Identification problems in graphs

selected topics

Florent Foucaud

LIMOS

Université Clermont Auvergne

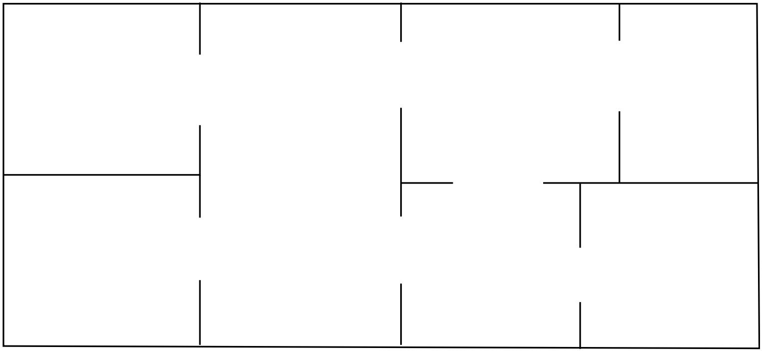
December 2024


PARIS
CLERMONT-FERRAND
LYON
BORDEAUX
MARSEILLE

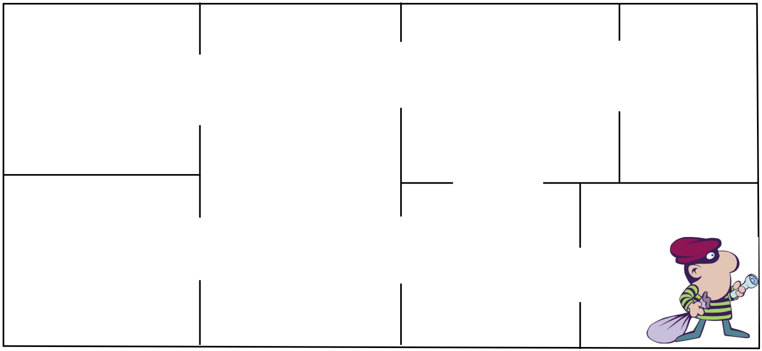

MICHELIN


Pascal


Saint Nectaire



Locating a burglar in a building



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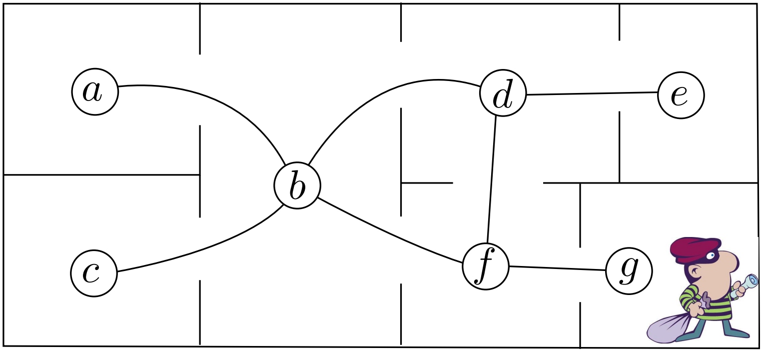
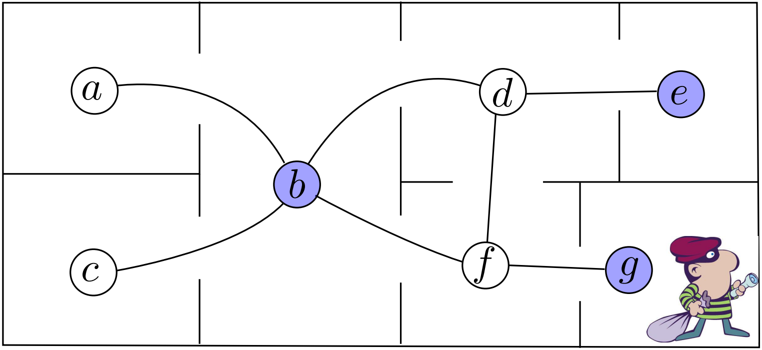


Building: undirected **graph** (rooms: *vertices*, doors: *edges*)

Detectors can detect movement in their room and adjacent rooms



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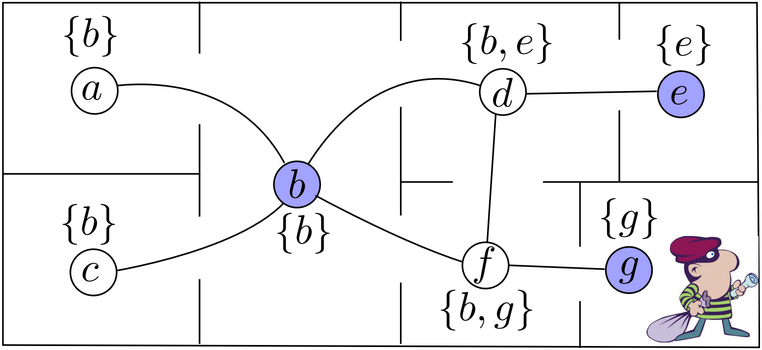

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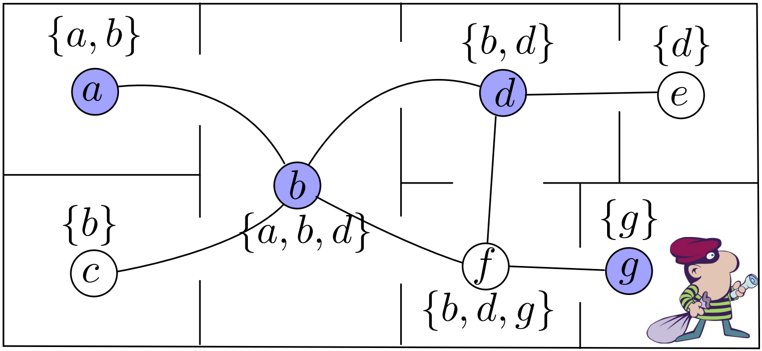

