Exclusive Graph Searching
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Abstract

This paper tackles the well known graph searching problem, where a team of searchers aims at capturing an intruder in a network, modeled as a graph. This problem has been mainly studied for its relationship with the pathwidth of graphs. All variants of this problem assume that any node can be simultaneously occupied by several searchers. This assumption may be unrealistic, e.g., in the case of searchers modeling physical searchers, or may require each individual node to provide additional resources, e.g., in the case of searchers modeling software agents. We thus introduce and investigate exclusive graph searching, in which no two or more searchers can occupy the same node at the same time. As for the classical variants of graph searching, we study the minimum number of searchers required to capture the intruder. This number is called the exclusive search number of the considered graph. Exclusive graph searching appears to be considerably more complex than classical graph searching, for at least two reasons: (1) it does not satisfy the monotonicity property, and (2) it is not closed under minor. Moreover, we observe that the exclusive search number of a tree may differ exponentially from the values of classical search numbers (e.g., pathwidth). Nevertheless, we design a polynomial-time algorithm which, given any n-node tree T, computes the exclusive search number of T in time $O(n^3)$. Moreover, for any integer k, we provide a characterization of the trees T with exclusive search number at most k. Finally, we prove that the ratio between the exclusive search number and the pathwidth of a graph is bounded by its maximum degree.

1 Introduction

Graph Searching was first introduced by Breisch [5,6] in the context of speleology, for solving the problem of rescuing a lost speleologist in a network of caves. Alternatively, graph searching

-- An extended abstract of this work has been presented in ESA 2013 [4]
can be defined as a particular type of cops-and-robber game, as follows. Given a graph $G$, modeling any kind of network, the goal is to design a strategy for a team of searchers moving in $G$ resulting in capturing an intruder. There are no limitations on the capabilities of the intruder, who may be arbitrary fast, be aware of the whole structure of the network, and be perpetually aware of the current positions of the searchers. The objective is to compute the minimum number of searchers required to capture the intruder in $G$.

To be more formal regarding the behavior of the intruder, it is more convenient to rephrase the problem in terms of clearing a network of pipes contaminated by some gas [15]. In this framework, a team of searchers aims at clearing the edges of a graph, which are initially contaminated. Searchers stand on the nodes of the graph, and can slide along its edges. Moreover, a searcher can be removed from one node and then placed to any other node, i.e., a searcher can “jump” from node to another. Sliding of a searcher along an edge, as well as positioning one searcher at each extremity of an edge, results in clearing that edge. Nevertheless, if there is a path free of searchers between a clear edge and a contaminated edge, then the former is instantaneously recontaminated. Thus, to actually keep an edge clear, searchers must occupy appropriate nodes for avoiding recontamination to occur.

Informally, a search strategy is a sequence of movements executed by the searchers, resulting in all edges being eventually clear. The main question tackled in the context of graph searching is, given a graph $G$, compute a search strategy minimizing the number of searchers required for clearing $G$. This number, denoted by $s(G)$, is called the search number of the graph $G$. For instance, one searcher is sufficient to clear a path graph, while two searchers are necessary (and sufficient) in a cycle: the search number of any path is 1, while the search number of any cycle is 2.

The above variant of graph searching is actually called mixed-search [3]. Other classical variants of graph searching are node-search [2], edge-search [14,15], connected-search [1], etc. All these variants suffer from two serious limitations as far as practical applications are concerned:

- First, all these works assume that any node can be simultaneously occupied by several searchers. This assumption may be unrealistic in several contexts. Typically, placing several searchers at the same node may simply be impossible in a physical environment in which, e.g., the searchers are modeling physical robots moving in a network of pipes. In the case of software agents deployed in a computer network, maintaining several searchers at the same node may consume local resources (e.g., memory, computation cycles, etc.). We investigate exclusive graph searching, i.e., graph searching bounded to satisfy the exclusivity constraint stating that no two or more searchers can occupy the same node at the same time.

- Second, most variants of graph searching also suffer from another unrealistic assumption: searchers are enabled to “jump” from one node of the graph, to another, potentially far away, node (e.g., see the classical mixed-search, defined above). We restrict ourselves to the more realistic internal search strategies [1], in which searchers are limited to move along the edges of the graph, that is, restricted to satisfy the internality constraint.

To sum up, we define exclusive-search as mixed-search with the additional exclusivity and internality constraints\(^1\). As for all classical variants of graph searching, we study the minimum number of searchers required to clear all edges of a graph $G$. This number is called the exclusive search number, denoted by $xs(G)$.

\(^{1}\)Note that, whenever exclusivity is not required, internality is not a strong constraint (difficult to overcome), since the jumping of one searcher from a node $u$ to a node $v$ can be replaced by sliding this searcher along a path from $u$ to $v$. However, the combination of exclusivity and internality makes the problem much more difficult.
We demonstrate that exclusive graph searching behaves very differently from classical graph searching, for at least two reasons. First, it does not satisfy the monotonicity property. That is, there are graphs (even trees) in which every exclusive search strategy using the minimum number of searchers requires recontamination occurring at some step of the strategy. Second, exclusive graph searching is not closed under taking minor (not even under subgraph). That is, there are graphs $G$ and $H$ such that $H$ is a subgraph of $G$, and $\text{xs}(H) > \text{xs}(G)$. The absence of these two properties (which will be formally established in the paper) makes exclusive-search considerably different from classical search, and its analysis requires introducing new techniques.

Our Results. First, in Section 2, we formally define exclusive graph searching and present basic properties for general graphs. Motivated by positive results for trees and inspired by the pioneering work of Parson [15] and Megiddo et al. [14], we essentially focus on trees. We observe that the exclusive search number of a graph can differ exponentially from the values of classical search numbers: in a tree, the former can be linear in the number of nodes $n$, while all classical search numbers of trees are at most $O(\log n)$. On the other hand, we prove that the ratio between the exclusive search number and other search numbers is bounded in the class of graphs with bounded maximum degree. Formally, we prove that $\text{xs}(G) \leq (\Delta - 1) \cdot (s(G) + 1)$ in any graph $G$ with maximum degree $\Delta$. Section 3 is devoted to proving some technical properties of exclusive graph searching in trees. Our main result (Section 4) is a polynomial-time algorithm which, given any $n$-node tree $T$, computes the exclusive search number $\text{xs}(T)$ of $T$ in time $O(n^3)$. Our algorithm is based on a new characterization of the trees with exclusive search number at most $k$, for any given $k \leq n$.

Related Work. Graph searching has mainly been studied in the centralized setting for its relationship with the treewidth and pathwidth of graphs [3, 10]. In particular, the pathwidth of a graph and its mixed-search number differ by at most one [3, 12]. An important property of mixed-graph searching is the monotonicity property. A strategy is monotone if no edges are recontaminated once they have been cleared. For any graph $G$, there is an optimal winning monotone (mixed-search) strategy [3]. By extension, mixed-search is said monotone. This enables to prove that the number of steps of an optimal strategy is polynomially bounded by the number of edges. Hence, the problem to decide the mixed-search number of a graph belongs to NP.

The problem of computing the search number of a graph is NP-hard [14]. However, this problem is polynomial in various graph classes [9, 11, 18]. In particular, it has been widely studied in the class of trees [8, 14–17]. More precisely, Parsons has given a nice characterization of trees with search number $k$: for any $k \geq 1$, a tree $T$ has search number at least $k + 1$ if and only if there is a node $v \in V(T)$ such that at least three components of $T \setminus v$ have search number at least $k$ [14, 15]. This result and the relative simplicity of its proof mainly come from the monotonicity of classical graph searching and from the fact that search number is not increasing by taking subtrees.

Other variants of graph searching have been introduced to deal with practical applications. Connected graph searching, in which the set of clear edges must always induce a connected subgraph (in order to ensure safe communications between the searchers), is not monotone in general [19] and it is not known if connected search is in NP. Connected search is however monotone in trees [1]. The connectivity constraint may only increase the search number of any graph by a factor up to two [7].

Concerning exclusive graph searching, a recent work has shown that computing the exclusive search number is NP-hard in planar graphs with maximum degree 3 [13]. In the same paper, it is proved that the computational complexities of monotone exclusive graph searching and pathwidth cannot be compared. Precisely, monotone exclusive graph searching is NP-complete.
in split graphs where pathwidth is known to be solvable in polynomial time. Moreover, monotone exclusive graph searching is in \( P \) in a subclass of star-like graphs where pathwidth is known to be NP-hard [13].

2 Exclusive Search

In this section, we provide the formal definition of exclusive graph searching, and present some basic general properties. All graphs considered in this paper are undirected, simple and connected.

Given a connected \( n \)-node graph \( G \), an exclusive search strategy in \( G \), using \( k \leq n \) searchers consists in (1) placing the \( k \) searchers at \( k \) different nodes of \( G \), and (2) performing a sequence of moves. A move consists in sliding one searcher from one extremity \( u \) of an edge \( e = \{u, v\} \) to its other extremity \( v \). Such a move can be authorized only if \( v \) is free of searchers. That is, exclusive-search limits the strategy to place at most 1 searcher at each node, at any point in time. The edges of graph \( G \) are supposed to be initially contaminated. An edge becomes clear whenever either a searcher slides along it, or one searcher is placed at each of its extremities. An edge becomes recontaminated whenever there is a path free of searchers from that edge to a contaminated edge. A search strategy is winning if its execution results in all edges of the graph \( G \) being simultaneously clear. The exclusive-search number of \( G \), denoted by \( \text{xs}(G) \) is the smallest number \( k \) for which there exists a winning search strategy in \( G \).

Now, we state and explain the main differences between exclusive search and all classical variants of graph searching. These differences are mainly due to the combination of the two restrictions introduced in exclusive search: two searchers cannot occupy the same node (exclusivity) and a searcher cannot “jump” (internality). Intuitively, the difficulty occurs when a searcher has to go from one node \( u \) to a far away node \( v \), and all paths from \( u \) to \( v \) contain an occupied node.

Consider a simple example of a star with central node \( c \) and \( f \) leaves. In the classical graph searching, one searcher can occupy \( c \), while a second searcher will sequentially clear all leaves, either by jumping from one leaf to another, or by sliding from one leaf to another, and therefore occupying several times the already occupied node \( c \). In exclusive graph searching, such strategies are not allowed. Intuitively, if a searcher \( r_1 \) has to cross a node \( v \) that is already occupied by another searcher \( r_2 \), the latter should step aside for letting \( r_1 \) pass. However, \( r_2 \) may occupy \( v \) to preserve the graph from recontamination, and moving away from \( v \) could lead to recontamination the whole graph. To avoid this, it may be necessary to use extra searchers (compared to the classical graph searching) that will guard several neighbors of \( v \) to prevent from recontamination when \( r_2 \) gives way to \( r_1 \). It follows that, as opposed to all classical search numbers, which differ by at most some constant multiplicative factor, the exclusive search number may be arbitrary large compared to the mixed-search number, even in trees. For instance, it is easy to check that \( \text{xs}(S_n) = n - 2 \) for any \( n \)-node star \( S_n \), \( n \geq 3 \). More generally,

Claim 1 For any tree \( T \) with maximum degree \( \Delta \geq 2 \), \( \text{xs}(T) > \Delta - 2 \).

Proof. We prove the following more general result. Let \( G \) be any connected graph with a cut-vertex \( v \) (so \( G \) has at least two edges) and let \( cc(v) \geq 2 \) be the number of the connected components in \( G \setminus \{v\} \), then \( \text{xs}(G) > cc(v) - 2 \). The result clearly holds if \( cc(v) = 2 \) since any strategy must use at least one searcher to clear any graph with at least one edge. Therefore, we may assume that \( cc(v) > 2 \).

