

A note on simplicial cliques

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Abstract

Motivated by an application in condensed matter physics and quantum information theory we prove that every non-null even-hole-free claw-free graph has a simplicial clique, that is, a clique K such that for every vertex $v \in K$, the set of neighbors of v outside of K is a clique. In fact, we prove the existence of a simplicial clique in a more general class of graphs defined by forbidden induced subgraphs.

1 Introduction

All graphs in this paper are finite and simple. Let G be a graph. A *hole* in G is an induced cycle of length at least four. By a *path* we always mean an induced path. For $v \in V(G)$ we denote by $N(v)$ the set of neighbors of v (so $v \notin N(v)$). G is *even-hole-free* if all holes in G have odd length, and G is *claw-free* if G has no induced subgraph isomorphic to $K_{1,3}$. A non-empty set $K \subseteq V(G)$ is a *simplicial clique* if K is a clique, and for every $v \in K$ we have that $N(v) \setminus K$ is a

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clique. The unique element of a simplicial clique of size one is called a *simplicial vertex*.

This paper is motivated by a question from condensed matter physics and quantum information theory concerning so-called *spin models*, i.e. models of interacting qubits (two-level quantum systems). Each spin model is defined by a Hamiltonian operator, and to every such Hamiltonian one can associate a graph, called its *frustration graph*. In [4] a new method is given that allows us to “solve a model” (meaning in this case to find the spectrum and the eigenvectors of the Hamiltonian) whose frustration graph is even-hole-free, claw-free, and has a simplicial clique. This augments earlier results of [1] where it is shown that models whose frustration graphs are line-graphs are solvable using certain classical tools. The solution method of [4] uses only the structure of the frustration graph, and it is an extension of both [5] and [6]. The authors of [4] raised a question:

1.1. Question: *Does every non-null even-hole-free claw-free graph have a simplicial clique?*

In other words, does their new solvability result hold for all models whose frustration graphs are even-hole-free and claw-free? In this note we answer their question affirmatively (the “dome of an edge” is defined before the statement of (2.2)); in fact we prove a stronger result:

1.2. *Let G be a non-null even-hole-free claw-free graph. Then one of the following holds:*

1. *G is chordal and has a simplicial vertex, or*
2. *for every hole H of G there is an edge ab of H such that the dome of ab is a simplicial clique.*

In particular, G has a simplicial clique.

We have a even stronger result, describing explicitly the structure of all such graphs, but the proof is harder, and we do not present it here. The main result of this paper is 2.2 which is a strengthening of 1.2, and we will explain it in Section 2.

We remark that the answer to 1.1 becomes negative if we omit either the assumption that the graph is even-hole-free or that the graph is claw-free. The complement of a cycle of odd length at least seven is a claw-free graph with no simplicial clique. Let k be an odd positive integer. The following is a construction of an even-hole-free graph G_k with $2k$ vertices and with no simplicial clique. Let the vertex set of G_k be the union of k disjoint pairs of adjacent vertices $\{a_i, b_i\}$ where $i \in \{1, \dots, k\}$. For $i = \{1, \dots, k-1\}$ add the edges $a_i a_{i+1}, a_i b_{i+1}, b_i a_{i+1}$; add also the edges $a_k a_1, a_k b_1, b_k a_1$. There are no more edges in G . It is easy to check the G_k is even-hole-free and has no simplicial clique.

In [2] an algorithm is presented that finds a simplicial clique in a claw-free graph if one exists. The authors of [4] also asked if that algorithm can be

simplified when the input is known to be even-hole-free. An easy corollary of our main result 1.2 is such a simpler, but slower, algorithm 4.1. In fact 4.1 works under the more general assumptions of 2.2.

2 A strengthening

The goal of this section is to present our main result 2.2.

Let G be a graph. For $X \subseteq V(G)$ we denote by $G[X]$ the graph induced by G on X . For $A \subseteq V(G)$ and $x \in V(G) \setminus A$, we say that x is *complete* to A if x is adjacent to every element of A , and that x is *anticomplete* to A if x is non-adjacent to every element of A . Two disjoint subsets $A, B \subseteq V(G)$ are *complete* to each other if every vertex of B is complete to A , and *anticomplete* to each other if every vertex of B is anticomplete to A .

