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DIAMETER IN WALK GRAPHS

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ABSTRACT. A walk W of length k is admissible if every two consecutive edges of W are distinct. If G is a graph, then its walk graph $W_k(G)$ has vertex set identical with the set of admissible walks of length k in G. Two vertices are adjacent in $W_k(G)$ if and only if one of the corresponding walks can be obtained from the other by deleting an edge from one end and adding an edge to the other end. We show that if the degree of every vertex in G is more than one, then $W_k(G)$ is connected and we find bounds for the diameter of $W_k(G)$.

1. Introduction and results

All graphs considered in this paper are finite, connected, without loops and multiple edges. By $\delta(G)$ we denote the minimum degree of G and by $d_G(u, v)$ we denote the distance between two vertices, u and v, in G. Let P_k be the set of paths of length k in G; and let W_k be the set of walks of length k in G in which no two consecutive edges are equal. The vertex set of the path graph $P_k(G)$ (of the walk graph $W_k(G)$) is the set P_k (W_k). Two vertices of $P_k(G)$ ($W_k(G)$) are joined by an edge if and only if one can be obtained from the other by “shifting” the corresponding paths (walks) in G.

Path graphs were investigated by Broersma and Hoede [**2**] as a natural generalization of line graphs (observe that $P_1(G)$ is the line graph of G, i.e., $P_1(G) = L(G)$). Walk graphs were investigated by Knor and Niepel [**3**] as a generalization of iterated line graphs. We have $P_1(G) = W_1(G)$, $P_2(G) = W_2(G)$ and for $k \geq 3$ the graph $P_k(G)$ is an induced subgraph of $W_k(G)$.

Using analogous methods as Belan and Jurica for path graphs in [**3**], it is easy to find the lower bound for the diameter of walk graphs:

$$\operatorname{diam}(W_k(G)) \geq \operatorname{diam}(G) - k.$$

Since $P_k(G) = W_k(G)$ if the graph G is a tree, analogously as for path graphs in [**3**], for arbitrary component H of walk graph $W_k(G)$ it can be proved

$$\operatorname{diam}(H) \leq \operatorname{diam}(G) + k(k-2),$$

providing that $\operatorname{diam}(G) \geq k$.

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In this paper we improve these results for graphs which do not contain vertices of degree one.

Theorem 1. *Let G be a graph with diameter $d \geq 1$ and $\delta(G) > 1$.*

A. *If $d \geq k-1$, then* $\operatorname{diam}(W_k(G)) \leq d+k$.

B. *If $d \leq k-2$, then* $\operatorname{diam}(W_k(G)) \leq 2k-2$.

Corollary 2. *Let G be a connected graph with $\delta(G) > 1$. Then $W_k(G)$ is connected.*

We remark that an analogy of Corollary 2 is not true for path graphs. By [**4**], we know that there exists a graph G with $\delta(G) = k-1$, such that $P_k(G)$ is disconnected.

Assertion 3. *For every d, for which $2 \leq d$ and $k-1 \leq d$, there exists a graph G with diameter d and $\delta(G) > 1$, such that* $\operatorname{diam}(W_k(G)) = d+k$.

Problem 4. *Let G be a graph with $\delta(G) > 1$ and let* $\operatorname{diam}(G) < k$. *Are the bounds for* $\operatorname{diam}(W_k(G))$ *of part B of Theorem 1 best possible?*

Theorem 5. *Let G be a graph with $\delta(G) > 1$.*

I. *If k is even, then* $\operatorname{diam}(W_k(G)) \geq \operatorname{diam}(G)$.

II. *If k is odd, then* $\operatorname{diam}(W_k(G)) \geq \operatorname{diam}(G) - 1$.

Observe that if G is a cycle, then $W_k(G)$ is isomorphic to G. Hence the lower bound for $\operatorname{diam}(W_k(G))$ is the best possible if k is even.

Assertion 6. *For every odd number k and $d \geq 2k$, there exists a graph G with diameter d and $\delta(G) > 1$, such that* $\operatorname{diam}(W_k(G)) = d-1$.

It is easy to show that if k is odd and $\operatorname{diam}(G) = 2$, then $W_k(G)$ can not be complete and hence $\operatorname{diam}(W_k(G)) \geq 2$.

We do not know if the lower bound of part II of Theorem 5 is best possible for $3 \leq d < 2k$. The value for the lower bound is equal either to $d-1$ or d.

