Pre-lecture brain teaser

We talked a lot about languages representing problems. Consider the problem of adding two numbers. What language class does it belong to?

ECE-374-B: Lecture 9 - Recursion, Sorting and Recurrences

Instructor: Abhishek Kumar Umrawal

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University of Illinois at Urbana-Champaign

About your instructor – Basic info

- Name: Abhishek Kumar Umrawal
- Webpage: ece.illinois.edu/about/directory/faculty/aumrawal
- Email: aumrawal@illinois.edu
- Office: ECEB 3054
- Office hours: Thursdays, 3 p.m. to 4 p.m., ECEB 4036

About your instructor – Education

- Purdue University, Ph.D. in Industrial Engineering
  Dissertation: Machine Learning Algorithms for Influence Maximization on Social Networks
- Purdue University, MS in Economics
- Indian Institute of Technology (IIT) Kanpur, MS in Statistics

About your instructor – Prior teaching experience

- University of Maryland, Visiting Lecturer of Computer Science and Electrical Engineering

About your instructor – Research interests

Core areas:

1. Combinatorial optimization
2. Approximation algorithms
3. Statistical learning theory
4. Reinforcement learning (RL)
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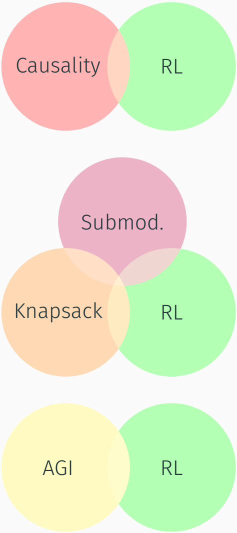
Intersections:



Working with me on research

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Preferred (but not required) skills:

- Mathematical thinking
- Probability and statistics
- Python programming – graphs, object-oriented programming, recursion, etc.
- Algorithms (you’re doing it this semester!)

You may fill out this form to provide further information.

Pre-lecture brain teaser

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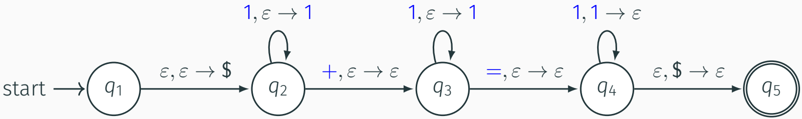
Pre-lecture brain teaser

Let's say we are adding two unary numbers.

$$3 + 4 = 7 \rightarrow 111 + 1111 = 1111111 \tag{1}$$

Seems like we can make a PDA that considers

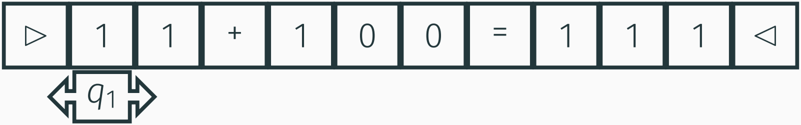


Pre-lecture brain teaser

What if we wanted add two binary numbers?

$$3 + 4 = 7 \rightarrow 11 + 100 = 111 \tag{2}$$

At least context-sensitive b/c we can build a finite Turing machine which takes in the encoding

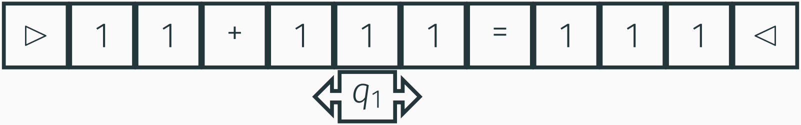


Pre-lecture brain teaser

What if we wanted add two binary numbers?

$$3 + 4 = 7 \to 11 + 100 = 111 \tag{3}$$

Computes value on left hand side



▷	1	1	+	1	1	1	=	1	1	1	◁

Pre-lecture brain teaser

What if we wanted add two binary numbers?

$$3+4=7 \rightarrow 11+100=111 \tag{4}$$

And compares it to the value on the right..

