Combinatorial Optimization

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Contents

0 Organization

- Prerequisites
  - Basic knowledge of graph algorithms
  - Linear Programming (LP Duality)
  - Programming skills in C++
- Exam
  - Qualification requires 50% of the points in theoretical & programming exercises
  - Oral exam
- Books
  - "Combinatorial Optimization", Korte & Vygen
  - "Understanding & Using Linear Programming", B. Gärtner, J. Matouset
  - Skript (theorems & definitions)
  - Further book recommendations are on the website

1 Matchings

1.1 Introduction

Definition 1.1.

1. A *matching* M in a graph $G = (V, E)$ is a set of pairwise disjointed edges, i.e. they don't have a common endpoint.

   $\nu(G) :=$ max. cardinality of a matching in G

2. An *edge cover* C of a graph $G = (V, E)$ is a subset of E s.t. $V = \bigcup_{e \in C} e$.

   $\zeta(G) :=$ min. cardinality of an edge cover in G

3. A matching is called *perfect* (or *1-factor*) if it is an edge cover

4. $v \in V$ with $v \in e \in M$ is called M*-covered*

5. $v \in V$ is called M*-exposed* if it is not M-covered

Definition 1.2.

1. A *stable set* (independent set) S is a set of pairwise non-adjacent vertices.

   $\alpha(G) :=$ max. cardinality of a stable set

2. A *vertex cover* C is a subset of V s.t. $E = \bigcup_{\{x,y\}\in E,\ x\in G}\{x,y\}$
   $\tau(G) :=$ min. cardinality of a vertex cover

Lemma 1.3.

1. $\alpha(G) + \tau(G) = |V|$
2. $\nu(G) + \zeta(G) = |V|$ *if* G *has no isolated vertices*
3. $\zeta(G) = \alpha(G)$ *if* G *is bipartite and has no isolated vertices*

Problem. Cardinalty Matching Problem
Input: Graph $G = (V, E)$
Task: Find a maximum cardinality matching

Problem. Maximum Weight Matching Problem (MWMP)
Input: Graph G, $c : E \to \mathbb{R}$
Task: Find a matching M maximizing $c(M)$

Problem. Minimum Weight Perfect Matching (MWPMP)
Input: Graph G, $c : E \to \mathbb{R}$
Task: Find a perfect matching of minimum weight or decide that no perfect matching exists in G

Lemma 1.4. *The MWMP is equivalent to the MWPMP (i.e. there exists a transformation with linear complexity)*

Proof. Given a MWPMP instance (G, c), define $c' := K - c$ ($K := 1 + \sum_{e\in E}|c(e)|$).
$\Rightarrow$ Any maximum weight matching is a maximum cardinality matching

Given a MVMP instance (G, c), define G' as 2 copies of G where the 2 copies of a vertex are joined by an edge.
$\Rightarrow$ G' has a perfect matching. Define:

$$c'(e) := \begin{cases} -c(e) & \text{if } e \text{ is in the first copy} \\ 0 & \text{else} \end{cases}$$

A minimum weight perfect matching in G' gives us a maximum weight matching in G. □

Definition 1.5. Let $G = (V, E)$ be a graph and $M \subseteq E$ a matching in G. A path P is *M-alternating* if its edges are alternatingly in and not in M. If both end points of this path are M-exposed, P is an *M-augmenting* path.

Lemma 1.6. *Given a matching M in G and an inclusion-wise maximal M-alternating path P,*

$$M\Delta P := M \setminus P \cup P \setminus M$$

is a matching. If P is M-augmenting, then $|M\Delta P| = |M| + 1$.

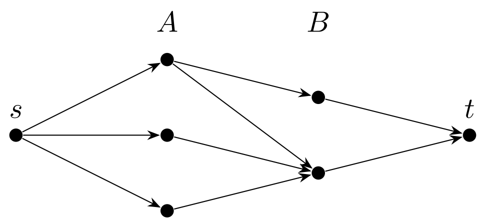


Figure 1: Example of the construction in Theorem 1.8

Theorem 1.7 (Petersen 1891, Berge 1957)**.** *Augmenting Path Theorem Given a graph $G = (V, E)$ and a matching M in G:*

$$|M| = \nu(G) \Leftrightarrow \nexists M\text{-augmenting path } P \text{ in } G$$

Proof.

"$\Rightarrow$": Clear

"$\Leftarrow$": Assume there exists a matching M' with $|M'| > |M|$. Let $G' := (V, M\Delta M')$.
$\Rightarrow |\delta_{G'}(v)| \leq 2 \ \forall v \in V$
$\Rightarrow G'$ is the union of disjoint circuits and paths
$\Rightarrow$ all circuits are even and have the same number of edges from M and M'
$\Rightarrow \exists$ a path P in G' starting and ending with an edge in M'
$\Rightarrow P$ is an alternating path

□

1.2 Bipartite Matching

Theorem 1.8 (König 1931)**.** *If G is bipartite, then $\nu(G) = \tau(G)$*

Proof. Add vertices s and t edges between them to all vertices of the respective partition. Direct all edges from s to t. Then $\nu(G)$ is maximum number of disjoint s-t-paths. Menger $\Rightarrow$ This is equal to the minimum number of vertices that disconnect t from s. □

Theorem 1.9 (Hall 1935)**.** *Let $G = (A \dot\cup B, E)$ be a bipartite graph. Then:*

$$G \text{ has a matching covering } A \Leftrightarrow |\Gamma(X)| \geq |X| \quad \forall X \subseteq A$$

Corollary 1.10. *Marriage Theorem*

$$|\Gamma(X)| \geq |X| \ \forall X \subseteq A \text{ and } |A| = |B| \Leftrightarrow G \text{ has a perfect matching}$$

Definition 1.12. The MWPMP for bipartite graphs is called *Assignment Problem.*

Theorem 1.13. *The Assignment Problem can be solved in time $O(nm + n^2 \log m)$.*

Proof. Use the Successive Shortest Paths algorithm in an auxiliary graph. $\square$

1.3 The Tutte Matrix & Randomized Matching

Definition 1.14. Let G be a simple, undirected graph. Let G' be an orientation of G and $(X_e)_{e\in E(G)}$. The *Tutte matrix* is defined as

$$T_G(X) := (T^*_{vw})_{v,w\in V(G)}$$

where

$$t^*_{vw} := \begin{cases} X_{\{v,w\}} & \text{if } (v,w) \in E(G) \\ -X_{\{v,w\}} & \text{if } -(v,w) \in E(G) \\ 0 & \text{else} \end{cases}$$

Remark 1.15. $T_G(X)$ is shew-symmetric (i.e. $T_G(X) = -(T_G(X))^t$). $\operatorname{rank}(T_G(X))$ is independent of the orientation of G. $\det(T_G(X))$ is a polyomial in X.

