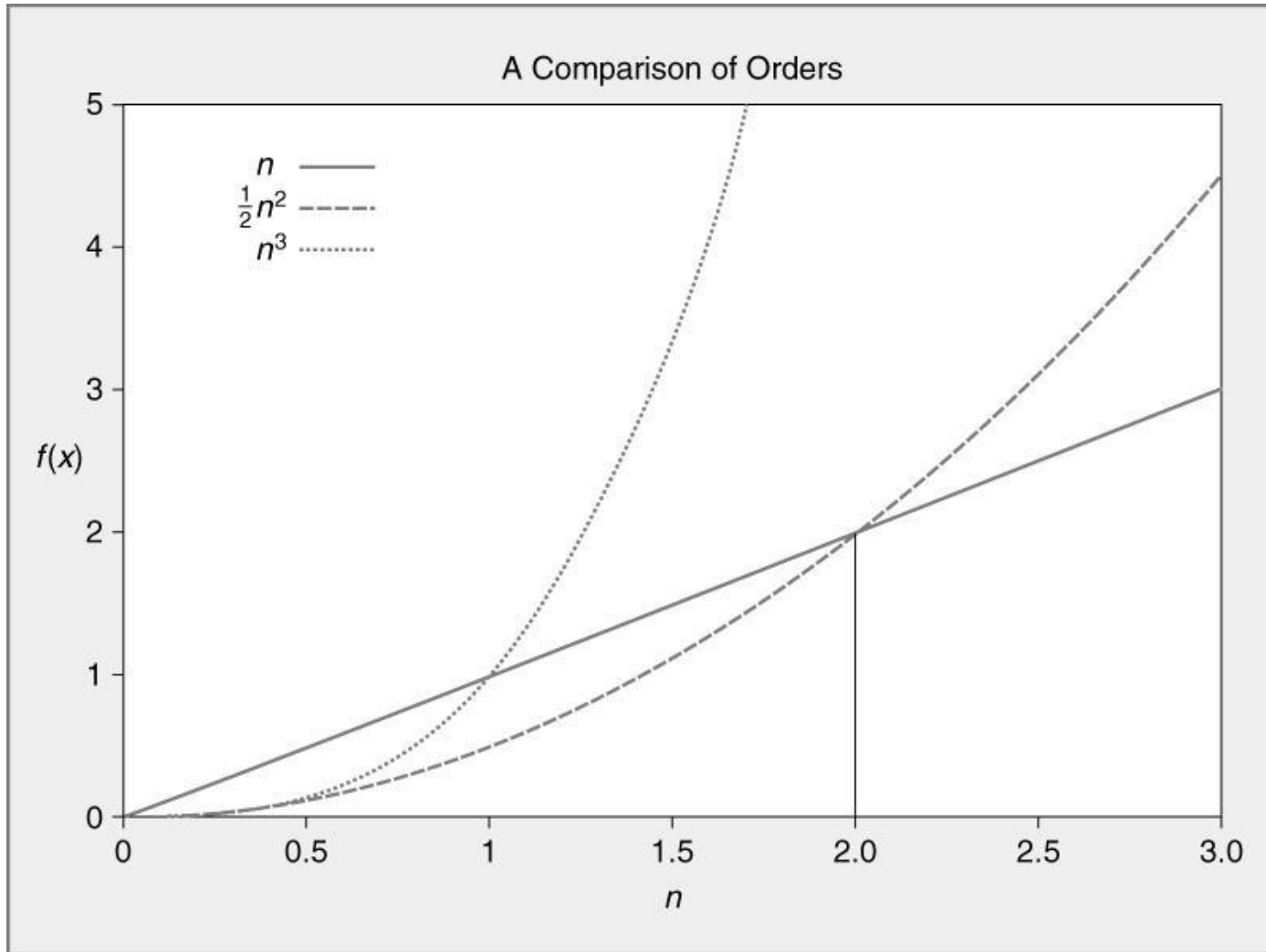
Asymptotic Complexity Categories

Complexity	Name	Example
■ $O(1)$	Constant	Array access
■ $O(\log(n))$	Logarithmic	Binary search
■ $O(n)$	Linear	Largest element
■ $O(n \log(n))$	$N \log N$	Optimal sort
■ $O(n^2)$	Quadratic	2D Matrix addition
■ $O(n^3)$	Cubic	2D Matrix multiply
■ $O(n^k)$	Polynomial	Linear programming
■ $O(k^n)$	Exponential	Integer programming
■ $O(n!)$	Factorial	Brute-force search TSP
■ $O(n^n)$	N to the N	

