

Graph theory notes for Math 189, Fall 2022

Dr Holmes

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Much of this is actually in Levin, but I want to write things out in more or less the way I presented them, and there are some things I did which he does not do.

Definition: A *graph* is an ordered pair (V, E) , where V is a set and E is a collection of two element subsets of V .

If $G = (V, E)$ is a graph, we say that elements of V are *vertices* of (or in) G and elements of E are *edges* of (or in) G .

If a is a vertex and e is an edge in G , we say that a is incident on e and that e is incident on a (in G) just in case $a \in e$.

If a and b are vertices in G , we say that a and b are *adjacent* in G just in case $\{a, b\}$ is an edge in G .

If e and f are edges in G , we say that e and f are adjacent just in case they are distinct and share an element.

Observation: We work with pictures of graphs, in which vertices are represented by dots and edges are represented by curves drawn between the dots.

We say that a graph is *planar* just in case it has a picture (drawn on an ordinary plane surface) in which the curves representing edges do not cross each other. A planar graph is likely to have pictures in which the edges do cross each other: we would be likely to call these non-planar pictures of a planar graph. A graph is non-planar if *all* pictures of that graph are non-planar. We will show later in the course that certain graphs are non-planar.

Related ideas we won't usually talk about: $G = (V, E)$ is a directed graph if each element of E is an ordered pair of elements of V (edges can be pictured as arrows from one vertex to another).

$G = (V, E)$ is a multigraph if each element of E is a three-element set two elements of which belong to V (the third element serves as a label, making it possible to draw many edges between the same two vertices).

Either graphs or multigraphs can have the definition modified to allow loops (edges from a vertex to itself): edges are sets of no more than two vertices, or no more than two vertices plus a non-vertex for multigraphs. Directed graphs naturally allow loops.

Identity of graphs: Two graphs are *equal* if they are literally the same ordered pair of sets.

Note that one can draw multiple different looking pictures of the same graph: a kind of question I might ask is, are these two pictures of graphs pictures of equal graphs (or of the same graph, same question).

Graphs $G_1 = (V_1, E_1)$ and $G_2 = (V_2, E_2)$ are *isomorphic* iff there is a bijection $f : V_1 \rightarrow V_2$ (a one-to-one function from V_1 onto V_2) such that for every $a, b \in V_1$, $\{a, b\} \in E_1$ if and only if $\{f(a), f(b)\} \in E_2$.

If two graphs are isomorphic, they have the same structure. A picture of one can be turned into a picture of the other simply by relabelling the vertices (the process of relabelling is recorded in the function f).

G_1 and G_2 might be the same and there might be an isomorphism from G_1 to G_2 other than the identity map on the vertices of the graph (the graph might have some kind of symmetry).

You may be asked to find isomorphisms from one graph to another or argue that there cannot be one.

Notice that isomorphic graphs must have the same number of vertices.

Degree of a vertex in a graph; degree sequence: The degree of a vertex a in G is the number of edges incident in a (or the number of vertices adjacent to a).

The degree sequence of a graph is the list of degrees of its vertices in nonincreasing order.

Notice that isomorphic graphs clearly must have the same degree sequence.

The converse is not true: try to draw a pair of graphs which are not isomorphic and have the same degree sequence.

Walks: Let $G = (V, E)$ be a graph and let a and b be vertices in G . A walk from a to b of length $n - 1$ is a function w from $\{1, \dots, n\}$ to V , a finite sequence of vertices, in which $w(1)$, which we usually write w_1 , is a and $w(n)$, which we usually write w_n , is b , and each pair $\{w_i, w_{i+1}\}$ ($1 \leq i < n$) belongs to E .

We say that a walk w from a to b is a path if and only if for all i, j , if $w_i = w_j$ then $\{i, j\} = \{1, n\}$: the only way vertices can be repeated in the graph is if the walk starts and ends at the same vertex.

A walk visits $c \in V$ just in case there is i such that $w_i = c$, and it traverses edge $\{c, d\}$ just in case there is i such that $w_i = c$ and $w_{i+1} = d$.

A path which has its beginning and end the same we call a *cycle*. We also call a graph a cycle if there is a cycle in it which visits all of its vertices and traverses all of its edges.

Notice that for any vertex a there is a walk of length 0 from a to a , namely the function from $\{1\}$ to V sending 1 to a .

Theorem: If there is a walk from a to b in G , then there is a path from a to b in G .

Proof: If there is a walk from a to b in G , there must be a walk w of shortest length n from a to b .