New Course Section: Introductory algorithms

Learning Objectives

At the end of the lecture, you should be able to understand

- the idea of an algorithm and algorithmic problems,
- how to reduce a problem into another,
- the design and analysis of recursive algorithms, and
- some example recursive algorithms for sorting and searching.

Brief intro to the Random Access Machine (RAM) model

Algorithms and Computing

- Algorithm solves a specific *problem*.
- Steps/instructions of an algorithm are *simple/primitive* and can be executed mechanically.
- Algorithm has a *finite description; same description* for all instances of the problem
- Algorithm implicitly may have *state/memory*

A computer is a device that

- *implements* the primitive instructions
- allows for an *automated* implementation of the entire algorithm by keeping track of state

Models of Computation vs Computers

- Model of Computation: an *idealized mathematical construct* that describes the primitive instructions and other details
- Computer: an actual *physical device* that implements a very specific model of computation

In this course: design algorithms in a high-level model of computation.

Question: What model of computation will we use to design algorithms?

Models of Computation vs Computers

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- Computer: an actual *physical device* that implements a very specific model of computation

In this course: design algorithms in a high-level model of computation.

Question: What model of computation will we use to design algorithms?

The standard programming model that you are used to in programming languages such as Java/C++. We have already seen the Turing Machine model.

Unit-Cost RAM Model

Informal description:

- Basic data type is an integer number
- Numbers in input fit in a *word*
- Arithmetic/comparison operations on words take constant time
- Arrays allow random access (constant time to access $A[i]$)
- Pointer based data structures via storing addresses in a word

Example

Sorting: input is an array of n numbers

- input size is n (ignore the bits in each number),
- comparing two numbers takes $O(1)$ time,
- random access to array elements,
- addition of indices takes constant time,
- basic arithmetic operations take constant time,
- reading/writing one word from/to memory takes constant time.

We will usually do not allow (or be careful about allowing):

- bitwise operations (and, or, xor, shift, etc).
- floor function.
- limit word size (usually assume unbounded word size).

What is an algorithmic problem?

What is an algorithmic problem?

An algorithmic problem is simply to compute a function $f : \Sigma^* \to \Sigma^*$ over strings of a finite alphabet.

Algorithm $\mathcal{A}$ solves f if for all **input strings** w, $\mathcal{A}$ outputs $f(w)$.

Types of Problems

We will broadly see three types of problems.

- Decision Problem: Is the input a YES or NO input?
  Example: Given graph G, nodes s, t, is there a path from s to t in G?
  Example: Given a CFG grammar G and string w, is $w \in L(G)$?
- Search Problem: Find a *solution* if input is a YES input.
  Example: Given graph G, nodes s, t, find an s-t path.
- Optimization Problem: Find a *best* solution among all solutions for the input.
  Example: Given graph G, nodes s, t, find a shortest s-t path.

Analysis of Algorithms

Given a problem P and an algorithm $\mathcal{A}$ for P we want to know:

- Does $\mathcal{A}$ **correctly** solve problem P?
- What is the **asymptotic worst-case running time** of $\mathcal{A}$?
- What is the **asymptotic worst-case space** used by $\mathcal{A}$.

Asymptotic running-time analysis: $\mathcal{A}$ runs in $O(f(n))$ time if:

"for all n and for all inputs I of size n, $\mathcal{A}$ on input I terminates after $O(f(n))$ primitive steps."

Algorithmic Techniques

- Reduction to known problem/algorithm
- Recursion, divide-and-conquer, dynamic programming
- Graph algorithms to use as basic reductions
- Greedy

Some advanced techniques not covered in this class:

- Combinatorial optimization
- Linear and Convex Programming, more generally continuous optimization method
- Advanced data structure
- Randomization
- Many specialized areas

Reductions

Reduction

Reducing problem A to problem B:

- Algorithm for A uses algorithm for B as a *black box*

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Q: How do you hunt a blue elephant?
A: With a blue elephant gun.

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Q: How do you hunt a red elephant?
A: Hold his trunk shut until it turns blue, and then shoot it with the blue elephant gun.

Reduction

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Q: How do you hunt a blue elephant?
A: With a blue elephant gun.