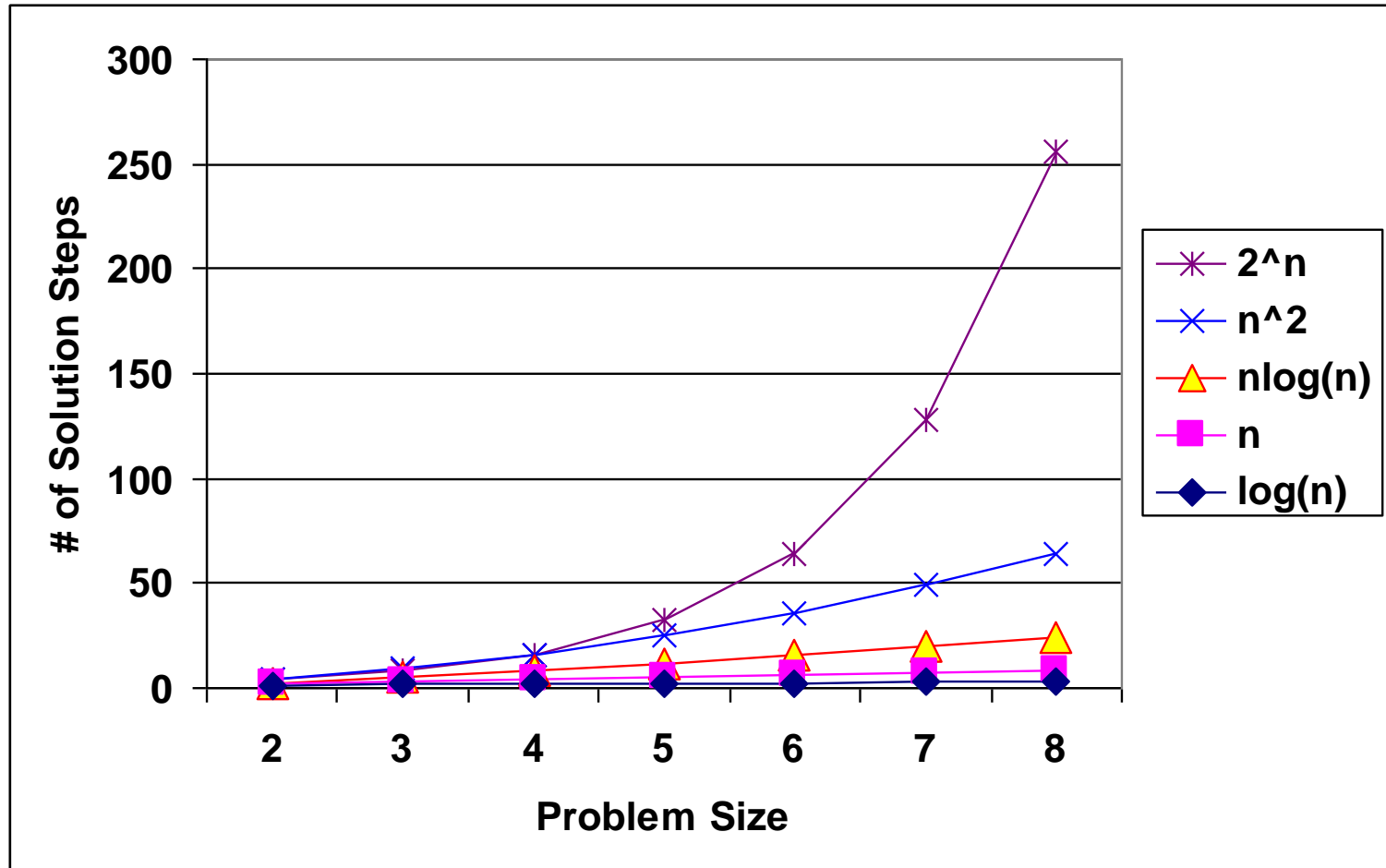
From smallest to largest

For size n , constant $k > 1$

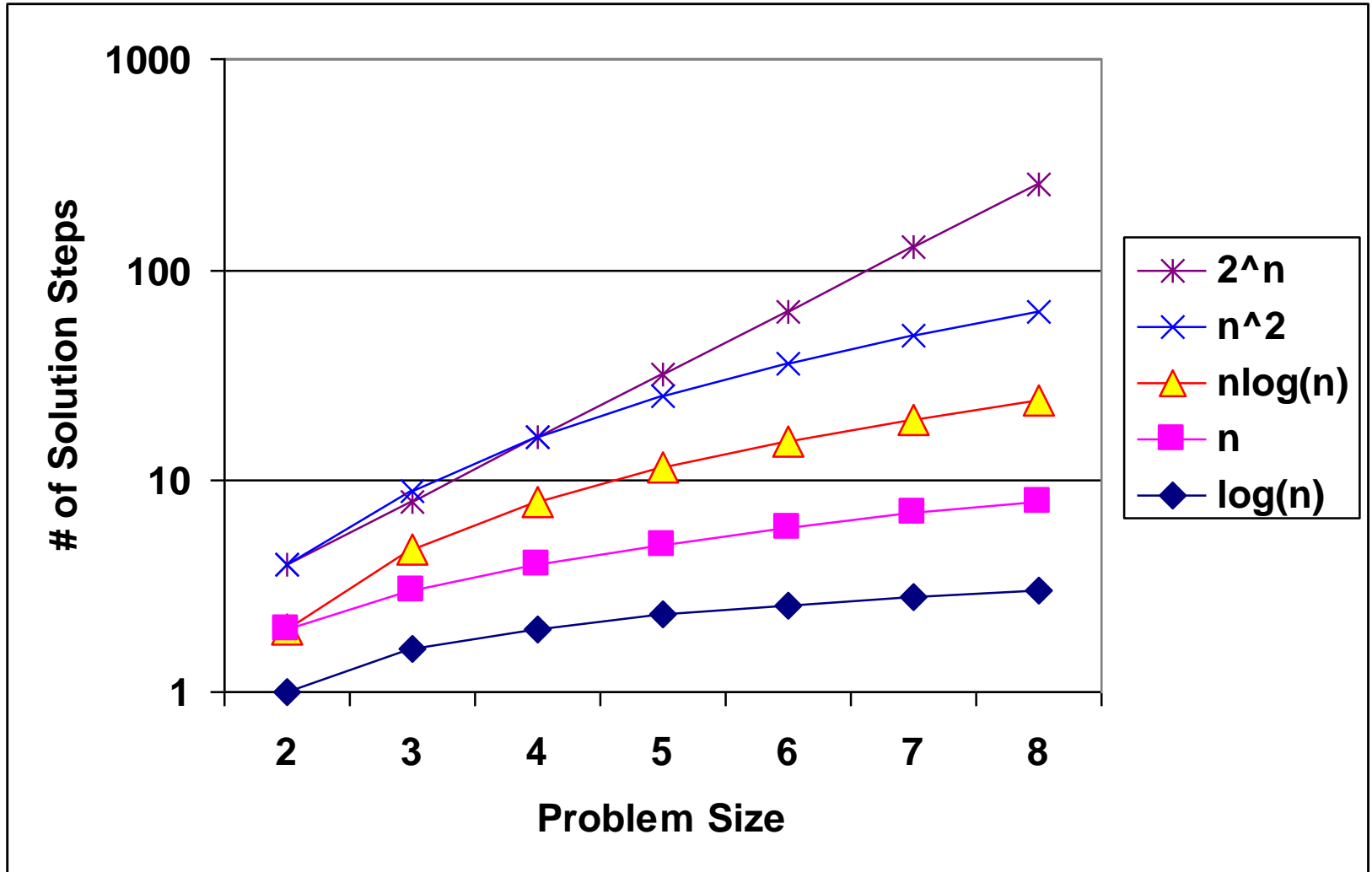
Comparison of Complexity



Complexity Category Example



Complexity Category Example



