Approximation Algorithms

Lecture 9:
Minimum-Degree Spanning Tree via Local Search

Part I:
Minimum-Degree Spanning Tree

Philipp Kindermann

Summer Semester 2020

Minimum-Degree Spanning Tree

Given: A connected graph $G = (V, E)$

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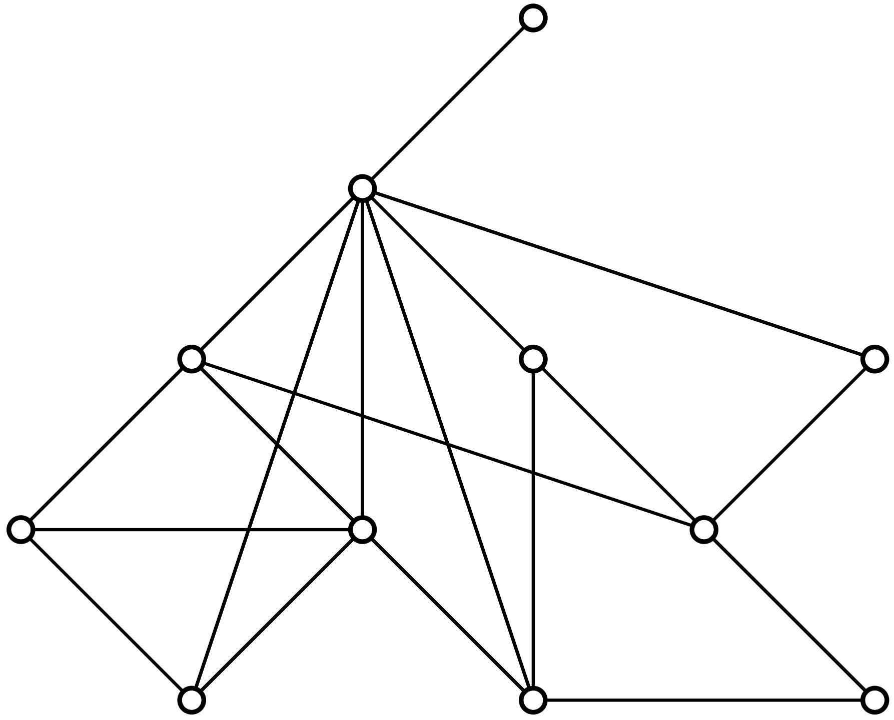
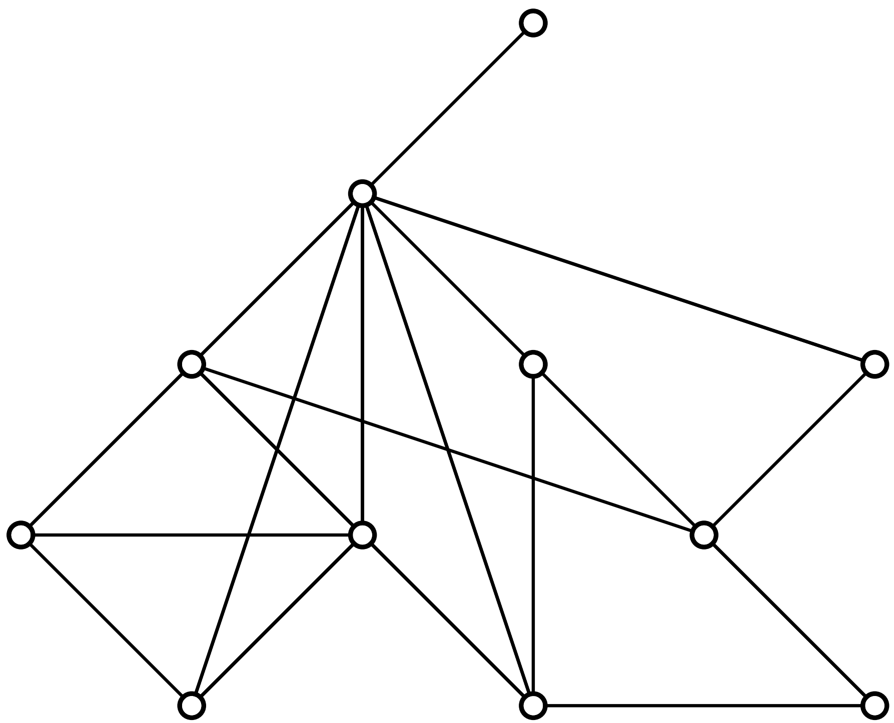


Minimum-Degree Spanning Tree

Given: A connected graph $G = (V, E)$

Task: Find a spanning tree T which has the minimum maximum degree $\Delta(T)$ among all spanning trees of G.



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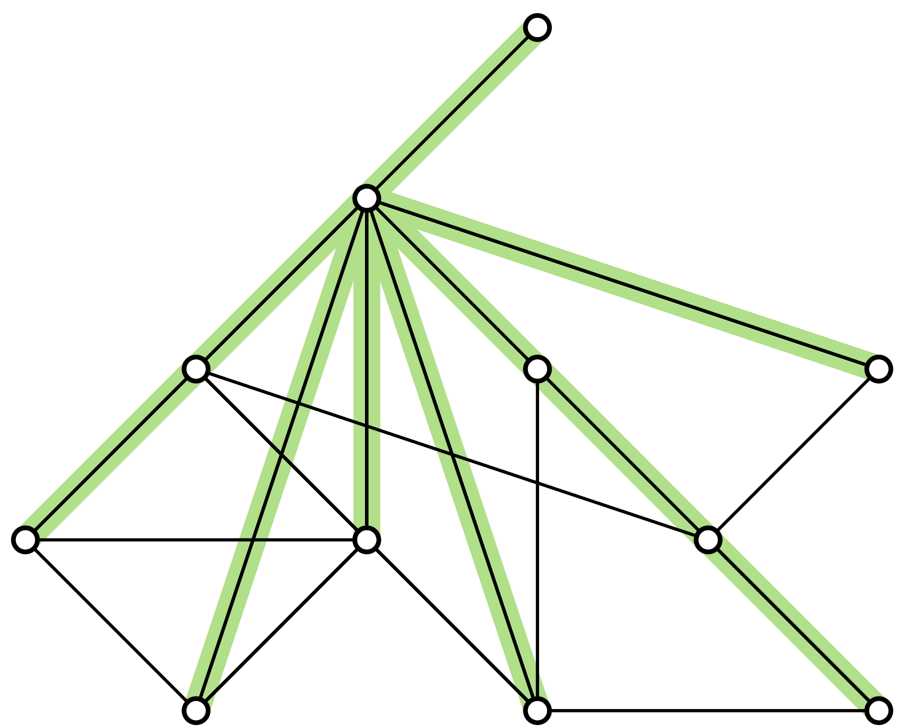

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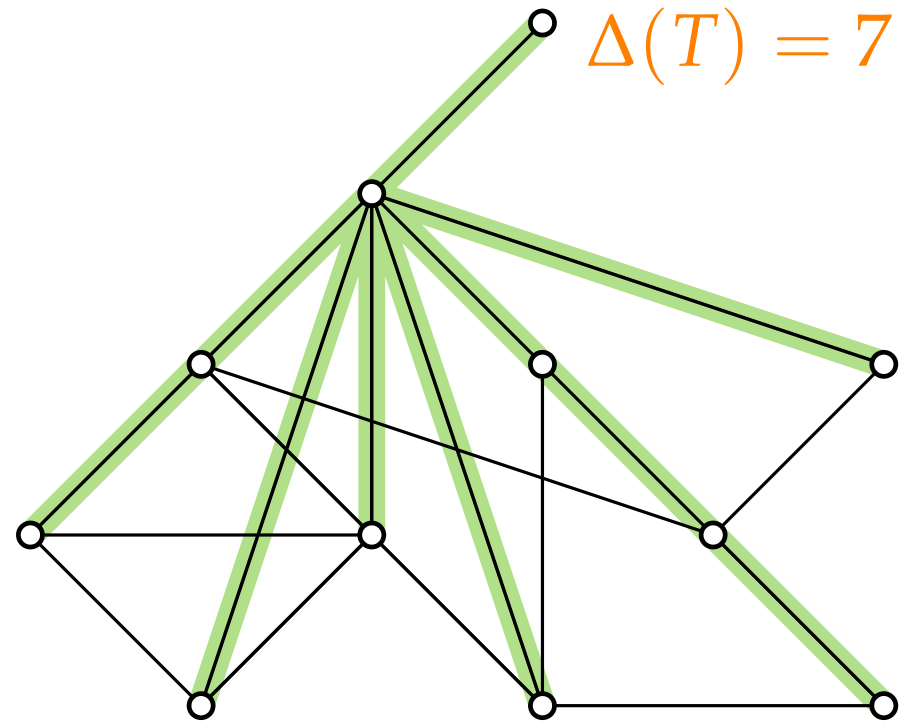

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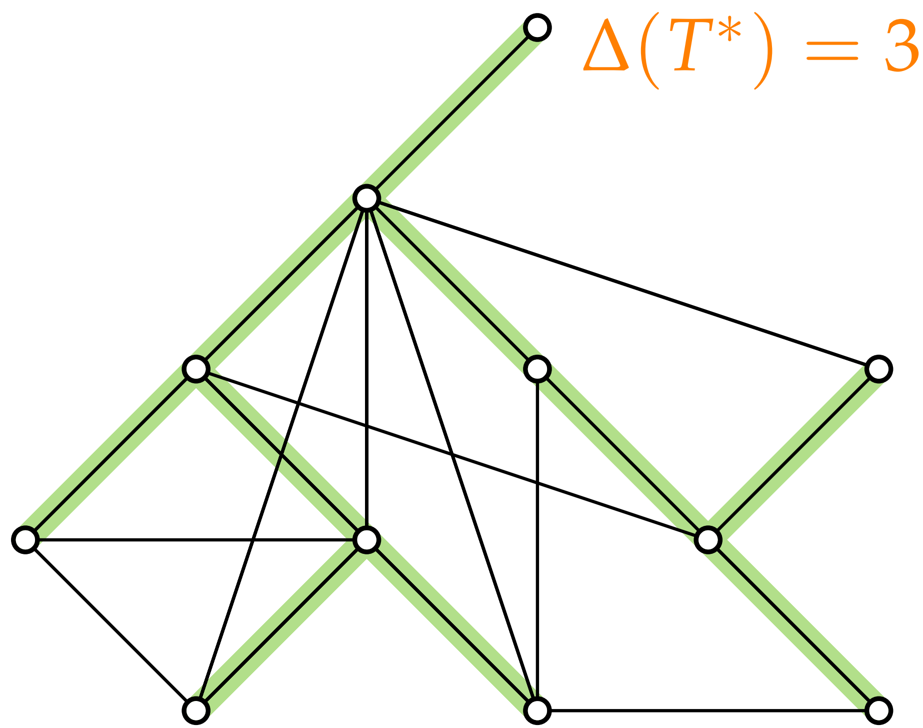

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Given: A connected graph $G = (V, E)$

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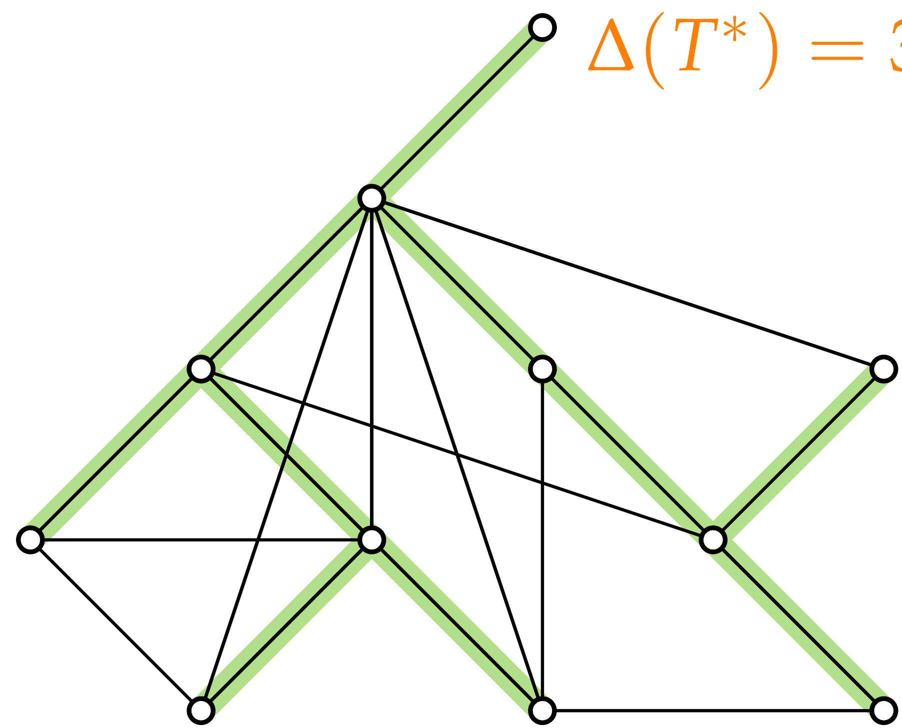
NP-hard

$\Delta(T^*) = 3$



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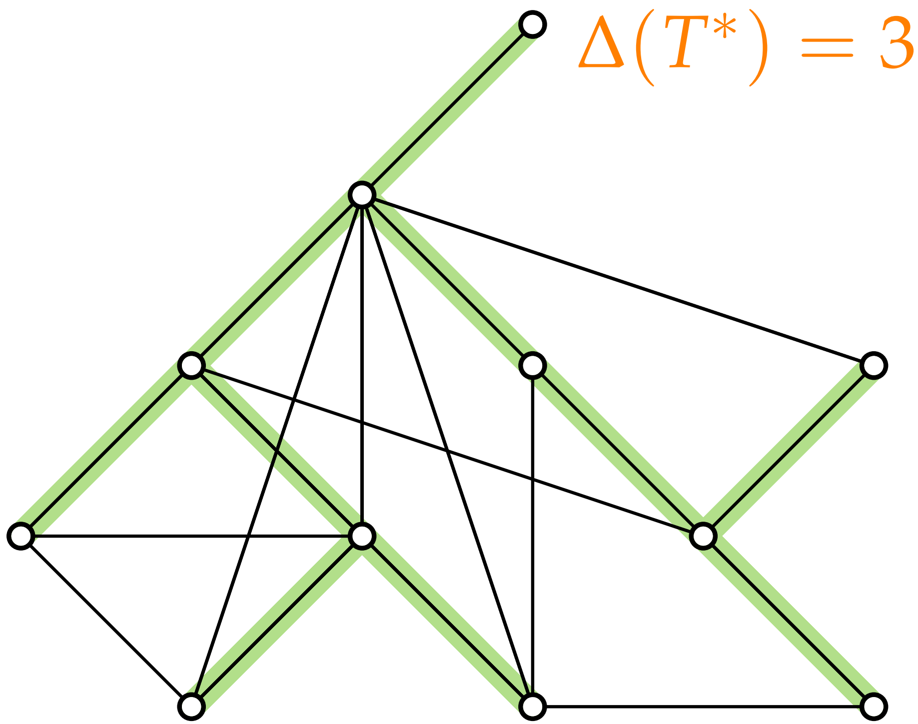
NP-hard 

Why?



Minimum-Degree Spanning Tree

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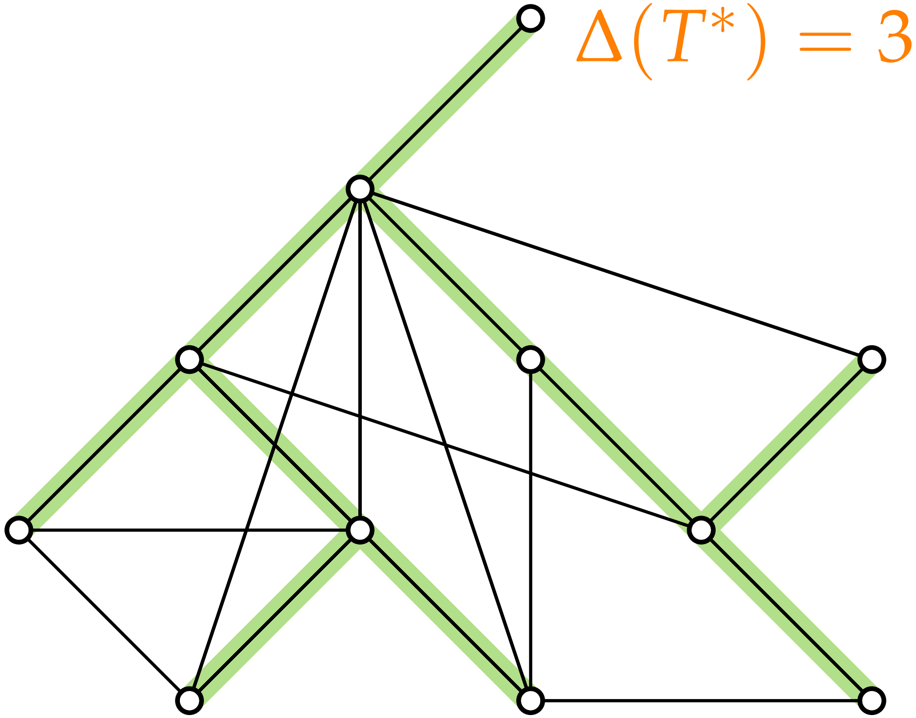
NP-hard 

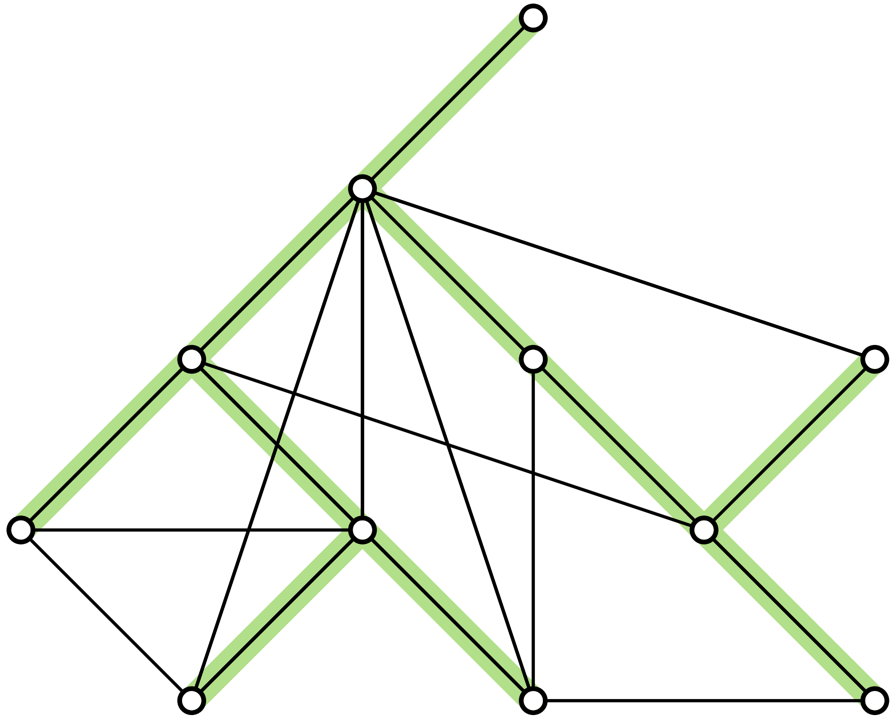
Why?

Special case of Hamiltonian Path!



Warmup

Obs. A spanning tree T has...



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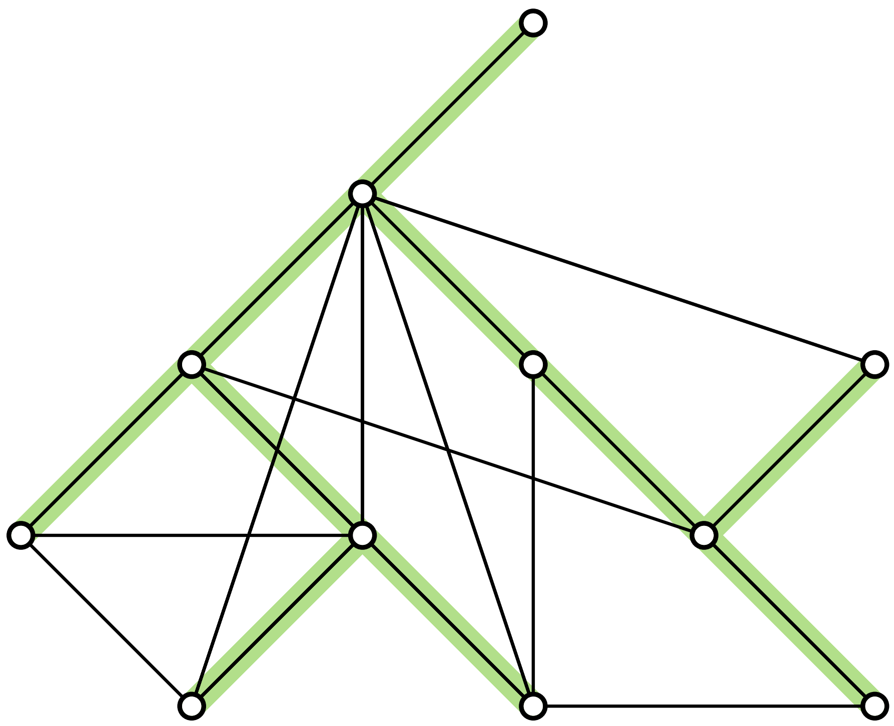
Obs. A spanning tree T has...

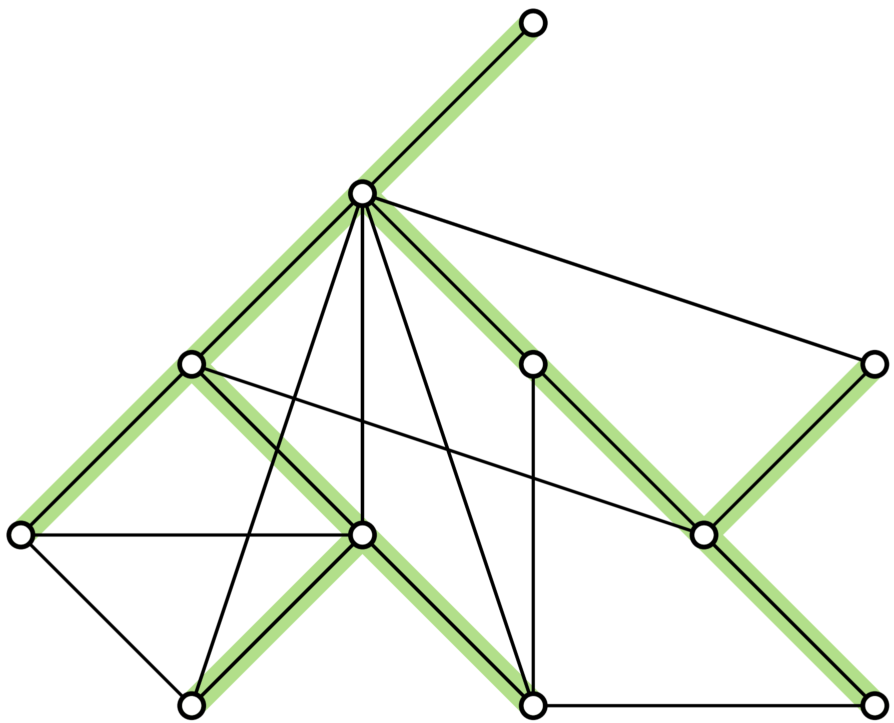
- n vertices and ? edges,



Warmup

Obs. A spanning tree T has...

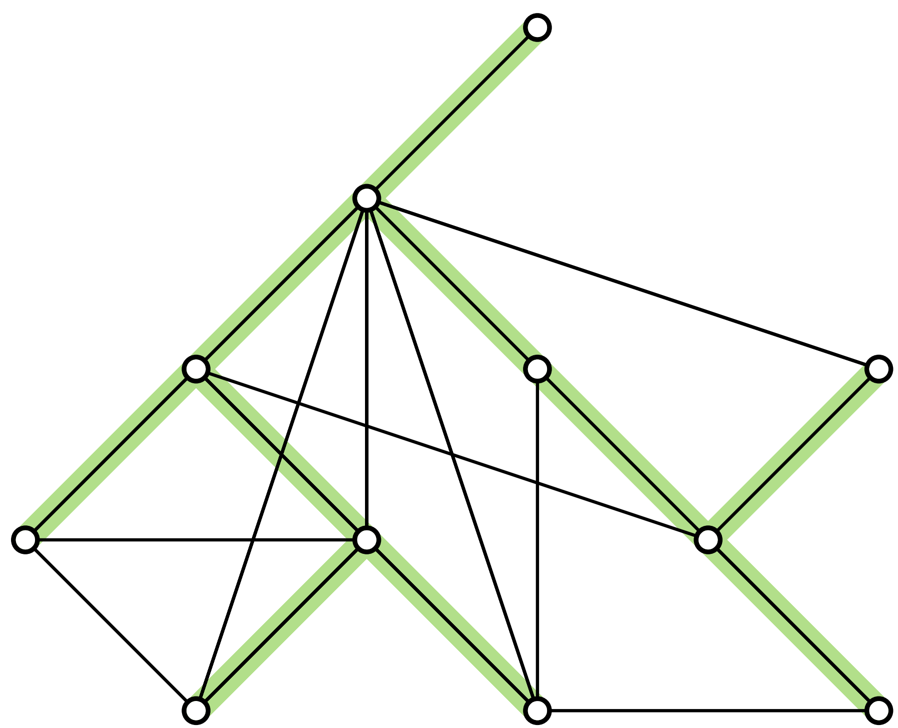
- n vertices and ? edges,
- sum of degrees $\sum_{v \in V} \deg_T(v) =$?



Warmup

Obs. A spanning tree T has...

- n vertices and ? edges,
- sum of degrees $\sum_{v \in V} \deg_T(v) =$?
- average degree ?



Warmup

Obs. A spanning tree T has...

- n vertices and $n-1$ edges,
- sum of degrees $\sum_{v \in V} \deg_T(v) =$?
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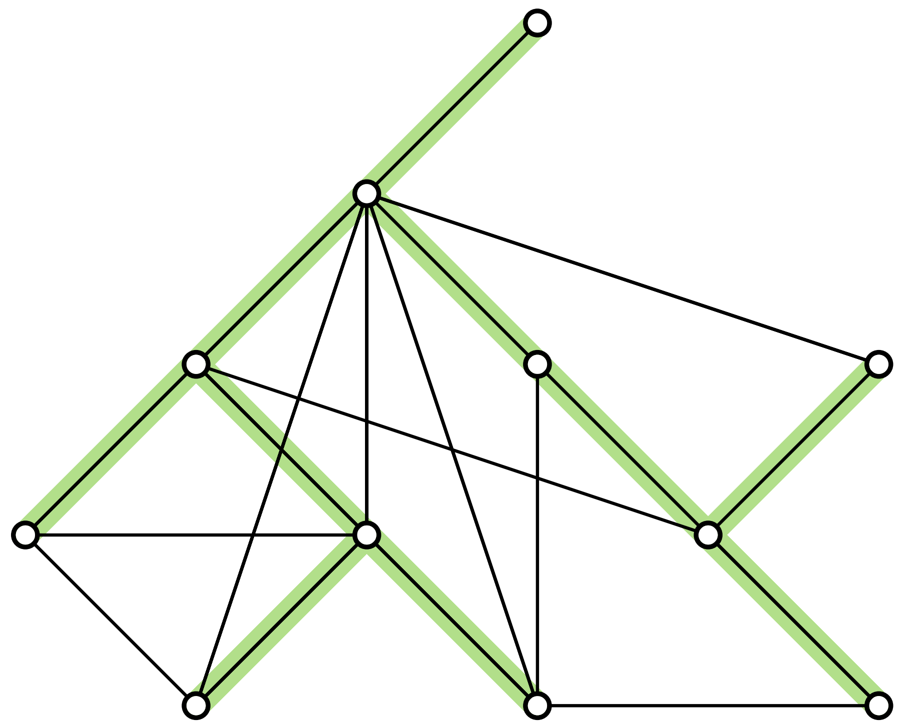
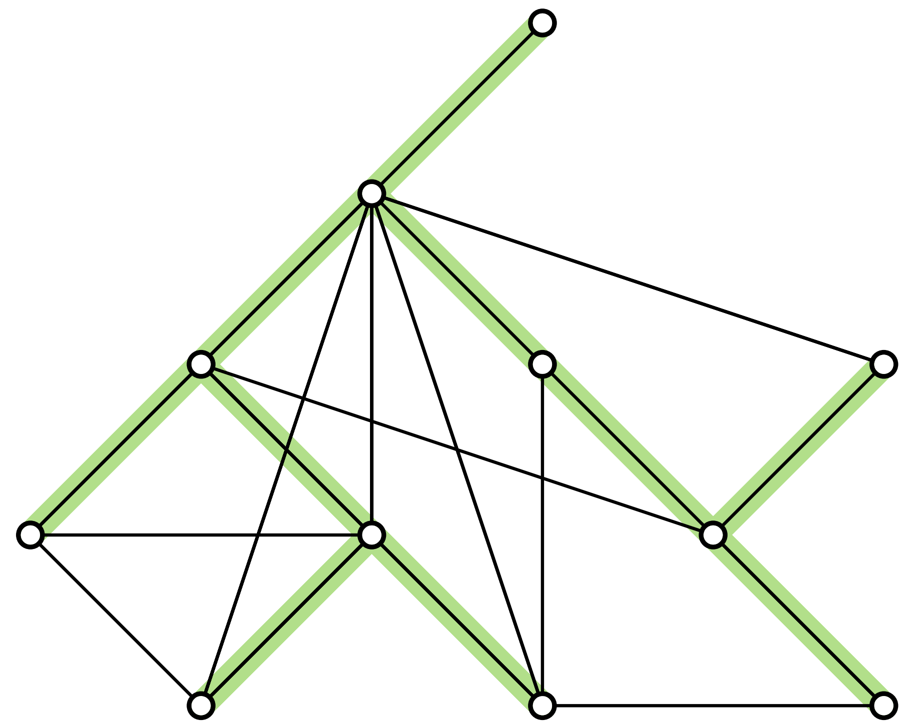


Warmup

Obs. A spanning tree T has...