Let \( v \) be a cut-vertex of a graph \( G \) and consider any strategy using at most \( cc(v) - 2 \) searchers. Initially, at least two components \( U \) and \( W \) of \( G \setminus \{v\} \) are unoccupied and so all
edges in these components are contaminated. Let us, consider the first step when a searcher occupies a node in one of these components, say $U$. That is, let us consider the first step when a searcher slides from $v$ to a node in $U$. But after this step, no searchers are occupying a node in $W$ which is still contaminated, no searcher is occupying $v$ and there is a connected component $C$ of $G \setminus (\{v\} \cup U \cup W)$ that contains no searchers. Hence, $C$ is fully (re)contaminated. Hence, at any step of the strategy, at least two connected components of $G \setminus \{v\}$ remain contaminated.

We proof on Claim 1 that an exponential increase in the number of searchers used to clear a graph since the mixed-search number of $n$-node trees is at most $O(\log n)$ [15]. On the positive side, we show that, for any graph $G$ with maximum degree $\Delta$, $xs(G) \leq (\Delta - 1)(s(G) + 1)$. To prove it, we consider a classical strategy $S$ for $G$ using $s(G)$ searchers. To build an exclusive strategy $S^*$ for $G$, we mimic $S$ using a team of $\Delta - 1$ searchers to “simulate” each searcher in $S$. For details, see the proof below.

Let $N(v)$ denote the set of neighbors of a node $v \in V(G)$ and let $N[v] = N(v) \cup \{v\}$ be the close neighborhood of node $v$.

**Theorem 1** For any connected graph $G$ with maximum degree $\Delta$,

$$s(G) \leq xs(G) \leq (\Delta - 1) \cdot (s(G) + 1).$$

Moreover, if $\Delta \leq 3$, $s(G) \leq xs(G) \leq s(G) + 1$.

**Proof.** $s(G) \leq xs(G)$ is a direct consequence of the definition since exclusive-search is a variant of mixed-search where searchers are more constrained.

To prove the second inequality, it is more convenient to deal with node-search. A node-search strategy is a search strategy where edges become clear only if both their ends are occupied simultaneously. The node-search number, denoted by $ns(G)$, of a graph $G$ is the smallest number of searchers needed to clear $G$ in this setting. It is well known that $ns(G) \leq s(G) + 1$ for any graph $G$ and that recontamination does not help for node-search [2,3]. Hence, we will prove here that $xs(G) \leq (\Delta - 1) \cdot ns(G)$ for any graph $G$ with maximum degree $\Delta$.

Let $S$ be a winning monotone node-search strategy of $G$ using $k \geq ns(G)$ searchers. Let $(s_1, \cdots, s_r)$ be the corresponding sequence of place and remove steps. Note that we can assume that a searcher is removed as soon as possible, i.e., if after some step $s_i$, a searcher occupies a node incident only to clear edges, no other searcher can be placed before this searcher is removed. We also may assume that there are no useless steps, i.e., no step consists in placing a searcher at a node incident to only clear edges nor in placing a searcher at an already occupied node. Last remark, before each step $s_i$ that consists in placing a searcher at a node $v$, all edges incident to $v$ are contaminated.

For any $i, 1 \leq i \leq r$, let $E_i$ be the set of clear edges after step $s_i$ and let $V_i$ be the set of occupied nodes after step $s_i$. By remark above, if $s_{i+1}$ consists in placing a new searcher, then every node of $V_i$ is incident to at least one contaminated edge after step $s_i$. We set $V_0 = E_0 = \emptyset$. Because the strategy is monotone, $E_{i-1} \subseteq E_i$ for any $1 < i \leq r$. Moreover, any path from an edge in $E_i$ and an edge in $E \setminus E_i$ must contain a node in $V_i$.

1. Let us first assume that $\Delta \leq 3$. In this case, we show that $xs(G) \leq ns(G)$. We use $S$ to define an exclusive strategy $S^*$ to clear $G$ using $k$ searchers. Initially, the $k$ searchers are placed at any arbitrary $k$ nodes. Then, the strategy consists of $r$ phases described below, where Phase $i$ of $S^*$ depends on step $s_i$ of $S$ ($i \leq r$). For any $1 \leq i \leq r$, we show that, if before Phase $i$, the nodes of $V_{i-1}$ were occupied and the edges of $E_{i-1}$ were clear, then after Phase $i$, the nodes of $V_i$ are occupied and the edges of $E_i$ are clear. In particular, this implies that after Phase $r$, the edges of $E_r = E$ are clear. Note that, before Phase 1,
the induction hypothesis holds since \( V_0 = E_0 = \emptyset \). Now, let \( 1 \leq i \leq r \) and assume that the induction hypothesis holds before Phase \( i \).

The easy case is when \( s_i \) is a remove-step. In that case, Phase \( i \) consists in doing nothing and the induction still holds before Phase \( i + 1 \).

Let us now assume that step \( s_i \) consists in placing a searcher at some node \( v \in V \). Therefore, \( |V_{i-1}| < k \) and there are searchers that are not occupying a node in \( V_{i-1} \) just before Phase \( i \). We call these searchers "free searchers". Let us consider the free searcher \( f \) in node \( x \) that is the closest to \( v \) just before Phase \( i \). The Phase \( i \) consists in "moving" \( f \) from \( w \) to \( v \). We show how it can be done without recontaminating any edge in \( E_{i-1} \) and then we show that the edges of \( E_i \) are clear at the end of the Phase \( i \).

Let \( P = (w, w_2, \ldots, u_{n_1}, v) \) be a shortest path from \( w \) to \( v \).

(a) First assume that \( P \) contains no nodes in \( V_{i-1} \). Then, no nodes in \( \{u_2, \ldots, u_{n_1}, v\} \) are occupied because we have considered the free searcher \( f \) that is closest to \( v \). Therefore, Phase \( i \) consists in sliding \( f \) from \( w \) to \( v \) along \( P \). Let \( F \) be the set of edges that are incident to some node of \( P \). To show that no edges in \( E_{i-1} \) is recontaminated during these moves, it is sufficient to point out that either \( F \subseteq E_{i-1} \) or \( F \subseteq E \setminus E_{i-1} \). Indeed, we already mentioned that any path between an edge in \( E_{i-1} \) and an edge in \( E \setminus E_{i-1} \) contains a node in \( V_{i-1} \). In other words, an edge of \( E_{i-1} \) might be recontaminated only by moving a searcher from a node in \( V_{i-1} \).

(b) Otherwise, there exist \( 2 \leq j \leq \ell < h \) such that, for any \( q < j \), \( u_q \notin V_{i-1} \); for any \( j \leq q \leq \ell \), \( u_q \in V_{i-1} \) and \( u_{q+1} \notin V_{i-1} \). In that case, \( f \) first slides from \( w \) to \( u_{j-1} \). No edges of \( E_{i-1} \) are recontaminated for the same reason as in the previous item. Then, we simulate the “jump” of the free searcher from \( u_{j-1} \) to \( u_{\ell+1} \) in the following way. For \( t \) from \( \ell \) down to \( j \), the searcher at \( u_t \) slides to \( u_{t+1} \). Finally, the free searcher occupying \( u_{j-1} \) slides to \( u_j \).

When a searcher moves from \( u_t \) to \( u_{t+1} \), the only two edges that might be recontaminated are \( \{u_{t-1}, u_t\} \) and \( \{u_{t+1}, u_t\} \) because \( u_t \) has degree at most three. However, \( \{u_{t+1}, u_t\} \) is clear as soon as the next searcher moves from \( u_{t-1} \) to \( u_t \).

Therefore, after these \( \ell - j + 2 \) moves, the edges of \( E_{i-1} \) are still clear, the nodes of \( V_{i-1} \) are still occupied and a (new) free searcher is occupying the node \( u_{\ell+1} \), i.e., the free searcher has progressed along \( P \).

The same process is done until a searcher reaches \( v \) (always following \( P \)).

To conclude, after Phase \( i \), a searcher is on \( v \) and all nodes of \( V_{i-1} \) are occupied, hence the nodes of \( V_i = V_{i-1} \cup \{v\} \) are occupied. Moreover, we showed above that the edges of \( E_{i-1} \) are still clear after Phase \( i \). Since \( E_i \setminus E_{i-1} \) is the set of edges that are incident to \( v \) and to some node in \( V_{i-1} \), they are clear as well at the end of this phase.

Hence, the induction hypothesis holds after Phase \( i \) and \( S^* \) is a winning strategy satisfying exclusivity for clearing \( G \) with \( k \) searchers. Hence, \( \text{xs}(G) \leq \text{ns}(G) \).

2. Now, let us consider the case of an arbitrary \( \Delta \). We use \( S \) to define an exclusive strategy \( S^* \) to clear \( G \) using \( (\Delta - 1)k \) searchers. As previously, \( S^* \) consists of \( r \) phases such that, after Phase \( i \), \( i \leq r \), we ensure that the edges in \( E_i \) are clear. The difference with previous case is that at each step, we ensure that all nodes of \( V_i \) are occupied after Phase \( i \) and, moreover, for any node \( v \in V_i \) at most two neighbors of \( v \) are not occupied.

As previously, all the searchers are placed on arbitrarily different nodes initially. Then, for each step \( s_i \) (\( 1 \leq i \leq r \)), if \( s_i \) is a remove-step then Phase \( i \) consists in doing nothing.
Otherwise, if \( s_i \) consists in placing a searcher at some node \( v \), this means that \(|V_{i-1}| < k\) and therefore there are at least \( \Delta - 1 \) free searchers. Here, each node in \( V_{i-1} \) is \textit{assigned} \( \leq \Delta - 1 \) searchers, the remaining searchers being the free searchers. Intuitively, a searcher assigned to a node \( v \) is dedicated to protect \( v \) from recontamination, either by occupying \( v \) or by occupying some neighbor of \( v \). To ensure this, Phase \( i \) consists in moving \( \Delta - 1 \) free searchers from their current positions either to \( v \) or to some neighbor of \( v \) until \( v \) is occupied and at most two neighbors of \( v \) are not occupied.

More precisely, while \( v \) has not been yet assigned \( \Delta - 1 \) searchers and there is still a node in \( N[v] \) that is unoccupied, we do the following. Let us consider a free searcher \( f \) not occupying a node in \( N[v] \) and that is closest to an unoccupied node \( x \) in \( N[v] \). \( f \) is assigned to \( v \) in the following manner. Let \( w \) be the node occupied by \( f \) at the end of Phase \( i - 1 \), and let \( P = (w = u_1, \ldots, u_h = x) \) be a shortest path from \( w \) to \( x \). As previously, if no nodes in \( \{u_2, \ldots, u_h\} \) are occupied, \( f \) simply slides along the path until it reaches \( x \).

Otherwise, w.l.o.g., assume that \( \{u_2, \ldots, u_j\} \) are occupied and \( u_{j+1} \) is not for some \( 2 \leq j < h \). Then, the strategy is the following. For \( t \) from \( j \) down to \( 1 \), if \( u_t \notin V_{i-1} \), the searcher at \( u_t \) slides to \( u_{t+1} \). Otherwise, if \( u_t \in V_{i-1} \) there are two cases. If there are two neighbors \( z \neq u_{t+1} \) and \( y \neq u_{t+1} \) of \( u_t \) that are not occupied, then the searcher at \( u_t \) slides to \( y \). Note that such a case may occur only if \( u_{t+1} \notin V_{i-1} \). Otherwise, the searcher at \( u_t \) slides to \( u_{t+1} \).

After Phase \( i \), all edges of \( E_i \) are clear and all nodes of \( V_i \) and their neighbors (but at most two per node in \( V_i \)) are occupied. Hence, the theorem follows.

Because the pathwidth of a graph \( G \) and its search number \( s(G) \) differ by at most one, Theorem 1 also proves that the ratio between the exclusive search number and the pathwidth of \( G \) is bounded by the degree of \( G \).

Note that the example of the \( n \)-node star \((S_n)\) shows that the inequalities in Theorem 1 are tight up to a constant ratio, since \( s(S_n) = 2 \) and \( xs(S_n) = n - 2 \) for any \( n \geq 4 \).

We now focus on monotonicity property. Indeed, another important difference of exclusive search compared to classical graph searching is that it is not monotone. As explained in the example of a star (at the beginning of the section), when a searcher needs to cross another one, letting the former searcher pass (to satisfy exclusivity) may lead to a recontamination of some edges. The goal of the winning strategy is to prevent a possible “uncontrolled” recontamination.

