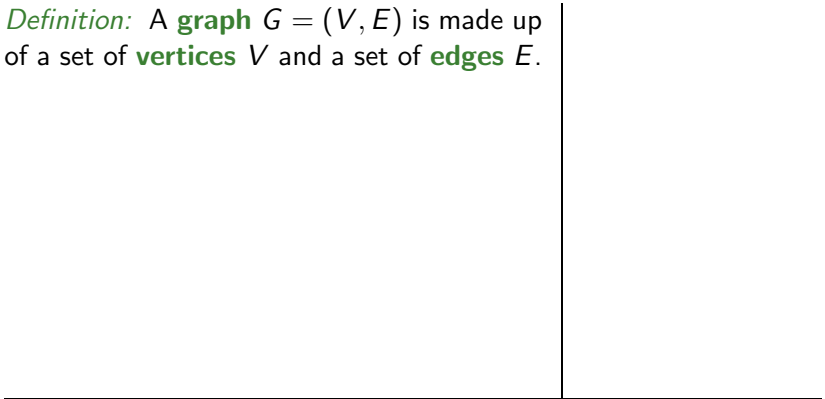


# Graph Theory

*Definition:* A **graph**  $G = (V, E)$  is made up of a set of **vertices**  $V$  and a set of **edges**  $E$ .



# Graph Theory

*Definition:* A **graph**  $G = (V, E)$  is made up of a set of **vertices**  $V$  and a set of **edges**  $E$ .

*Example.*  $G = (V, E)$  where  $V = \{v, w, x, y\}$ ,  
 $E = \{vw, vx, vy, wx\}$ .

# Graph Theory

*Definition:* A **graph**  $G = (V, E)$  is made up of a set of **vertices**  $V$  and a set of **edges**  $E$ . Think of a vertex  $v$  as a dot and an edge  $e = vw$  as a curve connecting  $v$  and  $w$ .

*Example.*  $G = (V, E)$  where  $V = \{v, w, x, y\}$ ,  $E = \{vw, vx, vy, wx\}$ .

# Graph Theory

*Definition:* A **graph**  $G = (V, E)$  is made up of a set of **vertices**  $V$  and a set of **edges**  $E$ .

Think of a vertex  $v$  as a dot and an edge  $e = vw$  as a curve connecting  $v$  and  $w$ .

A graph is **connected** if for every two vertices  $v$  and  $w$ , there is a path from  $v$  to  $w$ .

*Example.*  $G = (V, E)$  where  $V = \{v, w, x, y\}$ ,  
 $E = \{vw, vx, vy, wx\}$ .

# Graph Theory

*Definition:* A **graph**  $G = (V, E)$  is made up of a set of **vertices**  $V$  and a set of **edges**  $E$ .

Think of a vertex  $v$  as a dot and an edge  $e = vw$  as a curve connecting  $v$  and  $w$ .

A graph is **connected** if for every two vertices  $v$  and  $w$ , there is a path from  $v$  to  $w$ .

*Example.*  $G = (V, E)$  where  $V = \{v, w, x, y\}$ ,  
 $E = \{vw, vx, vy, wx\}$ .

T/F:  $G$  is connected.

# Graph Theory

*Definition:* A **graph**  $G = (V, E)$  is made up of a set of **vertices**  $V$  and a set of **edges**  $E$ .

Think of a vertex  $v$  as a dot and an edge  $e = vw$  as a curve connecting  $v$  and  $w$ .

A graph is **connected** if for every two vertices  $v$  and  $w$ , there is a path from  $v$  to  $w$ .

The **degree** of a vertex  $v$  is the number of edges connected to  $v$ .

A **leaf** is a vertex with degree 1.

*Example.*  $G = (V, E)$  where  $V = \{v, w, x, y\}$ ,  
 $E = \{vw, vx, vy, wx\}$ .

T/F:  $G$  is connected.

# Graph Theory

*Definition:* A **graph**  $G = (V, E)$  is made up of a set of **vertices**  $V$  and a set of **edges**  $E$ .

Think of a vertex  $v$  as a dot and an edge  $e = vw$  as a curve connecting  $v$  and  $w$ .

A graph is **connected** if for every two vertices  $v$  and  $w$ , there is a path from  $v$  to  $w$ .

The **degree** of a vertex  $v$  is the number of edges connected to  $v$ .

A **leaf** is a vertex with degree 1.

*Example.*  $G = (V, E)$  where  $V = \{v, w, x, y\}$ ,  
 $E = \{vw, vx, vy, wx\}$ .

deg  $v =$

deg  $y =$

T/F:  $G$  is connected.

# Graph Theory

*Definition:* A **graph**  $G = (V, E)$  is made up of a set of **vertices**  $V$  and a set of **edges**  $E$ .

Think of a vertex  $v$  as a dot and an edge  $e = vw$  as a curve connecting  $v$  and  $w$ .

A graph is **connected** if for every two vertices  $v$  and  $w$ , there is a path from  $v$  to  $w$ .

The **degree** of a vertex  $v$  is the number of edges connected to  $v$ .

A **leaf** is a vertex with degree 1.

*Example.*  $G = (V, E)$  where  $V = \{v, w, x, y\}$ ,  $E = \{vw, vx, vy, wx\}$ .

deg  $v =$

deg  $y =$

T/F:  $G$  is connected.

A **path** is a set of edges “in a line”:  $\{v_1 v_2, v_2 v_3, \dots, v_{k-1} v_k\}$

A **cycle** is a set of edges “in a circle”:  $\{v_1 v_2, v_2 v_3, \dots, v_{k-1} v_k, v_k v_1\}$



# Graph Theory

*Definition:* A **graph**  $G = (V, E)$  is made up of a set of **vertices**  $V$  and a set of **edges**  $E$ .

Think of a vertex  $v$  as a dot and an edge  $e = vw$  as a curve connecting  $v$  and  $w$ .