Theorem 1.16 (Tutte)**.** *A simple graph G has a perfect matching* $\Leftrightarrow \det(T_G(X)) \neq 0$

Proof. Let $V(G) = \{v_1, \dots, v_n\}$ and S_n be the permutation group.

$$\det T_G(X) = \sum_{\pi\in S_n} \operatorname{sgn}\pi \cdot \prod_{i=1}^{n} t^*_{v_i,v_{\pi(i)}}$$

Let $S'_n := \{\pi \in S_n \mid \prod_{i=1}^n t^*_{v_i,v_{\pi_i}} \neq 0\}$. Each $\pi \in S_n$ corresponds to a digraph $H_\pi := (V(G), \{(v_i, v_{\pi(i)}) \mid i \in [n]^1\})$. We have $|\delta^+(v) = 1 = |\delta^-(v)||\ \forall v \in V(H_\pi) \Rightarrow H_\pi$ is the union of disjoint circuits. If $\pi \in S'_n$, then $H_\pi \subset \overset{\Leftrightarrow}{G'}$.

If there exists $\pi \in S'_n$ s.t. H_π is a collection of even circuits, then this immediately yields a perfect matching in G (using every second edge of each circuit).

Otherwise, $\forall \pi \in S'_n$, H_π contains an odd circuit. Let $r(\pi) \in S'_n$ arise from π by reversing edges on the unique odd circuit containing a vertex with minimum index $\Rightarrow r(r(\pi)) = \pi$ and $\operatorname{sgn}(\pi) = \operatorname{sgn}(r(\pi))$. The second part is true since for reversing an odd cycle, we need an even number of swaps. Let $v_{i_1}, \dots, v_{i_{2k+1}}$ be the "first" odd circuit. Then $r(\pi)$ is attained by $2k$ swaps: For $j = 1, \dots, k$ swap $(\pi(i_{2j-1}), \pi(i_{2k}))$ and $(\pi(i_{2j}), \pi(i_{2k+1}))$.

[1] This is an abbreviation for $\{1, \dots, n\}$.

$\prod_{i=1}^n t^*_{v_i v_{\pi(i)}} = -\prod_{i=1}^n t^*_{v_i v_{r(\pi(i))}}$ since there is an odd number of sign changes to t^*. $\Rightarrow \det(T_G(X)) = 0$. We have shown that if G has no perfect matching, then $\det T_G(X) = 0$.

Assume that G has a perfect matching M. Define π as $\pi(i) = j, \pi(j) = i$ where $\{i, j\} \in M$. $\Rightarrow \prod_{i=1}^n t^*_{v_i v_{\pi(i)}} = \prod_{e \in M} -X_e^2$ cannot be canceled out. In particular, $\det T_G(X) \neq 0$. $\square$

Remark 1.17. Picking $X' \in [0,1]^{E(G)}$ at random, we almost surely have (since the zero set of a non-zero polynomial is a set of measure zero):

$$\det T_G(X') \neq 0 \Leftrightarrow G \text{ has a perfect matching}$$

Theorem 1.18 (Lovász 1979)**.** *Let G be a simple graph and $X \in [0,1]^{E(G)}$ chosen randomly. Then almost surely* $\operatorname{rank}(T_G(X)) = 2\nu(G)$.

1.4 Tutte's Matching Theorem

Let $X \subseteq V(G)$. $G - X$ consists of even and odd (in terms of the number of vertices) connected components. We define $q_G(X)$ to be the number of odd components in $G - X$.

Definition 1.19. A graph G satisfies the *Tutte Condition* if $q_G(X) \leq |X|$ for all $X \subseteq V(G)$. $\emptyset \neq X \subseteq V(G)$ is called *barrier* if $q_G(X) = |X|$.

Proposition 1.20. *For any graph G and any $X \subseteq V(G)$:*

$$q_G(X) - |X| \equiv |V(G)| \mod 2$$

Definition 1.21. A graph G is *factor-critical* if $G - v$ has a perfect matching for all $v \in V(G)$. A matching is called *near-perfect* if it covers $|V(G)| - 1$ vertices.

Proposition 1.22. *If G is factor-critical, then it is connected.*

Theorem 1.23 (Tutte 1947)**.** *A graph G has a perfect matching $\Leftrightarrow$ Tutte Condition holds (i.e. $q_G(X) \leq |X| \ \forall X \subseteq V(G)$)*

Proof.

"$\Rightarrow$": Clear

"$\Leftarrow$": We proceed by induction on $|V(G)|$. The case $|V(G)| = 2$ is clear.

Generally, if the Tutte Condition holds, then $|V(G)|$ must be even (pick $X = \emptyset$). Proposition 1.20 $\Rightarrow$ $q_G(X) - |X|$ is even. Every $x \in V(G)$ induces a barrier $\{x\}$. Let X be a maximum barrier. Then $G - X$ doesn't have any even components (since otherwise a single vertex of such a component could be added to X).

Claim: Each odd component is factor-critical.
Let C be an odd component in $G - X$, $v \in V(C)$. Assume that $C - v$ does not have a perfect matching. Induction Hypothesis $\Rightarrow$ $C - v$ violates Tutte Condition.
$\Rightarrow \exists Y \subseteq V(C - v) : q_{C-v}(Y) > |Y|$
$\overset{1.20}{\Rightarrow} q_{C-v}(Y) \geq |Y| + 2$
Observe $X \cap \{v\} = Y \cap \{v\} = X \cap Y = \emptyset$:

$$\begin{aligned} q_G(X \cup Y \cup \{v\}) &= q_G(X) - 1 + q_C(Y \cup \{v\}) \\ &= |X| - 1 + q_{C-v}(Y) \\ &\geq |X| - 1 + |Y| + 2 \\ &= |X \cup Y| + 1 \\ &= |X \cup Y \cup \{v\}| \end{aligned}$$

$\Rightarrow X \cup Y \cup \{v\}$ is a barrier
$\Rightarrow$ Claim

Let G' arise from G by contracting each odd component into a single vertex. We have $V(G') = X \dot\cup Z$ and G' is bipartite. We have to show that G' has a perfect matching. If not, then $\exists A \subseteq Z : |\Gamma_{G'}(A)| < |A|$ $\Rightarrow q_G(\Gamma_{G'}(A)) \geq |A| > |\Gamma_{G'}(A)|$ which contradicts the Tutte Condition.

