Graph Theory

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Chapter 1

Introduction

1.1 Definitions

A **graph** $G = (V, E)$ is a set V of *vertices* and a set E of unordered pairs of distinct vertices, called *edges*. Write vw or $\{v, w\}$ for the edge joining v and w, and say that v and w are **neighbours** or that they are *adjacent*.

In these notes, unless otherwise stated, graphs are:

- **finite**: $|V| \in \mathbb{N}$.
- **labelled**: vertices are distinguishable, usually $V = [n] := \{1, 2, \ldots, n\}$ for some $n \in \mathbb{N}$.
- **undirected**: edges are *unordered* pairs of vertices.
- **simple**: no loops $\{v, v\}$ or multiple edges (since E is not a multiset).

A graph G with vertex set $\{v_1, \ldots, v_n\}$ has **adjacency matrix** $A(G) = (a_{ij})$ where

$$a_{ij} = \begin{cases} 1 & \text{if } v_i v_j \in E, \\ 0 & \text{otherwise.} \end{cases}$$

$A(G)$ is a **symmetric** $n \times n$ 0-1 matrix with zero diagonal.

The **trivial graph** has at most one vertex. Hence it has no edges.

A **subgraph** of a graph $G = (V, E)$ is a graph $H = (W, F)$ such that $W \subseteq V$ and $F \subseteq E$.

We say that H is an **induced subgraph** if for all $v, w \in W$ if $vw \in E(G)$ then $vw \in E(H)$. Write $H = G[W]$, and say that H is the subgraph of G *induced by* the vertex set W.
The number of **vertices** of G, written $|G| = |V(G)|$, is called the *order* of G. The number of **edges** of G, sometimes written $||G|| = |E(G)|$, is called the *size* of G.

Two graphs $G = (V, E)$ and $H = (W, F)$ are **isomorphic** if there exists a *bijection* $\phi : V \to W$ such that $\phi(v)\phi(w) \in F$ if and only if $vw \in E$. The map ϕ is called a *graph isomorphism* or *isomorphism*.

1.2 The Degree of a Vertex

If $v \in e$ where v is a vertex and e is an edge, then we say that e is *incident with* v. The **degree** $d_G(v)$ of vertex v in a graph G is the number of *edges* of G which are *incident with* v. A vertex of degree 0 is an *isolated vertex.*

Let $N_G(v)$ be the set of all **neighbours** of v in G, then $d(v) = |N(v)|$.

Lemma 1.2.1 (The Handshaking Lemma)**.** In any graph, $G = (V, E)$,

$$\sum_{v \in V} d(v) = 2|E|.$$

Let $\delta(G) = \min_{v \in V} d(v)$ be the minimum degree in G, and $\Delta(G) = \max_{v \in V} d(v)$ be the maximum degree in G.

1.2.1 Some Special Graphs

A graph is k**-partite** if there exists a partition of its vertex set

$$V = V_1 \cup V_2 \cup \cdots V_k$$

into k nonempty disjoint subsets (parts) such that there are no edges between vertices in the same part.

The **complete graph** on r vertices, denoted K_r, has all $\binom{r}{2}$ edges present. The **complete bipartite graph** K_r, s has r vertices in one part of the vertex bipartition, s vertices in the other, and all rs present.

A graph is **regular** if every vertex has the same degree. If every vertex of a graph has degree d then we say that the graph is d-regular.

The **complement** of a graph G is the graph $\bar{G} = (V, \bar{E})$ where $vw \in \bar{E}$ if and only if $vw \notin E$. Note that $\bar{K_n}$ is the graph with n vertices and no edges.

If $G = (V, E)$ and $X \subset V$ then $G - X$ denotes the graph obtained from G by deleting all vertices in X and all edges which are incident with vertices in X. If $F \subseteq E$ then $G - F$ denotes the graph $(V, E - F)$ obtained from G by deleting the edges in F.

1.3 Paths and Cycles

A **walk** in the graph G is a sequence of vertices $v_0 v_1 v_2 \cdots v_k$ such that $v_i v_{i+1} \in E$ for $i = 0, 1, \ldots, k-1$. The **length** of this walk is k. The walk is **closed** if $v_0 = v_k$.