A graph is **connected** if for every two vertices  $v$  and  $w$ , there is a path from  $v$  to  $w$ .

The **degree** of a vertex  $v$  is the number of edges connected to  $v$ .

A **leaf** is a vertex with degree 1.

*Example.*  $G = (V, E)$  where  $V = \{v, w, x, y\}$ ,  
 $E = \{vw, vx, vy, wx\}$ .

deg  $v =$

deg  $y =$

T/F:  $G$  is connected.

T/F:  $G$  has a cycle.

A **path** is a set of edges “in a line”:  $\{v_1 v_2, v_2 v_3, \dots, v_{k-1} v_k\}$

A **cycle** is a set of edges “in a circle”:  $\{v_1 v_2, v_2 v_3, \dots, v_{k-1} v_k, v_k v_1\}$

# Graph Theory

*Definition:* A **graph**  $G = (V, E)$  is made up of a set of **vertices**  $V$  and a set of **edges**  $E$ .

Think of a vertex  $v$  as a dot and an edge  $e = vw$  as a curve connecting  $v$  and  $w$ .

A graph is **connected** if for every two vertices  $v$  and  $w$ , there is a path from  $v$  to  $w$ .

The **degree** of a vertex  $v$  is the number of edges connected to  $v$ .

A **leaf** is a vertex with degree 1.

*Example.*  $G = (V, E)$  where  $V = \{v, w, x, y\}$ ,  $E = \{vw, vx, vy, wx\}$ .

deg  $v =$

deg  $y =$

T/F:  $G$  is connected.

T/F:  $G$  has a cycle.

A **path** is a set of edges “in a line”:  $\{v_1 v_2, v_2 v_3, \dots, v_{k-1} v_k\}$

A **cycle** is a set of edges “in a circle”:  $\{v_1 v_2, v_2 v_3, \dots, v_{k-1} v_k, v_k v_1\}$

A **tree** is a connected graph containing no cycles.

A **forest** is a graph containing no cycles. (may not be connected)

# Graph Theory

*Definition:* A **graph**  $G = (V, E)$  is made up of a set of **vertices**  $V$  and a set of **edges**  $E$ .

Think of a vertex  $v$  as a dot and an edge  $e = vw$  as a curve connecting  $v$  and  $w$ .

A graph is **connected** if for every two vertices  $v$  and  $w$ , there is a path from  $v$  to  $w$ .

The **degree** of a vertex  $v$  is the number of edges connected to  $v$ .

A **leaf** is a vertex with degree 1.

*Example.*  $G = (V, E)$  where  $V = \{v, w, x, y\}$ ,  $E = \{vw, vx, vy, wx\}$ .

$\deg v =$

$\deg y =$

T/F:  $G$  is connected.

T/F:  $G$  has a cycle.

T/F:  $G$  is a tree.

A **path** is a set of edges “in a line”:  $\{v_1 v_2, v_2 v_3, \dots, v_{k-1} v_k\}$

A **cycle** is a set of edges “in a circle”:  $\{v_1 v_2, v_2 v_3, \dots, v_{k-1} v_k, v_k v_1\}$

A **tree** is a connected graph containing no cycles.

A **forest** is a graph containing no cycles. (may not be connected)

# Counting Trees

*Question:* How many trees are there?

# Counting Trees

*Question:* How many trees are there?

*Answer:* It depends.

# Counting Trees

*Question:* How many trees are there?

*Answer:* It depends.

- ▶ Are there restrictions?
  
- ▶ Are the vertices labeled?

# Counting Trees

*Question:* How many trees are there?

*Answer:* It depends.

- ▶ Are there restrictions?
  - ▶ We'll end by counting **binary trees**.
- ▶ Are the vertices labeled?

# Counting Trees

*Question:* How many trees are there?

*Answer:* It depends.

- ▶ Are there restrictions?
  - ▶ We'll end by counting **binary trees**.
- ▶ Are the vertices labeled?
  - ▶ Does this matter? **(Oh, yes!)**



# Counting Trees

*Question:* How many trees are there?

*Answer:* It depends.

- ▶ Are there restrictions?
  - ▶ We'll end by counting **binary trees**.
- ▶ Are the vertices labeled?
  - ▶ Does this matter? **(Oh, yes!)**
  - ▶ **Unlabeled** vs. **Labeled**: (**A000055** vs. **A000272**)

# Counting Trees

*Question:* How many trees are there?

*Answer:* It depends.

- ▶ Are there restrictions?
  - ▶ We'll end by counting **binary trees**.
- ▶ Are the vertices labeled?
  - ▶ Does this matter? **(Oh, yes!)**
  - ▶ **Unlabeled** vs. **Labeled**: (**A000055** vs. **A000272**)

★ We can label every unlabeled tree in *some number* of ways. ★

# Counting Trees

*Question:* How many trees are there?

*Answer:* It depends.

- ▶ Are there restrictions?
  - ▶ We'll end by counting **binary trees**.
- ▶ Are the vertices labeled?
  - ▶ Does this matter? **(Oh, yes!)**
  - ▶ **Unlabeled** vs. **Labeled**: (**A000055** vs. **A000272**)

★ We can label every unlabeled tree in *some number* of ways. ★

- ▶ There is **no nice formula** for the number of **unlabeled** trees.

# Counting Trees

*Question:* How many trees are there?

*Answer:* It depends.

- ▶ Are there restrictions?
  - ▶ We'll end by counting **binary trees**.
- ▶ Are the vertices labeled?
  - ▶ Does this matter? **(Oh, yes!)**
  - ▶ **Unlabeled** vs. **Labeled**: (**A000055** vs. **A000272**)

★ We can label every unlabeled tree in *some number* of ways. ★

- ▶ There is **no nice formula** for the number of **unlabeled** trees.
- ▶ There is **an amazingly nice formula** for the number of **labeled** trees.