□

Theorem 1.24 (Berge 1958)**.**

$$|V(G)| = 2\nu(G) + \max_{X \subseteq V(G)} (q_G(X) - |X|)$$

Proof. For $X \subseteq V(G)$, any matching has at least $q_G(X) - |X|$ uncovered vertices, so "$\geq$" holds.

For the other inequality, add $k := \max_{X \subseteq V(G)} (q_G(X) - |X|)$ new vertices and connect them to all existing vertices, yielding a new graph H.

We claim that H has a perfect matching. This then implies:

$$2\nu(G) + k \geq 2\nu(H) - k = |V(H)| - k = |V(G)|$$

Assume that H does not have a perfect matching. Then by Tutte's Theorem, there exists $Y \subseteq V(H)$ with $q_H(Y) > |Y|$. By 1.20, $k \equiv |V(G)| \mod 2$, therefore $|V(H)|$ is even, so $Y \neq \emptyset$. Y must contain all new vertices, otherwise $H - Y$ would be connected[2] and $q_H(Y) \leq 1 \leq |Y|$.

$$\Rightarrow q_G(Y \cap |V(G)|) = q_H(Y) > |Y| = |Y \cap V(G)| + k$$

which is a contradiction to the choice of k. □

[2]Note that Y cannot contain all old vertices, since otherwise $q_H(Y) < |Y|$.

1.5 Ear Decompositions of Factor-Critical Graphs

Definition 1.25. Let G be a graph. An *ear decomposition* of G is a sequence $r, P_1, \ldots, P_k$ with $G = (r, \emptyset) + P_1 + \ldots + P_k$ such that each P_i is either a path with exactly the endpoints located in $\{r\} \cup \bigcup_{j \in [i-1]} V(P_j)$ or a circuit where exactly one of the vertices belongs to $\{r\} \cup \bigcup_{j \in [i-1]} V(P_j)$.

$P_1, \ldots, P_k$ are called *ears*. If $|V(P_1)| \geq 3$ and $P_2, \ldots, P_k$ are paths we call it a *proper* ear decomposition.

Theorem 1.27 (Whitney 1932)**.** *Let G be an undirected graph. Then:*

$$G \text{ 2-connected} \Leftrightarrow G \text{ has a proper ear decomposition}$$

Definition 1.28. An ear decomposition is *odd* if every ear has odd length (in terms of the number of edges).

Theorem 1.29. *Let G be an undirected graph. Then*

$$G \text{ factor-critical} \Leftrightarrow G \text{ has an odd ear decomposition}$$

The first vertex r of the ear decomposition can be chosen arbitrarily.

Proof.

"$\Leftarrow$": Let G be a graph with an odd ear decomposition $r, P_1, \ldots, P_k$. P_1 is an odd circuit, so it is factor-critical. We use induction on the number of ears. Let P be the last ear and G' be G before adding P. By the induction hypothesis, G' is factor-critical. Given $v \in V(G)$, we have to show that $G - v$ has a perfect matching.

Case 1: $v \in V(G')$. Then $G' - v$ has a perfect matching. Adding every second edge of P (excluding the endpoints) to it, yields a perfect matching of $G - v$.

Case 2: $v \in V(G) \setminus V(G')$. Let x, y be the endpoints of P. Without loss of generality let $P_{[v,x]}$ be even. There exists a perfect matching in $G' - x$. Together with every second edge of $P_{[v,y]}$ and $P_{[v,x]}$ this is a perfect matching in $G - v$.

"$\Rightarrow$": Let $r \in V(G)$ be any vertex. Let M be a perfect matching in $G - r$. Suppose we have an odd ear decomposition for $G' \subseteq G$ with $r \in V(G')$ and $M \cap E(G')$ is a near-perfect matching in G' (i.e. all vertices in G' except for r are matched with other vertices in G').

If $G' \neq G$, there is an edge $\{x, y\} \in E(G) \setminus E(G')$ with $x \in V(G')$ (by Proposition 1.22). If $y \in V(G')$, then $\{x, y\}$ can be chosen as the next ear. Otherwise, construct an M-alternating odd ear, starting with $\{x, y\}$. Let N be a matching in $G - y$. $M \Delta N$ contains a y-r-path P. Let w be the first vertex in $P \cap V(G')$. w is M-exposed in $P_{[y,w]}$, y is

N-exposed in $P_{[y,w]}$. Therefore $P_{[y,w]}$ is even and together with $\{x, y\}$ it forms an M-alternating odd ear.

Inductively, this argument yields an odd ear decomposition.

$\square$

Definition 1.30. Let G be factor-critical and M a near-perfect matching. An M-alternating ear decomposition is an odd ear decomposition such that each ear is an M-alternating path or circuit C with:

$$|E(C) \cap M| = |E(C) \setminus M| - 1$$

Corollary 1.31. *For any factor-critical graph G and any near-perfect matching M in G, there exists in M-alternating ear decomposition of G.*

Definition 1.32. Let G be factor-critical, M a near-perfect matching and $r, P_1, \ldots, P_k$ an M-alternating ear decomposition of G. $\mu, \varphi : V(G) \to V(G)$ are *associated with the ear decomposition* if:

- $\{x, y\} \in M \Rightarrow \mu(x) = y$
- $\{x, y\} \in E(P_i) \setminus M$ and $x \notin \{r\} \cup \bigcup_{j \in [i]} V(P_j)$
  $\Rightarrow \varphi(x) = y$
- $\mu(r) = \varphi(r) = r$

Proposition 1.33. *Let G be a factor-critical graph and μ, φ functions associated with an M-alternating ear decomposition. Then this ear decomposition is unique up to the order of the ears. The Ear-Decomposition-Algorithm correctly determines an explicit list of the ears in linear time.*

Proof. Step 3 determines ears uniquely. The algorithm clearly runs in linear time. $\square$

Lemma 1.34. *Let G be factor-critical and μ, φ associated with an M-alternating ear decomposition. Then the maximal path given by the initial sequence*

$$x, \mu(x), \varphi(\mu(x)), \mu(\varphi(\mu(x))), \ldots \tag{1}$$

defines an M-alternating x-r-path of even length.

