# CMPSCI 250: Introduction to Computation

Lecture #22: Graphs, Paths, and Trees
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# Graphs, Paths, and Trees

- Graph Definitions
- Paths and the Path Predicate
- Cycles, Directed and Undirected
- Forests and Trees
- The Unique Simple Path Theorem
- Rooted Trees
- A Theorem About Trees

# Graph Definitions

- A **graph** is a set of points called **nodes** or **vertices**, together with a set of **edges**.
- In an **undirected graph** each edge connects two different nodes.
- In a **directed graph** each edge (or **arc**) goes from some node to some node, possibly the same one.

# The Edge Predicate

- Two graphs are considered to be equal if their **edge predicates** are the same.
- The edge predicate E(x, y) takes two nodes x and y as arguments, and is true if there is an edge from x to y (or between x and y, in the case of an undirected graph).
- There are also **multigraphs**, which are allowed to have more than one edge with the same starting point and ending point.
- Graphs can be **labelled** by assigning some information to each node or edge.

# Paths and the Path Predicate

- A **path** in a graph is a sequence of edges, where the endpoint of each edge is the starting point of the next edge.
- We can have **undirected paths** in an undirected graph or **directed paths** in a directed graph.
- The **path predicate** $P(x, y)$ is true if and only if there is a path from node x to node y. We define the path predicate and the set of paths recursively.

# Clicker Question #1

- Which of the following statements is *false*?
- (a) The relation P is reflexive on any directed or undirected graph.
- (b) The relation P is transitive on any undirected graph.
- (c) The relation P is symmetric on any undirected graph.
- (d) The relation P is symmetric on any directed graph.

# Answer #1

- Which of the following statements is *false*?
- (a) The relation P is reflexive on any directed or undirected graph.
- (b) The relation P is transitive on any undirected graph.
- (c) The relation P is symmetric on any undirected graph.
- *(d) The relation P is symmetric on any directed graph.*

# More About Paths

- For any node x, P(x, x) is true and the **empty path** λ is a path from x to x.
- If α is a path from x to y, and there is an edge from y to z, then P(x, z) is true and β is a path from x to z, where β consists of α followed by the edge (y, z).
- Thus if P(x, y) and E(y, z) are both true, then P(x, z) is true.

# Transitivity of Paths

- It stands to reason that if there is a path α from node x to node y, and a path β from node y to node z, then there exists a path from node x to node z obtained by first taking α and then taking β.
- Proving this will take an induction on the second path β, using the recursive definition of paths.

# Proving Transitivity

- The base case is when β is an empty path. In this case α, which is a path from x to y, is also the desired path from x to z because y = z.
- For the inductive case, assume that β is made by adding an edge (w, z) to some path γ from y to w, and that the IH applies to γ. So there exists a path from x to w made from α and γ. By the definition of paths, we can add the edge (w, z) to this path and get the desired path from x to z.

# Cycles

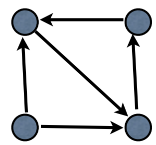
- A **cycle** is a path from a node to itself that meets certain “non-triviality” conditions.
- In an undirected graph, a cycle is a **simple** nonempty path from a node to itself, which means a path that does not reuse a node or edge.
- An undirected cycle must have three or more edges.

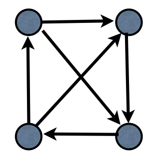
# Cycle Vocabulary

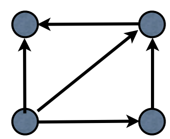
- A **directed cycle** in a directed graph is any nonempty directed path from a node to itself.
- A graph is **acyclic** if it has no cycles.
- A **directed acyclic graph** or **DAG** is a directed graph with no directed cycles.
- Acyclic undirected graphs (with no undirected cycles) are called **forests**.

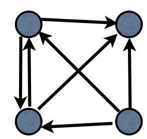
# Clicker Question #2

- Which of these directed graphs does *not* have a directed cycle?

(a) 

(b) 

(c) 

(d) 

# Answer #2

- Which of these directed graphs does *not* have a directed cycle?