Now suppose that $i < j$ and $w_i = w_j$. We define w'_k for $k \in \{1, n - (j - i)\}$ as w_k if $k \leq i$ and as $w_{k+(j-i)}$ otherwise. It is easy to verify that w' is a walk from a to b shorter than w , which is impossible. The definition just formalizes the idea of skipping everything in w between the identical w_i and w_j .

Definition (connected graph, 1): A graph G is *connected* just in case for each pair of vertices a, b there is a walk from a to b in G (equivalently, by previous theorem, just in case for each pair of vertices a, b there is a path from a to b in G).

Definition (connected graph, 2) : A graph $G = (V, E)$ is *disconnected* just in case there are disjoint nonempty sets A, B such that $A \cup B = V$ and for every $e \in E$, either $e \subseteq A$ or $e \subseteq B$ (i.e, there is no edge from a vertex in A to a vertex in B). A graph G is connected just in case it is not disconnected.

Temporary rule: We cannot define the same concept in two different ways without proving that the definitions are equivalent! For the moment, we call the concept defined by the first definition connected_1 and the concept defined by the second definition connected_2 .

This state of suspense will not last long.

Theorem: For any graph G , G is connected_1 if and only if it is connected_2 (so we can say just “connected”).

Proof: The proof falls into two parts, as is natural for the proof of an if and only if statement.

First we show that if G is connected_1 , it cannot be disconnected, and so must be connected_2 .

We do this by introducing a graph G arbitrarily, assuming that G is connected_1 , and further assuming that it is disconnected, and showing that a contradiction follows (remember that this is not an immediate contradiction, because disconnected means “not connected_2 ”).

Because we assume that $G = (V, E)$ is disconnected, we can choose disjoint nonempty sets A, B such that $A \cup B = V$ and there is no edge from an element of A to an element of B . Choose $a \in A$ and $b \in B$ (we can do this because A, B are not empty).

Since G is connected_1 , we can choose a walk w from a to b . Notice that $w_1 \in A$ and w_n is in B .

We use the well-ordering principle for a snappy proof here. Let S be the set of all j such that $w_j \in B$. S is nonempty since it contains n and bounded below (by 1) so it has a smallest element s . $s > 1$ since $w_1 \notin B$, so w_{s-1} is defined. Now there is an edge from w_{s-1} to w_s . $w_s \in B$ because $s \in S$, $s - 1 < s$ is not in S because s is the smallest element of S . So $w_{s-1} \notin B$. But this means $w_{s-1} \in A$. But this is a contradiction: we cannot have an edge from an element w_{s-1} of A to an element w_s of B .

Now we get to the second part of the proof: we need to show that if a graph G is connected₂ it must be connected₁.

We introduce a graph G arbitrarily and suppose that G is connected₂. We suppose for the sake of argument that it is not connected₁ and show that a contradiction follows.

Since $G = (V, E)$ is not connected₁, we can choose vertices $a, b \in G$ such that there is no walk from a to b .

Now we define A as the set of all vertices c in G such that there is a walk from a to c . We define B as $V - A$. Note that A is nonempty because $a \in A$, B is nonempty because $b \in B$ and $A \cup B$ is clearly V .

We claim that there cannot be a path from any $c \in A$ to any $d \in B$, which shows that G is disconnected, which is a contradiction. Let $c \in A$, $d \in B$, and w be a walk from c to d . There is a smallest i such that $w_i \in B$ by the well-ordering principle, and $i > 1$ because $w_1 = c \notin B$. Thus w_{i-1} exists, and $w_{i-1} \in A$ because $i - 1$ is less than the smallest index i of a vertex visited by the walk which is in B . Thus there is a walk w' from a to $w_{i-1} = w'_j$. But then $w' \cup \{(j + 1, w_i)\}$ is a walk from a to w_i (just tack w_i onto the walk w') so $w_i \in A$, and this contradicts the choice of w_i as the first vertex visited by the walk which is in B and so not in A .

Now we talk about trees.

Definition: A tree is a graph which is nonempty and contains no cycles.

Theorem: A graph G is a tree if and only if for any pair of vertices a, b in G there is exactly one path from a to b ,

Proof: We show that if G is any graph and there is more than one path from a to b , vertices in G , then there is a cycle in G , and so G is not a tree.