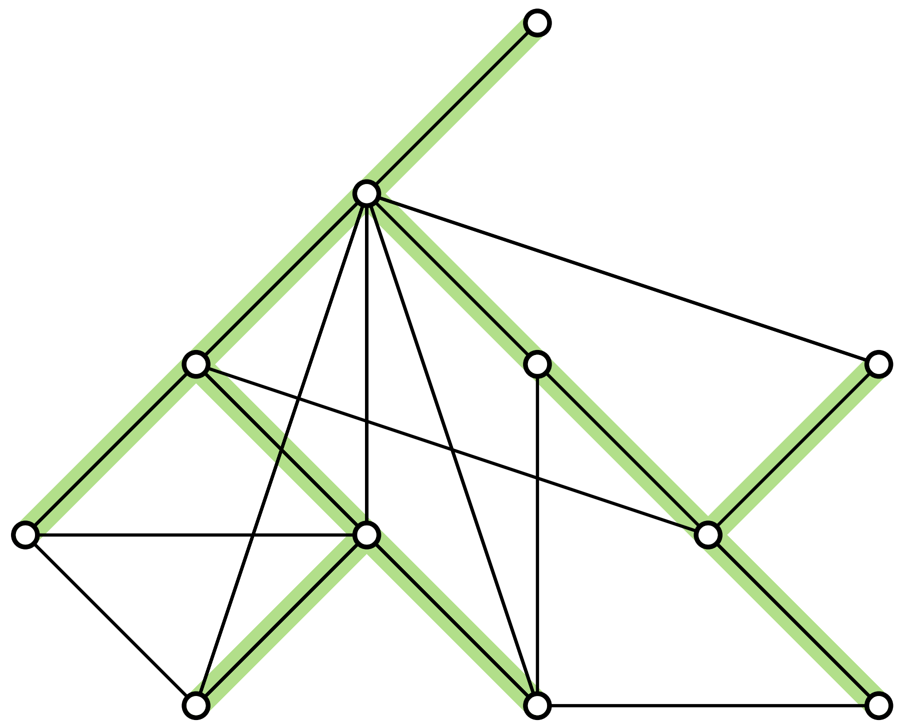
- n vertices and $n-1$ edges,
- sum of degrees $\sum_{v \in V} \deg_T(v) = 2n-2$,
- average degree ?



Warmup

Obs. A spanning tree T has...

- n vertices and $n-1$ edges,
- sum of degrees $\sum_{v \in V} \deg_T(v) = 2n - 2$,
- average degree < 2.



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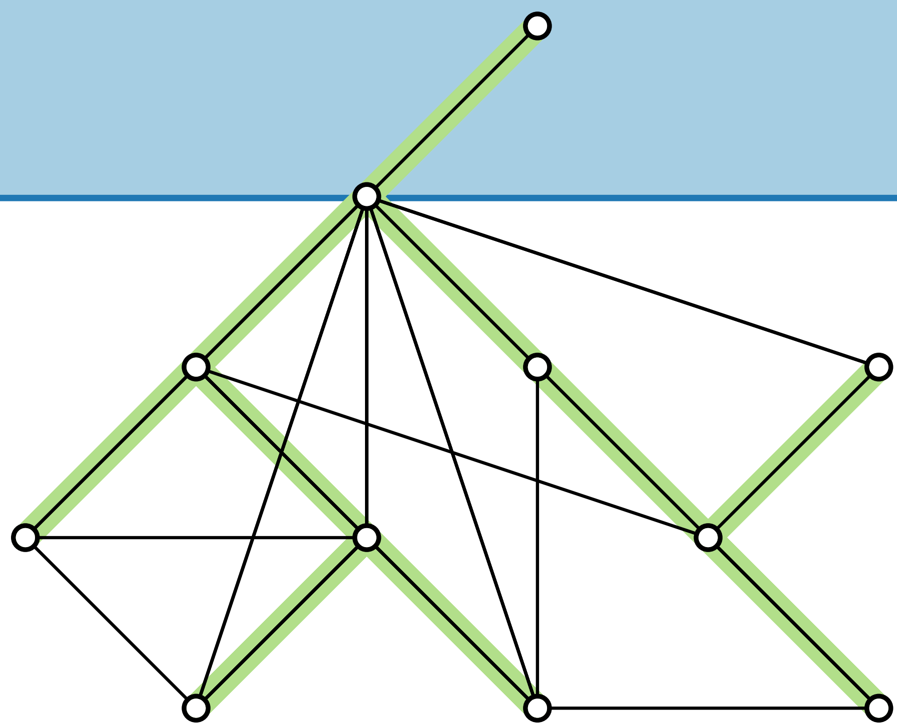
- average degree < 2.

Obs. Let $V' \subseteq V(G)$.
Then $\Delta(G) \geq$?



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Obs. A spanning tree T has...

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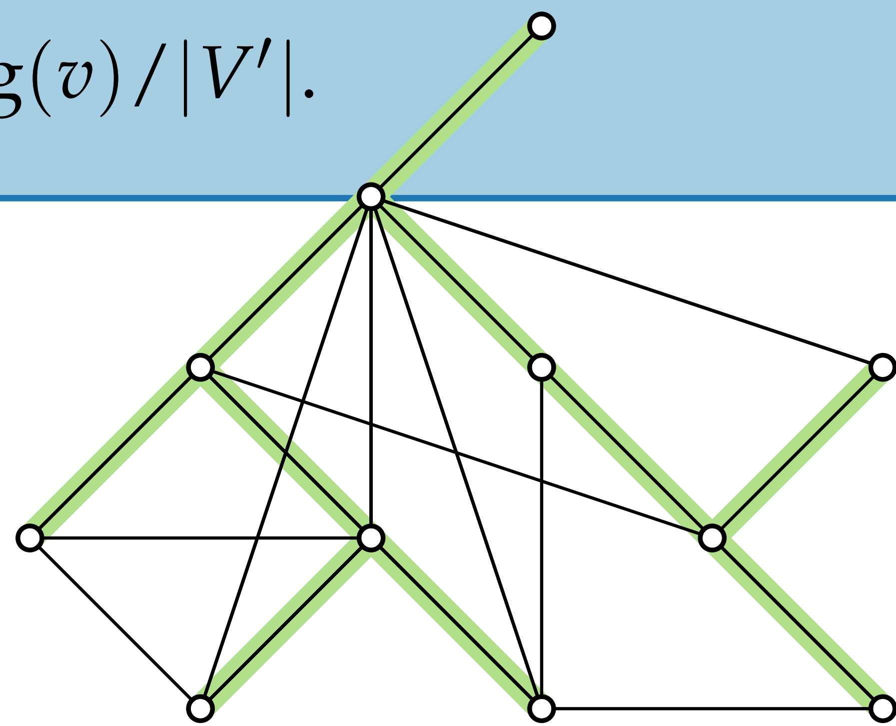
Obs. Let $V' \subseteq V(G)$.
Then $\Delta(G) \geq \sum_{v \in V'} \deg(v) / |V'|$.



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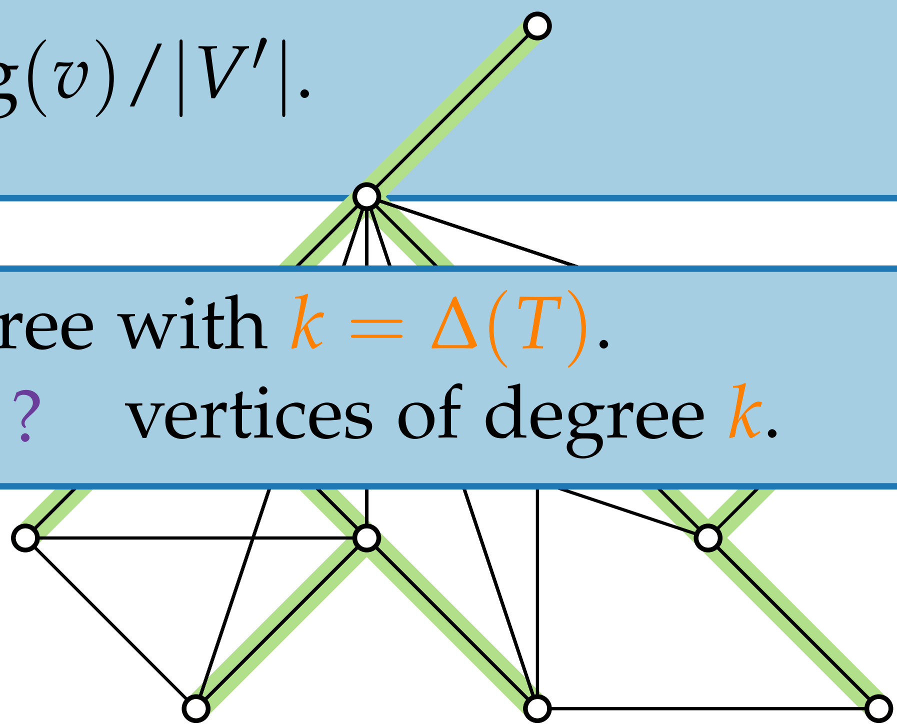
Obs. Let T be a spanning tree with $k = \Delta(T)$.
Then T has at most ? vertices of degree k.



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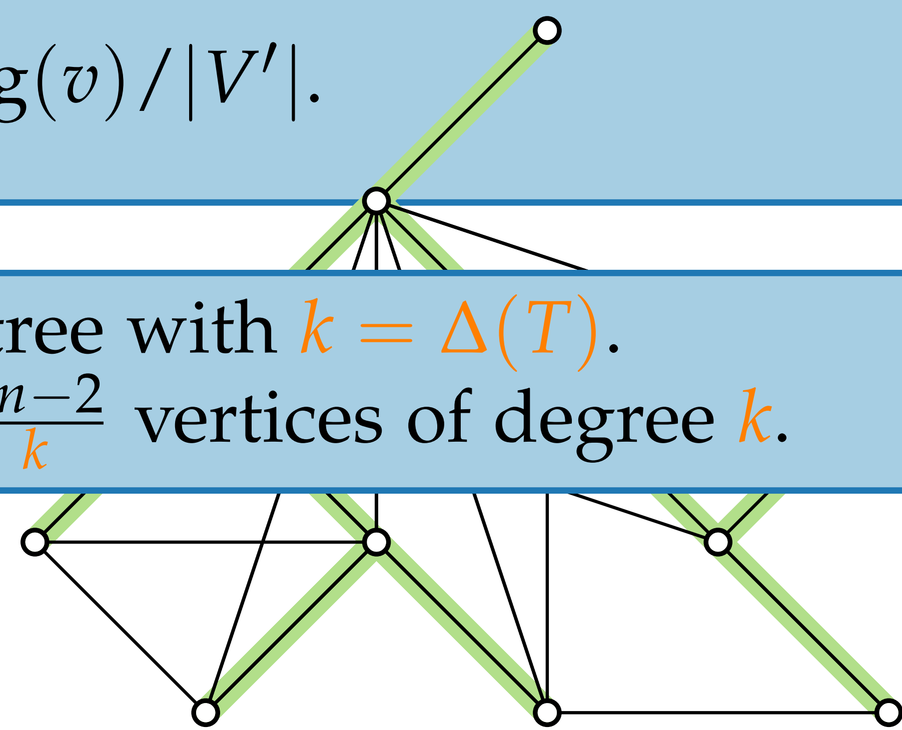
Then $\Delta(G) \geq \sum_{v \in V'} \deg(v) / |V'|$.

Obs. Let T be a spanning tree with $k = \Delta(T)$.
Then T has at most $\frac{2n-2}{k}$ vertices of degree k.



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Part II:
Edge Flips and Local Search

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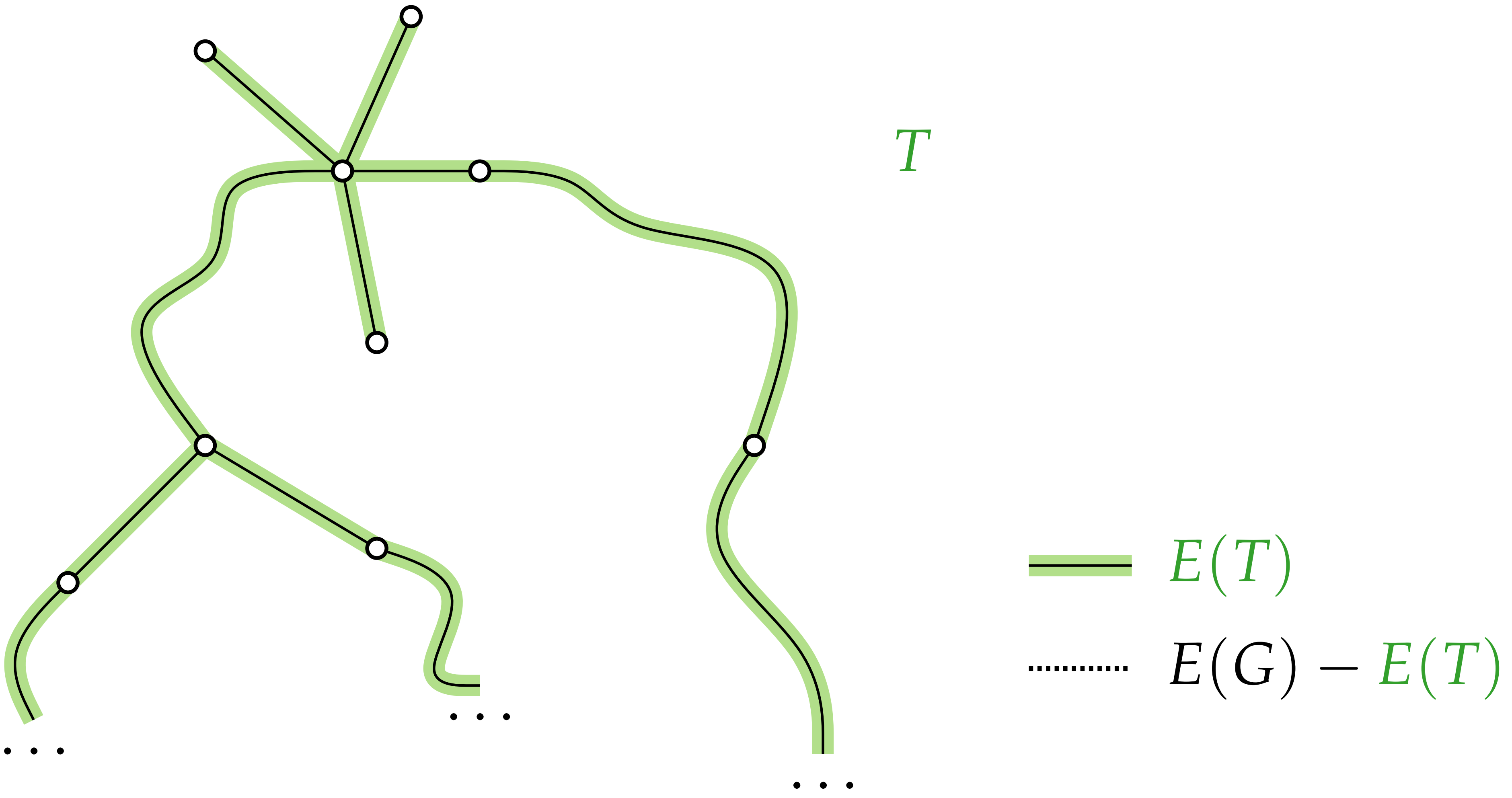
Edge Flips



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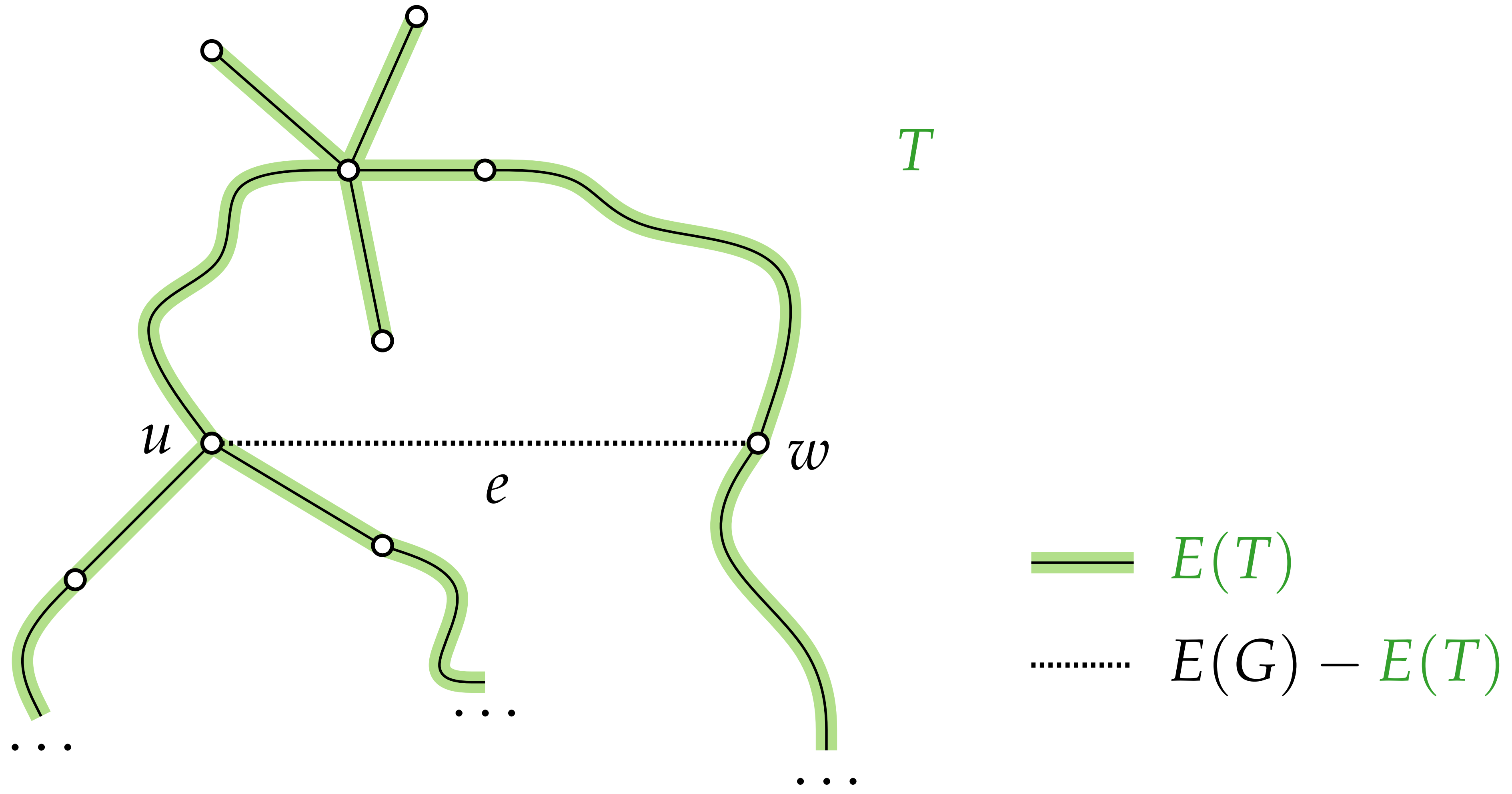

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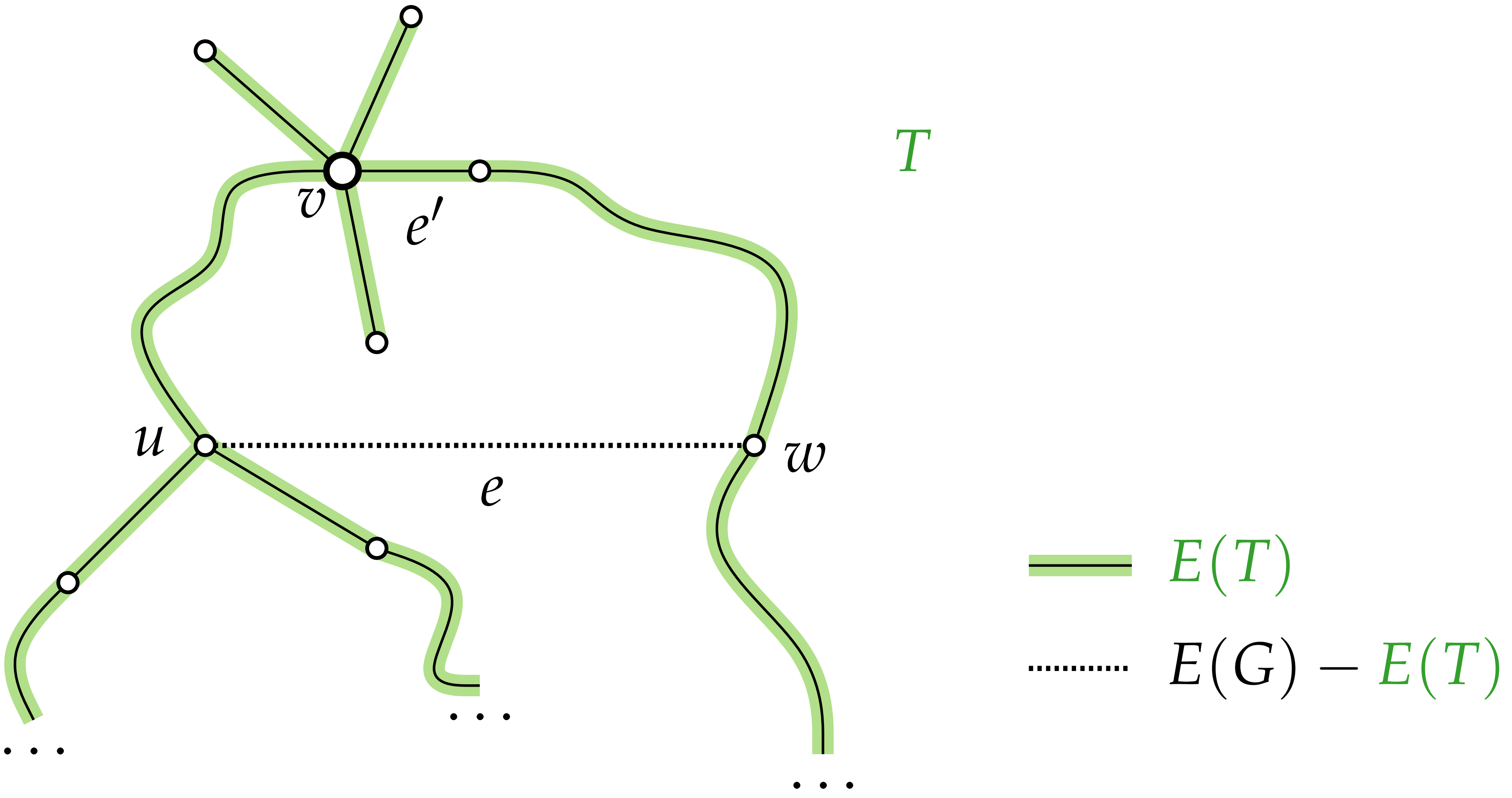

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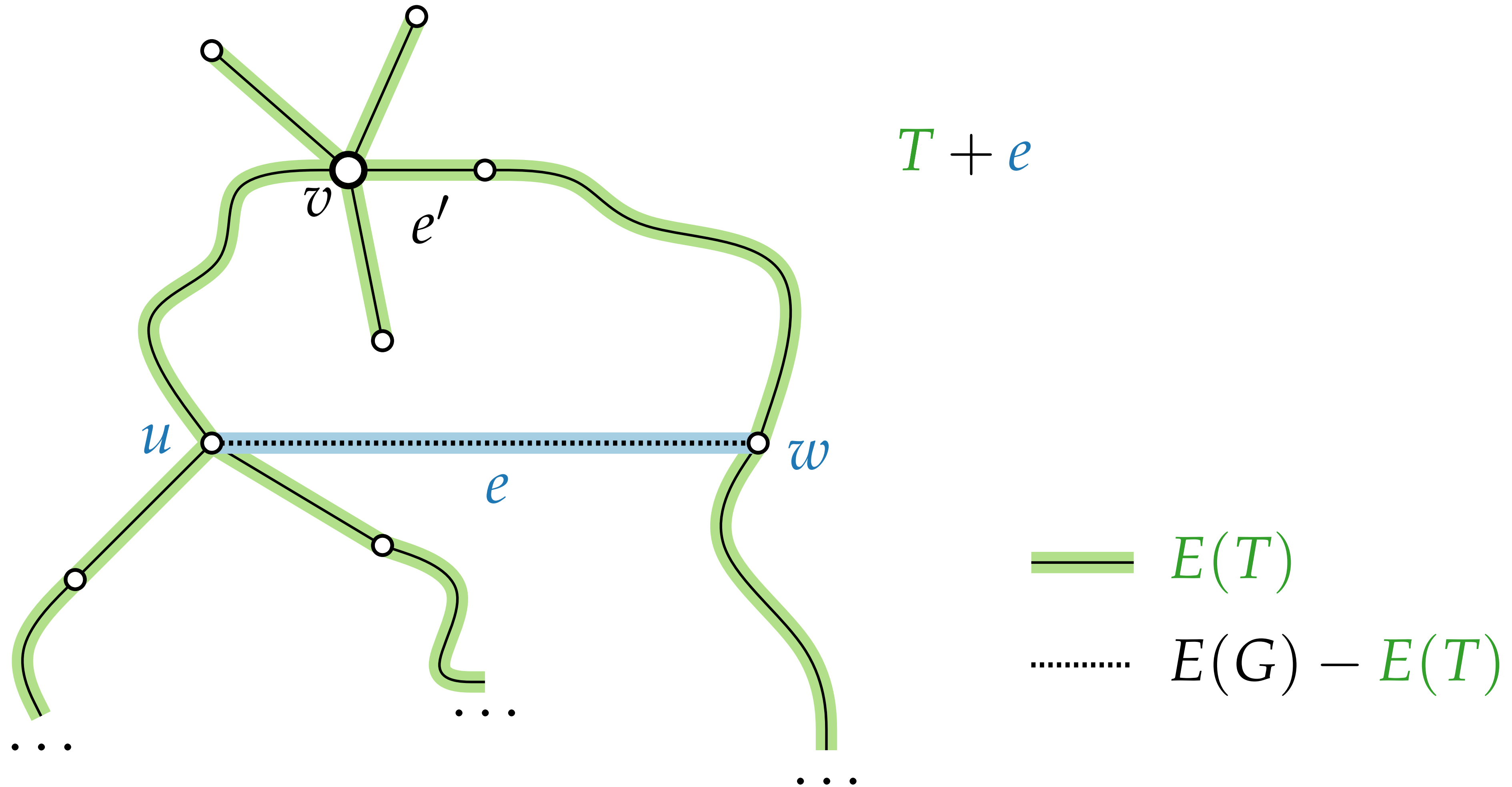