An **Euler tour** is a *closed walk* in a graph which uses every edge precisely once. A graph is Eulerian if it has an Euler tour.

Theorem 1.3.1 (Euler, 1736)**.** A connected graph is Eulerian if and only if every vertex has even degree.

A walk is a **path** if it does not visit any vertex more than once. A path is a sequence of *disinct* vertices, with subsequence vertices joined by an edge. A path $v_0 v_1 \ldots v_k$ with k edges is called a k-path and has length k.

If $k \geq 3$ and $P = v_0 v_1 \cdots v_{k-1}$ is a path of length $k-1$ then $C = P + v_0 v_{k-1}$ is a **cycle** of length k, also called a $k-cycle$. It is a closed walk which visits no internal vertex more than once.

An edge which joins two vertices of a cycle C, but which is not an edge of C, is called a **chord**. An **induced cycle** is a cycle which has no chords.

Proposition 1.3.2. Every graph G contains a path of length $\delta(G)$ and a cycle of length at least $\delta(G)+1$, if $\delta(G) \geq 2$.

Proof. Let $P = x_0 x_1 \ldots x_k$ be the longest path in G. By maximality of P, all neighbours of x_k lie on P. Hence $\delta(G) \leq d(x_k) \leq k = |\{x_0, x_1, \ldots, x_{k-1}\}|$, which proves the first statement. Let x_i be the smallest-indexed neighbour of x_k in P. Then $C = x_k x_i x_{i+1} \ldots x_{k-1} x_k$ is a cycle of length $\geq \delta(G)+1$ because C contains $d(x_k) \geq \delta(G)$ neighbours of x_k as well as x_k. □

The *minimum length* of a cycle in G is the **girth** of G, denoted by $g(G)$.

Given $x, y \in V$, let $d_G(x,y)$ be the length of a shortest path from x to y in G, called the **distance** from x to y in G. Set $d_G(x,y) = \infty$ if no such path exists.

We say that G is **connected** if $d_G(x,y)$ is finite for all $x, y \in V$.

Let the **diameter** of G be $\operatorname{diam}(G) = \max_{x,y \in V} d_G(x,y)$.

Proposition 1.3.3. Every graph G which contains a cycle satisfies $g(G) \leq 2\operatorname{diam}(G) + 1$.

Proof. Let C be a shortst cycle in G, so $|C| = g(G)$. For a contradiction, assume $g(G) \geq 2\operatorname{diam}(G) + 2$.

Choose vertices x, y on C with $d_C(x,y) \geq \operatorname{diam}(G)+1$. In G the distance $d_G(x,y)$ is strictly smaller, so any shortest path P from x to y in G is not a subgraph of C. But using P together with the shorter arc of C from x to y gives a closed walk of length $< |C|$. This closed walk contains a shorter cycle than C which is a contradiction. □

1.4 Connectivity

A maximal connected subgraph of G is called a **component** (or **connected component**) of G.

Proposition 1.4.1. The vertices of a connected graph can be labelled $v_1, v_2, \ldots, v_n$ such that $G_n = G$ and $G_i = G[v_1, \ldots, v_i]$ is connected for all i.

Proof. Choose v_1 arbitrarily. Now suppose that we have labelled $v_1, \ldots, v_i$ such that $G_j = G[v_1, \ldots, v_j]$ is connected for all $j = 1, \ldots, i$.

If $i < n$ then $G_i \neq G$, so there exists some $v_j \in \{v_1, \ldots, v_i\}$ with a $w \notin \{v_1, \ldots, v_i\}$ in G. (Otherwise $G_i \neq G$ is a component of G, impossible as G is connected.) Let $v_{i+1} = w$, then $G_{i+1} = G[v_1, \ldots, v_i]$ is connected. This completes the proof, by induction. □

Let $A, B \subseteq V$ be sets of vertices. An **(A, B)-path** in G is a path $P = x_0x_1 \cdots x_k$ such that

$$P \cap A = \{x_0\}, \quad P \cap B = \{x_k\}.$$

Let $A, B \subseteq V$ and let $X \subseteq V \cup E$ be a set of vertices and edges. We say that X **separates** A and B in G if every $(A, B)-$path in G contains a vertex or edge from X.
Note that we do not assume that A and B are disjoint and if X separates A and B then $A \cap B \subseteq X$.
We say that X **separates** two vertices a, b if $a, b \notin X$ and X separates the sets $\{a\}, \{b\}$.