Problem 7. *Let G be a graph with $\delta(G) > 1$ and let* $\operatorname{diam}(G) < 2k$. *Are the bounds for* $\operatorname{diam}(W_k(G))$ *of part II of Theorem 5 best possible?*

2. Proofs

We remark that throughout the paper we use k only for the length of walks for walk graph $W_k(G)$. We denote the vertices of $W_k(G)$ by small letters $a, b, \ldots,$ while the corresponding walks of length k in G we denote by capital letters $A, B, \ldots$ It means that if A is a walk of length k in G and a is a vertex in $W_k(G)$, then a is necessarily the vertex corresponding to the walk A.

Let A be a walk of length k in G. By $A(i)$, $0 \leq i \leq k$, we denote the i-th vertex of A. If A and B are walks in G such that $A = B$, then either $A(i) = B(k-i)$, $0 \leq i \leq k$; or $A(i) = B(i)$, $0 \leq i \leq k$.

Lemma 8. *Let A_0 and A'_0 be two admissible walks in G. If $A_0(0) = A'_0(0)$ and $A_0(1) \neq A'_0(1)$, then $d_{W_k(G)}(a_0, a'_0) \leq k$.*

Proof. We define k walks $A_1, A_2, \dots, A_k$ by "shifting forwards". Let $A_i(0) = A'_0(i)$ and $A_i(1) = A_{i-1}(0)$, $A_i(2) = A_{i-1}(1), \dots, A_i(k) = A_{i-1}(k-1)$, where $i = 1, 2, \dots, k$. We have

$$A_1(0) = A'_0(1) \neq A_0(1) = A_1(2) \qquad \text{and}$$
$$A_i(0) = A'_0(i) \neq A'_0(i-2) = A_{i-2}(0) = A_i(2), \qquad i = 2, 3, \dots, k.$$

Hence A_i are admissible walks and a_{i-1} and a_i are adjacent in $W_k(G)$. Therefore $d_{W_k(G)}(a_0, a_k) \leq k$. Since

$$\begin{aligned} A_k(0) &= A'_0(k), \\ A_k(1) &= A_{k-1}(0) = A'_0(k-1), \\ &\vdots \\ A_k(k) &= A_{k-1}(k-1) = \ldots = A_{k-k}(0) = A'_0(0), \end{aligned}$$

we have $A_k = A'_0$ and hence $d_{W_k(G)}(a_0, a'_0) \leq k$. □

Lemma 9. *Let G be a graph with $\delta(G) > 1$ and let A_0 and A'_0 be two admissible walks in G. Let $A_0(p) = A'_0(r)$ and $A_0(p+1) = A'_0(r+1)$. Then*

$$d_{W_k(G)}(a_0, a'_0) \leq 2k - 2.$$

Proof. Let $A_0(p) = A'_0(r)$, $A_0(p+1) = A'_0(r+1)$ and let $p \leq r$. (The case $r < p$ can be solved analogously.) We define the walks $A'_1, A'_2, \dots, A'_{k-r-1}$ by "shifting forwards". Let $A'_i(0)$ be an arbitrary vertex adjacent to $A'_{i-1}(0)$ distinct from $A'_{i-1}(1)$; and

$$A'_i(1) = A'_{i-1}(0), \quad A'_i(2) = A'_{i-1}(1), \quad \dots, \quad A'_i(k) = A'_{i-1}(k-1),$$

where $i = 1, 2, \dots, k-r-1$. Since $A'_i(0) \neq A'_{i-1}(1) = A'_i(2)$, $i = 1, 2, \dots, k-r-1$, the walks A'_i are admissible and the vertices a'_{i-1} and a'_i, $i = 1, 2, \dots, k-r-1$, are adjacent in $W_k(G)$. Therefore

$$d_{W_k(G)}(a'_0, a'_{k-r-1}) \leq k - r - 1.$$

In a similar way we define p walks $A_1, A_2, \dots, A_p$ by "shifting backwards". Let

$$A_i(0) = A_{i-1}(1), \quad A_i(1) = A_{i-1}(2), \quad \dots, \quad A_i(k-1) = A_{i-1}(k)$$

and let $A_i(k)$ be an arbitrary vertex adjacent to $A_i(k-1)$ distinct from $A_i(k-2)$, where $i = 1, 2, \dots, p$. The walks A_i are admissible and the vertices a_{i-1} and a_i, $i = 1, 2, \dots, p$, are adjacent in $W_k(G)$. Therefore

$$d_{W_k(G)}(a_0, a_p) \leq p.$$

We have

$$\begin{aligned} A_p(0) &= A'_{k-r-1}(k-1) && (\text{since } A_p(0) = A_{p-1}(1) = \ldots = A_0(p), \\ & && A'_{k-r-1}(k-1) = A'_{k-r-2}(k-2) = \ldots = A'_0(r)) \\ A_p(1) &= A'_{k-r-1}(k) && (\text{as } A_p(1) = A_{p-1}(2) = \ldots = A_0(p+1), \\ & && A'_{k-r-1}(k) = A'_{k-r-2}(k-1) = \ldots = A'_0(r+1)). \end{aligned}$$