Calculating Asymptotic Complexity

■ As n increases

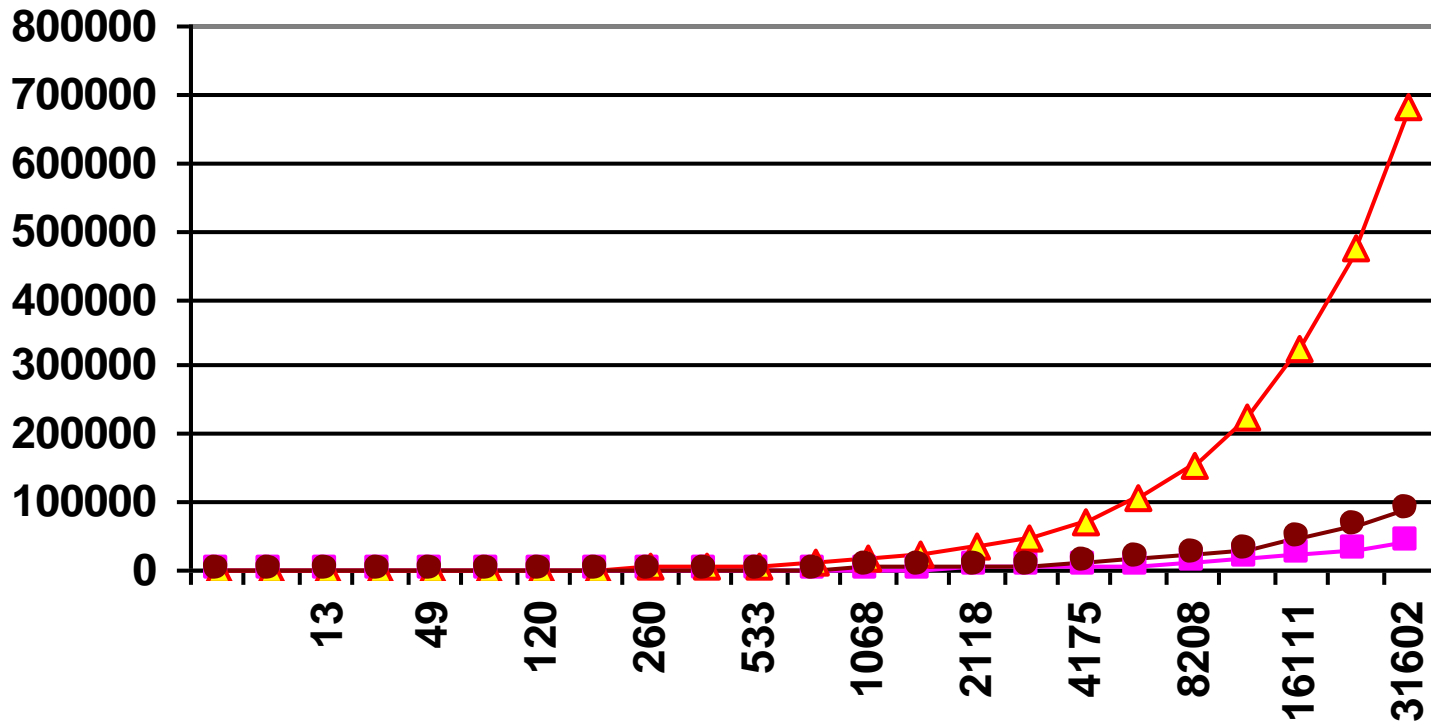
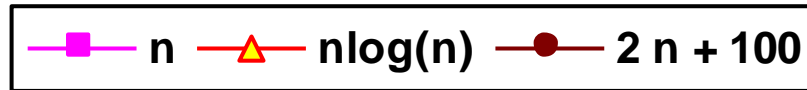
- Highest complexity term dominates
- Can ignore lower complexity terms

■ Examples

- $2n + 100 \Rightarrow O(n)$
- $n \log(n) + 10n \Rightarrow O(n \log(n))$
- $\frac{1}{2}n^2 + 100n \Rightarrow O(n^2)$
- $n^3 + 100n^2 \Rightarrow O(n^3)$
- $\frac{1}{100}2^n + 100n^4 \Rightarrow O(2^n)$

