CS 105: DIC on Discrete Structures

Graph theory

Applications of Hall's theorem

Lecture 36
Oct 28 2024

Last Topic: Graph theory

Basic definitions and concepts

- Basics: graphs, paths, cycles, walks, trails, ...
- Cliques and independent sets.
- Graph representations, isomorphisms and automorphisms.
- Matchings: perfect, maximal and maximum.

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1. Eulerian graphs: Using degrees of vertices.
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4. Maximum matchings: Using augmenting paths.
5. Perfect matchings in bipartite graphs: Using neighbour sets. – Hall's theorem

Recap: Matchings

Definitions

- Matching: set of edges with no shared end-points.
- The vertices incident to edges in a matching are called saturated. Others are unsaturated.
- Perfect matching: saturates every vertex in graph.
- Maximum matching: matching of maximum size (# edges).
- Maximal matching: cannot be enlarged by adding an edge.

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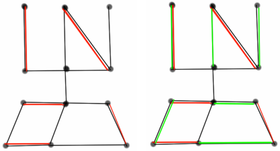

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Theorem

A matching M in G is a maximum matching iff G has no M-augmenting path.

Recap: Perfect matchings in bipartite graphs

Theorem (Hall'35)

A bipartite graph G with bipartitions X, Y has a matching that saturates X iff for all $S \subseteq X$, $|N(S)| \geq |S|$.

- For $v \in V$, its neighbour-set $N(v) = \{u \in V \mid (u, v) \in E\}$.
- For $S \subseteq V$, $N(S) = \{u \in V \mid (u, v) \in E \text{ for some } v \in S\}$.

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Proof: ($\implies$) is straightforward:

- Let M be a matching.
- Then for any $S \subseteq X$, each vertex of S is matched to a distinct vertex in $N(S)$
- So $|N(S)| \geq |S|$.

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- If G does not have any matching that saturates X, then surely any maximum matching of G does not saturate X.
- Let M be such a maximum matching. Then, we will construct $S \subseteq X$ s.t. $|N(S)| < |S|$.

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Proof: ($\Longleftarrow$) Thus, starting from a maximum matching M which does not saturate X, we construct $S \subseteq X, |N(S)| < |S|$.

- Let $u \in X$ be any unsaturated vertex of M.

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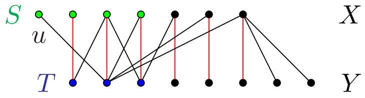

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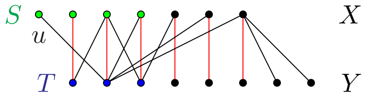

Claim: M matches T with $S \setminus \{u\}$ and $|N(S)| = |T|$.

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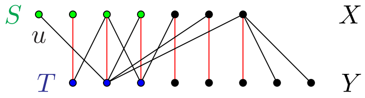

Claim: M matches T with $S \setminus \{u\}$ and $|N(S)| = |T|$.

- Every vertex of $S \setminus \{u\}$ has an edge in M to a vertex in T.

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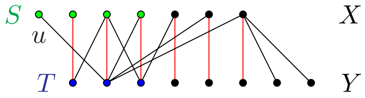

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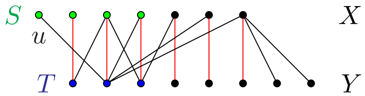

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- Every vertex of $S \setminus \{u\}$ has an edge in M to a vertex in T.
- Every vertex of T extends via M to a unique vertex of S.
- Thus, there is a bijection between T and $S \setminus \{u\}$.

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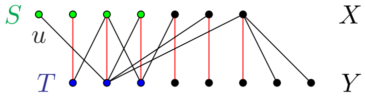

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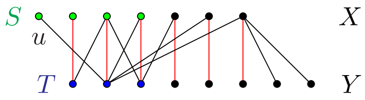

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- $T \subseteq N(S)$ (from T any M-alternating path will reach S).
- Conversely, if $v \in S$ has edge to $y \in Y \setminus T$, then path from u to v via M to y is an M-alternating path, implies $y \in T$.

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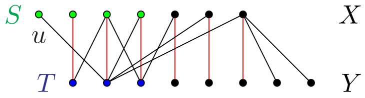

Claim: M matches T with $S \setminus \{u\}$ and $|N(S)| = |T|$.
Thus, $|N(S)| = |T| = |S| - 1 < |S|$ $\square$.

Applications of Hall's condition

Theorem (Hall'35)

A bipartite graph G with bipartitions X, Y has a matching that saturates X iff for all $S \subseteq X$, $|N(S)| \geq |S|$.

Application 1: The Marriage Theorem (1917)

- In a group of n women and n men, if every woman is compatible with k men and every man compatible with k women, then a perfect matching must exist!
- What is the formal statement?

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- For $k > 0$, every k-regular bipartite graph (i.e, every vertex has degree exactly k) has a perfect matching. Ex. Prove this!

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- If G is a k-regular X, Y bipartite graph, then $|X| = |Y|$. (why?)

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- Can you now verify Hall's condition?

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Let's play a game

A two player game on a graph

1. Given a graph G, two players will alternatively choose distinct vertices.
2. One player starts by choosing any vertex.
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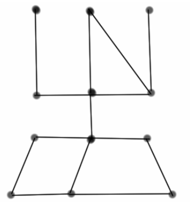

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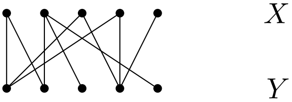

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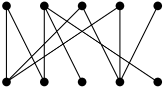
Appl2: Theorem (H.W: Qn 3.1.18 from Douglas West)

If G has a perfect matching, then player 2 has a winning strategy; otherwise, player 1 has a winning strategy.

Application 3: Another game

Consider the graph of a road network in a city. When a minister is visiting, the Chief of Police wants to place a policeman to watch every road. What is the minimum number of policemen required?



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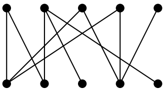

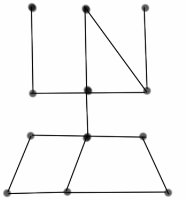

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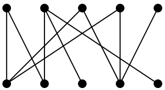

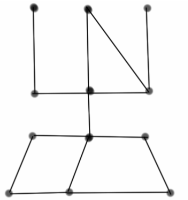

Definition

A vertex cover of a graph G is a set $Q \subseteq V$ that contains at least one endpoint of every edge. Vertices in Q are said to cover E.

Matchings and vertex covers

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Questions

1. What is the size of the minimum vertex cover in K_m, $K_{m,n}$?
2. If ℓ is size of maximum matching and k is size of vertex cover,
   2.1 how are ℓ, k related?
   2.2 Give an example of a graph where $k \neq \ell$

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So, how do you compute min no. of policemen required, i.e., the size of the minimum vertex covers?
Let's consider bipartite graphs...

A min-max theorem

Theorem (Konig '31, Egervary '31)

If G is a bipartite graph, then the size of the maximum matching of G equals the size of the minimum vertex cover of G.

A min-max theorem

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Proof.

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- Together this forms the desired matching (since H, H' are disjoint).

□