Now we define the walks $A_{p+1}, A_{p+2}, \dots, A_{p+k-1}$ as follows. Let

$$A_{p+i}(0) = A'_{k-r-1}(k-1-i) \qquad \text{and}$$
$$A_{p+i}(1) = A_{p+i-1}(0), \quad A_{p+i}(2) = A_{p+i-1}(1), \quad \dots, \quad A_{p+i}(k) = A_{p+i-1}(k-1),$$

$i = 1, 2, \dots, k-1$. The walks A_i are admissible and thevertices a_{i-1} and a_i, $i = 1, 2, \dots, k-1$, are adjacent in $W_k(G)$. Therefore

$$d_{W_k(G)}(a_p, a_{p+k-1}) \leq k-1.$$

We have

$$A_{p+k-1}(0) = A'_{k-r-1}(0), \quad A_{p+k-1}(1) = A_{p+k-2}(0) = A'_{k-r-1}(1), \quad \dots,$$
$$A_{p+k-1}(k) = A_{p+k-2}(k-1) = \dots = A_p(1) = A'_{k-r-1}(k).$$

Hence $a_{p+k-1} = a'_{k-r-1}$ and the distance

$$\begin{aligned} d_{W_k(G)}(a_0, a'_0) &\leq d_{W_k(G)}(a_0, a_p) + d_{W_k(G)}(a_p, a_{p+k-1}) + d_{W_k(G)}(a'_{k-r-1}, a'_0) \\ &\leq p + (k-1) + (k-r-1) = 2k-2+p-r. \end{aligned}$$

Since $p \leq r$,

$$d_{W_k(G)}(a_0, a'_0) \leq 2k-2.$$

□

Proof of Theorem 1. Let $\operatorname{diam}(W_k(G)) = d_{W_k(G)}(a_0, a'_0)$. Since the diameter of G is equal to d, we have $d_G(A_0(0), A'_0(0)) = d' \leq d$.

Observe that if $d \geq k-1$, then $2k-2 < d+k$; and if $d \leq k-2$, then $d+k \leq 2k-2$.

If some edge from A_0 is equal to some edge from A'_0, then $d_{W_k(G)}(a_0, a'_0) \leq 2k-2$, by Lemma 9.

Assume that A_0 and A'_0 are edge disjoint. Let $V = (v_0, v_1, \dots, v_{d'})$ be a path of length d' in G such that $v_0 = A_0(0)$ and $v_{d'} = A'_0(0)$. If the length of V is zero, we have $A_0(0) = A'_0(0)$ and $A_0(1) \neq A'_0(1)$. Then $d_{W_k(G)}(a_0, a'_0) \leq k$, by Lemma 8. Let V be a path of length at least one. We distinguish two cases:

I. Suppose that $v_1 \neq A_0(1)$ and $v_{d'-1} \neq A'_0(1)$. We define d' walks $A_1, A_2, \dots, A_{d'}$ by "shifting forwards". Let

$$A_i(0) = v_i, \quad A_i(1) = A_{i-1}(0), \quad \dots, \quad A_i(k) = A_{i-1}(k-1),$$

where $i = 1, 2, \dots, d'$. Since

$$A_1(0) = v_1 \neq A_0(1) = A_1(2) \qquad \text{and} \qquad A_i(0) = v_i \neq v_{i-2} = A_{i-1}(1) = A_i(2),$$

for $i = 2, 3, \dots, d'$; the walks A_i are admissible and the vertices a_{i-1} and a_i, $i = 1, 2, \dots, d'$, are adjacent in $W_k(G)$. Hence $d_{W_k(G)}(a_0, a_{d'}) \leq d'$. Now we have $A_{d'}(0) = v_{d'} = A'_0(0)$ and $A_{d'}(1) = A_{d'-1}(0) = v_{d'-1} \neq A'_0(1)$. By Lemma 8, $d_{W_k(G)}(a_r, a'_0) \leq k$, therefore