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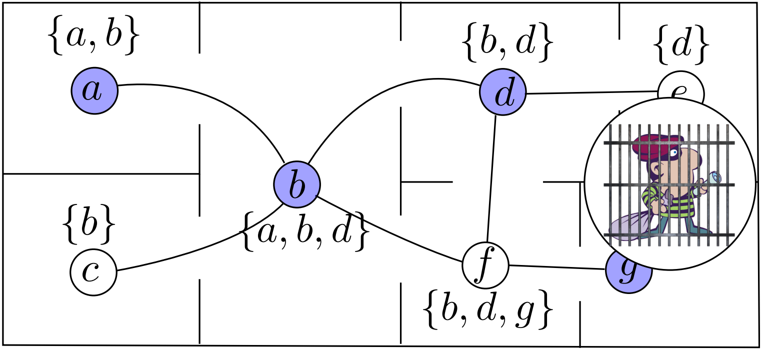

Building: undirected **graph** (rooms: *vertices*, doors: *edges*)

Domination in graphs

$V(G)$: set of vertices of G

Definition - Dominating set (Ore, 1960's) 

$D \subseteq V(G)$ dominating set of G:

- every vertex not in D has a neighbour in D

Domination

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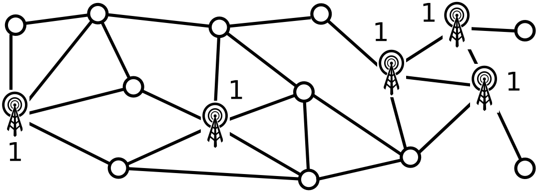
Motivation: covering problems in telecommunication networks



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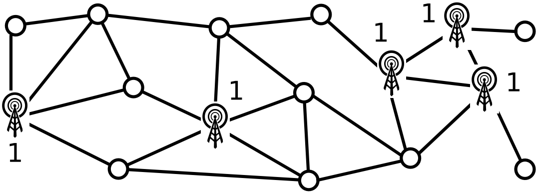

Notation: domination number $DOM(G)$: smallest size of a dominating set of G

A classic upper bound

Theorem (Domination bound, Ore, 1960's )

G graph of order n, no isolated vertices. Then $DOM(G) \leq \frac{n}{2}$.

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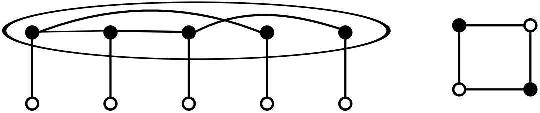
Tight examples:



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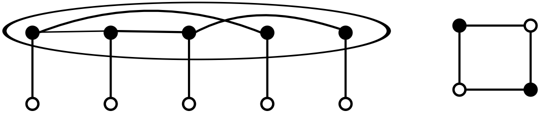


Proof: Consider an *inclusionwise minimal* dominating set D of G.

$\rightarrow$ its complement set $V(G) \setminus D$ is also a dominating set!

Thus, either D or $V(G) \setminus D$ has size at most $\frac{n}{2}$. □

Location-domination in graphs

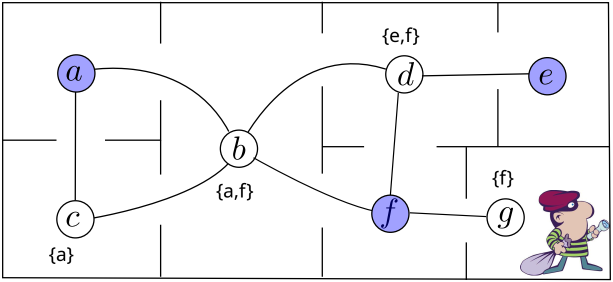
Location-domination

Definition - Locating-dominating set (Slater, 1980's) 

$D \subseteq V(G)$ locating-dominating set of G:

- for every vertex $v \in V(G)$, $N[v] \cap D \neq \emptyset$ (domination).
- $\forall u \neq v$ of $V(G) \setminus D$, $N(u) \cap D \neq N(v) \cap D$ (location).

Notation. location-domination number $LD(G)$,
smallest size of a locating-dominating set of G



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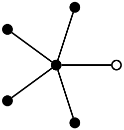
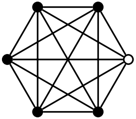
Tight examples:  

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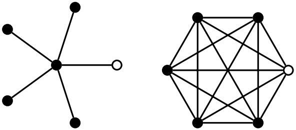
Tight examples: 

Remark: tight examples contain many twin-vertices!!

(Twins: vertices with the same sets of neighbours)

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Remark:

- twins are easy to detect
- twins have a trivial behaviour w.r.t. location-domination

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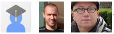
Conjecture (Garijo, González & Márquez, 2014 )

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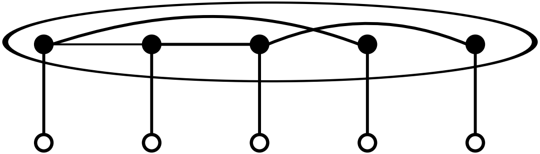
If true, tight: 1. domination-extremal graphs



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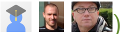
Conjecture (Garijo, González & Márquez, 2014 )

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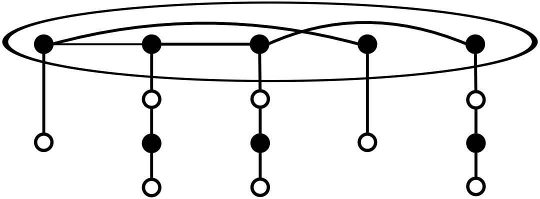

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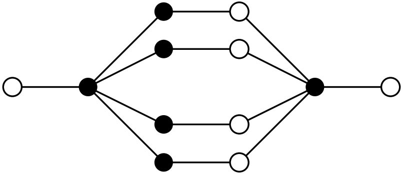
If true, tight: 3. a family with domination number 2



