PARTITION OF A GRAPH INTO CYCLES AND VERTICES

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Partition of a Graph into Cycles and Vertices

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Abstract

Let $G$ be a graph of order $n$ and $k$ a positive integer. A set of subgraphs $\mathcal{H} = \{H_1, H_2, \ldots, H_k\}$ is called a $k$-weak cycle partition (abbreviated $k$-WCP) of $G$ if $H_1, \ldots, H_k$ are vertex disjoint subgraphs of $G$ such that $V(G) = \bigcup_{i=1}^{k} V(H_i)$ and for all $i$, $1 \leq i \leq k$, $H_i$ is a cycle or $K_1$ or $K_2$. It has been shown by Enomoto and Li that if $|G| = n \geq k$ and if the degree sum of any pair of nonadjacent vertices is at least

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n - k + 1, then G has a k-WCP. We prove that if G has a k-WCP and if the minimum degree is at least \( \frac{n+2k}{3} \), then G can be partitioned into k subgraphs \( H_i \), 1 \( \leq i \leq k \), where \( H_i \) is a cycle or \( K_1 \).

1 Introduction

In this paper, we only consider finite undirected graphs without loops and multiple edges. For a vertex \( x \) of a graph \( G \), the neighborhood of \( x \) in \( G \) is denoted by \( N_G(x) \), and \( d_G(x) = |N_G(x)| \) is the degree of \( x \) in \( G \). With a slight abuse of notation, for a subgraph \( H \) of \( G \) and a vertex \( x \in V(G) - V(H) \), we also denote \( N_H(x) = N_G(x) \cap V(H) \) and \( d_H(x) = |N_H(x)| \). For a subset \( S \) of \( V(G) \), the subgraph induced by \( S \) is denoted by \( \langle S \rangle \), and \( G - S = \langle V(G) - S \rangle \). For a graph \( G \), \( |V(G)| \) is the order of \( G \), \( \delta(G) \) is the minimum degree of \( G \), and

\[
\sigma_2(G) = \min \{d_G(x) + d_G(y) | x, y \in V(G), x \neq y, xy \notin E(G)\}
\]

is the minimum degree sum of nonadjacent vertices. (When \( G \) is a complete graph, we define \( \sigma_2(G) = \infty \).)

If \( G = c_1c_2 \cdots c_k \) is a cycle, we let \( c_i \overrightarrow{c_j} \), for \( i \leq j \), be the subpath \( c_i c_{i+1} \cdots c_j \), and \( c_i \overleftarrow{c_j} = c_j c_{j-1} \cdots c_i \), where the indices are taken modulo \( p \). For any \( i \) and any \( l \geq 2 \), we put \( c_i^l = c_{i+l} \), \( c_i^{-l} = c_{i-l} \), \( c_i^l \) and \( c_i^{-l} \).

In this paper, “disjoint” means “vertex-disjoint,” since we only deal with partitions of the vertex set.

Suppose \( H_1, \cdots, H_k \) are disjoint subgraphs of \( G \) such that \( V(G) = \bigcup_{i=1}^{k} V(H_i) \) and for all \( i, 1 \leq i \leq k \), \( H_i \) is a cycle or \( K_1 \) or \( K_2 \), then we call \( H = \{H_1, H_2, \ldots, H_k\} \) a k-weak cycle partition (abbreviated k-WCP) of \( G \). If, in addition, for all \( i, 1 \leq i \leq k \), \( H_i \) is a cycle, then the union of these \( H_i \) is a 2-factor of \( G \) with \( k \) components. A sufficient condition for the existence of a 2-factor with a specified number of components was given by Brandt et al. [1].