Next we define a few types of graphs. A graph is called *chordal* if it has no holes. A *jewel* is a graph consisting of a hole $H = h_1 - \dots - h_k - h_1$ with $k \geq 4$ and a vertex $v \notin V(H)$ such that $N(v) \cap V(H) = \{h_1, h_2, h_3, h_4\}$. A *line wheel* is a graph consisting of a hole $H = h_1 - \dots - h_k - h_1$ with $k \geq 6$ and a vertex $v \notin V(H)$ such that three exist $i \in \{4, \dots, k-2\}$ with $N(v) \cap V(H) = \{h_1, h_2, h_i, h_{i+1}\}$. A *short prism* is a graph consisting of a hole $h_1 - h_2 - h_3 - h_4 - h_1$ and a path $p_1 - \dots - p_k$ such that $\{p_1, \dots, p_k\} \cap \{h_1, h_2, h_3, h_4\} = \emptyset$, p_1 is adjacent to h_1 and to h_2 , p_k is adjacent to h_3 and to h_4 , and there no other edges between $\{p_1, \dots, p_k\}$ and $\{h_1, h_2, h_3, h_4\}$. Finally, the *seven-antihole* is the complement of a cycle of seven vertices.

In what follows, whenever graph containment is mentioned, we will mean containment as an induced subgraph. We say that a graph G is *clean* if it G is claw-free and contains no jewel, line wheel, short prism or seven-antihole.

First we show:

2.1. *If G is claw-free and even-hole-free, then G is clean.*

Proof. Since G is even-hole free, and in particular C_4 -free, G does not contain short prisms or seven-antiholes. Since a jewel contains a hole H of length k , and a hole $h_1 - v - h_4 - h_5 - \dots - h_k - h_1$ of length $k - 1$, G does not contain a jewel. Finally, at least one of the holes H , $h_2 - \dots - h_i - v - h_2$, and $h_{i+1} - \dots - h_1 - v - h_{i+1}$ is even, and so G does not contain a line wheel. This proves 2.1. \square

We need one more definition. Let ab be an edge of a graph G . Let $X(ab) = \{a, b\} \cup (N(a) \cap N(b))$, and let $Y(ab)$ be the set of all vertices $y \in X(ab)$ such that $N(y) \setminus X(ab)$ is not a clique. We call the set $X(ab) \setminus Y(ab)$ the *dome* of ab . We can now state our main result.

2.2. *Let G be a non-null clean graph. Then one of the following holds:*

1. G is chordal and has a simplicial vertex, or
2. For every hole H of G there is an edge ab of H such that the dome of ab is a simplicial clique.

In particular, G has a simplicial clique.

In view of 2.1 we immediately deduce 1.2.

3 The proof of the main theorem

In this section we prove 2.2. We start with a lemma.

3.1. *Let G be a clean graph, let H be a hole in G , and let $v \in V(G) \setminus V(H)$. Then one of the following holds:*

1. v is anticomplete to $V(H)$.
2. $|V(H)| = 5$ and v is complete to $V(H)$.
3. v has exactly two neighbors in H and they are consecutive.
4. v has exactly three neighbors in H and they form a path of H .

Proof. Write $H = h_1 - \dots - h_k - h_1$. We may assume that v has a neighbor in $V(H)$, for otherwise 3.1.1 holds. If v is complete to $V(H)$, then, since G is claw-free and since $G[V(H) \cup \{v\}]$ is not a jewel, it follows that $k = 5$ and so 3.1.2 holds. Thus we may assume that v has a non-neighbor in $V(H)$, say v is adjacent to h_1 and not to h_k . Since G is claw-free, v is adjacent to h_2 , and $|N(v) \cap V(H)| \leq 4$. We may assume that v has a neighbor in $V(H) \setminus \{h_1, h_2, h_3\}$, for otherwise 3.1.3 or 3.1.4 holds. Since G is claw-free, $N(v) \cap (V(H) \setminus \{h_1, h_2, h_3\})$ is a clique, and therefore $|N(v) \cap (V(H) \setminus \{h_1, h_2, h_3\})| \leq 2$. Let $i \in \{1, \dots, k-1\} \setminus \{1, 2, 3\}$ be minimum such that v is adjacent to h_i . Since $\{v, h_{i-1}, h_i, h_{i+1}\}$ is not a claw, it follows that either

- $i = 4$ and v is adjacent to h_3 , or
- v is adjacent to h_{i+1} and v has no other neighbors in $V(H) \setminus \{h_1, h_2, h_3, h_i\}$.