More generally, we say that X *separates* G, and call X a **separating set** for G, if X separates two vertices of G. That is, X separates G if there exist distinct vertices $a, b \notin X$ such that X separates a and b.

If $X = \{x\}$ is a separating set for G, where $x \in V$, then we say that x is a **cut vertex**.

If $e \in E$ and $G - e$ has more components than G then e is a **bridge**.

The unordered pair (A, B) is a **separation** of G if $A \cup B = V$ and G has no edge between $A - B$ and $B - A$. The second conditions says that $A \cap B$ separates A from B in G. If both $A - B$ and $B - A$ are nonempty then the separation is **proper**. The order of the separation is $|A \cap B|$.

Definition. Let $k \in \mathbb{N}$. The graph G is **k-connected** if $|G| > k$ and $G - X$ is connected for all subsets $X \subseteq V$ with $|X| < k$.

The **connectivity** $\kappa(G)$ of G is defined by

$$\kappa(G) = \max\{k : G \text{ is } k\text{-connected}\}.$$

So, $\kappa(G) = 0$ iff G is trivial or G is disconnected. Also, $\kappa(K_n) = n - 1$ for all positive integers n.

Definition. Let $\ell \in \mathbb{N}$ and let G be a graph with $|G| \geq 2$. If $G - F$ is connected for all $F \subseteq E$ with $|F| < \ell$ then G is **ℓ-edge-connected**.

The **edge connectivity** $\lambda(G)$ is defined by

$$\lambda(G) = \max\{\ell : G \text{ is } \ell\text{-edge-connected}\}.$$

Proposition 1.4.2. If $|G| \geq 2$ then $\kappa(G) \leq \lambda(G) \leq \delta(G)$.

Theorem 1.4.3 (Mader, 1973)**.** Let k be a positive integer. Every graph G with average degree at least $4k$ has a $(k + 1)$-connected subgraph H with

$$\frac{|E(H)|}{|V(H)|} > \frac{|E(G)|}{|V(G)|} - k.$$

Proof. We write $|G|$ instead of $|V(G)|$. Let $\gamma = \frac{|E(G)|}{|G|} \geq 2k$. Consider subgraphs G' of G which satisfy:

$$|G'| \geq 2k \quad \text{and} \quad |E(G')| > \gamma(|G'| - k). \tag{1.1}$$

such graphs G' exists as G satisfies 1.1. (Average degree of G is $\frac{2|E(G)|}{|G|} \geq 4k$, so

$|G| \geq 4k$ and $\gamma(|G|-k) = |E(G)|\frac{(|G|-k)}{|G|} < |E(G)|$.)

Now let H be a subgraph of G of smallest order which satisfies 1.1. We continue the proof by proving three claims.

Claim 1. If G' satisfies 1.1 then $|G'| > 2k$.
Proof. If G' satisfies 1.1 and $|G'| = 2k$ then $|E(G')| > \gamma(|G'|-k) \geq 2k^2 > \binom{|G'|}{2}$, contradiction.

Claim 2. $S(H) > \gamma$.
Proof. For a contradiction, suppose that $S(H) \leq \gamma$. Let G' be obtained from H by deleting a vertex of degree $\leq \gamma$. Then $|G'| < |H|$ and G' satisfies 1.1, which is a contradiction. To see this, check:

$$\begin{aligned} |G'| = |H| - 1 &\geq 2k, \quad \text{by Claim 1, and} \\ |E(G')| \geq |E(H)| - \gamma &> \gamma(|H|-k-1), \quad \text{as } H \text{ satisfies 1.1} \\ &= \gamma(|G'|-k). \end{aligned}$$

Hence $S(H) > \gamma$. It follows that $|H| \geq \gamma$. Thus,

$$\frac{|E(H)|}{|H|} > \frac{\gamma(|H|-k)}{|H|}. \qquad \text{(as } H \text{ satisfies 1.1)}$$

Claim 3. H is $(k+1)$-connected.
Proof. By Claim 1, $|H| \geq 2k+1 \geq k+2$ as $k \geq 1$. So H is large enough. For a contradiction, suppose that H is not $(k+1)$-connected. Then H has a proper separation $\{U_1, U_2\}$ of order at most k.

