## Solutions to In-Class Problems Week 5, Mon.

**Problem 1.** There is a party. Some people shake hands an even number of times and some shake an odd number of times. Show that an even number of people shake hands an odd number of times.

**Solution.** We can represent the party by a graph. (Yeah, right.) Each person is represented by a vertex. If two people shake hands, then there is an edge between the corresponding vertices. This reduces the problem to the following theorem:

**Theorem 1.1.** *In every graph, there are an even number of vertices of odd degree.* 

*Proof.* Partitioning the vertices into those of even degree and those of odd degree, we know

$$\sum_{v \in V} d(v) \ = \sum_{d(v) \text{ is odd}} d(v) \ + \ \sum_{d(v) \text{ is even}} d(v)$$

The value of the lefthand side of this equation is even, and the second summand on the righthand side is even since it is entirely a sum of even values. So the first summand on the righthand side must also be even. But since it is entirely a sum of odd values, it must must contain an even number of terms. That is, there must be an even number of vertices with odd degree.

**Problem 2.** Define a *halfgraph* to be a graph with 2n vertices, all of degree exactly n, for some  $n \ge 1$ . Can a halfgraph have more than one connected component? If so, draw an example. If not, explain why.

**Solution.** No. If the graph has two or more connected components, then some connected component must have *n* or fewer vertices. (Otherwise, there would be more than 2n vertices in all.) Each vertex in this component can have degree at most n - 1.

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**Problem 3.** A set, *M*, of vertices of a graph is a *maximal connected* set if every pair of vertices in the set are connected, and any set of vertices properly containing *M* will contain two vertices that are not connected.

(a) What are the maximal connected subsets of the following (unconnected) graph?



**Solution.** There are three maximal subsets, each one equal to the vertices of one of the connected components of the graph.

(b) Explain the connection between maximal connected sets and connected components.

**Solution.** They are the same.

## (c) Prove it.

**Solution.** We first show that a connected component is a maximal set. A connected component consists of *all* the vertices connected to some vertex v. A larger set of vertices would, by definition, contain both v and a vertex, w, that is not in the connected component. This means that w is not connected to v, and therefore the larger set is not connected. So a connected component is maximal.

Conversely, suppose we have a maximal connected set, M. Since M connected, any vertex, v, in M is connected to all the other vertices in M. If there was any vertex, w, connected to v, that was not in M, then  $M \cup \{w\}$  would be connected and properly contain M, contradicting the maximality of M. So M consists of exactly the vertices connected to v, proving that it is a connected component.

**Problem 4.** (a) Describe a connected graph such that every vertex is on a simple cycle, but the graph is not 2-connected.

**Solution.** Two cycles connected by an edge.

(b) Prove that a graph is 2-connected iff it is connected and every edge is traversed by a simple cycle.

**Solution.** To prove the iff from left to right, we assume some edge, v-w, is not traversed by any simple cycle and then show that the graph is not 2-connected.

Now if there was a simple path between v and w that did not traverse this edge, then this path together with the edge, would be a simple cycle that traversed the edge. So every simple path from w to v must traverse this edge. So if this edge is removed, no simple path will connect v and w, which implies that no path whatsoever connects them. This proves the graph is not 2-connected.

Conversely, suppose the graph is connected but not 2-connected. We will show that edge is not on a simple cycle.

Since the graph is connected but not 2-connected, there must be a "cut' edge v-w whose removal leaves a disconnected graph. Now if there was a simple cycle that traversed this edge, then the cycle minus this edge would be a simple path, P, between v and w that did not traverse the edge. So any path connecting two points that traversed this edge could be replaced by a path containing P in place of the edge. Therefore, all edges that were connected before the edge was removed would still be connected after it is removed. So since the original graph was connected, it remains connected after the edge is removed. This would imply the graph was 2-connected, a contradiction. So there cannot be a simple cycle that traverses a cut edge.

Problem 5. How many spanning trees does the following graph have?



**Solution.** There are a **lot** of possible spanning trees: David wrote a computer program to solve the problem and found a total of 115 spanning trees.

So we didn't expect any teams to completely solve this problem. However, we did expect teams to start generating spanning trees and also to consider how to determine when they had them all.

There are efficient algorithms for counting spanning trees in arbitrary graphs, but they typically involve complex procedures like computing matrix determinants, which is tricky to do efficiently. For this particular problem, a more straighforward approach is to use a combination of brute force and case analysis, which is feasible, if tedious, to work out by hand.