# Counting Labeled Trees

Thm 6.2.5 The number of labeled trees is  $n^{n-2}$ . (drumroll....)

## Counting Labeled Trees

Thm 6.2.5 The number of labeled trees is  $n^{n-2}$ . (drumroll....)

# Counting Labeled Trees

**Thm 6.2.5** The number of labeled trees is  $n^{n-2}$ . (drumroll....)

*Proof.* We will construct a bijection between:

$$f : \left\{ \begin{array}{l} \text{labeled trees } \mathcal{T} \\ \text{with } n \text{ vertices} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\}.$$

# Counting Labeled Trees

**Thm 6.2.5** The number of labeled trees is  $n^{n-2}$ . (drumroll....)

*Proof.* We will construct a bijection between:

$$f : \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\}.$$

Given a tree  $T$ , create a list  $L$  called its **Prüfer sequence**:



# Counting Labeled Trees

**Thm 6.2.5** The number of labeled trees is  $n^{n-2}$ . (drumroll....)

*Proof.* We will construct a bijection between:

$$f : \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\}.$$

Given a tree  $T$ , create a list  $L$  called its **Prüfer sequence**:

- ▶ Start with the empty list  $L = ()$ .
- ▶ Repeat the following steps **until the tree has only two vertices**:

# Counting Labeled Trees

**Thm 6.2.5** The number of labeled trees is  $n^{n-2}$ . (drumroll....)

*Proof.* We will construct a bijection between:

$$f : \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\}.$$

Given a tree  $T$ , create a list  $L$  called its **Prüfer sequence**:

- ▶ Start with the empty list  $L = ()$ .
- ▶ Repeat the following steps **until the tree has only two vertices**:
  - ▶ **Find** the **leaf**  $v$  with the smallest label.

# Counting Labeled Trees

**Thm 6.2.5** The number of labeled trees is  $n^{n-2}$ . (drumroll....)

*Proof.* We will construct a bijection between:

$$f : \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\}.$$

Given a tree  $T$ , create a list  $L$  called its **Prüfer sequence**:

- ▶ Start with the empty list  $L = ()$ .
- ▶ Repeat the following steps **until the tree has only two vertices**:
  - ▶ **Find** the **leaf**  $v$  with the smallest label.
  - ▶ **Append** the label of  $v$ 's neighbor to  $L$ .

# Counting Labeled Trees

**Thm 6.2.5** The number of labeled trees is  $n^{n-2}$ . (drumroll....)

*Proof.* We will construct a bijection between:

$$f : \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\}.$$

Given a tree  $T$ , create a list  $L$  called its **Prüfer sequence**:

- ▶ Start with the empty list  $L = ()$ .
- ▶ Repeat the following steps **until the tree has only two vertices**:
  - ▶ **Find** the **leaf**  $v$  with the smallest label.
  - ▶ **Append** the label of  $v$ 's neighbor to  $L$ .
  - ▶ **Remove**  $v$  from the tree.

# Counting Labeled Trees

**Thm 6.2.5** The number of labeled trees is  $n^{n-2}$ . (drumroll....)

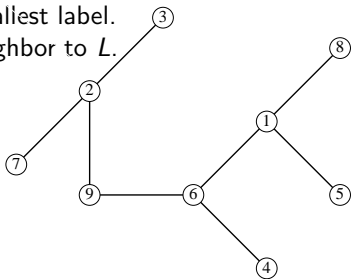
*Proof.* We will construct a bijection between:

$$f : \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\}.$$

Given a tree  $T$ , create a list  $L$  called its **Prüfer sequence**:

- ▶ Start with the empty list  $L = ()$ .
- ▶ Repeat the following steps **until the tree has only two vertices**:
  - ▶ **Find** the leaf  $v$  with the smallest label.
  - ▶ **Append** the label of  $v$ 's neighbor to  $L$ .
  - ▶ **Remove**  $v$  from the tree.

**Example.** The Prüfer sequence of this tree is  $(2, 6, 1, 2, 9, 1, 6)$ .



# Counting Labeled Trees

**Thm 6.2.5** The number of labeled trees is  $n^{n-2}$ . (drumroll....)

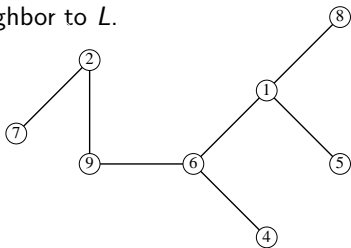
*Proof.* We will construct a bijection between:

$$f : \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\}.$$

Given a tree  $T$ , create a list  $L$  called its **Prüfer sequence**:

- ▶ Start with the empty list  $L = ()$ .
- ▶ Repeat the following steps **until the tree has only two vertices**:
  - ▶ **Find** the **leaf**  $v$  with the smallest label.
  - ▶ **Append** the label of  $v$ 's neighbor to  $L$ .
  - ▶ **Remove**  $v$  from the tree.

**Example.** The Prüfer sequence of this tree is  $(2, 6, 1, 2, 9, 1, 6)$ .



# Counting Labeled Trees

**Thm 6.2.5** The number of labeled trees is  $n^{n-2}$ . (drumroll....)

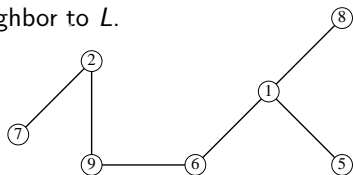
*Proof.* We will construct a bijection between:

$$f : \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\}.$$

Given a tree  $T$ , create a list  $L$  called its **Prüfer sequence**:

- ▶ Start with the empty list  $L = ()$ .
- ▶ Repeat the following steps **until the tree has only two vertices**:
  - ▶ **Find** the leaf  $v$  with the smallest label.
  - ▶ **Append** the label of  $v$ 's neighbor to  $L$ .
  - ▶ **Remove**  $v$  from the tree.

