Lec29 Trees and Rooted Trees Michael Monagan

April 7, 2021   11:14 AM

Lecture 29: Trees and Rooted Trees

Grimaldi 12.1, 12.2

Assignment #7 Solutions posted.
Assignment #8 is compulsory — worth 3% of course grade.
Will be posted "shortly". Due next Friday April 16th.

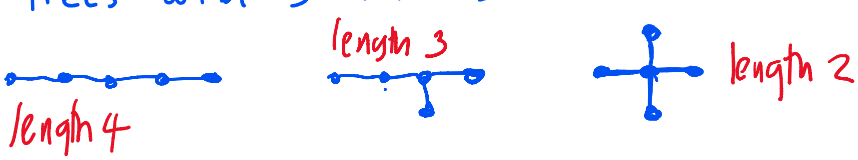
Definition (tree)

A multigraph G is a **tree** if G is connected and G does not contain a cycle.

Theorem (main properties of trees)

If $T = (V, E)$ is a tree then $|V| = |E| + 1$ and secondly, there is a unique path in T between every pair of vertices.

Examples Trees with 5 vertices



Removing any edge from a tree disconnects the tree.
Adding an edge to a tree creates a cycle.

Theorem (Characterization of Trees)

Let $G = (V, E)$ be a multigraph. The following statements are equivalent.

(1) *G is connected and has no cycle. (G is a tree)*

(2) *G is connected and $|V| = |E| + 1$.*

(3) *G has no cycle and $|V| = |E| + 1$.*

(4) *There is a unique path between every pair of vertices in G.*

Proof. We will prove $(1) \Rightarrow (2) \Rightarrow (3) \Rightarrow (1)$

We have proven $(1) \Rightarrow (4)$. Exercise $(4) \Rightarrow (1)$.

$(1) \Rightarrow (2)$ Given G is connected and G has no cycle. (G is a tree)

To prove: G is connected ✓ and $|V| = |E| + 1$. ✓ (last day)

$(2) \Rightarrow (3)$. Given G is connected and $|V| = |E| + 1$.

To prove G has no cycle and $|V| = |E| + 1$. ✓

Let's use induction on $n = |V|$. B

Base: $|V| = 1$. Using $|V| = |E| + 1 \Rightarrow |E| = 0$. $\Rightarrow G = \bullet$

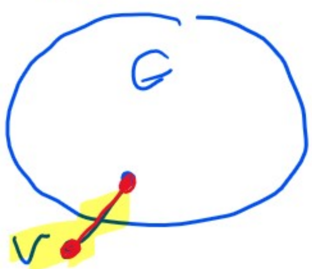
Clearly G has no cycle.

Proof (cont). Ind Step. $n = |V| > 1$.

Ind. Hyp. Assume $(2) \Rightarrow (3)$ holds for G with $|V| < n$.

If $|V| = |E| + 1$ a Lemma from last day said G has a vertex of degree 0 or ≥ 2 vertices of degree 1 (leaf vertices).

But $|V| > 1$ and G is connected. $\Rightarrow$ G has a leaf vertex v.



Observe $G - v$ is connected since G is connected.

G satisfies $|V| = |E| + 1$. Therefore in $G - v$

$|V| - 1 = |E| - 1 + 1$. Since $G - v$ has $n-1$ vertices.

by the Ind. Hyp. $G - v$ has no cycle.

This implies G has no cycle because v is a leaf.

$(3) \Rightarrow (1)$. G has no cycle and $|V| = |E| + 1$.

To prove G is connected? and G has no cycle ✓

Since G has no cycle it is a forest with $k \geq 1$ trees.

From last day $|V| = |E| + k$.

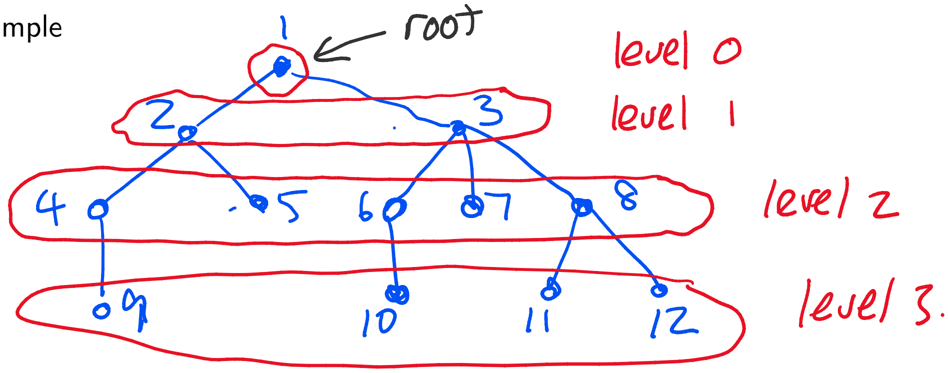
But $|V| = |E| + 1$.

Therefore $k = 1 \Rightarrow G$ has 1 tree $\Rightarrow G$ is connected.

Definition (rooted tree)

A **rooted tree** $T = (V, E)$ is a tree with a distinguished vertex called the **root**.
For every vertex $v \in V$ the **level** of v is the length of the path from v to the root.
Note: the root is the unique vertex at level 0.

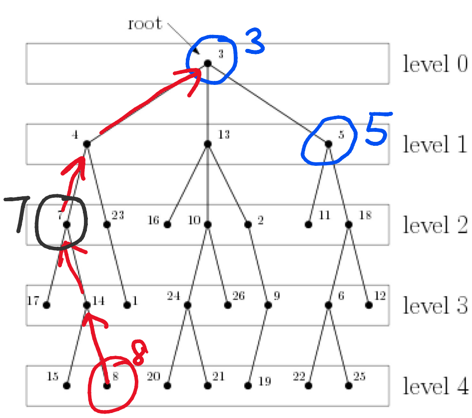
Example



Height 3.