Proof. We proceed by induction on the number of ears. Let $x \in V(G) \setminus \{r\}$ and P_i be the ear containing x. A subsequence of (1) is a subpath Q of P_i from x to $y \in \{r\} \cup \bigcup_{j \in [i-1]} V(P_j)$. Q starts with a matching edge and ends with a non-matching edge, so it has even length. If $y = r$, we are done, otherwise the statement follows from the induction hypothesis. $\square$

1.6 Edmond's Matching Algorithm

Definition 1.35. Let G be a graph, M a matching in G. A *blossom* in G with respect to M is a factor-critical subgraph of B of G such that $|M \cap E(B)| = \frac{|V(B)|-1}{2}$. The vertex $r \in V(B)$ that is exposed by M is called the *base* of B.

Definition 1.36. Let G be a graph, M a matching in G, B a blossom and Q a M-alternating v-r-path of even length from $v \in V(G)$ that is M-exposed to the base r of B. Additionally, let $E(Q) \cap E(B) = \emptyset$. $B + Q$ is called a M-flower.

Lemma 1.37. *Let G be a graph, M a matching in G. Suppose there is a M-flower $B+Q$. Let G', M' result from G and M by contracting $V(B)$ into a single vertex. Then:*

$$M \textit{ maximum matching in } G \Leftrightarrow M \textit{ maximum matching in } G'$$

Proof.

"$\Leftarrow$": Assume that M is not maximum in G. $N \coloneqq M \Delta E(Q)$ is a matching with $|N| = |M|$.
$\Rightarrow$ $\exists N$-augmenting path P in G. At least one endpoint x of P is in $V(B)$. If P and B are disjoint, let y be the other endpoint of P. Otherwise, let y be the first vertex on P in B. $P' \coloneqq P_{[x,y]}$ is an N'-augmenting path in G', so $|N'| = |M'| < \mu(G')$.

"$\Rightarrow$": Assume that M' is not maximum in G', so there exists a matching N' in G' with $|N'| > |M'|$. Let N_0 arise from N' in G, then N_0 contains ≤ 1 vertex from $V(B)$. Since B is factor-critical, N_0 can be extended by $k \coloneqq \frac{|V(G)|-1}{2}$ edges to a matching N in G. We have

$$|N| = |N_0| + k = \left|N'\right| + k > \left|M'\right| + k = |M|$$

so M is not maximum.

□

Lemma 1.39. *Let G be a graph, M a matching in G. $X \subseteq V(G)$ is the set of exposed vertices. We can find a shortest M-alternating X-X-walk of positive length in $O(|E(G)|)$ time.*

Proof. Define $D \coloneqq (V(G), A)$ where:

$$A \coloneqq \{(u,v) \mid \exists x \in V(G) : \{u,x\} \in E(G), \{x,v\} \in M\}$$

A shortest $X - \Gamma_G(X)$-path in D corresponds to a shortest X-X-walk in G. □

Theorem 1.40. *Let $P = v_0, \dots, v_t$ be a shortest M-alternating X-X-walk in G. Then either*

- *P is an M-augmenting path* or
- *$v_0, \dots, v_j$ is an M-flower for some $j \leq t$.*

Proof. If P is not a path, choose $i < j$ such that $v_i = v_j$ and j minimal. Then $v_0, \dots, v_{j-1}$ are distinct vertices. If $j - i$ is even, deleting $v_{i-1}, \dots, v_j$ from P yields a shorter walk, so $j - i$ is odd.

Case 1: j is even. Then i is odd and therefore $v_{i+1} = v_{j-1}$ must be the matching mate of $V_i = v_j$ which contradicts the minimality of j.

Case 2: j is odd. Then i is even, so $v_0, \dots, v_i$ is an M-alternating path of even length and $v_i, \dots, v_j$ is an M-alternating odd circuit, i.e. a blossom.

□

Algorithm 1: Edmond's Augmenting Path Search

Input: Graph G, matching M
Output: An M-augmenting path (if one exists)

$X :=$ set of exposed vertices
if *$\exists M$-alternating X-X-walk of positive length* **then**
  $P = v_0, \dots, v_t :=$ a shortest such walk
  if *P is a path* **then**
    return P
  else
    Choose j as in Theorem 1.40
    $v_0, \dots, v_j$ is an M-flower with blossom B
    Recurse on G/B
    Augment an M/B-augmenting path in G/B to an M-augmenting path P' in G
    return P'
else
  $\nexists M$-augmenting path

Theorem 1.41. *Given a graph G, a maximum cardinality matching can be found in time $O(n^2 m)$ where $n := |V(G)|, m := |E(G)|$*

Proof. Start with $M = \emptyset$ and iteratively find M-augmenting path P, set $M := M \Delta E(P)$. If no such path exists, then M is maximum. P can be found in time $O(mn)$[3]. Since M is maximum after at most $\frac{n}{2}$ augmentation, we have total running time $O(n^2m)$. $\square$

1.6.1 Growing forest - $O(n^3)$

Definition 1.42. Let G be a graph, M a matching in G. An *alternating forest* with respect to M in G is a forest F in G where:

- $V(F)$ contains all M-exposed vertices, each tree of F contains exactly one exposed vertex, its *root*.
- We call $v \in V(G)$ an outer (inner) vertex if it has even (odd) distance from the root of its component.
- $\forall v \in V(F)$ the unique path from v to the root of its component is M-alternating.
- $v \in V(G) \setminus V(F)$ is called *out-of-forest*.

Clearly, inner vertices always have degree 2 (we always assume that there are no matching edges that can immediately be added to F).