Let $H_i = H[U_i]$ for $i = 1, 2$. Since any vertex $v \in U_1 - U_2$ has $d_H(v) \geq S(H) > \gamma$ (by Claim 2), and all neighbours of v in H belong to H_1, we have $|H_1| \geq \gamma \geq 2k$. Similarly, $|H_2| \geq 2k$. By minimality of H, neither H_1 nor H_2 satisfies 1.1. Hence $|E(H_i)| \leq \gamma(|H_i|-k)$ for $i = 1, 2$. But then

$$\begin{aligned} |E(H)| &\leq |E(H_1)| + |E(H_2)| \\ &\leq \gamma(|H_1| + |H_2| - 2k) \\ &\leq \gamma(|H| - k), \qquad \text{(by inclusion-exclusion)} \end{aligned}$$

since $|U_1 \cup U_2| \leq k$. This contradicts 1.1 for H. So H is $(k+1)$-connected, completing the proof of Claim 3 and of the theorem. □

1.5 Trees and Forests

A graph with no cycles is a **forest** (also called an acyclic graph). A connected graph with no cycles is a **tree**.

Theorem 1.5.1. The following are equivalent for a graph T:

(i) T is a tree;

(ii) Any two vertices of T are linked by a *unique* path in T;

(iii) T is *minimally connected*: that is, T is connected but $T - e$ is disconnected for every $e \in E(T)$;

(iv) T is *maximally acyclic*: that is, T is acyclic but $T + xy$ has a cycle for any two nonadjacent vertices x, y in T.

Corollary 1.5.2. If G is connected then G has a spanning tree.

Proof. Let be a connected graph and let H be a minimal connected spanning subgraph of G. (Note H exists as G is a connected spanning subgraph of itself.) By theorem 1.5.1, H is a tree. □

Corollary 1.5.3. The vertices of a tree can be labelled as $v_1, \ldots, v_n$ so that for $i \geq 2$, vertex v_i has a unique neighbour in $\{v_1, \ldots, v_{i-1}\}$.

Proof. We use the labelling from Proposition 1.4.1. This labels the vertices of a given tree G as $v_1, \ldots, v_n$ such that $G[v_1, \ldots, v_n]$ is connected. Let $i \geq 1$ then $G[v_1, \ldots, v_i]$ is a tree. Note $G[v_1, \ldots, v_{i+1}]$ is connected by Proposition 1.4.1, so v_{i+1} has at least one neighbour in $G[v_1, \ldots, v_i]$.

For a contradiction, suppose that v_{i+1} has two neighbours z and w in $G[v_1, \ldots, v_i]$. There is a (unique) path P in $G[v_1, \ldots, v_i]$ between z and w, and this path does not visit v_{i+1}. Hence $P \cup \{zv_{i+1}, wv_{i+1}\}$ is a cycle in G, contradiction. □

Corollary 1.5.4. A connected graph with n vertices is a tree if and only if it has $n - 1$ edges.

Proof. Suppose that G is a tree on n vertices. The result is true when $n = 1$. Now suppose the result is true when $n = k$. Let G be a tree on $k + 1$ vertices. Let v be a leaf in G (e.g .take an end vertex of a longest path in G.) Then $G - v$ is a tree on k vertices, so $G - v$ has $k - 1$ edges (inductive hypothesis). Therefore G has k edges as v has degree 1. This concluses the proof, by induction.

Conversely, suppose that $G$is connected with n vertices and $n-1$ edges. Then G contains a spanning tree H, by an earlier corollary. Then H has exactly $n - 1$ edges, since it is a tree on n vertices. Hence $H = G$, so G is a tree. □

Corollary 1.5.5. If T is a tree and G is any graph with $\delta(G) \geq |T| - 1$ then G has a subgraph isomorphic to T.

