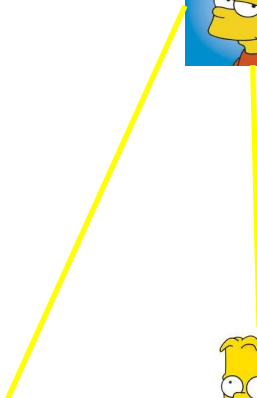# Paths, Trees, and Flowers

Jack Edmonds

Introduction and background

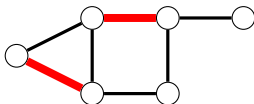Edmonds maximum matching algorithm

Matching-duality theorem

Work scheduling

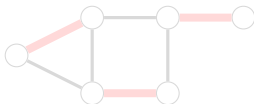Schedule workers in pairs. What is the optimal assignment?

Matching

Matching in a graph is a set of edges, no two of which meet at a common vertex.
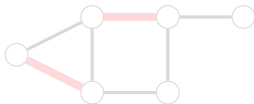

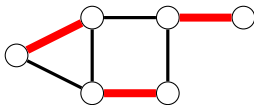Maximum matching is a matching of maximum cardinality.

Matching

Matching in a graph is a set of edges, no two of which meet at a common vertex.
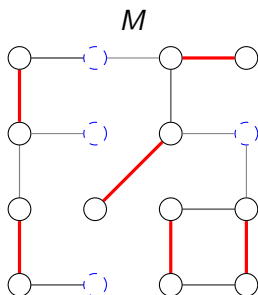

Maximum matching is a matching of maximum cardinality.

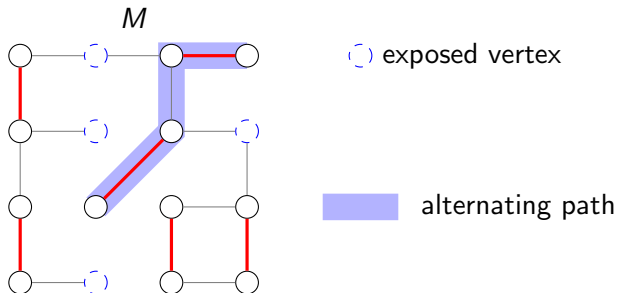# Exposed vertex

Exposed(free) vertex is a vertex that is not incident with any edge in M

exposed vertex

Alternating path

Alternating path is a path whose edges are alternately in M and $\overline{M}$

exposed vertex

alternating path

Different kinds of alternating path

An alternating path between two matched vertices

An alternating path between two exposed vertices

An alternating path between a matched vertex and an exposed vertex

An alternating cycle

Different kinds of alternating path

An alternating path between two matched vertices

An alternating path between two exposed vertices

An alternating path between a matched vertex and an exposed vertex

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Different kinds of alternating path

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Different kinds of alternating path

An alternating path between two matched vertices

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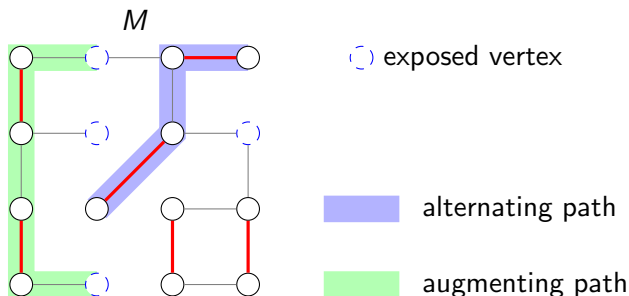An alternating path between a matched vertex and an exposed vertex
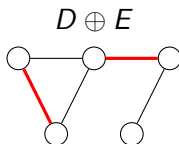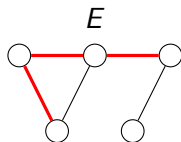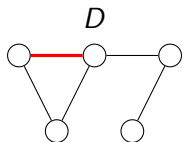