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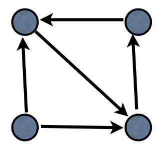

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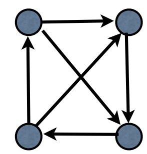

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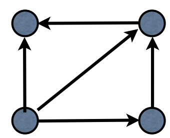

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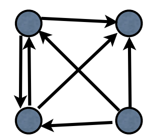


# Forests and Trees

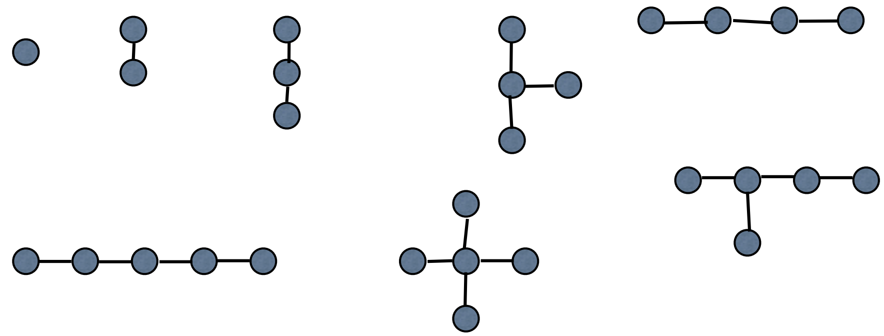
- Any undirected graph can be divided into **connected components**.
- It is easy to show that the path predicate in an *undirected graph* is an equivalence relation, and we define the connected components to be the equivalence classes of this relation.
- They are the maximal subgraphs that are connected -- a node's connected component is the subgraph formed by all the nodes to which it has a path.

# Forests and Trees

- An undirected graph with no cycles is called a **forest** because it is divided into one or more connected components called **trees**.
- A tree, in graph theory, is a **connected** undirected graph with no cycles. Remember that we can draw a graph with the nodes and edges anywhere, as long as the edges connect the correct nodes. So a graph-theoretic tree may or may not look like the other trees in computer science.

# Small Graph-Theoretic Trees

- Trees of one, two, or three nodes have only one shape per size.
- There are two shapes of four-node trees, and three shapes of five-node trees.



# Unique Simple Path Theorem

- **Theorem**: If x and y are nodes in a tree T, there is exactly one simple path in T from x to y. (Remember that a simple path is one that does not reuse a node or edge.)
- **Proof**: First, there must be at least one path because a tree is defined to be a connected graph, where every node has a path to every other node.

# Unique Simple Path Theorem

- Could there be two different simple paths $\alpha$ and $\beta$ from x to y? Suppose there were. Let z be the first node where the two paths split (z might be x). Let u be the next node after z on $\alpha$, and v be the next node after z on $\beta$. Note that z, u, and v are three different nodes.

# Unique Simple Path Theorem

- There must be some point w, at or after u on $\alpha$ and at or after v on $\beta$, that is on both paths. (Certainly y is such a point, but let w be the earliest one, which might be u or v.)
- Then there is a simple path from z to u to w to v to z, and since this path has at least three edges, it is a cycle. But T is a tree, so our assumption that there were two paths has led to a contradiction.

# Rooted Trees

- A **rooted tree** is a graph-theoretic tree with one of its nodes designated as the **root**. We can make a directed tree out of the undirected rooted tree by directing every edge away from the root.
- If we now draw such a tree with the root at the top, it looks like other "trees" we have seen in computer science.

# Rooted Tree Vocabulary

- If we call the root Level 0, we have its **children** at level 1, the nodes to which it now has directed edges. Level 1 nodes have children at Level 2, and so forth.
- The **depth** of a tree is its largest level number, which is the length of the longest directed path from the root.
- Nodes with no children are called **leaves**.

# Clicker Question #3

- Here are four undirected trees, each with a designated root node. If we make each into a rooted tree with that root, which has a depth of exactly 3?