$$d_{W_k(G)}(a_0, a'_0) \leq k + d' \leq k + d.$$

II. Suppose that at least one of the edges $A_0(0)A_0(1)$, $A'_0(0)A'_0(1)$ belongs to V.

a) Let $A_0 \not\subset V$ and $A'_0 \not\subset V$. Let t (s) be the smallest positive integer such that $v_{t+1} \neq A_0(t+1)$ $(v_{d'-(s+1)} \neq A'_0(s+1))$. It means that

$$A_0 = (v_0 = A_0(0), \ldots, v_t = A_0(t), A_0(t+1), \ldots, A_0(k)) \qquad \text{and}$$
$$A'_0 = (A'_0(k), \ldots, A'_0(s+1), v_{d'-s} = A'_0(s), \ldots, v_{d'} = A'_0(0)).$$

Since the walks A_0 and A'_0 are edge disjoint, it is evident that $t \leq d' - s$.

We define t walks $A_1, A_2, \ldots, A_t$ by "shifting backwards" as follows. Let

$$A_i(0) = A_{i-1}(1) = v_i, \quad A_i(1) = A_{i-1}(2), \quad \ldots, \quad A_i(k-1) = A_{i-1}(k)$$

and let $A_i(k)$ be an arbitrary vertex adjacent to $A_i(k-1)$ distinct from $A_i(k-2)$, where $i = 1, 2, \ldots, t$.

Analogously we define s walks $A'_1, A'_2, \ldots, A'_s$. Let

$$A'_i(0) = A'_{i-1}(1) = v_{d'-i}, \quad A'_i(1) = A'_{i-1}(2), \quad \ldots, \quad A'_i(k-1) = A'_{i-1}(k)$$

and let $A'_i(k)$ be an arbitrary vertex adjacent to $A'_i(k-1)$ distinct from $A'_i(k-2)$, where $i = 1, 2, \ldots, s$.

The walks A_i (A'_i) are admissible and the vertices a_{i-1} and a_i, $i = 1, 2, \ldots, t$ (a'_{i-1} and a'_i, $i = 1, 2, \ldots, s$), are adjacent in $W_k(G)$. Therefore

$$d_{W_k(G)}(a_0, a_t) \leq t \qquad \text{and} \qquad d_{W_k(G)}(a'_0, a'_s) \leq s.$$

We have

$$\begin{aligned} &A_t(0) = v_t, && A'_s(0) = v_{d'-s} \quad \text{and} \\ &A_t(1) = A_{t-1}(2) = \ldots = A_0(t+1), && A'_s(1) = A'_{s-1}(2) = \ldots = A'_0(s+1). \end{aligned}$$

Assume that $t < d' - s$. We have $A_t(1) = A_0(t+1) \neq v_{t+1}$, $A'_s(1) = A'_0(s+1) \neq v_{d'-(s+1)}$ and $d(A_t(0), A'_s(0)) = d' - s - t$. In the same way as in part I of this proof it can be shown that $d_{W_k(G)}(a_t, a'_s) \leq d' - s - t + k$. Then

$$\begin{aligned} d_{W_k(G)}(a_0, a'_0) &\leq d_{W_k(G)}(a_0, a_t) + d_{W_k(G)}(a_t, a'_s) + d_{W_k(G)}(a'_s, a'_0) \\ &\leq t + (d' - s - t + k) + s = d' + k \leq d + k. \end{aligned}$$

Suppose that $t = d' - s$. Then $A_t(0) = A'_s(0)$. Since A_0 and A'_0 are edge-disjoint, $A_t(1) = A_0(t+1) \neq A'_0(s+1) = A'_s(1)$, and by Lemma 8, $d_{W_k(G)}(a_t, a'_s) \leq k$. Hence

$$d_{W_k(G)}(a_0, a'_0) \leq t + k + s = d' + k \leq d + k.$$

b) Let $A_0 \subset V$. (The case $A'_0 \subset V$ can be solved in a similar manner.) Suppose that $B_0 = A_0$, where $B_0(i) = A_0(k - i)$, $i = 0, 1, \ldots, k$. Then instead of A_0 we consider B_0, instead of V consider $V' = (v'_0 = v_k = B_0(0), v'_1 = v_{k+1}, \ldots, v'_{d'-k} = v_{d'} = A'_0(0))$ and proceed analogously as above. □

