Advance Kernel: FEEDBACK VERTEX SET

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Problem Definition

FEEDBACK VERTEX SET **Parameter:** k
Input: An undirected graph G and a positive integer k.
Question: Does there exists a subset X of size at most k such that $G - X$ is acyclic?

X is called feedback-vertex set (fvs) of G.

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Goal is to obtain a polynomial kernel for FEEDBACK VERTEX SET.

What reduction rules we already know?

Reduction.FVS

If there is a loop at a vertex v*, delete* v *from the graph and decrease* k *by one.*

What reduction rules we already know?

Multiplicity of a multiple edge does not influence the set of feasible solutions to the instance (G, k).

Reduction.FVS

If there is an edge of multiplicity larger than 2, reduce its multiplicity to 2.

What reduction rules we already know?

Any vertex of degree at most 1 does not participate in any cycle in G, so it can be deleted.

Reduction.FVS

If there is a vertex v *of degree at most* 1*, delete* v*.*

What reduction rules we already know?

Concerning vertices of degree 2, observe that, instead of including into the solution any such vertex, we may as well include one of its neighbors.

Reduction.FVS

If there is a vertex v of degree 2, delete v and connect its two neighbors by a new edge.

What do we achieve after all these?

After exhaustively applying these four reduction rules, the resulting graph G

(P1) contains no loops,

(P2) has only single and double edges, and

(P3) has minimum vertex degree at least 3.

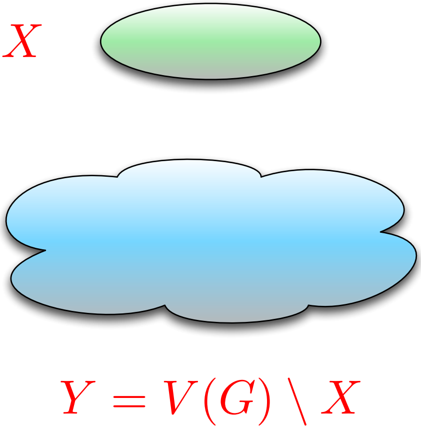
Stopping rule.

A rule that stops the algorithm if we already exceeded our budget.

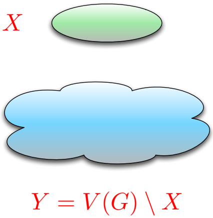
Reduction.FVS

If $k < 0$*, terminate the algorithm and conclude that* (G, k) *is a no-instance.*

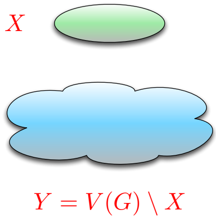
A picture :)



Maximum degree is **d**.

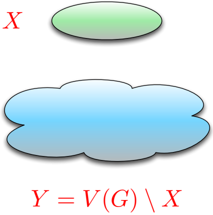


Maximum degree is $\mathbf{d}$.



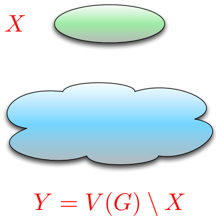
$$\sum_{v \in V(G)} \text{degree}(v) = 2|E(G)|$$

Maximum degree is **d**.



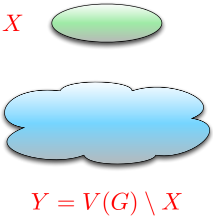
$$3|V(G)| \leqslant \sum_{v \in V(G)} \text{degree}(v) = 2|E(G)|$$

Maximum degree is **d**.



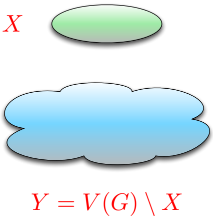
$$1.5|V(G)| \leqslant |E(G)|$$

Maximum degree is **d**.



$$|E(G)| \leqslant d|X| + (|V(G)| - |X| - 1)$$

Maximum degree is **d**.



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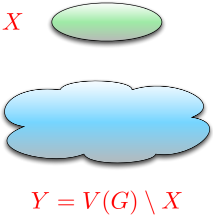

$$1.5|V(G)| \leqslant |E(G)| \leqslant d|X| + (|V(G)| - |X|)$$

$$\implies |V(G)| \leqslant 2(d-1)|X| \leqslant 2(d-1)k.$$

Summarizing:

Lemma

If a graph G *has minimum degree at least* 3*, maximum degree at most* d*, and feedback vertex set of size at most* k*, then it has less than* $2(d-1)k$ *vertices and less than* $2(d-1)dk$ *edges.*

Summarizing: (possible to prove)

Lemma

If a graph G *has minimum degree at least* 3*, maximum degree at most* d*, and feedback vertex set of size at most* k*, then it has less than* $(d+1)k$ *vertices and less than* $2dk$ *edges.*

A new rule

Reduction.FVS

If $|V(G)| \geqslant (d+1)k$ *or* $|E(G)| \geqslant 2dk$, *where* d *is the maximum degree of* G, *then terminate the algorithm and return that* (G, k) *is a no-instance.*

So what do we need to get the polynomial kernel?

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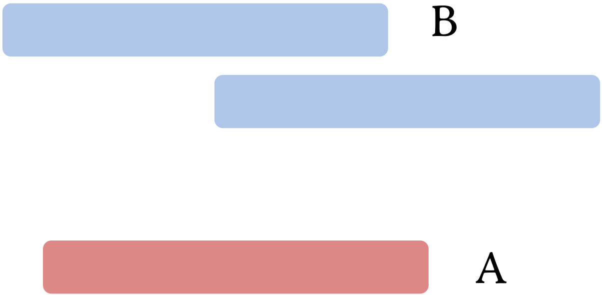
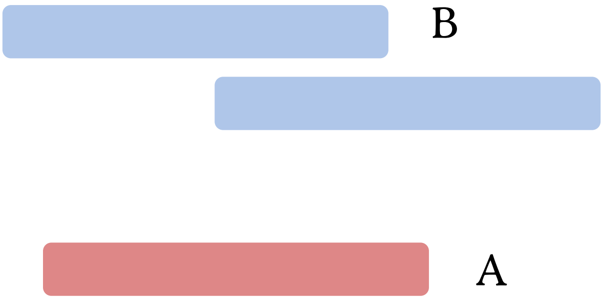
Bound the maximum degree of the graph by a polynomial in k.

Part 2: Recap

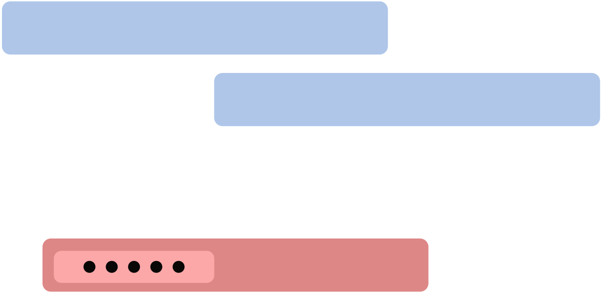
A Tale of 2 Matchings



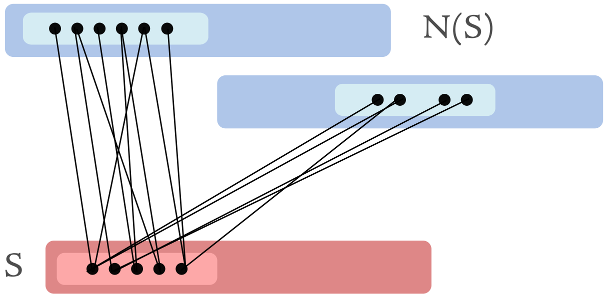
Consider a bipartite graph one of whose parts (say B) is at least twics as big as the other (call this A).