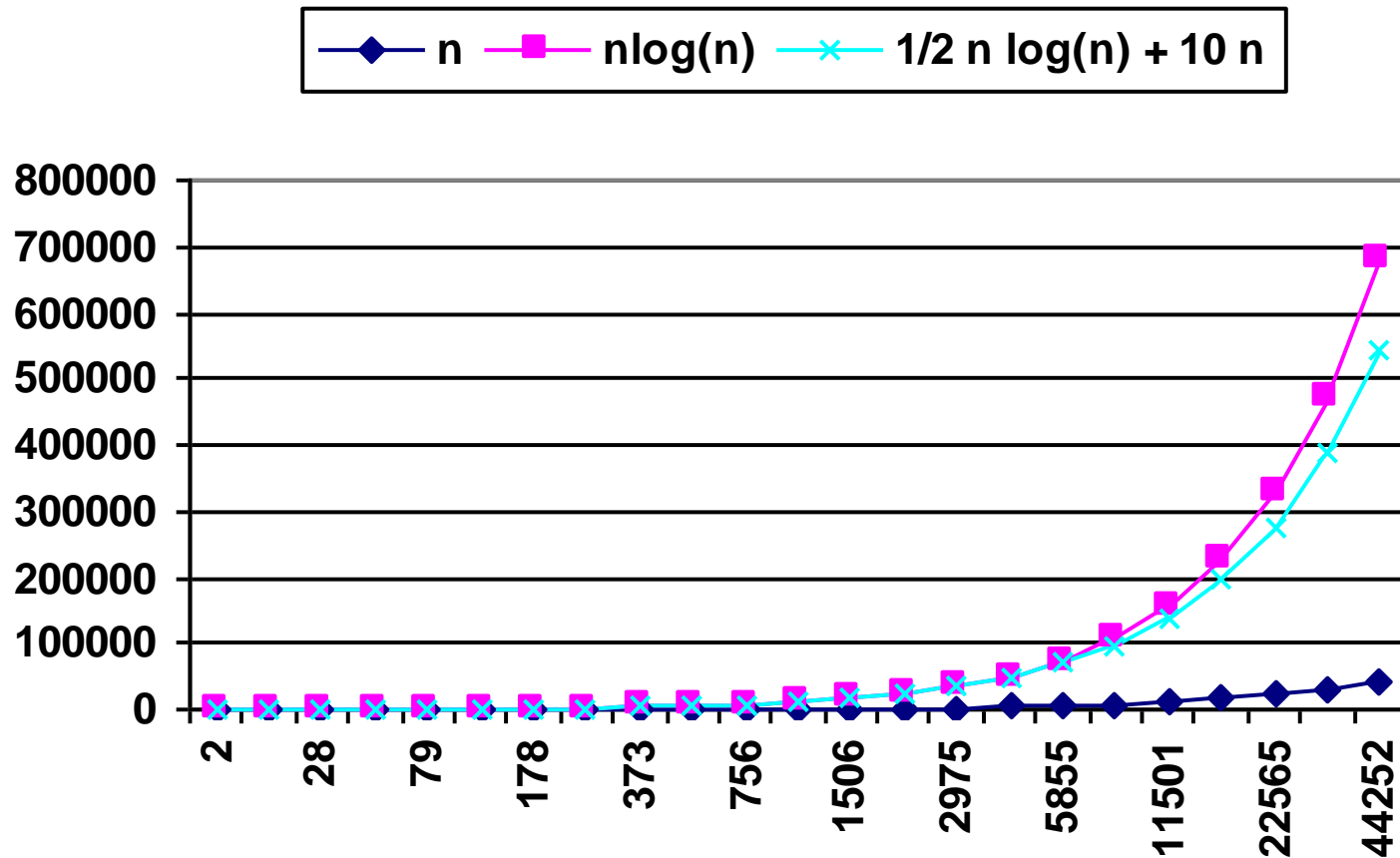
Complexity Examples

■ $2n + 100 \Rightarrow O(n)$