An alternating cycle

Augmenting path

Augmenting path is a simple alternating path between exposed vertices

M

exposed vertex

alternating path

augmenting path
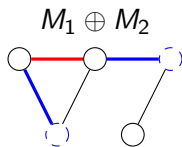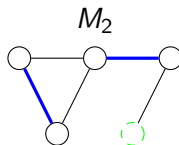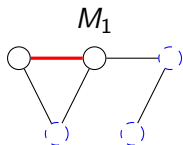
Symmetric difference

Symmetric difference of two sets D and E is defined as
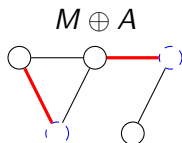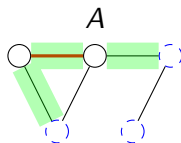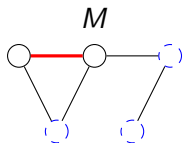$$D \oplus E = (D - E) \cup (E - D)$$

Alternating path

For any two matchings M_1 and M_2 in graph G, the components of the graph formed by $M_1 \oplus M_2$ are paths and circuits which are alternating for M_1 and M_2. Each path end-point is exposed for either M_1 or M_2.

Augmenting path

A is an augmenting path in (G, M). $M \oplus A$ is a matching of G larger than M by one.

Berge's theorem

Theorem - Berge(1957)

M is not a maximum matching if and only if there exists an augmenting path with respect to M

- Proof: if M_2 is a larger matching than M, some component of graph $M \oplus M_2$ must contain more M_2 edges than M, such a component is an augmenting path for (G, M).
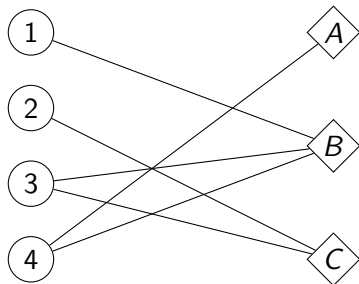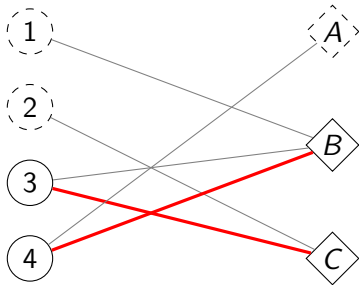
Algorithm

MAXIMUM-MATCHING(G)
1   $M = \emptyset$
2   **repeat**
3   **if** there is an augmenting path P with respect to M
4               $M = M \oplus P$
5   **until** there isn't an augmenting path with respect to M
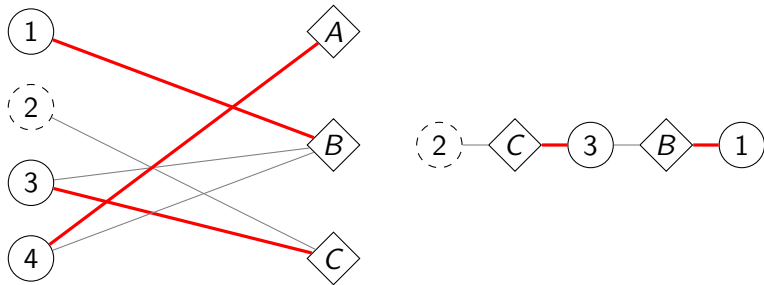6   **return** M

Bipartite Matching

Left circles represent boys, right diamonds represent girls, and
edges are their preferences. We want to make maximum number of
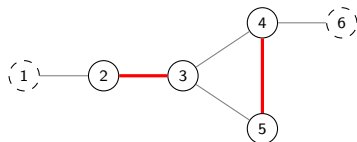couples.