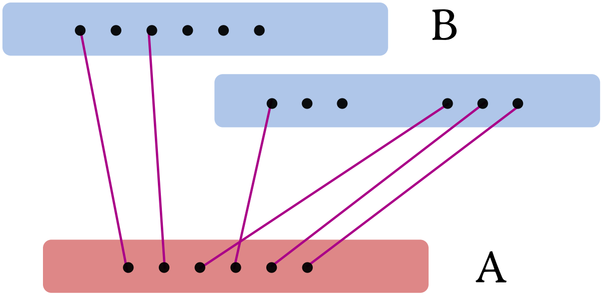
Assume that there are no isolated vertices in B.



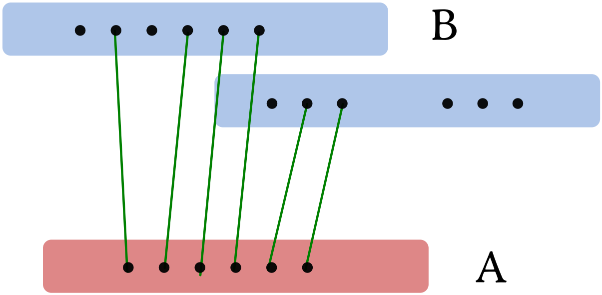
Suppose, further, that for every subset S in A,



Suppose, further, that for every subset S in A, $N(S)$ is at least twice as large as $|S|$.



Then there exist two matchings saturating A,



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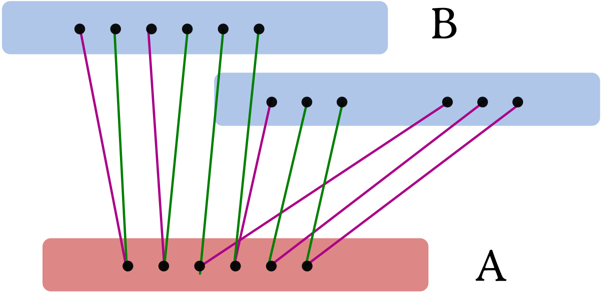

Then there exist two matchings saturating A, and disjoint in B.

Claim:

If $|\mathrm{B}| \geqslant 2|A|$, then there exists a subset X of A such that:

there exists 2 matchings saturating the subset X that are vertex-disjoint in B.

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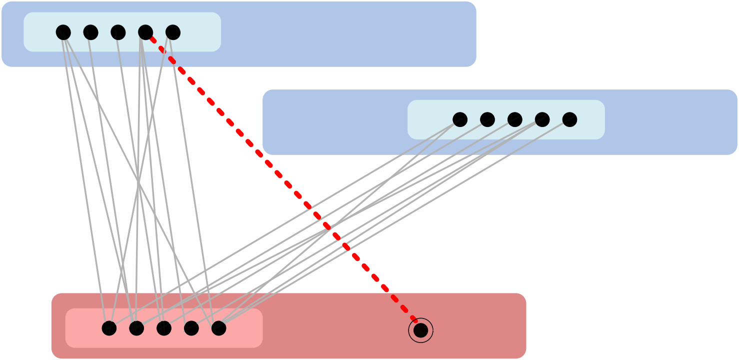
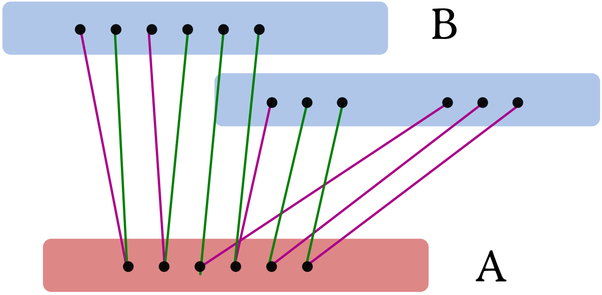
$$\text{there exists 2 matchings saturating the subset } X \text{ that are vertex-disjoint in } B,$$

provided B does not have any isolated vertices.

Crucially: it turns out that the endpoints of the matchings in B (the larger set) do not have neighbors outside X.




B
A

q-Expansion Lemma

Let $q \geqslant 1$ be a positive integer and G be a bipartite graph with vertex bipartition (A, B) such that

(i) $|B| \geqslant q|A|$, and
(ii) there are no isolated vertices in B.

Then there exist nonempty vertex sets $X \subseteq A$ and $Y \subseteq B$ such that

- there is a q-expansion of X into Y, and
- no vertex in Y has a neighbor outside X, that is, $N(Y) \subseteq X$.

Furthermore, the sets X and Y can be found in time polynomial in the size of G.

q-Expansion Lemma

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We will use this lemma with $q = 2$.

Part 3

2-Expansions and FVS

- For VERTEX COVER – if a vertex has degree $k+1$ then we must have it in the solution.

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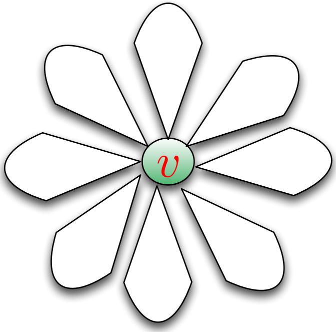
What would be the analogous rule for FEEDBACK VERTEX SET.

For VERTEX COVER – wanted to hit edges and for FEEDBACK VERTEX SET – want to hit cycles..

Flower



$k+1-$ vertex disjoint cycles passing through it

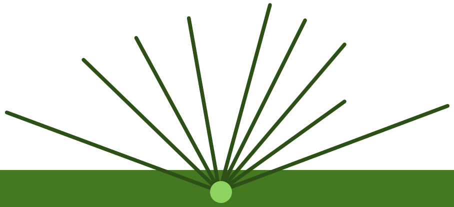
Flower Rule.

Reduction.FVS

If there is a $k+1$*-flower passing through a vertex* v *then* $(G \setminus \{v\}, k-1)$.

In what follows, given a high degree vertex (more than some $k^{O(1)}$) in polynomial time either we will find a $k+1$-flower or find ways to delete some edges from the graph.

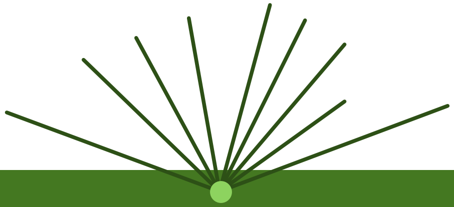
Ingredients



a high-degree vertex, v

Ingredients

a small hitting set,
sans v



a high-degree vertex, v

Ingredients

Given a high-degree vertex v, finding a small feedback vertex set that does not contain v.

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A subset whose removal makes the graph acyclic.

Given a high-degree vertex v, finding a small feedback vertex set that does not contain v.

A polynomial function of k.

Given a high-degree vertex v, finding a small feedback vertex set that does not contain v.

Given a high-degree vertex v, finding a small feedback vertex set that does not contain v.

Find an approximate feedback vertex set T.

Given a high-degree vertex v, finding a small feedback vertex set that does not contain v.

If T does not contain v, we are done.

Given a high-degree vertex v, finding a small feedback vertex set that does not contain v.

Else: $v \in \mathsf{T}$. Delete $\mathsf{T} \setminus v$ from G.

Given a high-degree vertex v, finding a small feedback vertex set that does not contain v.

The only remaining cycles pass through v.