Proposition 1.43. *In any alternating forest, the number of outer vertices that are not the root equals the number of inner vertices.*

Proof. For all outer vertices, there exists exactly one inner vertex on its path to the root. $\square$

Lemma 1.44. *Given a graph G, a matching M, an alternating forest F with respect to M in G. Then, either M is a maximum matching or $\exists$ outer vertex $x \in V(F)$, an edge $\{x, y\} \notin E(F)$ such that one of the following holds:*

- *Grow: $y \notin V(F)$ and therefore $\{y, z\} \in M$ with $z \notin V(F)$. In this case, y, z and $\{x, y\}, \{y, z\}$ can be added to F.*
- *Augment: y is an outer vertex in a different connected component in F. In this case, M can be augmented along $P(x) \cup \{x, y\} \cup P(y)$ where $P(z)$ denotes the unique path from $z \in V(F)$ to the root of its connected component.*
- *Shrink: y is an outer vertex in the same component as x. Let r be the first vertex on $P(x)$ that is also on $P(y)$. Then $|\delta_F(r)| \geq 3$, so y is an outer vertex and $\left|E(F_{[x,r]})\right|, \left|E(F_{[y,r]})\right|$ are even. Together with $\{x, y\}$ these paths form a blossom with ≥ 3 vertices.*

[3]Here, m is the time required for finding a walk and the recursion depth is bounded by n.

Proof. We show that if none of these cases apply, M is maximum. Let X be the set of inner vertices, $s := |X|$ and t be the number of outer vertices. All outer vertices are isolated in $G - X$, so $G - X$ and $q_G(X) - |X| = t - s$. By Berge's formula (1.24), $t - s$ vertices are exposed by any matching, so M is maximum. $\square$

Definition 1.45. Let G be a graph, M a matching in G. A subgraph F of G is a *general blossom forest* with respect to M if there exists a partition $V(F) = V_1 \dot\cup \ldots \dot\cup V_k$ such that $F_i = F[V_i]$ is a maximal factor-critical subgraph of F with $|M \cap E(F_i)| = \frac{|V_i|-1}{2}$ ($i \in [k]$) and after contracting each V_i, we obtain an M-alternating forest F'. F_i is called an outer (inner) blossom if V_i is an outer (inner) vertex in F'.

A *special blossom forest* is a general blossom forest where each inner blossom is a single vertex.

Store a special blossom forest with 3 functions $\mu, \varphi, \rho : V(G) \to V(G)$:

$$\mu(x) := \begin{cases} x & \text{if } x \text{ is exposed in } M \\ y & \text{if } \{x, y\} \in M \end{cases}$$

$$\varphi(x) := \begin{cases} x & \text{if } x \text{ is the base of an outer blossom or } x \text{ is out-of-forest} \\ y & \text{if } x \text{ is an inner vertex and } \{x, y\} \in E(F) \setminus M \\ y & \text{if } x \text{ is an outer vertex (i.e. in an outer blossom) and } \mu, \varphi \text{ are associated with an } M\text{-alternating ear decomposition of } x\text{'s blossom, } \{x, y\} \in E(F) \setminus M \end{cases}$$

$$\rho(x) := \begin{cases} x & \text{if } x \text{ is an inner vertex or out-of-forest} \\ y & \text{if } x \text{ is an outer vertex and } y \text{ is the base of the outer blossom containing } x \ (y = x \text{ is possible).} \end{cases}$$

Proposition 1.46. *Let F be a special blossom forest with respect to M and μ, φ, ρ as above. Then:*

1. *For all outer vertices x, $P(x) :=$ maximal path given by subsequence of $x, \mu(x), \varphi(\mu(x)), \mu(\varphi(\mu(x))), \ldots$ is an M-alternating path from x to q where q is the root of the component containing x.*

2. *A vertex x is*

   - *an outer vertex* $\Leftrightarrow \mu(x) = x \lor \varphi(\mu(x)) \neq \mu(x)$
   - *an inner vertex* $\Leftrightarrow \varphi(\mu(x)) = \mu(x) \land \varphi(x) \neq x$
   - *out-of-forest* $\Leftrightarrow \mu(x) \neq x \land \varphi(x) = x \land \varphi(\mu(x)) = \mu(x)$

Proof.

1. By definition of μ, φ and lemma 1.33 some initial subsequence of $P(x)$ ends at the base r of the blossom containing x. If $r = q$, we are done. Otherwise $\mu(r), \varphi(\mu(r))$ are next elements in a sequence leading to outer vertex $\varphi(\mu(r))$. This can be iterated.

2. Since the conditions are mutually exclusive, it suffices to show one implication for all the statements.

   - If x is outer, it is a root ($\mu(x) = x$) or $P(x)$ is a path of length at least 2, so $\varphi(\mu(x)) \neq \mu(x)$.
   - If x is inner, then $\mu(x)$ is the base of an outer blossom. Therefore $\varphi(\mu(x)) = \mu(x)$. $P(\mu(x))$ is a path of length at least 2, so $\varphi(x) \neq x$.
   - If x is out-of-forest, then x is covered by M so $\mu(x) \neq x$. By definition of φ, $\varphi(x) = x$. $\mu(x)$ is out-of-forest as well, so $\varphi(\mu(x)) = \mu(x)$.

□

Lemma 1.47. *Following invariants hold:*

a) $\{\{x, \mu(x)\} \mid x \in V(G), \mu(x) \neq x\}$ *is a matching*

b) $\{\{x, \mu(x)\} \mid \underbrace{x \in V(G), \varphi(\mu(x)) = \mu(x) \wedge \varphi(x) \neq x}_{\text{inner vertices}}\} \cup \{\{x, \varphi(x)\} \mid x \in V(G), \varphi(x) \neq x\}$ *forms the edge set of a special blossom forest.*

c) μ, φ, ρ *satisfy the conditions in definition 1.45 (special blossom forest).*

Proof. a) holds as μ only changes in *Augment*. b) is correct after initialization and after the reset in the *Augment* step. It is preserved by *Grow* steps.

In a *Shrink* step, r (the first vertex that the paths from x, y to the root share) is a root or has $|\delta(r)| = 3$ (i.e. it is the base of a blossom), so it is an outer vertex. We define a blossom $B := \{v \in V(G) \mid \varphi(v) \in V(P(x)_{[x,r]}) \cup V(P(y)_{[y,r]})\}$. Consider $\{u, v\} \in F$ with $u \in B, v \notin B$. If $\{u, v\} \in M$, we have $u = r, v = \mu(r)$ (since $F[B]$ contains a near-perfect matching). u was an outer vertex before shrinking and $F[B]$ being factor-critical follows from c) and the characterization by ear-decompositions.