**Example.** The Prüfer sequence of this tree is  $(2, 6, 1, 2, 9, 1, 6)$ .



# Counting Labeled Trees

**Thm 6.2.5** The number of labeled trees is  $n^{n-2}$ . (drumroll....)

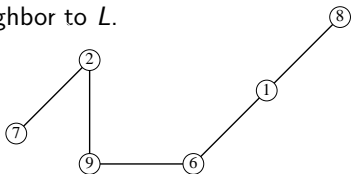
*Proof.* We will construct a bijection between:

$$f : \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\}.$$

Given a tree  $T$ , create a list  $L$  called its **Prüfer sequence**:

- ▶ Start with the empty list  $L = ()$ .
- ▶ Repeat the following steps **until the tree has only two vertices**:
  - ▶ **Find** the leaf  $v$  with the smallest label.
  - ▶ **Append** the label of  $v$ 's neighbor to  $L$ .
  - ▶ **Remove**  $v$  from the tree.

**Example.** The Prüfer sequence of this tree is  $(2, 6, 1, 2, 9, 1, 6)$ .





# Counting Labeled Trees

**Thm 6.2.5** The number of labeled trees is  $n^{n-2}$ . (drumroll....)

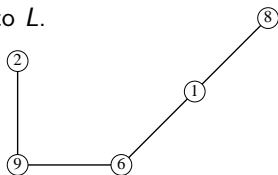
*Proof.* We will construct a bijection between:

$$f : \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\}.$$

Given a tree  $T$ , create a list  $L$  called its **Prüfer sequence**:

- ▶ Start with the empty list  $L = ()$ .
- ▶ Repeat the following steps **until the tree has only two vertices**:
  - ▶ **Find** the leaf  $v$  with the smallest label.
  - ▶ **Append** the label of  $v$ 's neighbor to  $L$ .
  - ▶ **Remove**  $v$  from the tree.

**Example.** The Prüfer sequence of this tree is  $(2, 6, 1, 2, 9, 1, 6)$ .



# Counting Labeled Trees

**Thm 6.2.5** The number of labeled trees is  $n^{n-2}$ . (drumroll....)

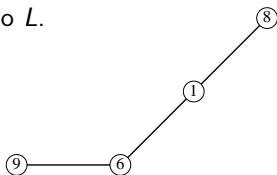
*Proof.* We will construct a bijection between:

$$f : \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\}.$$

Given a tree  $T$ , create a list  $L$  called its **Prüfer sequence**:

- ▶ Start with the empty list  $L = ()$ .
- ▶ Repeat the following steps **until the tree has only two vertices**:
  - ▶ **Find** the **leaf**  $v$  with the smallest label.
  - ▶ **Append** the label of  $v$ 's neighbor to  $L$ .
  - ▶ **Remove**  $v$  from the tree.

**Example.** The Prüfer sequence of this tree is  $(2, 6, 1, 2, 9, 1, 6)$ .



# Counting Labeled Trees

**Thm 6.2.5** The number of labeled trees is  $n^{n-2}$ . (drumroll....)

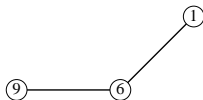
*Proof.* We will construct a bijection between:

$$f : \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\}.$$

Given a tree  $T$ , create a list  $L$  called its **Prüfer sequence**:

- ▶ Start with the empty list  $L = ()$ .
- ▶ Repeat the following steps **until the tree has only two vertices**:
  - ▶ **Find** the **leaf**  $v$  with the smallest label.
  - ▶ **Append** the label of  $v$ 's neighbor to  $L$ .
  - ▶ **Remove**  $v$  from the tree.

**Example.** The Prüfer sequence of this tree is  $(2, 6, 1, 2, 9, 1, 6)$ .



# Counting Labeled Trees

**Thm 6.2.5** The number of labeled trees is  $n^{n-2}$ . (drumroll....)

*Proof.* We will construct a bijection between:

$$f : \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\}.$$

Given a tree  $T$ , create a list  $L$  called its **Prüfer sequence**:

- ▶ Start with the empty list  $L = ()$ .
- ▶ Repeat the following steps **until the tree has only two vertices**:
  - ▶ **Find** the **leaf**  $v$  with the smallest label.
  - ▶ **Append** the label of  $v$ 's neighbor to  $L$ .
  - ▶ **Remove**  $v$  from the tree.

**Example.** The Prüfer sequence of this tree is  $(2, 6, 1, 2, 9, 1, 6)$ .



# Counting Labeled Trees

**Thm 6.2.5** The number of labeled trees is  $n^{n-2}$ . (drumroll....)

*Proof.* We will construct a bijection between:

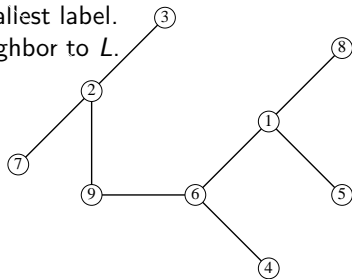
$$f : \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\}.$$

Given a tree  $T$ , create a list  $L$  called its **Prüfer sequence**:

- ▶ Start with the empty list  $L = ()$ .
- ▶ Repeat the following steps **until the tree has only two vertices**:
  - ▶ **Find** the **leaf**  $v$  with the smallest label.
  - ▶ **Append** the label of  $v$ 's neighbor to  $L$ .
  - ▶ **Remove**  $v$  from the tree.

