

Counting Binary Trees

Joseph Chuang-Chieh Lin (林莊傑)

Department of Computer Science & Engineering,
National Taiwan Ocean University

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Outline

1 Counting Binary Trees

2 Selection Trees

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Counting Binary Trees

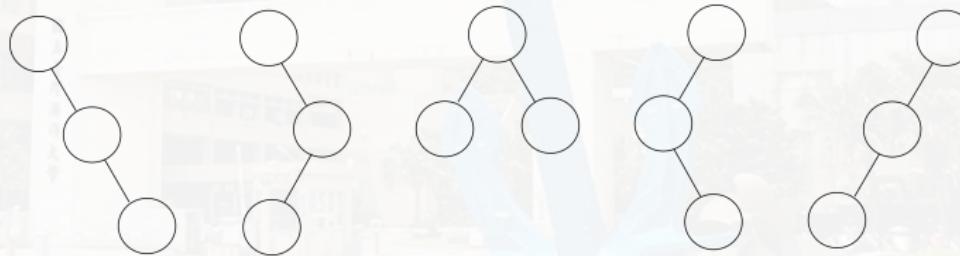
- Consider the following three disparate problems:
 - The number of distinct binary trees having n nodes.
 - The number of distinct permutations of the numbers from 1 to n obtainable by a **stack**.
 - The number of distinct ways of multiplying $n + 1$ matrices.

Counting Binary Trees

- Consider the following three disparate problems:
 - ➊ The number of distinct binary trees having n nodes.
 - ➋ The number of distinct permutations of the numbers from 1 to n obtainable by a **stack**.
 - ➌ The number of distinct ways of multiplying $n + 1$ matrices.
- Amazingly, **these problems have the same solution!**

Problem One

- The number of distinct binary trees having n nodes.



* Example of $n = 3$.

Problem Two

- The number of distinct permutations of the numbers from 1 to n obtainable by a stack.
 - ① push 1 → pop → push 2 → pop → push 3 → pop ⇒ 123.
 - ② push 1 → pop → push 2 → push 3 → pop → pop ⇒ 132.
 - ③ push 1 → push 2 → push 3 → pop → pop → pop ⇒ 321.
 - ④ push 1 → push 2 → pop → pop → push 3 → pop ⇒ 213.
 - ⑤ push 1 → push 2 → pop → push 3 → pop → pop ⇒ 231.
- ★ Example of $n = 3$.

Problem Three

- The number of distinct ways of multiplying $n + 1$ matrices.
 - ① $((M_1 \times M_2) \times M_3) \times M_4$.
 - ② $(M_1 \times (M_2 \times M_3)) \times M_4$.
 - ③ $M_1 \times ((M_2 \times M_3) \times M_4)$.
 - ④ $M_1 \times (M_2 \times (M_3 \times M_4))$.
 - ⑤ $(M_1 \times M_2) \times (M_3 \times M_4)$.

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Stack Permutation (1/4)

- Recall: preorder, inorder and postorder traversal of a binary tree.
 - Each traversal requires a **stack**.

Every binary tree has a unique pair of preorder/inorder sequences.

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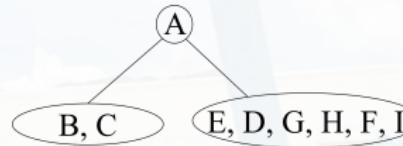
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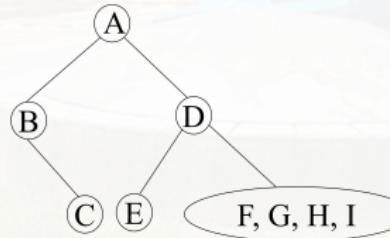
- The number of distinct binary trees is equal to the number of **inorder permutations** obtainable from binary trees having the preorder permutation, $1, 2, \dots, n$.

Stack Permutation (2/4)

- preorder: A B C E D G H F I
- inorder: B C A E D G H F I



- preorder: A B C (D E F G H I)
- inorder: B C A (E D F G H I)



Stack Permutation (3/4)

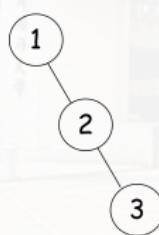
- We can show that

the number of distinct permutations obtainable by passing the numbers $\{1, 2, \dots, n\}$ through a stack is equal to the number of distinct binary trees with n nodes.