In the former case $G[V(H) \cup \{v\}]$ is a jewel. Thus we may assume that the latter case holds. Since $|N(v) \cap V(H)| \leq 4$, it follows that $N(v) \cap V(H) = \{h_1, h_2, h_i, h_{i+1}\}$. But now $G[V(H) \cup \{v\}]$ is a line wheel, a contradiction. This proves 3.1. \square

Now we turn to the proof of 2.2.

Proof. If G has no hole, then G is chordal, and therefore has a simplicial vertex [3], and 1.2.1 holds. Thus we may assume that G has a hole. For an integer $k \geq 4$ a subset $W \subseteq V(G)$ is k -structured if (here the addition is mod k):

- W is the disjoint union of k non-empty cliques K_1, \dots, K_k ,
- for every $i \in \{1, \dots, k\}$ every $v \in K_i$ has a neighbor in K_{i-1} and a neighbor in K_{i+1} , and
- if $i, j \in \{1, \dots, k\}$ and $i \neq j \pm 1$ then K_i is anticomplete to K_j .

We call the partition (K_1, \dots, K_k) a k -structure of W .

Let H be a hole of G . Then H has length $k \geq 4$, and $V(H)$ is a k -structured set. If possible, choose H with $k \geq 5$. Let $W \subseteq V(G)$ be a k -structured set with k -structure (K_1, \dots, K_k) , where each K_i contains exactly one vertex of H , and such that W is inclusion-wise maximal with this property. In what follows addition and subtraction of indices of the k -structure is mod k .

(1) *If $a, b \in K_1$ and $N(b) \cap K_2 \not\subseteq N(a) \cap K_2$, then $N(b) \cap K_k \subseteq N(a) \cap K_k$.*

If for each $i \in \{2, k\}$ there exists $a_i \in (N(b) \setminus N(a)) \cap K_i$, then $\{b, a_k, a, a_2\}$ is a claw in G , a contradiction. This proves (1).

(2) *For every $a, b \in K_1$ either $N(a) \cap K_2 \subseteq N(b) \cap K_2$, or $N(b) \cap K_2 \subseteq N(a) \cap K_2$.*

Suppose there exist $a' \in (N(a) \setminus N(b)) \cap K_2$ and $b' \in (N(b) \setminus N(a)) \cap K_2$. Since K_1 and K_2 are cliques, a is adjacent to b , and a' is adjacent to b' . Now $a-a'-b'-b-a$ is a hole of length four. Let $C = N(a) \cap K_k$ and $C' = N(a') \cap K_3$. By (1) b is complete to C , and b' is complete to C' . Switching the roles of a and b , we deduce that b is anticomplete to $K_k \setminus C$, and, similarly, b' is anticomplete to $K_3 \setminus C'$. Since the graph $G[\bigcup_{i=3}^k K_i]$ is connected, there is a path $P = p_1 \dots p_t$ in $G[\bigcup_{i=3}^k K_i]$ with $p_1 \in C$ and $p_t \in C'$; we may assume P is chosen with t minimum. Then $p_2, \dots, p_{t-1} \notin C \cup C'$, and therefore $V(P) \setminus \{p_1, p_t\}$ is anticomplete to $\{a, b, a', b'\}$. But now $G[a, a', b, b', p_1, \dots, p_t]$ is a short prism in G , a contradiction. This proves (2).

(3) *For every $i \in \{1, \dots, k\}$, K_i is complete to at least one of K_{i-1}, K_{i+1} .*

We may assume $i = 1$. Suppose there exist $u \in K_k, v, w \in K_1$ and $z \in K_2$ (where possibly $v = w$) such that u is not adjacent to w , and v is not adjacent to z .