\textbf{Claim 2} \textit{Exclusive graph searching is not monotone, even in trees.}

Figure 1: A tree where no optimal exclusive search strategy is monotone.

\textbf{Proof.} Let \( T \) be a tree with a node set \( \{a_1, a_2, a_3, b, c_1, c_2, c_3\} \) such that \( \{a_1, a_2, b, c_2, c_1\} \) is a path and \( a_3 \) is adjacent to \( a_2 \) and \( c_3 \) is adjacent to \( c_2 \) see Figure 1.
We first prove that $\alpha G(T) = 2$. A winning strategy using two searchers is defined as follows: choose $\{a_1, a_3\}$ as initial positions and place searchers $X$ and $Y$ on these nodes respectively. Then, $Y$ slides along the edges of the path from $a_3$ to $c_2$, $X$ slides along the edges from $a_1$ to $b$, $Y$ goes to $c_3$ (here the edge $\{b, c_2\}$ is recontaminated), and finally, $X$ slides to $c_1$. The fact that $\alpha G(T) > 1$ is obvious and follows Claim 1.

Finally, consider any winning strategy using two searchers, we show that there is a step with recontamination. There are two cases to be considered. Either the set of initial positions contains no nodes in $C = \{c_1, c_2, c_3\}$ (or symmetrically in $A = \{a_1, a_2, a_3\}$), or one searcher initially occupies a node in $C$ and the other searcher occupies a node in $A$.

In the first case, i.e., no nodes in $C$ are occupied initially, consider the first step when $c_1$ or $c_3$, w.l.o.g., say $c_1$, is occupied. This can be done only by moving a searcher along the edge $\{c_2, c_1\}$. But then, the edge $\{b, c_2\}$ is recontaminated by $\{c_2, c_3\}$ (since $c_3$ has never been occupied yet).

In the second case, consider the first searcher to reach $b$, w.l.o.g., it comes from $a_2$. Then, it is easy to verify that $\{a_2, b\}$ is recontaminated because a single searcher cannot have cleared $\{a_1, a_2\}$ and $\{a_3, a_2\}$ simultaneously.

Last, but not least, contrary to classical graph searching, exclusive graph searching is not closed under minor. We show below that though taking a subgraph can decrease the connectivity and “help” the searchers in the classical case, it does not do so in general in the exclusive search. Formally, we show the following.

Claim 3 For any $\Delta \geq 3$, there exists a graph $G$ with $2\Delta + 1$ nodes and an induced subgraph $H$ such that $\alpha G(H) = \Delta - 1$ and $\alpha G(G) \leq 3$.

Proof. Let $H$ be a $(\Delta + 1)$-node star. By Claim 1, $\alpha G(H) \geq \Delta - 1$ and it is easy to check that $\alpha G(H) = \Delta - 1$. Let $G$ be a graph built from a cycle with a set of nodes $(a_1, \cdots, a_{2\Delta})$ (in this order), and by adding a node $c$ adjacent to $a_{2i}$ for any $1 \leq i \leq \Delta$. $H$ is an induced subgraph of $G$. Finally, $\alpha G(G) \leq 3$: place searchers at each node in $\{c, a_1, a_2\}$. The searcher at $a_2$ then slides to $a_{2\Delta}$ along the path induced by $V(G) \setminus \{a_1, c\}$.

Actually, there is an even more surprising behaviour of exclusive graph searching. Consider any (mixed) search strategy $S$ that clears a graph $G$, let $H$ be any subgraph and let $k$ be the maximum number of searchers that occupy the nodes of $H$ at some step of $S$. Then, $s(H) \leq k$ [folklore]. In other words, since $s(H)$ searchers are required to clear $H$, there must be a step of $S$ where at least $s(H)$ searchers are occupying simultaneously some nodes of $H$. Note that this property is one of the key points of the proof of the Parsons’ characterization [15].

Unfortunately, this property is not true anymore for exclusive graph searching even restricted to trees. Indeed, let $\Delta > 3$ and let $T$ be the tree obtained from a star $S$ with leaves $(a_1, \cdots, a_\Delta)$ by adding, for any $3 \leq i \leq \Delta$, two neighbors $b_i$ and $c_i$ to $a_i$. Note that $T \setminus S$ induces a graph that is not connected. Consider the following exclusive search strategy: start with one searcher at any node $b_i$, $3 \leq i \leq \Delta$ and one searcher at $a_1$; the searcher at $a_1$ slides to the center of $S$; then, sequentially for $i$ from $3$ to $\Delta$, the searcher at $b_i$ goes to $a_i$ and then to $c_i$; finally, the searcher at the center goes to $a_2$. At any step of the described strategy, at most 2 searchers are occupying the nodes in $S$, while $\alpha G(S) = \Delta - 1$.

Nevertheless, we prove in Lemma 1 that this property remains true for some particular subtrees of trees (roughly, when $T \setminus S$ is connected). As a corollary, it follows that exclusive-search is closed under subgraph in trees.
3 Exclusive search number is closed under taking subtrees

This section is devoted to proving that the exclusive search number of trees is closed under taking subtrees. Theorem 2 will be used to prove the necessary conditions for our main result (Theorem 3 in the next section).

**Theorem 2** For any tree $T$ and any subtree $R$ of $T$, $\text{xs}(R) \leq \text{xs}(T)$.

Contrary to classical graph searching, the proof of Theorem 2 is not trivial, due to of the exclusivity property. To prove it, we will transform an exclusive strategy $S$ for a tree $T$ into a strategy $S'$ for a subtree $R$ using the same number of searchers, and without violating the exclusivity property. Before going into the details of the proof and to point out the main difficulties, let us briefly recall the proof of the fact that the mixed-search number is closed under taking subgraphs. Let $S_m = (s_1, \ldots, s_r)$ be a mixed-search strategy that clears a graph $G$ using $k \geq s(G)$ searchers and let $H$ be any subgraph of $G$. Then, a mixed-search strategy clearing $H$ can be obtained as follows. For any $i \leq r$ such that $s_i$ is a step that does not concerns the nodes of $H^2$, remove $s_i$ from $S_m$. For any $i \leq r$, if $s_i$ consists in sliding a searcher along $(u, v] \in E(G)$ (from $u$ to $v$) where $u \in V(G) \setminus V(H)$ and $v \in V(H)$, then replace $s_i$ by the step placing a searcher at $v$. Finally, for any $i \leq r$, if $s_i$ consists in sliding a searcher along $(u, v] \in E(G)$ (from $u$ to $v$) where $u \in V(H)$ and $v \in V(G) \setminus V(H)$, then replace $s_i$ by the step removing a searcher from $u$. It is easy to check that the obtained sequence of moves is a mixed-search strategy that clears $H$ using at most $k$ searchers.

A key point when designing the mixed-search strategy for $H$ is that some searchers may be removed from the graph when they are useless and placed at some node later when they become useful (for instance when a step of $S_m$ slides a searcher from a node in $V(G) \setminus V(H)$ to a node of $H$). Note that when a searcher is removed from $H$, it does not interfere with the moves of other searchers. Such removals are not allowed in exclusive search strategy. On the contrary, in an exclusive search strategy, any searcher must occupy some node of $H$ since the beginning of the strategy and without disturbing the motions of other searchers. Moreover, notice that, a searcher may occupy some node that must be crossed by some other searcher (according to mixed-search strategy for $H$). Then, in the exclusive strategy, the moves should be adapted to avoid violation of the exclusivity constraint.

The next two Propositions are technical results that will be used to deal with these problems in trees and finally to prove Lemma 1. Informally, these propositions state that, if there exists a sequence of moves in a tree, then we can initially add a searcher without disturbing the whole motion of the searchers. That is, we are able to clear the same part of the tree even with the extra searcher “in the middle”. Moreover, in some cases, we can keep some control on the final position of the extra searcher with respect to its initial position.

**Notations.** Let $G = (V, E)$ be a graph and $S = (s_1, \ldots, s_r)$ be a sequence of moves. A state after step $s_i$ (or before step $s_{i+1}$) consists of a pair $(I, F)$ where $I$ is the set of nodes occupied by some searchers after step $s_i$ and $F$ is a subset of cleared edges (after $s_i$). Moreover, we impose that, for any two incident edges $e \in F$ and $f \notin F$, their common end is in $I^3$. Note that $F$ does not necessarily contain all clear edges. We say that $S$ is a sequence from state $C$ to state $C'$ if $C$ is the state before the first step of $S$ and $C'$ is the state after its last step.

We recall that for any $v \in V(G)$, $N(v)$ denotes the set of the neighbors of $v$ and $N[v] = N(v) \cup \{v\}$.

\(^2\)That is, $s_i$ consists in either placing a searcher at a node of $V(G) \setminus V(H)$, or removing a searcher from a node of $V(G) \setminus V(H)$, or sliding a searcher along an edge in $(u, v] \in E(G)$ where $u, v \in V(G) \setminus V(H)$.

\(^3\)This constraint is only to avoid considering pathological cases when a sequence $S$ starts from a state $(I, F)$ and some edges of $F$ are recontaminated before the first move of $S$. 


Proposition 1 Let $T$ be a tree, $S = (s_1, \cdots, s_r)$ be a sequence of exclusive-search moves from state $C = (I, F)$ to state $C' = (I', F')$ and let $v \in V(T) \setminus I$. There exists a sequence $S'$ of moves in $T$ from $(I \cup \{v\}, F)$ to $(I' \cup \{w\}, F')$, where $w \in V(T) \setminus I'$. Moreover, if $v \notin I'$ then $w = v$.

Proof. If $|V(T)| = 1$, the claim clearly holds. Indeed, since $v \in V(T) \setminus I$, then $I = \emptyset$. In that case, $S'$ consists only in placing a searcher at $v$. Assume by induction on $n > 1$ that the claim holds for any tree $T$ with $|V(T)| < n$. We now show that it holds if $|V(T)| = n$ by induction on $r > 0$.

If the first step $s_1$ of $S$ consists of sliding a searcher from $x \in I$ to $y \neq v$, let $F$ be the set of clear edges after this step in $S$.

- If $r = 1$, then $S$ goes from state $(I, F)$ to state $(I \cup \{y\} \setminus \{x\}, F')$ (where $F = F'$ and $I' = I \cup \{y\} \setminus \{x\}$). Then $S'$ only executes the step $s_1$ and the result clearly holds.

More precisely, $S'$ starts from $(I \cup \{v\}, F)$ (possible since $v \notin I$) and then moves the searcher at $x$ along the edge $\{x, y\}$ (possible since $v \neq y$). The set of edges that are cleared at the end of such strategy must be a super-set of (or equal to) the subset $\overline{F}$ of edges cleared at the end of $S$ (in $S'$, there is one searcher more, so no edge can be recontaminated by $S'$ while it is not recontaminated by $S$). Hence, $F = F'$ is a subset of cleared edges after $S'$. Therefore, the state $(I' \cup \{v\}, F')$ is achieved by $S'$.

In other words, $S'$ goes from $(I \cup \{v\}, F)$ to $(I' \cup \{v\}, F')$.

- Otherwise, the sequence $(s_2, \cdots, s_r)$ goes from $((I \cup \{y\}) \setminus \{x\}, F)$ to $(I', F')$. By induction, there is a sequence $S^*$ of moves from $((I \cup \{y, v\}) \setminus \{x\}, F)$ to $(I' \cup \{w\}, F')$ where $w \notin I'$ and $w = v$ if $v \notin I'$. The sequence $(s_1, S^*)$ starting from $(I \cup \{v\}, F)$ satisfies the requirements.

Otherwise, let us assume that the first step $s_1$ of $S$ consists in sliding a searcher from $x \in I \setminus N(v)$ to $v$.

If $r = 1$, then the sequence that starts from $(I \cup \{v\}, F)$ and does nothing satisfies the requirements.