Find An Augmenting Path Using BFS
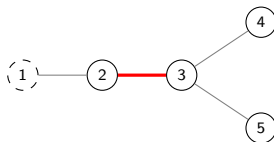
Find An Augmenting Path Using BFS

Examples of BFS failure on non-bipartite graphs
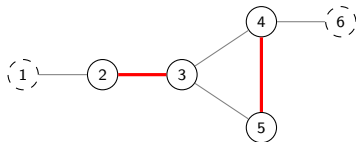
- Initial graph

- Using BFS

Examples of BFS failure on non-bipartite graphs
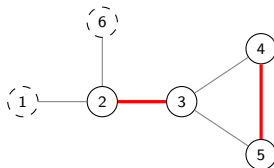
- Initial graph

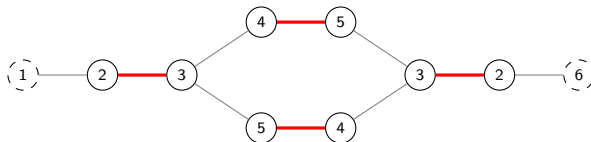- Allow a vertex to be visited at both odd and even levels, we find an augmenting path

Examples of BFS failure on non-bipartite graphs
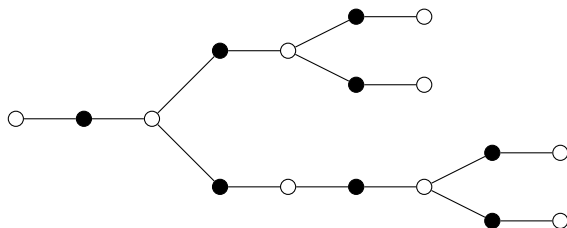
▶ Initial graph

▶ But the augmenting path we find may not be a simple path

Alternating Tree

Alternating Tree is a tree J, each of whose edges joins an odd
vertex to an even vertex so that each odd vertex of J
meets exactly two edges of J.

- An alternating tree contains one more even vertex
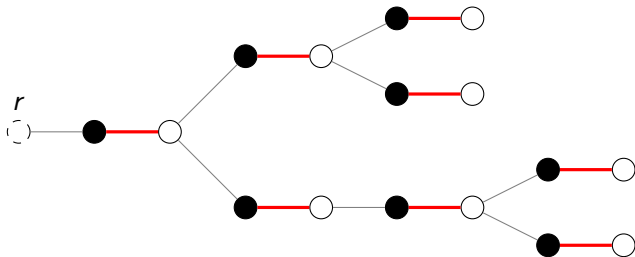than odd vertices.

Planted Tree

Planted tree is an alternating tree $J(M)$ of G for matching M s.t.
$M \cap J$ is a maximum matching of J.

Root is a vertex r in J which is exposed.

Planted Tree

In planted tree $J(M)$ every alternating path $P(M)$, which has even vertex v and the matching edge to v at one of its ends, is a subpath of the alternating path $P_v(M)$ in $J(M)$ which joins v to the root r.

From any vertex in the planted tree we can easily find the path back to the root!
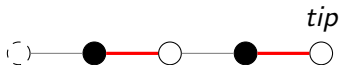
Augmenting Tree

Augmenting tree is a planted tree $J(M)$ plus an edge e of G such that one end-point of e is an even vertex v_1 of J and the other end-point v_2 is exposed not in J.
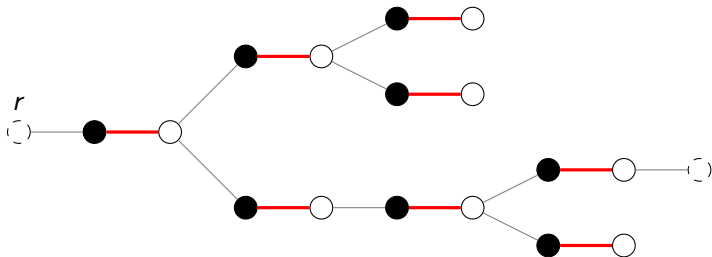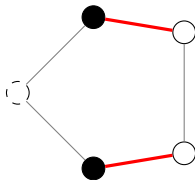
Stem

Stem is an alternating path with an exposed vertex at one end and a matching edge at the other end.

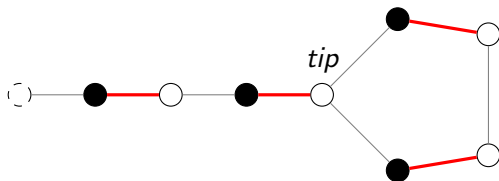Tip is the non-exposed end vertex in the stem.