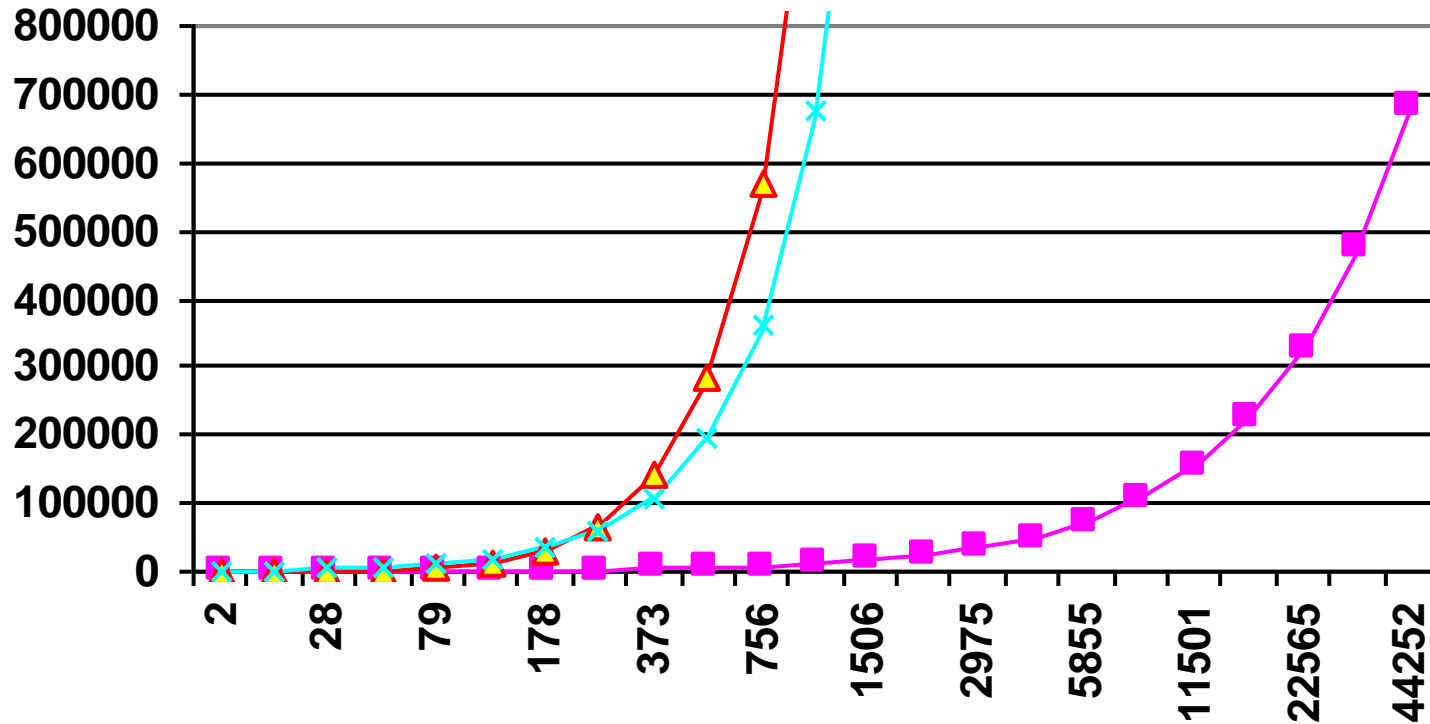
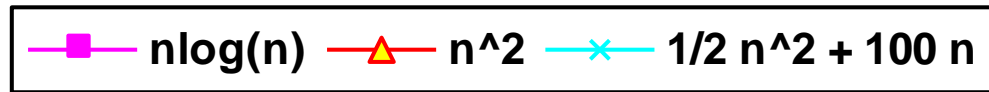
Complexity Examples