Given a high-degree vertex v, finding a small feedback vertex set that does not contain v.

Find an optimal cut set for paths from $N(v)$ to $N(v)$.

Given a high-degree vertex v, finding a small feedback vertex set that does not contain v.

Why is this cut set small enough?

Given a high-degree vertex v, finding a small feedback vertex set that does not contain v.

When is this cut set small enough?

Given a high-degree vertex v, finding a small feedback vertex set that does not contain v.

When is this cut set small enough?

When the largest collection of vertex disjoint paths from $\mathsf{N}(v)$ to $\mathsf{N}(v)$ is small.

Given a high-degree vertex v, finding a small feedback vertex set that does not contain v.

When is this cut set small enough?

When the largest collection of vertex disjoint paths from $\mathsf{N}(v)$ to $\mathsf{N}(v)$ is *not* small...

Given a high-degree vertex v, finding a small feedback vertex set that does not contain v.

When is this cut set small enough?

When the largest collection of vertex disjoint paths from $\mathsf{N}(v)$ to $\mathsf{N}(v)$ is *not* small... we get a reduction rule.

Given a high-degree vertex v, finding a small feedback vertex set that does not contain v.

When is this cut set small enough?

More than k vertex-disjoint paths from $N(v)$ to $N(v)$
$\rightarrow$ v belongs to *any* feedback vertex set ($k+1$-flower) of size at most k.

Given a high-degree vertex v, finding a small feedback vertex set that does not contain v.

So either v “forced”, or we have feedback vertex set of suitable size.
Notice that we need to arrive at either situation in “polynomial time”.

Approximate fvs

- There is a factor 2 approximation algorithm for FEEDBACK VERTEX SET. So use this to get T. If $|\mathsf{T}| > 2\mathsf{k}$ return no-instance. Else, we have the desired T.
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Approximate fvs

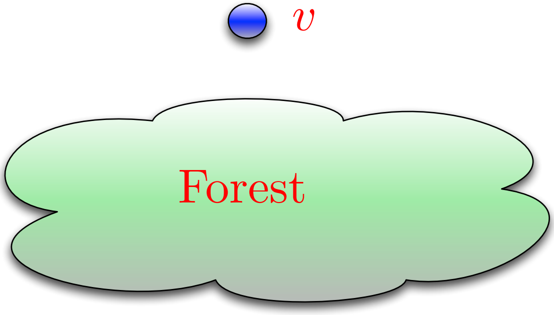
- There is a factor 2 approximation algorithm for FEEDBACK VERTEX SET. So use this to get T. If $|\mathsf{T}| > 2\mathsf{k}$ return no-instance. Else, we have the desired T.
- We have seen if G has minimum degree 3, then any fvs of size at most k contains one among the first $3\mathsf{k}$ vertices of highest degree. Use this to get T of size $3\mathsf{k}^2$ or return no-instance.

fvs without v when $v \in \mathsf{T}$.

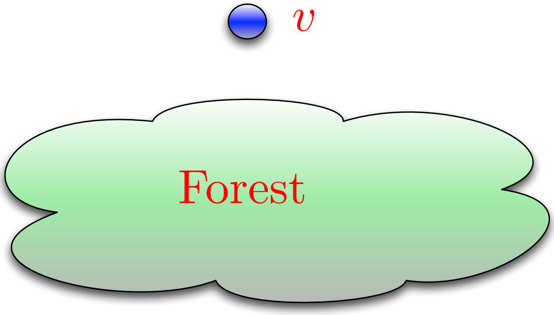
- $Z_v = \mathsf{T} \setminus \{v\} + W$(something more).

fvs without v when $v \in \mathsf{T}$.

- $\mathsf{Z}_v = \mathsf{T} \setminus \{v\} + W$(something more).



fvs without v when $v \in \mathsf{T}$.



W will be a fvs for Forest $+ v$.

- Check whether there is a $k+1$-flower containing v in Forest $+ v$ (if yes then we have reduction rule). (How to find?)
-
-

- Check whether there is a $k+1$-flower containing v in $\text{Forest}+v$ (if yes then we have reduction rule). (How to find?)
- Else, we can show that there is fvs for $\text{Forest}+v$ of size at most $2k$.
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- Check whether there is a $k+1$-flower containing v in Forest $+ v$ (if yes then we have reduction rule). (How to find?)
- Else, we can show that there is fvs for Forest $+ v$ of size at most $2k$.
- Prove it for yourself a bound of $O(k)$ – this is not very hard :).

Book – Gallai Theorem

Theorem (Gallai)

Given a simple graph G*, a set* $T \subseteq V(G)$ *and an integer* s*, one can in polynomial time find either*

1. *a family of* $s + 1$ *pairwise vertex-disjoint* T*-paths, or*
2. *a set* B *of at most* $2s$ *vertices, such that in* $G \setminus B$ *no connected component contains more than one vertex of* T*.*

What did we show.

- For every vertex v either there is a $k+1$-flower passing through v or there is a Z_v of size at most $4k$ that does not include v and is a fvs of G.
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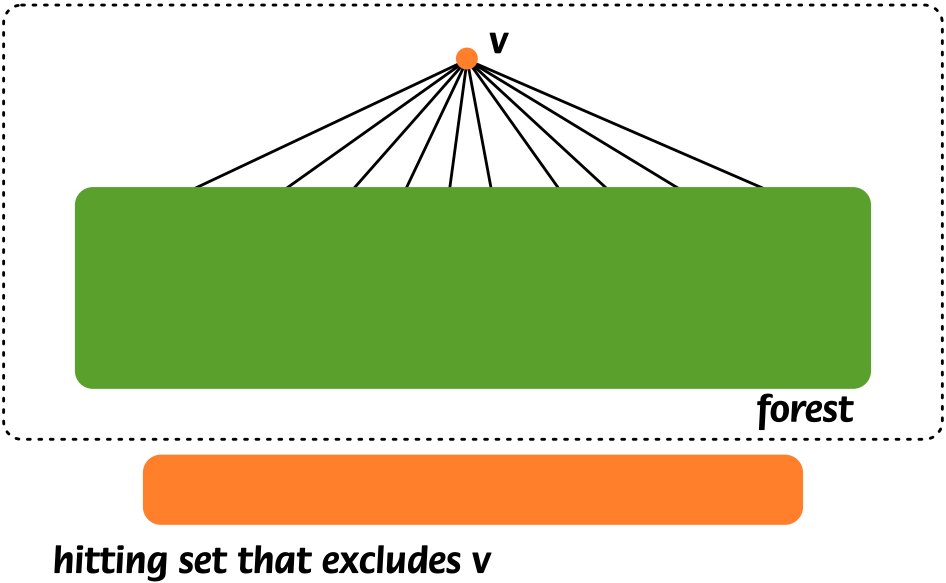
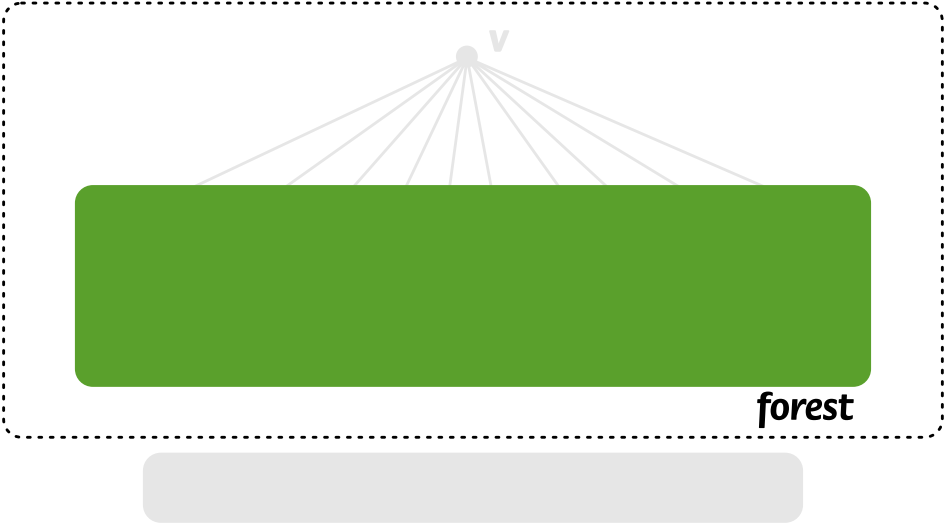
What did we show.