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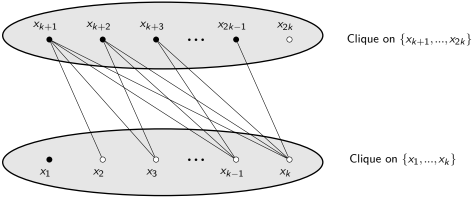
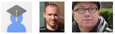
If true, tight: 4. family with dom. number 2: complements of half-graphs



Conjecture (Garijo, González & Márquez, 2014 )

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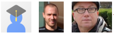
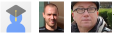
Theorem (Garijo, González & Márquez, 2014 )

Conjecture true if G has independence number $\geq n/2$. (e.g. bipartite)

Conjecture (Garijo, González & Márquez, 2014 )

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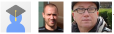
Theorem (Garijo, González & Márquez, 2014 )

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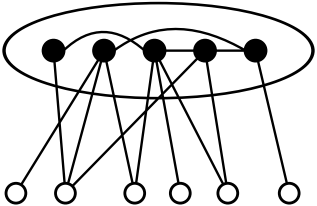
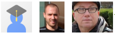
Proof: every vertex cover of a twin-free graph is a locating-dominating set



Conjecture (Garijo, González & Márquez, 2014 )

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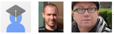
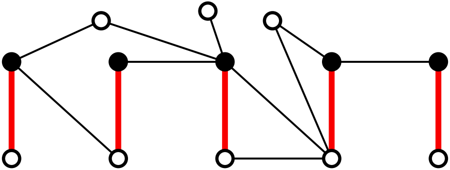
$\alpha'(G)$: matching number of G

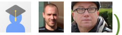
Theorem (Garijo, González & Márquez, 2014 )

If G has no 4-cycles, then $LD(G) \leq \alpha'(G) \leq \frac{n}{2}$.

Proof:

- Consider special maximum matching M
- Select one vertex in each edge of M



Conjecture (Garijo, González & Márquez, 2014 )

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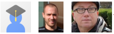
Theorem (Garijo, González & Márquez, 2014 )

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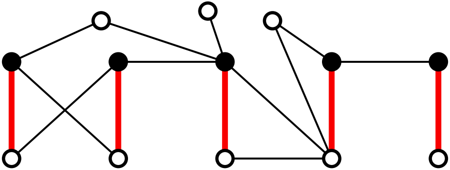
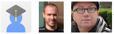


Upper bound: a conjecture - special graph classes

Conjecture (Garijo, González & Márquez, 2014 )

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Conjecture verified for other graph classes:

- split graphs
- cobipartite graphs
- line graphs
- block graphs
- subcubic graphs
- ...

Upper bound: a conjecture - general bound

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Theorem (F., Henning, Löwenstein, Sasse, 2016   )

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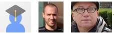
Conjecture (Garijo, González & Márquez, 2014 )

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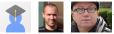
proof of Lemma: consider a smallest dominating set D that maximizes the number of edges inside D. For every $d \in D$, there must be a vertex $f(d)$ only dominated by d (otherwise $D \setminus \{d\}$ is a dominating set). If $f(d) \neq d$, it is a private neighbour of d. If $f(d) = d$, d has no neighbour in D. But since there is no isolated vertex in G, d has a neighbour c in $V(G) \setminus D$, that has 2 neighbours in D. Then, $D \setminus \{d\} \cup \{c\}$ contains more edges than D, a contradiction: so, $f(d) \neq d$. □

Conjecture (Garijo, González & Márquez, 2014 )

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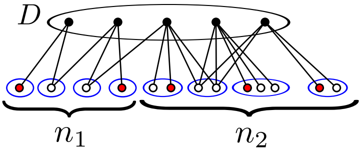
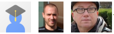
Thus $|D| \leq n_1 + n_2$. Take such D that is inclusionwise maximal.



Conjecture (Garijo, González & Márquez, 2014 )

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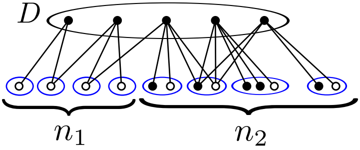
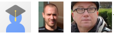


Conjecture (Garijo, González & Márquez, 2014 )

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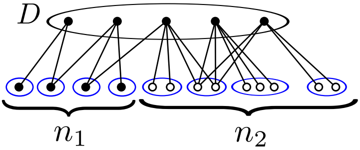
- there is a LD-set of size $n - n_1 - n_2$
- there is a LD-set of size $|D| + n_1$ because D is maximal



Upper bound: a conjecture - general bound

Conjecture (Garijo, González & Márquez, 2014   )

G graph of order n, no isolated vertices, no twins. Then $LD(G) \leq \frac{n}{2}$.

Theorem (F., Henning, Löwenstein, Sasse, 2016   )

G graph of order n, no isolated vertices, no twins. Then $LD(G) \leq \frac{2}{3}n$.

Proof: • There exists a dominating set D such that each vertex of D has a private neighbour in $V(G) \setminus D$. (classic lemma by Bollobas-Cockayne, 1979)
Thus $|D| \leq n_1 + n_2$. Take such D that is inclusionwise maximal.

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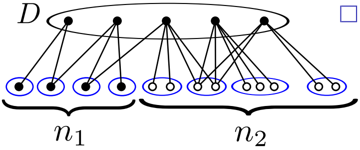

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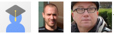
Conjecture (Garijo, González & Márquez, 2014 )

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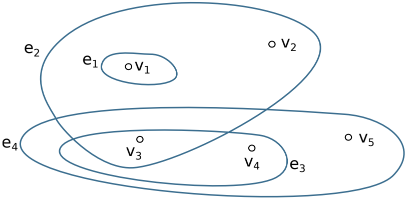
Theorem (Bousquet, Chuet, Falgas-Ravry, Jacques, Morelle, 2024)

G graph of order n, no isolated vertices, no twins. Then $LD(G) \leq \frac{5}{8}n = 0.625n$.