■ $\frac{1}{2} n \log(n) + 10 n \Rightarrow O(n \log(n))$



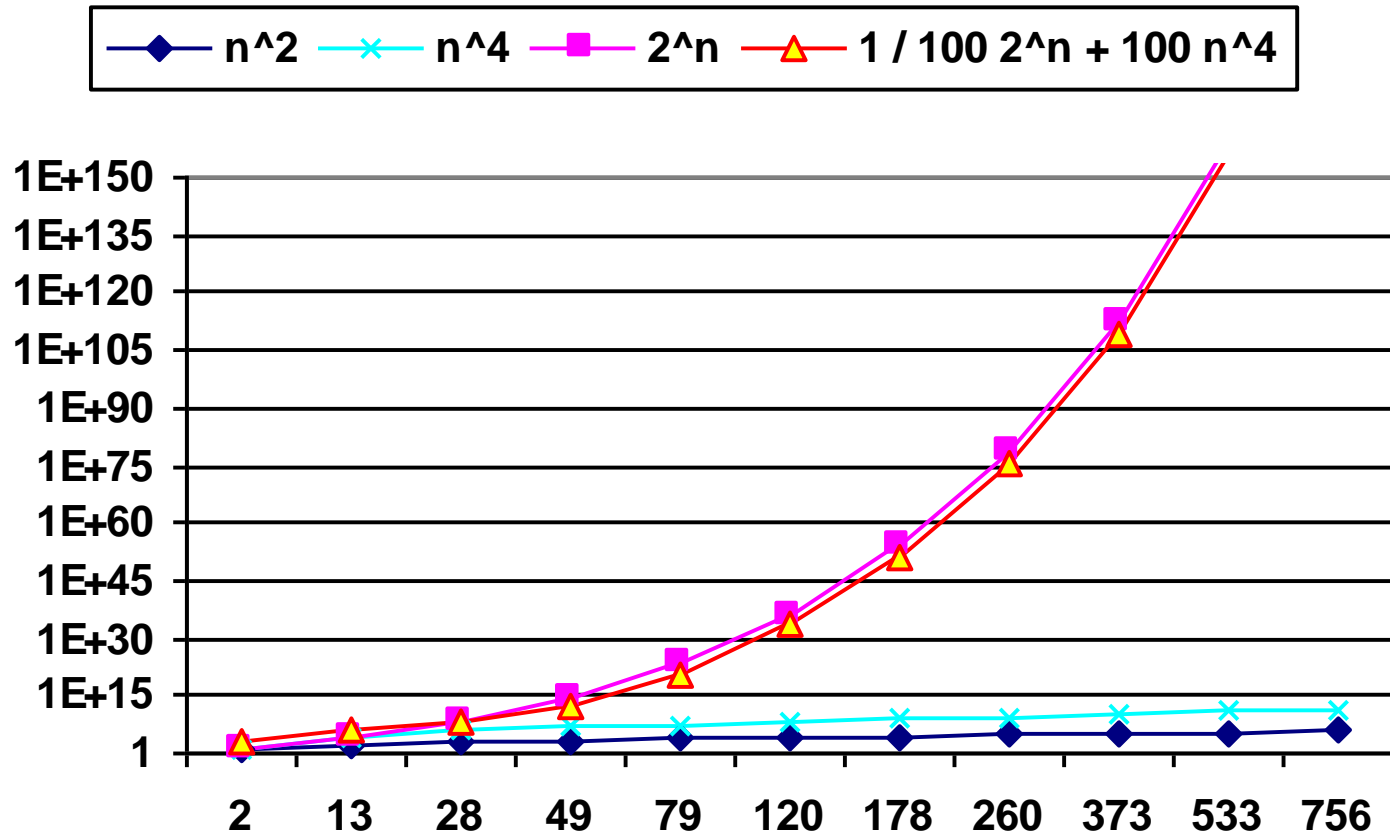
Complexity Examples

■ $\frac{1}{2} n^2 + 100 n \Rightarrow O(n^2)$



Complexity Examples

■ $1/100 2^n + 100 n^4 \Rightarrow O(2^n)$



Types of Case Analysis

- **Can analyze different types (cases) of algorithm behavior**
- **Types of analysis**
 - **Best case**
 - **Worst case**
 - **Average case**
 - **Amortized**

Types of Case Analysis

■ Best case

- Smallest number of steps required
- Not very useful
- Example \Rightarrow Find item in first place checked

Types of Case Analysis

■ Worst case

- Largest number of steps required
- Useful for upper bound on worst performance
 - Real-time applications (e.g., multimedia)
 - Quality of service guarantee
- Example ⇒ Find item in last place checked

Quicksort Example

■ Quicksort

- One of the fastest comparison sorts
- Frequently used in practice

■ Quicksort algorithm

- Pick **pivot** value from list
- Partition list into values smaller & bigger than pivot
- Recursively sort both lists

Quicksort Example

■ Quicksort properties

- Average case = $O(n \log(n))$

- Worst case = $O(n^2)$

 - Pivot \approx smallest / largest value in list

 - Picking from front of nearly sorted list

■ Can avoid worst-case behavior

- Select random pivot value

Types of Case Analysis

■ Average case

- Number of steps required for “typical” case
- Most useful metric in practice
- Different approaches
 - Average case
 - Expected case

