

Discrete Mathematics in Computer Science

C3. Acyclicity

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C3.1 Acyclic (Di-) Graphs

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C3.1 Acyclic (Di-) Graphs

Acyclic

Similarly to connectedness, the presence or absence of **cycles** is an important practical property for (di-) graphs.

Definition (acyclic, forest, DAG)

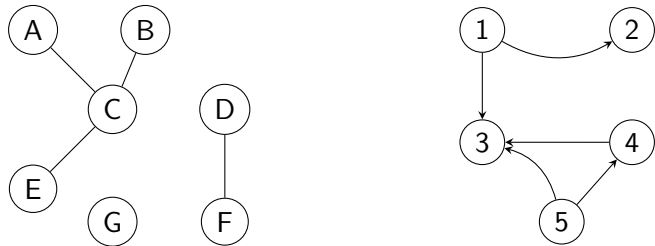
A graph or digraph G is called **acyclic** if there exists no cycle in G .

An acyclic graph is also called a **forest**.

An acyclic digraph is also called a **DAG** (directed acyclic graph).

German: azyklisch/kreisfrei, Wald, DAG

Acyclic (Di-) Graphs – Example



Trees

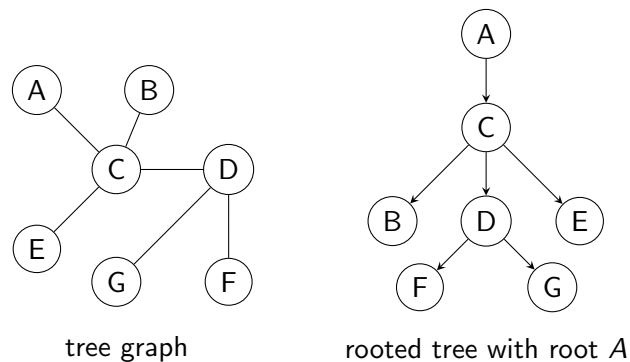
Definition (tree)

A connected forest is called a **tree**.

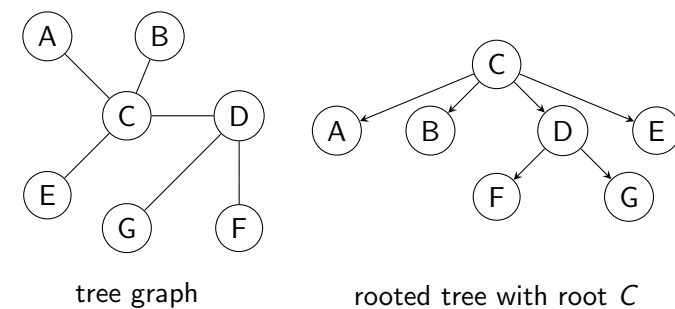
German: Baum

- ▶ **Tree** is also a word for a recursive data structure, which consists of either a **leaf** or a **parent node** with one or more **children**, which are themselves trees.
- ▶ This other kind of tree is also called a **rooted tree** to distinguish it from a tree as a graph.
- ▶ The two meanings of “tree” are distinct but closely related.

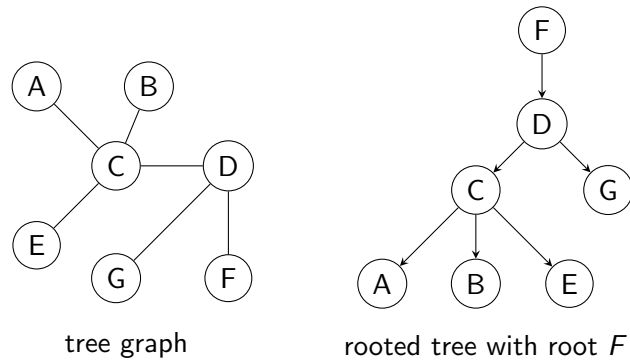
Tree Graphs vs. Rooted Trees – Example (1)



Tree Graphs vs. Rooted Trees – Example (2)



Tree Graphs vs. Rooted Trees – Example (3)



From Tree Graphs to Rooted Trees

General procedure for converting tree graphs into rooted trees:

- ▶ Select any vertex v . Make v the root of the tree.
- ▶ Initially, v is the only **pending** vertex, and there are no **processed** vertices.
- ▶ As long as there are pending vertices:
 - ▶ Select any pending vertex u .
 - ▶ Make all neighbours v of u that are not yet processed children of u and mark them as pending.
 - ▶ Change u from pending to processed.