For c), it's clear that μ always represents a matching. $\varphi(x) = x$ if x is not an outer vertex. Therefore, $\mu + \varphi$ represent an M-alternating ear decomposition of B. During *Shrink*, $\varphi(v)$ is not changed if $\varphi(v) = r$. Therefore, the odd ear decomposition for $B' :=$ blossom containing r, is the correct starting point. The next ear is $P(x)_{[x,x']} \cup P(y)_{[y,y']} + \{x, y\}$, where x' (y') is the first vertex in B' on $P(x)_{[x,r]}$ ($P(y)_{[y,r]}$).

For each ear Q of a former blossom $B'' \subseteq B$, $Q \setminus (E(P(x)) \cup E(P(y)))$ form a new ear (since it is created by removing an even path). φ, μ represent this ear-decomposition. $\square$

Theorem 1.48. *Edmond's cardinality matching algorithm correctly determines a maximum matching in $O(n^3)$ time, where $n := |V(G)|$.*

Proof. By lemma 1.47 and proposition 1.46, the algorithm maintains a special blossom forest. Let M, F be the final matching and forest. x an outer vertex implies that $\forall y \in \Gamma(x) : y$ is inner and $\varphi(y) = \varphi(x)$. Define:

$$B := \text{set of inner vertices}$$
$$B := \text{set of bases of (outer) blossoms}$$

Then every unmatched vertex is in B. Matched vertices in B have matching mates in X and $|B| = |X| + |V(G)| - 2|M|$. (Outer) blossoms are odd connected components in $G - X$, so by Berge's theorem (1.24), at least $|B| - |X|$ vertices remain uncovered by any matching, so M is maximum.

We now consider the running time: The status (outer, inner, out-of-forest) for a given vertex can be checked in constant time (proposition 1.46). Therefore, *Grow*, *Augment* and *Shrink* can be implemented in $O(n)$ time. There are at most n calls to *Grow* and *Shrink* per augment and at most $\frac{n}{2}$ *Augments*. This implies the running time $O(n^3)$. $\square$

Remark 1.49. The time for *Shrink* can be reduced to $O(\log n)$ using a binary tree, leading to a running time of $O(nm \log n)$ in total. Tarjan (1974), Gabow & Tarjan (1983) proved a running time of $O(nm\alpha(m, n))$ (where α is the inverse Ackermann function) or $O(nm)$.

Remark 1.50. It's not necessary to reset everything after augmenting. It suffices to reset the 2 trees that were changed by the augmentation. Gabow & Tarjan (1983) showed that it's possible to augment all paths of the same length in $O(m)$ time. There are $2\sqrt{\nu(G)} + 2$ different path lengths, so in total this results in a running time of $O(\sqrt{n}m)$.

Remark 1.51 (Skew-symmetric flows). Goldberg & Karzanov (2003) (and Fremuth-Pagen & Jungnickel (2003)) used *Generalized Max-Flow* to achieve a running time of $O(\sqrt{n}m\frac{\log\frac{m}{n}}{\log n})$.

1.7 Gallai-Edmonds Decomposition

Proposition 1.52. *Let G be a graph, $X \subseteq V(G)$ with $|V(G)| - 2\nu(G) = q_G(X) - |X|$. Then any maximum matching of G*

- *contains a perfect matching in the even components of $G - X$.*
- *contains a near-perfect matching in odd components of $G - X$.*

- *matches all $x \in X$ to distinct odd components.*

Proof. Follows directly from Berge's theorem (1.24). $\square$

Theorem 1.53. *Let G be a graph and:*

$$Y := \{v \in V(G) \mid \exists \text{ maximum matching that exposes } v\}$$

Define $X := \Gamma(Y)$ and $W := V(G) \setminus (X \cup Y)$. Then:

1. *X attains $\max_{X' \subseteq V(G)} q_G(X') - |X'|$.*
2. *$G[Y]$ is the union of factor-critical subgraphs and $G[W]$ is the union of even connected components.*
3. *Any maximum matching in G*
   - *contains a perfect matching in $G[W]$.*
   - *contains a near-perfect matching in each component of $G[Y]$.*
   - *matches all $x \in X$ to distinct connected components*

Y, X, W is called Gallai-Edmonds decomposition *of G.*

Proof. Consider the matching M and special blossom forest F at the end of the algorithm. Let X' (Y') be the set of inner (outer) vertices and W' the set of out-of-forest vertices.

Claim. *X', Y', W' satisfy 1., 2. and 3.*

(Proof of theorem 1.48).

Proposition 1.52 implies that any maximum matching covers all vertices in $V(G) \setminus Y'$, so $Y \subseteq Y'$. For the other inclusion, let $v \in Y'$. Then $M \Delta P(v)$ is a maximum matching exposing v, so $v \in Y$ and $Y' = Y$. By definition, $X = X'$ and $W = W'$. $\square$

Corollary 1.54. *A graph G has a perfect matching $\Leftrightarrow \forall U \subseteq V(G)$, $G - U$ has at most $|U|$ factor-critical components.*

1.8 Minimum Weight Perfect Matching

We use the following Integer Programming formulation:

$$\begin{aligned} \min \quad & \sum_{e \in E(G)} c_e x_e \\ \text{s.t.} \quad & \sum_{e \in \delta(v)} x_e = 1 \qquad v \in V(G) \\ & x_e \in \{0, 1\} \end{aligned}$$

and the corresponding relaxation where we only require $x_e \geq 0$. The dual problem of this is:

$$\begin{aligned} \max \sum_{v \in V(G)} & z_v \\ \text{s.t.} \quad z_v + z_w \leq c_e & \qquad \{v,w\} \in E(G) \end{aligned}$$

Proposition 1.55 (Hungarian Method)**.** *Let G be a graph, $c \in \mathbb{R}^{E(G)}$ and $z \in \mathbb{R}^{V(G)}$ with $z_v + z_w \leq c_e$ for all $e = \{v,w\} \in E(G)$. Define:*

$$G_z \coloneqq (V(G), \{e = \{v,w\} \mid z_v + z_w = c_e\})$$

Let M be a matching in G_z, F a maximal alternating forest in G_z with respect to M. Let X/Y be the set of inner/outer vertices. Then:

1. *If M is a perfect matching in G_z, then it is a minimum-weight perfect matching in G.*
2. *If $\Gamma_G(y) \subseteq X$ for all $y \in Y$, then M is a maximum matching.*
3. *If neither 1. nor 2. hold, define:*

$$\epsilon \coloneqq \min\{\min_{e=\{v,w \in E(G[Y])\}} \frac{c_e - z_v - z_w}{2}, \min_{e \in \delta(Y) \cap \delta(V(F))} c_e - z_v - z_w\}$$

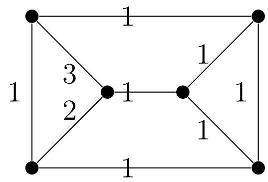
Set $z'_v \coloneqq z_v - \epsilon$ for all $v \in X$, $z'_v \coloneqq z_v + \epsilon$ for all $v \in Y$ and $z'_v \coloneqq z_v$ for all $v \in V(G) \setminus (X \cup Y)$. Then z' is a feasible dual solution and $M \cup E(F) \subseteq E(G_{z'})$. Additionally, $\Gamma_{G_{z'}}(y) \setminus X \neq \emptyset$ for some $y \in Y$.