Blossom

Blossom is an odd cycle in G for which $M \cap B$ is a maximum matching in B with one vertex exposed for $M \cap B$.
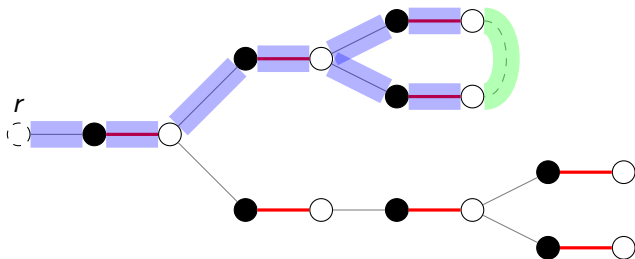
Flower

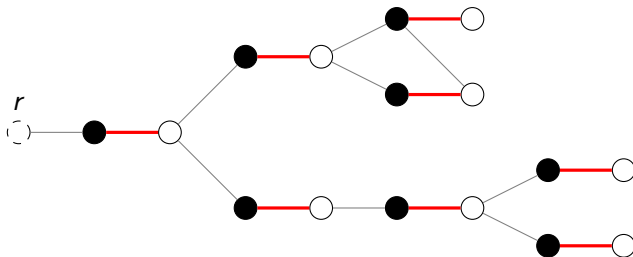Flower consists of a blossom and a stem which intersect only
at the tip of the stem.

Flowered tree

Flowered tree is a planted tree J plus an edge e of G which joins a pair of even vertices of J. The union of e and the two paths which join its even-vertex end-points to the root of of J is a flower, F.
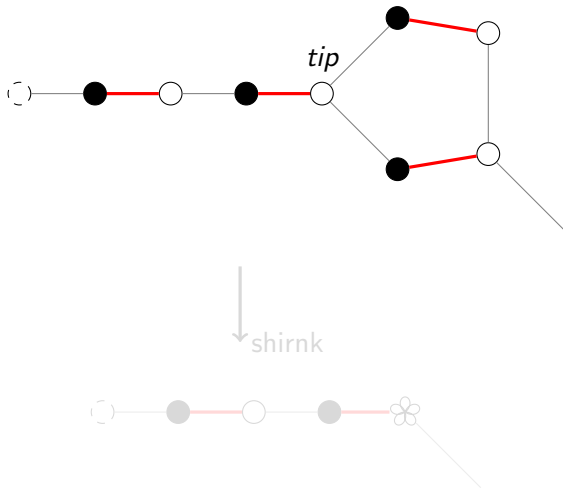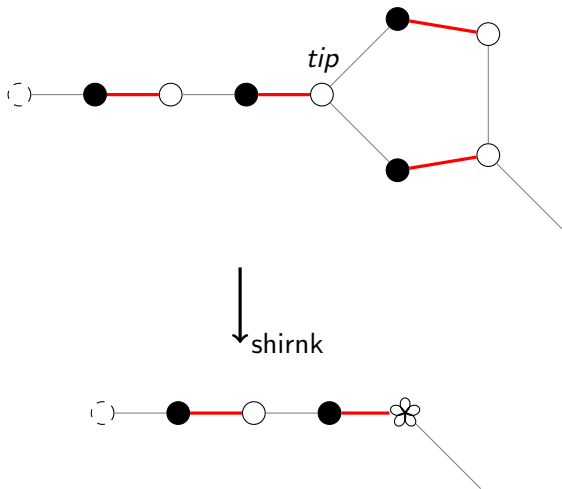
Hungarian tree