- For every vertex v either there is a $k+1$-flower passing through v or there is a Z_v of size at most $4k$ that does not include v and is a fvs of G.
- In the first case we apply Flower Rule.
- Assume that the first case does not happen, so we have Z_v of size at most $4k$ for every vertex $v \in V(G)$.

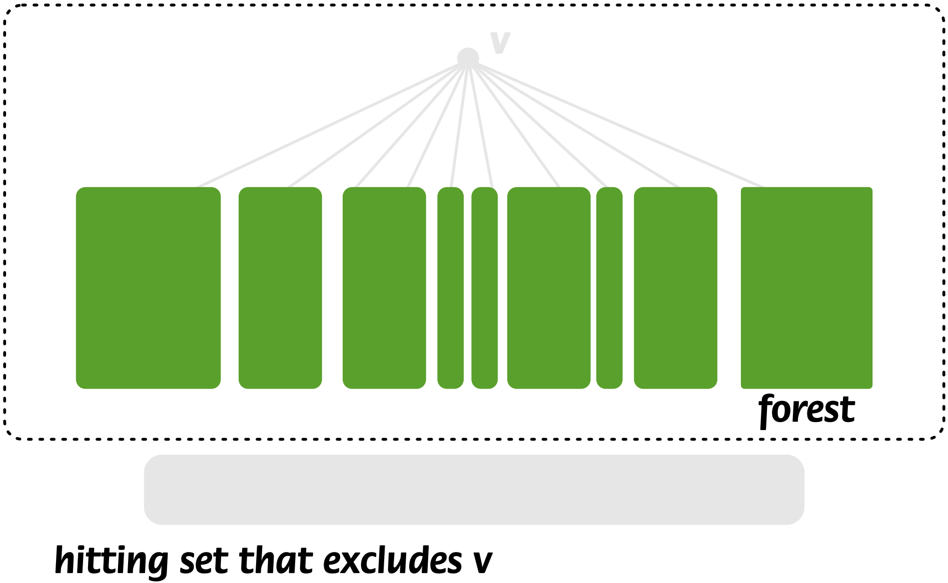

v
forest
hitting set that excludes v



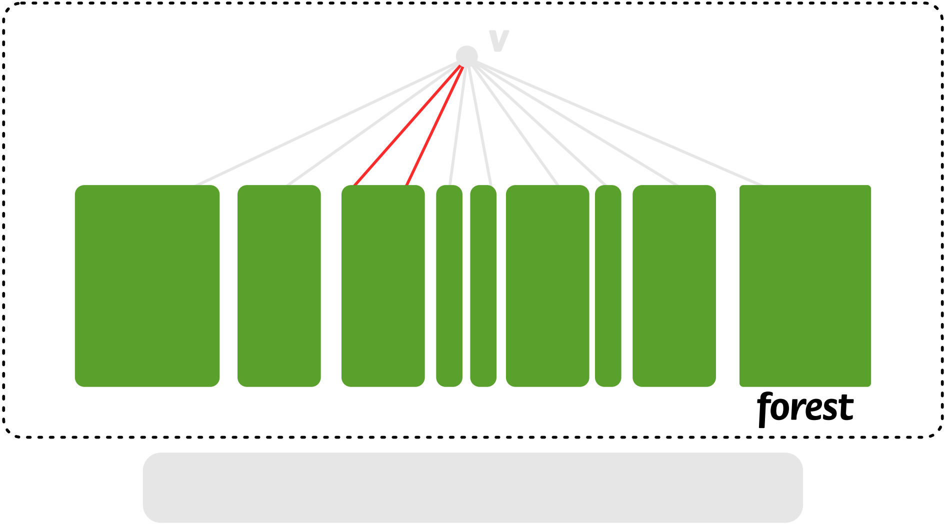
hitting set that excludes v

Focussing on the green Part

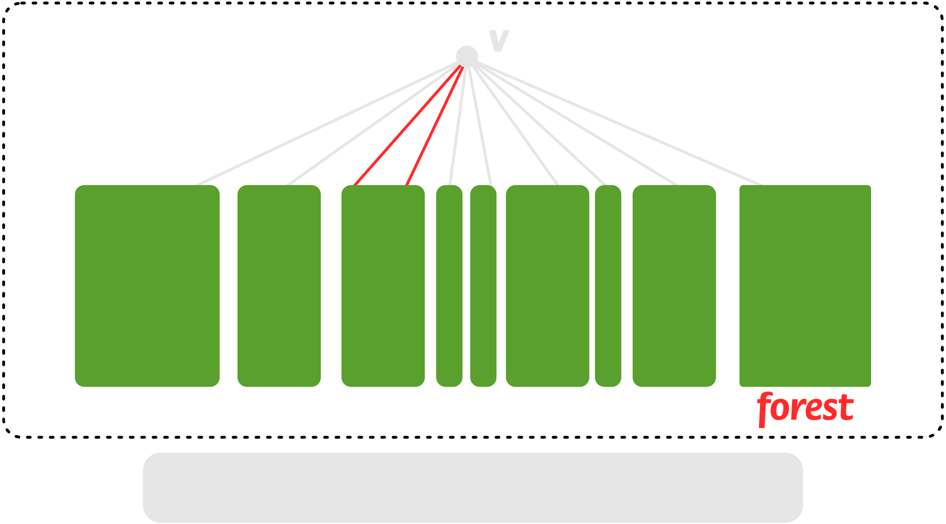
Consider the connected components of $V(G) \setminus (Z_v \cup \{v\})$.


v
forest
hitting set that excludes v

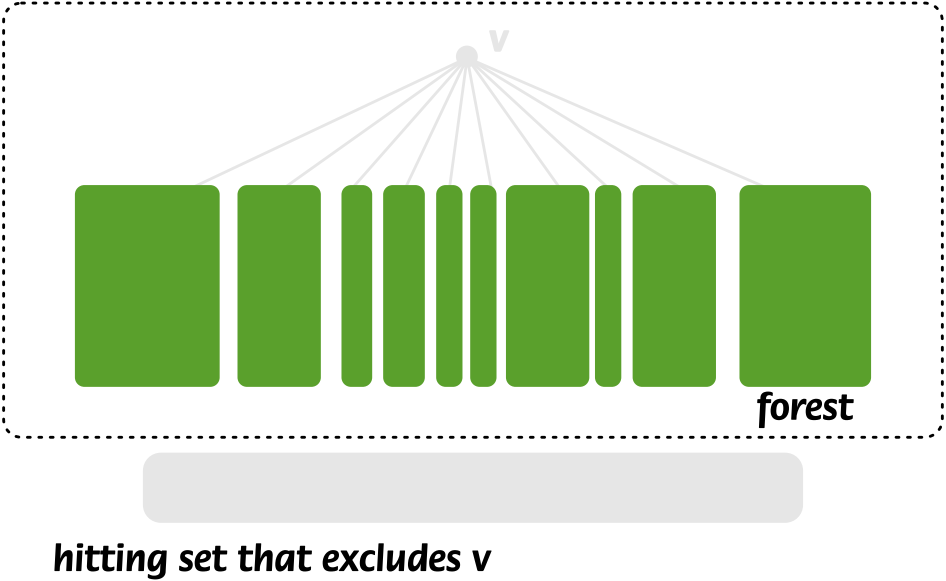
Could v have two neighbor in a connected components of $\mathsf{V}(\mathsf{G}) \setminus (\mathsf{Z}_v \cup \{v\})$?