Q: How do you hunt a red elephant?
A: Hold his trunk shut until it turns blue, and then shoot it with the blue elephant gun.

Q: How do you shoot a white elephant?
A: Embarrass it till it becomes red. Now use your algorithm for hunting red elephants.

UNIQUENESS: Distinct Elements Problem

Problem Given an array A of n integers, are there any *duplicates* in A?

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Naive algorithm:

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DistinctElements(A[1..n])
    for $i = 1$ to $n - 1$ do
        for $j = i + 1$ to $n$ do
            if ($A[i] = A[j]$)
                return YES
    return NO
```

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Running time:

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```

Running time: $O(n^2)$

Reduction to Sorting

```
DistinctElements(A[1..n])
    Sort $A$
    for $i = 1$ to $n - 1$ do
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Running time: $O(n)$ plus time to sort an array of n numbers

Important point: algorithm uses sorting as a *black box*

Advantage of naive algorithm: works for objects that cannot be “sorted”. Can also consider hashing but outside scope of current course.

Two sides of Reductions

Suppose problem A reduces to problem B

- Positive direction: Algorithm for B implies an algorithm for A
- Negative direction: Suppose there is no "efficient" algorithm for A then it implies no efficient algorithm for B (technical condition for reduction time necessary for this)

Two sides of Reductions

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Example: Distinct Elements reduces to Sorting in $O(n)$ time

- An $O(n \log n)$ time algorithm for Sorting implies an $O(n \log n)$ time algorithm for Distinct Elements problem.
- If there is *no* $o(n \log n)$ time algorithm for Distinct Elements problem then there is *no* $o(n \log n)$ time algorithm for Sorting.

Recursion as self reductions

Recursion

Reduction: reduce one problem to another

Recursion: a special case of reduction

- reduce problem to a *smaller* instance of *itself*
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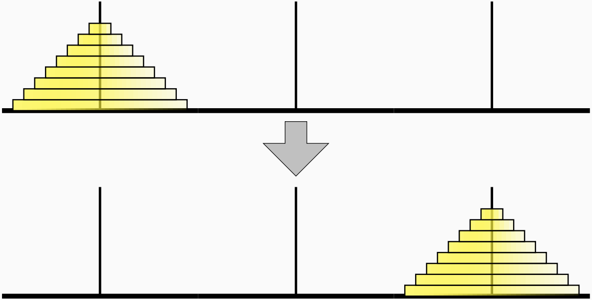
- Problem instance of size n is reduced to *one or more* instances of size $n-1$ or less.
- For termination, problem instances of small size are solved by some other method as *base cases*

Recursion

- Recursion is a very powerful and fundamental technique
- Basis for several other methods
    - Divide and conquer
    - Dynamic programming
    - Enumeration and branch and bound etc
    - Some classes of greedy algorithms
- Makes proof of correctness easy (via induction)
- Recurrences arise in analysis

Tower of Hanoi



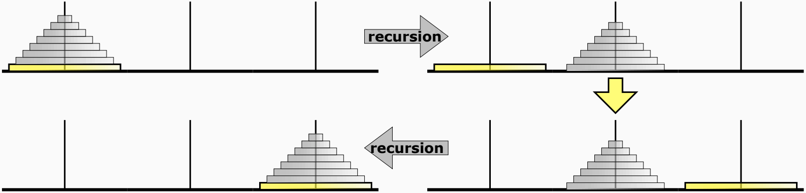
The Tower of Hanoi puzzle

Move stack of *n* disks from peg 1 to peg 2, one disk at a time.

Rule: cannot put a larger disk on a smaller disk.

Question: what is a strategy and how many moves does it take?