Separating sets in hypergraphs

Definition - Separating set (Rényi, 1961 )

Hypergraph $(X,\mathscr{E})$. A separating set is a subset $C \subseteq X$ such that each edge $e \in \mathscr{E}$ contains a distinct subset of C.



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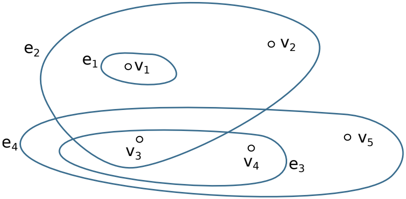

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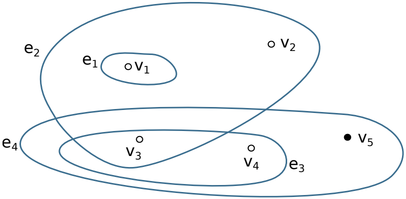

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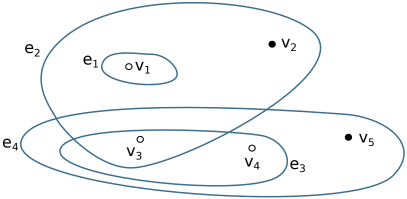

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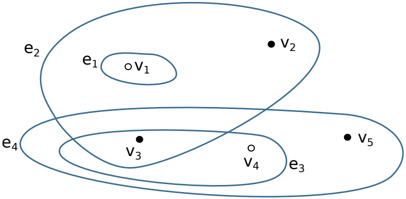

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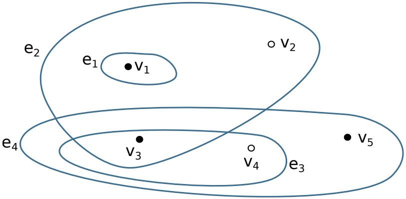

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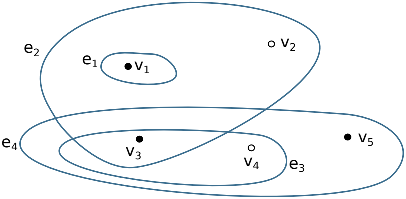

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Also known as Separating system, Distinguishing set, Test cover, Distinguishing transversal, Discriminating code...

Applications

- network-monitoring, fault detection (burglar)
- medical diagnostics: testing samples for diseases (*test cover*)
- biological identification (attributes of individuals)
- learning theory: teaching dimension
- machine learning: V-C dimension (Vapnik, Červonenkis, 1971)
- graph isomorphism: canonical representation of graphs (Babai, 1982)
- logic definability of graphs (Kim, Pikhurko, Spencer, Verbitsky, 2005)

Proposition

For a hypergraph $(X, \mathscr{E})$, a separating set C has size at least $\log_2(|\mathscr{E}|)$.

Proof: Must assign to each edge, a distinct subset of C: $|\mathscr{E}| \leq 2^{|C|}$. □

General bounds, Bondy's theorem

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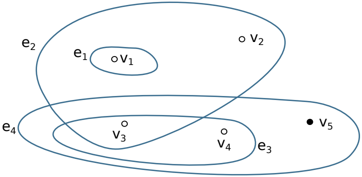

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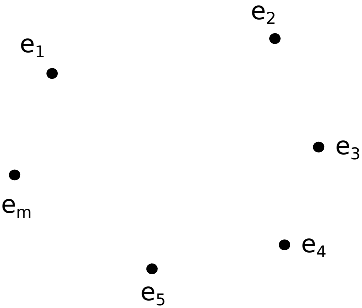

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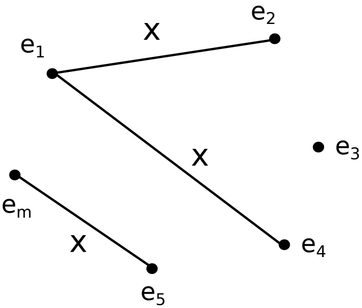

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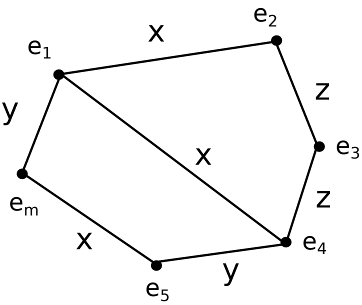

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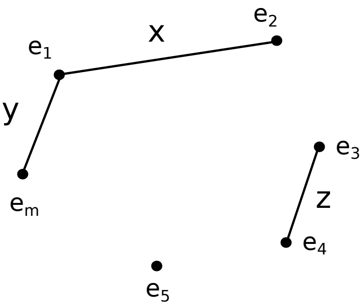

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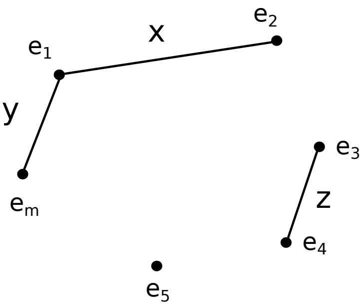

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So, at most $|\mathscr{E}|-1$ "problematic" vertices.
→ Find "non-problematic vertex", omit it. □

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Special cases of separating sets in hypergraphs (graph-based):

- identifying codes
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- locally identifying coloring
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Open identifying codes in graphs

(a.k.a. open locating-dominating sets)

Open identifying codes

G: undirected graph $\quad N(u)$: set of neighbours of v

Definition - open identifying code (Seo, Slater, 2010  )

Subset D of $V(G)$ such that:

- D is a **total dominating set**: $\forall u \in V(G)$, $N(u) \cap D \neq \emptyset$, and
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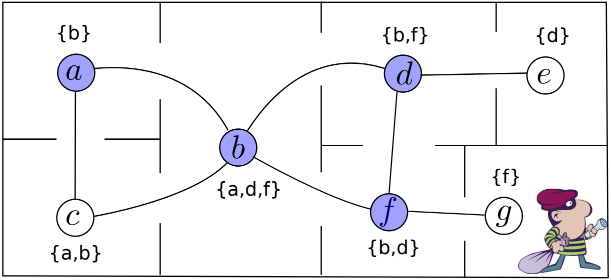
Notation. $OID(G)$: open identifying code number of G, minimum size of an open identifying code in G



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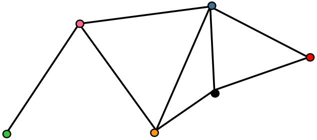

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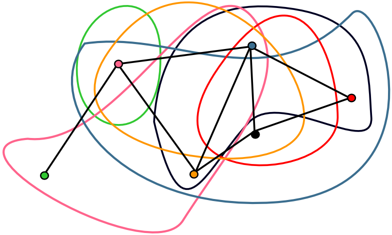

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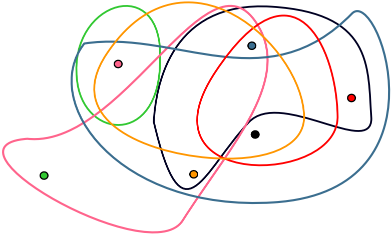

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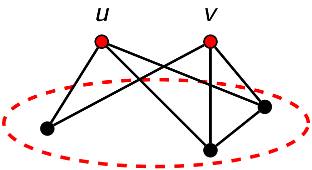

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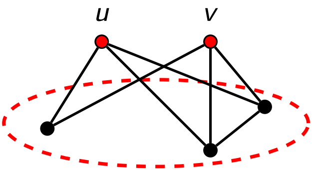

Proposition

A graph is **locatable** if and only if it has no **isolated vertices** and **open twins**.

Lower bound on $OID(G)$

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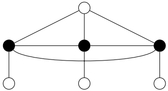

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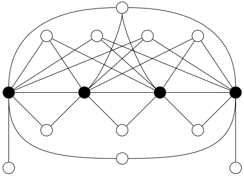
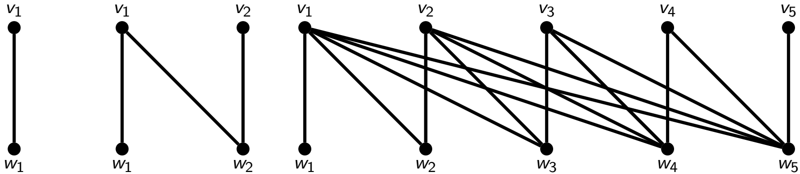


□

Definition - Half-graph H_k (Erdős, Hajnal, 1983  )

Bipartite graph on vertex sets $\{v_1, \ldots, v_k\}$ and $\{w_1, \ldots, w_k\}$, with an edge $\{v_i, w_j\}$ if and only if $i \leq j$.

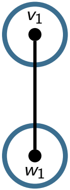


$H_1 = P_2$ $H_2 = P_4$ H_5

Upper bound on $OID(G)$?

Definition - Half-graph H_k (Erdős, Hajnal, 1983  )

Bipartite graph on vertex sets $\{v_1, \ldots, v_k\}$ and $\{w_1, \ldots, w_k\}$, with an edge $\{v_i, w_j\}$ if and only if $i \leq j$.



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Some vertices **forced** in any open identifying code because of domination

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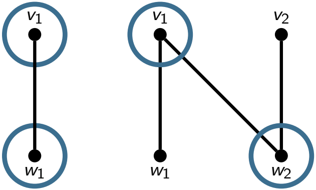

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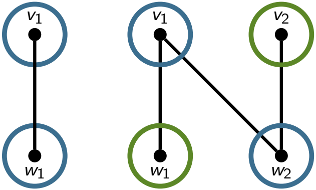

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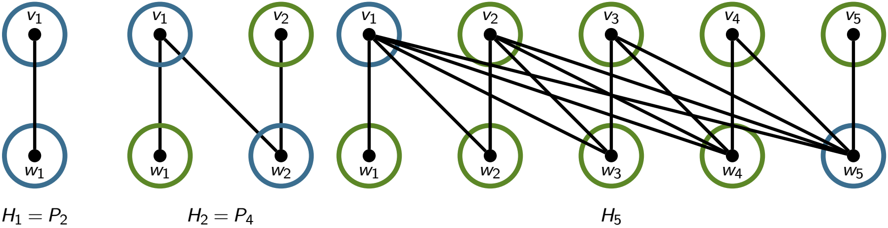

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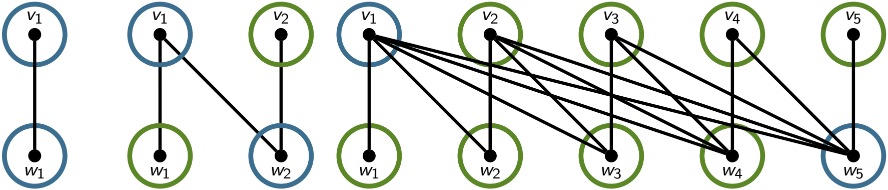

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Proposition

For every half-graph H_k of order $n = 2k$, $OID(H_k) = n$.

Theorem (F., Ghareghani, Roshany Tabrizi, Sharifani, 2021   )

Let G be a connected locatable graph of order n.

Then, $OID(G) = n$ if and only if G is a half-graph.

Characterizing "bad graphs" for open identifying codes

Theorem (F., Ghareghani, Roshany Tabrizi, Sharifani, 2021   )

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• By induction, G' is a half-graph. We can conclude that G is a half-graph too, after some case analysis. □

Lower bounds
(neighbourhood complexity)

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G graph, n vertices, $LD(G) = k$. Then, $n \leq 2^k + k - 1$.