Theorem 1 Suppose \( |G| = n \geq 4k \) and \( \sigma_2(G) \geq n \). Then \( G \) can be partitioned into \( k \) cycles, that is, \( G \) contains \( k \) disjoint cycles \( H_1, \cdots, H_k \) satisfying \( V(G) = \bigcup_{i=1}^{k} V(H_i) \).
In order to generalize 2-factors, Enomoto and Li [5] defined \( k \)-WCP by considering single edge and single vertex as degenerated cycles. They showed that weaker conditions than Theorem 1 are sufficient for the existence of \( k \)-WCP.

**Theorem 2** Let \( G \) be a graph of order \( n \) and \( k \) any positive integer with \( k \leq n \). If \( \sigma_2(G) \geq n - k + 1 \), then \( G \) has a \( k \)-WCP, except \( G = C_5 \) and \( k = 2 \).

Note that a single vertex can be considered as a cycle of one vertex. Our purpose of this paper is to study the existence of a \( k \)-WCP \( \{H_1, H_2, \ldots, H_k\} \), each of \( H_i \) is either a cycle or a single vertex. Firstly, we show that under a weaker condition on degree sum, there is a \( k \)-WCP containing at most one \( K_2 \). Secondly, we show that under a weaker condition on minimum degree, there is a \( k \)-WCP without \( K_2 \).

**Theorem 3** Let \( G \) be a graph of order \( n \geq k + 12 \) that has a \( k \)-WCP. If \( \sigma_2(G) \geq \frac{2n + k - 4}{3} \), then \( G \) has a \( k \)-WCP containing at most one subgraph isomorphic to \( K_2 \).

**Theorem 4** Let \( G \) be a \( k \)-WCP graph of order \( n \) that has a \( k \)-WCP. If \( \delta(G) \geq \frac{n + 2k}{3} \), then \( G \) has a \( k \)-WCP without \( K_2 \).

The graphs \( G_t = mK_1 + (m + t)K_2 \), \( t \in \{1, 2\} \), show that both Theorem 3 and Theorem 4 are best possible. By Theorem 2 and Theorem 4, we get

**Theorem 5** Suppose \(|G| = n \geq 7k - 3\) and \( \delta(G) \geq \frac{n - k + 1}{2} \). Then \( G \) can be partitioned into \( k \) disjoint subgraphs \( H_i \), \( 1 \leq i \leq k \), where \( H_i \) is a cycle or \( K_1 \).

### 2 Proof of Theorem 3

Let \( \mathcal{H} \) be a \( k \)-WCP such that \( t(\mathcal{H}) \), the number of \( K_2 \)'s in \( \mathcal{H} \), achieves the minimum.
Let us suppose, to the contrary, that Theorem 3 is false. Then, \( t := t(\mathcal{H}) \geq 2 \). Denote \( \mathcal{H} = \{H_1, H_2, \ldots, H_k\} \) so that \( H_i, 1 \leq i \leq t, \) is a \( K_2 \) of \( G \). Suppose \( V(H_i) = \{u_i, v_i\}, 1 \leq i \leq t \). Set
\[
A = \{v \in V(G) : v \text{ is not in any cycle of } \mathcal{H}\},
\]
and
\[
B = \{v \in V(G) : v \text{ is in some cycle of } \mathcal{H}\}.
\]
Then, \( V(G) = A \cup B \). We first have
\[
(2.1) \quad N_A(u_i) \cap N_A(v_i) = \emptyset, \quad 1 \leq i \leq t.
\]
Suppose, to the contrary, that \( x \in N_A(u_i) \cap N_A(v_i) \). Then, \( x \in V(H_j) \) for some \( j \) with \( j \neq i \) and \( |V(H_j)| \leq 2 \). Set \( C^{(1)} = xu_iu_i x \) and
\[
\mathcal{H}^{(1)} = \begin{cases} 
(\mathcal{H} \setminus \{H_i, H_j\}) \cup \{C^{(1)}, V(H_j) \setminus \{x\}\}, & \text{if } j \leq t \\
(\mathcal{H} \setminus \{H_i, H_j, H_l\}) \cup \{C^{(1)}, u_i, v_i\}, & \text{if } j > t,
\end{cases}
\]
where \( l \) is any integer in \( \{1, 2, \ldots, t\} \setminus \{i\} \). Then, \( \mathcal{H}^{(1)} \) is a \( k \)-WCP with \( t(\mathcal{H}^{(1)}) < t \), contrary to the choice of \( \mathcal{H} \). Hence (2.1) is true.