Tower of Hanoi via Recursion



The Tower of Hanoi algorithm; ignore everything but the bottom disk

Recursive Algorithm

```
Hanoi($n$, src, dest, tmp):
    if ($n > 0$) then
        Hanoi($n-1$, src, tmp, dest)
        Move disk $n$ from src to dest
        Hanoi($n-1$, tmp, dest, src)
```

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```

$T(n)$: time to move n disks via recursive strategy

$$T(n) = 2T(n-1) + 1 \qquad n > 1 \qquad \text{and } T(1) = 1$$

Analysis

$$\begin{aligned}
T(n) &= 2T(n-1)+1 \\
&= 2^2T(n-2)+2+1 \\
&= \ldots \\
&= 2^iT(n-i)+2^{i-1}+2^{i-2}+\ldots+1 \\
&= \ldots \\
&= 2^{n-1}T(1)+2^{n-2}+\ldots+1 \\
&= 2^{n-1}+2^{n-2}+\ldots+1 \\
&= (2^n-1)/(2-1)=2^n-1
\end{aligned}$$

Merge Sort

Sorting

Input Given an array of n elements

Goal Rearrange them in ascending order

MergeSort

1. Input: Array $A[1 \dots n]$

$$A\ L\ G\ O\ R\ I\ T\ H\ M\ S$$

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4. Merge the sorted arrays

$$A\ G\ H\ I\ L\ M\ O\ R\ S\ T$$

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Merging Sorted Arrays

- Use a new array C to store the merged array
- Scan A and B from left-to-right, storing elements in C in order

$$A\ G\ L\ O\ R \qquad H\ I\ M\ S\ T$$

$$A$$

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$$A\,G\,L\,O\,R \qquad H\,I\,M\,S\,T$$
$$A\,G\,H\,I\,L\,M\,O\,R\,S\,T$$

- Merge two arrays using only constantly more extra space (in-place merge sort): doable but complicated and typically impractical.

Formal Code

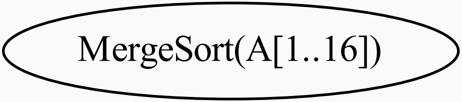
```
MERGESORT($A[1\,..\,n]$):
  if $n > 1$
      $m \gets \lfloor n/2 \rfloor$
      MERGESORT($A[1\,..\,m]$)
      MERGESORT($A[m+1\,..\,n]$)
      MERGE($A[1\,..\,n], m$)
```

```
MERGE($A[1\,..\,n], m$):
  $i \gets 1$;  $j \gets m+1$
  for $k \gets 1$ to $n$
      if $j > n$
          $B[k] \gets A[i]$;  $i \gets i+1$
      else if $i > m$
          $B[k] \gets A[j]$;  $j \gets j+1$
      else if $A[i] < A[j]$
          $B[k] \gets A[i]$;  $i \gets i+1$
      else
          $B[k] \gets A[j]$;  $j \gets j+1$

  for $k \gets 1$ to $n$
      $A[k] \gets B[k]$
```

Running time analysis of merge-sort: Recursion tree method

Recursion tree



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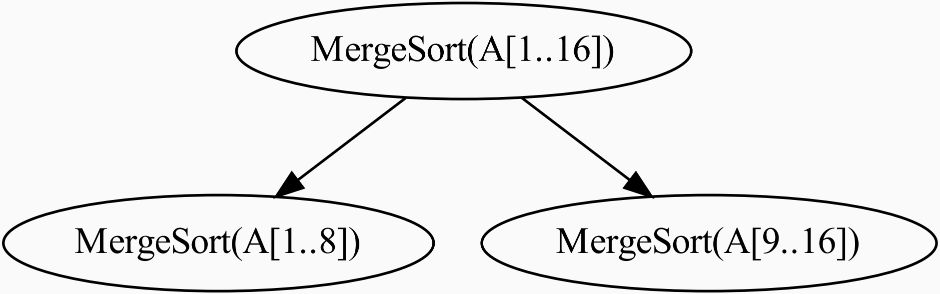
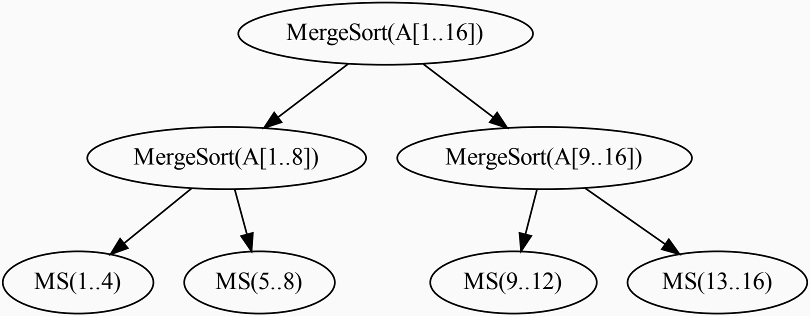