Hungarian tree is an alternating tree whose even vertices are
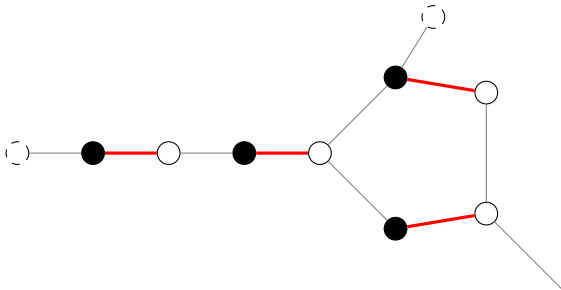joined by edges of G only to its inner vertices.
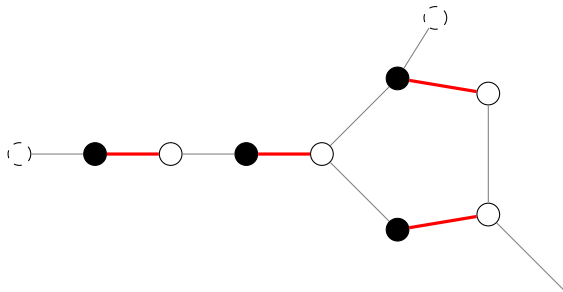
Shrinking the blossom

tip
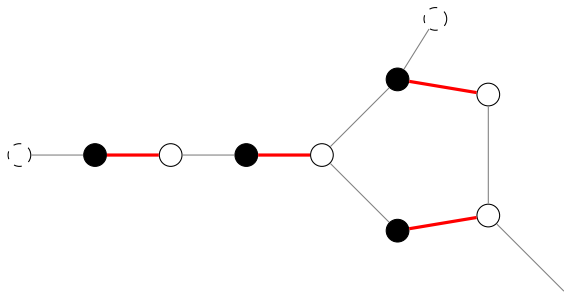
shirnk

Shrinking the blossom

tip

shirnk

Finding augmenting path
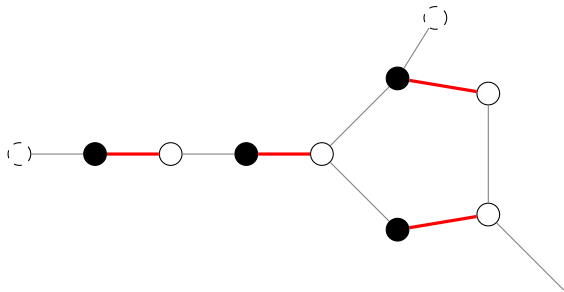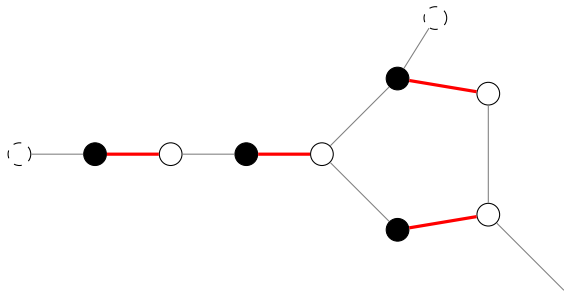
A exposed vertex is a planted tree.

Finding augmenting path

Extend to a larger planted tree
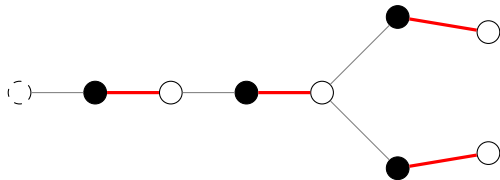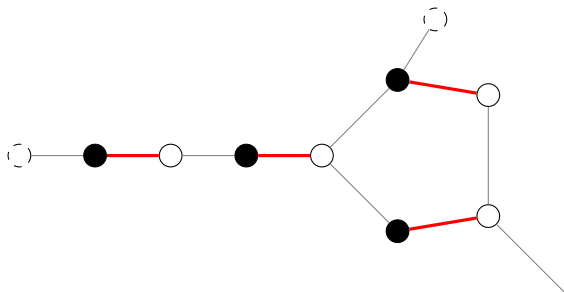
Finding augmenting path

