A Fast Matching Algorithm

Algorithm 28 Bimatch-Hopcroft-Karp\( (G) \)

1: \( M \leftarrow \emptyset \)
2: repeat
3: let \( \mathcal{P} = \{P_1, \ldots, P_k\} \) be maximal set of vertex-disjoint, shortest augmenting path w.r.t. \( M \).
4: \( M \leftarrow M \oplus (P_1 \cup \cdots \cup P_k) \)
5: until \( \mathcal{P} = \emptyset \)
6: return \( M \)

We call one iteration of the repeat-loop a phase of the algorithm.
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Lemma 1

Given a matching $M$ and a maximal matching $M^*$ there exist $|M^*| - |M|$ vertex-disjoint augmenting path w.r.t. $M$.

Proof:

Similar to the proof that a matching is optimal if it does not contain an augmenting path.

Consider the graph $G = (V, M \cup M^*)$ and mark edges in this graph blue if they are in $M$ and red if they are in $M^*$.

The connected components of $G$ are cycles and paths.

The graph contains $k = |M^*| - |M|$ more red edges than blue edges.

Hence, there are at least $k$ components that form a path starting and ending with a red edge. These are augmenting paths w.r.t. $M$. 
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Let $P_1,\ldots,P_k$ be a maximal collection of vertex-disjoint, shortest augmenting paths w.r.t. $M$ (let $\ell = |P_i|$).

$M' \equiv M \oplus (P_1 \cup \cdots \cup P_k) = M \oplus P_1 \oplus \cdots \oplus P_k$.

Let $P$ be an augmenting path in $M'$.

Lemma 2
The set $A \equiv M \oplus (M' \oplus P) = (P_1 \cup \cdots \cup P_k) \oplus P$ contains at least $(k + 1)\ell$ edges.
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Proof.

- The set describes exactly the symmetric difference between matchings $M$ and $M' \oplus P$.
- Hence, the set contains at least $k + 1$ vertex-disjoint augmenting paths w.r.t. $M$ as $|M'| = |M| + k + 1$.
- Each of these paths is of length at least $\ell$. 
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Lemma 3

\( P \) is of length at least \( \ell + 1 \). This shows that the length of a shortest augmenting path increases between two phases of the Hopcroft-Karp algorithm.

Proof.

If \( P \) does not intersect any of the \( P_1, \ldots, P_k \), this follows from the maximality of the set \{\( P_1, \ldots, P_k \)\}.

Otherwise, at least one edge from \( P \) coincides with an edge from paths \( P_1, \ldots, P_k \).

This edge is not contained in \( A \).

Hence, \( |A| \leq k\ell + |P| - 1 \).

The lower bound on \( |A| \) gives \( (k + 1)\ell \leq |A| \leq k\ell + |P| - 1 \), and hence \( |P| \geq \ell + 1 \).
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If the shortest augmenting path w.r.t. a matching $M$ has $\ell$ edges then the cardinality of the maximum matching is of size at most $|M| + \frac{|V|}{\ell + 1}$.

Proof.
The symmetric difference between $M$ and $M^*$ contains $|M^*| - |M|$ vertex-disjoint augmenting paths. Each of these paths contains at least $\ell + 1$ vertices. Hence, there can be at most $\frac{|V|}{\ell + 1}$ of them.
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Lemma 4
The Hopcroft-Karp algorithm requires at most $2\sqrt{|V|}$ phases.

Proof.

- After iteration $\lfloor \sqrt{|V|} \rfloor$ the length of a shortest augmenting path must be at least $\lfloor \sqrt{|V|} \rfloor + 1 \geq \sqrt{|V|}$.
- Hence, there can be at most $|V|/(\sqrt{|V|} + 1) \leq \sqrt{|V|}$ additional augmentations.
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Lemma 5

One phase of the Hopcroft-Karp algorithm can be implemented in time $O(m)$.

construct a “level graph” $G'$:

- construct Level 0 that includes all free vertices on left side $L$
- construct Level 1 containing all neighbors of Level 0
- construct Level 2 containing matching neighbors of Level 1
- construct Level 3 containing all neighbors of Level 2
- ...  
- stop when a level (apart from Level 0) contains a free vertex 

can be done in time $O(m)$ by a modified BFS
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- a shortest augmenting path **must** go from Level 0 to the last layer constructed
- it can only use edges between layers
- construct a **maximal** set of vertex disjoint augmenting path connecting the layers
- for this, go forward until you either reach a free vertex or you reach a “dead end” \( v \)
- if you reach a free vertex delete the augmenting path and all incident edges from the graph
- if you reach a dead end backtrack and delete \( v \) together with its incident edges
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Analysis: Shortest Augmenting Path for Flows

cost for searches during a phase is $\mathcal{O}(mn)$

- a search (successful or unsuccessful) takes time $\mathcal{O}(n)$
- a search deletes at least one edge from the level graph

there are at most $n$ phases

Time: $\mathcal{O}(mn^2)$. 
Analysis for Unit-capacity Simple Networks

cost for searches during a phase is $O(m)$
  ▶ an edge/vertex is traversed at most twice

need at most $O(\sqrt{n})$ phases
  ▶ after $\sqrt{n}$ phases there is a cut of size at most $\sqrt{n}$ in the residual graph
  ▶ hence at most $\sqrt{n}$ additional augmentations required

Time: $O(m\sqrt{n})$. 

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