MergeSort(A[1..16])

MergeSort(A[1..8])

MergeSort(A[9..16])

Recursion tree



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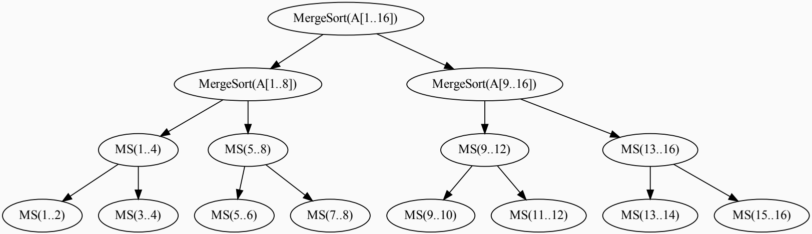

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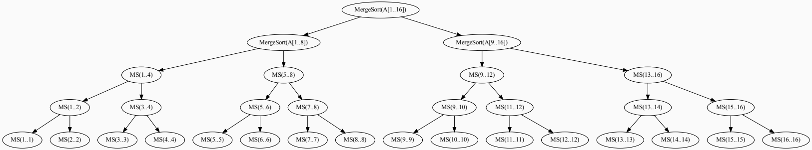
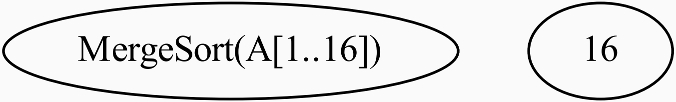


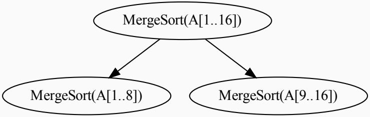
Recursion tree: subproblem sizes

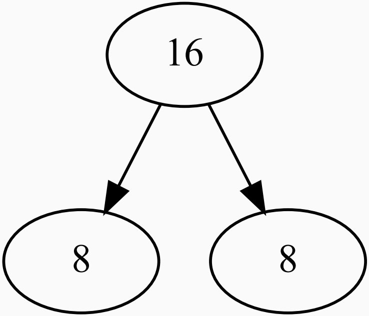


MergeSort(A[1..16])

16

Recursion tree: subproblem sizes





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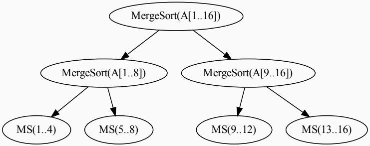

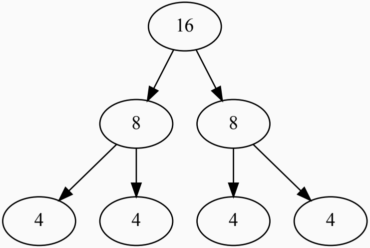

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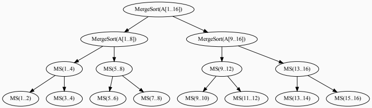