First we claim that v, w can be chosen in such a way that uv and wz are edges. Suppose not; then we may assume that v is non-adjacent to both u and z . Since (K_1, \dots, K_k) is a k -structure, there exist $n_u, n_z \in K_1$ such that u is adjacent to n_u , and z is adjacent to n_z . Since v is anticomplete to $\{u, z\}$, it follows from (1) that n_u is non-adjacent to z , and n_z is non-adjacent to u . But now we can choose $v = n_u$ and $w = n_z$, and the claim holds.

In view of the claim in the previous paragraph we assume that uv and wz are adjacent (and in particular $v \neq w$). Let $u' \in K_k$ be a neighbor of w ; by (2) u' is adjacent to v . Now the set $T = \bigcup_{i=3}^{k-1} K_i$ is non-empty and connected, and both u' and z have neighbors in T . Consequently, there is a path R from u' to z with $V(R) \setminus \{u', z\} \subseteq T$. Let $x \in V(R)$ be the neighbor of u' . Then $x \in K_{k-1}$, and by (1) x is adjacent to u . It follows from the definition of a k -structure that $V(R) \setminus \{z, x, u'\}$ is anticomplete to $\{u, u', v, w\}$. But now the hole $z-w-v-u-x-R-z$ together with the vertex u' forms a jewel in G , a contradiction. This proves (3).

Let $j \in \{1, \dots, k\}$. For every $i \in \{2, \dots, k-2\}$, $a_j \in K_j$ and

(4) *$a_i \in K_{j+i}$, there is a path P from a_j to a_i with $V(P) \subseteq \bigcup_{t=j}^{j+i} K_t$ and using exactly one vertex from each of K_j, \dots, K_{j+i} .*

We may assume $j = 1$. The proof is by induction on i . Suppose first that $i = 2$. Since by (3) K_2 is complete to at least one of K_1, K_3 , it follows that a_1 and a_3 have a common neighbor $a_2 \in K_2$. Now $a_1-a_2-a_3$ is the required path.

Now assume that $i > 2$, let $a_{i-1} \in K_{i-1}$ be a neighbor of a_i . By the inductive hypothesis there is a path P from a_1 to a_{i-1} with $V(P) \subseteq \bigcup_{r=j}^{i+j-1} K_r$ using exactly one vertex from each of K_j, \dots, K_{i+j-1} . Now $a_j-P-a_{i-1}-a_i$ is the required path. This proves (4).

Let $v \in V(G) \setminus W$. For $i \in \{1, \dots, k\}$ let $N_i = K_i \cap N(v)$ and $M_i = K_i \setminus N_i$. The following hold for every $i \in \{1, \dots, k\}$:

- (5) *1. N_i is anticomplete to at least one of M_{i-1}, M_{i+1} .*
2. If $k > 4$, then M_i is anticomplete to at least one of N_{i-1}, N_{i+1} .

We may assume $i = 1$. By (3) we may assume that K_1 is complete to K_2 .

We first prove the first statement. We may assume that there exists $m_2 \in M_2$, for otherwise the claim holds. Now if $n_1 \in N_1$ has a neighbor $m_k \in M_k$, then $\{n_1, v, m_2, m_k\}$ is a claw, a contradiction. This proves that N_1 is anticomplete to at least one of M_k, M_2 , and (5).1 follows.

Next we prove the second statement. We may assume that there exists $n_2 \in N_2$, for otherwise the claim holds. Let $n_k \in N_k \cap N(m_1)$. By (4) there exists a path P from n_2 to n_k with $V(P) \subseteq \bigcup_{i=2}^k K_i$ with $|V(P) \cap K_i| = 1$ for every $i \in \{2, \dots, k\}$. But now we get a contradiction applying 3.1 to the hole $m_1-n_2-P-n_k-m_1$ and the vertex v . This proves (5).2 and completes the proof of (5).

