Journal of Combinatorial Theory, Series B **82**, 319–321 (2001)
doi:10.1006/jctb.2000.2029, available online at http://www.idealibrary.com on IDEAL®

NOTE

A Short Proof of Mader's $\mathcal{S}$-Paths Theorem

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Received April 19, 2000

For an undirected graph $G=(V,E)$ and a collection $\mathcal{S}$ of disjoint subsets of V, an *$\mathcal{S}$-path* is a path connecting different sets in $\mathcal{S}$. We give a short proof of Mader's min-max theorem for the maximum number of disjoint $\mathcal{S}$-paths. © 2001 Academic Press

Let $G=(V,E)$ be an undirected graph and let $\mathcal{S}$ be a collection of disjoint subsets of V. An *$\mathcal{S}$-path* is a path connecting two different sets in $\mathcal{S}$. Mader [4] gave the following min-max relation for the maximum number of (vertex-) disjoint $\mathcal{S}$-paths, where $S:=\bigcup\mathcal{S}$.

Mader's $\mathcal{S}$-Paths Theorem. *The maximum number of disjoint $\mathcal{S}$-paths is equal to the minimum value of*

$$|U_0|+\sum_{i=1}^{n}\lfloor\tfrac{1}{2}|B_i|\rfloor, \tag{1}$$

taken over all partitions $U_0, ..., U_n$ of V such that each $\mathcal{S}$-path disjoint from U_0 traverses some edge spanned by some U_i. Here B_i denotes the set of vertices in U_i that belong to S or have a neighbour in $V\setminus(U_0\cup U_i)$.

Lovász [3] gave an alternative proof by deriving it from his matroid matching theorem. Here we give a short proof of Mader's theorem.

Let μ be the minimum value obtained in (1). Trivially, the maximum number of disjoint $\mathcal{S}$-paths is at most μ, since any $\mathcal{S}$-path disjoint from U_0 and traversing an edge spanned by U_i traverses at least two vertices in B_i.

I. First, the case where $|T|=1$ for each $T\in\mathcal{S}$ was shown by Gallai [2] by reduction to matching theory as follows: Let the graph $\tilde{G}=(\tilde{V},\tilde{E})$ arise from G by adding a disjoint copy G' of $G-S$ and making the copy v' of each $v\in V\setminus S$ adjacent to v and to all neighbours of v in G.

0095-8956/01 $35.00

We claim that $\tilde{G}$ has a matching of size $\mu + |V \backslash S|$. Indeed, by the Tutte–Berge formula [5, 1] it suffices to prove that for any $\tilde{U}_0 \subseteq \tilde{V}$,

$$|\tilde{U}_0| + \sum_{i=1}^{n} \lfloor \tfrac{1}{2} |\tilde{U}_i| \rfloor \geqslant \mu + |V \backslash S|, \tag{2}$$

where $\tilde{U}_1, ..., \tilde{U}_n$ are the components of $\tilde{G} - \tilde{U}_0$. Now if for some $v \in V \backslash S$ exactly one of v, v' belongs to $\tilde{U}_0$, then we can delete it from $\tilde{U}_0$, thereby not increasing the left-hand side of (2). So we can assume that for each $v \in V \backslash S$, either $v, v' \in \tilde{U}_0$ or $v, v' \notin \tilde{U}_0$. Let $U_i := \tilde{U}_i \cap V$ for $i = 0, ..., n$. Then $U_1, ..., U_n$ are the components of $G - U_0$, and we have

$$|\tilde{U}_0| + \sum_{i=1}^{n} \lfloor \tfrac{1}{2} |\tilde{U}_i| \rfloor = |U_0| + \sum_{i=1}^{n} \lfloor \tfrac{1}{2} |U_i \cap S| \rfloor + |V \backslash S| \geqslant \mu + |V \backslash S| \tag{3}$$

(since in this case $B_i = U_i \cap S$ for $i = 1, ..., n$), showing (2).

So $\tilde{G}$ has a matching M of size $\mu + |V \backslash S|$. Let N be the matching $\{vv' \mid v \in V \backslash S\}$ in $\tilde{G}$. As $|M| = \mu + |V \backslash S| = \mu + |N|$, the union $M \cup N$ has at least μ components with more edges in M than in N. Each such component is a path connecting two vertices in S. Then contracting the edges in N yields μ disjoint $\mathscr{S}$-paths in G.