Proof of Assertion 3. Led $2 \leq d$ and $k - 1 \leq d$. Assume that V, A and A' are three vertex-disjoint paths, where $V = (v_1, v_2, \ldots, v_{d-1})$, $A = (A(0), A(1), \ldots, A(k))$

and $A' = (A'(0), A'(1), \dots, A'(k))$. Denote by G a graph consisting of V, A, A' and edges $A(i)v_1$, $A'(i)v_{d-1}$, $i = 0, 1, \dots, k$. Then the diameter

$$\operatorname{diam}(G) = d(d_G(A(0), A'(0)) = d) \qquad \text{and} \qquad d_{W_k(G)}(a, a') = d + k.$$

By part A of Theorem 1, $\operatorname{diam}(W_k(G)) \le \operatorname{diam}(G) + k$, therefore

$$\operatorname{diam}(W_k(G)) = d + k.$$

□

Proof of Theorem 5. Let $\operatorname{diam}(G) = d_G(v_0, v_d) = d$. Let $V = (v_0, v_1, \dots, v_d)$ be a path of length d in G.

I. Suppose k is even. Denote by A_0 (A') a walk of length k in G, where $A_0\left(\frac{k}{2}\right) = v_0$ $(A'\left(\frac{k}{2}\right) = v_d)$. We show that $d_{W_k(G)}(a_0, a') \ge d$. Let us prove it by contradiction and assume that $d_{W_k(G)}(a_0, a') = s \le d - 1$. Let $(a_0, a_1, \dots, a_s = a')$ be a path of length s in $W_k(G)$. The vertices a_{i-1}, a_i are adjacent in $W_k(G)$, therefore $A_i\left(\frac{k}{2}\right) = A_{i-1}\left(\frac{k}{2} + 1\right)$ or $A_i\left(\frac{k}{2}\right) = A_{i-1}\left(\frac{k}{2} - 1\right)$, $i = 1, 2, \dots, s$. Hence

$$d_G\left(A_i\left(\frac{k}{2}\right), A_{i-1}\left(\frac{k}{2}\right)\right) = 1, \qquad i = 1, 2, \dots, s, \qquad \text{and}$$

$$d_G(v_0, v_d) = d_G\left(A_0\left(\frac{k}{2}\right), A'\left(\frac{k}{2}\right)\right) \le s,$$

a contradiction.

II. Suppose k is odd. Let A_0 be a walk of length k with the central edge v_0v_1, where $v_0 = A_0\left(\frac{k-1}{2}\right)$, $v_1 = A_0\left(\frac{k+1}{2}\right)$; and let A' be a walk of length k with the central edge $v_{d-1}v_d = A'\left(\frac{k-1}{2}\right) A'\left(\frac{k+1}{2}\right)$ in G. We show that $d_{W_k(G)}(a_0, a') \ge d - 1$. Assume the contrary and let $d_{W_k(G)}(a_0, a') = t \le d - 2$. Let $(a_0, a_1, \dots, a_t = a')$ be a path of length t in $W_k(G)$. Since a_{i-1} and a_i, $i = 1, 2, \dots, t$, are adjacent vertices in $W_k(G)$, the central edges of A_{i-1} and A_i have to be adjacent in G. Then it is easy to see that

$$\max\left\{d_G\left(A_0\left(\frac{k-1}{2}\right), A_i\left(\frac{k-1}{2}\right)\right), d_G\left(A_0\left(\frac{k-1}{2}\right), A_i\left(\frac{k+1}{2}\right)\right)\right\} \le i+1,$$

$i = 1, 2, \dots, t$, a contradiction. □

Proof of Assertion 6. Let k be odd and $d \ge 2k$. Assume that C and C' are two edge-disjoint cycles;

$$C = (c_0, c_1, \dots, c_{2k} = c_0) \qquad \text{and} \qquad C' = (c'_0, c'_1, \dots, c'_{2(d-k)} = c'_0).$$

Let $c_k = c'_{d-k}$ and let G be the graph consisting of C and C'. Then

$$V = (c_0, c_1, \dots, c_k = c'_{d-k}, c'_{d-k-1}, \dots, c'_0)$$

is the diameter path of G and the diameter is $\operatorname{diam}(G) = k + (d - k) = d$. In the following, we denote by

$$B_1 = (c_0, c_1, \dots, c_k), \qquad B_2 = (c_k, c_{k+1}, \dots, c_{2k} = c_0),$$
$$B_3 = (c'_{d-k}, c'_{d-k-1}, \dots, c'_{d-2k}), \qquad B_4 = (c'_{d-k}, c'_{d-k+1}, \dots, c'_d)$$

the paths of length k in G. Note that $d_{W_k(G)}(b_i, b_j) = k$, where $i, j \in \{1, 2, 3, 4\}$, $i < j$.