Chapter 2

Matchings and Hamilton Cycles

Two edges in a graph are called **independent** if they have no vertices in common.
A set M of pairwise independent edges in a graph is called a **matching**.

Given $G = (V, E)$ and $U \subseteq V$, say that $M \subseteq E$ is a **matching of U** if M is matching and every vertex in U is incident with an edge of M. We say that the vertices in U are matched by M, and t hat the vertices not incident with any edge of M are **unmatched**.

A matching M is a **maximal matching** of G if $M \cup \{e\}$ is not a matching for any $e \in E - M$.
A **maximum matching** of G is a matching of G such that no set of edges with size greater than $|M|$ is a matching.

A **perfect matching** of G is a matching of G which matches every vertex of G. Note: a perfect matching is a 1-regular spanning subgraph of G also called a **1-factor** of G.

A k**-factor** is a k-regular spanning subgraph. A **2-factor** in a graph is the union of disjoint cycles which covers all the vertices.

2.1 Matchings in Bipartite Graphs

Let $G = (V, E)$ be a bipartite graph with vertex bipartition $V = A \cup B$. Here A, B are nonempty disjoint sets. We use the convention that all vertices called $a, a', a'', \ldots$ belong to A and similarly for B.

Let M be matching in G. A path in G which starts at an *unmatched* vertex of A and contains, alternately, edges from $E - M$ and from M, is called an **alternating path** with respect to M.
If an alternating path P ends in an unmatched vertex of B then it is called an **augmenting path**.

Definition 2.1.1. A set $U \subseteq V$ is a **cover** (or **vertex cover**) of G if every edge of G is incident with a vertex in U.

Theorem 2.1.2 (König, 1931)**.** Let G be a bipartite graph. The size of a maximum matching in G is equal to the size of the minimum vertex cover of G.

Proof. Let $\hat{U}$ be a cover in G and let Mbe a maximum matching. Then $|\hat{U}| \geq |M|$ as we must cover every edge of M. Hence it suffices to construct a cover U of G with $|U| = |M|$.

We build U be choosing one vertex from each edge of M to place into U, as follows:

- If $ab \in M$ and some alternating path in G with respect to M ends in b. Then put b into U otherwise put a into U.

Let $ab \in E$. If $ab \in M$ then $a \in U$ or $b \in U$ by definition of U. Now assume $abb \notin M$. Since M is maximum, there exists $a'b' \in M$ with $a = a'$ or $b = b'$. If a is unmatched in M then $b = b'$ for some $a'b' \in M$. Hence ab is an alternating path ending in $b = b'$, so we chose b' to go into U from the edge $a'b' \in M$. So the edge ab is covered by U in this case.

Hence we assume that $a = a'$ for some $a'b' \in M$. If $a = a' \in U$ then we are done. Otherwise $b' \in U$, so there is an alternating path P ending in b'. Then $P = a_1b_1a_2b_2 \dots b'$, and we have three cases:

(i) P does not include a or b. Then $Pab = a_1a_2 \dots b'ab$ is an alternating path in G with respect to M. By maximality of M, b is matched or else we have an augmenting path. Hence $b \in U$ as b is the chosen vertex from its matching edge.

(ii) If b is on P before a, or $b \in P$ and $a \notin P$, then $P = a_1b_1a_2 \dots b \dots b'$. Then we let $P' = a_1b_1 \dots b$. This is an alternating path ending in b, so finish proof as case above.

(iii) If a is on P before b, or $a \in P$ and $b \notin P$. Then $P = a_1b_1 \dots a_rb_r \dots b'$ and we take $P' = a_1b_1 \dots ab$. This is an alternating path ending in b, so finish proof as case above.

This proves U is a cover of G and since $|U| = |M|$, this completes the proof. $\square$

For a subset $S \subseteq A$, let $N(S) = \bigcup_{v \in S} N(v)$ be the set of vertices in B which are neighbours of some vertex in S.