II. We now consider the general case. Fixing V, choose a counterexample E, $\mathscr{S}$ minimizing

$$|E| - |\{\{t, u\} \mid t, u \in V, \exists T, U \in \mathscr{S} : t \in T, u \in U, T \neq U\}|. \tag{4}$$

By Part I, there exists a $T \in \mathscr{S}$ with $|T| \geqslant 2$. Then T is independent in G, since any edge e spanned by T can be deleted without changing the maximum and minimum value in Mader's theorem (as any $\mathscr{S}$-path traversing e contains an $\mathscr{S}$-path not traversing e and as deleting e does not change any set B_i), while decreasing (4).

Choose $s \in T$. Replacing $\mathscr{S}$ by $\mathscr{S}' := (\mathscr{S} \backslash \{T\}) \cup \{T \backslash \{s\}, \{s\}\}$ decreases (4), but not the minimum in Mader's theorem (as each $\mathscr{S}$-path is an $\mathscr{S}'$-path and as $\bigcup \mathscr{S}' = S$). So there exists a collection $\mathscr{P}$ of μ disjoint $\mathscr{S}'$-paths. We can assume that no path in $\mathscr{P}$ has any internal vertex in S.

Necessarily, there is a path $P_0 \in \mathscr{P}$ connecting s with another vertex in T, all other paths in $\mathscr{P}$ being $\mathscr{S}$-paths. Let u be an internal vertex of P_0. Replacing $\mathscr{S}$ by $\mathscr{S}'' := (\mathscr{S} \backslash \{T\}) \cup \{T \cup \{u\}\}$ decreases (4), but not the minimum in Mader's theorem (as each $\mathscr{S}$-path is an $\mathscr{S}''$-path and as $\bigcup \mathscr{S}'' \supset S$). So there exists a collection $\mathscr{Q}$ of μ disjoint $\mathscr{S}''$-paths. Choose $\mathscr{Q}$ such that no internal vertex of any path in $\mathscr{Q}$ belongs to $S \cup \{u\}$ and such that $\mathscr{Q}$ uses a minimal number of edges not used by $\mathscr{P}$.

Necessarily, u is an end of some path $Q_0 \in \mathscr{Q}$, all other paths in $\mathscr{Q}$ being $\mathscr{S}$-paths. As $|\mathscr{P}| = |\mathscr{Q}|$ and as u is not an end of any path in $\mathscr{P}$, there exists an end v of some path $P \in \mathscr{P}$ that is not an end of any path in $\mathscr{Q}$. Now P intersects at least one path in $\mathscr{Q}$ (since otherwise $P \neq P_0$, and $(\mathscr{Q} \setminus \{Q_0\}) \cup \{P\}$ would consist of μ disjoint $\mathscr{S}$-paths). So when following P starting at v, there is a first vertex w that is on some path in $\mathscr{Q}$, say, on $Q \in \mathscr{Q}$.

For any end x of Q let Q^x be the $x-w$ part of Q. Let P^v be the $v-w$ part of P and let U be the set in $\mathscr{S}''$ containing v. Then for any end x of Q we have that Q^x is part of P or the other end of Q belongs to U, since otherwise by rerouting part Q^x of Q along P^v, Q remains an $\mathscr{S}''$-path disjoint from the other paths in $\mathscr{Q}$, while we decrease the number of edges used by $\mathscr{Q}$ and not by $\mathscr{P}$, contradicting the minimality assumption.

Let y, z be the ends of Q. We can assume that $y \notin U$. Then Q^z is part of P, hence Q^y is not a part of P (as Q is not a part of P, as otherwise $Q = P$, and hence v is an end of Q), so $z \in U$. As z is on P and also as v belongs to U and is on P, we have $P = P_0$. So $U = T \cup \{u\}$ and $Q = Q_0$ (since Q^z is part of P, so $z = u$). But then rerouting part Q^z of Q along P^v gives μ disjoint $\mathscr{S}$-paths, contradicting our assumption.

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