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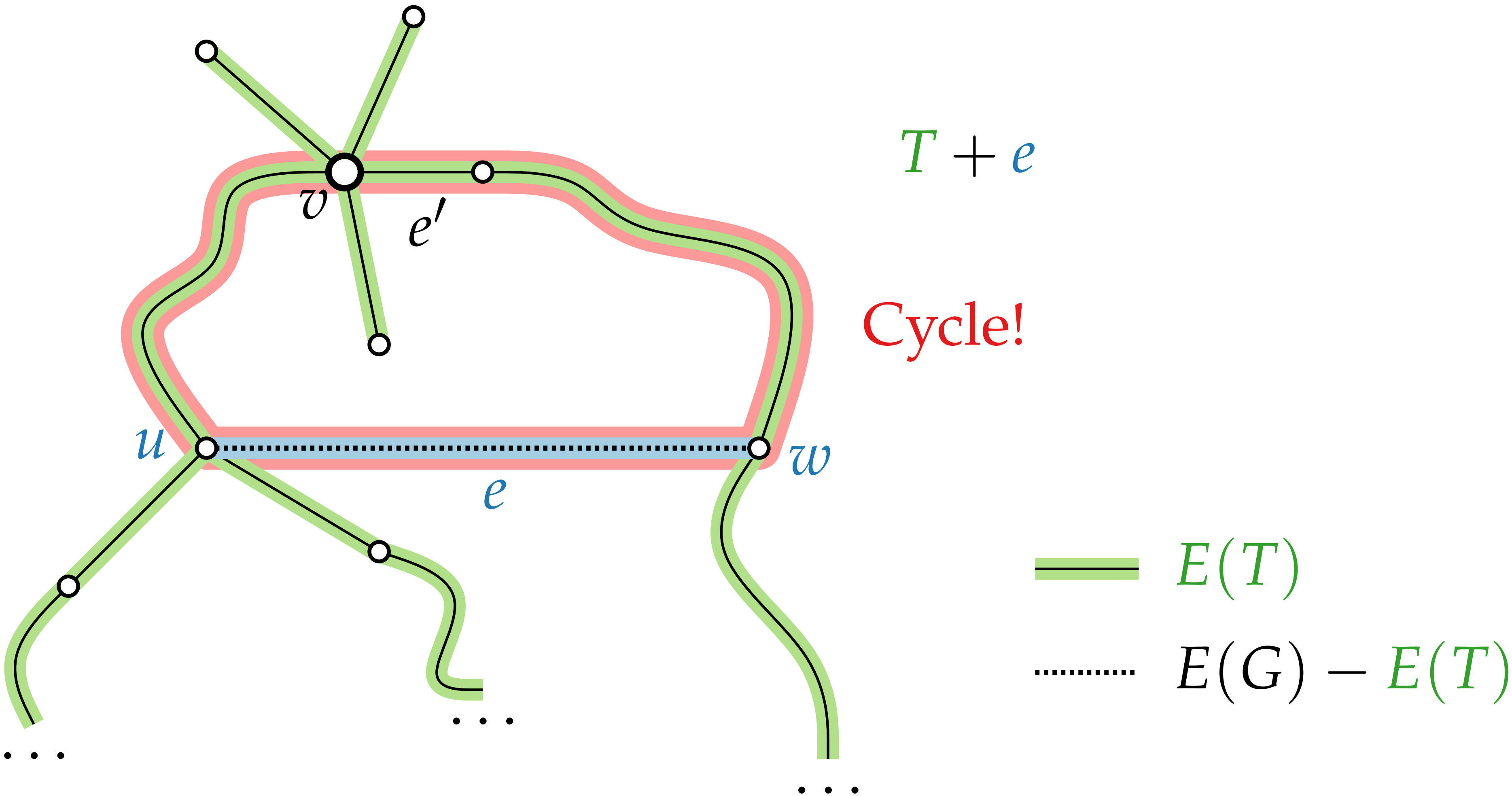

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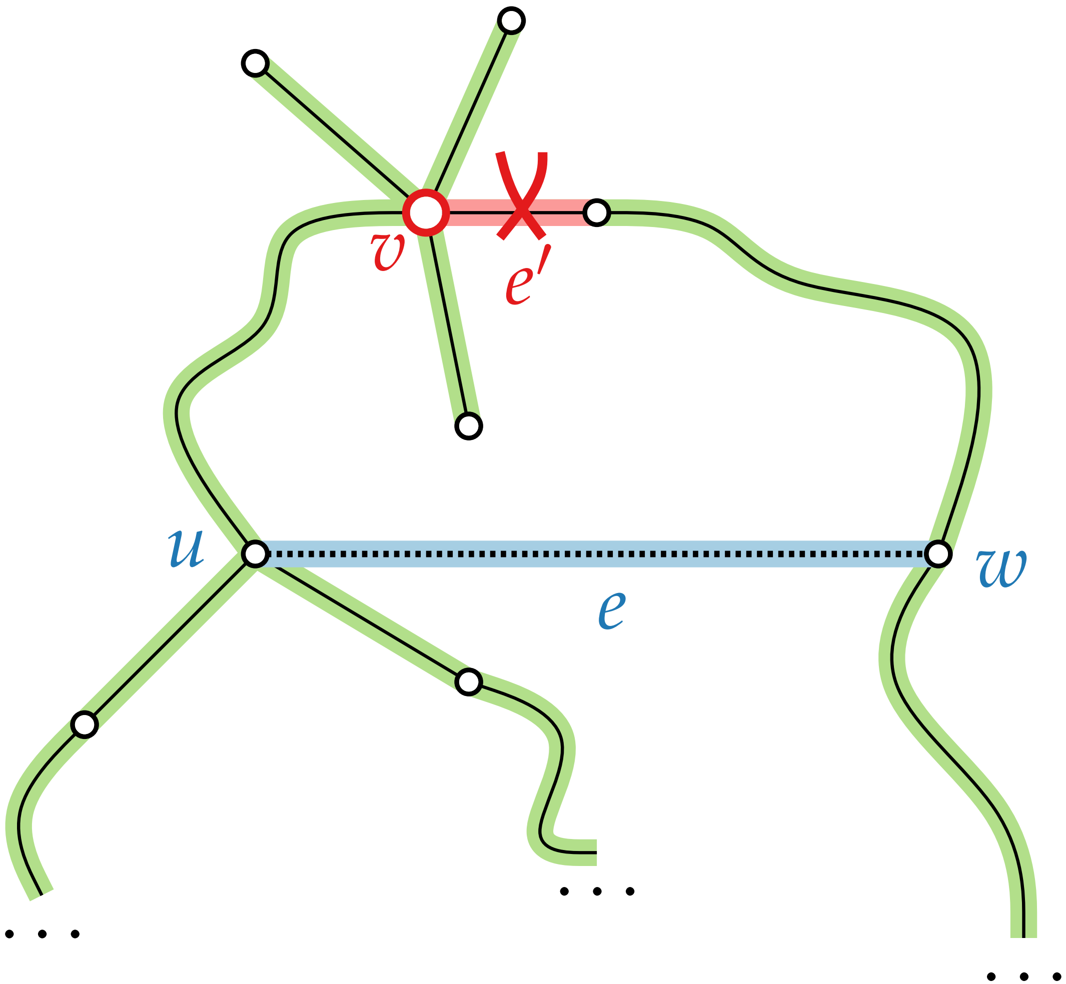
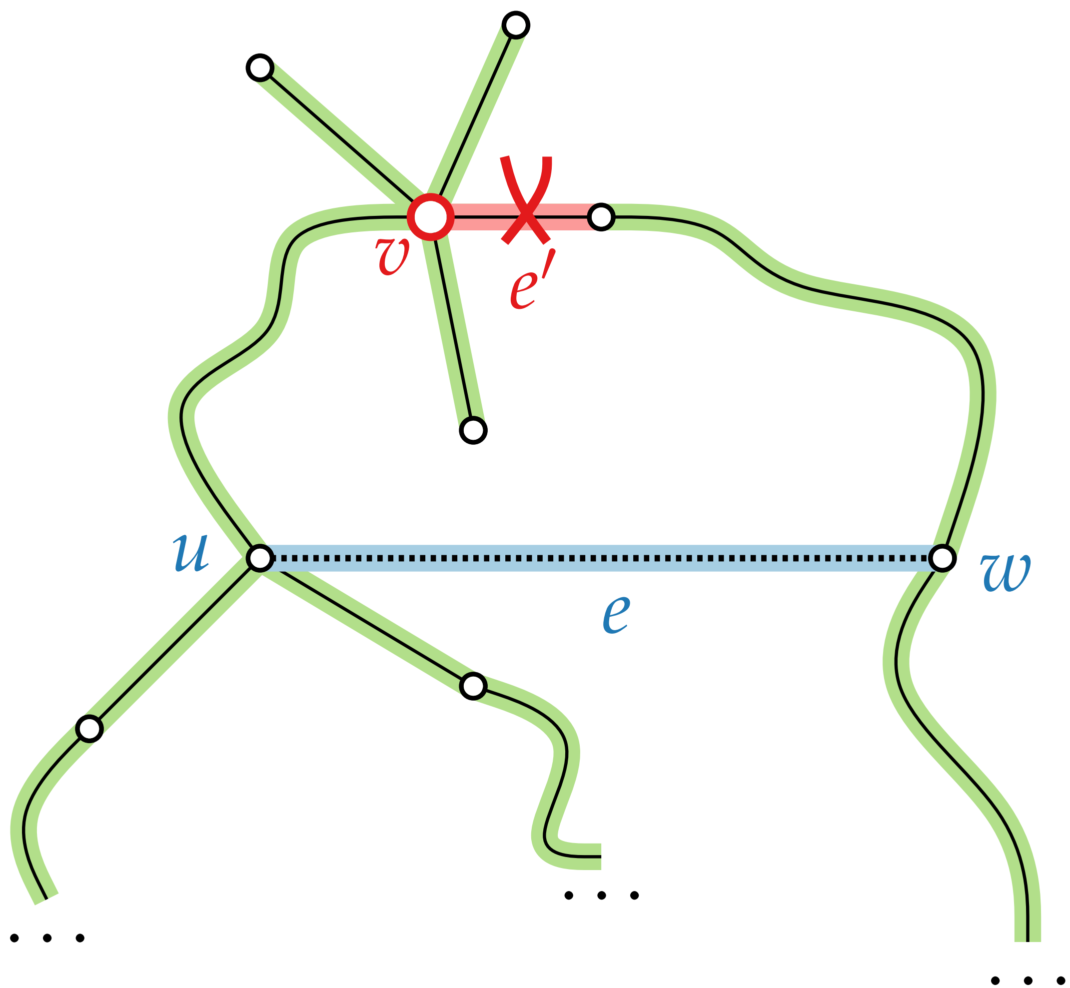


$T + e - e'$
is a new spanning tree

$E(T)$
$E(G) - E(T)$

Edge Flips

Def. An **improving flip** in T for a vertex v and an edge $uw \in E(G) \setminus E(T)$ is a flip with
$\deg_T(v) >$



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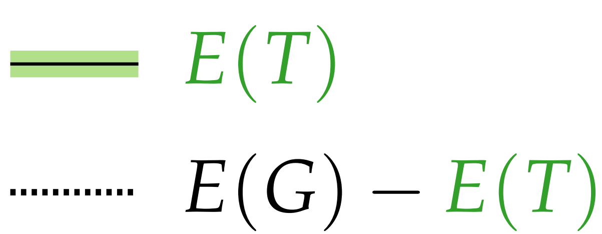
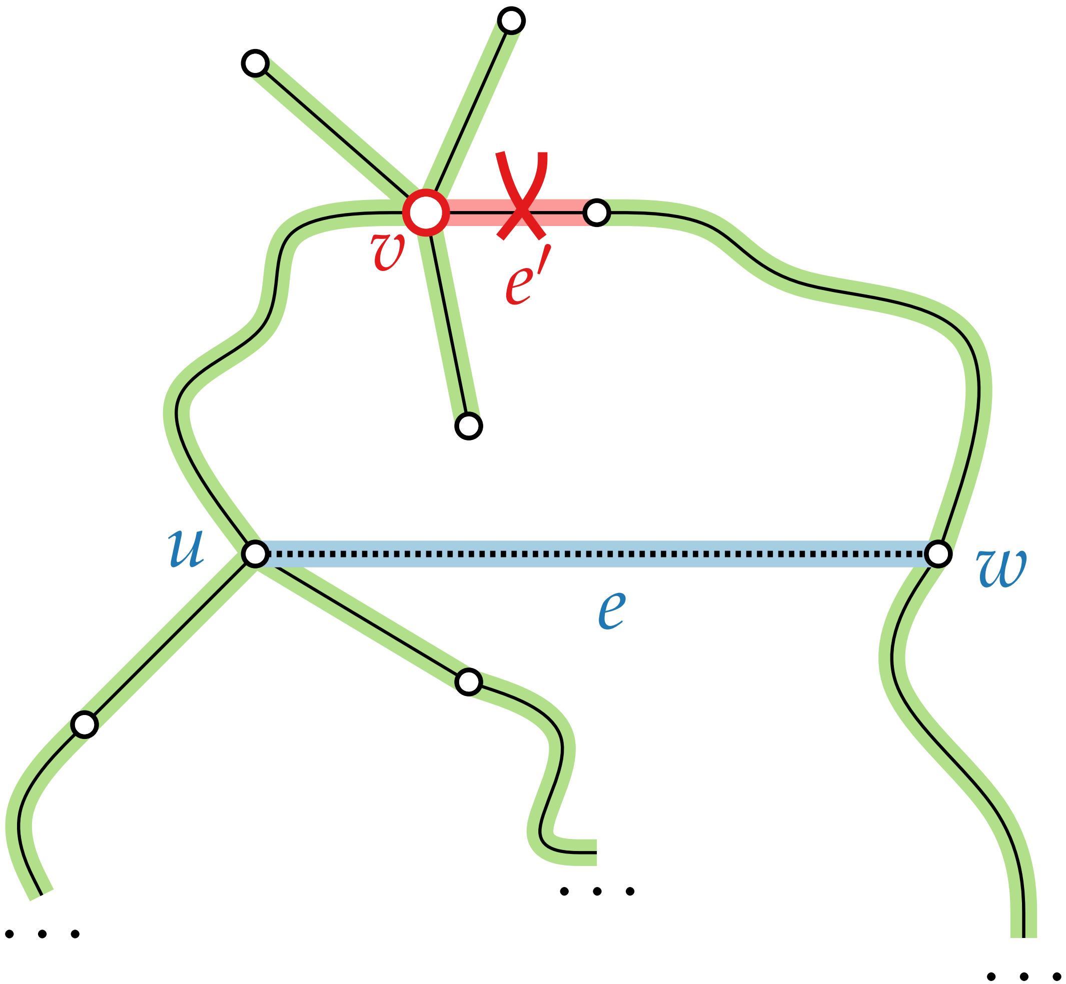


Edge Flips

Def. An **improving flip** in T for a vertex v and an edge $uw \in E(G) \setminus E(T)$ is a flip with $\deg_T(v) > \max\{\deg_T(u), \deg_T(w)\} + 1$.



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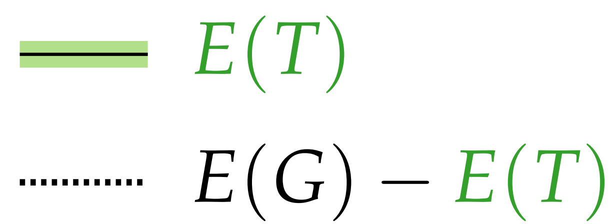

Local Search

MinDegSpanningTreeLocalSearch(G)

$T \leftarrow$ any spanning tree of G

while $\exists$ improving flip in T for a vertex v with $\deg_T(v) \geq \Delta(T) - \ell$ **do**

  do the improving flip

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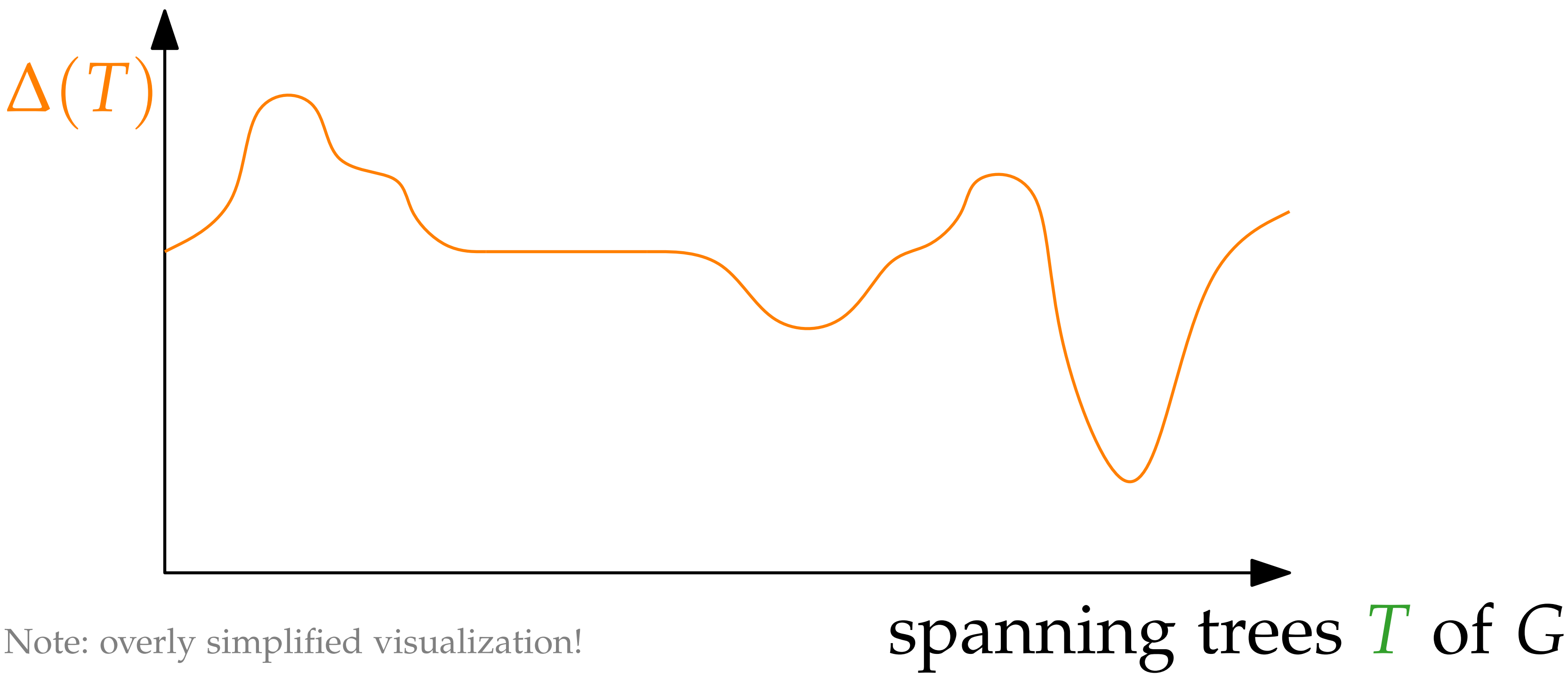

Note: overly simplified visualization!

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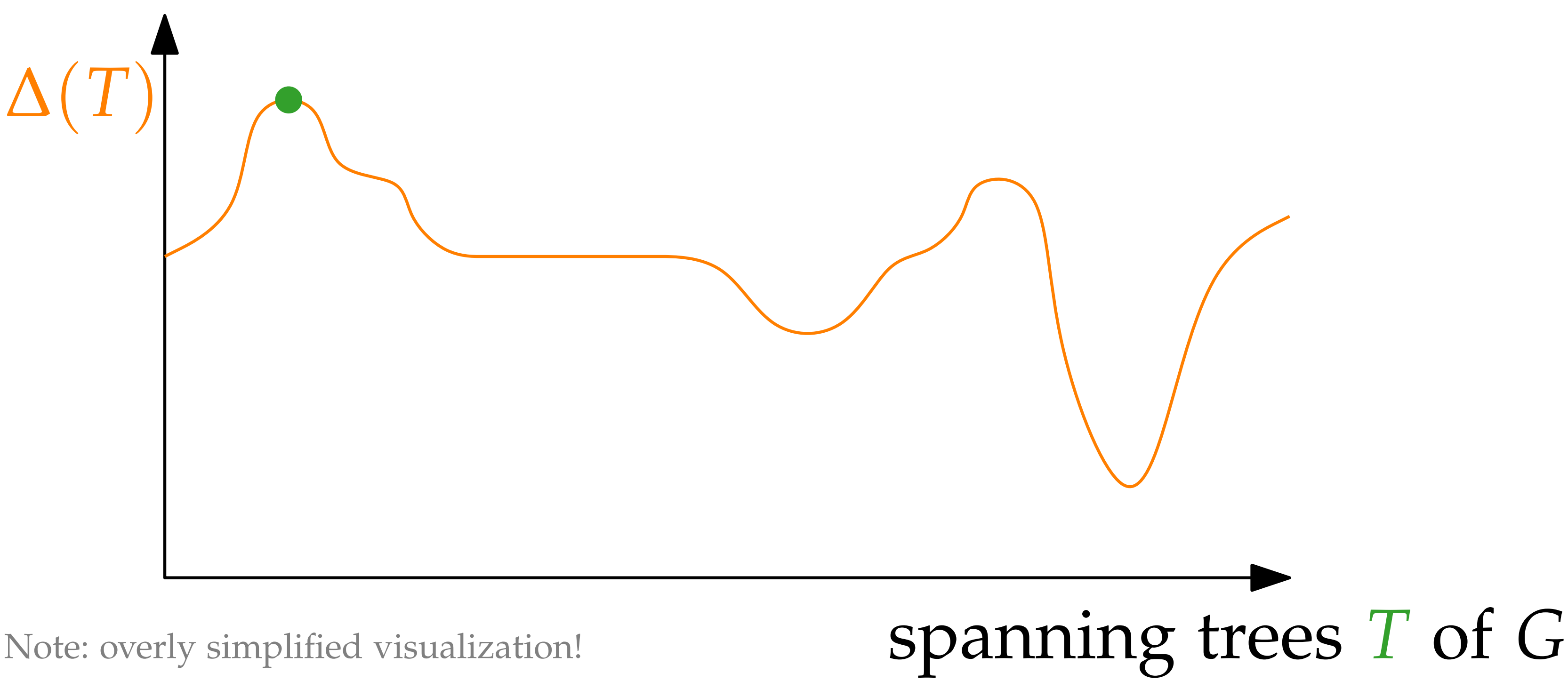

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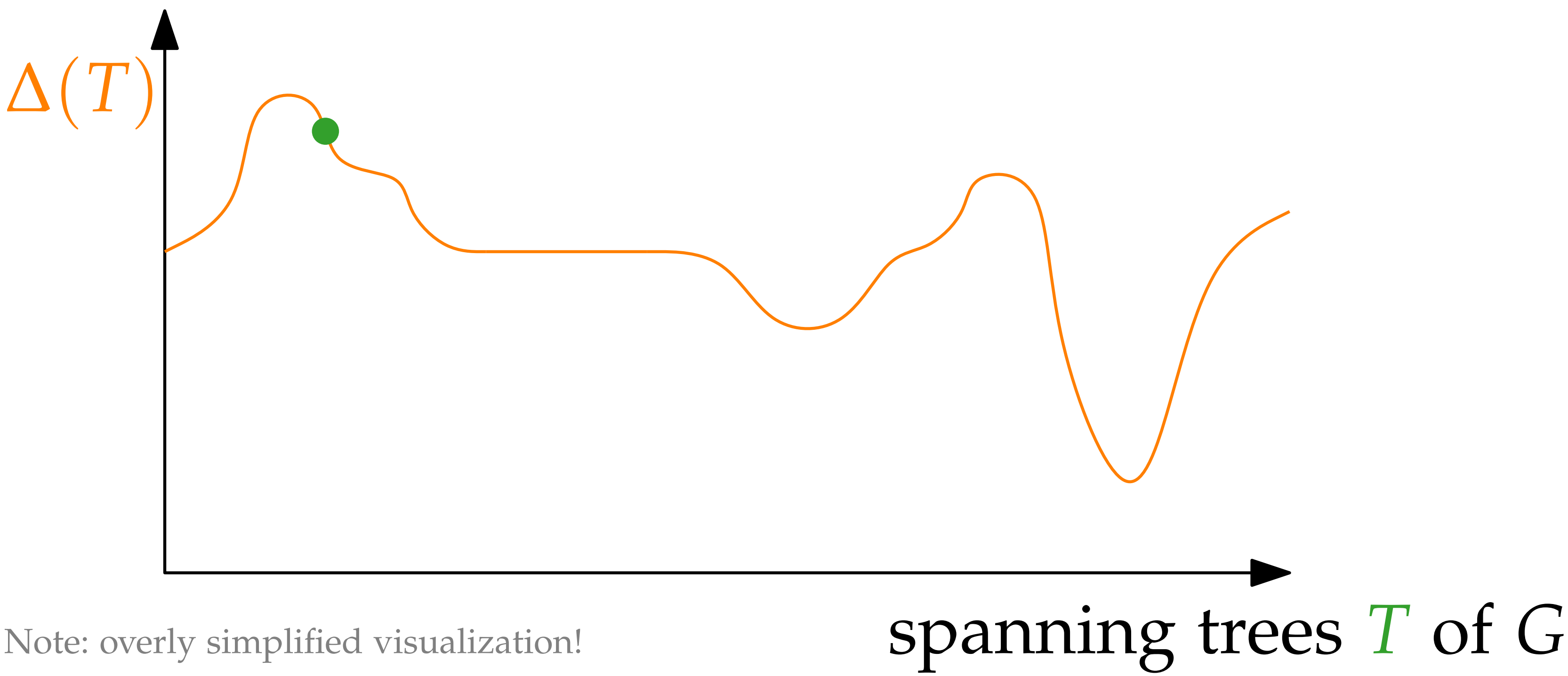

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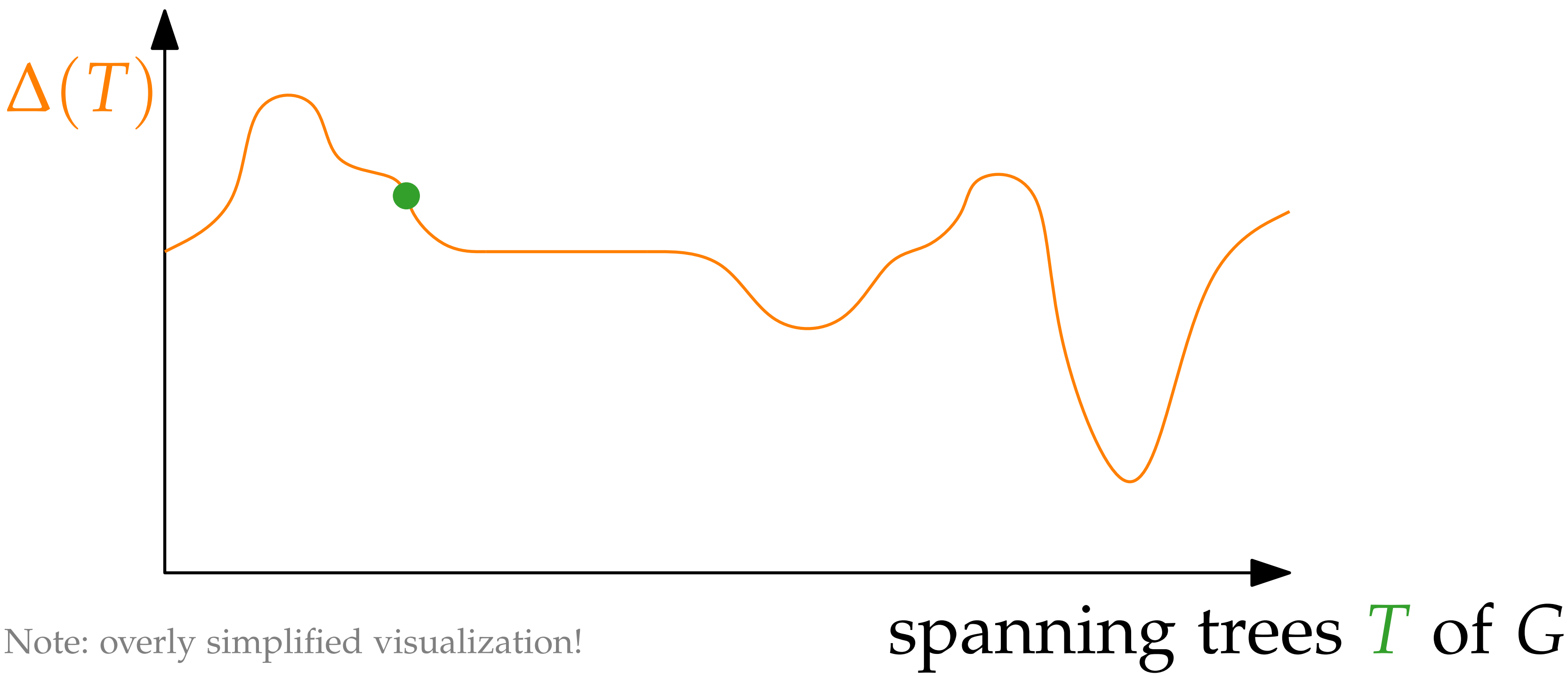