Extend to a larger planted tree..
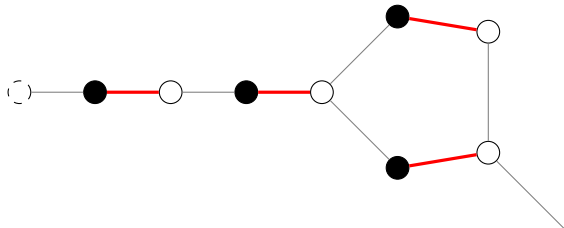
Finding augmenting path

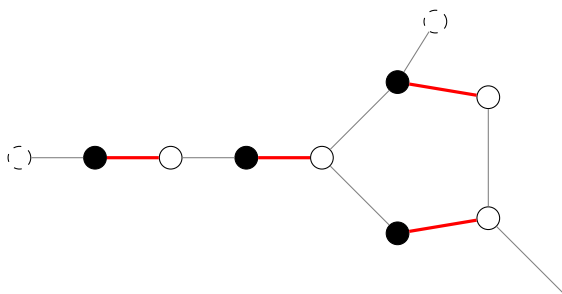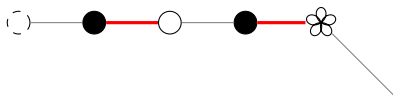Extend to a larger planted tree....

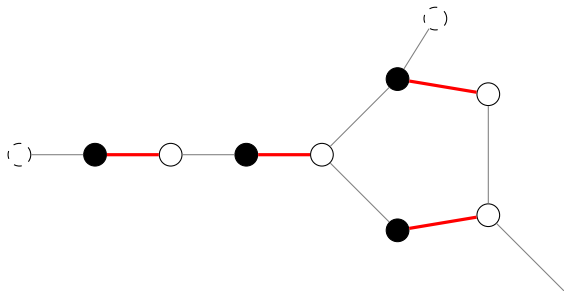# Finding augmenting path

Find a blossom!

Finding augmenting path

Shrink it!

Finding augmenting path

Extend to an augmenting tree!
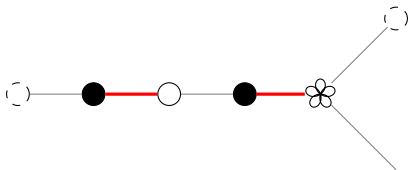
Finding augmenting path
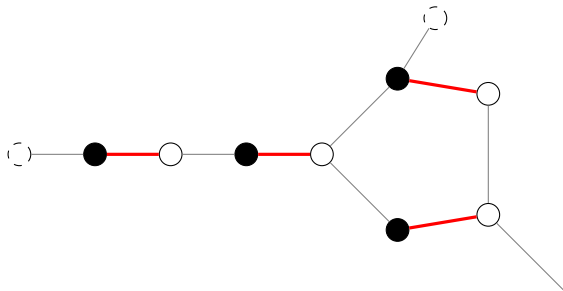
Find the augmenting path.
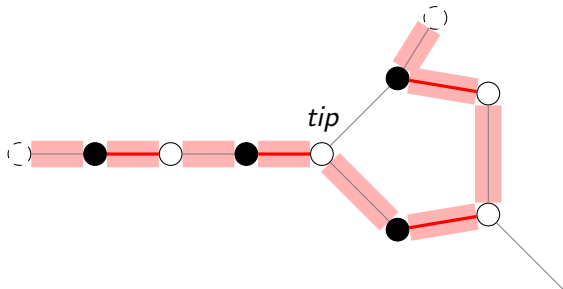
Examples

A graph $G = (V, E)$ and a matching M.
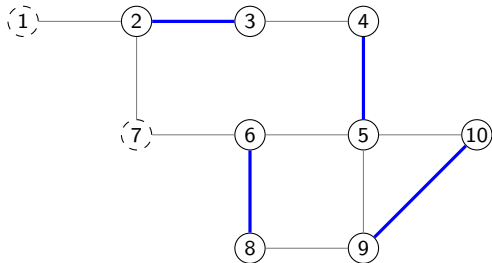
Start a BFS from 1, encounter the odd cycle 5-10-9.
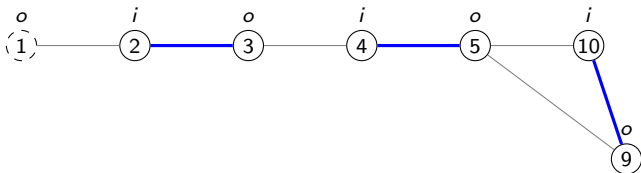
Examples