(2.2) If \( t \geq 3 \), then \( d_{H_i}(u_j) + d_{H_i}(v_j) \leq 1, \quad 1 \leq i \neq j \leq t \).

To derive (2.2), we suppose, without loss of generality, that \( d_{H_1}(u_1) + d_{H_2}(v_1) > 1 \). Then, since both \( \langle H_1 \rangle \) and \( \langle H_2 \rangle \) are connected, \( V(H_1) \cup V(H_2) \) contains a cycle \( C^{(2)} \). Define
\[
\mathcal{H}^{(2)} = \begin{cases} 
(\mathcal{H} \setminus \{H_1, H_2\}) \cup \{C^{(2)}, (V(H_1) \cup V(H_2)) \setminus V(C^{(2)})\}, & \text{if } |C^{(2)}| = 3 \\
(\mathcal{H} \setminus \{H_1, H_2, H_3\}) \cup \{C^{(2)}, u_3, v_3\}, & \text{if } |C^{(2)}| = 4.
\end{cases}
\]
Then, \( \mathcal{H}^{(2)} \) is a \( k \)-WCP with at most \( t - 2 \) subgraphs isomorphic to \( K_2 \), a contradiction. Hence (2.2) is true.

(2.3) \( d_{H_i}(u_i) = d_{H_i}(v_i) = 0, \quad 2 \leq i \leq t \).

Suppose (2.3) is false, then \( V(H_1) \cup V(H_t) \) contains a path, say \( u_1v_1u_1v_t \), of length 3. By (2.1), we have \( u_1v_1u_1v_t \notin E(G) \). Hence,
\[
d_G(u_1) + d_G(v_1) + d_G(u_t) + d_G(v_t) \geq 2\sigma_2(G).
\]
On the other hand, to avoid a \( k \)-WCP with \( t - 2 \) \( K_2 \)'s, we have for every cycle \( C \) in \( H \) that \( N_C^{++}(u_1), N_C^{++}(v_1), N_C(u_i), N_C(v_i) \) are pairwise disjoint. This implies \( d_C(u_1) + d_C(v_1) + d_C(u_i) + d_C(v_i) \leq |C| \), and hence

\[
d_B(u_1) + d_B(v_1) + d_B(u_i) + d_B(v_i) \leq |B|.
\]

Note that \( \{ H_j : 1 \leq j \leq k, |H_j| \leq 2 \} \) is a \((|A| - t)\)-weak partition of \( \langle A \rangle \). By (2.1) and (2.2), we get

\[
d_A(u_1) + d_A(v_1) + d_A(u_i) + d_A(v_i) \leq \begin{cases} 2|A|, & \text{if } t = 2 \\ 2(|A| - t + 1), & \text{if } t \geq 3. \end{cases}
\]

This together with \(|A| \leq \begin{cases} (k - 1) + t, & \text{if } t \leq 11 \\ k + t, & \text{if } t \geq 12 \end{cases} \) implies

\[
d_A(u_1) + d_A(v_1) + d_A(u_i) + d_A(v_i) \leq |A| + k + 1.
\]

Since \( V(G) = A \cup B \), we have

\[
d_G(u_1) + d_G(v_1) + d_G(u_i) + d_G(v_i) \leq (|A| + k + 1) + |B| = n + k + 1,
\]

which implies \( \frac{4n+2k-8}{3} \leq 2\sigma_2(G) \leq n + k + 1 \), contrary to \( n \geq k + 12 \). Hence, (2.3) is true.