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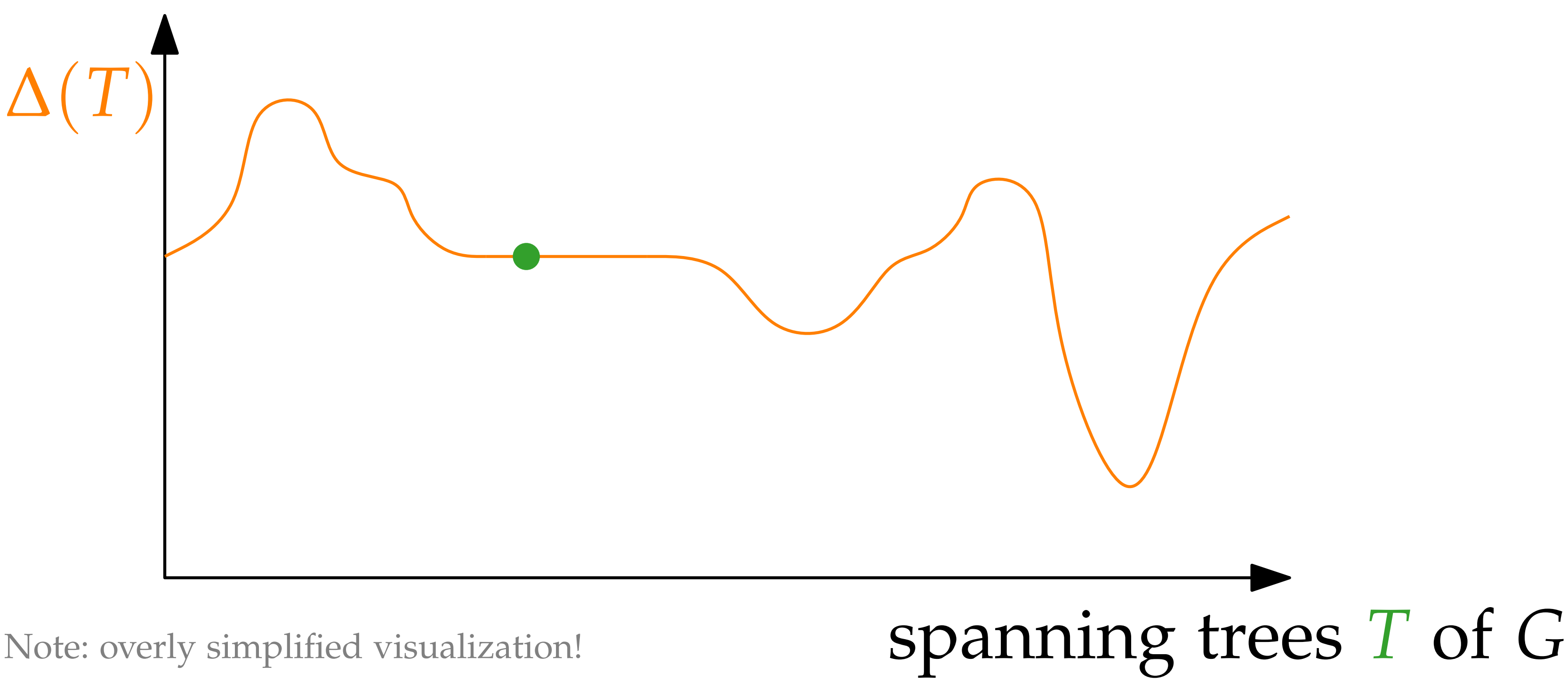

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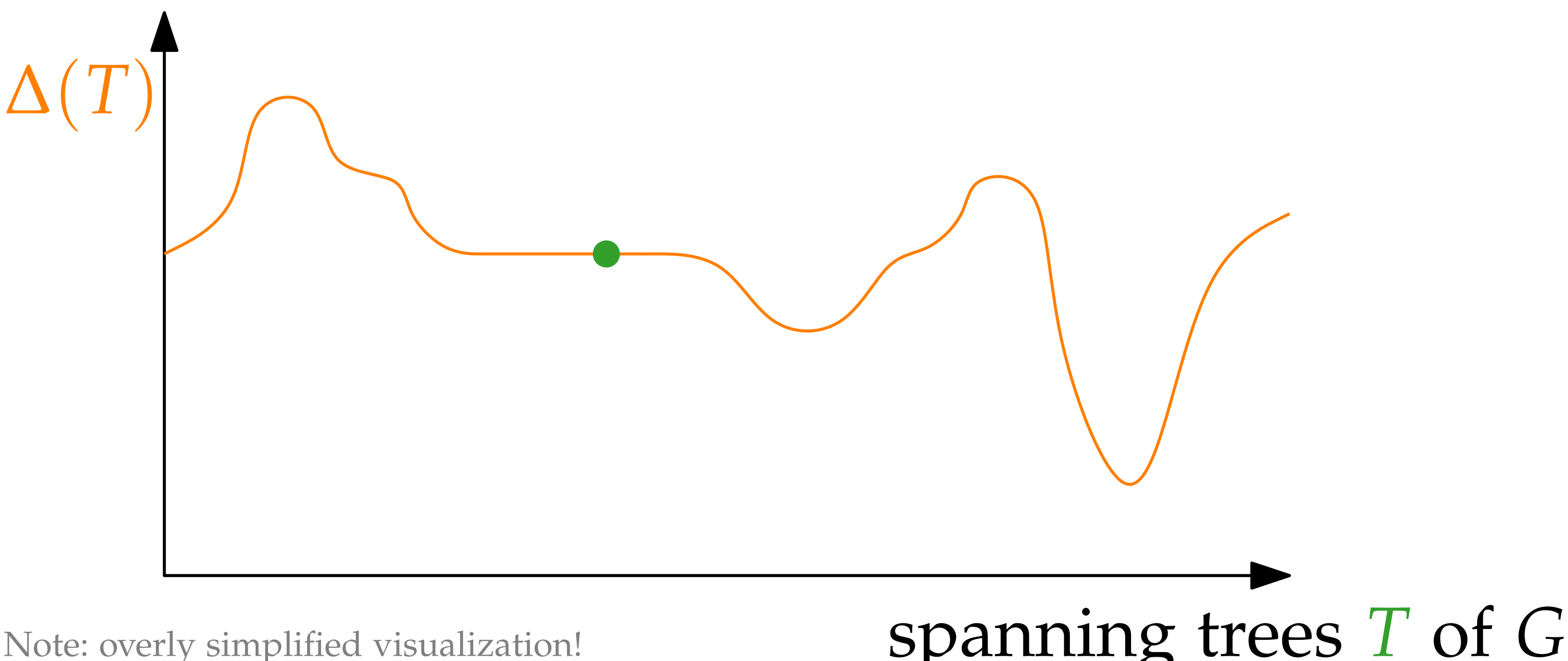

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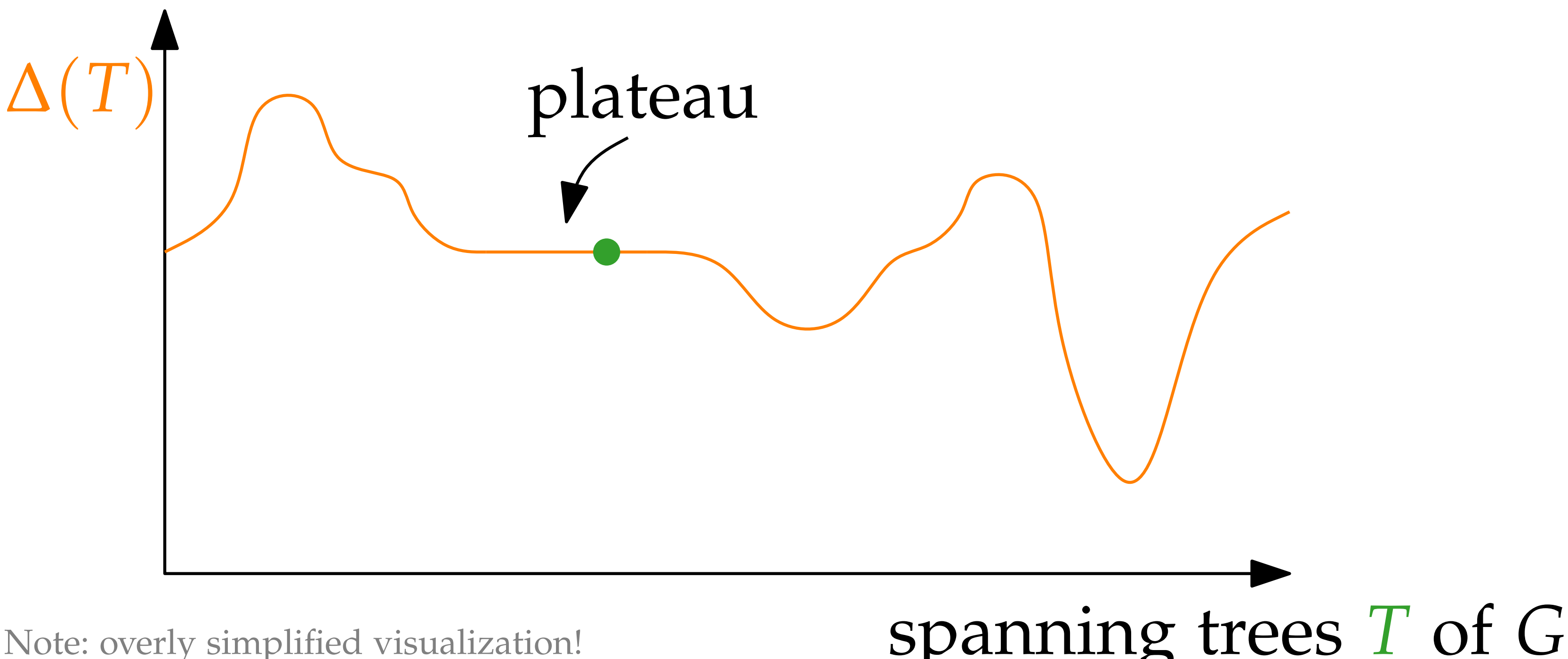

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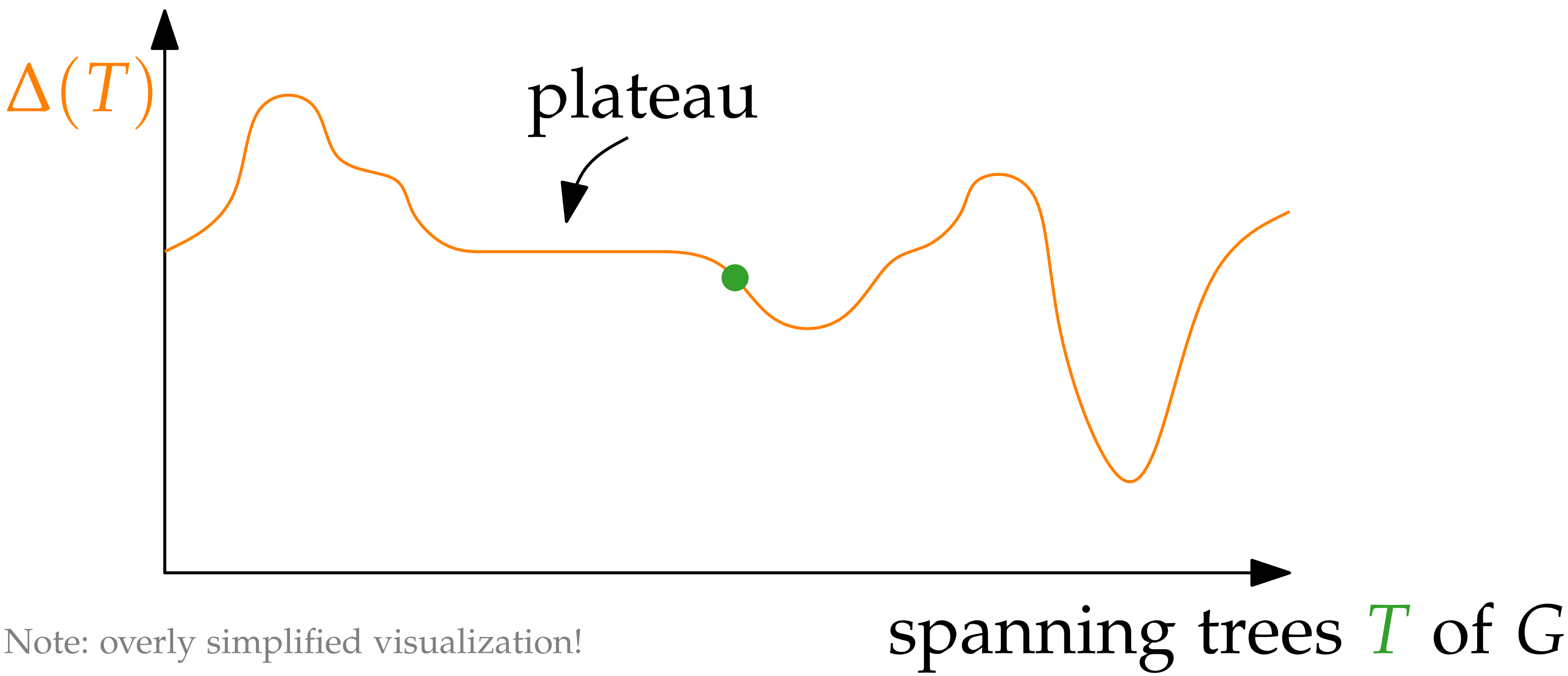

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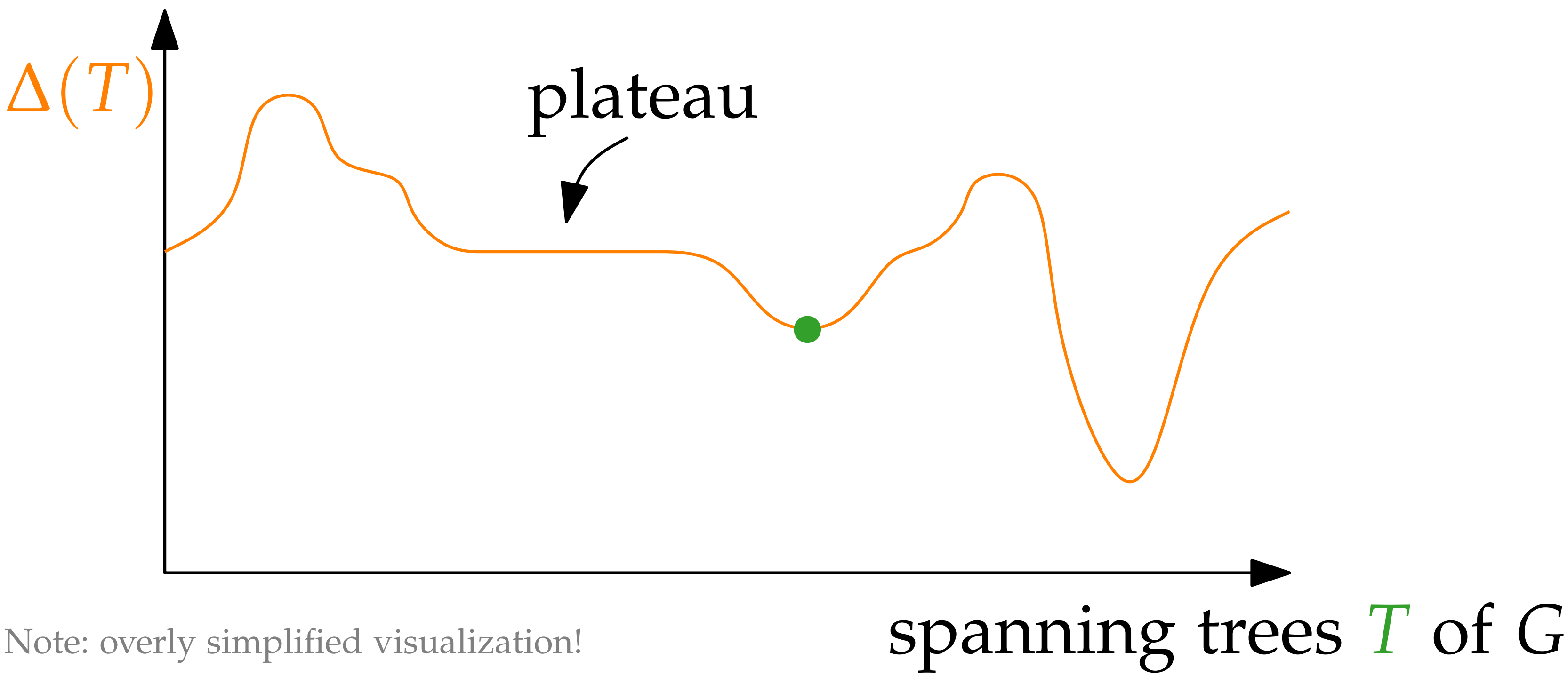

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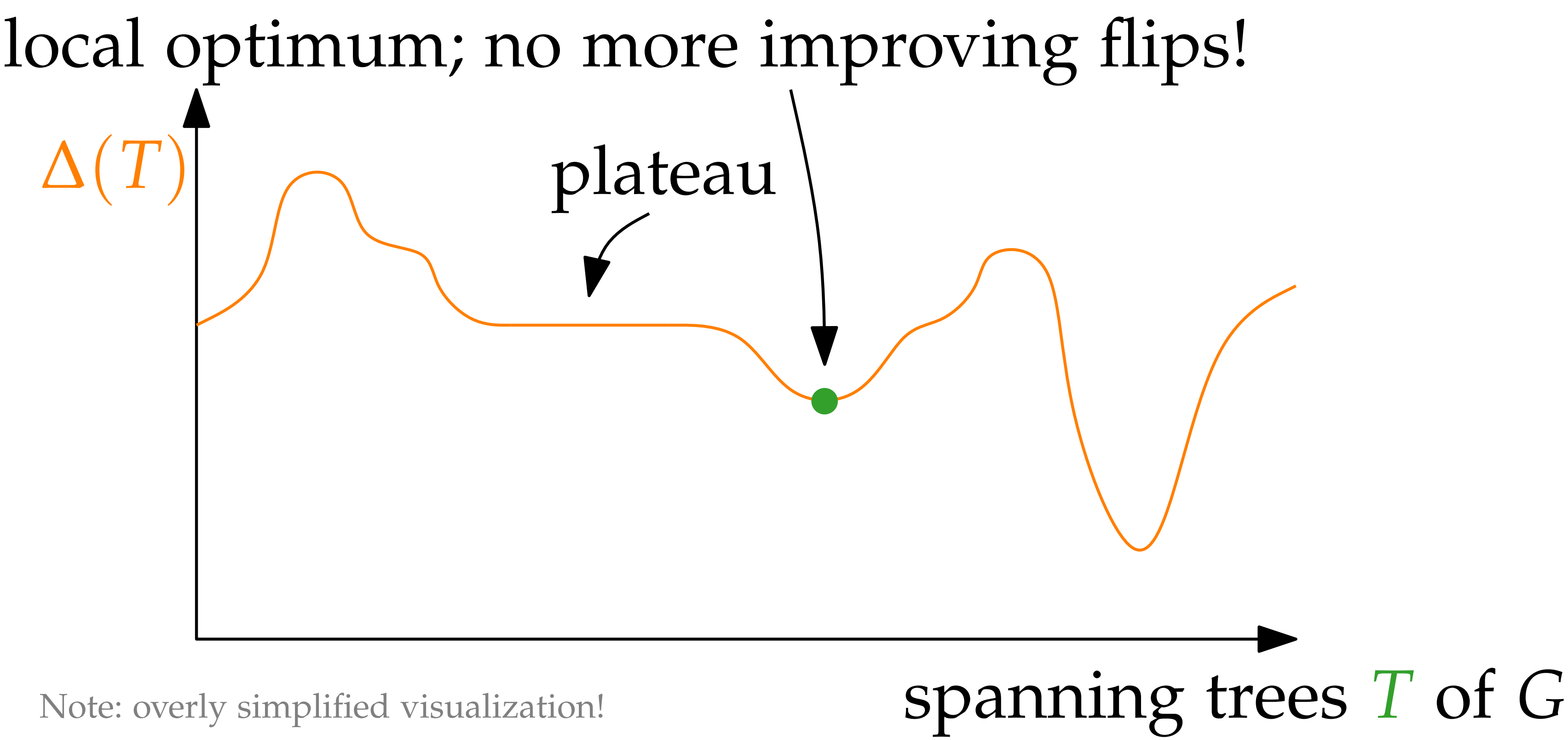

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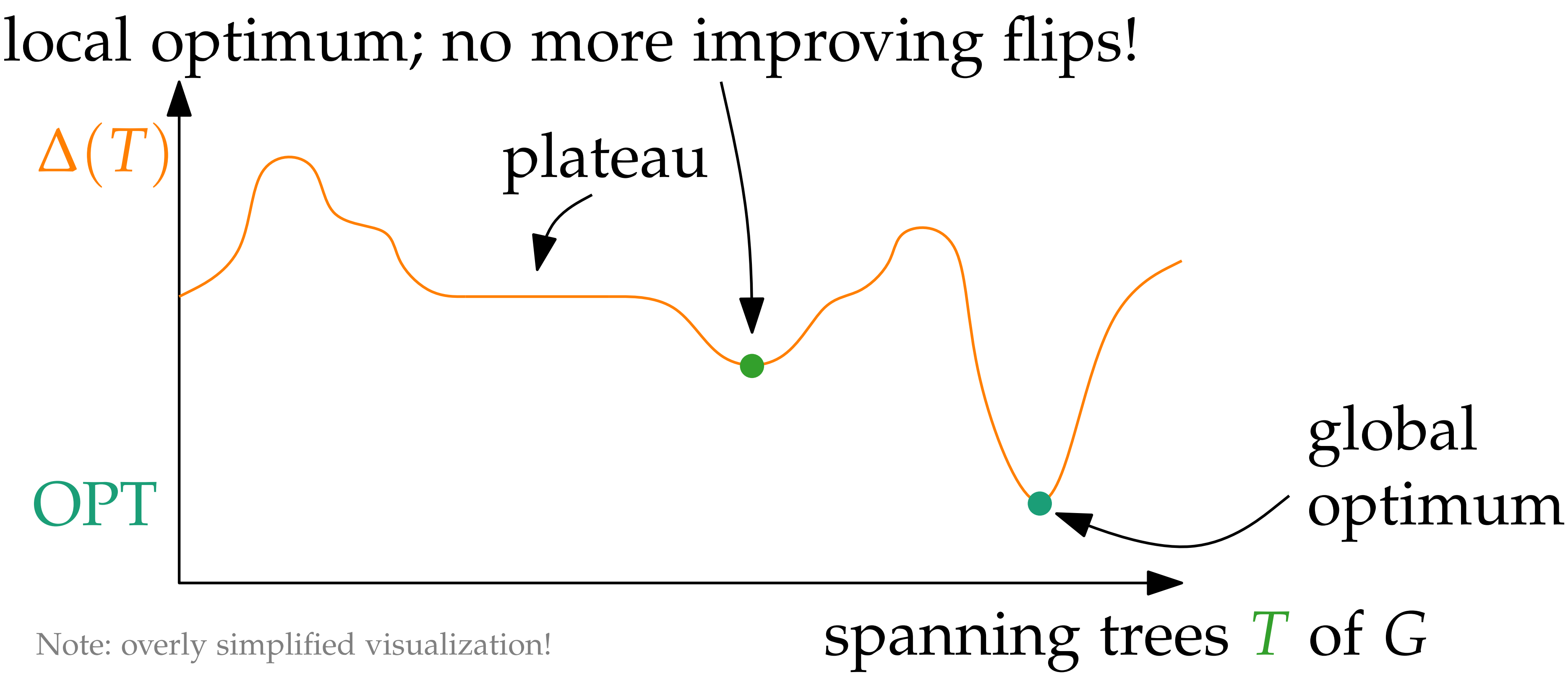

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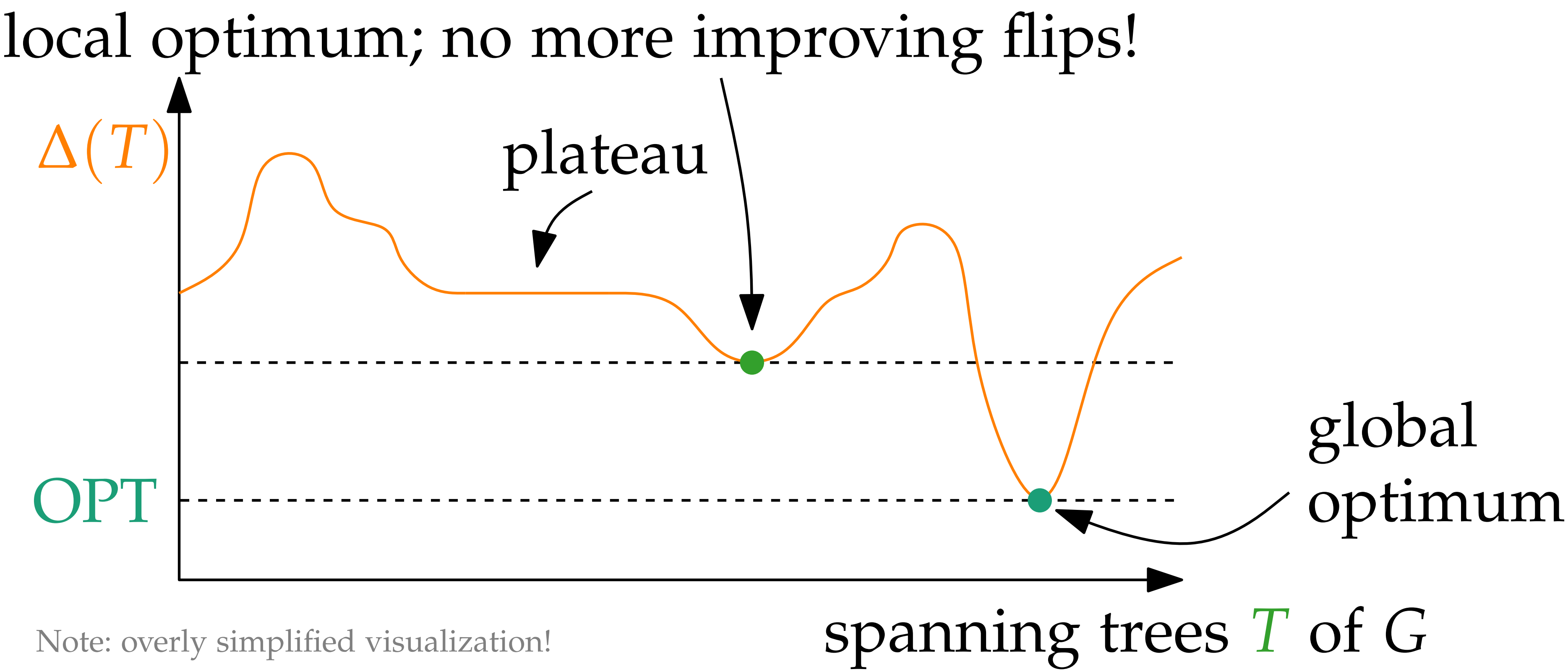