Shrink 5,10,9 into a single macrovertex. Continue the search, and encounter the cycle (5,10,9)-6-8.
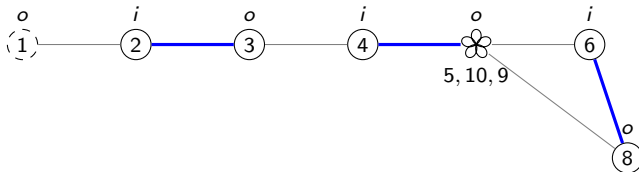
Shrink (5,10,9),6,8 into a single macro vertex. Continue the serch, and encounter a exposed vertex 7.
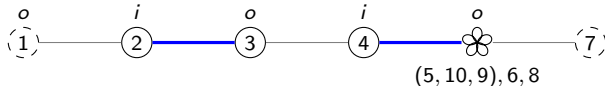
Examples

An augmenting path in the shrunken graph is found. By unshrinking, we get the following augmenting path P in the original graph.

Applying $M = M \oplus P$ yeilds following enlarged matching in the original graph.
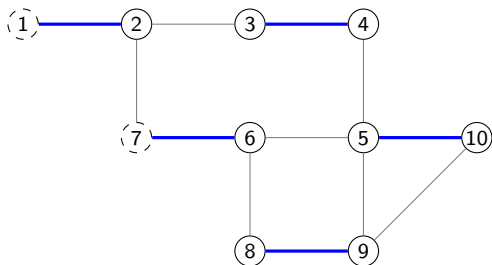
Matching-duality theorem

Linear programming duality theorem

If

$$x \geq 0, Ax \leq c$$
$$y \geq 0, A^T y \geq b$$

for given real vectors b and c and real matrix A, then for real vectors x and y,

$$max_x(b, x) = min_y(c, y)$$

when such extrema exist.

König theorem

In a bipartite graph, the maximum size of a matching is equal to the minimum size of a vertex cover.

Matching-duality theorem

Odd set cover in a graph consists of a collection of vertices S and odd-cardinality sets of vertices $O_1, O_2, ..., O_t$, disjoint from one another and from S, such that every edge of G is either incident with a vertex in S or lies within an odd set O_j.

The capacity of the odd-set cover is defined as: $|S| + \sum\limits_{j=1}^{t} \frac{|O_j|-1}{2}$

vertices S

odd-sets O$_j$
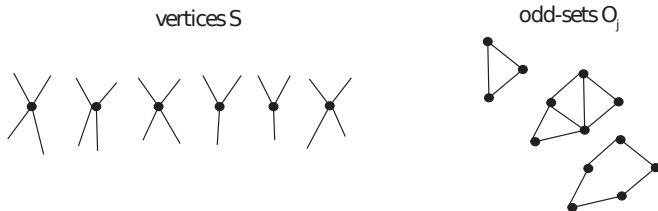
Matching-duality theorem

General König theorem

If M is a maximum matching and C is a minimum odd-set cover then

$$|M| = capacity(C)$$

- ▶ Proof:

    It is obvious that the capacity-sum of any odd-set cover in G is at least as large as the cardinality of any matching in G, so we have only to prove the existence in G of an odd-set cover and a matching for which the numbers are equal.

Matching-duality theorem

- Proof:

  For a pertect matching M with no exposed vertices, the odd-set cover consists of two sets, one set containing one of the vertices, the other containing all the other vertices.

  For a graph which has a matching with one exposed vertices, the odd-set cover may be taken as one set containing all the vertices of the graph.

  The general case can be proven by induction.