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Stack Permutation (4/4)

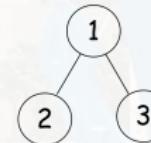
- visit node → push to stack;
 - going left → keep visiting next node
 - going right → pop the stack
- the leaf → pop the stack until empty



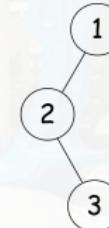
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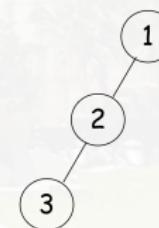
(1, 3, 2)



(2, 1, 3)



(2, 3, 1)



(3, 2, 1)

Go Back to the Matrix Multiplication

- Computing the product of n matrices are related to the distinct binary tree problem.
- $n = 3$:
 - ① $(M_1 \times M_2) \times M_3$.
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- $n = 4$:
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- $n = 4$:
 - ① $((M_1 \times M_2) \times M_3) \times M_4$ (push, pop, push, pop, push, pop)
 - ② $(M_1 \times (M_2 \times M_3)) \times M_4$ (?)
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Matrix Multiplication (2/2)

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- Trivially, $b_1 = 1$, $b_2 = 1$.
- We have also derived that $b_3 = 2$ and $b_4 = 5$.
- We can compute that

$$b_n = \sum_{i=1}^{n-1} b_i b_{n-i}, \text{ for } n > 1.$$

Distinct Binary Trees

- Similarly, the number of **distinct binary trees** of n nodes is

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Distinct Binary Trees

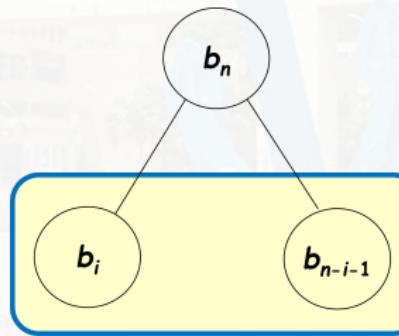
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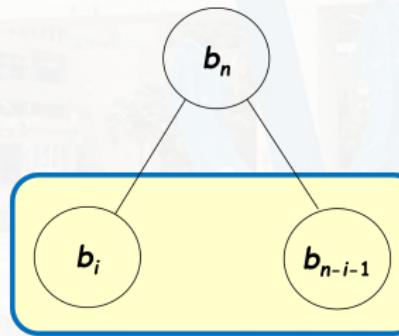
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- But, how to compute b_n exactly?

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 &= 1 + x \sum_{j=0}^{\infty} \sum_{k=0}^j b_k b_{j-k} x^j \\
 &= 1 + x \left(\sum_{j=0}^{\infty} b_j x^j \right)^2 = 1 + xB(x)^2.
 \end{aligned}$$



The Generating Function Trick

- By the recurrence relation we get:

$$xB(x)^2 = B(x) - 1.$$

- Solving the recurrence relation, we have

$$\begin{aligned}B(x) &= \frac{1 - \sqrt{1 - 4x}}{2x} \\&= \frac{1}{2x} \left(1 - \sum_{n \geq 0} \binom{1/2}{n} (-4x)^n \right) \\&= \sum_{m \geq 0} \binom{1/2}{m+1} (-1)^m 2^{2m+1} x^m.\end{aligned}$$

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By the Binomial Theorem...

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* supplementary: Stirling's approximation

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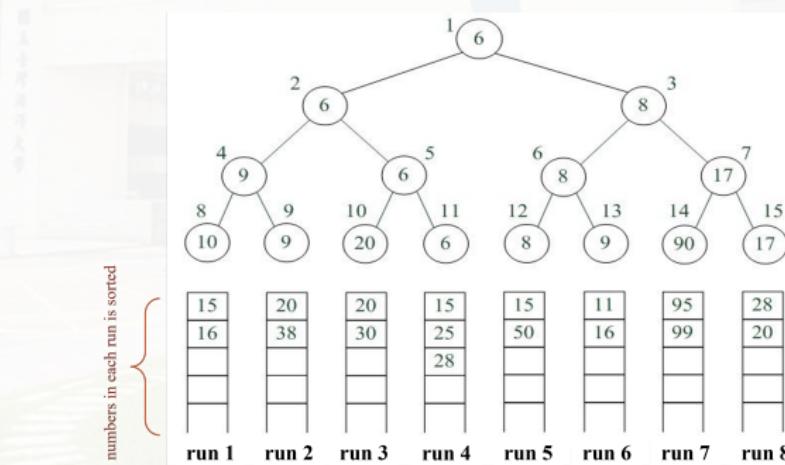
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Winner Selection Tree

(Winner) Selection Tree: $O(n \lg k)$ time.