**Example.** The Prüfer sequence of this tree is  $(2, 6, 1, 2, 9, 1, 6)$ .

★ This rule is well defined. ★



# Counting Labeled Trees

There is an inverse rule

$$g : \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\}.$$

## Counting Labeled Trees

There is an inverse rule

$$g : \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\}.$$

Given a list  $L$ , create a new list  $U$  (used vertices) and tree  $T$ :

# Counting Labeled Trees

There is an inverse rule

$$g : \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\}.$$

Given a list  $L$ , create a new list  $U$  (used vertices) and tree  $T$ :

- ▶ Start with the empty list  $U = ()$ .
- ▶ Repeat the following steps **until  $L$  is empty**:



# Counting Labeled Trees

There is an inverse rule

$$g : \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\}.$$

Given a list  $L$ , create a new list  $U$  (used vertices) and tree  $T$ :

- ▶ Start with the empty list  $U = ()$ .
- ▶ Repeat the following steps **until  $L$  is empty**:
  - ▶ **Find** the **least vertex  $u$**  on neither  $L$  nor  $U$

# Counting Labeled Trees

There is an inverse rule

$$g : \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\}.$$

Given a list  $L$ , create a new list  $U$  (used vertices) and tree  $T$ :

- ▶ Start with the empty list  $U = ()$ .
- ▶ Repeat the following steps **until  $L$  is empty**:
  - ▶ **Find** the **least vertex**  $u$  on neither  $L$  nor  $U$  –and–
  - Find** the **first vertex**  $l$  on list  $L$ .

# Counting Labeled Trees

There is an inverse rule

$$g : \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\}.$$

Given a list  $L$ , create a new list  $U$  (used vertices) and tree  $T$ :

- ▶ Start with the empty list  $U = ()$ .
- ▶ Repeat the following steps **until  $L$  is empty**:
  - ▶ **Find** the **least vertex**  $u$  on neither  $L$  nor  $U$  –and–  
**Find** the **first vertex**  $l$  on list  $L$ .
  - ▶ **Add** the edge  $(u, l)$  to  $T$ .

# Counting Labeled Trees

There is an inverse rule

$$g : \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\}.$$

Given a list  $L$ , create a new list  $U$  (used vertices) and tree  $T$ :

- ▶ Start with the empty list  $U = ()$ .
- ▶ Repeat the following steps **until  $L$  is empty**:
  - ▶ **Find** the **least vertex**  $u$  on neither  $L$  nor  $U$  –and–  
**Find** the **first vertex**  $l$  on list  $L$ .
  - ▶ **Add** the edge  $(u, l)$  to  $T$ .
  - ▶ **Add**  $u$  to the list  $U$  –and–  
**Remove**  $l$  from  $L$ .

# Counting Labeled Trees

There is an inverse rule

$$g : \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\}.$$

Given a list  $L$ , create a new list  $U$  (used vertices) and tree  $T$ :

- ▶ Start with the empty list  $U = ()$ .
- ▶ Repeat the following steps **until  $L$  is empty**:
  - ▶ **Find** the **least vertex**  $u$  on neither  $L$  nor  $U$  –and–  
**Find** the **first vertex**  $l$  on list  $L$ .
  - ▶ **Add** the edge  $(u, l)$  to  $T$ .
  - ▶ **Add**  $u$  to the list  $U$  –and–  
**Remove**  $l$  from  $L$ .
- ▶ Add edge between **vtx not in  $U$** .

# Counting Labeled Trees

There is an inverse rule

$$g : \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\}.$$

Given a list  $L$ , create a new list  $U$  (used vertices) and tree  $T$ :

- ▶ Start with the empty list  $U = ()$ .
- ▶ Repeat the following steps **until  $L$  is empty**:
  - ▶ **Find** the **least vertex**  $u$  on neither  $L$  nor  $U$  –and–  
**Find** the **first vertex**  $l$  on list  $L$ .
  - ▶ **Add** the edge  $(u, l)$  to  $T$ .
  - ▶ **Add**  $u$  to the list  $U$  –and–  
**Remove**  $l$  from  $L$ .
- ▶ Add edge between **vtx not in  $U$** .

**Example.** This method takes the Prüfer sequence  $(2, 6, 1, 2, 9, 1, 6)$  and returns our original  $T$ .

# Counting Labeled Trees

There is an inverse rule

$$g : \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\}.$$

Given a list  $L$ , create a new list  $U$  (used vertices) and tree  $T$ :

- ▶ Start with the empty list  $U = ()$ .
- ▶ Repeat the following steps **until  $L$  is empty**:
  - ▶ **Find** the **least vertex**  $u$  on neither  $L$  nor  $U$  –and–  
**Find** the **first vertex**  $l$  on list  $L$ . (2,6,1,2,9,1,6)    ()    (3,2)
  - ▶ **Add** the edge  $(u, l)$  to  $T$ .
  - ▶ **Add**  $u$  to the list  $U$  –and–  
**Remove**  $l$  from  $L$ .
- ▶ Add edge between **vtx not in  $U$** .

**Example.** This method takes the Prüfer sequence  $(2, 6, 1, 2, 9, 1, 6)$  and returns our original  $T$ .

# Counting Labeled Trees

There is an inverse rule

$$g : \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\}.$$

Given a list  $L$ , create a new list  $U$  (used vertices) and tree  $T$ :

- ▶ Start with the empty list  $U = ()$ .
- ▶ Repeat the following steps **until  $L$  is empty**:
  - ▶ **Find** the **least vertex**  $u$  on neither  $L$  nor  $U$  –and–  
**Find** the **first vertex**  $l$  on list  $L$ .
  - ▶ **Add** the edge  $(u, l)$  to  $T$ .
  - ▶ **Add**  $u$  to the list  $U$  –and–  
**Remove**  $l$  from  $L$ .
- ▶ Add edge between **vtx not in  $U$** .

$$\begin{array}{r} \hline (2,6,1,2,9,1,6) \quad () \quad (3,2) \\ \hline (6,1,2,9,1,6) \quad (3) \quad (4,6) \end{array}$$

**Example.** This method takes the Prüfer sequence  $(2, 6, 1, 2, 9, 1, 6)$  and returns our original  $T$ .



# Counting Labeled Trees

There is an inverse rule

$$g : \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\}.$$

Given a list  $L$ , create a new list  $U$  (used vertices) and tree  $T$ :

- ▶ Start with the empty list  $U = ()$ .
- ▶ Repeat the following steps **until  $L$  is empty**:
  - ▶ **Find** the **least vertex**  $u$  on neither  $L$  nor  $U$  –and–  
**Find** the **first vertex**  $l$  on list  $L$ .
  - ▶ **Add** the edge  $(u, l)$  to  $T$ .
  - ▶ **Add**  $u$  to the list  $U$  –and–  
**Remove**  $l$  from  $L$ .
- ▶ Add edge between **vtx not in  $U$** .