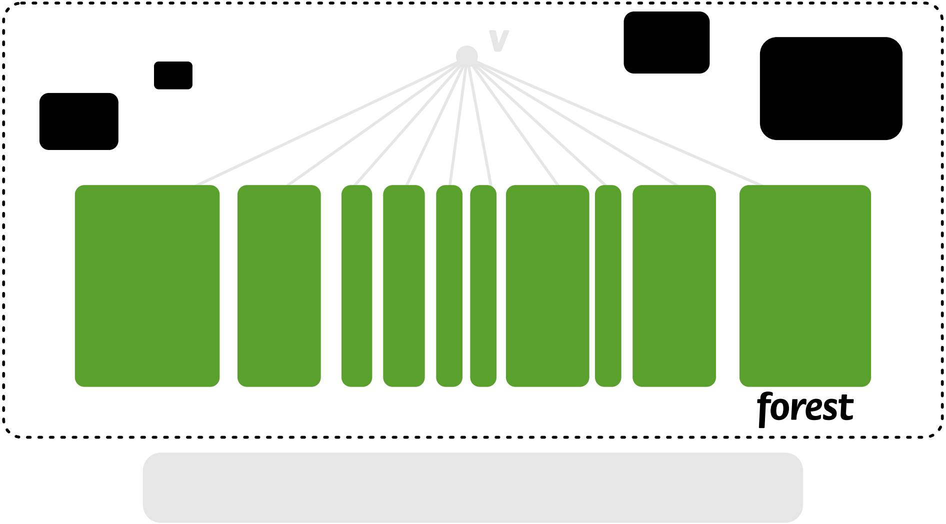
hitting set that excludes v



hitting set that excludes v

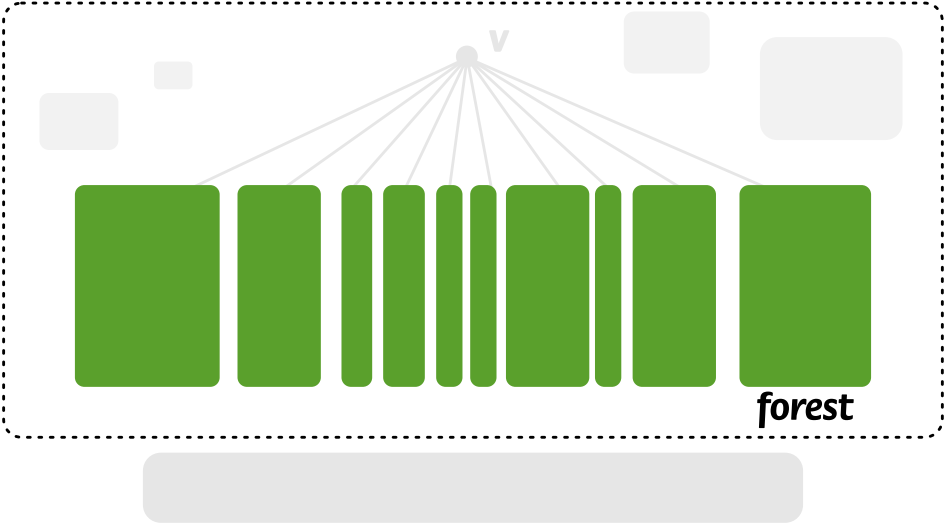

v
forest
hitting set that excludes v

There could be components in $V(G) \setminus (Z_v \cup \{v\})$ that do not see any neighbor of v. Important, for us is that any component contains at most one neighbor of v and we will focus on them.



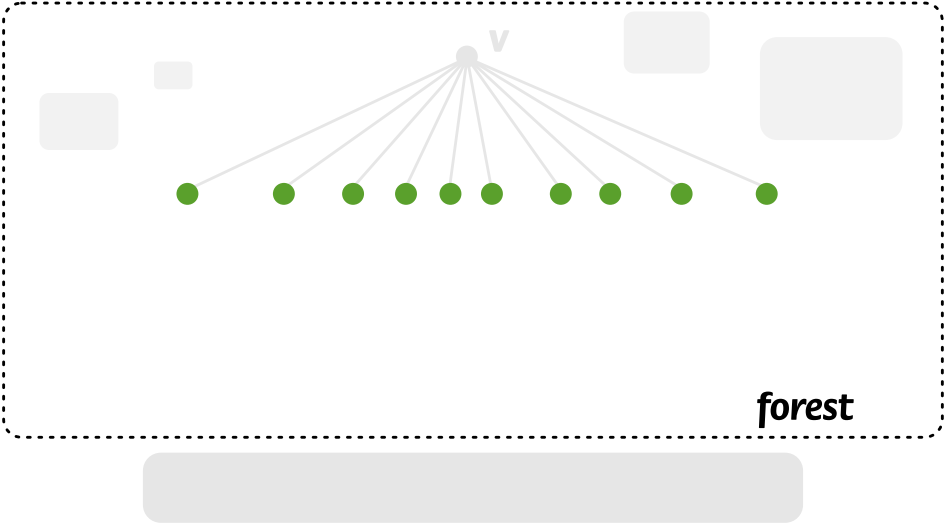
hitting set that excludes v

To bound the degree of v or to delete an edge incident to v we only focus on those components that contain some (exactly one) neighbor of v.



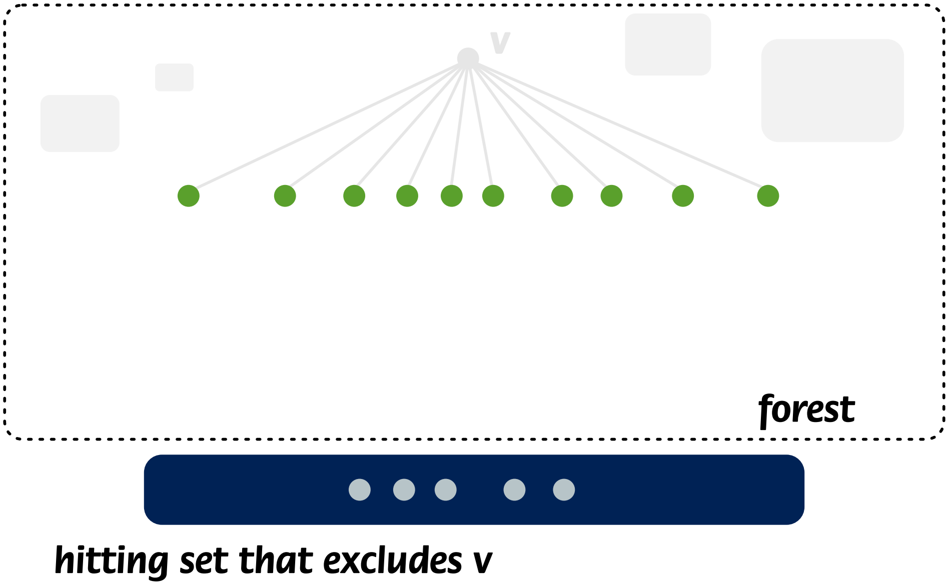
hitting set that excludes v

To apply 2-expansion lemma we need a bipartite graph. In one part (say B) we will have a vertex for every component in $V(G) \setminus (Z_v \cup \{v\})$ that contains a neighbor of v.