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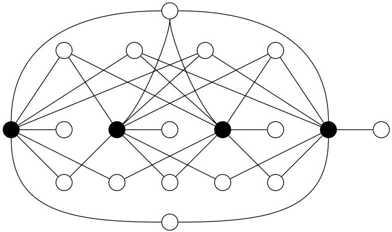
Tight example ($k = 4$):



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Theorem (Slater, 1980's )

G tree of order n, $LD(G)=k$. Then $n \leq 3k-1 \rightarrow LD(G) \geq \frac{n+1}{3}$.

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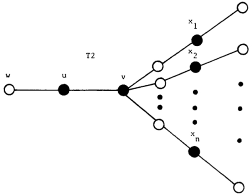

FIG. 2. Tree T2

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Proof: Recall: a tree of order n has $n-1$ edges. Consider a LD-set S of size k.

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In total we need $c_1+2(n-k-c_1) = 2n-2k-c_1 \geq 2n-3k$ edges in the tree. So:

$2n-3k \leq n-1$ and so, $n \geq 3k-1$. □

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Theorem (Rall & Slater, 1980's  )

G planar graph, order n, $LD(G)=k$. Then $n \leq 7k-10 \rightarrow LD(G) \geq \frac{n+10}{7}$.

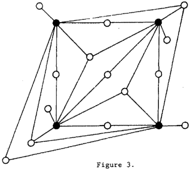
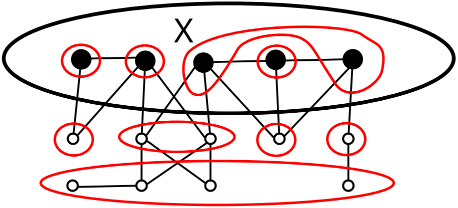
Tight examples: 

Figure 3.

Neighbourhood complexity of a graph G:

maximum number $|\{N(v) \cap X\}|$ of neighbourhoods inside any set X of k vertices, as a function of k



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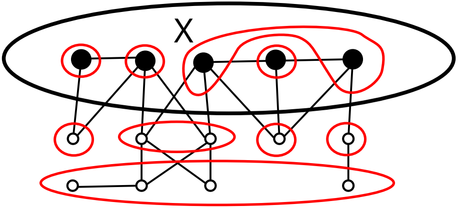

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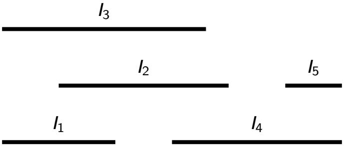
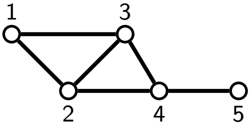
- General graphs : exponential neighbourhood complexity 2^k
- Trees/planar graphs : linear neighbourhood complexity $O(k)$

Interval graphs

Definition - Interval graph

Intersection graph of intervals of the real line.





Theorem (F., Mertzios, Naserasr, Parreau, Valicov, 2017    )

G interval graph of order n, $LD(G) = k$.

Then $n \leq \frac{k(k+1)}{2}$, i.e. $LD(G) = \Omega(\sqrt{n})$.

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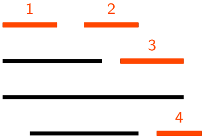

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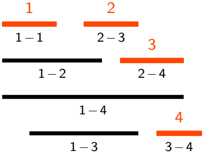

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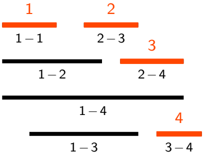

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- Each vertex intersects a consecutive set of intervals of D when ordered by left points.

$$\rightarrow n \leq \sum_{i=1}^{k} (k - i) = \frac{k(k+1)}{2}.$$

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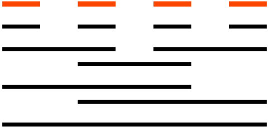
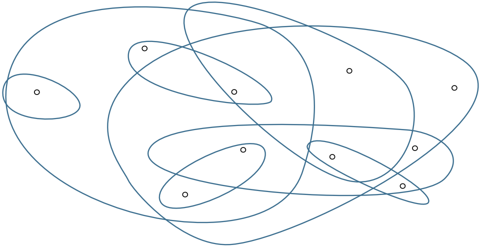
Tight:



Measure of intersection complexity of sets in a hypergraph $(X, \mathscr{E})$
(initial motivation: machine learning, 1971)

A set $S \subseteq X$ is shattered:

for every subset $S' \subseteq S$, there is an edge e with $e \cap S = S'$.



V-C dimension of H: maximum size of a shattered set in H

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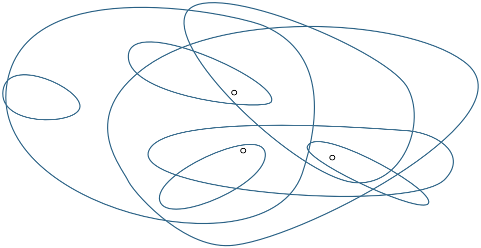

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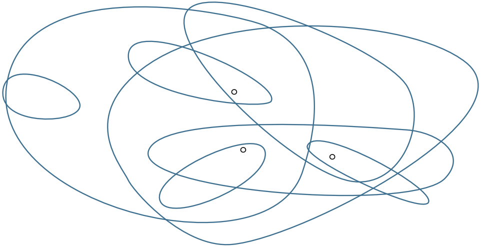

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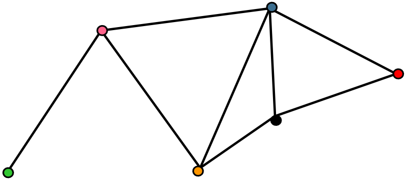
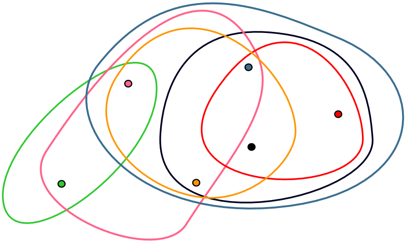
Typically bounded for geometric hypergraphs: 

V-C dimension of a graph: V-C dimension of its open/closed neighbourhood hypergraph





Vapnik-Červonenkis dimension - graphs

V-C dimension of a graph: V-C dimension of its open/closed neighbourhood hypergraph

Typically bounded for geometric intersection graphs:

→ interval graphs ($d = 2$), C_4-free graphs ($d = 2$), line graphs ($d = 4$), permutation graphs ($d = 3$), unit disk graphs ($d = 3$), planar graphs ($d = 4$)...