(2.4) \( d_A(u_1) + d_A(v_1) \leq \frac{2|A| + k - 5}{3} \).

Recall that \( \{ H_i : 1 \leq i \leq k, |H_i| \leq 2 \} \) is a \((|A| - t)\)-WCP of \( \langle A \rangle \) with \( t \) subgraphs isomorphic to \( K_2 \) and \( |A| - 2t \) subgraphs isomorphic to \( K_1 \). By (2.1) and (2.3), we have \( d_A(u_1) + d_A(v_1) \leq |A| - 2t + 2 \leq \min \{ |A| - 2, k - t + 2 \} \leq \frac{2(|A| - 2 + k - 2)}{3} \). Hence, (2.4) is true for \( t \geq 3 \). Assume now \( t = 2 \). Then, \(|A| \leq k + 2\) implying that \( B \neq \emptyset \). So, \(|A| \leq (k - 1) + 2\) and the assertion follows from \( d_A(u_1) + d_A(v_1) \leq |A| - 2t + 2 = |A| - 2 \leq k - 1 \). Therefore, (2.4) is true.

(2.5) \( V(G) \neq A \).

Indeed, if \( V(G) = A \), then by (2.4) we have \( d_G(u_1) + d_G(v_1) \leq \frac{2n+k-8}{3} < \sigma_2(G) \). Similarly, \( d_G(u_2) + d_G(v_2) \leq \sigma_2(G) \). Hence,

\[
d_G(u_1) + d_G(v_1) + d_G(u_2) + d_G(v_2) < 2\sigma_2(G).
\]
This implies \( \{u_1u_2, v_1v_2\} \cap E(G) \neq \emptyset \). Without loss of generality, assume \( u_1u_2 \in E(G) \). By (2.1), we have \( u_1v_2, u_2v_1 \notin E(G) \) and hence

\[
(d_G(u_1) + d_G(v_2)) + (d_G(u_2) + d_G(v_1)) \geq 2\sigma_2(G).
\]

This contradiction completes the proof of (2.5).

It follows from (2.5) that \( \mathcal{H} \) contains at least one cycle. Let \( C \) be any cycle in \( \mathcal{H} \).

(2.6) \( N_C^+(u_1) \cap N_C(v_1) = \emptyset \).

To justify (2.6), we assume, to the contrary, that \( x \in N_C^+(u_1) \cap N_C(v_1) \). Set \( C^{(3)} = x \overline{C} x^{-1} u_1v_1x \) and \( \mathcal{H}^{(3)} = (\mathcal{H} \setminus \{C, H_1, H_2\}) \cup \{C^{(3)}, u_2, v_2\} \). Then, \( \mathcal{H}^{(3)} \) is a \( k \)-WCP with \( t(\mathcal{H}^{(3)}) < t(\mathcal{H}) \). This contradiction proves (2.6).

Similarly, we have

(2.7) \( N_C^{++}(u_1) \cap N_C(v_1) = N_C^{++}(u_1) \cap N_C^+(u_1) = \emptyset \).

It follows from (2.6) and (2.7) that \( 2d_G(u_1) + d_G(v_1) \leq |C| \). By symmetry, we also have \( 2d_G(v_1) + d_G(u_1) \leq |C| \). Hence

(2.8) \( d_G(u_1) + d_G(v_1) \leq \frac{2|C|}{3} \).