Let us assume that $r > 1$. There are two cases: either $v$ remains occupied during the whole strategy $S$, or let $s_i, 1 < i \leq r$, be the first step such that the searcher at $v$ slides to some node $y \in N(v)$. Let $T_1, \cdots, T_p$ be the connected components of $T \setminus \{v\}$ where $T_p$ is the component of $x$.

1. Consider the first case, i.e., from $s_1$, $v$ is always occupied in $S$. We may assume (up to reordering the steps in $S$) that $S$ applies move $s_1$, and then applies the moves in $T_1, \cdots, T_p$ sequentially, i.e., any move in $T_i$ is performed before any move in $T_{i+1}$ for any $1 \leq i < p$.

Let $S^*$ be the restriction of $(s_2, \cdots, s_r)$ to $T_p$ (that is the subsequence of the moves that consists in sliding along an edge of $T_p$). The sequence $S^*$ starts from $((I \cap V(T_p)) \setminus \{x\}, F)$, where $F$ is the set of edges of $E(T_p)$ that are cleared after step $s_1$ of $S$. Moreover, $S^*$ terminates in $(I' \cap V(T_p), F' \cap E(T_p))$.

Since $|V(T_p)| < |V(T)|$, using induction, there is a sequence of moves $S^p$ in $T_p$ that starts from $((I \cap V(T_p)) \cup \{x\}, F)$ and terminates in $(I' \cap V(T_p) \cup \{w\}, F' \cap E(T_p))$ where $w \notin I' \cap V(T_p)$ and $w = x$ if $x \notin I' \cap V(T_p)$.

Then, the following sequence of moves proves the claim. Starting from $(I \cup \{v\}, F)$, apply sequentially the moves of $S$ in $T_1, \cdots, T_{p-1}$ and finally apply the sequence of moves $S^p$.

2. Now, let $s_i, 1 < i \leq r$, be the first step of $S$ such that the searcher at $v$ slides to some node $y \in N(v)$. Let $(I', F')$ be the state reached by $S$ after this step. Note that $v \notin I'$.
Therefore, the sequence of moves \((s_{t+1}, \ldots, s_r)\) allows to go from state \((I', F')\) to state \((I', F')\). By induction on \(r\), there is sequence of moves \(S^{**}\) that allows to go from \((I' \cup \{v\}, F')\) to \((I' \cup \{v\}, F')\), where \(w \notin I'\) and \(w = v\) if \(v \notin I'\).

It only remains to prove that there is a sequence \(S^*\) of moves that starts in \((I \cup \{v\}, F)\) and terminates in \((I' \cup \{v\}, F')\). The sequence of moves that consists of applying the moves in \(S^*\) and then the moves in \(S^{**}\) will then satisfy the requirements.

Let \(S^{i-1}\) be the sequence of moves \((s_2, \ldots, s_{i-1})\) and let \((I^{i-1}, F^{i-1})\) be the state reached by \(S^{i-1}\). We may assume (up to reordering the steps in \(S^{i-1}\)) that \(S^{i-1}\) applies move \(s_1\), and then applies the moves in \(T_1, \ldots, T_p\) sequentially.

Let us define \(S^*\) as follows. First, apply sequentially the moves of \(S^{i-1}\) in \(T_1, \ldots, T_{p-1}\). Then,

(a) if \(y \neq x\), move the searcher at \(v\) to \(y\) and the searcher at \(x\) to \(v\) and then apply the moves of \(S^{i-1}\) in \(T_p\).

(b) Otherwise, as in previous item, by induction since \(|V(T_p)| < |V(T)|\), from the sequence of moves of \(S^{i-1}\) restricted to \(T_p\), we can define a sequence \(S\) of moves in \(T_p\) that starts in the same state as in \(S^{i-1}\) (restricted to \(T_p\)) plus one extra searcher at \(x\) and that reach the same final state as in \(S^{i-1}\) (restricted to \(T_p\)) with the extra searcher still at \(x\). Apply \(S\) to terminate \(S^*\).

\[\square\]

**Proposition 2** Let \(T\) be a tree and let \(S = (s_1, \ldots, s_r)\) be a sequence of moves from \(C = (I, F)\) to \(C' = (I', F')\). Assume that there is \(v \in I\) such that \(v\) is occupied only during the first \(r - 1\) steps of \(S\) and \(s_r\) consists in sliding the searcher at \(v\) to one of its neighbors. Note that \(v \notin I'\). There exists \(w \in V(T) \setminus I\) and a sequence \(S'\) of moves in \(T\) starting from \((I \cup \{w\}, F)\) and ending in state \((I' \cup \{v\}, F')\).

**Proof.** We build a strategy \(S' = (s'_1, \ldots, s'_p)\) with an extra searcher \(f\) (compared with \(S\)) that starts in some node \(w \notin I\) and ends in \(v\) such that, at the end of \(S'\), all edges in \(F'\) are cleared and the set of occupied nodes is \(I' \cup \{v\}\).

We need to find an unoccupied initial position \(w\) for \(f\), such that it ensures that \(v\) will be occupied at the end of the sequence of moves. Let \(\{v = w_\ell, \ldots, w_1 = w\}, \ell > 1\), be the path defined as follows. \(w \in V(T) \setminus I\), i.e., \(w_1\) is not initially occupied in \(S\). For any \(1 < j \leq \ell, w_j\) is initially (in \(S\)) occupied by a searcher, i.e., \(w_j \in V(T) \cap I\), and the first move of this searcher in \(S\), at step \(s_j^*\), is to slide from \(w_j\) to \(w_{j-1}\). Such a path clearly exists and \(s_j^* > s_{j-1}^*\) (meaning step \(s_j^*\) occurs before step \(s_{j+1}^*\) in \(S\)) for any \(1 \leq j < \ell\). In particular, note that \(s_{\ell}^* = s_r\).

Strategy \(S'\) initially places \(f\) at \(w_1 = w\) and other searchers are placed at the nodes of \(I\).

Let \((I_2, F_2)\) be the state reached by \(S\) just before step \(s_\ell^*\) (when the searcher at \(w_2\) moves for the first time and goes to \(w_1 = w\)). Note that \(w \notin I_2 \cup I\). Therefore, by Proposition 1, there is sequence \(S_2\) of moves that goes from state \((I \cup \{w_1\}, F)\) to \((I_2 \cup \{w\}, F_2)\).

Therefore, starting with \(f\) in \(w\) and executing \(S_2\), we obtain the same state as in \(S\) before \(s_\ell^*\), but with \(f\) still in \(w\) (possibly more edges may have been cleared). Then \(s_\ell^*\) moves a searcher from \(w_2 \in I_2\) to \(w_1\). Actually, since both \(w_2\) and \(w_1\) are occupied after executing \(S_2\), we have reached the state after step \(s_\ell^*\) in \(S\), having \(f\) in \(w_2\).

Assume that we have executing the sequence of moves \((S_2, \ldots, S_i), i < \ell, \) and that we have reached the state \((I_i \cup \{w_1\}, F_i)\) where \((I_i, F_i)\) is the state reached by \(S\) after step \(s_i^*\) (in particular, \(w_i \notin I_i\)). Let \((I_{i+1}, F_{i+1})\) be the state reached by \(S\) just before step \(s_{i+1}^*\). Note
that \( w_{i+1} \notin I_{i+1} \). By Proposition 1, there is sequence \( S_{i+1} \) of moves that goes from state \((I_i \cup \{w_i\}, F_i)\) to \((I_{i+1} \cup \{w_i\}, F_{i+1})\). Then \( s^*_{i+1} \) moves a searcher from \( w_{i+1} \in I_{i+1} \) to \( w_i \). Actually, since both \( w_{i+1} \) and \( w_i \) are occupied after executing \( S_{i+1} \), we have reached the state after step \( s^*_{i+1} \) in \( S \), having \( f \) in \( w_{i+1} \).

Going on in that way, the sequence of moves \((S_2, \ldots, S_r)\) satisfies the desired requirements.

\[ \square \]

**Definition 1** Given a node \( v \) in a tree \( T \), a connected component of \( T \setminus \{v\} \) is called a branch at \( v \).

We are now ready to prove the main lemma.

**Lemma 1** Let \( T \) be any tree and \( R \) be a branch at \( v \in V(T) \). Let \( S' = (s'_1, \ldots, s'_r) \) be any exclusive strategy for \( T \) and let \( k \) be the maximum number of searchers occupying simultaneously (at the same step) some nodes of \( R \). Then \( \text{xas}(R) \leq k \).

**Proof.** Let \( u \) be the node of \( R \) that is adjacent to \( v \) and let \( e = \{u, v\} \in E(T) \).

Note that, for all \( i \leq r \), \( s'_i \) consists of the sliding of a searcher along an edge of \( E(T) \). We consider the restriction of \( S' \) to \( R \) and we build the sequence \( S \) of moves as follows. Let \( I \) be the set of nodes of \( R \) that are initially occupied by a searcher in \( S' \). In \( S \), let us start by placing one searcher at each node of \( I \). Then, for any step \( s'_i \) of \( S' \), if \( s'_i \) consists of sliding a searcher along an edge \( \{x, y\} \in E(T) \) we keep this move; if \( s'_i \) consists of sliding a searcher along an edge \( \{x, y\} \in E(T) \setminus \{E(R) \cup \{e\}\} \) (i.e., \( v \notin \{x, y\} \)), we remove \( s'_i \); if \( s'_i \) consists in sliding a searcher from \( v \) to \( u \), we add a particular move that consists in putting a searcher at \( u \) and if \( s'_i \) consists in sliding a searcher from \( u \) to \( v \), we add a particular move that consists in removing a searcher at \( u \).

Therefore, \( S = (s_1, \ldots, s_p) \) is a sequence of moves that are either sliding a searcher along an edge of \( R \), or a particular step which is either placing a searcher at \( u \) or removing a searcher at \( u \). It is easy to check that this sequence results in the clearing of all edges in \( R \), no more than \( k \) nodes are occupied at any step, and any node is never occupied by more than one searcher.

We prove by induction on the number of particular steps of \( S \) (removing or placing a searcher) that \( \text{xas}(R) \leq k \). First assume that \( S \) contains no particular steps. Clearly, it is an exclusive strategy, using \( k \) searchers and clearing all edges of \( R \). Therefore, the result holds.

If \( S \) contains some particular steps, we build a new strategy \( S^* \) with same properties and one less particular step. The result then follows by induction. There are three cases to be considered.

1. Assume that the last particular step \( s_i \) \((i \leq p)\) of \( S \) is a removal step. Let \((I, F)\) be the state after this step and let \((I', F')\) be the state at the end of \( S \). Note that \( u \notin I \) and \( |I| < k \).

   By Proposition 1, there is a sequence \( S^* \) of moves from \((I \cup \{u\}, F)\) to \((I' \cup \{w\}, F')\) with \( w \in V(R) \setminus I' \). Hence, the sequence of moves \((s_1, \ldots, s_{i-1}, S^*)\) clears all edges in \( R \) and no more than \( k \) nodes are occupied at some step. Moreover, it has less particular moves than \( S \), therefore the result holds by induction.

2. Assume that the first particular step \( s_i \) \((i \leq p)\) of \( S \) is a placing step. Let \((I, F)\) be the state at the beginning of \( S \) and let \((I', F')\) be the state before this step \( s_i \). Note that \( u \notin I' \), that \( |I| < k \) and that \((I' \cup \{u\}, F')\) is the state just after \( s_i \).

   By Proposition 2 and Proposition 1, there is a sequence \( S^* \) of moves from \((I \cup \{w\}, F)\) to \((I' \cup \{u\}, F')\) with \( w \in V(R) \setminus I \). Hence, the sequence of moves \((S^*, s_{i+1}, \ldots, s_p)\) clears
all edges in \( R \) and no more than \( k \) nodes are occupied at some step. Moreover, it has less particular moves than \( S \), therefore the result holds by induction.

3. If none of the previous cases hold, then there are \( 1 \leq i < j \leq p \) such that \( s_i \) is a removal step, \( s_j \) is a placing step and \( s_l \) is not a particular step for all \( i < l < j \). Let \(( I, F)\) be the state after step \( s_i \) and let \(( I', F')\) be the state before step \( s_j \). Note that \( u \notin I \cup I' \), that \( |I| = |I'| < k \) and that \(( I' \cup \{u\}, F')\) is the state just after \( s_j \).