Theorem 2.1.3 (Hall, 1935)**.** Let G be a bipartite graph. Then G contains a matching of A if and only if

$$|N(S)| \geq |S| \quad \text{for all } S \subseteq A. \tag{2.1}$$

Proof. We have that this condition is necessary. Now suppose that (2.1) holds. For a contradiction, suppose that G has no matching of A. Then König's Theorem (Theorem 2.1.2) says that G has a cover U with $|U| < |A|$. Suppose that $U = A' \cup B'$ with $A' \subseteq A$ and $B' \subseteq B$. Then $|A'| + |B'| = |U| < |A|$, so $|B'| < |A| - |A'| = |A - A'|$. Since U is a cover, G has no edges from $A - A'$ to $B - B'$. Hence $N(A - A') \subseteq B'$, and so $|N(A - A')| \leq |B'| < |A - A'|$. This contradicts Hall's condition 2.1 for $S = A - A'$. Hence G contains a matching of A. $\square$

Corollary 2.1.4. Let G be a bipartite graph and $d \in \mathbb{N}$. If $|N(S)| \geq |S| - d$ for all $S \subseteq A$ then G has a matching of size $|A| - d$.

Proof. Add d new vertices to B and join each of them by an edge to each vertex of A. Then for all $S \subseteq A$, in the new graph G', $|N_{G'}(S) \geq |S| - d + d = |S|$. Hall's condition is satisfied in G'. Therefore there is a matching M in G' which matches all of A. At least $|A| - d$ edges in M are edges of G. $\square$

Corollary 2.1.5. If G is a k-regular bipartite graph then G has a perfect matching.

Proof. Assume $k \geq 1$. Since G is k-regular, $|E(G) = k|A| = k|B|$, so $|A| = |B|$. Hence it suffices to prove that G contains a matching of A. Every set $S \subseteq A$ is joined to $N(S)$ by a total of $k|S|$ edges. These edges are a subset of the $k|N(S)|$ edges incident with $|N(S)$. Hence $k|S| \leq k|N(S)|$

and diving by k shows that Hall's condition holds. Thus, G has a matching of A. $\square$

Corollary 2.1.6. Every regular graph of positive even degree has a 2-factor.

Proof. Let G be any $2k$-regular graph, $k \geq 1$. Without loss of generality, suppose that G is connected (or apply this argument to each component). By Theorem 1.3.1, G has an Euler tour $v_0 v_1 \ldots v_{l-1} v_l$ where $v_l = v_0, e_i = v_i v_{i+1} \in E(G)$ using each edge exactly once.

Replace each vertex $v \in V$ with a pair of vertices v^-, v^+, and replace every edge $e_i = v_i v_{i+1}$ by the edge $v_i^+ v_{i+1}^-$. The resulting graph G' is a k-regular bipartite graph. Hence by Corollary 2.1.5, G' has a perfect matching (1-factor). Collapse every vertex pair (v^-, v^+) back into a single vertex v, for all $v \in V$. The 1-factor of G' becomes a 2-factor of G. $\square$

2.2 Hamilton Cycles

A **Hamilton cycle** is a connected 2-factor. That is, it is a cycle which includes every vertex.

Say G is **Hamiltonian** if it contains a Hamilton cycle. A Hamiltonian graph G must be connected with minimum degree $\delta(G) \geq 2$.

Theorem 2.2.1 (Dirac, 1952)**.** Every graph with $n \geq 3$ vertices and with minimum degree at least $n/2$ has a Hamilton cycle.

Proof. Let G be a graph with minimum degree $\geq n/2$ and $n \geq 3$ vertices. Then G is connected, as otherwise the degree of any vertex in the smaller component must be $< n/2$. Let $P = x_0 \ldots x_k$ be a longest path in G. by maximality, all neighbours of x_0 and x_k lie on P. So at least $n/2$ of the vertices $x_0, \ldots, x_{k-1}$ are adjacent to x_k and at least $n/2$ of these same vertices satisfy $x_0 x_{i+1} \in E(G)$. By the pigeonhole principle, as $k < n$, there exists $i \in \{0, \ldots, k-1\}$ with $x_0 x_{i+1}, , x_i x_k \in E(G)$. $\square$