Graph Isomorphism

Definition. Two simple graphs $G$ and $H$ are isomorphic $G \cong H$ if there is a vertex bijection $V_G \rightarrow V_H$ that preserves adjacency and non-adjacency structures.

Cayley's Formula

The number of labeled trees on $n$ nodes is $n^{n-2}$.

Put another way, it counts the number of spanning trees of a complete graph $K_n$.

We proved it by finding a bijection between the set of Prüfer sequences and the set of labeled trees.

Planar Graphs

Theorem: In any connected planar graph with $V$ vertices, $E$ edges and $F$ faces, then

$$V - E + F = 2$$

Theorem: In any connected planar graph with at least 3 vertices:

$$E \leq 3V - 6$$

Lemma: In any connected planar graph with at least 3 vertices:

$$3F \leq 2E$$

Is $K_5$ planar?

$K_5$ has 5 vertices and 10 edges, thus

$$E = 10 \leq 3 \times 5 - 6 = 9$$

which is false, therefore $K_5$ is not planar.

Outline

Bipartite Graphs
Kuratowski Theorem
Graph Coloring
Bipartite Matching
Bipartite Graphs

A graph is bipartite if the vertices can be partitioned into two sets $V_1$ and $V_2$ such that all edges go only between $V_1$ and $V_2$ (no edges go from $V_1$ to $V_1$ or from $V_2$ to $V_2$).

The complete bipartite graphs $K_{m,n}$ have the property that two vertices are adjacent if and only if they do not belong together in the bipartition subsets.

Is $K_{3,3}$ planar?

Theorem: In any connected planar graph with at least 3 vertices:

$$E \leq 3V - 6$$

$K_{3,3}$ has 5 vertices and 9 edges, thus

$$E = 9 \leq 3 \times 6 - 6 = 12$$

Not conclusive!

Is $K_{3,3}$ planar?

$$\Sigma(\text{edge, face}) \leq 2E$$, since each edge is associated with at most 2 faces

$$\Sigma(\text{edge, face}) \geq 4F$$, since graph contains no simple triangle regions of 3 edges.

It follows, that

$$4F \leq 2E$$

and for $K_{3,3}$ we have

$$4F \leq 18$$

From Euler's theorem: $V - E + F = 2$

$$F = 2 + 9 - 6 = 5$$.

Contradiction!

Planar Bipartite Graphs

The previous example established two simple criteria for testing whether a given planar graph is bipartite.

Theorem: In any bipartite planar graph with at least 3 vertices:

$$E \leq 2V - 4$$

Lemma: In any bipartite planar graph with at least 3 vertices:

$$4F \leq 2E$$

Kuratowski Theorem (1930)

Theorem. A graph is planar if and only if it contains no subgraph isomorphic to a subdivision of $K_5$ or $K_{3,3}$.

For any graph on $V$ vertices there are efficient algorithms for checking if the graph is planar. The best one runs in linear time $O(V)$

Subdivision and Contraction

Definition. Subdividing an edge means inserting a new vertex (of degree two) into this edge.

Petersen graph
**Theorem.** A graph is planar if and only if it contains no subgraph isomorphic to a subdivision of $K_5$ or $K_{3,3}$.

The Petersen graph

Remove B to get a subgraph

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**Theorem.** A graph is planar if and only if it contains no subgraph isomorphic to a subdivision of $K_5$ or $K_{3,3}$.

Subdivision and Contraction

**Definition.** Subdividing an edge means inserting a new vertex (of degree two) into this edge.

**Definition.** An edge contraction is an operation which removes an edge from a graph while simultaneously merging the two vertices it used to connect.

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**Wagner Theorem**

**Theorem.** Graph $G$ is planar if and only if it contains no subgraph that can be contracted to one of the two Kuratowski subgraphs.

Is the Petersen graph planar?

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**Coloring Planar Graphs**

A coloring of a graph is an assignment of a color to each vertex such that no neighboring vertices have the same color.
Theorem: Any simple planar graph can be colored with 6 colors.

Proof. (by induction on the number of vertices).

If \( G \) has six or less vertices, then the result is obvious. Suppose that all such graphs with \( V-1 \) vertices are 6-colorable.

Remove a vertex of degree less than 6, use IH.

Put it back, since it has at most 5 adjacent vertices, we have enough colors. QED

Theorem: Every simple planar graph has a vertex of degree at most 5.

Proof. \( \sum \text{deg}(v_k) = 2E \leq 2 (3V - 6) \)

Average degree: \( \frac{1}{V} \sum \text{deg}(v_k) \leq 6 - 12/V < 6 \)

Thus, there exists a vertex of degree at most 5.

Theorem: Any simple planar graph can be colored with less than or equal to 5 colors.

Graph Coloring

Proof (repeat the 6-colors proof)

Pick a vertex \( v \) of degree 5. Label the vertices adjacent to \( v \) as \( x_1, x_2, x_3, x_4 \) and \( x_5 \).