Proof. 1. Let M' be a minimum-weight perfect matching.

$$\begin{aligned} \sum_{e \in M'} c_e &= \sum_{v \in V(G)} z_v + \sum_{e=\{v,w\} \in M'} (c_e - z_v - z_w) \\ &\geq \sum_{v \in V(G)} z_v \\ &= \sum_{v \in V(G)} z_v + \sum_{e=\{v,w\} \in M} (c_e - z_v - z_w) \\ &= \sum_{e \in M} c_e \end{aligned}$$

2. Each outer vertex is an odd blossom (singleton) of $G - x$. By Berge (1.24), at least $|Y| - |X|$ vertices remain uncovered.
3. z' stays feasible by the choice of ϵ. Edges in $E(F), M$ remain tight. By 1. and 2., $\exists y \in Y :\ \Gamma_{G_{z'}}(y) \setminus X \neq \emptyset$.

□



Remark 1.56. For bipartite graphs, the adjacency matrix is totally unimodular, so the LP has integral vertices.

We define $\mathcal{A} := \{X \subseteq V(G) \text{ odd}\}$ and add the blossom inequalities

$$\sum_{e \in \delta(X)} x_e \geq 1 \qquad \forall X \in \mathcal{A}$$

to the LP relaxation. The new dual problem is then:

$$\begin{aligned} \max & \sum_{A \in \mathcal{A}} z_A \\ \text{s.t.} & \sum_{A \in \mathcal{A}, e \in \delta(A)} z_A \leq c_e \\ & z_A \geq 0 \qquad (A \in \mathcal{A}, |A| \geq 3) \end{aligned}$$

Edmond's Algorithm starts with an empty matching $x = 0$ and dual feasible solution:

$$z_A := \begin{cases} \frac{1}{2} \min\{c(e) \mid e \in \delta(A)\} & |A| = 1 \\ 0 & \text{else} \end{cases}$$

We always ensure that z is dual feasible and that (x, z) satisfy complementary slackness:

$$x_e > 0 \Rightarrow \sum_{A \in \mathcal{A}, e \in \delta(A)} z_A = c_e$$

$$z_A > 0, |A| > 1 \Rightarrow \sum_{e \in \delta(A)} x_e = 1$$

Definition 1.57. $c_z(e) := c(e) - \sum_{A \in \mathcal{A}, e \in \delta(A)} z_A$ is the *reduced cost* of e.

Theorem 1.58. *There are at most* $\frac{7}{2} |V(G)|^2$ *of the repeat-until loop in algorithm 4.*

Proof. $\mathcal{B}$ is laminar at any time, i.e. for $X, Y \in \mathcal{B}$ we have $(X \subseteq Y) \vee (Y \subseteq X) \vee (X \cap Y = \emptyset)$. Therefore $|\mathcal{B}| \leq 2 |V(G)|$.

Observation. *Any* U *added to* $\mathcal{B}$ *during* Shrink *will not be "unpacked" before the next* Augment.

Proof. After *Shrink*, there exists an even length M-augmenting R-U-path. It remains in G_z until the next *Augment* or until U is included in another blossom $U' \supseteq U$ which is not resolved before an *Augment* (inductively). $\square$

Between 2 augments:

- # *Unpacks* $\leq |\mathcal{B}|$ at beginning of the sequence
- # *Shrinks* $\leq |\mathcal{B}|$ at the end of the sequence

Therefore, there are at most $4\,|V(G)|$ *Unpack* and *Shrink* operations between 2 augments. For each dual change without *Unpack*, we have: $z_B > 0 \quad \forall B \in \mathcal{B}$, so ϵ is not determined by z_B. Therefore $\exists e = \{X, Y\}$ with $X \notin \mathcal{X}, Y \in \mathcal{Y}$ where $c_z(e)$ becomes 0.

Case 1: $X \notin \mathcal{Y}$. Then $|V(G_z) \setminus (\mathcal{X} \cup \mathcal{Y})|$ decreases.

Case 2: $X \in \mathcal{Y}$. Then $\exists$ X-Y M-alternating walk in the next iteration.

In particular, such a dual change can occur at most $|V(G)|$ times between 2 augmentations.

In total, there are at most $\frac{1}{2}\,|V(G)|$ *Augment* steps. Therefore, there are $\frac{1}{2}\,|V(G)|^2\,(4 + |V(G)| + 2\,|V(G)|)$ $\square$

Algorithm 2: Minimum-Weight Perfect Matching

Input: Graph G with edge weights $c : E(G) \to \mathbb{R}$
Output: A minimum-weight perfect matching M in (G, c)

Corollary 1.59. *A minimum-weight perfect matching can be computed in* $O(n^2 m)$ *time where* $n := |V(G)|$ *and* $m = |E(G)|$.

Proof. Theorem 1.58 times $O(m)$. $\square$

Remark 1.60. To achieve $O(n^3)$ running time, one can modify the algorithm:

1. Use a General Blossom Forest to avoid recomputing the R-R-walks from scratch. We then have mappings $\mu_v, \varphi_v^i, \rho_v^i$ for $1 \leq i \leq k_v$ where k_v is the number of blossoms that contain v.
2. Store all vertices in a heap (ordered by their criticality for dual-feasibility) to speed up the computation of ϵ.

Gabow (1990) showed a running time of $O(n(m+n\log n))$. Gabow & Tarjan (1991) showed a running time of $O(m\log(nW)\sqrt{n\alpha(m,n)\log n})$ where $W := \max_{e\in E(G)} |c(e)|$.