Suppose that A, A' are any two walks of length k in G. We prove that

$$d_{W_k(G)}(a, a') \leq d - 1.$$

We partition the walks of length k into three sets S_1, S_2 and S_3, where S_1 is the set of those, being part of C; S_2 those in C'; and S_3 the remaining ones. There are six cases to distinguish.

I. Let $A, A' \in S_1$. Since A and A' are the walks in the cycle C of length $2k$, it is easy to see that

$$d_{W_k(G)}(a, a') \leq k$$

($d_{W_k(G)}(a, a') = k$ if and only if A and A' are edge-disjoint).

II. Let $A, A' \in S_2$. By analogy, since C_2 is the cycle of length $2(d-k)$ and $A, A' \subset C_2$, we have

$$d_{W_k(G)}(a, a') \leq d - k.$$

III. Let $A, A' \in S_3$. Then $A \cap B_i$ and $A' \cap B_j$ are paths of length at least $\frac{k+1}{2}$ for some $i, j \in \{1, 2, 3, 4\}$, in G. Consequently, $d_{W_k(G)}(a, b_i) \leq \frac{k-1}{2}$ and $d_{W_k(G)}(a', b_j) \leq \frac{k-1}{2}$. We know that $d_{W_k(G)}(b_i, b_j) = k$ if $i \neq j$, hence

$$d_{W_k(G)}(a, a') \leq 2k - 1 \leq d - 1.$$

IV. Let $A \in S_1$ and $A' \in S_2$. Since $A \cap B_1$ or $A \cap B_2$ is a path of length at least $\frac{k+1}{2}$ in G, we have $d_{W_k(G)}(a, b_i) \leq \frac{k-1}{2}$, where $i = 1$ or 2. Let

$$B'_3 = (c'_{d-k}, c'_{d-k-1}, \ldots, c'_0), \qquad B'_4 = (c'_{d-k}, c'_{d-k+1}, \ldots, c'_{2(d-k)})$$

be the paths of length $d-k$ in G. Suppose that $A' \cap B'_3$ is a path of length at least $\frac{k+1}{2}$ in G. Then there exists a path $A'_s \subset B'_3$ of length k in G, such that $d_{W_k(G)}(a', a'_s) \leq \frac{k-1}{2}$. Since B'_3 is the path of length $d-k$ and A'_s, B_3 are the subpaths of B'_3 of length k, $d_{W_k(G)}(a'_s, b_3) \leq d - 2k$. Therefore

$$d_{W_k(G)}(a', b_3) \leq d_{W_k(G)}(a', a'_s) + d_{W_k(G)}(a'_s, b_3) \leq \frac{k-1}{2} + d - 2k$$

and hence

$$\begin{aligned} d_{W_k(G)}(a, a') &\leq d_{W_k(G)}(a, b_i) + d_{W_k(G)}(b_i, b_3) + d_{W_k(G)}(b_3, a') \\ &\leq \frac{k-1}{2} + k + \left(\frac{k-1}{2} + d - 2k\right) = d - 1. \end{aligned}$$

If $A' \cap B'_3$ is a path of length less than $\frac{k+1}{2}$ in G, then $A' \cap B'_4$ is a path of length at least $\frac{k+1}{2}$. It can be proved in a similar manner that

$$d_{W_k(G)}(a, a') \leq d - 1.$$

V. Let $A \in S_1$ and $A' \in S_3$. Since $d_{W_k(G)}(a, b_i) \leq \frac{k-1}{2}$, where $i = 1$ or 2; and $d_{W_k(G)}(a', b_j) \leq \frac{k-1}{2}$, where $j \in \{1, 2, 3, 4\}$, we have

$$d_{W_k(G)}(a, a') \leq 2k - 1$$

VI. Let $A \in S_2$ and $A' \in S_3$. By IV, we know that $d_{W_k(G)}(a, b_i) \leq \frac{k-1}{2} + d - 2k$ for $i = 3$ or $i = 4$, and analogously as in IV it can be shown that $d_{W_k(G)}(a, a') \leq d - 1$.

By part II of Theorem 5, the diameter of every walk graph is greater than or equal to $d - 1$, therefore

$$\operatorname{diam}(W_k(G)) = d - 1.$$

□

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