Note that \( \{V(H_i) : 1 \leq i \leq k, H_i \text{ is a cycle}\} \) is a partition of \( B \). By (2.8), we have

\[
d_B(u_1) + d_B(v_1) \leq \frac{2|B|}{3}.
\]

This together with (2.4) implies \( d_G(u_1) + d_G(v_1) \leq \frac{2|A| + k - 5}{3} + \frac{2|B|}{3} = \frac{2n + k - 5}{3} < \sigma_2(G) \). Similarly, we have \( d_G(u_2) + d_G(v_2) < \sigma_2(G) \). On the other hand, by an argument similar to the proof of (2.5), we can get \( d_G(u_1) + d_G(v_1) + d_G(u_2) + d_G(v_2) \geq 2\sigma_2(G) \). This contradiction completes the proof of Theorem 3.
3 Proof of Theorem 4

Note that $\sigma_2(G) \geq 2\delta(G) \geq \frac{2n+4k}{3}$. By an argument similar to that in the proof of Theorem 3, we can derive that $G$ has a $k$-WCP, which contains at most one subgraph isomorphic to $K_2$. Among all of these partitions, choose one, say $\mathcal{H}$, such that $c(\mathcal{H})$, the number of cycles in the partition, achieves the minimum.

Let us suppose, to the contrary, that Theorem 4 is false. Then, $\mathcal{H}$ contains exactly one subgraph isomorphic to $K_2$. Denote $\mathcal{H} = \{H_1, H_2, \ldots, H_k\}$, where $H_1 = uv$ is a $K_2$ of $\mathcal{H}$.

(3.1) $c(\mathcal{H}) \geq 1$.

Indeed, if $c(\mathcal{H}) = 0$, then $|V(G)| = k + 1$ and hence $\delta(G) \geq \frac{n+2k}{3} > n - 1$, a contradiction. Hence, (3.1) is true.

Define $A$ and $B$ the same as those in Section 2. To avoid a desired $k$-WCP, we have

(3.2) For every cycle $C$ in $\mathcal{H}$, $N_C^{++}(u) \cap N_C(v) = N_C^{++}(u) \cap N_C^{+}(u) = \emptyset$.

(3.3) There exists a cycle $C$ in $\mathcal{H}$ such that $N_C^+(u) \cap N_C(v) \neq \emptyset$.

Indeed, if (3.3) is false, then by (3.2), we have for every cycle $C$ in $\mathcal{H}$ that $2d_C(u) + d_C(v) \leq |C|$, and hence $2d_B(u) + d_B(v) \leq |B|$. Since $|A| = 2 + (k - 1 - c(\mathcal{H})) \leq k$,

$$2d_C(u) + d_C(v) = (2d_A(u) + d_A(v)) + (2d_B(u) + d_B(v)) \leq 3(|A| - 1) + |B| \leq n + 2k - 3,$$

contrary to $\delta(G) \geq \frac{n+2k}{3}$. Hence, (3.3) is true.

By (3.3), there exists a cycle $C$ in $\mathcal{H}$ such that $N_C^+(u) \cap N_C(v) \neq \emptyset$. Let $x \in N_C^+(u) \cap N_C(v)$.

(3.4) $N_C^-(x^{-}) \cap N_C(v) = \emptyset$. 

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Suppose, to the contrary, that \( y \in N_G(x^-) \cap N_G(v) \). Then \( x^-y^- \in E(G) \), which implies \( y \neq x \). Set \( C^{(1)} = y \overarc{C} x^-y^- \overarc{C} xy \). Then \( (H \setminus \{C, H_1\}) \cup \{C^{(1)}, u\} \) is a desired \( k \)-WCP. This contradiction completes the proof of (3.4).

(3.5) \( N_G(v) \cap N_G^{++}(u) = \emptyset \).

To derive (3.5), suppose \( y \in N_G(v) \cap N_G^{++}(u) \). Then, \( y^-u \in E(G) \). Note that \( x^-u \in E(G) \). By (3.2), we have \( y \neq x \). Similarly, by \( x, y \in N_G(v) \), we have \( y \neq x^+ \). Set \( C^{(2)} = y \overarc{C} x^-uy^-yx \). Then \( (H \setminus \{C, H_1\}) \cup \{C^{(2)}, y^-\} \) is a desired \( k \)-WCP. This contradiction proves (3.5).