Suppose u and v are distinct paths from a to b , $u_1 = v_1 = a$; $u_m = v_n = b$. Let i be the smallest integer such that $u_i \neq v_i$ (there must be such an integer because the paths are different). Now find the first u_j with $j > i - 1$ such that $u_j = v_k$ for some k . There is one because $u_m = v_n = b$. Observe that u_j (and so v_k) is different from all u_s with $s < i$, because this is a path, so in fact $k \geq i$. We define w_I as w_{i-2+I}

for $I \leq j - (i - 2)$ (in other words, follow u from u_{i-1} to u_j) then $w_I = v_{k-(I-(j-(i-2)))}$ for $j - (i - 2) < I < (j - (i - 2)) + (k - (i - 2))$ [the exact indexing here might be off]: the idea is to have a sequence of the u_s 's starting at u_{i-1} and ending at u_j , then a sequence of v_s 's starting at v_k and going down to $v_{i-1} = u_{i-1}$. This is a cycle.

Now if G is a tree, there is a walk and thus a path from a given a to a given b because a tree is connected, and only one such path because if there were two such paths there would be a cycle in G .

Suppose G is a graph in which there is a unique path from any given vertex a to any other given vertex b . G is then connected because there is a path, and so a walk, from each vertex to each other and it contains no cycle because for any two distinct vertices in a cycle (and any cycle has at least 3 vertices and so does contain two distinct vertices) there are obviously two paths from each to the other (going in opposite directions around the cycle).

The theorem is proved.

Theorem: A tree with at least two vertices, and finitely many vertices, has at least two vertices of degree one.

The book doesn't note the requirement that the graph be finite.

Proof: Since the tree has finitely many vertices, there is a longest path in the tree. Let p be this path, from $a = p_1$ to $b = p_n$. We claim that both a and b are of degree one.

Suppose b is of degree greater than one. Then there is an edge from b to p_{n-1} and also an edge from b to some other vertex c . c cannot be any p_i , because this would create a cycle. But this means that the path $p \cup \{(n+1, c)\}$, tagging c onto the end of p after b , is a path longer than p , which is impossible.

A very similar argument, tacking on another vertex at the beginning of the path p , shows that a cannot be of degree greater than 1.

Theorem: A tree $G = (V, E)$ which is finite and has at least one vertex satisfies $|E| = |V| - 1$.

Proof: We prove this by induction on $|V|$. If $|V| = 1$, the graph has one vertex and no edges, so $|E| = 0 = 1 - 1 = |V| - 1$,

Now suppose that the theorem is true for all graphs with k vertices. Let G be a graph with $k + 1$ vertices. G has at least one vertex of degree 1, which we call v_0 , which belongs to a single edge $\{v_0, v_1\}$.

Consider $G- = (V - \{v_0\}, E - \{\{v_0, v_1\}\})$. This is a graph: we removed a single vertex and also removed all edges containing it.

It is a tree. If it contained a cycle, G would contain a cycle, and G is a tree. The unique path in G from any element a to any element b of $G-$ will not go through v_0 , because v_0 can only appear in a path in G as an endpoint. So the path in G from a to b is also a path in $G-$, so $G-$ is connected (because this works for any pair of vertices there), so $G-$ is a tree.

Now $G-$ has k vertices, so by ind hyp it contains $k - 1$ edges. That means that G contains $k + 1$ vertices and k edges, and the theorem is proved ($|E| = k = (k + 1) - 1 = |V| - 1$).

Definition: If $G = (V, E)$ is a connected graph, we say that $T = (V, E')$ is a spanning tree for G iff $E' \subseteq E$. A spanning tree for G has the same vertices as G and all of its edges are edges in G .

Theorem: Any connected graph has a spanning tree.

Proof: It is obvious that a graph which is not connected cannot have a spanning tree.

We argue by induction on the number of edges that a connected graph must have a spanning tree.

A connected graph with 2 or fewer edges cannot contain a cycle (which must contain at least three edges) so it is its own spanning tree.

Suppose all graphs with k edges which are connected have spanning trees. Let G be a graph with $k + 1$ edges. If it does not contain a cycle, it is a tree and is its own spanning tree. If it does contain a cycle, choose one edge from the cycle to delete. If a walk from vertex a to vertex b went through the deleted edge, there is still a walk from a to b , because the deleted edge can be replaced by the rest of the cycle. So the graph with the edge deleted is a connected graph with k edges, by ind hyp has a spanning tree, which will also be a spanning tree for G .

Notice that it follows from this theorem that a connected graph with $k > 0$ vertices must have at least $k - 1$ edges, because deleting some

number of them gives a tree with k vertices which has exactly $k - 1$ edges.