Theorem 1.61. *Let G be a graph. The set of vectors $x \in \mathbb{R}^{E(G)}$ satisfying*

$$\begin{aligned} x_e &\geq 0 & e &\in E(G) \\ x(\delta(v)) &= 1 & v &\in V(G) \\ x(\delta(A)) &\geq 1 & A &\subseteq V(G) \text{ with } |A| \text{ odd} \end{aligned}$$

is the convex hull of all perfect matchings in G. It is called the perfect matching polytope.

Proof. For any objective function $c : E(G) \to \mathbb{R}$, the minimum-weight perfect matching algorithm produces an integral primal and a dual solution that satisfy complementary slackness. In particular, all vertices of the polytope are integral. □

Theorem 1.62. *Let G be a graph. The set of vectors $x \in \mathbb{R}^{E(G)}$ satisfying*

$$\begin{aligned} x_e &\geq 0 & e &\in E(G) \\ x(\delta(v)) &\leq 1 & v &\in V(G) \\ x(E(G[A])) &\leq \frac{|A|-1}{2} & A &\subseteq V(G) \text{ with } |A| \text{ odd} \end{aligned}$$

is the convex hull of all matchings in G. It is called the matching polytope.

Proof. Any matching solution x satisfies these conditions. Let x be any solution that satisfies the conditions. We have to show that x is a convex combination of matching solutions. Define H by:

$$\begin{aligned} V(H) :=& \{(v,i) \mid v \in V(G), i \in \{1,2\}\} \\ E(H) :=& \{\{(v,i),(w,i)\} \mid \{v,w\} \in E(G), i \in \{1,2\}\} \\ & \cup \{\{(v,1),(v,2)\} \mid v \in V(G)\} \end{aligned}$$

We set $y_{\{(v,i),(w,i)\}} := x_{\{v,w\}}$ for all $\{v,w\} \in E(G), i \in \{1,2\}$ and $y_{\{(v,1),(v,2)\}} := 1 - x(\delta(v))$ for all $v \in V(G)$. Then $y \geq 0$ and $y(\delta_H(x)) = 1$ for all $x \in V(H)$.

Claim. *y satisfies the inequalities of the perfect matching polytope (in particular the blossom inequalities).*

If this is true, by 1.62 y is a convex combination of perfect matchings. $H[\{(v,1) \mid v \in V(G)\}]$ is isomorphic to G, so x is a convex combination of matchings in G.

We now prove the claim: Let $X \subseteq V(G)$ with $|X|$ odd. We have to show that $y(\delta_H(X)) \geq 1$. Define:

$$\begin{aligned} A :=& \{v \in V(G) \mid (v,1) \in X, (v,2) \notin X\} \\ B :=& \{v \in V(G) \mid (v,1) \in X, (v,2) \in X\} \\ C :=& \{v \in V(G) \mid (v,1) \notin X, (v,2) \in X\} \end{aligned}$$

Define $A_i := A \cap (V(G) \times \{i\})$ and $B_i := B \cap (V(G) \times \{i\})$. $|B_1 \cup B_2|$ is even, so (since $|X|$ is odd) $|A|$ or $|C|$ is odd. Without loss of generality, let $|A|$ be odd.

$$\begin{aligned}
\sum_{e \in \delta_H(X)} y_e &\geq \sum_{v \in A_1} \underbrace{\sum_{e \in \delta_H(v)} y_e}_{=1} - 2 \cdot \sum_{e \in E(H[A_1])} y_e - \sum_{e \in \delta(A_1) \cap \delta(B_1)} y_e \\
&\quad + \sum_{e \in \delta(A_2) \cap \delta(B_2)} \\
&= |A_1| - 2 \cdot \sum_{e \in E(G[A])} x_e \\
&\geq |A_1| - (|A| - 1) \\
&= 1
\end{aligned}$$

□

Theorem 1.63. *The matching polyhedron is TDI (Totally Dual Integral), i.e. for all $c \in \mathbb{Z}^{E(G)}$ for which the dual program of ($\max c^t x s.t. \ldots$) has a finite optimum solution, it has an integral optimum solution.*

Proof. The dual is

$$\begin{aligned}
\min \sum_{v \in V(G)} y_v &+ \sum_{e \in \mathcal{A},\ |A|>1} \frac{|A|-1}{2} z_A \\
s.t. \sum_{v \in e} y_v &+ \sum_{A \in \mathcal{A},\ |A|>1, e \in E(G[A])} z_A \geq c(e) \qquad && e \in E(G) \\
& \qquad y, z \geq 0
\end{aligned}$$

Let (G, c) be a counterexample such that $|V(G)| + |E(G)| + \sum_{e \in E(G)} |c(e)|$ is minimum. Then:

- $c(e) \geq 1$ for all $e \in E(G)$, since otherwise e could be deleted.
- G has no isolated vertices.

Claim. *In an optimum solution (y, z), $y = 0$.*

Proof. If $y_v > 0$, then $x(\delta(v)) = 1$ for all optimum solutions x. Decreasing $c(e)$ by 1 for all $e \in \delta(v)$ yields a smaller feasible instance (G, c') where the weight of x is decreased by 1 and x remains optimum. By assumption, (G, c') is not a counterexample, so there exists an integral optimum solution (y', z'). Increasing y'_v by one yields some optimum in (G, c) which has optimum integral solution $(y' + \mathbb{1}_v, z')$. □

Let $(y = 0, z)$ be a dual optimum solution such that

$$\sum_{A \in \mathcal{A}, |A|>1} |A|^2 \, z_A$$

is maximum.

Claim. *$\mathcal{F} \coloneqq \{A : z_A > 0\}$ is laminar.*

If not, there exist $X, Y \in \mathcal{F}: \; X \cap Y, X \setminus Y, Y \setminus X \neq \emptyset$. We proceed by "uncrossing". Let $\epsilon \coloneqq \{z_X, z_Y\} > 0$.

Case 1: $|X \cap Y|$ is odd. Then $|X \cup Y|$ is odd. Define:

$$\begin{aligned} z'_X &\coloneqq z_X - \epsilon \\ z'_y &\coloneqq z_y - \epsilon \\ z'_{X \cap Y} &\coloneqq z_{X \cap Y} + \epsilon && \text{(unless } |X \cap Y| = 1\text{)} \\ z'_{X \cup Y} &\coloneqq z_{X \cup Y} + \epsilon \\ z'_A &\coloneqq z_A && \text{elsewhere} \end{aligned}$$

Then (y, z') is a dual optimum solution.

□