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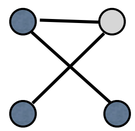

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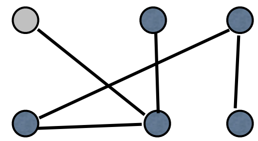

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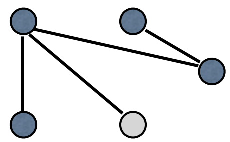

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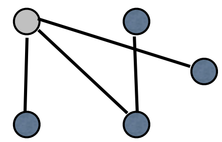

# Answer #3

- Here are four undirected trees, each with a designated root node. If we make each into a rooted tree with that root, which has a depth of exactly 3?

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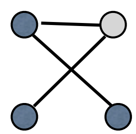

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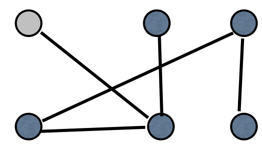

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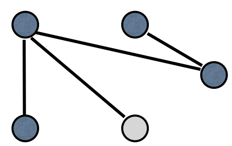

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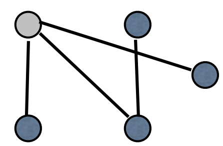
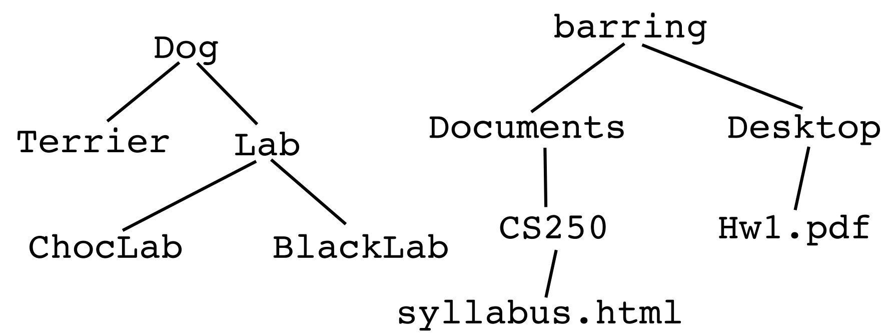


# Examples of Trees

- Such trees model many kinds of **hierarchies**, such as parts of an organization, inheritance of classes in Java, or the hierarchy of directories (folders) on a computer.



# A Recursive Tree Definition

- A single node, with no edges, is a rooted tree and the node is its root.
- We can make a rooted tree out of one or more existing rooted trees plus a new node x. The root of the new tree is x, and we add edges from x to the roots of each of the existing trees.
- The only possible rooted trees are those made by the two rules above.

# Induction on Rooted Trees

- This is a recursive definition of rooted trees.
- As with our other recursively defined types, we now have a new Law of Mathematical Induction for rooted trees.
- If we prove P(T) whenever T has only one node, and that P(T) is true when T is made from subtrees $U_1, U_2, \ldots, U_k$ and $P(U_i)$ is true for all i, then we may conclude that P(T) is true for any rooted tree T.

# A Theorem About Rooted Trees

- Let's use this induction rule to prove a theorem.
- **Theorem**: If T is any rooted tree with n nodes and e edges, then e = n - 1.
- Base Case: If T is a one-node tree, then e = 0 and n = 1 so e = n - 1 is true.
- Now we have to set up the inductive step.

# A Theorem About Rooted Trees

- Inductive Step: Let T be made by the second rule from $U_1$, $U_2$,..., $U_k$ and say that each of the $U_i$'s has $n_i$ nodes and $e_i$ edges, so that $e_i = n_i - 1$ by the IH.
- T has all the nodes and edges from all the subtrees, plus one new node (its root) and k new edges (one from its root to each of the existing roots).

# A Theorem About Rooted Trees

- So n, the number of nodes in T, is the sum of the $n_i$'s plus 1.
- And e, the number of edges in T, is the sum of the $e_i$'s plus k.
- The sum S of the $e_i$'s is the sum of the $n_i$'s minus k, so e = S + k and n = (S + k) + 1, and therefore = n - 1.
- We've completed the inductive step and thus proved our P(T) for all rooted trees T.