(2,6,1,2,9,1,6)	()	(3,2)
(6,1,2,9,1,6)	(3)	(4,6)
(1,2,9,1,6)	(3,4)	(5,1)

**Example.** This method takes the Prüfer sequence  $(2, 6, 1, 2, 9, 1, 6)$  and returns our original  $T$ .

# Counting Labeled Trees

There is an inverse rule

$$g : \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\}.$$

Given a list  $L$ , create a new list  $U$  (used vertices) and tree  $T$ :

- ▶ Start with the empty list  $U = ()$ .
- ▶ Repeat the following steps **until  $L$  is empty**:
  - ▶ **Find** the **least vertex**  $u$  on neither  $L$  nor  $U$  –and–  
**Find** the **first vertex**  $l$  on list  $L$ .
  - ▶ **Add** the edge  $(u, l)$  to  $T$ .
  - ▶ **Add**  $u$  to the list  $U$  –and–  
**Remove**  $l$  from  $L$ .
- ▶ Add edge between **vtx not in  $U$** .

(2,6,1,2,9,1,6)	()	(3,2)
(6,1,2,9,1,6)	(3)	(4,6)
(1,2,9,1,6)	(3,4)	(5,1)
(2,9,1,6)	(3,4,5)	(7,2)

**Example.** This method takes the Prüfer sequence  $(2, 6, 1, 2, 9, 1, 6)$  and returns our original  $T$ .

# Counting Labeled Trees

There is an inverse rule

$$g : \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\}.$$

Given a list  $L$ , create a new list  $U$  (used vertices) and tree  $T$ :

- ▶ Start with the empty list  $U = ()$ .
- ▶ Repeat the following steps **until  $L$  is empty**:
  - ▶ **Find** the **least vertex**  $u$  on neither  $L$  nor  $U$  –and–  
**Find** the **first vertex**  $l$  on list  $L$ .
  - ▶ **Add** the edge  $(u, l)$  to  $T$ .
  - ▶ **Add**  $u$  to the list  $U$  –and–  
**Remove**  $l$  from  $L$ .
- ▶ Add edge between **vtx not in  $U$** .

(2,6,1,2,9,1,6)	()	(3,2)
(6,1,2,9,1,6)	(3)	(4,6)
(1,2,9,1,6)	(3,4)	(5,1)
(2,9,1,6)	(3,4,5)	(7,2)
(9,1,6)	(3,4,5,7)	(2,9)

**Example.** This method takes the Prüfer sequence  $(2, 6, 1, 2, 9, 1, 6)$  and returns our original  $T$ .

# Counting Labeled Trees

There is an inverse rule

$$g : \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\}.$$

Given a list  $L$ , create a new list  $U$  (used vertices) and tree  $T$ :

- ▶ Start with the empty list  $U = ()$ .
- ▶ Repeat the following steps **until  $L$  is empty**:
  - ▶ **Find** the **least vertex**  $u$  on neither  $L$  nor  $U$  –and–  
**Find** the **first vertex**  $l$  on list  $L$ .
  - ▶ **Add** the edge  $(u, l)$  to  $T$ .
  - ▶ **Add**  $u$  to the list  $U$  –and–  
**Remove**  $l$  from  $L$ .
- ▶ Add edge between **vtx not in**  $U$ .

**Example.** This method takes the Prüfer sequence  $(2, 6, 1, 2, 9, 1, 6)$  and returns our original  $T$ .

(2,6,1,2,9,1,6)	()	(3,2)
(6,1,2,9,1,6)	(3)	(4,6)
(1,2,9,1,6)	(3,4)	(5,1)
(2,9,1,6)	(3,4,5)	(7,2)
(9,1,6)	(3,4,5,7)	(2,9)
(1,6)	(2,3,4,5,7)	(8,1)

# Counting Labeled Trees

There is an inverse rule

$$g : \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\}.$$

Given a list  $L$ , create a new list  $U$  (used vertices) and tree  $T$ :

- ▶ Start with the empty list  $U = ()$ .
- ▶ Repeat the following steps **until  $L$  is empty**:
  - ▶ **Find** the **least vertex**  $u$  on neither  $L$  nor  $U$  –and–  
**Find** the **first vertex**  $l$  on list  $L$ .
  - ▶ **Add** the edge  $(u, l)$  to  $T$ .
  - ▶ **Add**  $u$  to the list  $U$  –and–  
**Remove**  $l$  from  $L$ .
- ▶ Add edge between **vtx not in  $U$** .

**Example.** This method takes the Prüfer sequence  $(2, 6, 1, 2, 9, 1, 6)$  and returns our original  $T$ .

(2,6,1,2,9,1,6)	()	(3,2)
(6,1,2,9,1,6)	(3)	(4,6)
(1,2,9,1,6)	(3,4)	(5,1)
(2,9,1,6)	(3,4,5)	(7,2)
(9,1,6)	(3,4,5,7)	(2,9)
(1,6)	(2,3,4,5,7)	(8,1)
(6)	(2,3,4,5,7,8)	(1,6)

# Counting Labeled Trees

There is an inverse rule

$$g : \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\}.$$

Given a list  $L$ , create a new list  $U$  (used vertices) and tree  $T$ :

- ▶ Start with the empty list  $U = ()$ .
- ▶ Repeat the following steps **until  $L$  is empty**:
  - ▶ **Find** the **least vertex**  $u$  on neither  $L$  nor  $U$  –and–  
**Find** the **first vertex**  $l$  on list  $L$ .
  - ▶ **Add** the edge  $(u, l)$  to  $T$ .
  - ▶ **Add**  $u$  to the list  $U$  –and–  
**Remove**  $l$  from  $L$ .
- ▶ Add edge between **vtx not in**  $U$ .