(3.6) \( N_G^+(x^-) \cap N_G^{++}(u) \subseteq \{x^-, x^+\} \).

Suppose the contrary: \( y \in N_G^+(x^-) \cap N_G^{++}(u) \subseteq \{x^-, x^+\} \). Then, \( y \neq x \). Set \( C^{(3)} = x^-y^- \overarc{C} x^-y^- \overarc{C} x+y \) and \( C^{(4)} = x \overarc{C} y^+ux \). Since \( y \neq x^-x, x^+ \), \( C^{(3)} \) and \( C^{(4)} \) are disjoint cycles of \( G \). So, \( (H \setminus \{C, H_1\}) \cup \{C^{(3)}, C^{(4)}\} \) is a desired \( k \)-WCP. This proves (3.6).

It follows from (3.4)-(3.6) that \( d_G(x^-) + d_G(u) + d_G(v) \leq |C| + 2 \). Similarly, we have \( d_G(x) + d_G(u) + d_G(v) \leq |C| + 2 \). Therefore,

(3.7) \( d_G(x^-) + d_G(x) + 2d_G(u) + 2d_G(v) \leq 2|C| + 4 \).

Note that \( |A| = k + 1 - c(H) \). To avoid a desired \( k \)-WCP, every vertex of \( A \) is not insertable in \( C \). Hence,

(3.8) \( N_A(x^-) \cap N_A(x) = \emptyset \).

(3.9) \( c(H) \geq 2 \).

Indeed, if \( c(H) = 1 \), then by (3.7) we have

\[
d_B(x^-) + d_B(x) + 2d_B(u) + 2d_B(v) \leq 2|B| + 4.
\]

Recall that \( |A| \leq k \). Since \( u, v \in A \), by (3.8),

\[
d_G(x^-) + d_G(x) + 2d_G(u) + 2d_G(v)
\]

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\[ \begin{align*}
&= (d_A(x^-) + d_A(x) + 2d_A(u) + 2d_A(v)) \\
&\quad + (d_B(x^-) + d_B(x) + 2d_B(u) + 2d_B(v)) \\
&\leq (5|A| - 4) + (2|B| + 4) \\
&\leq 2n + 3k,
\end{align*} \]
contrary to \( \delta(G) \geq \frac{n+2k}{3} \). This proves (3.9).

In the following, we let \( C' \) be any cycle in \( \mathcal{H} \setminus \{C\} \). To avoid a desired \( k \)-WCP, we have

(3.10) \( N_{C'}(v) \cap N_{C'}(v) = N_{C'}^{++}(x^-) \cap N_{C'}(v) = \emptyset \).

(3.11) \( N_{C'}^{++}(x^-) \cap N_{C'}(v) = \emptyset \).

Suppose, to the contrary, that \( y \in N_{C'}^{++}(x^-) \cap N_{C'}(v) \). Set
\[ C'' = x \K_{C'} y \]
and \( \mathcal{H}' = (\mathcal{H} \setminus \{C, C', uv\}) \cup \{C'', y-y, u\} \). Then, \( \mathcal{H}' \) is a \( k \)-WCP of \( G \) containing one \( K_2 \) and \( c(\mathcal{H}') < c(\mathcal{H}) \). This contradiction completes the proof of (3.11).

It follows from (3.10) and (3.11) that \( d_{C'}(x^-) + 2d_{C'}(v) \leq |C'| \). Similarly, we have \( d_{C'}(x) + 2d_{C'}(u) \leq |C'| \), and hence

(3.12) \( d_{C'}(x^-) + d_{C'}(x) + 2d_{C'}(u) + 2d_{C'}(v) \leq 2|C'| \).

By (3.7) and (3.12), we see that
\[ d_B(x^-) + d_B(x) + 2d_B(u) + 2d_B(v) \leq 2|B| + 4. \]
By an argument similar to that in the proof of (3.9), we can get a contradiction. This completes the proof of Theorem 4.

References


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