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$O(k^2)$: interval, permutation, line...

$O(k)$: cographs, unit interval, bipartite permutation, block...

Graph classes of bounded expansion: all shallow minors of its members have bounded average degree → e.g. planar graphs, minor-closed classes, bounded degree...

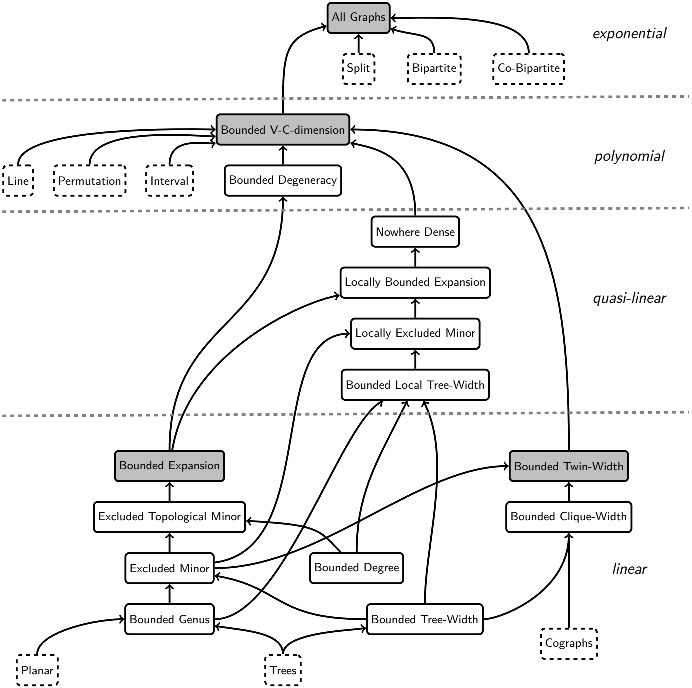
Theorem (Reidl, Sánchez-Villaamil, Stavropoulos, 2019   )

Let $\mathscr{C}$ be a graph class of bounded expansion. Let G in $\mathscr{C}$, order n, and $LD(G) = k$.
Then, $n \leq f(\mathscr{C})k$.

Recently introduced structural measure: twin-width.

Theorem (Bonnet, F., Lehtilä, Parreau, 2024   )

Let G be a graph of twin-width at most d and order n, and $LD(G) = k$.
Then, $n \leq (d+2)2^{d+1}k$.


All Graphs
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Bipartite
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Bounded V-C-dimension
polynomial
Line
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Interval
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Nowhere Dense
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Bounded Twin-Width
Excluded Topological Minor
Bounded Clique-Width
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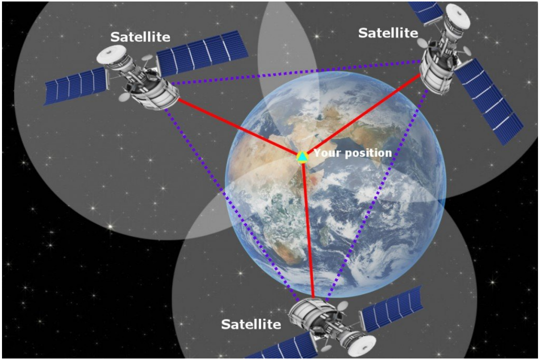
linear
Bounded Genus
Bounded Tree-Width
Cographs
Planar
Trees

Metric dimension

Determination of Position in 3D euclidean space

GPS/GLONASS/Galileo/Beidou/IRNSS:
need to know the exact position of 4 satellites + distance to them



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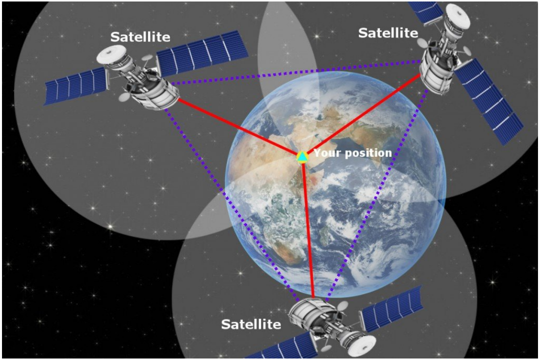

Question

Does the “GPS” approach also work in undirected unweighted graphs?

Now, $w \in V(G)$ distinguishes $\{u, v\}$ if $dist(w, u) \neq dist(w, v)$

Definition - Resolving set (Slater, 1975 - Harary & Melter, 1976)   

$R \subseteq V(G)$ resolving set of G:

$$\forall u \neq v \text{ in } V(G), \text{ there exists } w \in R \text{ that distinguishes } \{u, v\}.$$

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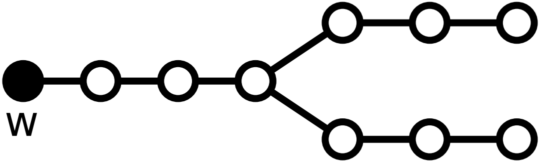

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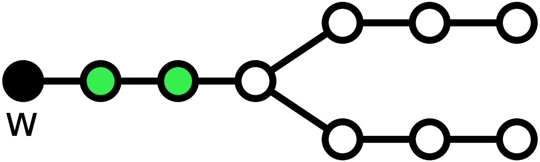