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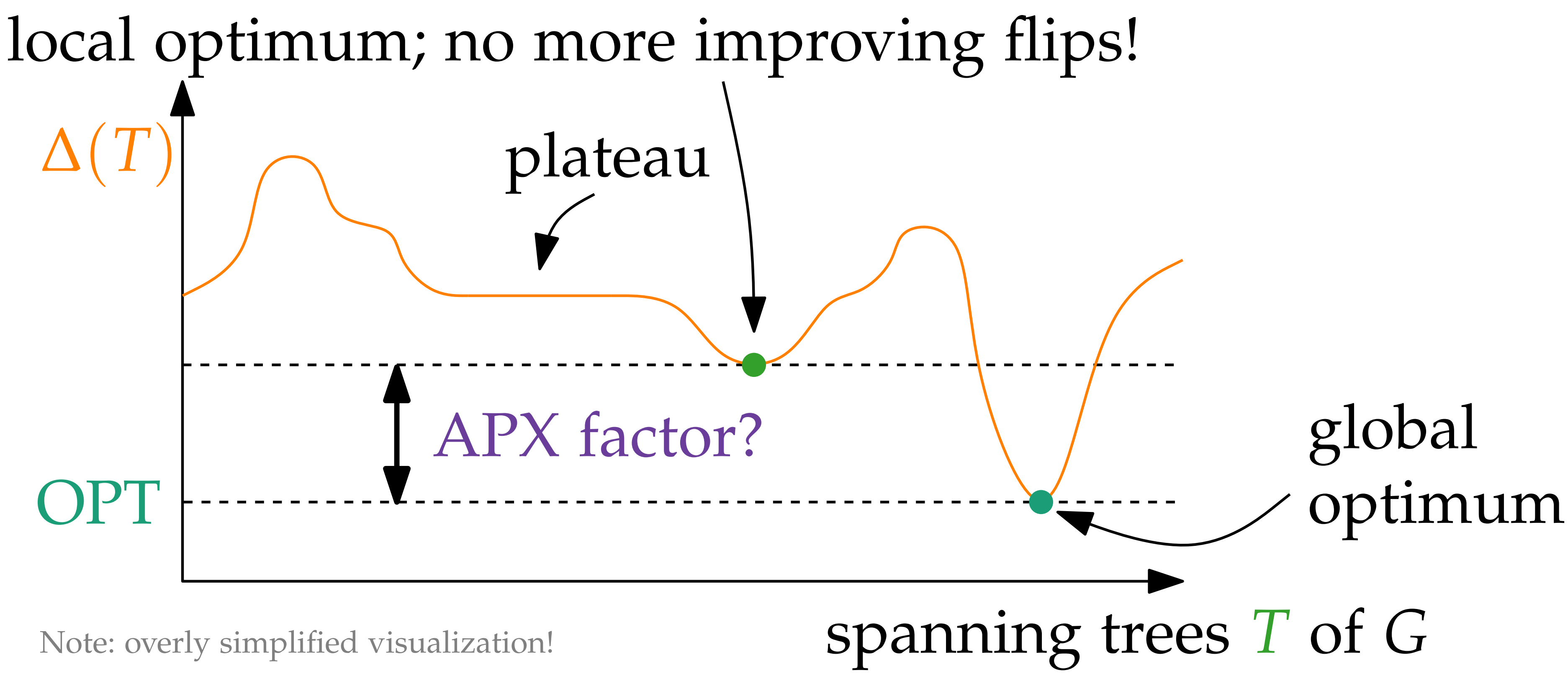

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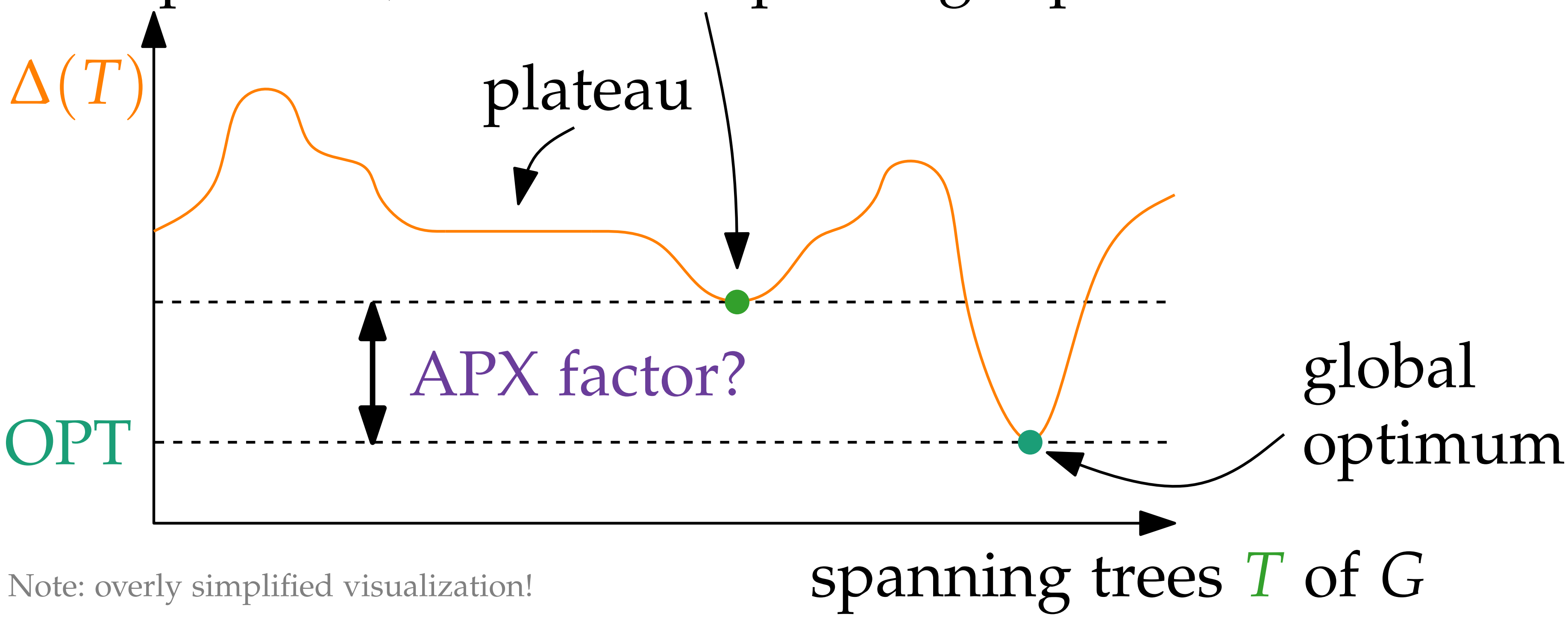
- Termination?

local optimum; no more improving flips!



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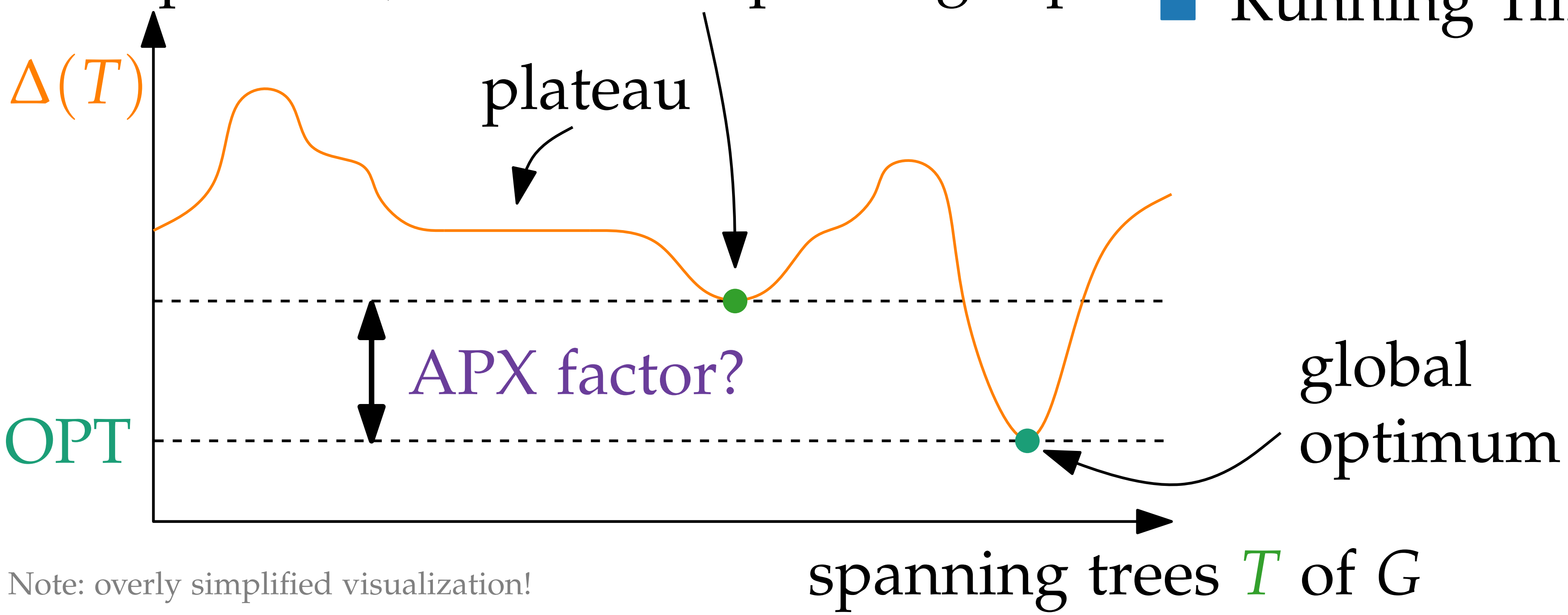
- Termination?
- Running Time?

local optimum; no more improving flips!



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- ℓ?

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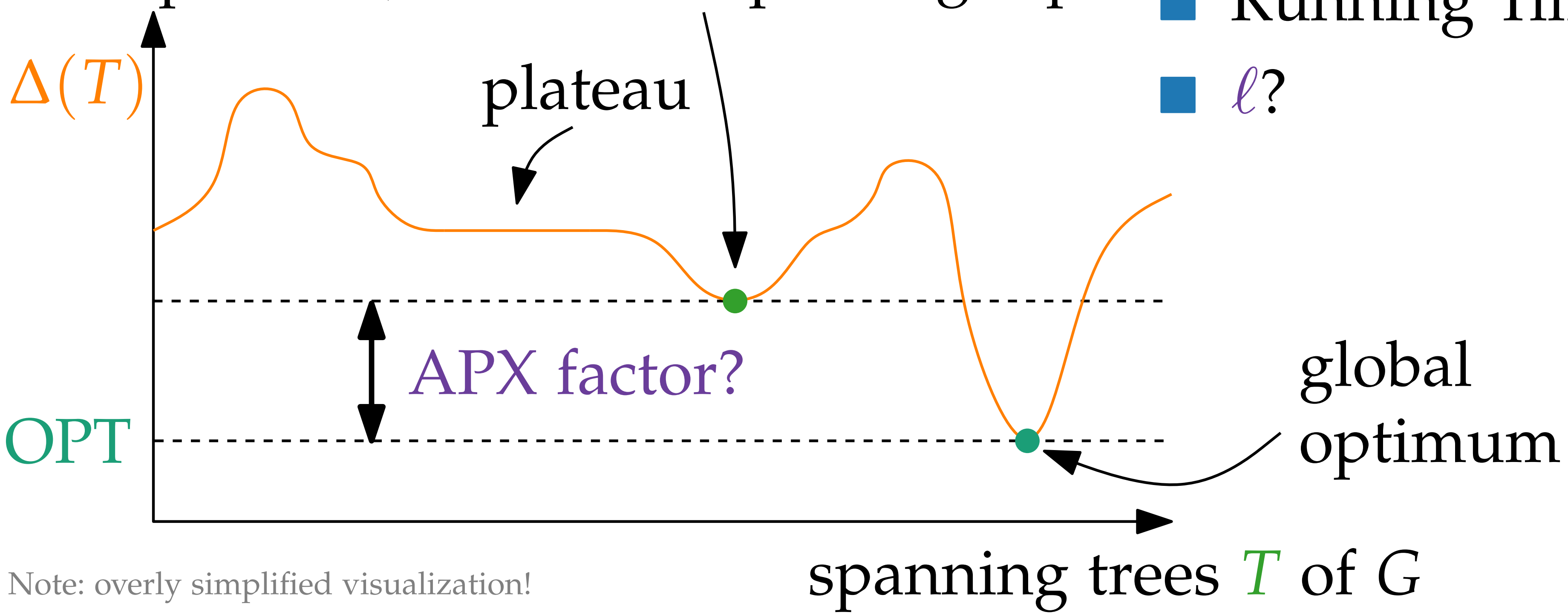

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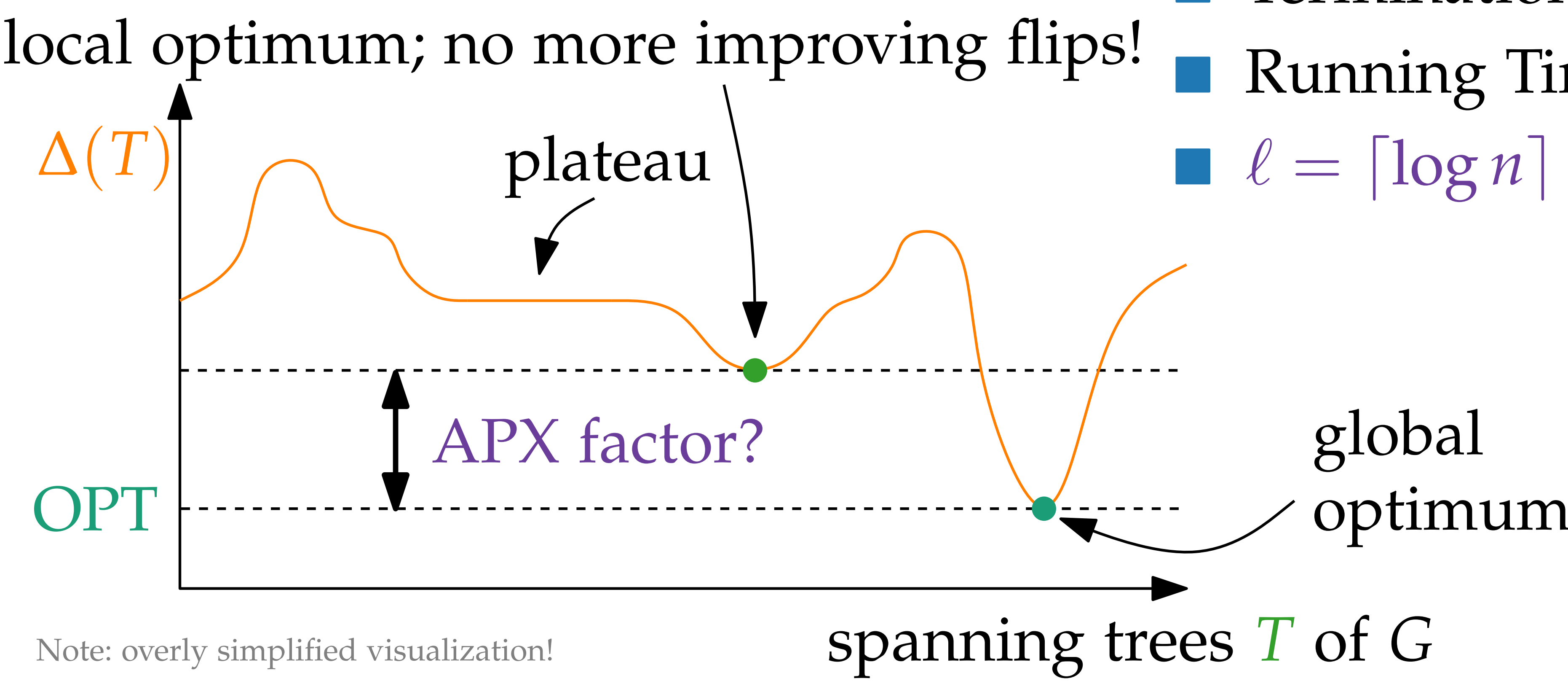
- Termination?
- Running Time?
- $\ell = \lceil \log n \rceil$



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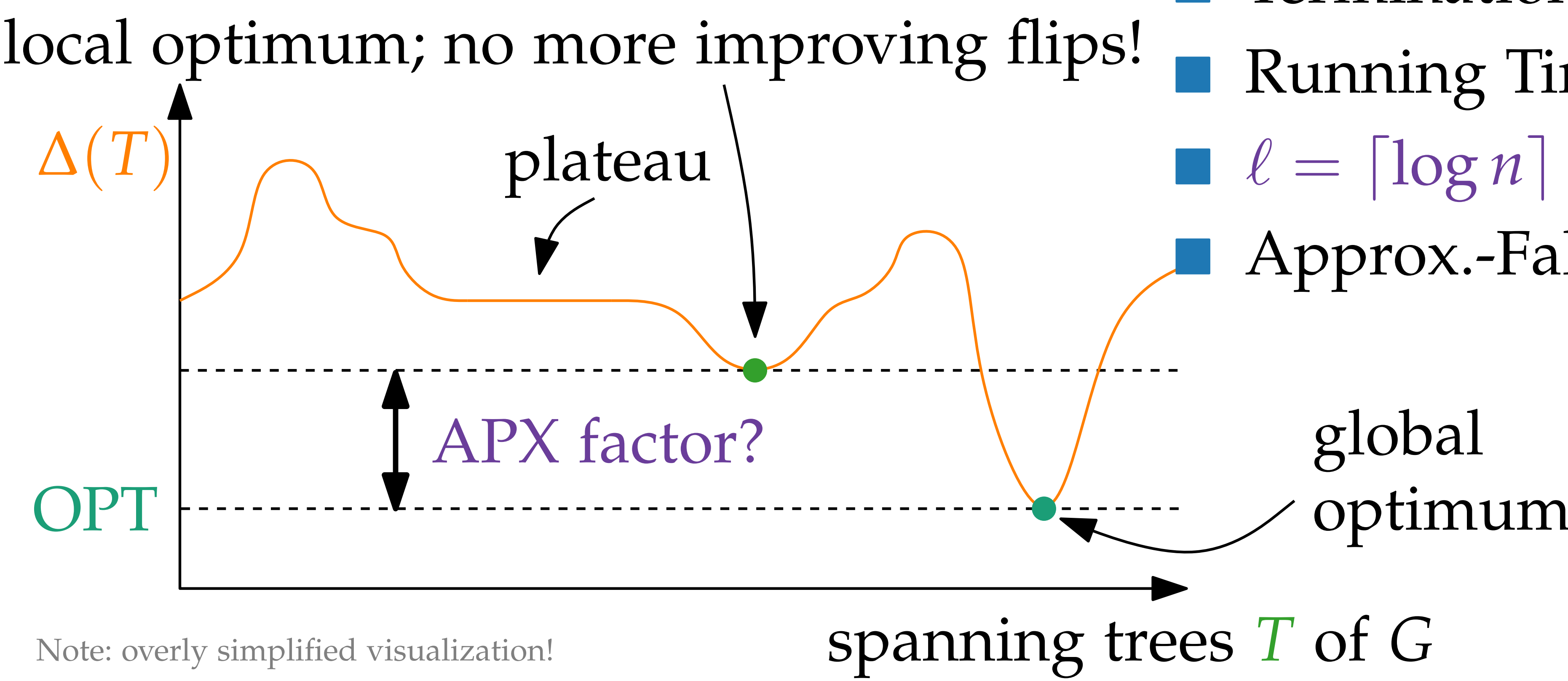
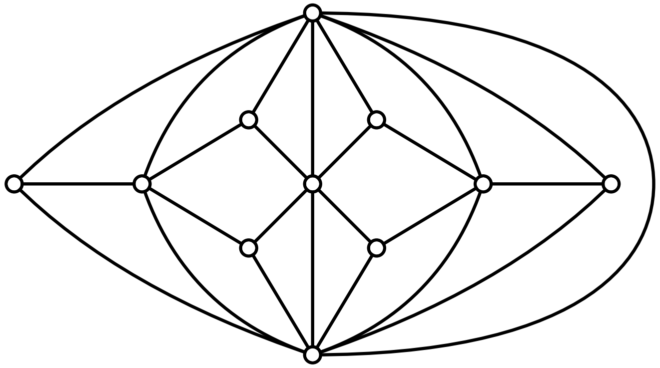
- Termination?
- Running Time?
- $\ell = \lceil \log n \rceil$
- Approx.-Faktor?

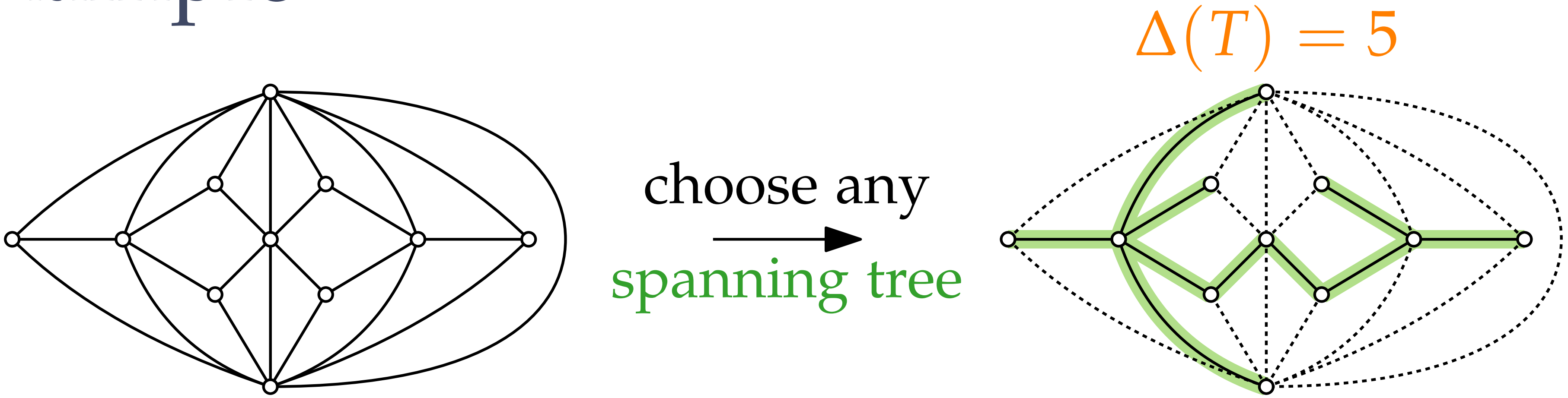


Note: overly simplified visualization!