From Proposition 1, there is a sequence \( S^* \) of moves from \(( I \cup \{u\}, F)\) to \(( I' \cup \{u\}, F')\). Hence, the sequence of moves \(( s_1, \ldots, s_i, S^*, s_{j+1}, \ldots, s_p)\) clears all edges in \( R \) and no more than \( k \) nodes are occupied at some step. Moreover, it has less particular moves than \( S \), therefore the result holds by induction.

\( \square \)

Note that, in particular, previous lemma implies that \( \text{xs}(R) \leq \text{xs}(T) \) for any branch \( R \) of any tree \( T \).

**Proof of Theorem 2:** We only need to prove the result when \( V(T) \setminus V(R) \) is a leaf of \( T \) and then the result follows by induction on \( |V(T) \setminus V(R)| \). Hence, let \( v \) be the leaf of \( T \) such that \( R = T \setminus \{v\} \). Then, \( R \) is a branch at \( v \) of \( T \) and by Lemma 1, it follows that \( \text{xs}(R) \leq \text{xs}(T) \).

## 4 Exclusive Search in Trees

This section is devoted to our main result. We present a polynomial-time algorithm which, given any tree \( T \), computes the exclusive search number \( \text{xs}(T) \) of \( T \) and an exclusive search strategy enabling \( \text{xs}(T) \) searchers to clear \( T \). Our algorithm is based on a characterization of the trees with exclusive search number at most \( k \), for any given \( k \). Our characterization establishes a relationship between the exclusive-search number of \( T \) and the exclusive-search number of some of the branches adjacent to any node in \( T \).

**Theorem 3** Let \( k \geq 1 \). For any tree \( T \), \( \text{xs}(T) \leq k \) if and only if, for every node \( v \) in \( T \), the following three properties hold:

1. \( \delta(v) \leq k + 1 \) where \( \delta(v) \) is the degree of \( v \) in \( T \).
2. for any branch \( B \) at \( v \), \( \text{xs}(B) \leq k \);
3. for any even \( i > 1 \), at most \( i \) branches \( B \) at \( v \) have \( \text{xs}(B) \geq k - i/2 + 1 \).

To prove the theorem, we first prove (Section 4.1) that, for any tree \( T \) and \( k \geq 1 \), \( \text{xs}(T) \leq k \), only if the conditions of Theorem 3 are satisfied. Then, we show that any tree satisfying these conditions can be decomposed in a particular way, depending on \( k \) (Figure 2). Next, in Section 4.3, we describe an exclusive search strategy using at most \( k \) searchers, that clears any tree decomposed in such a way.

From the characterization of Theorem 3, it follows that \( \text{xs}(T) \) can be computed by dynamic programming on \( T \) in polynomial-time. Moreover, such an algorithm computes the corresponding decomposition (see Section 4.3 and Section 4.4). Hence, the following result holds:

**Theorem 4** There exists a polynomial-time algorithm that computes \( \text{xs}(T) \) and a corresponding exclusive search strategy for any tree \( T \).

**Definition 2** A configuration is a set of distinct nodes \( C \subseteq V(T) \) that describes the positions of \(|C| \) searchers in \( T \).
4.1 Necessary Conditions for Theorem 3

We first show that the conditions of Theorem 3 are necessary. The fact that the first condition is necessary directly follows from Claim 1. The second condition is necessary by Theorem 2. The fact that the third condition is necessary mainly relies on Lemma 1.

**Lemma 2** Let \( k \geq 1 \). For any tree \( T \), if there exist \( v \in V(T) \) and an even integer \( i > 1 \) such that there is a set \( B = \{ T_j : \text{xs}(T_j) \geq k - i/2 + 1 \} \) of branches at \( v \) and \(|B| > i\), then \( \text{xs}(T) > k \).

**Proof.** Let \( S \) be any exclusive strategy that clears \( T \). By Lemma 1, for any \( j \leq |B| \), there is a step of the strategy \( S \) such that at least \( k - i/2 + 1 \) searchers occupy simultaneously nodes in \( T_j \). Let \( s_j \) be the last such step of \( S \) that occurs in \( T_j \). W.l.o.g. assume that \( s_{j-1} < s_j \), for any \( 1 < j \leq |B| \), and we may assume that, before step \( s_j \), \( T_j \) is not completely clear (this means that \( S \) uses \( k - i/2 + 1 \) searchers in \( T_j \) only if it is really needed). Then, at step \( s_{i/2+1} \), at least \( k - i/2 + 1 \) searchers are in \( T_{i/2+1} \), some nodes have been cleared in \( T_j \) for any \( j \leq i/2 \), and \( T_j \) cannot become fully contaminated anymore until the end of the strategy (otherwise there would be another step after \( s_j \) where \( k - i/2 + 1 \) searchers are in \( T_j \)).

For the sake of contradiction, let us assume that \( S \) uses at most \( k \) searchers. Then, at step \( s_{i/2+1} \), at least \( k - i/2 + 1 \) searchers are in \( T_{i/2+1} \) and there are at most \( i/2 - 1 \) searchers outside \( T_{i/2+1} \). That is, at that moment, there is at least one branch \( X \in \{ T_{i/2+2}, \ldots, T_{|B|} \} \) \((|B| > i)\) at \( v \) with still contaminated edges, and at least one branch \( Y \in \{ T_1, \ldots, T_{i/2} \} \) at \( v \) with (at least) some clear edges that must not be recontaminated and no searchers occupy nodes in both these branches. If there is no searcher at \( v \), \( Y \) is fully recontaminated. Therefore, we obtain a contradiction.

Otherwise, there is a searcher in \( v \). However, since there is at least one non cleared yet branch without any searcher in it, it has to be cleared by moving there at least one searcher. For that, the searcher from \( v \) have to move. However, if this searcher moves (no matter where), there will be still at most \( i/2 - 1 \) searchers outside \( T_{i/2+1} \) and hence, at least one cleared and one uncleared branch without any searcher, and no searcher in \( v \). The cleared branch will be fully recontaminated. Therefore, we obtain a contradiction.

4.2 Avenue, Decomposition and Notations

In this section, we show that any tree satisfying the conditions of Theorem 3 admits a particular shape. Moreover, for the purpose of clarity, we introduce some others notations. Figure 2 depicts a particular structure that we prove to exist for any tree \( T \) satisfying the conditions of Theorem 3, for \( k \geq 1 \). Specifically, following [14], we prove that there is a path \( A = (u_1, \ldots, u_p) \) in \( T \) called avenue (bold line in Figure 2) such that \( p \geq 1 \) and, for any component \( T' \) of \( T \setminus A \), there is an exclusive strategy that clears \( T' \) using \( < k \) searchers, i.e., \( \text{xs}(T') < k \). The proof of the existence of such a path \( A \) is very similar to the one given in [14] in the case of edge graph searching. We give the proof for our case of exclusive search below.

**Claim 1** Let a tree \( T \) satisfy the conditions of Theorem 3 for \( k \geq 1 \). Then, there is a subpath \( A \) in \( T \) such that, for any connected component \( S \) of \( T \setminus A \), \( \text{xs}(S) < k \).

**Proof.** If \( T \) is a path, then let \( A = T \). Otherwise, if \( \text{xs}(S) < k \) for every branch \( S \) at every node of \( T \), then choose any node \( u_1 \in V(T) \) and set \( V(A) = \{ u_1 \} \). Otherwise, let \( u_1 \in V(T) \) be a node with the maximum number of branches having search number \( k \). Note that, by the condition 3 of Theorem 3 (for \( i = 2 \)), there are at most two such branches. Then, there are two cases to consider:
Let a tree $T_1$ of Theorem 3, $\forall x \in T_1$, $\forall y \in T_1$. Hence, each node of the avenue $S$ in $T$, i.e., $\{u_2\} = N(u_1) \cap S$. Then, either all connected components $S \in T \setminus \{u_1, u_2\}$ with $xs(S) < k$ and then, $V(A) = \{u_1, u_2\}$. Or, there is a branch $S'$ at $u_2$, $u_1 \notin S'$ with $xs(S') = k$. In this case, continue this iterative process of decomposition with $u_2$ and its neighbor $u_3 \in N(u_2) \cap S'$ as before with $u_1$ and $u_2$. Proceed till two adjacent nodes $u_{p-1}$ and $u_p$ are found such that all connected components of $T \setminus A$, $A = \{u_1, \ldots, u_p\}$, are such that each of them, $S''$, has $xs(S'') < k$.

- Second, if there are two branches $S$ and $S'$ at $u_1$ such that $xs(S) = xs(S') = k$, let $u_2 \in N(u_1) \cap S$ and $u_2' \in N(u_1) \cap S'$. Then, $\{u_1, u_2, u_2'\} \in A$. If $R$ and $R'$ are two branches at $u_2$ with $xs(R) = xs(R') = k$, then by Lemma 2, one of these branches, say $R'$, has to contain $u_1$ (otherwise, $xs(T) > k$). Let $u_3 \in N(u_2) \cap R$. Then, $\{u_1, u_2, u_3, u_2'\} \in A$. Let us continue this process iteratively, till for every connected component $S \in T \setminus A$, $xs(S) < k$. The process clearly terminates since, at each step, there are at most two components of $T \setminus A$ with $xs = k$ and their size strictly decreases.

\[ \Box \]

**Notations.** Let a tree $T$ satisfy the conditions of Theorem 3 for $k \geq 1$ and let $A$ be an avenue in $T$. Hence, each node of the avenue $A$ satisfies the condition 3 of Theorem 3. We introduce some notations depicted in Figure 2. In particular, the ordering of the branches incident to the nodes of the avenue will be crucial in next sections.

Let $A = \{u_1, \ldots, u_p\}$ be the avenue in $T$. Let $R^1 \subseteq T \setminus A$ be a branch at $u_1$ maximizing $ws(R^1) < k$ (out of all the branches in $T \setminus A$). Let $S^p \subseteq T \setminus A$ be the branch at $u_p$ (different from $R^1$ if $p = 1$), and maximizing $ws(S^p)$ (out of the branches at $u_p$). Let $x \in N(u_1) \cap R^1$ and $y \in N(u_p) \cap S^p$.

For every $1 \leq i \leq p$, let $v^i_1, \ldots, v^i_{d_i}$ be the neighbors of $u_i$ not in $A \cup \{x, y\}$ (by the condition 1 of Theorem 3, $d_i \leq k - 1$ for any $1 \leq i \leq p$). Let $T^i_j$ be the branch at $u_i$ containing $v^i_j$, for any $1 \leq j \leq d_i$. For any $1 \leq i \leq p$, the nodes $v^i_1, \ldots, v^i_{d_i}$, are ordered such that $xs(T^i_j) \geq xs(T^i_{d_i}) \geq xs(T^j_2) \geq xs(T^i_{d_i-1}) \geq xs(T^i_3) \geq \cdots$. By definition of $A$, for any $1 \leq i \leq p$ and any $1 \leq j \leq d_i$, $xs(T^i_j) \leq k - 1$. For $i > 1$, let $R^i$ be the branch at $u_i$ containing $u_{i-1}$ and for $i < p$, let $S^i$ be the branch at $u_i$ containing $u_{i+1}$. Set $R^{p+1} = T \setminus S^p$. 

\[ \Box \]
In the next section, we describe a strategy, called $\text{ExclusiveClear}$, based on this decomposition and allowing $k$ searchers to clear $T$ in an exclusive way. The strategy consists in clearing the subtrees of $T \setminus A$, starting with the subtrees that are adjacent to $u_1$, then the ones adjacent to $u_2$ and so on, finishing in $u_p$. To clear a subtree $T'$ of $T \setminus A$, we proceed in a recursive way. That is, we recursively use $\text{ExclusiveClear}$ on $T'$ using $k' < k$ searchers. The first difficulty is to ensure that no subtrees that have been cleared are recontaminated. For this purpose, when clearing $T'$, the remaining $k - k'$ searchers that are not needed to clear it are used to prevent recontamination. The second difficulty is to ensure exclusivity: while these $k - k'$ searchers are protecting from recontamination, $k'$ searchers should be able to enter $T'$ to clear it.