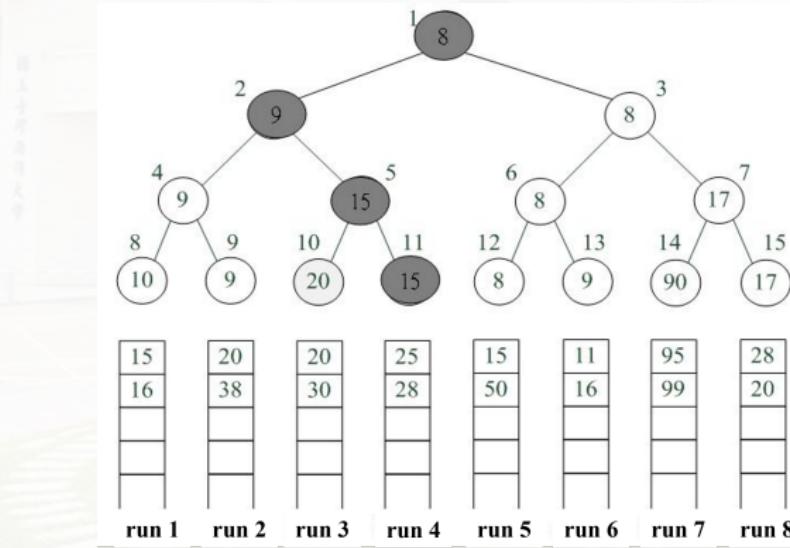
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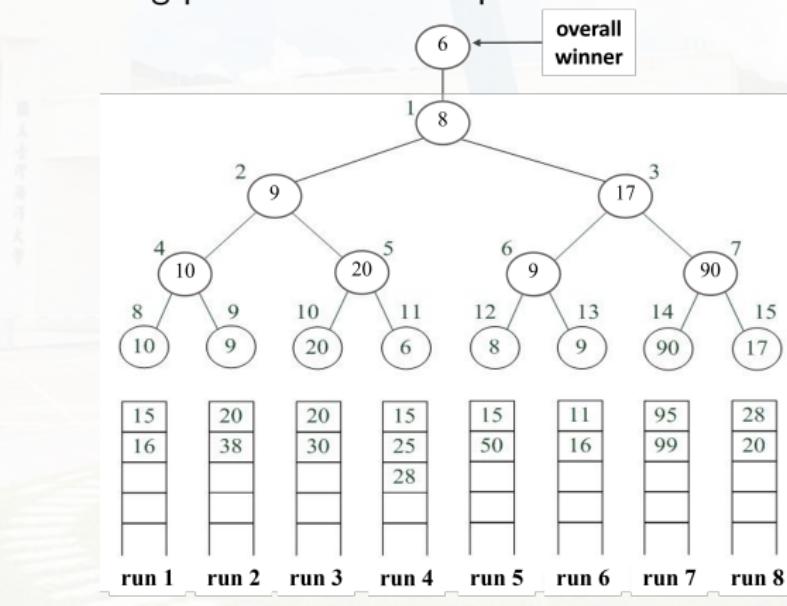
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Loser Selection Tree

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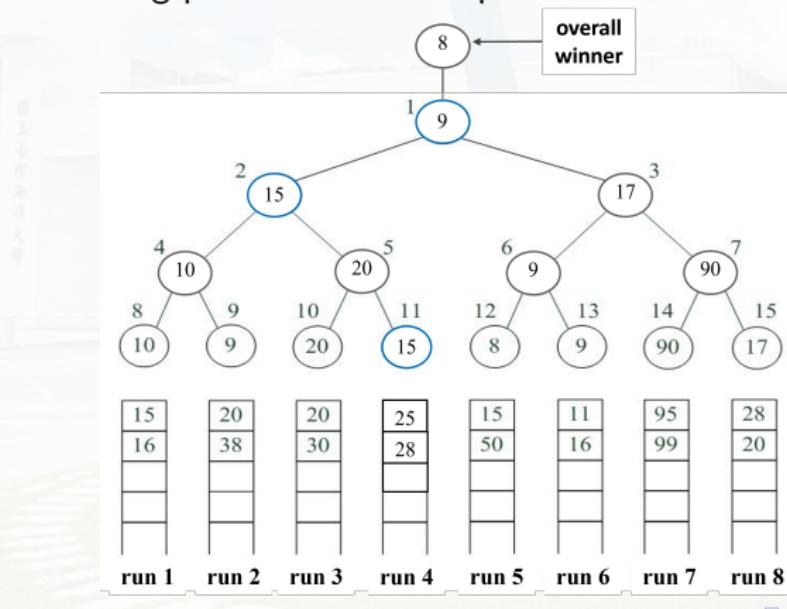
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Note for the Loser Selection Tree

- Comparison with the sibling is required for the first construction.
- After the first construction, we only need to compare each node with its parent; “push” the smaller key value upward and left the “larger” key value as the **loser**.

Discussions