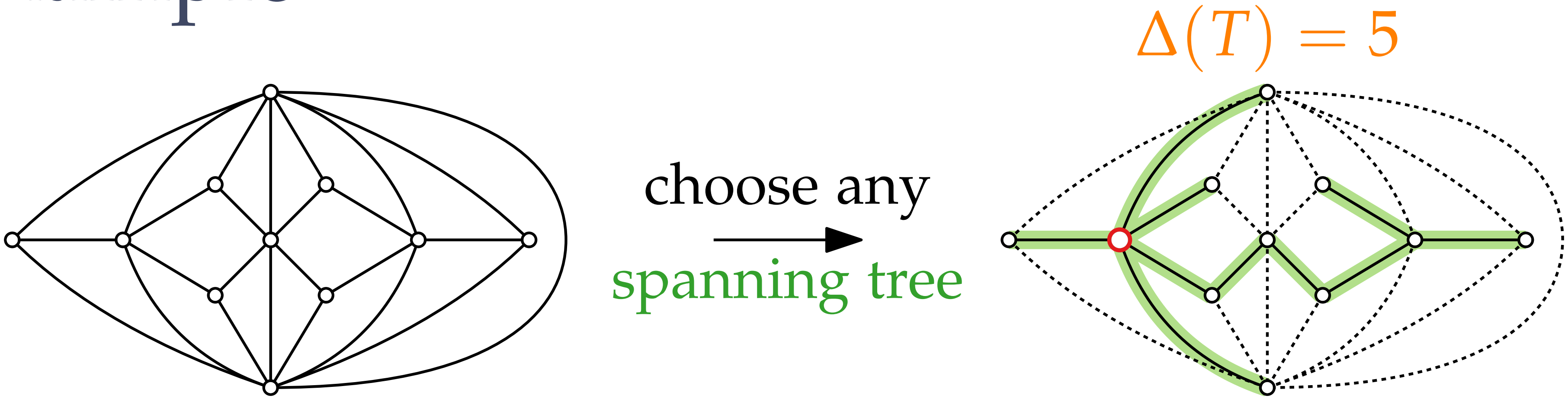
Example



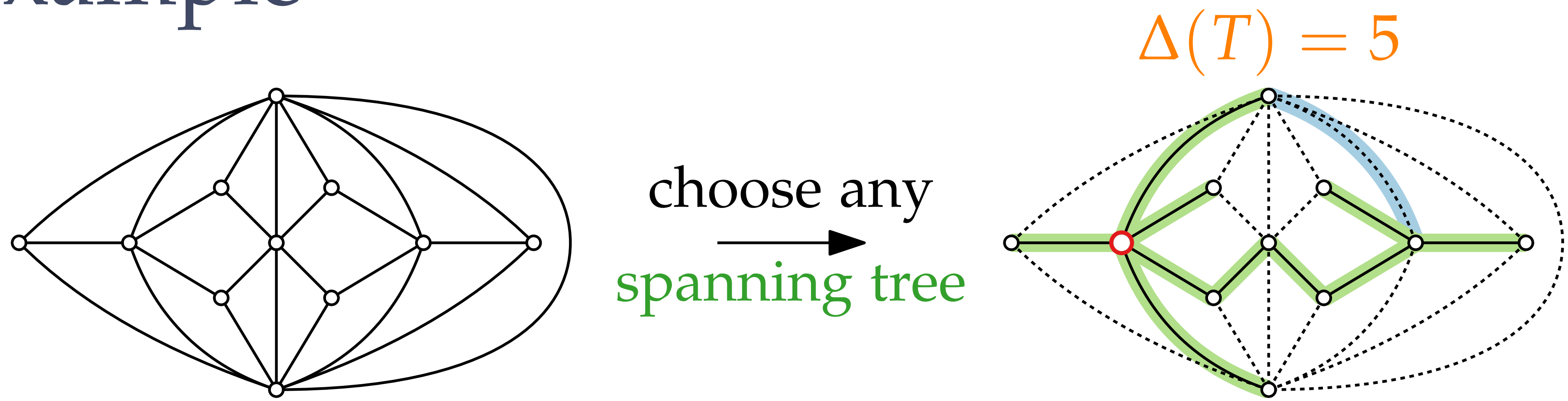
Example



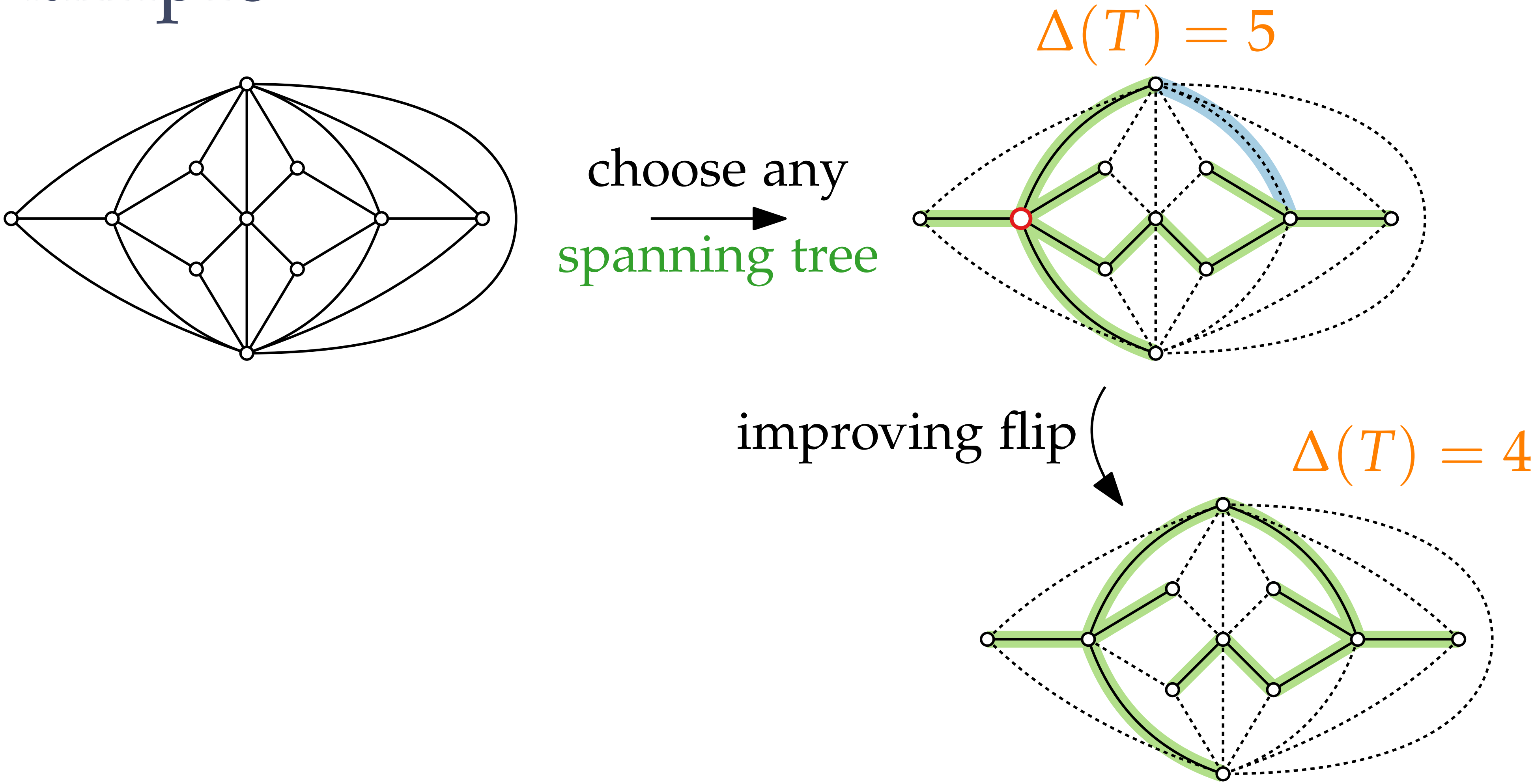
Example



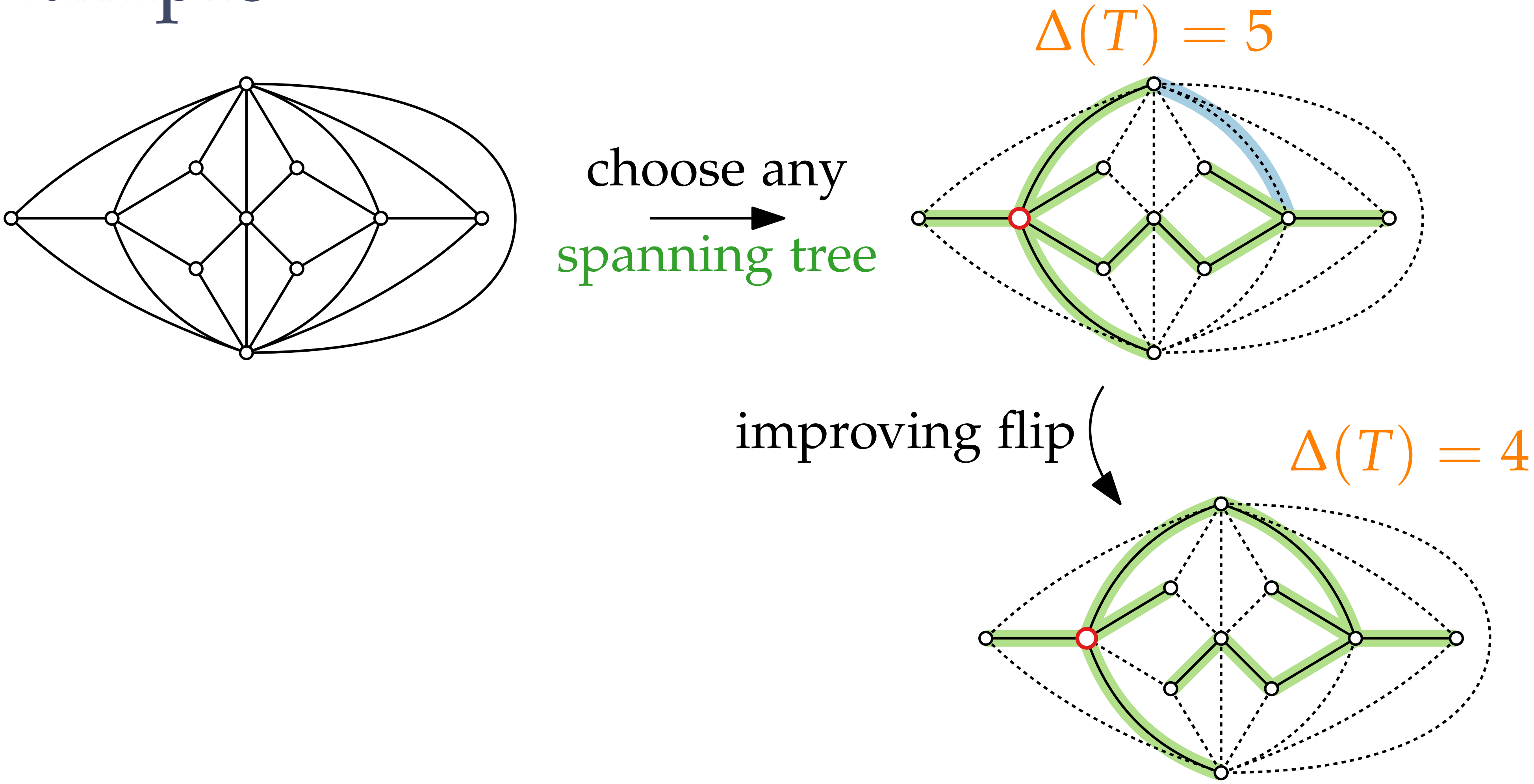
Example



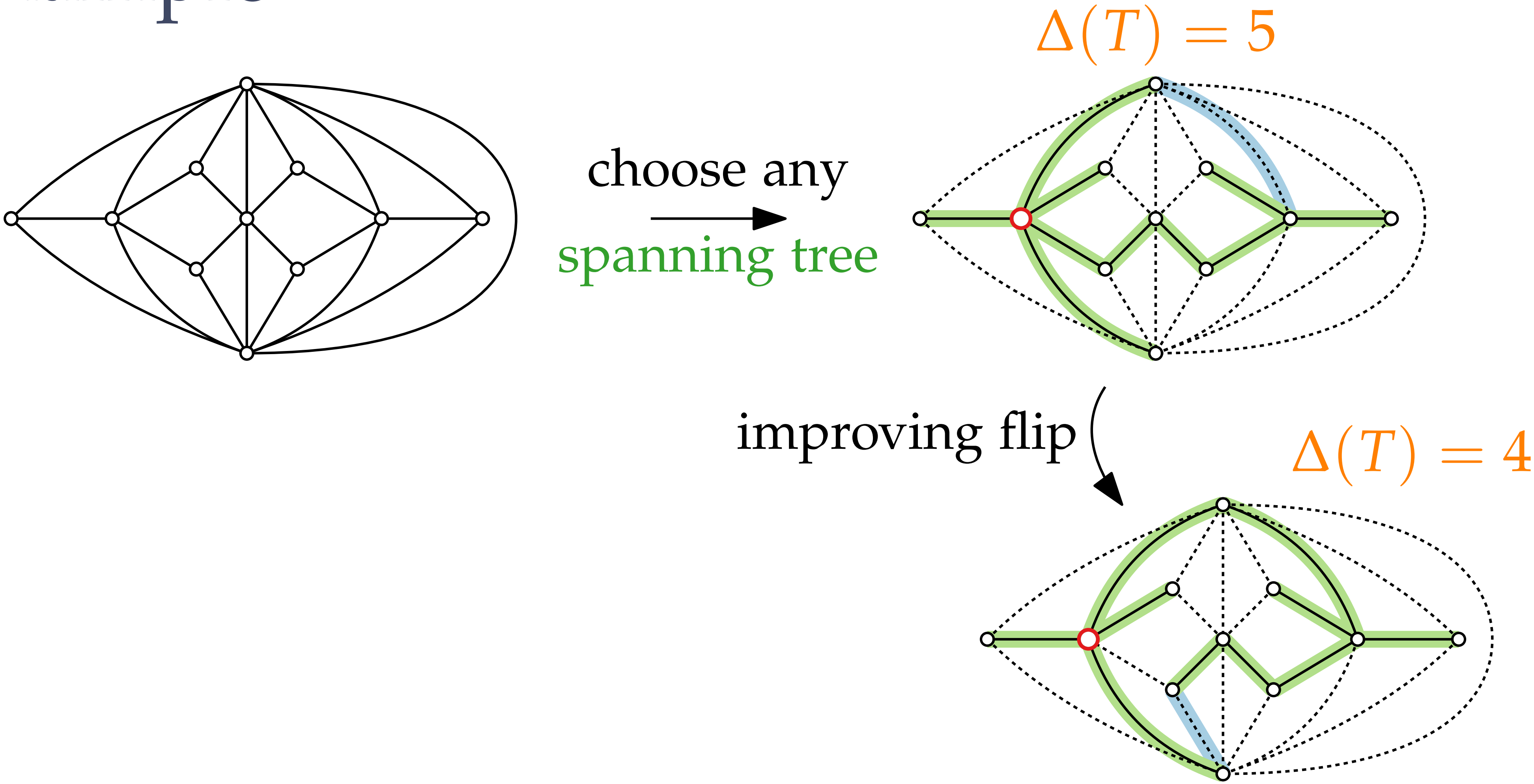
Example



Example



Example



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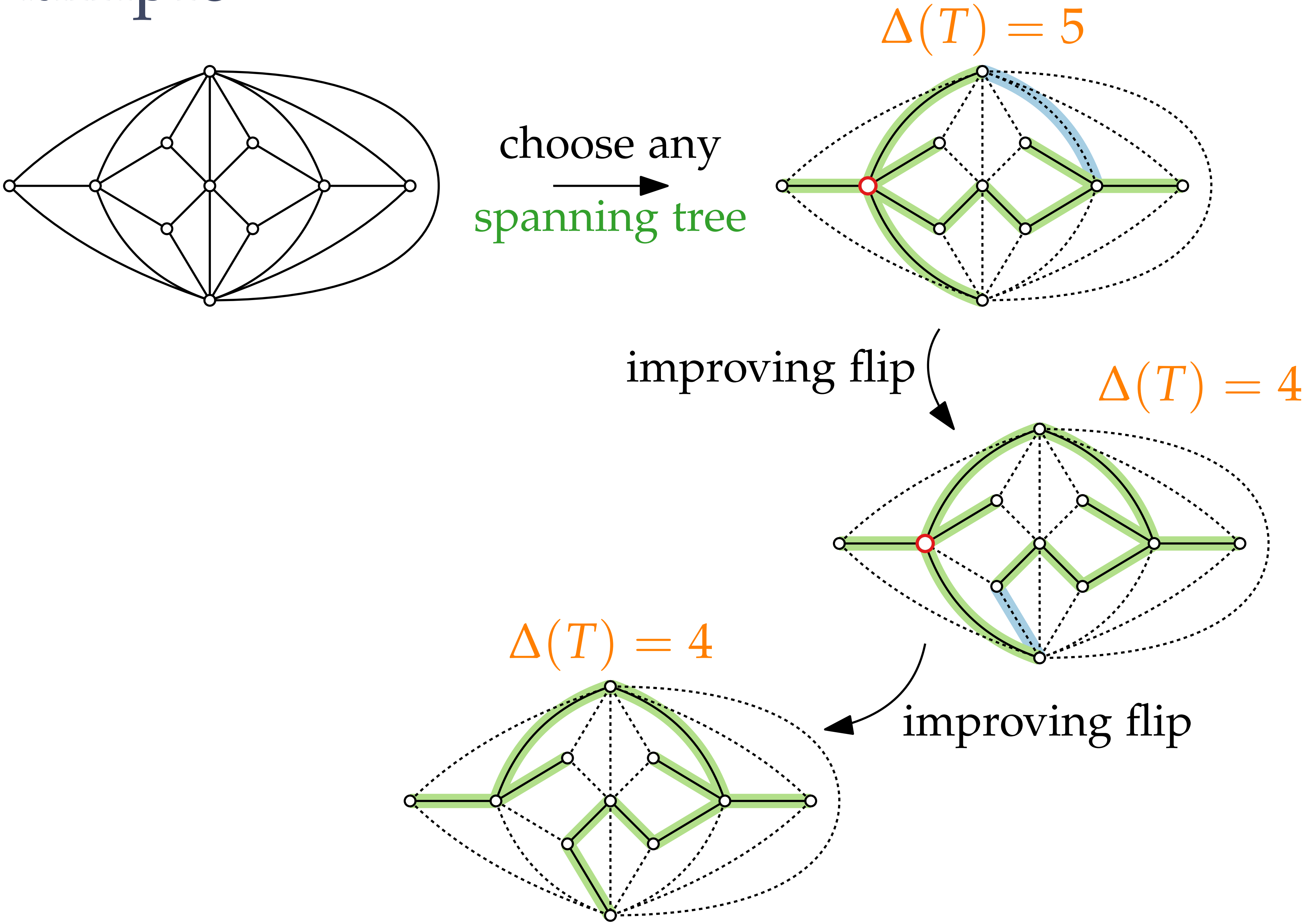
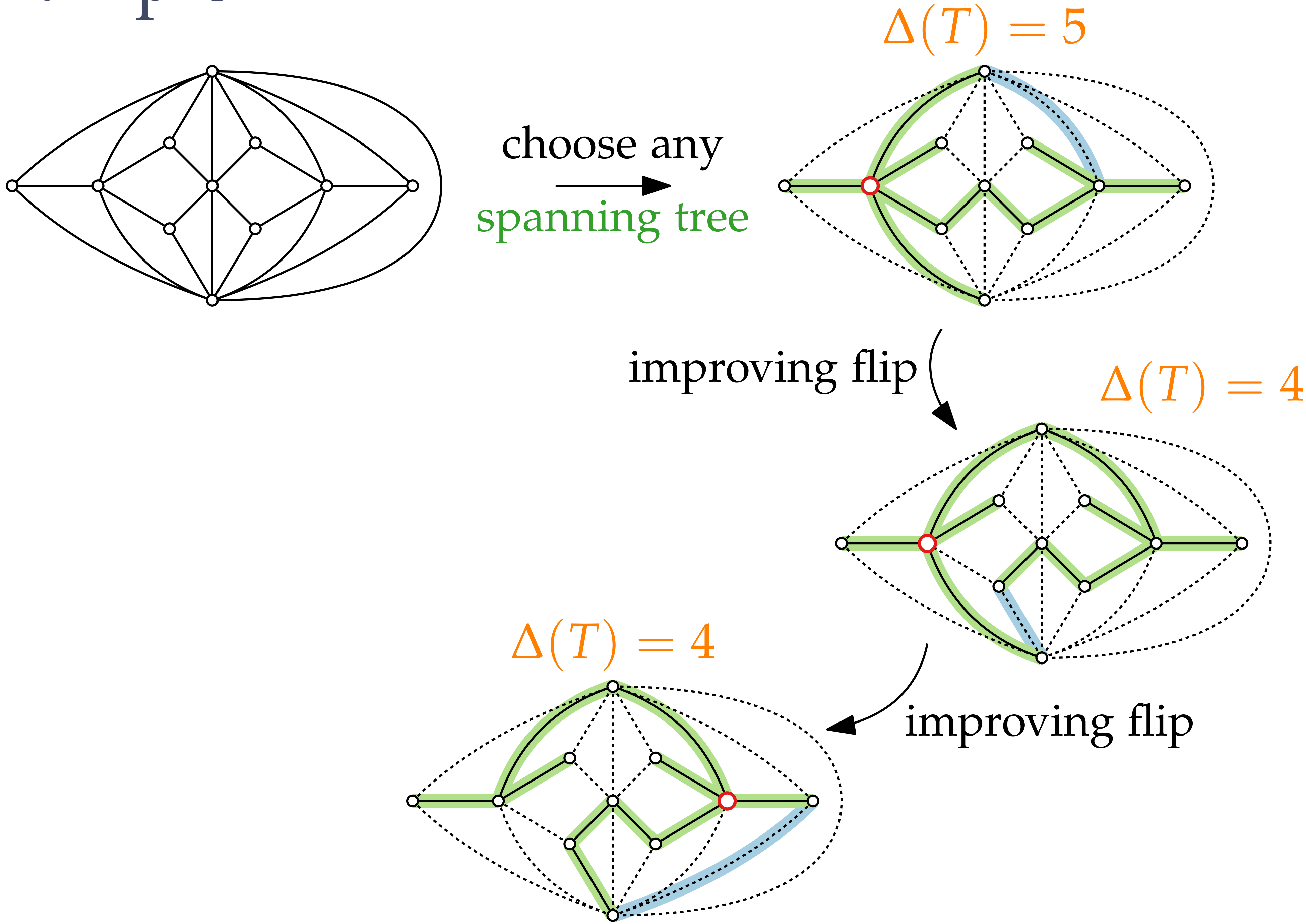

choose any
spanning tree
$\Delta(T) = 5$
improving flip
$\Delta(T) = 4$
improving flip
$\Delta(T) = 4$

Example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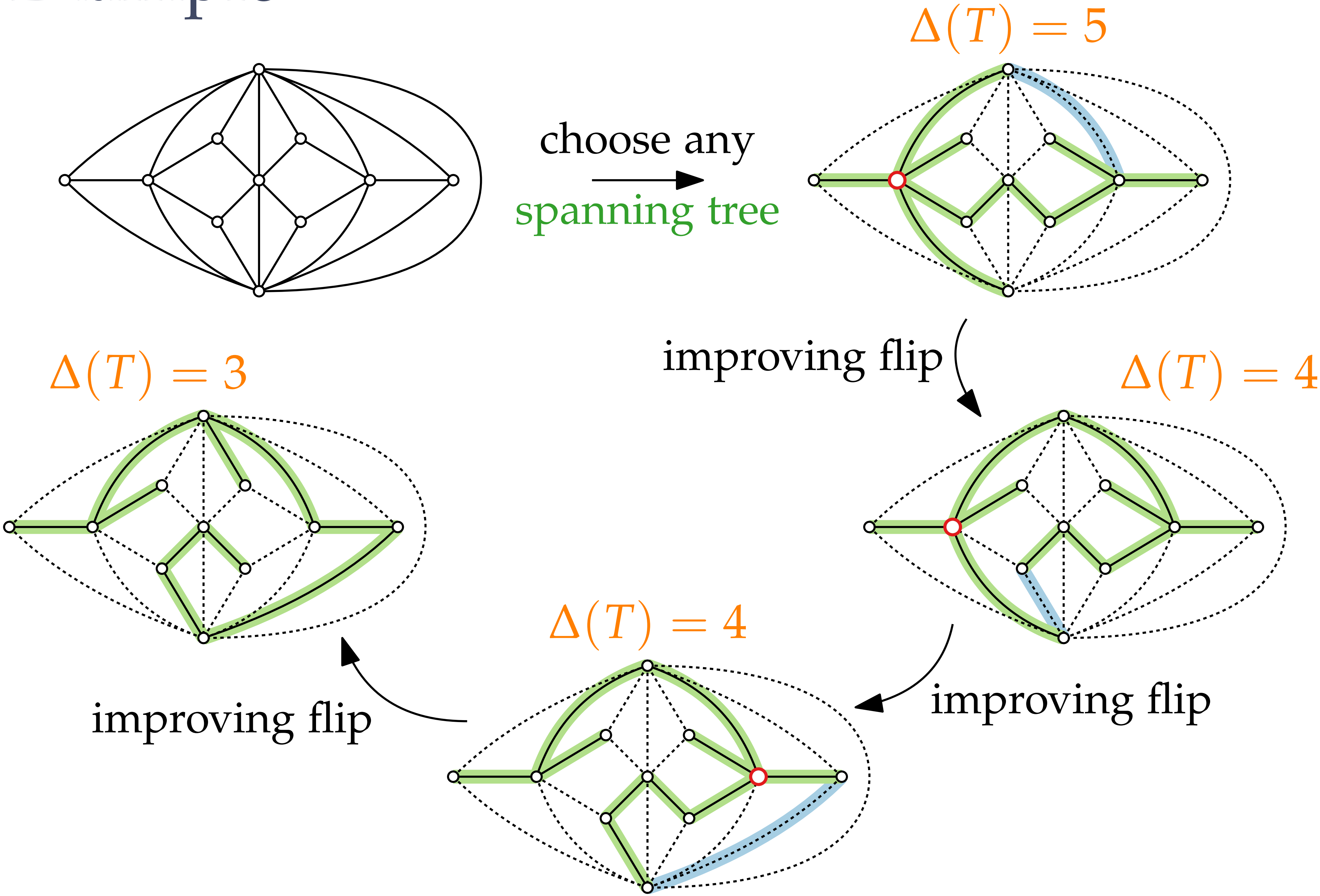
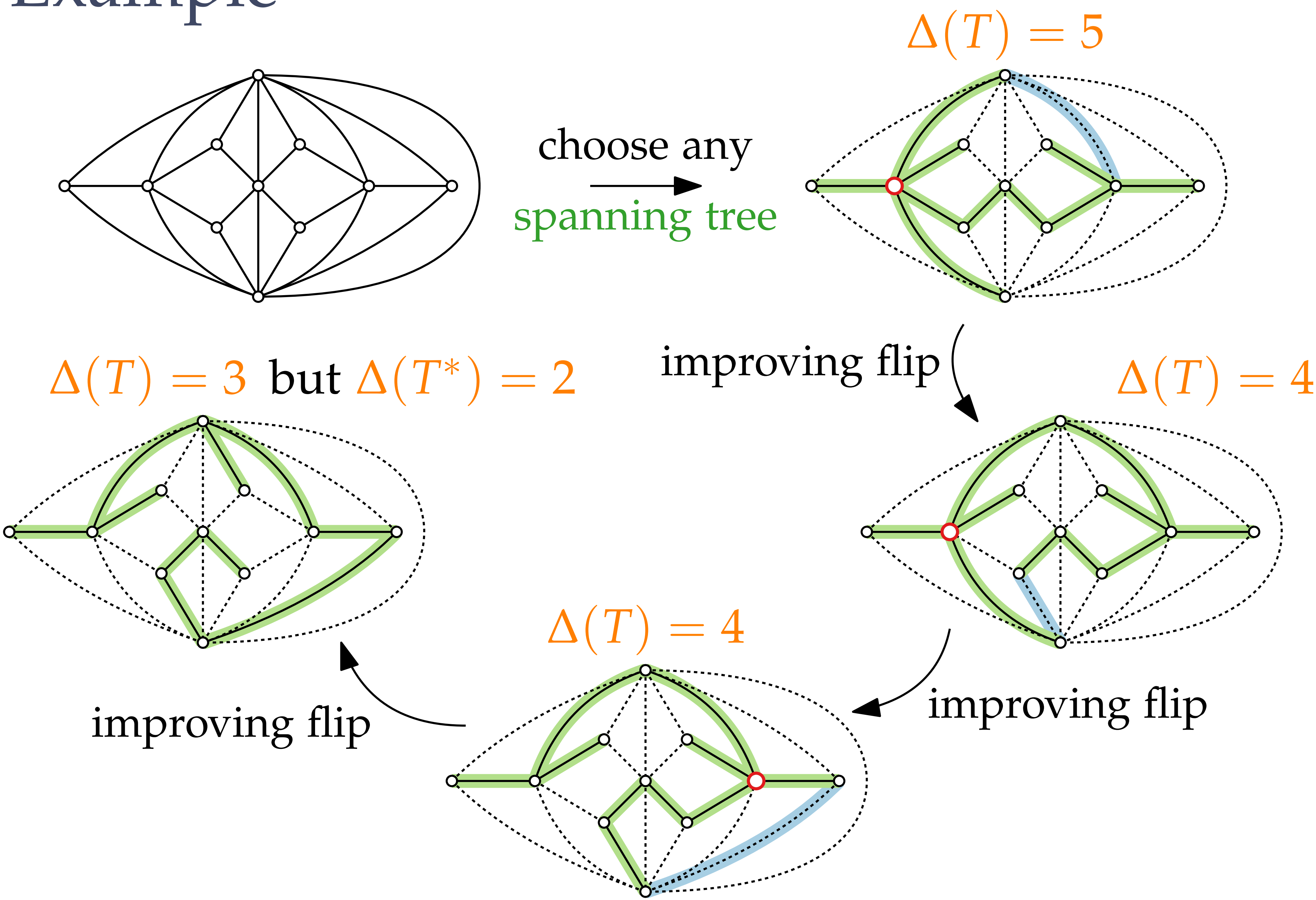
Example



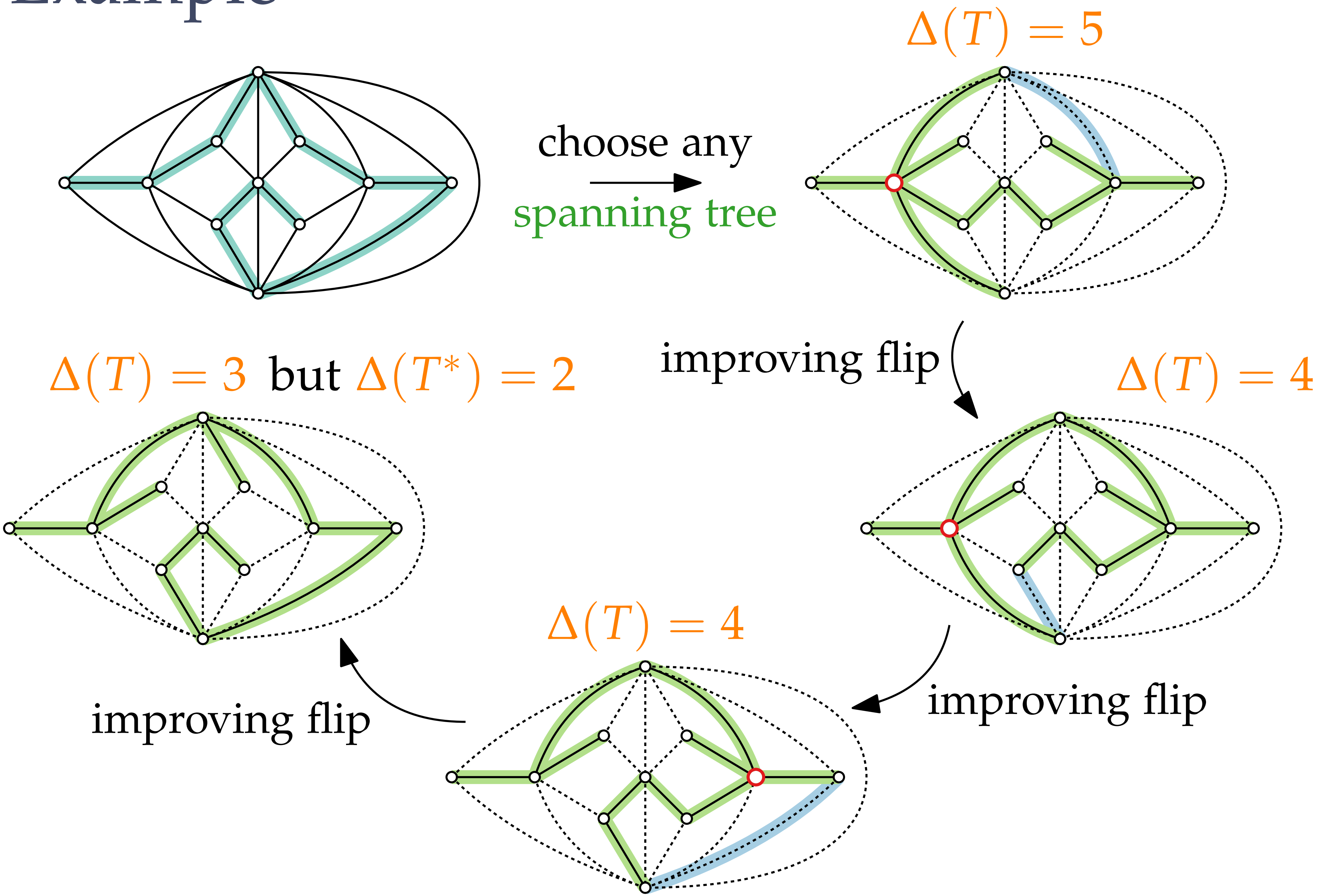
choose any
spanning tree
$\Delta(T) = 5$
improving flip
$\Delta(T) = 4$
improving flip
$\Delta(T) = 4$
improving flip
$\Delta(T) = 3$

Example



choose any
spanning tree
$\Delta(T) = 5$
improving flip
$\Delta(T) = 4$
improving flip
$\Delta(T) = 4$
improving flip
$\Delta(T) = 3$ but $\Delta(T^*) = 2$

Example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$\Delta(T) = 5$
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$\Delta(T) = 4$
improving flip
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$\Delta(T) = 3$ but $\Delta(T^*) = 2$