Let $v \in V(G) \setminus W$ and for $i \in \{1, \dots, k\}$, let $N_i = N(v) \cap K_i$ and

- (6) *$M_i = K_i \setminus N_i$. Either N_i is non-empty for at most two consecutive values of $i \pmod k$ or $k = 5$ and v is complete to W .*

First we claim that we can choose j, l with $N_j \neq \emptyset$ and $N_l \neq \emptyset$, and such that $j = l \pm 2$. If $N_i \neq \emptyset$ for every $i \in \{1, \dots, k\}$, then the claim holds. Thus we may assume that some N_i s are empty, and some are not. By shifting the indices, we may assume $N_1 \neq \emptyset$ and $N_k = \emptyset$. We may assume that $N_t \neq \emptyset$ for some $t \in \{3, \dots, k-1\}$ for otherwise (6).1 holds with $i = 1$. Let $n_1 \in N_1$ and $n_t \in N_t$. By (4) there exists a path P from n_1 to n_t such that $V(P) \subseteq \bigcup_{j=1}^t K_j$ and P uses exactly one vertex from each of K_1, K_2, \dots, K_t . Also by (4) there exists a path Q from n_t to n_1 such that $V(Q) \subseteq K_1 \cup \bigcup_{j=t}^k K_j$ and Q uses exactly one vertex from each of $K_t, K_{t+1}, \dots, K_k, K_1$. Now $H = n_1-P-n_t-Q-n_1$ is a hole, and $n_1, n_t \in V(H)$. Applying 3.1 to H and v we deduce that $t \in \{3, k-1\}$, and we can set $j = 1$ and $l = t$.

Thus we may assume that N_k and N_2 are both non-empty. For $i \in \{2, k\}$ let $a_i \in N_i$. By (3) a_k and a_2 have a common neighbor $a_1 \in K_1$.

Suppose $\bigcup_{i=3}^{k-1} K_i = \emptyset$. Since W is maximal, $(K_1 \cup \{v\}, K_2, \dots, K_k)$ is not a k -structure for $W \cup \{v\}$, and therefore there exists $a'_1 \in M_1$. By symmetry we may assume that K_1 is complete to K_2 . Let $a'_3 \in K_3$ be a neighbor of a_2 ; then $a'_3 \in M_3$, contrary to (5).1. This proves that $\bigcup_{i=3}^{k-1} K_i \neq \emptyset$.

Suppose $k = 4$. Then there is symmetry between K_1 and K_3 , and we deduce that $N_i \neq \emptyset$ for every $i \in \{1, \dots, 4\}$. By (3) we may assume that K_1 is complete to K_2 , and K_3 to K_4 . Now 3.1 implies that either N_1 is anticomplete to N_4 , or N_3 is anticomplete to N_2 . By symmetry we may assume that N_1 is anticomplete to N_4 . Let $n_1 \in N_1$ and $n_4 \in N_4$, and let $m_1 \in K_1$ be adjacent to n_4 and $m_4 \in K_4$ be adjacent to n_1 . Then $m_1 \in M_1$ and $m_4 \in M_4$. By (2) applied to m_1 and n_1 , we deduce that m_1 is adjacent to m_4 . If there exists $m_2 \in M_2$, then $\{n_1, v, m_2, m_4\}$ is a claw, a contradiction. This proves (using symmetry) that $M_2 \cup M_3 = \emptyset$. Let $n_2 \in K_2$, and let $n_3 \in K_3$ be adjacent to n_2 . Then $n_2 \in N_2$ and $n_3 \in N_3$. But now $G[v, m_4, n_2, n_4, n_1, n_3, m_1]$ is a seven-antihole, a contradiction. This proves that $k \geq 5$.

By (5).2 it follows that $a_1 \in N_1$. We claim that $k = 5$ and v is complete to W , and (6) holds. Suppose v has a non-neighbor in W . Since $\{v, a_k, a_2, x\}$ is not a claw for any $x \in \bigcup_{i=4}^{k-2} K_i$, it follows that $\bigcup_{i=4}^{k-2} N_i = \emptyset$.