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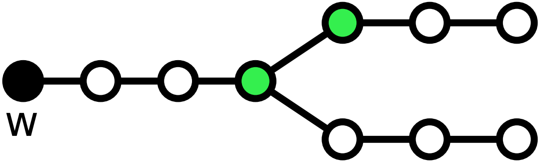

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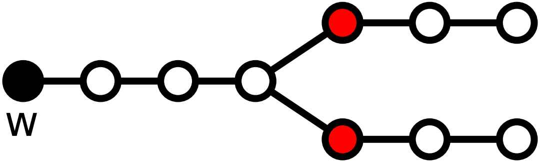

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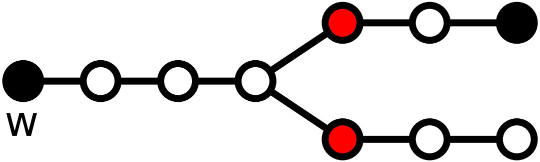

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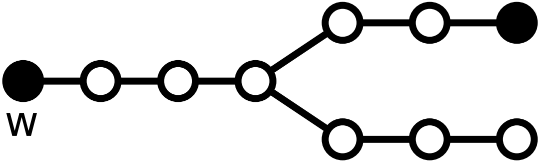

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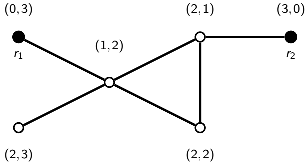

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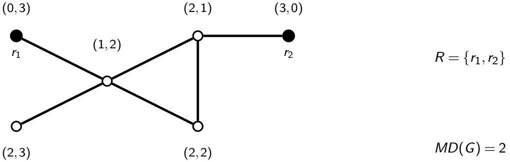

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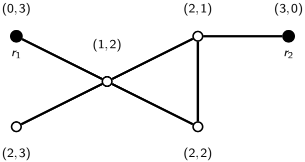

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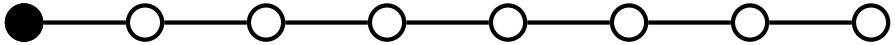
Remark

- Any locating-dominating set is a resolving set, hence $MD(G) \leq LD(G)$.
- A locating-dominating set can be seen as a “distance-1-resolving set”.

Examples



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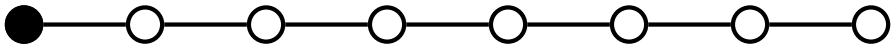

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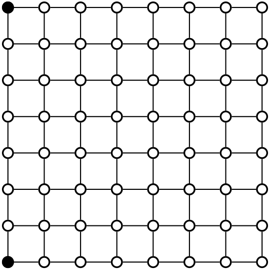
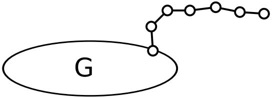


Proposition

For any square grid G, $MD(G) = 2$.

Trees

Leg: path with all inner-vertices of degree 2, endpoints of degree ≥ 3 and 1.



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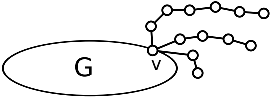

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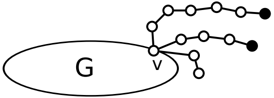

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R resolving set. If v has k legs, at least $k-1$ legs contain a vertex of R.

Simple leg rule: if v has $k \geq 2$ legs, select $k-1$ leg endpoints.

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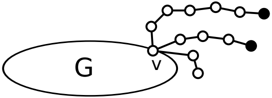

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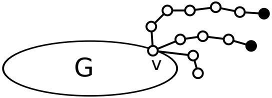

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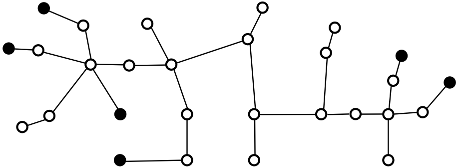

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G of order n, diameter D, $MD(G) = k$. Then $n \leq D^k + k$.

(diameter D: maximum distance between two vertices)

Proof: Every vertex not in the solution R is assigned to a unique vector of length k, with values in $\{1, \ldots, D\}$: D^k possibilities, plus the k ones in R. □

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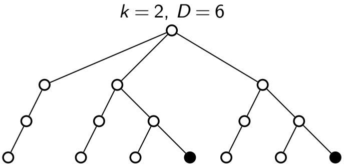
→ Proof is similar as that for locating-dominating sets.

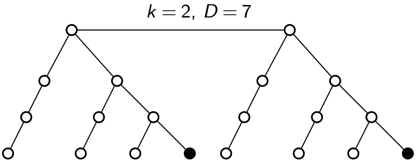
Theorem (Beaudou, Dankelmann, F., Henning, Mary, Parreau, 2018 )

T a tree with diameter D and $MD(T) = k$, then

$$n \leq \begin{cases} \frac{1}{8}(kD+4)(D+2) & \text{if } D \text{ even,} \\ \frac{1}{8}(kD-k+8)(D+1) & \text{if } D \text{ odd.} \end{cases} = \Theta(kD^2)$$

Bounds are tight.





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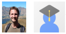
Theorem (Joret, Rambaud, 2024 )

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Planar graphs

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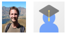
Theorem (Joret, Rambaud, 2024 )

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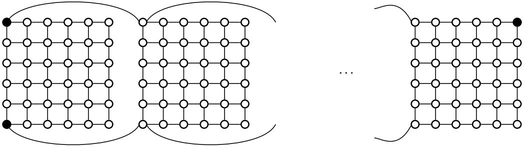

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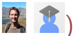
Theorem (Joret, Rambaud, 2024 )

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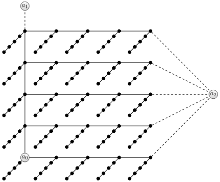
Tight? Planar example with treewidth 2 and $n = \Theta(kD^3)$:



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