hitting set that excludes v

To apply 2-expansion lemma we need a bipartite graph. In one part (say B) we will have a vertex for every component in $V(G) \setminus (Z_v \cup \{v\})$ that contains a neighbor of v. The other part A will be Z_v.


v
forest
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- So we have A and B. We put an edge between a vertex x in A and a vertex w in B, if x is adjacent to some vertex in the component represented by the vertex w. Essentially, we have obtained this bipartite graph by contracting the components.
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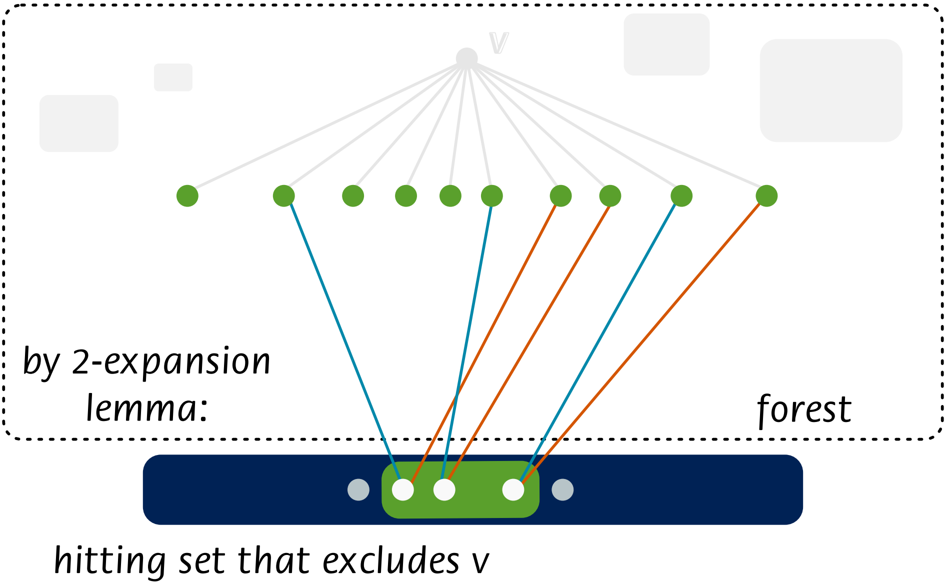
- If $|B| < 2|A| \leqslant 8k$ then v already has its degree bounded by $8k$. So assume that

$$|B| > 2|A|$$

Now by expansion lemma (applied with $q = 2$) we have that there exist nonempty vertex sets $X \subseteq A$ and $Y \subseteq B$ such that

- there is a 2-expansion of X into Y, and
- no vertex in Y has a neighbor outside X, that is, $N(Y) \subseteq X$.


v
by 2-expansion
lemma:
forest
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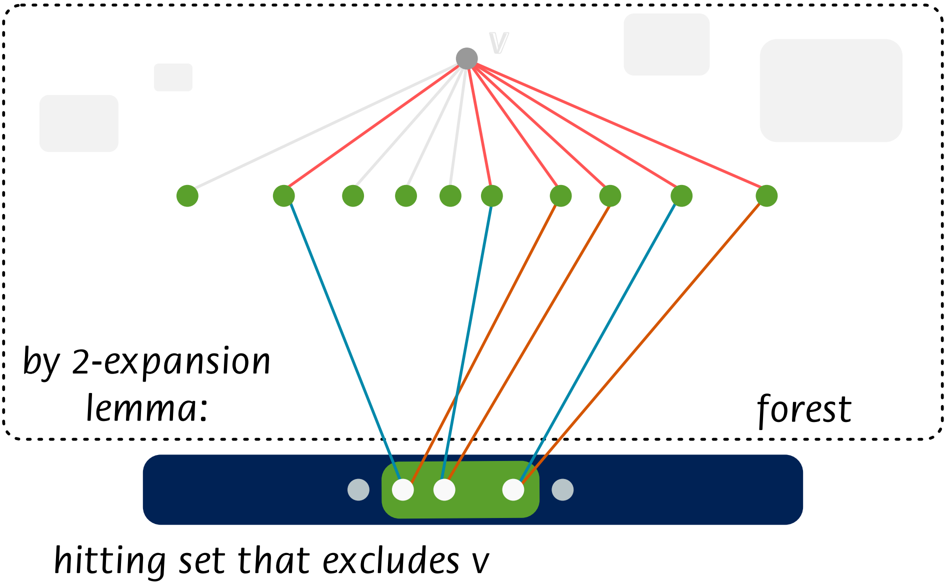
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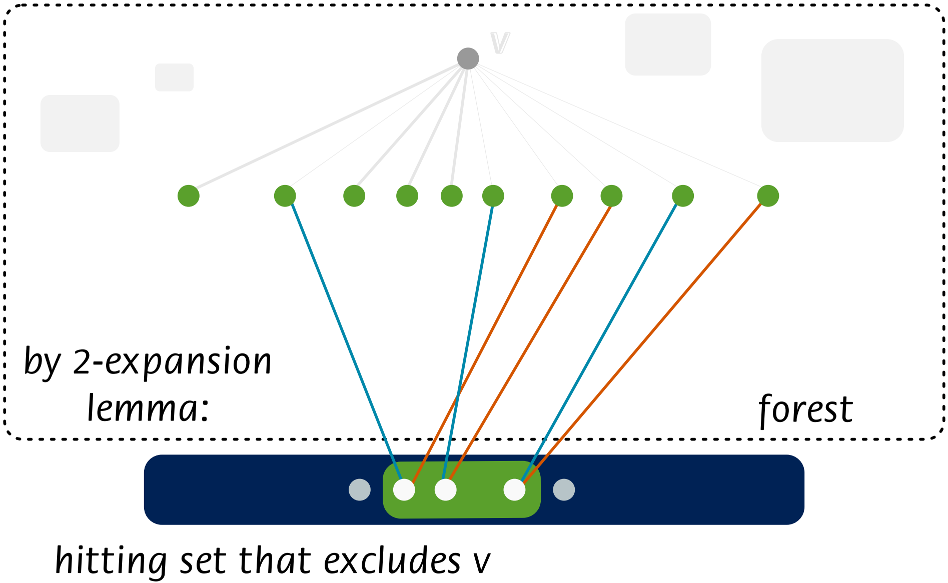
So the reduction rule is: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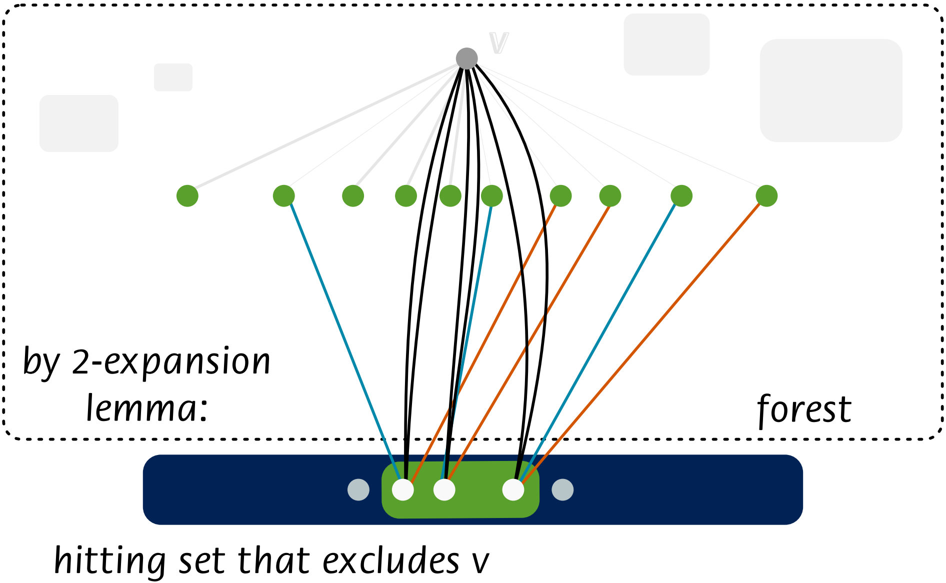
... and add the following edges if already not present.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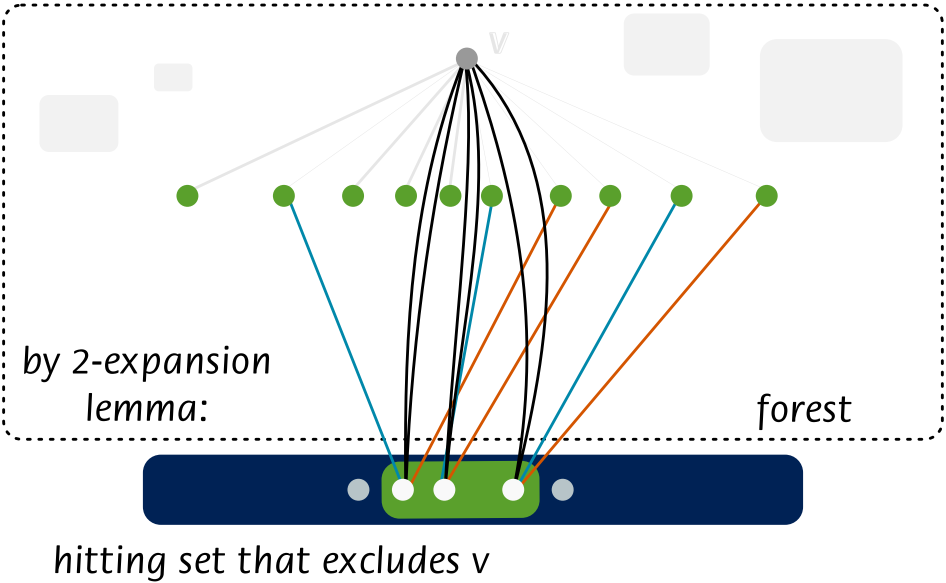
Let us argue correctness!