**Example.** This method takes the Prüfer sequence  $(2, 6, 1, 2, 9, 1, 6)$  and returns our original  $T$ .

(2,6,1,2,9,1,6)	()	(3,2)
(6,1,2,9,1,6)	(3)	(4,6)
(1,2,9,1,6)	(3,4)	(5,1)
(2,9,1,6)	(3,4,5)	(7,2)
(9,1,6)	(3,4,5,7)	(2,9)
(1,6)	(2,3,4,5,7)	(8,1)
(6)	(2,3,4,5,7,8)	(1,6)
()	(1,2,3,4,5,7,8)	(6,9)

# Counting Labeled Trees

There is an inverse rule

$$g : \left\{ \begin{array}{l} \text{lists } L \text{ of length } (n-2) \\ \text{taken from } \{1, \dots, n\} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{labeled trees } T \\ \text{with } n \text{ vertices} \end{array} \right\}.$$

Given a list  $L$ , create a new list  $U$  (used vertices) and tree  $T$ :

- ▶ Start with the empty list  $U = ()$ .
- ▶ Repeat the following steps **until  $L$  is empty**:
  - ▶ **Find** the **least vertex  $u$**  on neither  $L$  nor  $U$  –and–  
**Find** the **first vertex  $l$**  on list  $L$ .
  - ▶ **Add** the edge  $(u, l)$  to  $T$ .
  - ▶ **Add**  $u$  to the list  $U$  –and–  
**Remove**  $l$  from  $L$ .
- ▶ Add edge between **vtx not in  $U$** .

**Example.** This method takes the Prüfer sequence  $(2, 6, 1, 2, 9, 1, 6)$  and returns our original  $T$ .

$(2, 6, 1, 2, 9, 1, 6)$	$()$	$(3, 2)$
$(6, 1, 2, 9, 1, 6)$	$(3)$	$(4, 6)$
$(1, 2, 9, 1, 6)$	$(3, 4)$	$(5, 1)$
$(2, 9, 1, 6)$	$(3, 4, 5)$	$(7, 2)$
$(9, 1, 6)$	$(3, 4, 5, 7)$	$(2, 9)$
$(1, 6)$	$(2, 3, 4, 5, 7)$	$(8, 1)$
$(6)$	$(2, 3, 4, 5, 7, 8)$	$(1, 6)$
$()$	$(1, 2, 3, 4, 5, 7, 8)$	$(6, 9)$

## Counting Binary Trees

*Definition:* A **binary tree** has a special vertex called its **root**. From this vertex at the top, the rest of the tree is drawn downward. Each vertex may have a **left child** and/or a **right child**.



## Counting Binary Trees

*Definition:* A **binary tree** has a special vertex called its **root**. From this vertex at the top, the rest of the tree is drawn downward. Each vertex may have a **left child** and/or a **right child**.

*Example.* The number of binary trees with 1, 2, 3 vertices is:

## Counting Binary Trees

*Definition:* A **binary tree** has a special vertex called its **root**. From this vertex at the top, the rest of the tree is drawn downward. Each vertex may have a **left child** and/or a **right child**.

*Example.* The number of binary trees with 1, 2, 3 vertices is:

*Example.* The number of binary trees with 4 vertices is:

## Counting Binary Trees

*Definition:* A **binary tree** has a special vertex called its **root**. From this vertex at the top, the rest of the tree is drawn downward. Each vertex may have a **left child** and/or a **right child**.

*Example.* The number of binary trees with 1, 2, 3 vertices is:

*Example.* The number of binary trees with 4 vertices is:

*Conjecture:* The number of binary trees on  $n$  vertices is \_\_\_\_\_.

## Counting Binary Trees

*Proof:* Every binary tree either:

- ▶ Has no vertices ( $x^0$ ) –or–
- ▶ Breaks down as one root vertex ( $x$ ) along with two binary trees beneath ( $B(x)^2$ ).

## Counting Binary Trees

*Proof:* Every binary tree either:

- ▶ Has no vertices ( $x^0$ ) —or—
- ▶ Breaks down as one root vertex ( $x$ )  
along with two binary trees beneath ( $B(x)^2$ ).

Therefore, the generating function for binary trees satisfies

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

## Counting Binary Trees

*Proof:* Every binary tree either:

- ▶ Has no vertices ( $x^0$ ) —or—
- ▶ Breaks down as one root vertex ( $x$ )  
along with two binary trees beneath ( $B(x)^2$ ).

Therefore, the generating function for binary trees satisfies

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

$$\text{We conclude } b_n = \frac{1}{n+1} \binom{2n}{n}.$$

## Counting Binary Trees

*Proof:* Every binary tree either:

- ▶ Has no vertices ( $x^0$ ) —or—
- ▶ Breaks down as one root vertex ( $x$ )  
along with two binary trees beneath ( $B(x)^2$ ).

Therefore, the generating function for binary trees satisfies

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

$$\text{We conclude } b_n = \frac{1}{n+1} \binom{2n}{n}. \quad \text{😊}$$

# Counting Binary Trees

*Proof:* Every binary tree either:

- ▶ Has no vertices ( $x^0$ ) —or—
- ▶ Breaks down as one root vertex ( $x$ )  
along with two binary trees beneath ( $B(x)^2$ ).

Therefore, the generating function for binary trees satisfies

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

$$\text{We conclude } b_n = \frac{1}{n+1} \binom{2n}{n}. \quad \text{😊}$$

**Another way:** Find a recurrence for  $b_n$ .



# Counting Binary Trees

*Proof:* Every binary tree either:

- ▶ Has no vertices ( $x^0$ ) —or—
- ▶ Breaks down as one root vertex ( $x$ )  
along with two binary trees beneath ( $B(x)^2$ ).