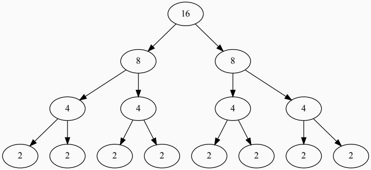

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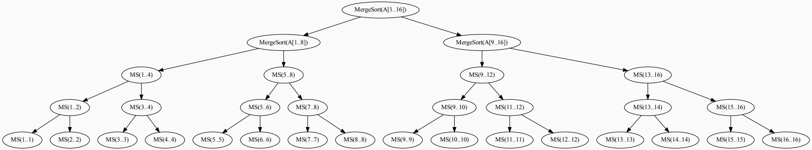
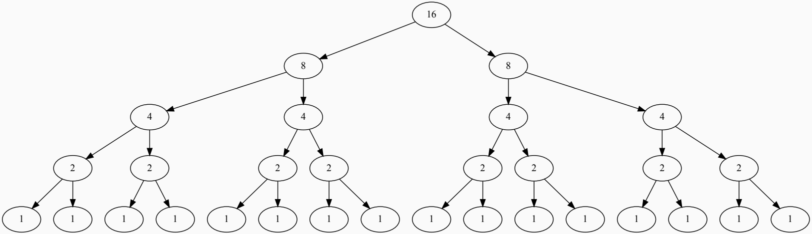
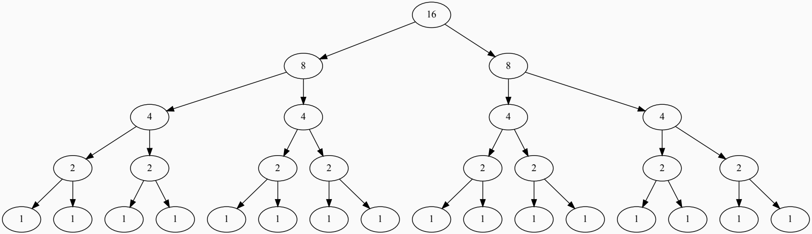




Recursion tree: Total work?



Running Time

$T(n)$: time for merge sort to sort an n element array

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$$T(n) = T(\lfloor n/2 \rfloor) + T(\lceil n/2 \rceil) + cn$$

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$$T(n) = T(\lfloor n/2 \rfloor) + T(\lceil n/2 \rceil) + cn$$

What do we want as a solution to the recurrence?

Almost always only an *asymptotically* tight bound. That is we want to know $f(n)$ such that $T(n) = \Theta(f(n))$.

- $T(n) = O(f(n))$ - upper bound
- $T(n) = \Omega(f(n))$ - lower bound

Solving Recurrences: Some Techniques

- Know some basic math: geometric series, logarithms, exponentials, elementary calculus
- Expand the recurrence and spot a pattern and use simple math
- Recursion tree method — imagine the computation as a tree
- Guess and verify — useful for proving upper and lower bounds even if not tight bounds

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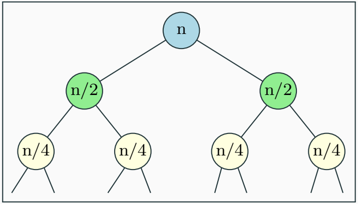
Albert Einstein: “Everything should be made as simple as possible, but not simpler.”

Know where to be loose in analysis and where to be tight. Comes with practice, practice, practice!

Recursion Trees : MergeSort: n is a power of 2



- Unroll the recurrence.
  $T(n) = 2T(n/2) + cn$

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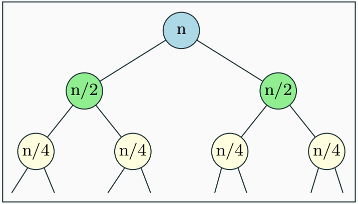

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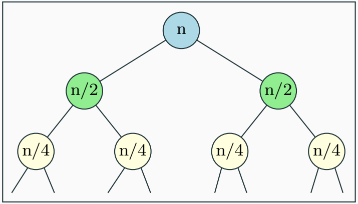

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- Identify a pattern. At the *i*th level total work is *cn*.

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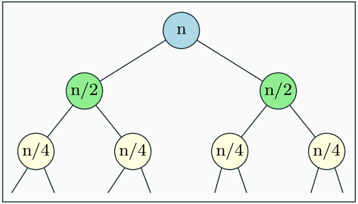

- Unroll the recurrence.
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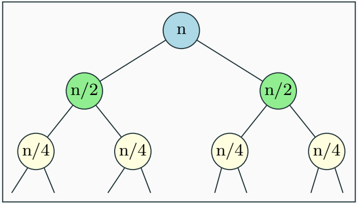
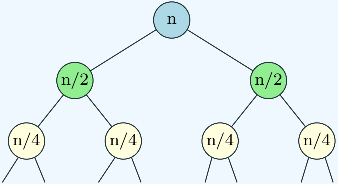
- Identify a pattern. At the ith level total work is cn.
- Sum over all levels.