Approaches to Average Case

■ Average case

■ Average over all possible inputs

- Assumes all inputs have the same probability

■ Example

- Case 1 = 10 steps, Case 2 = 20 steps
- Average = 15 steps

■ Expected case

■ Weighted average over all possible inputs

- Based on probability of each input

■ Example

- Case 1 (90%) = 10 steps, Case 2 (10%) = 20 steps
- Average = 11 steps

Average Case Example

■ Example problem

■ Average # of comparisons needed to find a number in the (sorted) array $A[] = \{1, 4, 8, 12, 15\}$ using

■ Linear search

- Start from beginning, compare elements one at a time

■ Binary search

- Start from middle of array at index k , compare element
- If not element, repeat for top or bottom half of remaining array depending on whether element is smaller or greater than $A[k]$

Average Case : Linear Search

■ Algorithm

■ Find # of comparisons needed for each case

■ 1 → 1 comparison (1)

■ 4 → 2 comparisons (1, 4)

■ 8 → 3 comparisons (1, 4, 8)

■ 12 → 4 comparisons (1, 4, 8, 12)

■ 15 → 5 comparisons (1, 4, 8, 12, 15)

■ Calc average = total # of comparisons / # cases

■ Total # comparisons = $1 + 2 + 3 + 4 + 5 = 15$

■ # cases = 5

■ Average = 3 comparisons / number

Average Case : Binary Search

■ Algorithm

■ Find # of comparisons needed for each case

■ 1 → 3 comparisons (8, 4, 1)

■ 4 → 2 comparisons (8, 4)

■ 8 → 1 comparisons (8)

■ 12 → 2 comparisons (8, 12)

■ 15 → 3 comparisons (8, 12, 15)

■ Calc average = total # of comparisons / # cases

■ Total # comparisons = $3 + 2 + 1 + 2 + 3 = 11$

■ # cases = 5

■ Average = 2.2 comparisons / number

Average Case Example

■ Example problem 2

- Average # of comparisons needed to find a number in a sorted array $A[n]$ of size n using
 - Linear search
 - Binary search
- For simplicity, we assume elements are stored in $A[1] \dots A[n]$

Average Case : Linear Search

■ Algorithm

■ Find # of comparisons needed for each case

■ $A[1] \rightarrow 1$ comparison (A[1])

■ $A[2] \rightarrow 2$ comparisons (A[1], A[2])

■ ...

■ $A[n] \rightarrow n$ comparisons (A[1] ... A[n])

■ Calc average = total # of comparisons / # cases

■ Total # comparisons = $1 + 2 + \dots + n = \frac{1}{2} n^2 + 1$

■ # cases = n

■ Average $\approx \frac{1}{2} n$ comparisons / number

Average Case : Binary Search

■ Algorithm

■ Find # of comparisons needed for each case

■ $A[n/2]$ → 1 comp (A[n/2])

■ $A[n/4], A[3n/4]$ → 2 comps (A[n/2], A[n/4])

■ ...

■ $A[1], A[3] \dots A[n]$ → $\log_2(n)$ comparisons

■ (A[n/2], A[n/4], A[n/8]...A[1])

■ Calc average = total # of comparisons / # cases

■ Total # comparisons = $n/2 * \log_2(n) +$

■ $n/4 * \log_2(n) - 1 + \dots + 1 = n \log_2(n)$

■ # cases = n

■ Average $\approx \log_2(n)$ comparisons / number

Sample problem

- **Given an array a of integers**
 - **find the subrange that has the maximum sum**
 - e.g., find low , $high$ that maximizes
$$a[low] + a[low+1] + \dots + a[high]$$
 - only non empty ranges ($low \leq high$)
 - If a contained only nonnegative integers, would be $low = 0$, $high = a.length - 1$
 - but a can contain negative numbers
 - Can assume that arithmetic overflow isn't an issue

One solution

```
public static int findBestRange(int [] a) {  
    int bestSum = a[0];  
    for(int low = 0; low < a.length; low++)  
        for(int high = low; high < a.length; high++) {  
            int sum = 0;  
            for(int i = low; i <= high; i++) sum += a[i];  
            if (bestSum < sum)  
                bestSum = sum;  
        }  
    return bestSum;  
}
```

// What is the complexity of the algorithm used here?

Can you find a better algorithm?