The Forward Direction

The Forward Direction

$$\text{FVS} \leqslant \mathsf{k} \text{ in } \mathsf{G} \Rightarrow \text{FVS} \leqslant \mathsf{k} \text{ in } \mathsf{H}$$

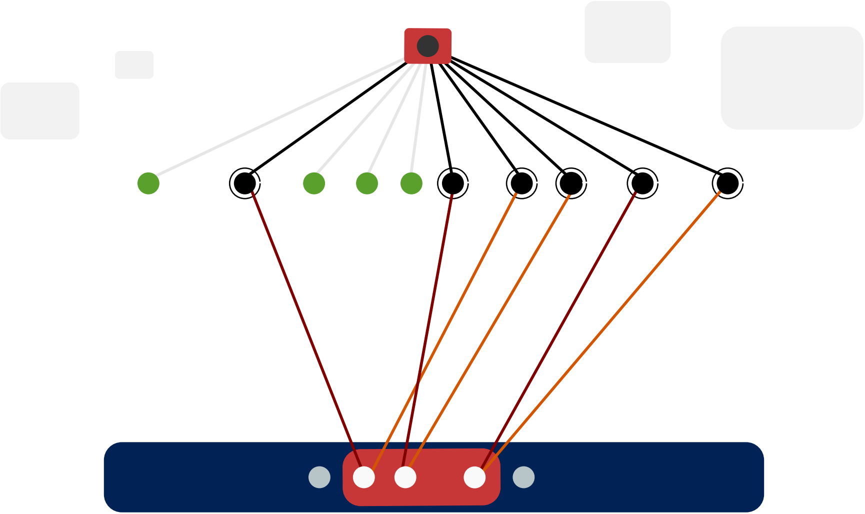


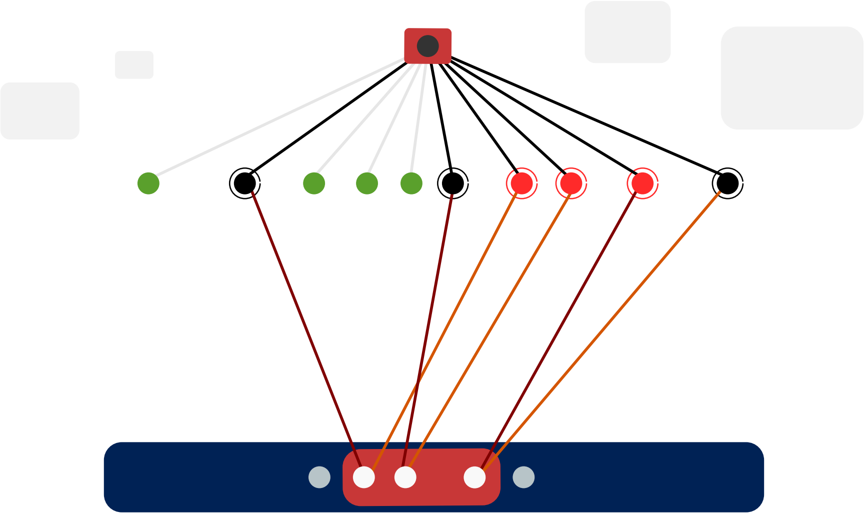
v
by 2-expansion lemma:
forest
hitting set that excludes v

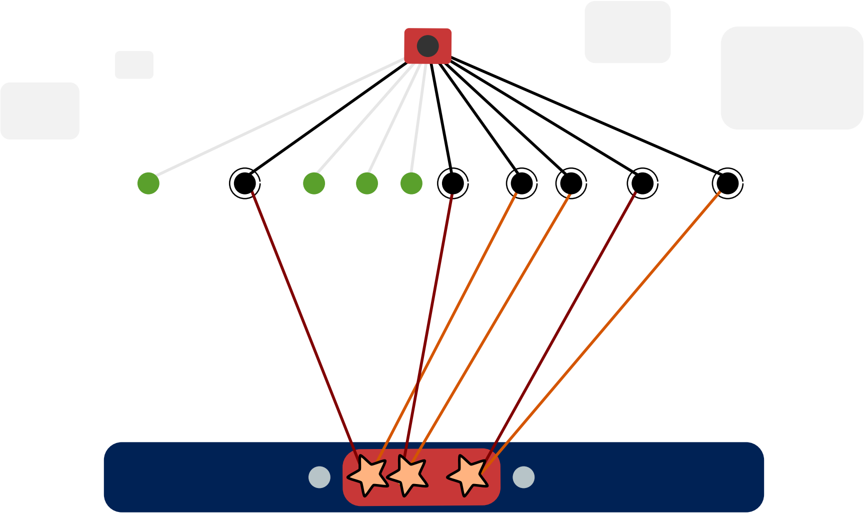
If G has a FVS that either contains v or all of X, we are in good shape.