### 4.3 Exclusive Search Strategy to Clear Trees

Let $k \geq 1$ and let $T$ be any tree satisfying the conditions of Theorem 3. That is, for any $v \in V(T)$, $v$ has degree at most $k + 1$, for any branch $B$ at $v$, $\text{xS}(B) \leq k$ and, for any even $i > 1$, at most $i$ branches $B$ at $v$ have $\text{xS}(B) \geq k - i/2 + 1$.

By the previous claim, $T$ admits an avenue as described in the previous subsection. We use the same notations as in previous subsection and in Figure 2. In this section, we describe a search strategy that clears $T$ using $k$ searchers.

By definition, our following recursive strategy $\text{ExclusiveClear}$ ensures that all moves are performed along paths free of searchers, satisfying the exclusivity and internally properties. Moreover, it is easy to check that it actually clears $T$. To prove its correctness, it is sufficient to show that it uses at most $k$ searchers (in particular, when applying the sub-procedures $\text{bringSearchers}$ or $\text{transfer}$ defined below). The formal proof mainly relies on the properties of the decomposition.

A formal description of $\text{ExclusiveClear}$ is given in Algorithm 1 and the detailed description follows. Before that, let us introduce some new notations. For $u, v \in V(T)$ and $U \subseteq V(T)$, let $u \leadsto v$ denote the sequence of slidings bringing the searcher at $u$ to $v$; and let $U \leadsto v$ denote the sequence of slidings bringing a searcher, occupying some closest to $v$, node of $U$, to $v$, along a path free of searchers (in both cases).

**Strategy $\text{ExclusiveClear}$**. For ease of description, let us assume that $|V(R^1)| \geq k - 1$. Let $I$ be a subset of $u_1$ and $k - 1$ distinct nodes in $R^1$. The strategy starts by placing the searchers at the nodes of $T^4$. By definition of $A$, $\text{xS}(R^1) \leq k - 1$. Then, the $k - 1$ searchers in $R^1$ apply $\text{ExclusiveClear}(R^1)$ (such a strategy exists by induction). It is important to mention that the searcher at $u_1$ preserves $R^1$ from being recontaminated by the rest of $T$. After this sequence of moves, all edges in $E(R^1 \cup \{(x, u_1)\})$ are cleared. Finally, a searcher in $R^1$ that is closest to $x$ goes to $x$. After this step, $R^1$ is clear and $u_1$ and $x$ are occupied. Moreover, all searchers are at nodes in $R^1 \cup \{u_1\}$.

Then, we aim at clearing the remaining subtrees of $T \setminus A$ that are adjacent to $u_1$, that is, the subtrees $T_{i1}^1, \ldots, T_{di}^1$ (see Figure 2). Moreover, after clearing any subtree $T_{i1}^1$, we need to preserve it from recontamination. Notice that, during the clearing of a subtree $T_{i1}^1$, $u_1$ will always be occupied. However, to ensure that exclusivity property is satisfied when searchers go from one subtree $T_{i1}^1$ to the next one $T_{i+1}^1$ (during the $\text{bringSearchers}$ procedure explained later), we need to clear $u_1$ and then other nodes must be occupied to avoid recontamination.

In order to use as few searchers as possible, the cleaning of the subtrees adjacent to $u_1$ must be done in a specific order. The order used to clear the subtrees is defined by partitioning these subtrees into two sets $S_1$ and $S_2$ built as follows. Each subtree is considered one after the other, in the non-increasing order of $\text{xS}$. In this order, we assign the first subtree to $S_1$, the second

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4If $|V(R^1)| < k - 1$, then the strategy starts by placing one searcher at $u_1$, then as much as possible searchers at the nodes of $R^1$, then at the nodes of $T_{i1}^1$, of $T_{i2}^1$, and so on, until the $k$ searchers are placed.
Algorithm 1 ExclusiveClear strategy

Require: Tree $T$ satisfying the conditions of Theorem 3 for $k \geq 1$. Notations are recalled in Figure 2.

1: Initially, the searchers occupy $k-1$ nodes of $R^1$ and $u_1$ (if $|V(R^1)| < k-1$, all nodes of $R^1$ are occupied and then the nodes of $T^1_1, T^1_2$, etc., by $k-1$ searchers).

2: ExclusiveClear($R^1$)
3: $R^1 \rightsquigarrow x$
4: for all $1 \leq i \leq p$ do
5: for all $1 \leq j_0 \leq d_i + 1$ do
6: if $i = p \land j_0 = d_p + 1$ then
7: $u_p \rightsquigarrow y$
8: $R^{p+1} \rightsquigarrow u_p$
9: bring_searchers($p, d_p + 1$)
10: ExclusiveClear($S^p$) /* end of the strategy */
11: else if $j_0 = d_i + 1 \land i < p$ then
12: $u_i \rightsquigarrow u_{i+1}$
13: $R_{i+1} \rightsquigarrow u_i$
14: else
15: if $j_0 = 1$ then
16: bring_searchers($i, 1$)
17: else if $1 < j_0 \leq \lfloor d_i/2 \rfloor$ then
18: if there is a searcher in $R^i$ then
19: $R^i \rightsquigarrow u_{i-1}$
20: else
21: $u_i \rightsquigarrow u_{i-1}$ ($u_0 = x$)
22: let $j < j_0$ such that there is a searcher in $T^i_{j} \setminus v^i_{j}$.
23: $v^i_{j} \rightsquigarrow u_{i}$
24: $T^i_{j} \rightsquigarrow v^i_{j}$
25: bring_searchers($i, j_0$)
26: else if $\lfloor d_i/2 \rfloor < j_0 < d_i + 1$ then
27: $u_i \rightsquigarrow u_{i+1}$ ($u_{p+1} = y$)
28: $R^{i+1} \rightsquigarrow u_i$
29: bring_searchers($i, j_0$)
30: ExclusiveClear($T^{i+1}_{j_0}$)
31: $T^{i+1}_{j_0} \rightsquigarrow v^{i+1}_{j_0}$
32: if $j_0 = \lfloor d_i/2 \rfloor$ then
33: transfer($i$)
one to \(S_2\), the third one to \(S_1\), the fourth one to \(S_2\), and we continue to divide the subtrees until each of them is assigned to one of the two sets. Note that the formula given in Figure 2 respects this order. The resulting \(S_1 = \{T_1^1, \ldots, T_{[d_1/2]}^1\}\) and \(S_2 = \{T_{[d_1/2]+1}^1, \ldots, T_{d_1}^1\}\) such that \(\text{xs}(T_1^1) \geq \text{xs}(T_{d_1}^1) \geq \text{xs}(T_2^1) \geq \text{xs}(T_{d_1-1}^1) \geq \text{xs}(T_3^1) \geq \text{xs}(T_{d_1-2}^1)\).

The clearing of the subtrees is then divided into three phases. The subtrees in \(S_1\) are cleared first, in the non-increasing order of their \(\text{xs}\). Then, the searchers are moved in a particular way (Using Procedure \text{transfer}). Finally, the subtrees in \(S_2\) are cleared in the non-decreasing order of their \(\text{xs}\).

Let us detail each phase.

- Let \(1 \leq i < [d_1/2]\). Let us assume that \(R^1, T_1^1, \ldots, T_{i-1}^1\) have been cleared, that \(u_1, x, v_1^1, \ldots, v_{i-1}^1\) are occupied by searchers and all other searchers are occupying nodes in \(R^1, T_1^1, \ldots, T_{i-1}^1\) and \(u_1\).
  
  First, Procedure \text{bring_searchers} is used to move \(k' = \text{xs}(T_i^1)\) searchers to nodes of \(T_i^1\) without recontaminating the subtrees that have already been cleared. When \(k'\) searchers are in \(T_i^1\) and \(u_1, x, v_1^1, \ldots, v_{i-1}^1\) are occupied, \(\text{ExclusiveClear}(T_i^1)\) is applied recursively to clear \(T_i^1\) using the \(k'\) searchers. Finally, a searcher in \(T_i^1\) reaches \(v_i^1\).

  Below, we detail Procedure \text{bring_searchers} and we prove that \(k' = \text{xs}(T_i^1)\) searchers are actually available to clear \(T_i^1\).

  Each time that a subtree \(T_j^1 \in S_1\) has been cleared, one searcher is left on its root \(v_j^1\) (its node adjacent to \(u_1\)). That is, once a new subtree is cleared, we somehow lose one searcher to clear the next one. This is balanced by the fact that the number of searchers needed to clear the next subtree does not increase, according to the order of clearing established above, and provided by the properties of \(T\).

- After clearing the subtrees in \(S_1\), there are searchers currently “blocked” in the roots of the cleared subtrees. More precisely, \(R^1, T_1^1, \ldots, T_{[d_1/2]}^1\) have been cleared and \(u_1, x, v_1^1, \ldots, v_{[d_1/2]}^1\) are occupied by searchers.

  In order to “re-use” these searchers to clear the remaining subtrees, the strategy changes. Now, the roots of the still contaminated subtrees (set \(S_2\)) will be occupied to prevent recontamination of the cleared subtrees (set \(S_1\)). Procedure \text{transfer} (explained later) is used to occupy these nodes, ensuring no recontamination of the subtrees and satisfying the exclusivity property. After \text{transfer}, the searchers at the roots of the cleared subtrees become free, i.e., it is possible now to use them to clear the next subtrees.

  More precisely, after this phase, \(R^1, T_1^1, \ldots, T_{[d_1/2]}^1\) are still clear and \(u_1, u_2, v_1^1, \ldots, v_{d_1}^1\) are occupied by searchers.

- Then, the subtrees in \(S_2\) have to be cleared in the non-decreasing order of their \(\text{xs}\). Each time that a subtree \(T_j^2 \in S_2\) has been cleared, the searcher on its root \(v_j^1\) becomes free. That is, we somehow gain a searcher to clear the next subtree, whose search number may increase, according to the properties of \(T\).

  More precisely, let \([d_1/2] + 1 \leq i \leq d_1\). Let us assume that \(R^1, T_1^1, \ldots, T_{i-1}^1\) have been cleared, that \(u_1, u_2, v_1^1, \ldots, v_{d_1}^1\) are occupied by searchers and all other searchers are occupying nodes in \(R^1, T_1^1, \ldots, T_{i-1}^1\) and \(u_1, u_2\).

  First, Procedure \text{bring_searchers} is used to move \(k' = \text{xs}(T_i^1)\) searchers to nodes of \(T_i^1\) without recontaminating the subtrees that have already been cleared. When \(k'\) searchers are in \(T_i^1\) and \(u_1, u_2, v_{i+1}^1, \ldots, v_{d_1}^1\) are occupied, \(\text{ExclusiveClear}(T_i^1)\) is applied recursively to clear \(T_i^1\) using the \(k'\) searchers.
Once all subtrees of $T \setminus A$ adjacent to $u_1$ are cleared, the searcher at $u_1$ goes to $u_2$ (unless it is already occupied). Now, all the searchers in $R^2$ (see Figure 2) become free. Then, a similar strategy is applied for the subtrees of $T \setminus A$ adjacent to $u_2$, and so on, until all the subtrees adjacent to $u_p$ are cleared.

We now describe more precisely two sub-procedures that are used to implement the strategy we have given above.

**Procedure bring_searchers.** It remains to detail how the searchers, once a subtree has been cleared, go to the next subtree, satisfying exclusivity and preventing recontamination. To do so, let $1 \leq i \leq p$ and let us consider the step of the strategy when the branch $R^i$ (see Fig. 2) and all subtrees $T^i_1, \cdots, T^i_{j_0-1}$ ($1 < j_0 \leq d_i$) are cleared (the grey subtrees in Fig. 3(a)).