Approximation Algorithms

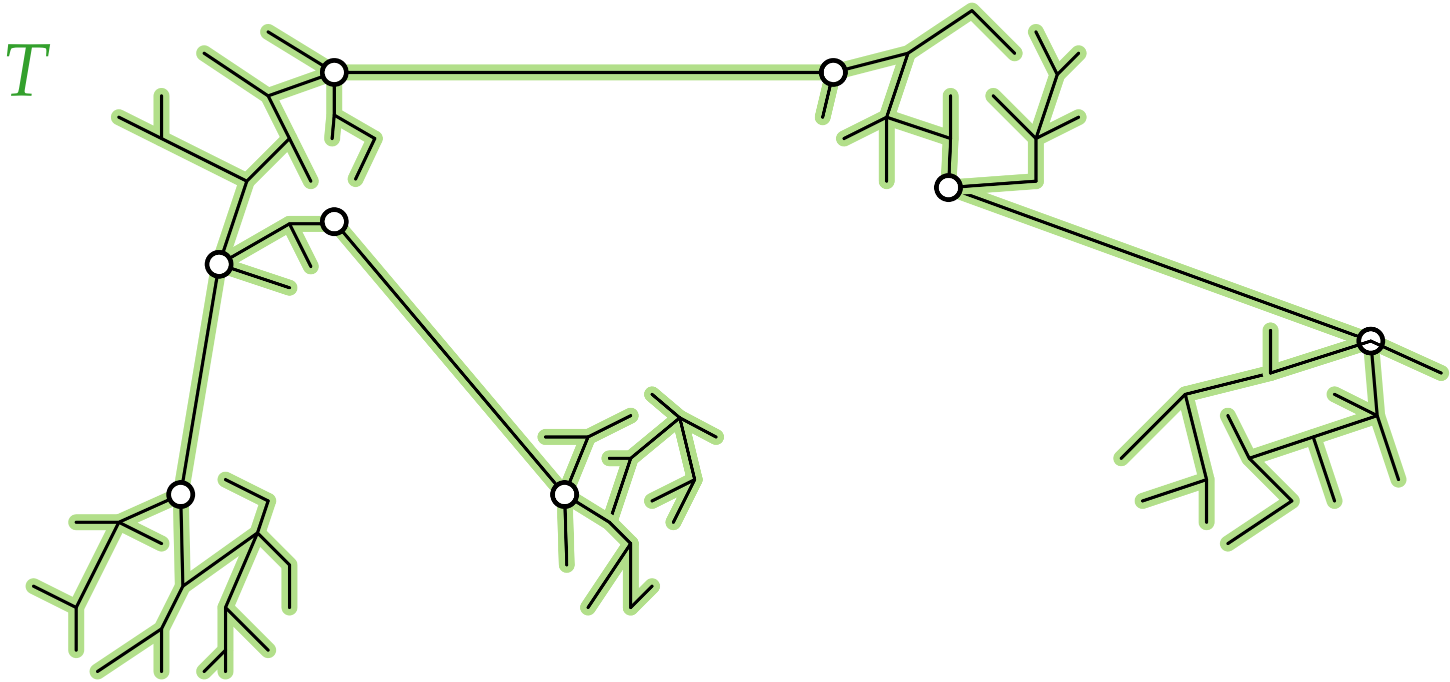
Lecture 9:
Minimum-Degree Spanning Tree
via Local Search

Part III:
Lower Bound

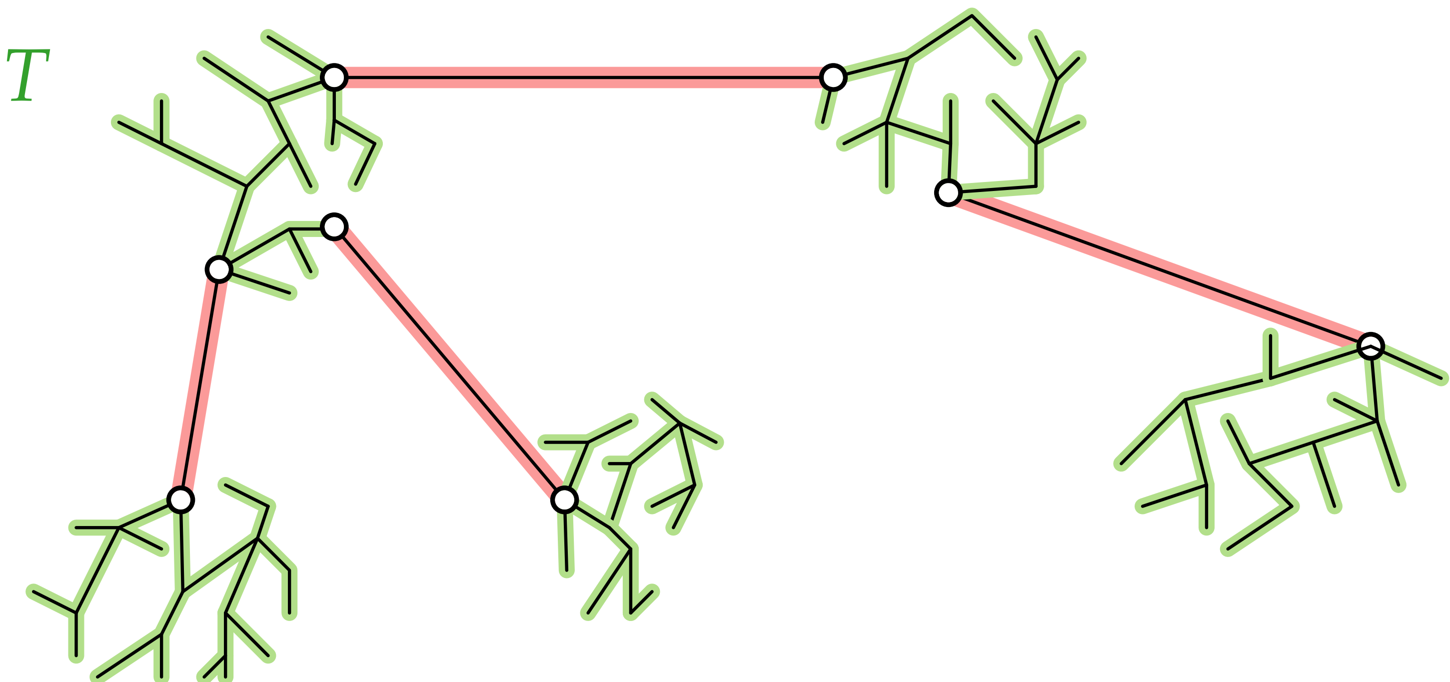
Philipp Kindermann

Summer Semester 2020

Decomposition

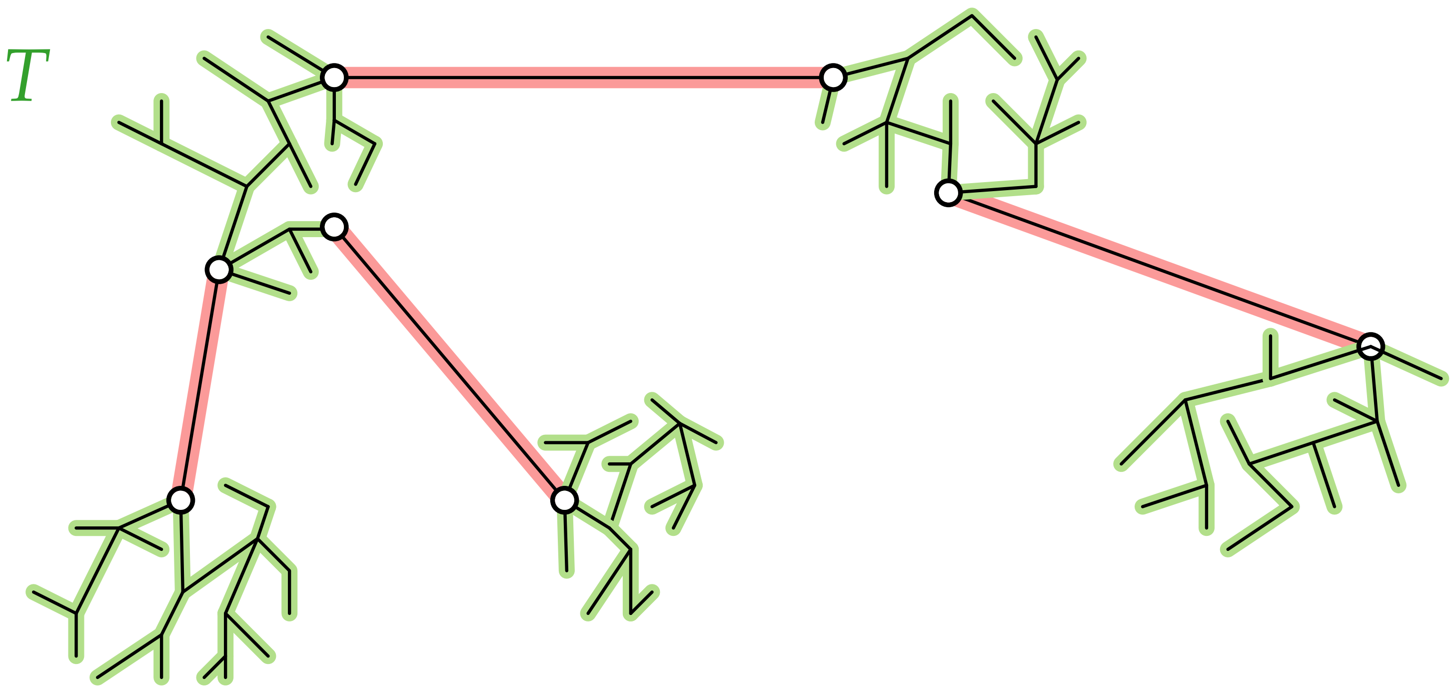


Decomposition



Decomposition

- Removing k edges decomposes T into $k+1$ components



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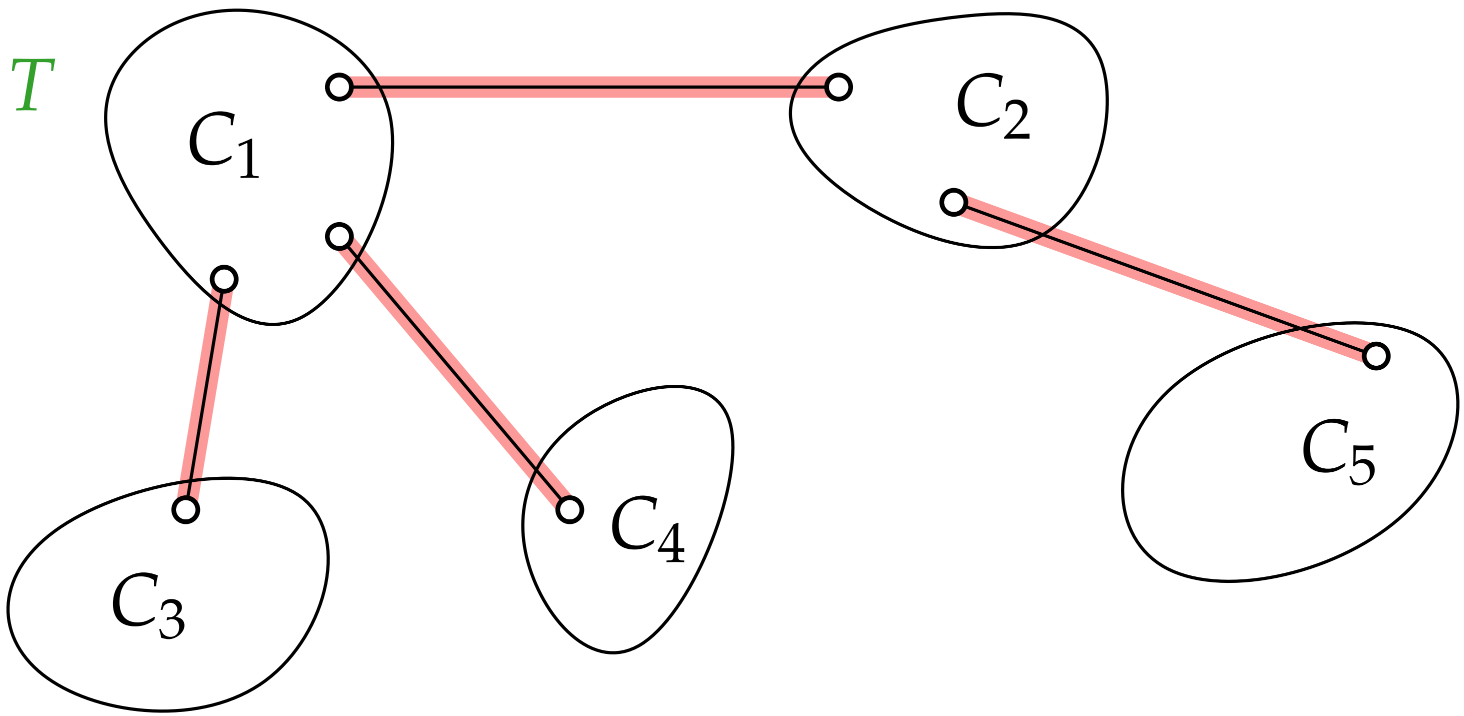
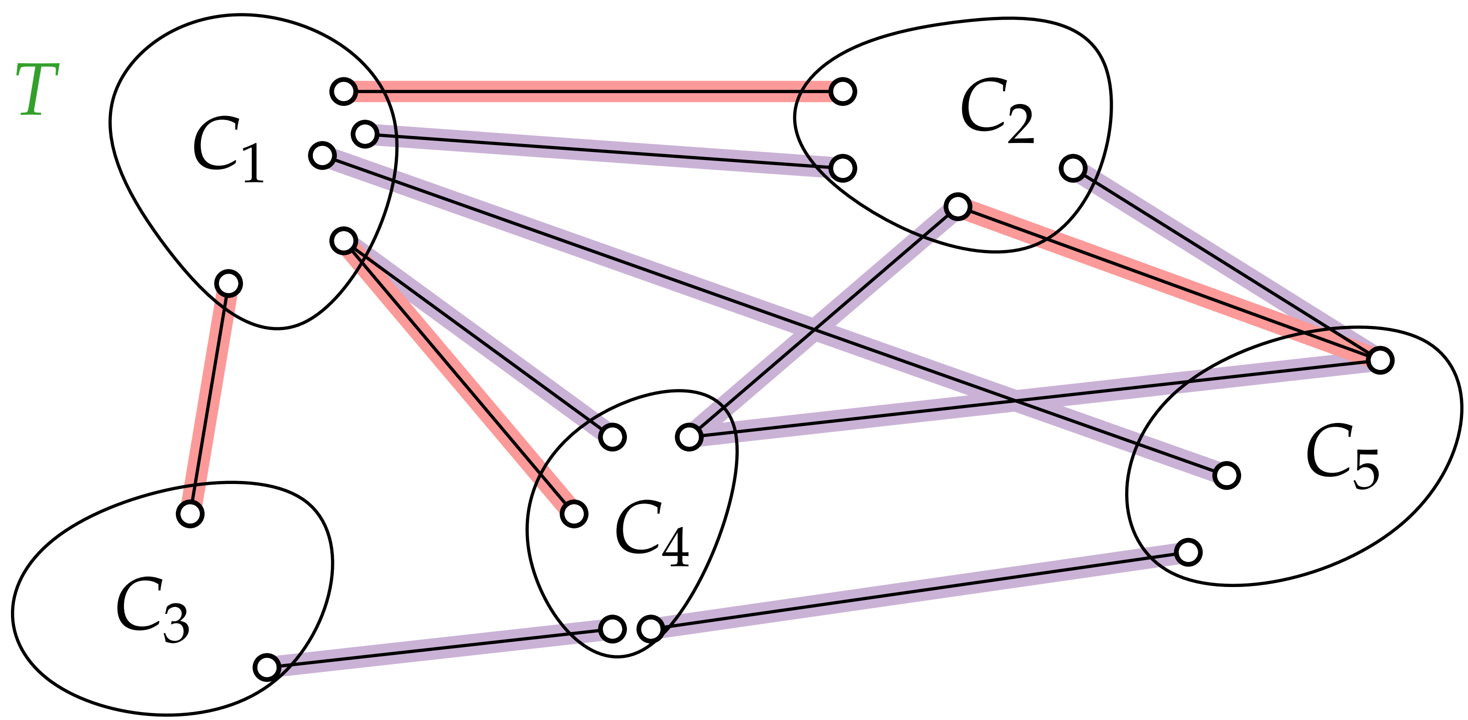


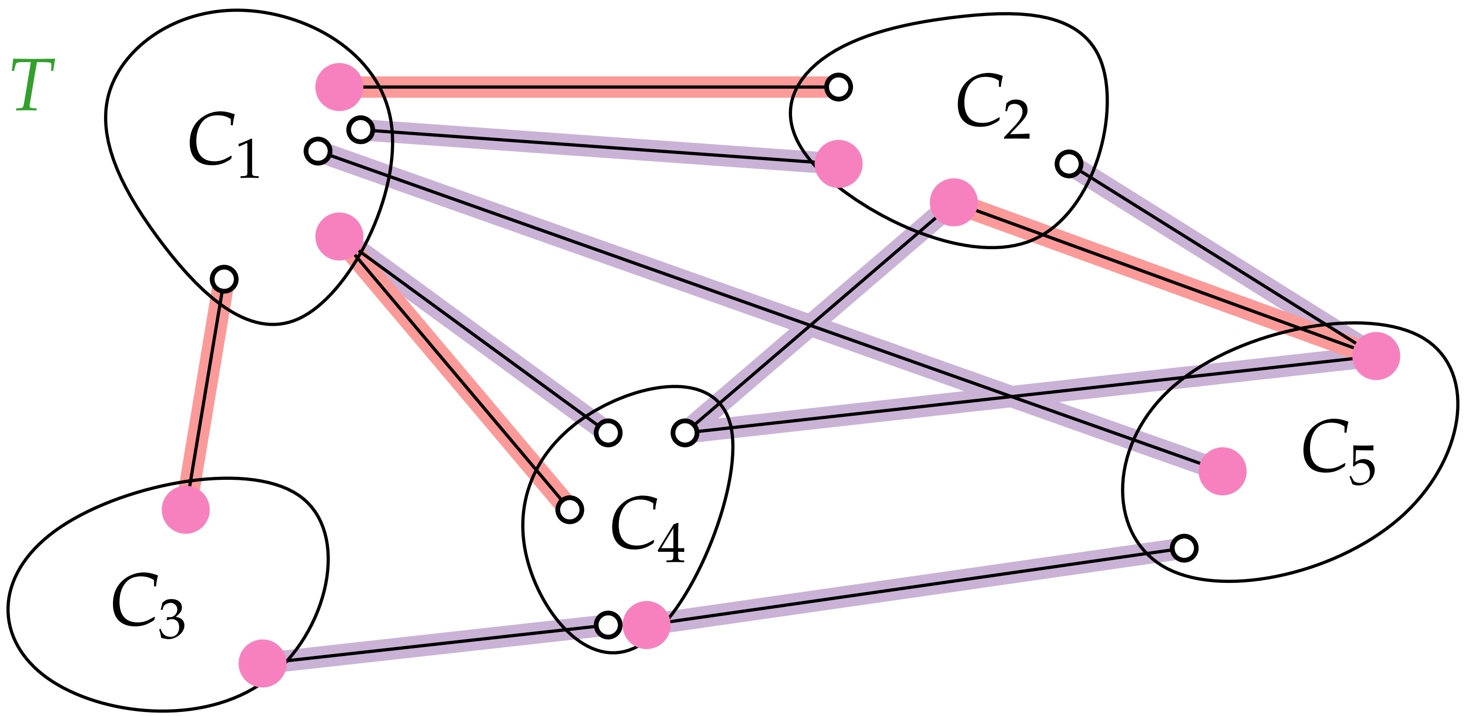
Decomposition

- Removing k edges decomposes T into $k+1$ components
- $E' :=$ {edges is G btw. different components $C_i \neq C_j$}.



Decomposition

- Removing k edges decomposes T into $k+1$ components
- $E' :=$ {edges is G btw. different components $C_i \neq C_j$}.
- $S :=$ vertex cover of E'.



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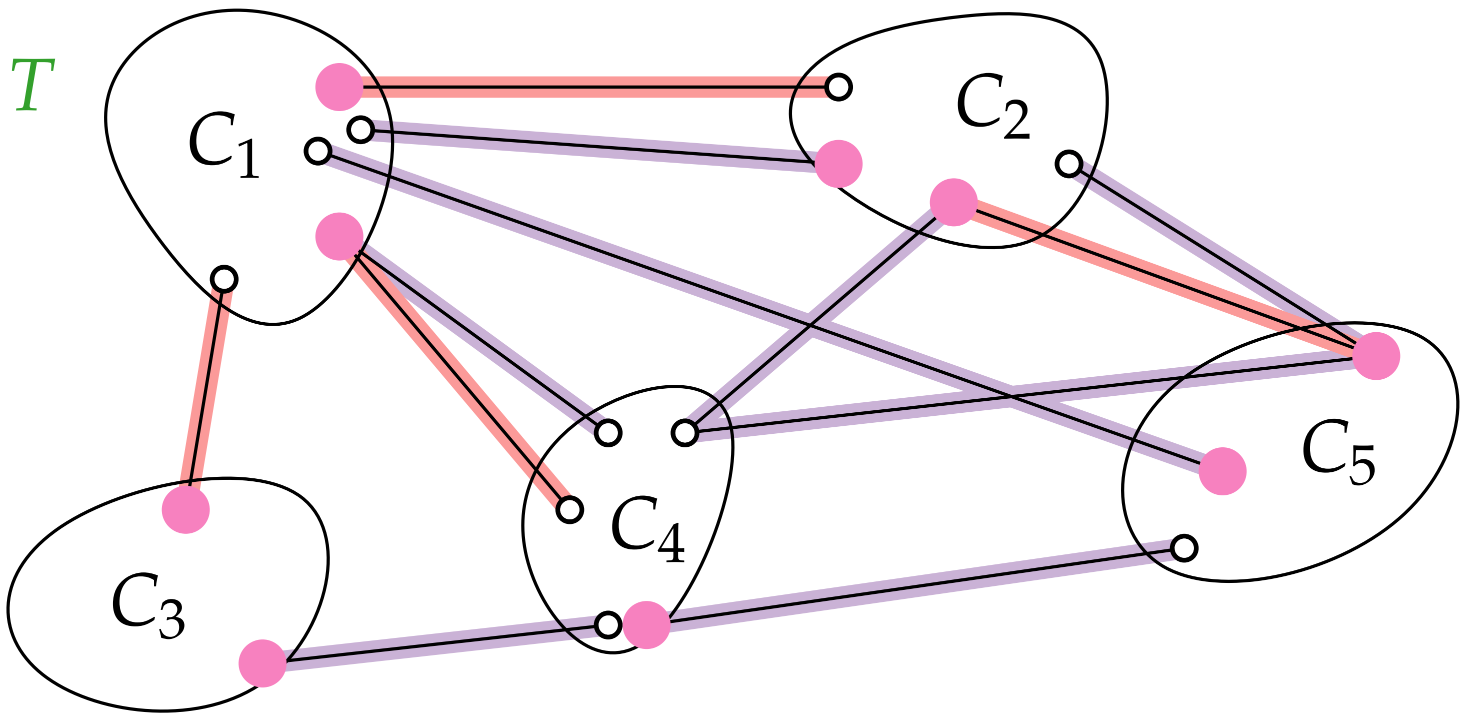

- $E(T^*) \cap E' \geq k$ for opt. spanning tree T^*

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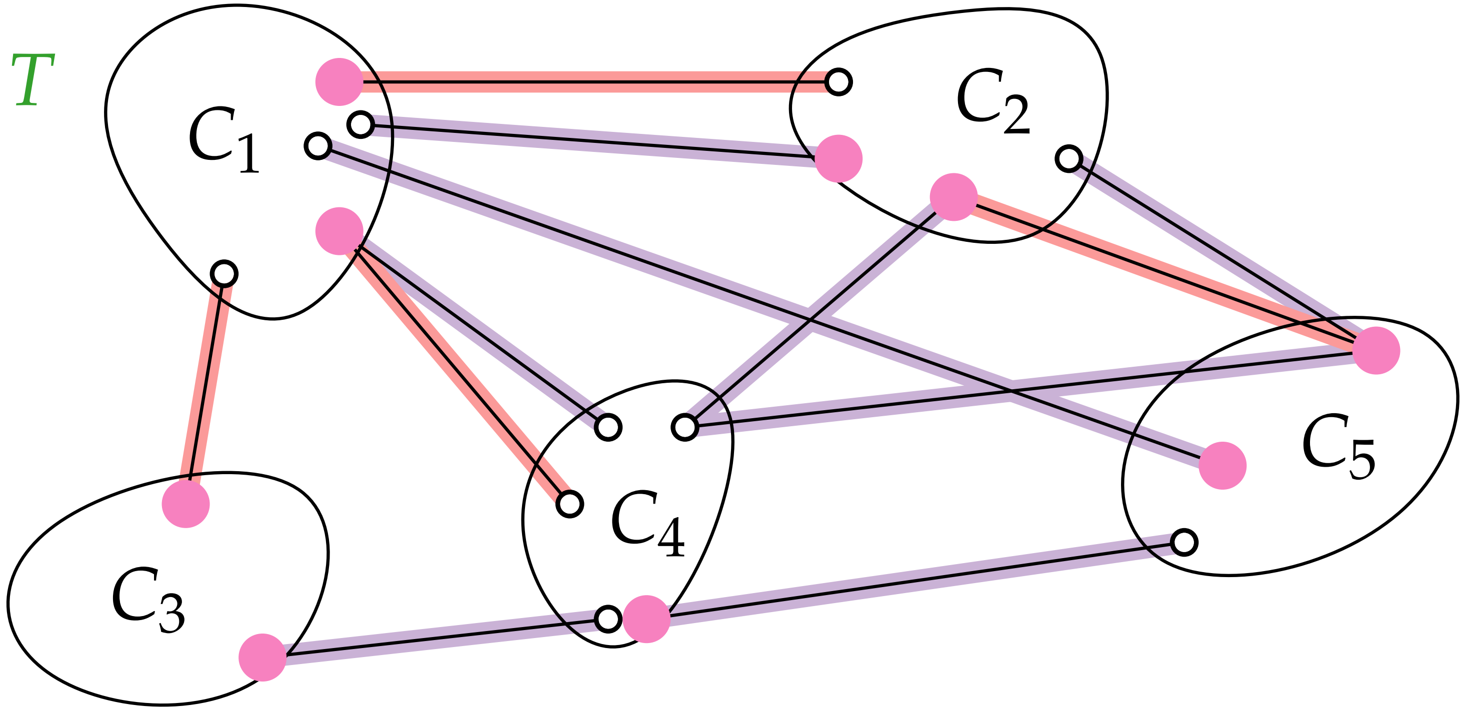

- $E(T^*) \cap E' \geq k$ for opt. spanning tree T^*
- $\sum_{v \in S} \deg_{T^*}(v) \geq k$

Decomposition $\Rightarrow$ Lower Bound for OPT

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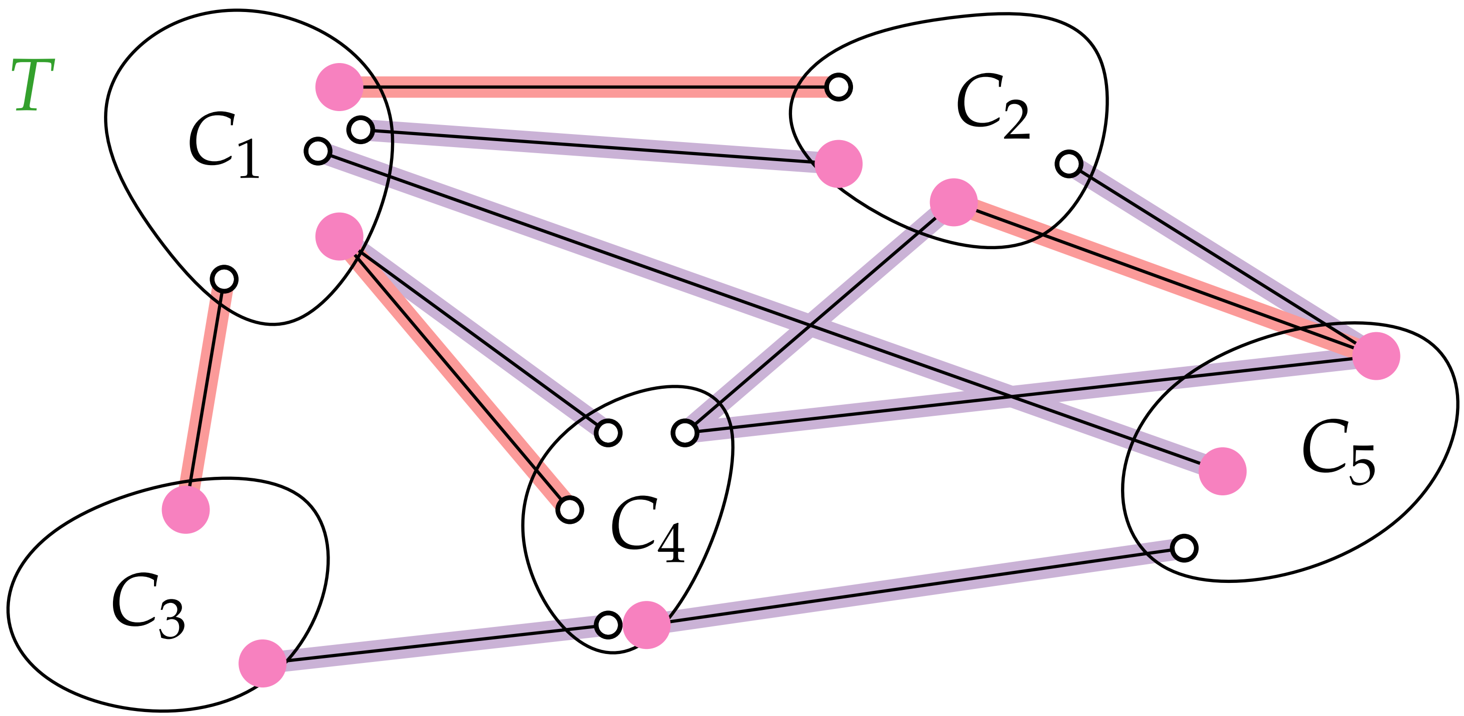