Assume that \( x_4 \) and \( x_5 \) are not adjacent to each other.

Why we can assume this?

If they all adjacent, we get \( K_5 \).

Remove edges \( (v, x_1), (v, x_2) \) and \( (v, x_3) \).

Contract edges \( (v, x_4), (v, x_5) \). Vertices \( v, x_4, x_5 \) will be replaced by \( y \), so neighbors of \( v, x_4, x_5 \) will be neighbors of \( y \).

We obtain a new graph \( H \) with two less vertices.

By IH the graph \( H \) can be colored with 5 colors.

Next, we assign \( y \)-color to \( x_4 \) and \( x_5 \)

We give \( v \) a color different from all colors used on the four vertices \( x_1, x_2, x_3 \) and \( y \). QED

4 Color Theorem (1976)

Theorem: Any simple planar graph can be colored with less than or equal to 4 colors.

It was proven in 1976 by K. Appel and W. Haken. They used a special-purpose computer program.

Since that time computer scientists have been working on developing a formal program proof of correctness. The idea is to write code that describes not only what the machine should do, but also why it should be doing it.

In 2005 such a proof has been developed by Gonthier, using the Coq proof system.

Bipartite Matching

A graph is bipartite if the vertices can be partitioned into two disjoint (also called independent) sets \( V_1 \) and \( V_2 \) such that all edges go only between \( V_1 \) and \( V_2 \) (no edges go from \( V_1 \) to \( V_1 \) or from \( V_2 \) to \( V_2 \))

Personnel Problem. You are the boss of a company. The company has \( M \) workers and \( N \) jobs. Each worker is qualified to do some jobs, but not others. How will you assign jobs to each worker?
Bipartite Graphs

Theorem. A graph is bipartite iff it does not have an odd length cycle.

Proof. \( \implies \)
If it's bipartite and has a cycle, its length must be even.

Proof. \( \impliedby \)
Fix a vertex \( v \). Define two sets of vertices
\( A = \{ w \in V \mid \text{even length shortest path from } v \text{ to } w \} \)
\( B = \{ w \in V \mid \text{odd length shortest path from } v \text{ to } w \} \)
If \( x \) and \( y \) from \( A \), they cannot be adjacent. By contradiction. There will be an odd length cycle. The same argument for \( B \). These sets provide a bipartition.

Is a tree always a bipartite graph?

Bipartite Matching

Definition. A subset of edges is a matching if no two edges have a common vertex (mutually disjoint).

Definition. A maximum matching is a matching with the largest possible number of edges.

Bipartite Matching

Definition. A perfect matching is a matching in which each node has exactly one edge incident on it.

A perfect matching is like a bijection, which requires that \( |V_1| = |V_2| \) and in which case its inverse is also a bijection.

Hall's (marriage) Theorem

Theorem. (without proof)
Let \( G \) be bipartite with \( V_1 \) and \( V_2 \).
For any set \( S \subseteq V_1 \), let \( N(S) \) denote the set of vertices adjacent to vertices in \( S \).

Then, \( G \) has a perfect matching if and only if
\( |S| \leq |N(S)| \)
for every \( S \subseteq V_1 \).
Alternating Path
A matching $M$ has some matched and some unmatched vertices. $(y_1,x_2),(y_3,x_4)$
Alternating path has edges alternating between $M$ and $E - M$. Path $x_1, y_1, x_2, y_3, x_4$ is alternating.
An alternating path is augmenting if both of its endpoints are free vertices.
Path $x_1, y_1, x_2, y_3, x_4, y_4$ is augmenting.

Augmenting Matching
If a matching $M$ (in green) has an augmenting path, then we get a larger matching by swapping the edges on the augmenting path.

Hungarian Algorithm
The algorithm starts with any matching and constructs a tree via a breadth-first search to find an augmenting path.
If the search succeeds, then it yields a matching having one more edge than the original.
Then we search again (it most it happens is $V/2$) for a new augmenting path.
If the search is unsuccessful, then the algorithm terminates and must be the largest-size matching that exists.

What is the runtime complexity of the Hungarian algorithm?
Complexity of BFS - $O(V+E)$
We run it $V/2$ times
This, the runtime is $O(VE)$.

Proof of Correctness
The algorithm clearly terminates, since we match one vertex per step.
Suppose that there were another matching $M_1$ that used more edges than $M$.
Overlap $M$ and $M_1$ - the result is a union of cycles and paths.
There is a path that have more $M_1$ edges than from $M$.
This path is an augmenting path. Contradiction.

Rook Attack
This problem asks us to place a maximum number of rooks (they move horizontally and vertically) on a chessboard with some squares cut out (forbidden positions)
Rook Attack
This problem asks us to place a maximum number of rooks on a chessboard with some squares cut out.

The number of non-attacking rooks equals the number of edges in a matching.

Planar Graphs
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Bipartite Matching

Here's What You Need to Know...