We do not prove that this procedure always works. A proof of correctness can be given based on the results we show next.

C3.2 Unique Paths in Trees

Unique Paths in Trees

Theorem

Let $G = (V, E)$ be a graph.

Then G is a tree iff there exists exactly one path from any vertex $u \in V$ to any vertex $v \in V$.

Unique Paths In Trees – Proof (1)

Proof.

$(\Rightarrow)$: G is a tree. Let $u, v \in V$.

We must show that there exists exactly one path from u to v .

We know that at least one path exists because G is connected.

It remains to show that there cannot be two paths from u to v .

If $u = v$, there is only one path (the empty one).

(Any longer path would have to repeat a vertex.)

We assume that there exist two different paths from u to v ($u \neq v$) and derive a contradiction. ...

Unique Paths In Trees – Proof (2)

Proof (continued).

Let $\pi = \langle v_0, v_1, \dots, v_n \rangle$ and $\pi' = \langle v'_0, v'_1, \dots, v'_m \rangle$ be the two paths (with $v_0 = v'_0 = u$ and $v_n = v'_m = v$).

Let i be the smallest index with $v_i \neq v'_i$, which must exist because the two paths are different, and neither can be a prefix of the other (else v would be repeated in the longer path).

We have $i \geq 1$ because $v_0 = v'_0$.

Let $j \geq i$ be the smallest index such that $v_j = v'_k$ for some $k \geq i$.

Such an index must exist because $v_n = v'_m$.

Then $\langle v_{i-1}, \dots, v_{j-1}, v'_k, \dots, v'_{i-1} \rangle$ is a cycle, which contradicts the requirement that G is a tree. ...

Unique Paths In Trees – Proof (3)

Proof (continued).

$(\Leftarrow)$: For all $u, v \in V$, there exists exactly one path from u to v .

We must show that G is a tree, i.e., is connected and acyclic.

Because there exist paths from all u to all v , G is connected.

Proof by contradiction: assume that there exists a cycle in G ,

$\pi = \langle u, v_1, \dots, v_n, u \rangle$ with $n \geq 2$.

(Note that all cycles have length at least 3.)

From the definition of cycles, we have $v_1 \neq v_n$.

Then $\langle u, v_1 \rangle$ and $\langle u, v_n, \dots, v_1 \rangle$ are two different paths

from u to v_1 , contradicting that there exists exactly one path from every vertex to every vertex. Hence G must be acyclic. $\square$

C3.3 Leaves and Edge Counts in Trees and Forests

Leaves in Trees

Definition

Let $G = (V, E)$ be a tree.

A **leaf** of G is a vertex $v \in V$ with $\deg(v) \leq 1$.

Note: The case $\deg(v) = 0$ only occurs in single-vertex trees ($|V| = 1$). In trees with at least two vertices, vertices with degree 0 cannot exist because this would make the graph disconnected.

Theorem

Let $G = (V, E)$ be a tree with $|V| \geq 2$.
Then G has at least two leaves.

Leaves in Trees – Proof

Proof.

Let $\pi = \langle v_0, \dots, v_n \rangle$ be path in G with maximal length among all paths in G .

Because $|V| \geq 2$, we have $n \geq 1$ (else G would not be connected).

We show that vertex v_n has degree 1: v_{n-1} is a neighbour in G .

Assume that it were not the only neighbour of v_n in G , so u is another neighbour of v_n . Then:

- ▶ If u is not on the path, then $\langle v_0, \dots, v_n, u \rangle$ is a longer path: contradiction.
- ▶ If u is on the path, then $u = v_i$ for some $i \neq n$ and $i \neq n-1$. Then $\langle v_i, \dots, v_n, v_i \rangle$ is a cycle: contradiction.

By reversing π we can show $\deg(v_0) = 1$ in the same way. $\square$

Edges in Trees

Theorem

Let $G = (V, E)$ be a tree with $V \neq \emptyset$.
Then $|E| = |V| - 1$.

Edges in Trees – Proof (1)

Proof.

Proof by induction over $n = |V|$.

Induction base ($n = 1$):

Then G has 1 vertex and 0 edges.

We get $|E| = 0 = 1 - 1 = |V| - 1$.

Induction step ($n \rightarrow n+1$):

Let $G = (V, E)$ be a tree with $n+1$ vertices ($n \geq 1$).

From the previous result, G has a leaf u .

Let v be the only neighbour of u .