We may assume that there is $a_3 \in N_3$. Since $\{v, a_2, a_k, a_3\}$ is not a claw, it follows that a_2 is adjacent to a_3 . By (4) there is a path P from a_3 to a_k with $V(P) \subseteq \bigcup_{j=3}^k K_j$ and using exactly one vertex from each of K_3, \dots, K_k . Now $H = a_k a_1 a_2 a_3 P a_k$ is a hole, and 3.1 implies that $k = 5$ and v is complete to $V(H)$. We have proved that $N_i \neq \emptyset$ for every $i \in \{1, \dots, 5\}$ thus restoring the symmetry of the 5-structure. Since for $n_1 \in N_1$, $n_2 \in N_2$ and $n_4 \in N_4$, $\{v, n_1, n_2, n_4\}$ is not a claw, we deduce (using symmetry) that N_i is complete to N_{i+1} for every $i \in \{1, \dots, 5\}$.

Next suppose that both M_5 and M_2 are non-empty. By (3) we may assume that K_1 is complete to K_2 . By (5).1, N_1 is anticomplete to M_5 . Since every vertex of M_5 has a neighbor in K_1 , it follows that $M_1 \neq \emptyset$. By (5).2 M_1 is anticomplete to N_5 , but now $m_1 \in M_1$ and $n_1 \in N_1$ contradict (2). By symmetry we may assume M_i is non-empty for at most two consecutive values of i , and that $M_1 \cup M_2 \cup M_3 = \emptyset$. By (5).2 N_4 is anticomplete to M_5 , and similarly M_4 is anticomplete to N_5 . By symmetry we may assume that $M_4 \neq \emptyset$. But now $m_4 \in M_4$ and $n_4 \in N_4$ contradicts (2). This proves (6).

For $i \in \{1, \dots, k\}$ let $K_{i,i+1}$ be the set of all vertices of $V(G) \setminus W$ that have a neighbor in K_i , a neighbor in K_{i+1} , and no neighbor in $W \setminus (K_i \cup K_{i+1})$.

The following statements hold

1. $K_i \cup K_{i+1} \cup K_{i,i+1}$ is a clique.
- (7) 2. If u is complete to W , then u is anticomplete to $K_{i,i+1}$.
3. $K_{i,i+1}$ is anticomplete to $K_{i-1,i}$.

Let $v \in K_{1,2}$. For $i \in \{1, 2\}$ let $N_i = K_i \cap N(v)$, and let $M_i = K_i \setminus N_i$. By (5).1 N_1 is anticomplete to M_2 , and N_2 is anticomplete to M_1 . If there exists $m_1 \in M_1$, then n_1, m_1 contradict (2). Thus $M_1 = \emptyset$, and by symmetry $M_2 = \emptyset$. This proves that $K_{1,2}$ is complete to $K_1 \cup K_2$.

Suppose $k_1 \in K_1$ is non-adjacent to $k_2 \in K_2$. Let P be a path from k_2 to a vertex $k_k \in K_k$ as in (4), such that $|V(P) \cap K_i| = 1$ for every $i \in \{2, 3, \dots, k\}$. By (3) K_1 is complete to K_k , and so $H = k_k - k_1 - v - k_2 - P - k_k$ is a hole. Let $k'_1 \in K_1 \cap N(k_2)$, then $G[V(H) \cup \{k'_1\}]$ is a jewel in G , a contradiction. This proves that K_1 is complete to K_2 .

Since $\{k_1, k_k, a, b\}$ is not a claw for any $k_1 \in K_1$, $k_k \in K_k \cap N(k_1)$ and $a, b \in K_{1,2}$, it follows that $K_{1,2}$ is a clique, and therefore $K_1 \cup K_2 \cup K_{1,2}$ is a clique. This proves (7).1.

Next suppose that u is complete to W and u is adjacent to $w \in K_{1,2}$. By (6) $k = 5$. Let $k_3 \in K_3$ and $k_5 \in K_5$. Then $\{u, w, k_3, k_5\}$ is a claw, a contradiction. This proves (7).2.

Finally, suppose that $w_k \in K_{k,1}$ is adjacent to $w_2 \in K_{1,2}$. Let $k_1 \in K_1$, $k_2 \in K_2$ and $k_k \in K_k$, and let P be a path from k_2 to k_k as in (4) such that $|V(P) \cap K_i| = 1$ for every $i \in \{2, 3, \dots, k\}$. Then $H = k_2 - P - k_k - w_k - w_2 - k_2$ is a hole and $G[V(H) \cup \{k_1\}]$ is a jewel, a contradiction. This proves (7).3 and completes the proof of (7).