Definition (rooted tree terminology)

- The **height** of a rooted tree is the maximum level of a vertex.
  A rooted tree consisting of just a root vertex has height 0.
- Every non-root vertex v at level i is adjacent to exactly one vertex u at level $i - 1$. We call u the **parent** of v and we say that v is a **child** of u.
- For every vertex v there is a walk "up the tree" to the root obtained by moving to the parent vertex at each step. If u is another vertex on this walk, we call u an **ancestor** of v and v a **descendant** of u.

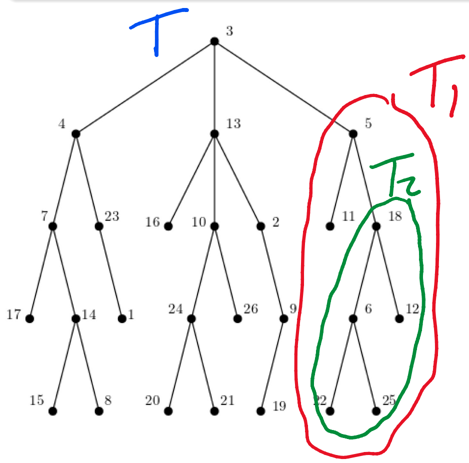


3 is the parent of vertex 5
5 is a child of vertex 3.
7 is an ancestor of vertex 8.
8 is a descent of vertext 7.

We are frequently interested in working with rooted trees recursively. Therefore, it will be helpful to think of a rooted tree as composed out of smaller rooted trees.

Definition (subtree)

Let v be a vertex of a rooted tree T with level i. Define T' to be the subgraph of T induced by v together with its descendants. Then T' forms a new rooted tree with root vertex v. We say that T' with root v is the **subtree** of T at v.



T1 is a subtree of T.
T2 is a subtree of T1.

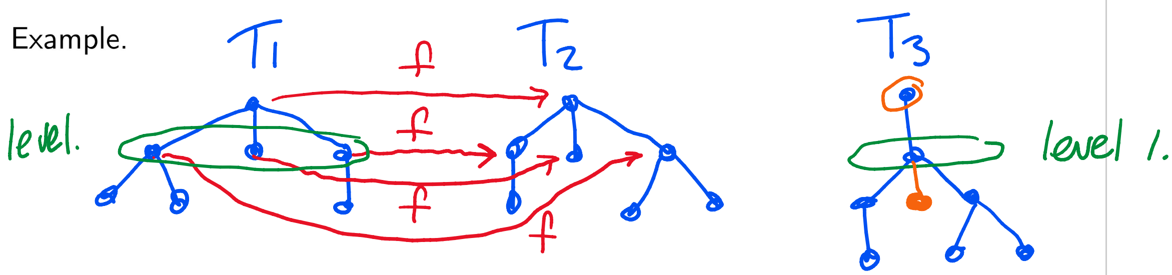
Definition (isomorphism of rooted trees)

Let T_1, T_2 be rooted trees with $T_i = (V_i, E_i)$ for $i = 1, 2$. We say that T_1 and T_2 are **isomorphic** if there exists a bijection $f : V_1 \to V_2$ satisfying:

(1) $\{f(u), f(v)\} \in E_2 \Leftrightarrow \{u, v\} \in E_1$

(2) For every $v \in V_1$ the level of v and $f(v)$ is the same.
In particular, f sends the root of T_1 to the root of T_2.

Example.



T1 is isomorphic to T2 as a rooted tree but not to T3 because the # of vertices at level 1 differs.
But T2 (hence also T1) is isomorphic to T3 as a tree.

Definition

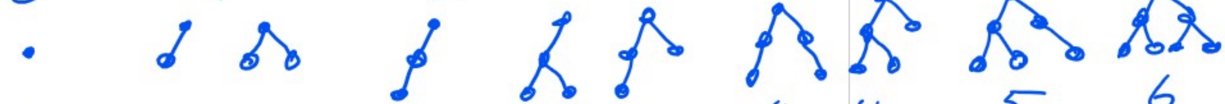
non-leaf vertex

A rooted tree is m-**ary** if every internal node has at most m children. A 2-ary tree is called **binary** tree. Every vertex has ≤ 2 children.

Exercise. Find all binary trees with height 0, 1, and 2 up to isomorphism.

Height 0 1 2

Trees.



#Edges 0 1 2 2 3 3 4 4 5 6

Let b_n denote the number of binary trees of height at most n. Find b_0, b_1, b_2.

$$b_0 = 1 \qquad b_1 = b_0 + 2 = 3 \qquad b_2 = b_1 + 7 = 10.$$

Use the recursive structure of rooted trees find a recurrence for b_n.

We will remove the root vertex which leaves at most two binary trees of less height.

CASE 0 children 1 child 2 children

In Case 1 there are b_{n-1} binary trees for C.

In Case 2 there are $\binom{b_{n-1}}{2}$ ways to choose two distinct binary trees of height $\leq n-1$ for A and B plus b_{n-1} ways to choose the same one for A and B.

Hence $b_0 = 1$, $b_n = \underset{\text{0 children}}{1} + \underset{\text{1 child}}{b_{n-1}} + \underbrace{\binom{b_{n-1}}{2} + b_{n-1}}_{\text{2 children}}$. for $n \geq 1$.

Check $b_2 = 1 + b_1 + \binom{b_1}{2} + b_1$
$= 1 + 3 + \binom{3}{2} + 3 = 1 + 3 + 3 + 3 = 10.$ ✓