We describe the procedure in the case when $j_0 \leq \lceil \frac{d_i}{2} \rceil$. The case when $\lceil \frac{d_i}{2} \rceil + 1 \leq j_0 \leq d_i$ is similar.

As explained before, at this step, the nodes in $\{u_i, v^i_1, \cdots, v^i_{j_0-1}\}$ are occupied, and all other searchers are free and occupy nodes of $R^j$ and $T^j_i$, for $j < j_0$. It is ensured that also $u_{i-1}$ (if $i = 1$, set $u_{i-1} = x$) will be occupied.

Let $k - j_0$ be the number of free searchers, i.e., searchers not occupying $\{u_i, v^i_1, \cdots, v^i_{j_0-1}\}$. We first prove that $k - j_0 \geq \text{xs}(T^i_{j_0})$. Indeed, by definition of the ordering of $T^i_1, \cdots, T^i_{d_i}$, there are at least $2(j_0 - 1) + 3$ branches at $u_i$ with exclusive search number at least $\text{xs}(T^i_{j_0})$. Namely, $\text{xs}(R^i) \geq \text{xs}(T^i_{j_0})$, $\text{xs}(S^i) \geq \text{xs}(T^i_{j_0})$, and $\text{xs}(T^i_0) \geq \text{xs}(T^i_{j_0}) \geq \text{xs}(T^i_2) \geq \cdots \geq \text{xs}(T^i_{d_i-1}) \geq \text{xs}(T^i_{j_0})$. By the condition 3 of Theorem 3, we get that $\text{xs}(T^i_{j_0}) \leq k - j_0$ (since the number of branches at $u_i$ with exclusive search number at least $k - j_0 + 1$ is at most $2j_0$).

The process bring_searchers($i, j_0$) is applied to bring $\text{xs}(T^i_{j_0})$ searchers into $T^i_{j_0}$. The searchers are brought one by one, from the clear part to $T^i_{j_0}$, without recontamination (but possibly the edges incident to $u_i$) and satisfying the exclusivity property.

Figure 3(a) depicts one phase of this process. Before each phase (but the last one, which is slightly different), there is a free searcher at some node $b$, either in $T^i_j \setminus v^i_j$ (for some $j < j_0$) or in $R^i \setminus u_{i-1}$. First, the searcher at $u_i$ goes to the furthest unoccupied node in $T^i_{j_0}$ (dotted line 1 in Fig. 3(a)). Second, the searcher at $v^i_j$ (or at $u_{i-1}$) goes to $u_i$ (dotted line 2 in Fig. 3(a)). Finally, the searcher at $b$ goes to $v^i_j$ (or to $u_{i-1}$) (dotted line 3 in Fig. 3(a)). Clearly, doing so, no recontamination occurs in the cleared subtrees (but in $u_i$) and exclusivity is satisfied.

**Procedure transfer.** Let $1 \leq i \leq p$ and $j_0 = \lfloor d_i/2 \rfloor$. Just after clearing $T^i_{j_0}$, we reach a configuration where the nodes in $\{u_i, v^i_1, \cdots, v^i_{j_0}\}$ are occupied, $T^i_{j_0}$ is clear, and all other searchers are at nodes of $R^j$ or $T^j_i$ ($j \leq j_0$). First, the searcher at $u_i$ goes to $u_{i-1}$ unless it is already occupied.
As explained before, the nodes in \( \{v_{j_0+1}^i, \ldots, v_{d_i}^i\} \) must now be occupied before clearing any subtree \( T_j^i \), for \( j > j_0 \). This is the role of sub-process \( \text{transfer}(i) \). The searchers are brought one by one, from the clear part to \( \{v_{j_0+1}^i, \ldots, v_{d_i}^i\} \), without recontamination and satisfying exclusivity.

Figure 3(b) depicts one phase of this process. By the condition 1 of Theorem 3, \( d_i + 2 \leq k+1 \). This ensures that, before each phase, there is a free searcher at some node \( b \) either in \( T_j^i \setminus \{v_j^i\} \) (for some \( j \leq j_0 \)) or in \( R_i \setminus \{u_{i-1}\} \). First, the searcher at \( v_j^i \) (if \( b \in V(T_j^i) \)) or at \( u_{i-1} \) (otherwise) goes to \( u_i \) (unless \( u_i \) is occupied) (dotted line 1 in Fig. 3(b)). Second, the searcher at \( b \) goes to \( v_j^i \) (or \( u_{i-1} \)) (dotted line 2 in Fig. 3(b)). Finally, the searcher at \( u_i \) goes to an unoccupied node in \( \{v_{j_0+1}^i, \ldots, v_{d_i}^i\} \) (dotted line 3 in Fig. 3(b)). Once all these nodes are occupied, the searcher at \( u_{i-1} \) goes back to \( u_i \). Clearly, doing so, exclusivity is satisfied and no recontamination occurs in the cleared subtrees. This, in particular, since either all the nodes \( \{u_{i-1}, v_1^i, \ldots, v_{j_0-1}^i\} \), or \( u_i \), are always occupied during \( \text{transfer}(i) \).

### 4.4 Polynomial-time algorithm

From the characterization of Theorem 3, it follows that \( \text{xs}(T) \) can be computed recursively for any tree \( T \). This section is devoted to the design of such a polynomial-time algorithm. The algorithm to compute \( \text{xs} \) follows the one designed in [14] to compute the edge-search number of trees. The main difference between our algorithm and the one of [14] comes from the third item of our characterization (Theorem 3) for which we require our dynamic programming algorithm to keep more information (fields “neighbors” and “branches” below).

**Avenue and types of rooted trees.** First let us refine the definition of avenue in order to ensure its unicity. Let \( T \) be a tree with \( \text{xs}(T) = k \). An avenue is a subpath \( A = (u_1, \ldots, u_p) \) in \( T \) such that \( p > 1 \), \( u_1 \) and \( u_p \) have exactly one branch with exclusive search number \( k \) (containing \( v_2 \) and \( v_{p-1} \) respectively) and, for any \( 2 \leq i < p \), \( u_i \) has exactly two branches with exclusive search number \( k \) (containing \( v_{i-1} \) and \( v_{i+1} \) respectively). Note that the definition of a branch in our work (Definition 1) differs a bit from the one in [14]. We adapt the algorithm below according to this definition.

The proof of Claim 1 shows that

**Claim 2** Let \( T \) be a tree with \( \text{xs}(T) = k \). Either \( T \) has a vertex \( v \) (called hub) such that all branches at \( v \) have exclusive search number \( < k \), or \( T \) has a unique avenue \( (u_1, \ldots, u_p) \) and \( p > 1 \).

The algorithm takes a tree \( T \) rooted in \( r \in V(T) \) and recursively computes \( \text{xs}(T) \). The location of the root relatively to the avenue is important, therefore we need the following notations (borrowed from [14]). By Claim 2, there are 4 possible types:

**Type H.** All branches at \( r \) have exclusive search number \( < k \). In that case, \( r \) is called the hub of \( T \).

**Type E.** \( T \) has a unique avenue \( (u_1, \ldots, u_p) \) and \( r \) belongs to a branch at \( u_1 \) or \( u_p \) with exclusive search number \( < k \), or \( r \in \{u_1, u_p\} \) (in the latter case, we moreover impose that \( p > 1 \), otherwise this is the case of Type H).

**Type I.** \( T \) has a unique avenue \( (u_1, \ldots, u_p) \), \( p > 1 \) and \( r \in \{u_2, \ldots, u_{p-1}\} \).

**Type M.** \( T \) has a unique avenue \( (u_1, \ldots, u_p) \) and \( r \) belongs to a branch \( M \) at \( u_i \) \((2 \leq i < p)\) with exclusive search number \( < k \).
**Recursive algorithm.** The algorithm recursively computes the following information record, denoted by

\[ info(T, r) = [\text{type}, \text{xs}, \text{branches}, M-\text{info}, \text{neighbors}] \]

associated with tree \( T \) (whose root \( r \) is chosen arbitrarily).

Note that the only difference with the algorithm designed in [14] comes from the fields \( \text{neighbors} \) and \( \text{branches} \).

The five fields of \( info(T, r) \) are defined as follows

- **type.** It is the type \((H, E, I \text{ or } M)\) of the tree \( T \) rooted at \( r \).
- **xs.** It is the exclusive search number \( \text{xs}(T) \) of \( T \).
- **branches.** For any branch \( B \) at \( r \), \( \text{branches} \) contains the value of \( \text{xs}(B) \).
- **M-info.** If \( \text{type} = M \), let \((u_1, \ldots, u_p)\) be the avenue of \( T \) and let \( B \) be the branch at \( u_i \) that contains \( r \). This field contains the information record \( info(B, r) \) associated with the branch \( B \) at \( u_i \) containing \( r \). Otherwise, it is nil.
- **neighbors.** If \( r \) has degree one in \( T \), then \( \text{neighbors} = \text{nil} \).

Otherwise, \( \text{neighbors} \) is a set of information records, one record for every branch \( B \) at \( r \).

More precisely, for any branch \( B \) at \( r \), \( \text{neighbors} \) contains the record \([\text{type}(S), \text{xs}(S), \text{branches}(S), M-\text{info}(S), \text{nil}]\) associated to the subtree \( S = B \cup \{r\} \) rooted at \( r \).

The algorithm (the computation of \( info(T, r) \)) proceeds as follows. If \( T \) is an edge, then \( info(T, r) = [H, 1, \{0\}, \text{nil}, \text{nil}] \). Otherwise,

- If \( r \) has degree at least 2, then procedures \( \text{merge} \) (see below) and \( \text{re-root} \) are applied to compute \( info(T, r) \). Precisely, let \( r_1, \ldots, r_d \) be the neighbors of \( r \). For every \( 1 \leq i \leq d \), let \( T_i = B_i \cup \{r\} \) be the subtree of \( T \) that consists of \( r \) plus the branch \( B_i \) at \( r \) in \( T \) that contains \( r_i \). The algorithm first recursively computes \( info(T_i, r) \) for every \( i \leq d \). Then, \( info(T, r) = \text{merge}(info(T_1, r), \ldots, info(T_d, r)) \).

- If \( r \) has degree 1, then procedure \( \text{re-root} \) (see below) is applied to compute \( info(T, r) \). Precisely, let \( r_1 \) be the neighbor of \( r \). First \( info(T, r_1) \) is computed and then \( info(T, r) = \text{re-root}(info(T, r_1)) \).

**4.4.1 Procedure merge**

Procedure \( \text{merge} \) is used to compute \( info(T, r) \) from the information records of the branches of \( T \). Namely, \( info(T, r) = \text{merge}(info(T_1, r), \ldots, info(T_d, r)) \). The procedure \( \text{merge} \) is defined as follows

When Procedure \( \text{merge} \) has more than two arguments \((d > 2)\), it is defined recursively by \( \text{merge}(X_1, \ldots, X_d) = \text{merge}(X_1, \text{merge}(X_2, \ldots, X_d)) \). The case \( d = 2 \) is defined as follows.

Let \( T \) be any rooted tree obtained from two rooted trees \( T_1 \) and \( T_2 \) by identifying their roots into a single vertex \( r \), the root of \( T \). Let \( info(T_1, r) = [\text{type}_1, \text{xs}_1, \text{branches}_1, M-\text{info}_1, \text{neighbors}_1] \) and \( info(T_2, r) = [\text{type}_2, \text{xs}_2, \text{branches}_2, M-\text{info}_2, \text{neighbors}_2] \). Then, \( info(T, r) = \text{merge}(info(T_1, r), info(T_2, r)) \) is computed as follows.

We may assume that \( \text{xs}_1 \geq \text{xs}_2 \).
Computation of neighbors. For \( i \in \{1, 2\} \), if \( r \) has degree 1 in \( T_i \), set \( \text{neighbors}_i^\ast = \{\text{info}(T_i, r)\} \) and set \( \text{neighbors}_i^\sharp = \text{neighbors}_i \) otherwise. Then, \( \text{neighbors} = \text{neighbors}_1^\ast \cup \text{neighbors}_2^\sharp \).