Recursion Trees : MergeSort: n is a power of 2

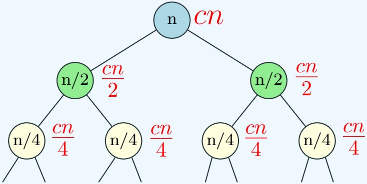


- Unroll the recurrence.
  $T(n) = 2T(n/2) + cn$
- Identify a pattern. At the *i*th level total work is cn.
- Sum over all levels. The number of levels is $\log n$. So total is $cn \log n = O(n \log n)$.

Recursion Trees

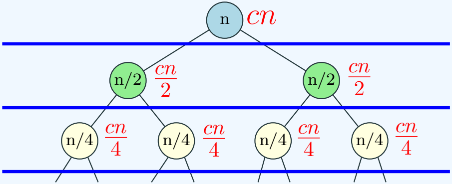


Recursion Trees



Work in each node

Recursion Trees



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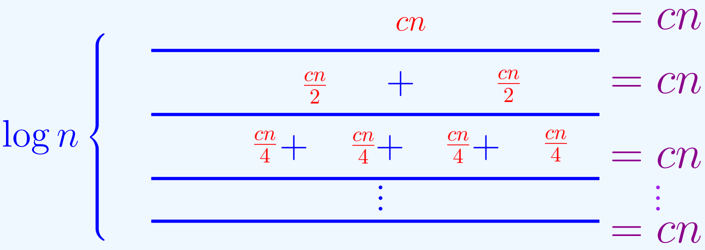
Recursion Trees



$\log n$

$$cn = cn$$

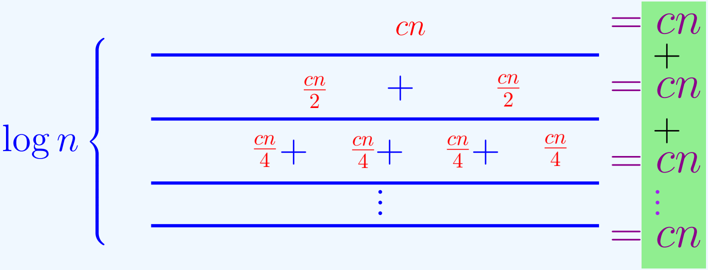
$$\frac{cn}{2} + \frac{cn}{2} = cn$$

$$\frac{cn}{4} + \frac{cn}{4} + \frac{cn}{4} + \frac{cn}{4} = cn$$

$$\vdots \qquad \vdots$$

$$= cn$$

Recursion Trees



$$= cn \log n = O(n \log n)$$

Merge Sort Variant

Question: Merge Sort splits into 2 (roughly) equal sized arrays. Can we do better by splitting into more than 2 arrays? Say k arrays of size n/k each?

Binary Search

Binary Search in Sorted Arrays

Input Sorted array A of n numbers and number x

Goal Is x in A?

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```
BinarySearch ($A[a..b]$, $x$):
        if ($b - a < 0$) return NO
        $mid = A[\lfloor (a+b)/2 \rfloor]$
        if ($x = mid$) return YES
        if ($x < mid$)
                return BinarySearch ($A[a..\lfloor (a+b)/2 \rfloor - 1]$, $x$)
        else
                return BinarySearch ($A[\lfloor (a+b)/2 \rfloor + 1..b]$,$x$)
```

Binary Search in Sorted Arrays

Input Sorted array A of n numbers and number x

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```
BinarySearch (A[a..b], x):
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        if (x = mid) return YES
        if (x < mid)
            return BinarySearch (A[a..⌊(a + b)/2⌋ - 1], x)
        else
            return BinarySearch (A[⌊(a + b)/2⌋ + 1..b],x)
```

Analysis: $T(n) = T(\lfloor n/2 \rfloor) + O(1)$. $T(n) = O(\log n)$.

Observation: After k steps, size of array left is $n/2^k$