For $i \in \{1, \dots, k\}$, let $V(H) \cap K_i = \{h_i\}$. Choose $i \in \{1, \dots, k\}$ such that K_i is complete to K_{i+1} and, if possible, such that $K_{i,i+1} \neq \emptyset$; we may assume $i = 1$. Set $a = h_1$ $b = h_2$.

By (6), every vertex of $X(ab) = \{a, b\} \cup (N(a) \cap N(b))$ either belongs to K or is complete to W (and $k = 5$). Since if $y \in X(a, b)$ is complete to W , then y has two non-adjacent neighbors in $V(G) \setminus X(ab)$, it follows that K contains the dome of ab . By (7).1 K is a clique.

We prove that K is a simplicial clique, and therefore K equals the dome of ab . Suppose K is not a simplicial clique, and let $v \in K$ and $u, w \in V(G) \setminus K$ be such that u and w are adjacent to v , and u is non-adjacent to w . Suppose first that u is complete to W . By (6) $k = 5$. By (7).2 $v \notin K_{1,2}$. For $i \in \{1, \dots, 5\}$ let $k_i \in K_i$. We may assume that $v = k_1$. Since u is non-adjacent to w , it follows that $w \notin W$. Since $G[k_1, u, k_3, w, k_2]$ is not a jewel in G , it follows that w is not complete to W . By (5).1 w has a neighbor in at least one of K_2, K_5 . By (6) $w \in K_{1,2} \cup K_{5,1}$. Since $w \notin K$, it follows that $w \in K_{5,1}$. By (7).1 K_5 is complete to K_1 . It follows from the choice of K_1, K_2 that there exists $k \in K_{1,2}$. By (7).2 u is non-adjacent to k , and by (7).3 w is non-adjacent to k . But now $\{k_1, u, k, w\}$ is a claw in G , a contradiction. This proves that u is not complete to W . By symmetry, w is not complete to W .

Now suppose $v \in K_1$. Since $u, w \notin K$, it follows from (6) that $u, w \in K_k \cup K_{k,1}$. But then u is adjacent to w by (7).1, a contradiction. This proves that $v \notin K_1$, and, by symmetry, $v \notin K_2$.

It follows that $v \in K_{1,2}$. Moreover, applying the previous argument to an arbitrary vertex of $K_1 \cup K_2$ in the role of v , we deduce that no vertex of $K_1 \cup K_2$ is complete to $\{u, w\}$. Since $\{v, u, w, p\}$ is not a claw for $p \in K_1 \cup K_2$ it follows that every vertex of $K_1 \cup K_2$ has a neighbor in $\{u, w\}$. Since $u, w \notin K$, (7).1 implies that each of u, w is anticomplete to at least one of K_1, K_2 . By switching u and w if necessary, we may assume that u has a neighbor in K_1 and is anticomplete to K_2 . By (5).1 u has a neighbor in K_k , but now $u \in K_{k,1}$ is

adjacent to $v \in K_{1,2}$, contrary to (7).3. This proves 1.2. \square

4 The Algorithm

In this section we use 2.2 to design a simple algorithm that finds a simplicial clique in a clean graph.

4.1. *There is an algorithm with the following specifications.*

Input: *A non-null clean graph G .*

Output: *A simplicial clique in G .*

Running time: $O(|V(G)|^5)$.

Proof. Let $|V(G)| = n$. First, for every vertex $v \in V(G)$ check if $N(v)$ is a clique. If the answer is yes for some v , then output a simplicial clique $\{v\}$. This step can be done in time $O(n^3)$.

Now for every edge ab compute $X(ab), Y(ab)$ and the dome of ab , and check if the dome of ab is a simplicial clique. This step can be done in time $O(n^5)$.

By 2.2 one of the two steps of the algorithm will return a simplicial clique of G . This proves 4.1. \square

We remark that the algorithm of 4.1 can be used to produce, in time $O(|V(G)|^2)$, a list of at most $|V(G)|^2$ sets one of which is guaranteed to be a simplicial clique. The rest of the running time is spent checking whether each of the sets is a simplicial clique.

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