Computation of branches. Let branches of \( \text{info}(T, r) \) be \( \text{branches}_1 \cup \text{branches}_2 \).

Computation of \( x_s \), type and \( M\text{-info} \). Let \( \ell' \) be the smallest integer such that, for any even \( i > 1 \), at most \( i \) branches \( B \) at \( r \) in \( T \) have \( x_s(B) \geq \ell' - i/2 + 1 \), and \( x_s(B) \leq \ell' \). Clearly, \( \ell' \) can be computed using branches. Let \( \ell = \max\{\ell', x_s, d\} \) where \( d \) equals the degree of \( r \) in \( T \) minus one.

1. If \( \ell > x_s^1 \), then \( \text{info}(T, r) = [H, \ell, \text{branches}, nil, \text{neighbors}] \).

   Now, we may assume that \( \ell = x_s^1 \).

2. If \( x_s^1 = x_s^2 \), there are the following cases.

   (a) If \( \text{type}_1 = \text{type}_2 = H \), then \( \text{info}(T, r) = [H, \ell, \text{branches}, nil, \text{neighbors}] \).

   (b) If \( \text{type}_1 = H \) and \( \text{type}_2 = E \) or vice versa, then \( \text{info}(T, r) = [E, \ell, \text{branches}, nil, \text{neighbors}] \).

   (c) If \( \text{type}_1 = \text{type}_2 = E \), then \( \text{info}(T, r) = [I, \ell, \text{branches}, nil, \text{neighbors}] \).

   (d) If \( \text{type}_1 = I \) and \( \text{type}_2 = H \), or vice versa, then \( \text{info}(T, r) = [I, \ell, \text{branches}, nil, \text{neighbors}] \).

   (e) Otherwise (at least one of \( T_1 \) or \( T_2 \) is of type \( M \), or one is of type \( I \) and the other of type \( I \) or \( E \)), then at least 3 branches at \( r \) in \( T \) have exclusive search number at least \( x_s^1 \). Therefore, in that case, \( \ell \geq \ell' > x_s^1 \). Hence, this case is treated in the previous item.

3. \( x_s^1 > x_s^2 \).

   (a) If \( \text{type}_1 = H, E \) or \( I \), then \( \text{info}(T, r) = [\text{type}_1, \ell, \text{branches}, nil, \text{neighbors}] \).

   (b) Otherwise, \( \text{type}_1 = M \). In that case, Procedure merge is called on \( T_2 \) and \( M \) (the branch where \( r \) stands in \( T_1 \)), using \( \text{info}(T_2, r) \) and \( M\text{-info} = \text{info}(M, r) \). Let \( [\text{type}', x_s', \text{branches}', M\text{-info}', \text{neighbors}'] = \text{merge}(\text{info}(T_2, r), \text{info}(M, r)) \) be the result of this call.

   - If \( x_s' < x_s^1 \), then \( \text{info}(T, r) = [M, \ell, \text{branches}, [\text{type}', x_s', \text{branches}', M\text{-info}', \text{neighbors}], \text{neighbors}] \).
   - Otherwise, \( \text{info}(T, r) = [H, \ell, \text{branches}, nil, \text{neighbors}] \).

**Lemma 3** The procedure merge computes \( \text{info}(T, r) \) from \( \text{info}(T_1, r) \) and \( \text{info}(T_2, r) \), where \( T \) is the \( n \)-node tree obtained by identifying the roots of two trees \( T_1 \) and \( T_2 \). Moreover, its time-complexity is \( O(n) \).

**Proof.** The proof is by case analysis, corresponding to the cases in the description of the procedure.

1: \( \ell > x_s^1 \). In this case, all branches at \( r \) have exclusive search number at most \( x_s^1 < \ell \). Moreover, \( \ell \) is the smallest integer that satisfies the conditions of Theorem 3. Hence, the result follows.

2a: \( \ell = x_s^1, x_s^1 = x_s^2, \text{type}_1 = \text{type}_2 = H \). In this case, both trees have the root as hub, and their union is a tree in which all branches at the root have search number less than \( x_s^1 = x_s^2 \). The new tree has the root as a hub, and its exclusive search number is \( \ell \), by Theorem 3.
2b: \( \ell = \mathbf{x}_1, \mathbf{x}_2 = \mathbf{x}_2, \text{type}_1 = H, \text{type}_2 = E \). The new tree can be searched with \( \ell \), by Theorem 3. \( T \) has an avenue of length at least one, with \( r \) as an endpoint, and hence it is type \( E \).

2c: \( \ell = \mathbf{x}_1, \mathbf{x}_2 = \mathbf{x}_2, \text{type}_1 = \text{type}_2 = E \). The avenue of \( T \) is the shortest path that contains both the avenues of \( T_1 \) and \( T_2 \), and this avenue can be used to search \( T \) with \( \ell \) searchers. Since \( r \) is one of the interior points on the avenue, \( T \) is type \( I \).

2d: \( \ell = \mathbf{x}_1, \mathbf{x}_2 = \mathbf{x}_2, \text{type}_1 = I, \text{type}_2 = H \). The root of \( T_1 \) is a node on the interior of its avenue, and after combination with \( T_2 \) the off-avenue branches at that root will all continue to have a search number less than \( \mathbf{x}_1 = \mathbf{x}_2 \). Thus, \( T \) has the same type as \( T_1 \) and \( \mathbf{x} = \ell \).

2e: As already said, this case is treated in Case 1.

3a: \( \ell = \mathbf{x}_1, \mathbf{x}_2 > \mathbf{x}_2, \text{type}_1 = H, E, \) or \( I \). If \( \text{type}_1 \) is \( H \), then the root continues to have only branches with search number less than \( \mathbf{x}_1 \) in \( T \), so \( T \) is of type \( H \) and has search number \( \ell \). If \( \text{type}_1 \) is \( E \), \( T \) has an avenue of length at least one, with \( r \) on a branch at an endpoint (possibly it is the endpoint), so \( T \) is of type \( E \). If \( \text{type}_1 = I \), the argument of Case 2d applies, so \( T \) is of type \( I \) and has search number \( \ell \).

3b: \( \ell = \mathbf{x}_1, \mathbf{x}_2 > \mathbf{x}_2 \) and \( \text{type}_1 = M \). The search number for \( T \) depends on the search number \( \mathbf{x}_1(T') \) of the union of the \( M \)-tree for \( T_1 \) with \( T_2 \). If \( \mathbf{x}_1' = \mathbf{x}_1(T') < \mathbf{x}_1 \), then the avenue of \( T \) is exactly the same as the avenue of \( T_1 \), the same search number \( \mathbf{x}_1 = \ell \) suffices, and \( T' \) is now the \( M \)-tree of \( T \). If \( \mathbf{x}_1' \geq \mathbf{x}_1 \), then \( T \) is type \( H \) with search number \( \ell \), by Theorem 3.

Every case of the function takes a constant time, but the case 3b which makes the recursive call \( \text{merge}(\text{info}(T_2, r), \text{info}(M, r)) \) on a tree obtained from the identification of \( r \) in \( T_2 \) and \( M \) which has strictly smaller exclusive search number. The time-complexity \( O(\mathbf{x}_1(T)) = O(n) \) follows. \( \square \)

### 4.4.2 Procedure re-root

The procedure \textit{re-root} is defined as follows. Let us assume that \( r \) has a unique neighbor \( r' \) in \( T \).

Let \( \text{info}(T, r') = [\text{type}', \mathbf{x}_1', \text{branches}', M-\text{info}', \text{neighbors}'] \) (that has been computed recursively). Then, \( \text{info}(T, r) = [\text{type}, \mathbf{x}_1, \text{branches}, M-\text{info}, \text{neighbors}] \) is computed as follows.

**Computation of \( \mathbf{x}_1 \).** Since the tree is not modified (only the root changes), \( \mathbf{x}_1 = \mathbf{x}_1' \).

**Computation of \( \text{branches} \).** Let \( \{r_1', \ldots, r_h'\} \) be the set of neighbors of \( r' \) but \( r \). For any \( i \leq h \), let \( B_i' \) be the branch at \( r' \) containing \( r_i' \). By definition, for any \( i \leq h \), \text{neighbors}' contains the information record \( \text{info}(B_i' \cup \{r_i'\}, r') \) associated to the subtree \( B_i' \cup \{r_i'\} \) rooted in \( r' \). Applying the sub-procedure \text{merge} allows us to compute

\[
\text{info}(T \setminus \{r\}, r') = \text{merge}(\text{info}(B_1' \cup \{r'\}), \ldots, \text{info}(B_h' \cup \{r'\}, r'))
\]

that contains \( \mathbf{x}_1(T \setminus \{r\}) \). Note that no recursive call of the main algorithm is done at this step.

The field \text{branches} of \( \text{info}(T, r) \) is set to \( \{\mathbf{x}_1(T \setminus \{r\})\} \).
Computation of type and M-info.

1. If $type' = E$, then $type = E$ and $M\text{-}info = nil$.

2. If $type' = H$, then $type = E$ and $M\text{-}info = nil$.

3. If $type' = I$ and $xs' = 1$ (i.e., $T$ is a path with end $r$) then $type = E$ and $M\text{-}info = nil$.
   If $type' = I$ and $xs' > 1$, then $type = M$ and $M\text{-}info = [H, \{0\}, \emptyset, nil, nil]$.

4. If $type' = M$, then $type = M$, $M\text{-}info = re\text{-}root(M\text{-}info')$.

Computation of neighbors. Because $r$ has degree 1 in $T$, $neighbors = nil$.

Lemma 4 For any $n$ node tree $T$ that is not just a single edge, the procedure re-root computes $info(T, r)$ from $info(T, r')$, where $T$ is rooted at a leaf $r$ and $r'$ is the neighbor of $r$. Moreover, its time-complexity is $O(n^2)$.

Proof. The correctness of re-root directly follows from the correctness of merge by Lemma 3.

All steps are executed in constant-time but, the application of $merge(info(B'_i \cup \{r'\}), \cdots, info(B'_j \cup \{r'\}, r'))$ which takes time $O(n)$ by Lemma 3, and the recursive call $re\text{-}root(M\text{-}info')$ to a tree with smaller exclusive search number. Overall, the time-complexity is $O(n^2)$. \qed

4.4.3 Time-complexity

Theorem 5 The algorithm described in this section computes $info(T, r)$ for any tree $T$ rooted in $r$ and having $n$ nodes in $O(n^3)$ time.

Proof. The correctness of the algorithm follows immediately from Lemmas 3 and 4.

The worst case is when $r$ has a unique neighbor $r'$. Let $B'_1, \cdots, B'_d$ be the branches at $r'$ and let $B_i = B'_i \cup \{r'\}$ for any $1 \leq i \leq d$. We may assume that $T$ is not an edge, so $d \geq 2$ ($r'$ has degree at least 2). Let $n_i$ be the size of $B_i$ and note that $\sum_{1 \leq i \leq d} n_i = n + d - 1$. First $info(B_i, r')$ is computed for any $1 \leq i \leq d$. Then, $merge(B_1, \cdots, B_d)$ is computed, which consists of $O(n)$ merging of two subtrees taking $O(n)$-time each. Finally, the algorithm executes re-root($T, r'$) which takes time $O(n^2)$.

Let $g(n)$ be the complexity of the algorithm applied to an $n$-node tree. By previous paragraph, we get that $g(n) = \sum_{1 \leq i \leq d} g(n_i) + O(n^2)$. Since $\sum_{1 \leq i \leq d} n_i = O(n)$, we get by induction that $g(n) = O(n^3)$. \qed

5 Conclusion

In this paper, we have defined and study a new graph searching parameter, namely the exclusive search number of graphs. It appears that, contrary to all previous variants of graph searching games, the exclusive search number is not related to pathwidth. An interesting open-problem is to determine if exclusive graph searching is related to other graph parameters related to vertices layouts such as cutwidth or bandwidth.

It has been recently proved that computing the exclusive search number is NP-hard [13]. Is this problem Fixed Parameter Tractable? Do approximation algorithms exist?
References