Let $e = \{u, v\}$ be the connecting edge. $\dots$

Edges in Trees – Proof (2)

Proof (continued).

Consider the graph $G' = (V', E')$
with $V' = V \setminus \{u\}$ and $E' = E \setminus \{e\}$.

- ▶ G' is acyclic: every cycle in G' would also be present in G (contradiction).
- ▶ G' is connected: for all vertices $w \neq u$ and $w' \neq u$, G has a path π from w to w' because G is connected. Path π cannot include u because u has only one neighbour, so traversing u requires repeating v . Hence π is also a path in G' .

Hence G' is a tree with n vertices, and we can apply the induction hypothesis, which gives $|E'| = |V'| - 1$.

It follows that

$$|E| = |E'| + 1 = (|V'| - 1) + 1 = (|V| - 1) - 1 + 1 = |V| - 1. \quad \square$$

Edges in Forests

Theorem

Let $G = (V, E)$ be a forest.

Let C be the set of connected components of G .

Then $|E| = |V| - |C|$.

This result generalizes the previous one.

Edges in Forests – Proof

Proof.

Let $C = \{C_1, \dots, C_k\}$.

For $1 \leq i \leq k$, let $G_i = (C_i, E_i)$ be G restricted to C_i , i.e., the graph whose vertices are C_i and whose edges are the edges $e \in E$ with $e \subseteq C_i$.

We have $|V| = \sum_{i=1}^k |C_i|$ because the connected components form a partition of V .

We have $|E| = \sum_{i=1}^k |E_i|$ because every edge belongs to exactly one connected component. (Note that there cannot be edges between different connected components.)

Every graph G_i is a tree with at least one vertex: it is connected because its vertices form a connected component, and it is acyclic because G is acyclic. This implies $|E_i| = |C_i| - 1$.

Putting this together, we get

$$|E| = \sum_{i=1}^k |E_i| = \sum_{i=1}^k (|C_i| - 1) = \sum_{i=1}^k |C_i| - k = |V| - |C|. \quad \square$$

C3.4 Characterizations of Trees

Characterizations of Trees

Theorem

Let $G = (V, E)$ be a graph with $V \neq \emptyset$.

The following statements are equivalent:

- ① G is a tree.
- ② G is acyclic and connected.
- ③ G is acyclic and $|E| = |V| - 1$.
- ④ G is connected and $|E| = |V| - 1$.
- ⑤ For all $u, v \in V$ there exists exactly one path from u to v .

Characterizations of Trees – Proof (1)

Reminder:

- (1) G is a tree.
- (2) G is acyclic and connected.
- (3) G is acyclic and $|E| = |V| - 1$.
- (4) G is connected and $|E| = |V| - 1$.
- (5) For all $u, v \in V$ there exists exactly one path from u to v .

Proof.

We know already:

- ▶ (1) and (2) are equivalent by definition of trees.
- ▶ We have shown that (1) and (5) are equivalent.
- ▶ We have shown that (1) implies (3) and (4).

We complete the proof by showing (3) $\Rightarrow$ (2) and (4) $\Rightarrow$ (2). ...

Characterizations of Trees – Proof (2)

Reminder:

- (2) G is acyclic and connected.
- (3) G is acyclic and $|E| = |V| - 1$.

Proof (continued).

(3) $\Rightarrow$ (2):

Because G is acyclic, it is a forest.

From the previous result, we have $|E| = |V| - |C|$,
where C are the connected components of G .

But we also know $|E| = |V| - 1$. This implies $|C| = 1$.

Hence G is connected and therefore a tree. ...

Characterizations of Trees – Proof (3)

Reminder:

- (2) G is acyclic and connected.
- (4) G is connected and $|E| = |V| - 1$.

Proof (continued).

(4) $\Rightarrow$ (2):

In graphs that are not acyclic, we can remove an edge without changing the connected components: if $\langle v_0, \dots, v_n, v_0 \rangle$ ($n \geq 2$) is a cycle, remove the edge $\{v_0, v_1\}$ from the graph.

Every walk using this edge can substitute $\langle v_1, \dots, v_n, v_0 \rangle$ (or the reverse path) for it.

Iteratively remove edges from G in this way while preserving connectedness until this is no longer possible. The resulting graph (V, E') is acyclic and connected and therefore a tree.

This implies $|E'| = |V| - 1$, but we also have $|E| = |V| - 1$.

This yields $|E| = |E'|$ and hence $E' = E$: the number of edges removable in this way must be 0. Hence G is already acyclic. $\square$