Therefore, the generating function for binary trees satisfies

$$B(x) = 1 + xB(x)^2. \quad \text{We conclude } b_n = \frac{1}{n+1} \binom{2n}{n}. \quad \text{😊}$$

**Another way:** Find a recurrence for  $b_n$ . Note:

$$b_4 = b_0b_3 + b_1b_2 + b_2b_1 + b_3b_0.$$

# Counting Binary Trees

*Proof:* Every binary tree either:

- ▶ Has no vertices ( $x^0$ ) —or—
- ▶ Breaks down as one root vertex ( $x$ )  
along with two binary trees beneath ( $B(x)^2$ ).

Therefore, the generating function for binary trees satisfies

$$B(x) = 1 + xB(x)^2. \quad \text{We conclude } b_n = \frac{1}{n+1} \binom{2n}{n}. \quad \text{😊}$$

**Another way:** Find a recurrence for  $b_n$ . Note:

$$b_4 = b_0b_3 + b_1b_2 + b_2b_1 + b_3b_0.$$

In general,  $b_n = \sum_{i=0}^{n-1} b_i b_{n-1-i}$ .

# Counting Binary Trees

*Proof:* Every binary tree either:

- ▶ Has no vertices ( $x^0$ ) —or—
- ▶ Breaks down as one root vertex ( $x$ )  
along with two binary trees beneath ( $B(x)^2$ ).

Therefore, the generating function for binary trees satisfies

$$B(x) = 1 + xB(x)^2. \quad \text{We conclude } b_n = \frac{1}{n+1} \binom{2n}{n}. \quad \text{😊}$$

**Another way:** Find a recurrence for  $b_n$ . Note:

$$b_4 = b_0b_3 + b_1b_2 + b_2b_1 + b_3b_0.$$

In general,  $b_n = \sum_{i=0}^{n-1} b_i b_{n-1-i}$ . Therefore,  $B(x)$  equals

$$1 + \sum_{n \geq 1} \left( \sum_{i=0}^{n-1} b_i b_{n-1-i} \right) x^n$$

# Counting Binary Trees

*Proof:* Every binary tree either:

- ▶ Has no vertices ( $x^0$ ) —or—
- ▶ Breaks down as one root vertex ( $x$ )  
along with two binary trees beneath ( $B(x)^2$ ).

Therefore, the generating function for binary trees satisfies

$$B(x) = 1 + xB(x)^2. \quad \text{We conclude } b_n = \frac{1}{n+1} \binom{2n}{n}. \quad \text{😊}$$

**Another way:** Find a recurrence for  $b_n$ . Note:

$$b_4 = b_0b_3 + b_1b_2 + b_2b_1 + b_3b_0.$$

In general,  $b_n = \sum_{i=0}^{n-1} b_i b_{n-1-i}$ . Therefore,  $B(x)$  equals

$$1 + \sum_{n \geq 1} \left( \sum_{i=0}^{n-1} b_i b_{n-1-i} \right) x^n = 1 + x \sum_{n \geq 1} \left( \sum_{i=0}^{n-1} b_i b_{n-1-i} \right) x^{n-1} =$$

# Counting Binary Trees

*Proof:* Every binary tree either:

- ▶ Has no vertices ( $x^0$ ) —or—
- ▶ Breaks down as one root vertex ( $x$ )  
along with two binary trees beneath ( $B(x)^2$ ).

Therefore, the generating function for binary trees satisfies

$$B(x) = 1 + xB(x)^2. \quad \text{We conclude } b_n = \frac{1}{n+1} \binom{2n}{n}. \quad \text{😊}$$

**Another way:** Find a recurrence for  $b_n$ . Note:

$$b_4 = b_0b_3 + b_1b_2 + b_2b_1 + b_3b_0.$$

In general,  $b_n = \sum_{i=0}^{n-1} b_i b_{n-1-i}$ . Therefore,  $B(x)$  equals

$$1 + \sum_{n \geq 1} \left( \sum_{i=0}^{n-1} b_i b_{n-1-i} \right) x^n = 1 + x \sum_{n \geq 1} \left( \sum_{i=0}^{n-1} b_i b_{n-1-i} \right) x^{n-1} =$$

$$1 + x \sum_{k \geq 0} \left( \sum_{i=0}^k b_i b_{k-i} \right) x^k =$$

# Counting Binary Trees

*Proof:* Every binary tree either:

- ▶ Has no vertices ( $x^0$ ) —or—
- ▶ Breaks down as one root vertex ( $x$ )  
along with two binary trees beneath ( $B(x)^2$ ).

Therefore, the generating function for binary trees satisfies

$$B(x) = 1 + xB(x)^2. \quad \text{We conclude } b_n = \frac{1}{n+1} \binom{2n}{n}. \quad \text{😊}$$

**Another way:** Find a recurrence for  $b_n$ . Note:

$$b_4 = b_0b_3 + b_1b_2 + b_2b_1 + b_3b_0.$$

In general,  $b_n = \sum_{i=0}^{n-1} b_i b_{n-1-i}$ . Therefore,  $B(x)$  equals

$$1 + \sum_{n \geq 1} \left( \sum_{i=0}^{n-1} b_i b_{n-1-i} \right) x^n = 1 + x \sum_{n \geq 1} \left( \sum_{i=0}^{n-1} b_i b_{n-1-i} \right) x^{n-1} =$$

$$1 + x \sum_{k \geq 0} \left( \sum_{i=0}^k b_i b_{k-i} \right) x^k = 1 + x \left( \sum_{k \geq 0} b_k x^k \right) \left( \sum_{k \geq 0} b_k x^k \right) = 1 + xB(x)^2.$$