Consider now a FVS that:

- Does not contain v,
- and omits at least one vertex of X.







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For every vertex v in X that a FVS of G leaves out,

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it must pick a vertex u that kills no more than all of X.

The Reverse Direction

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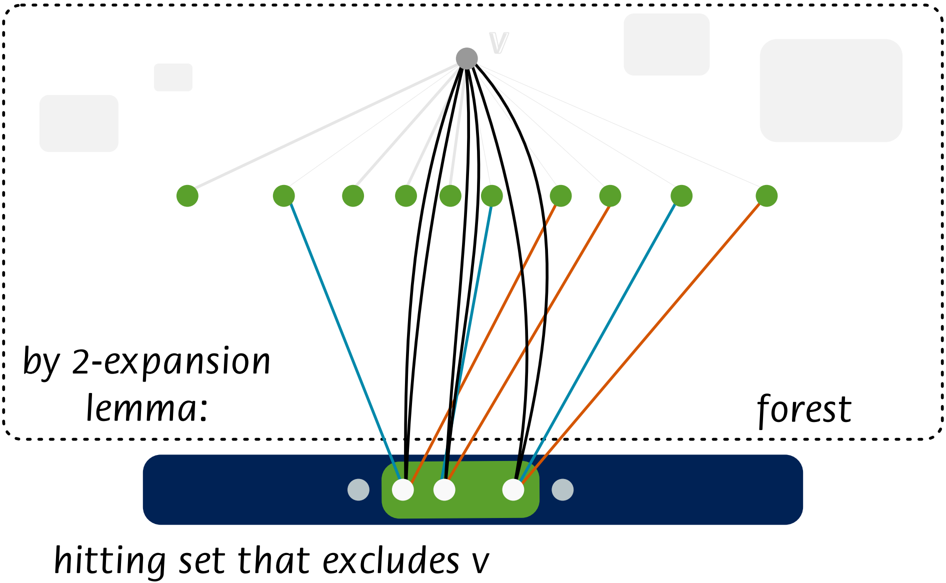
$$\text{FVS} \leqslant k \text{ in } G \Leftarrow \text{FVS} \leqslant k \text{ in } H$$

If FVS in H contains v then the same works for G also as $G \setminus \{v\}$ is isomorphic to $H \setminus \{v\}$. So assume that FVS in H does not contain v.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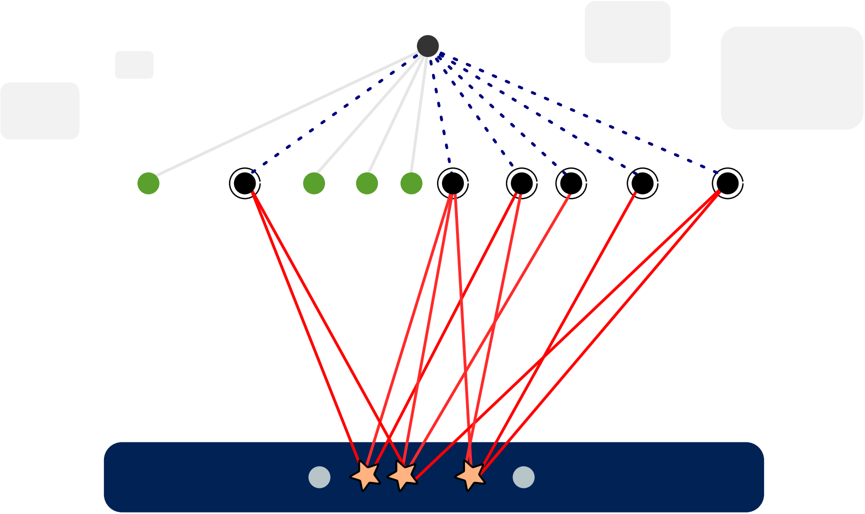
Let W be a FVS of H, the Only Danger for W to be a FVS of G:

Cycles that:

- pass through v,
- non-neighbors of v in H (neighbors in G, however)
- and do not pass through X.



Let W be a FVS of H, the Only Danger for W to be a FVS of G:

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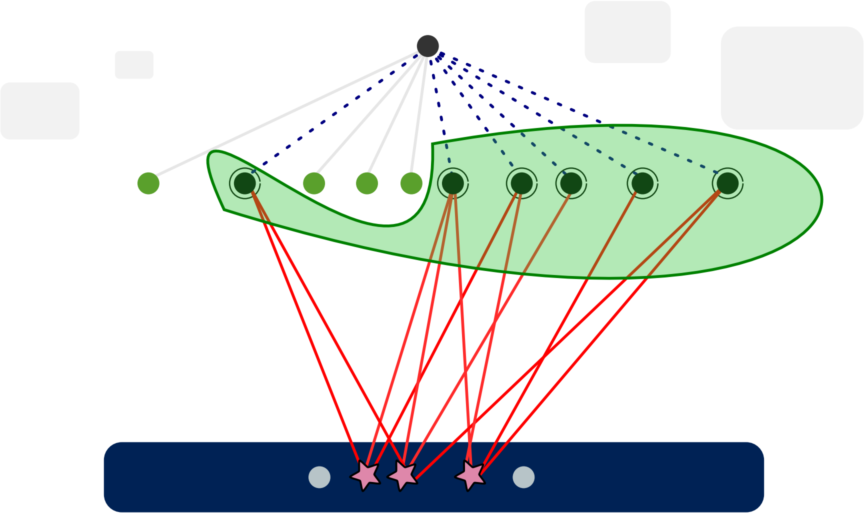
However recall that $\mathsf{N(Y)} \subseteq \mathsf{X}$.



Wrapping Up

- A priori it is not obvious that previous Reduction Rule actually makes some simplification of the graph, since it *substitutes some set of edges with some other set of double edges!*
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- A priori it is not obvious that previous Reduction Rule actually makes some simplification of the graph, since it *substitutes some set of edges with some other set of double edges!*
- We need to formally prove that the reduction rules cannot be applied infinitely, or superpolynomially many times.

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We shall do this using a *potential method*: we define a measure of the instance at hand, which is

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We shall do this using a *potential method*: we define a measure of the instance at hand, which is

- never negative,
- initially it is polynomially bounded by the size of the instance, and
- strictly decreases whenever any of the reductions is applied.

Wrapping Up

For an instance (G, k), let $E_{\neg 2}(G)$ be the set of all the loops and edges of G except for edges of multiplicity 2. Define

$$\varphi(G) = 2|V(G)| + |E_{\neg 2}(G)|.$$

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Potential φ strictly decreases whenever applying some reduction rule (of course, providing that the rule did not terminate the algorithm) – need to show.

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For the last rule we remove a nonempty set of single edges from the graph, thus decreasing $|E_{\neg 2}(G)|$, while the introduced double edges are not counted in this summand.

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Danger: One needs to be careful with other rules though!

Final Result

Theorem

FEEDBACK VERTEX SET *admits a kernel with at most* $O(k^2)$ *vertices and* $O(k^2)$ *edges.*

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We will probably see that this is optimal under some natural complexity theory assumptions.

Thanks.