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Lemma 1.
$\Rightarrow$ OPT $\geq$

Decomposition $\Rightarrow$ Lower Bound for OPT

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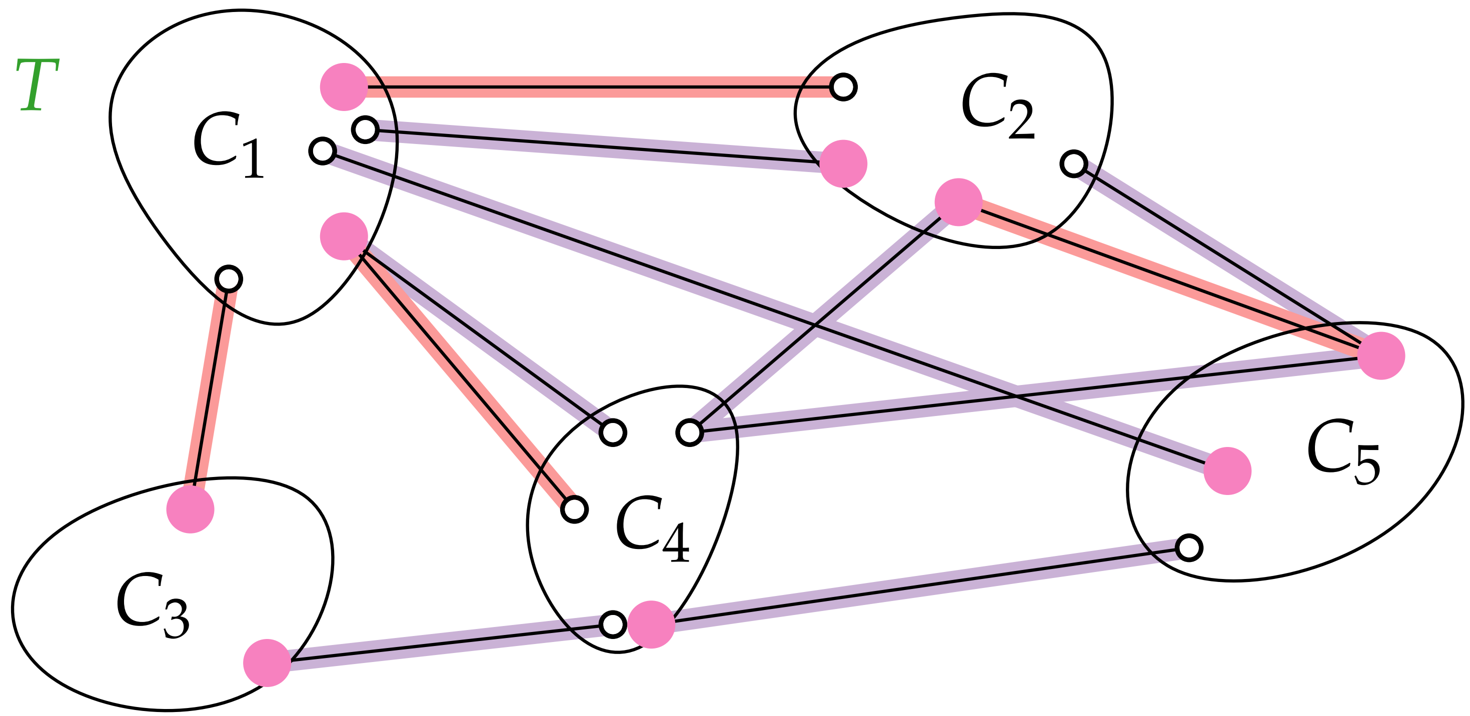


- $E(T^*) \cap E' \geq k$ for opt. spanning tree T^*
- $\sum_{v \in S} \deg_{T^*}(v) \geq k$

Lemma 1.
$\Rightarrow$ OPT $\geq k / |S|$

Approximation Algorithms

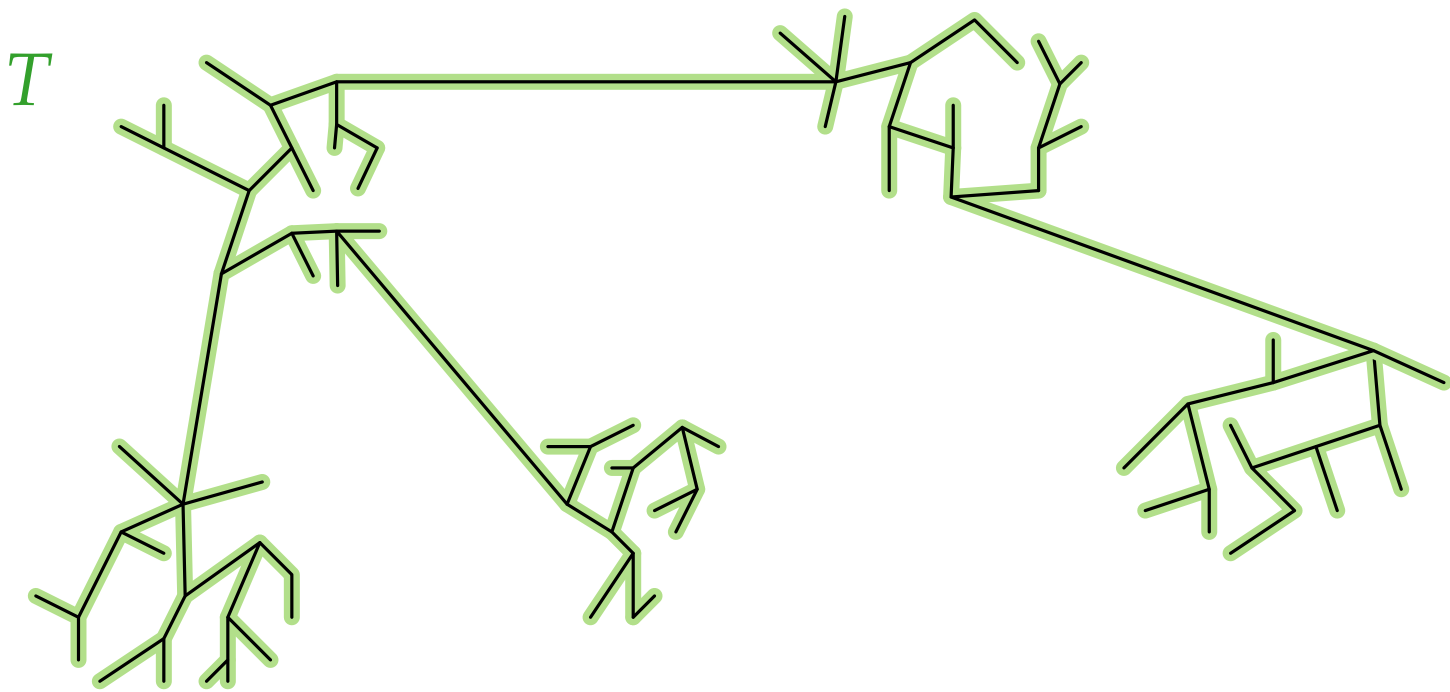
Lecture 9:
Minimum-Degree Spanning Tree
via Local Search

Part IV:
More Lemmas

Philipp Kindermann

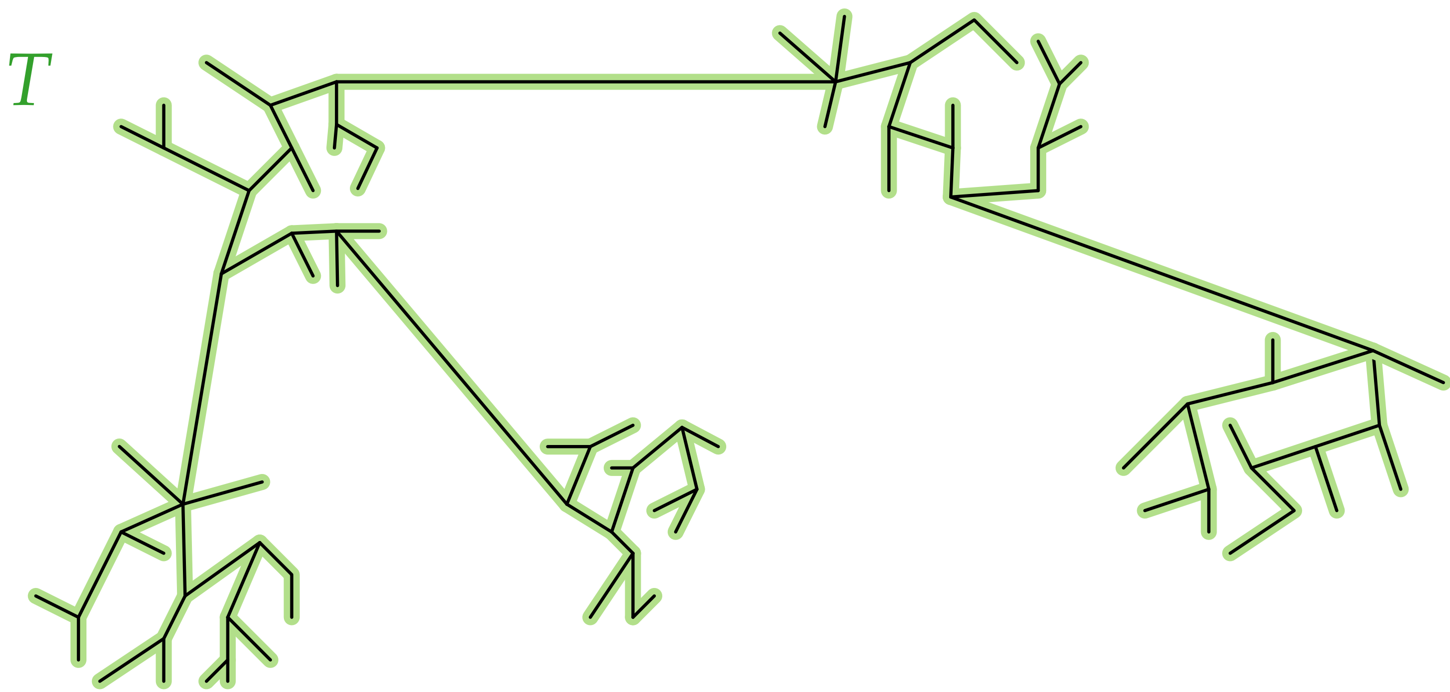
Summer Semester 2020

More Lemmas



More Lemmas

Let S_i be the vertices v in T with $\deg_T(v) \geq i$.



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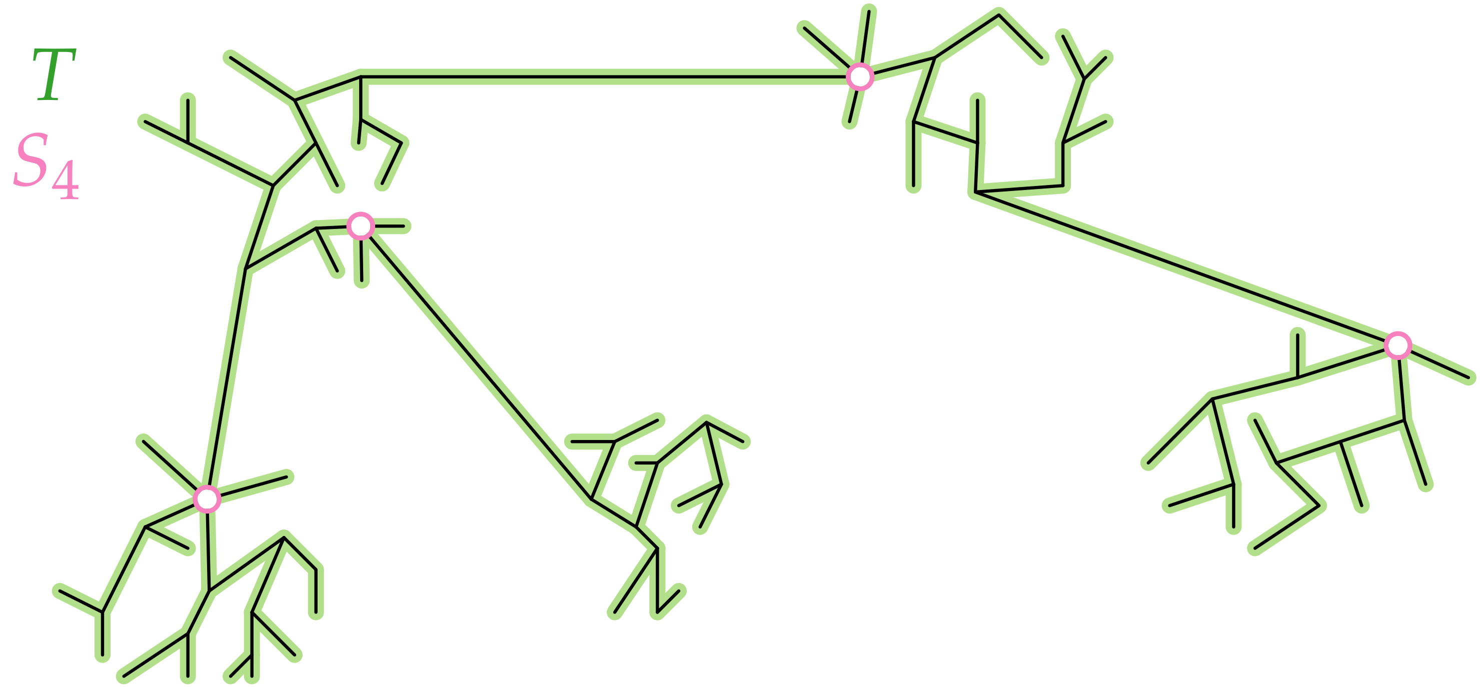
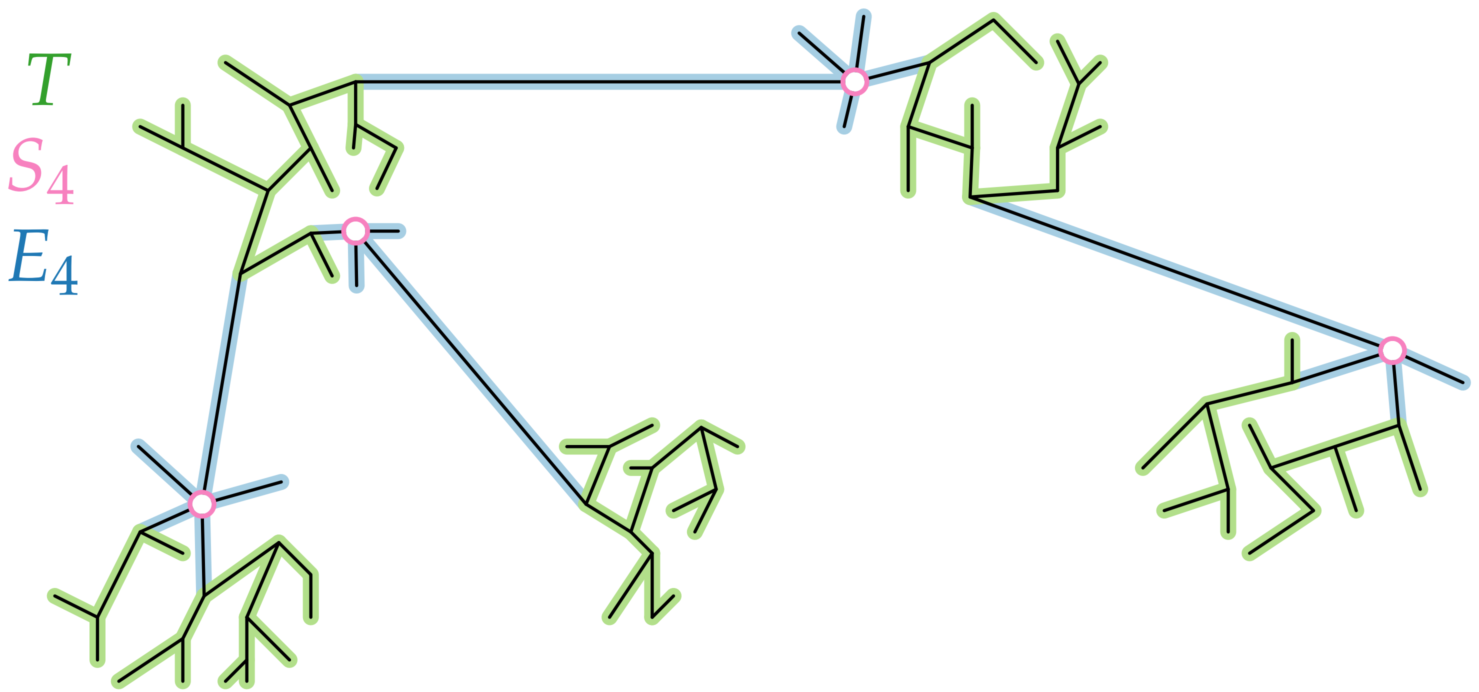


More Lemmas

Let S_i be the vertices v in T with $\deg_T(v) \geq i$.
Let E_i be the edges in T incident to S_i.



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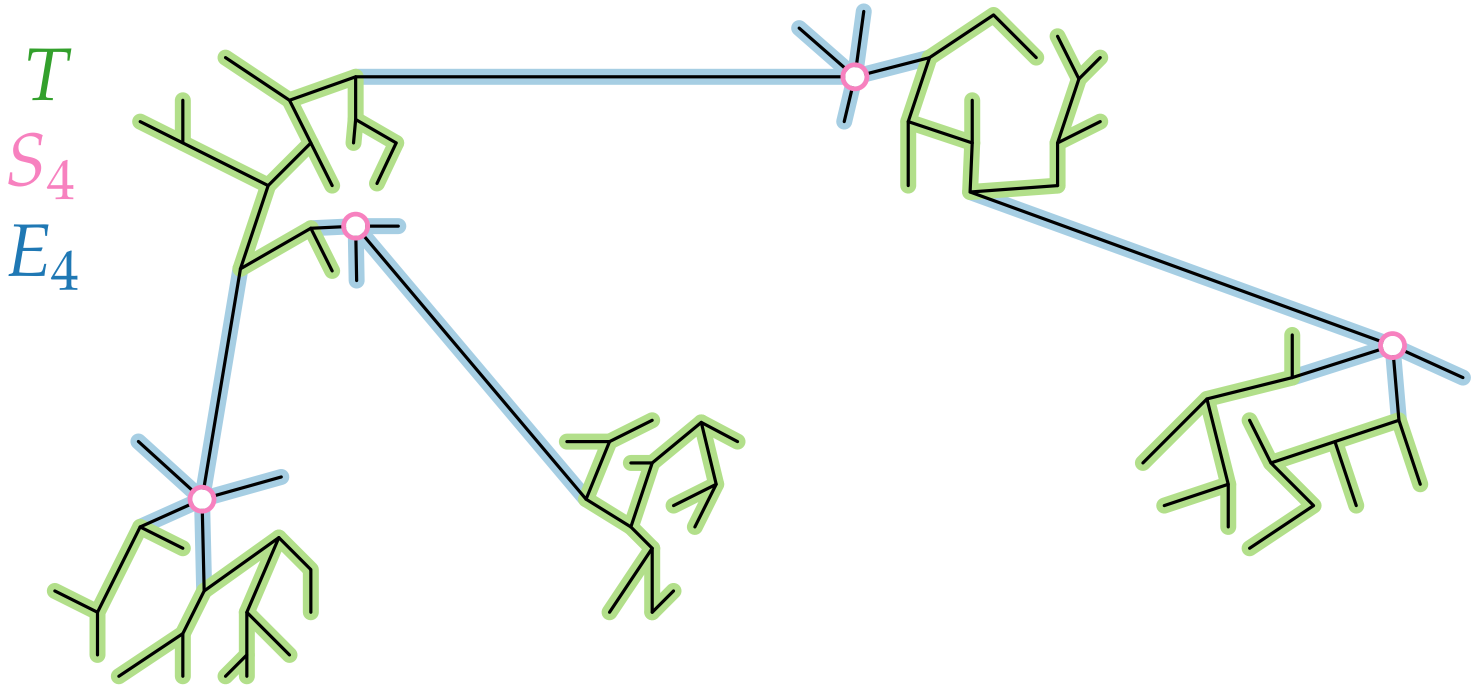
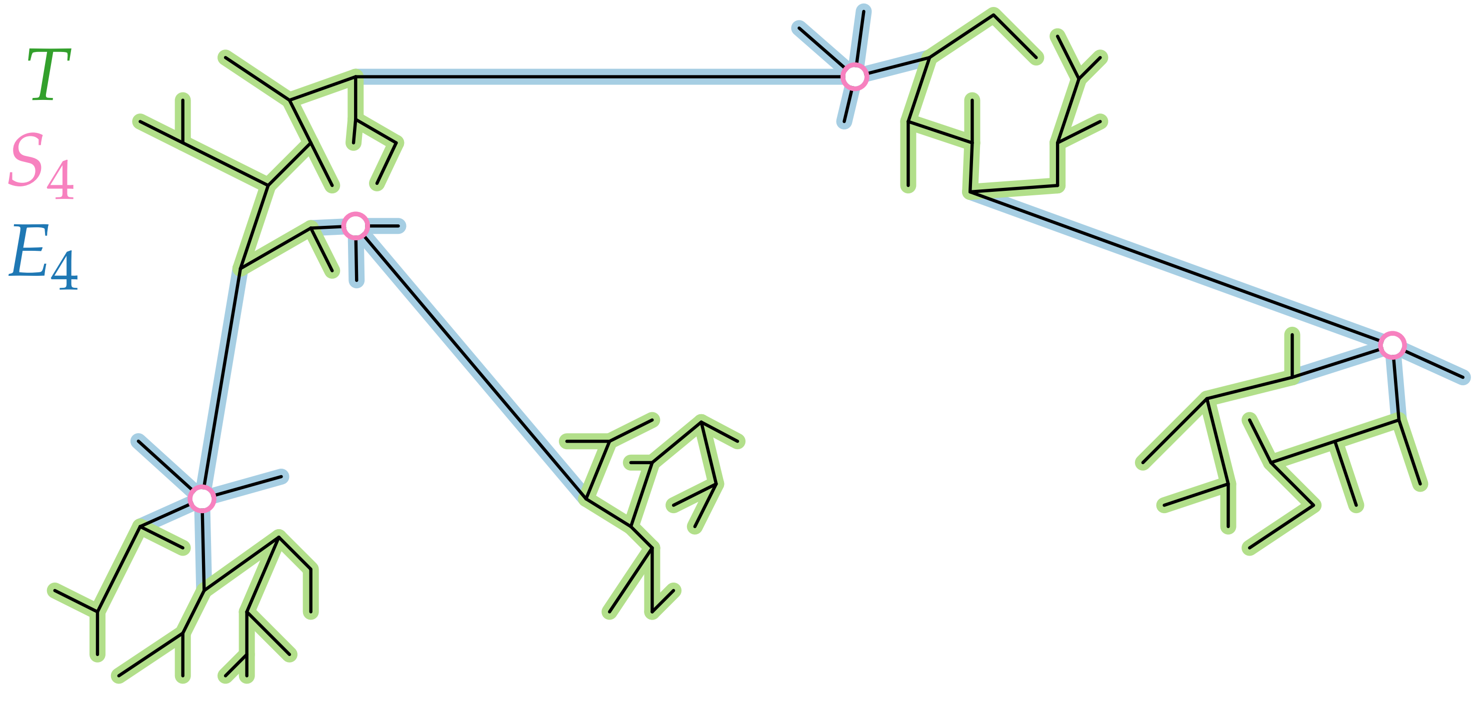


More Lemmas

$\Rightarrow S_1 \supseteq S_2 \supseteq \ldots$

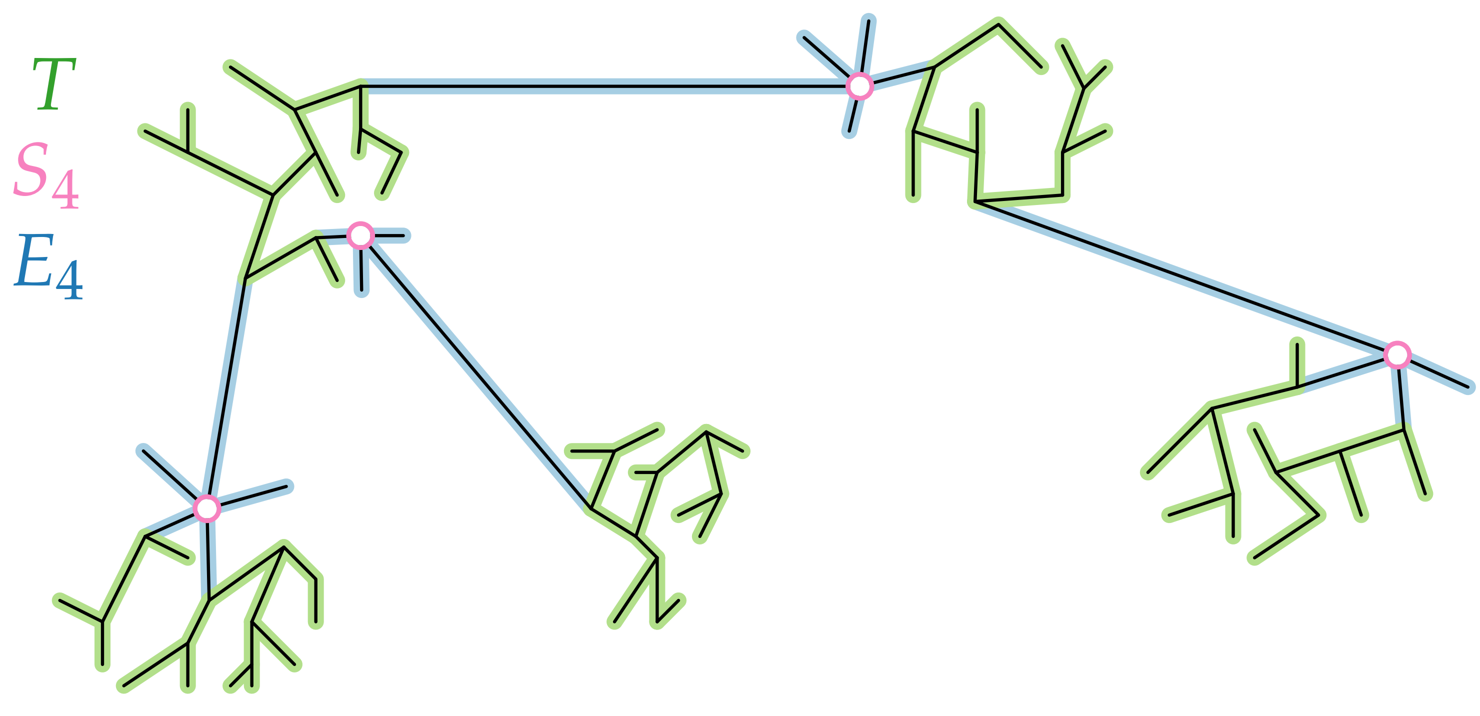
Let S_i be the vertices v in T with $\deg_T(v) \geq i$.
Let E_i be the edges in T incident to S_i.



More Lemmas

Let S_i be the vertices v in T with $\deg_T(v) \geq i$.
Let E_i be the edges in T incident to S_i.

$\Rightarrow S_1 \supseteq S_2 \supseteq \ldots$
$\Rightarrow S_1 = V(G)$



More Lemmas

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$\Rightarrow S_1 \supseteq S_2 \supseteq \dots$
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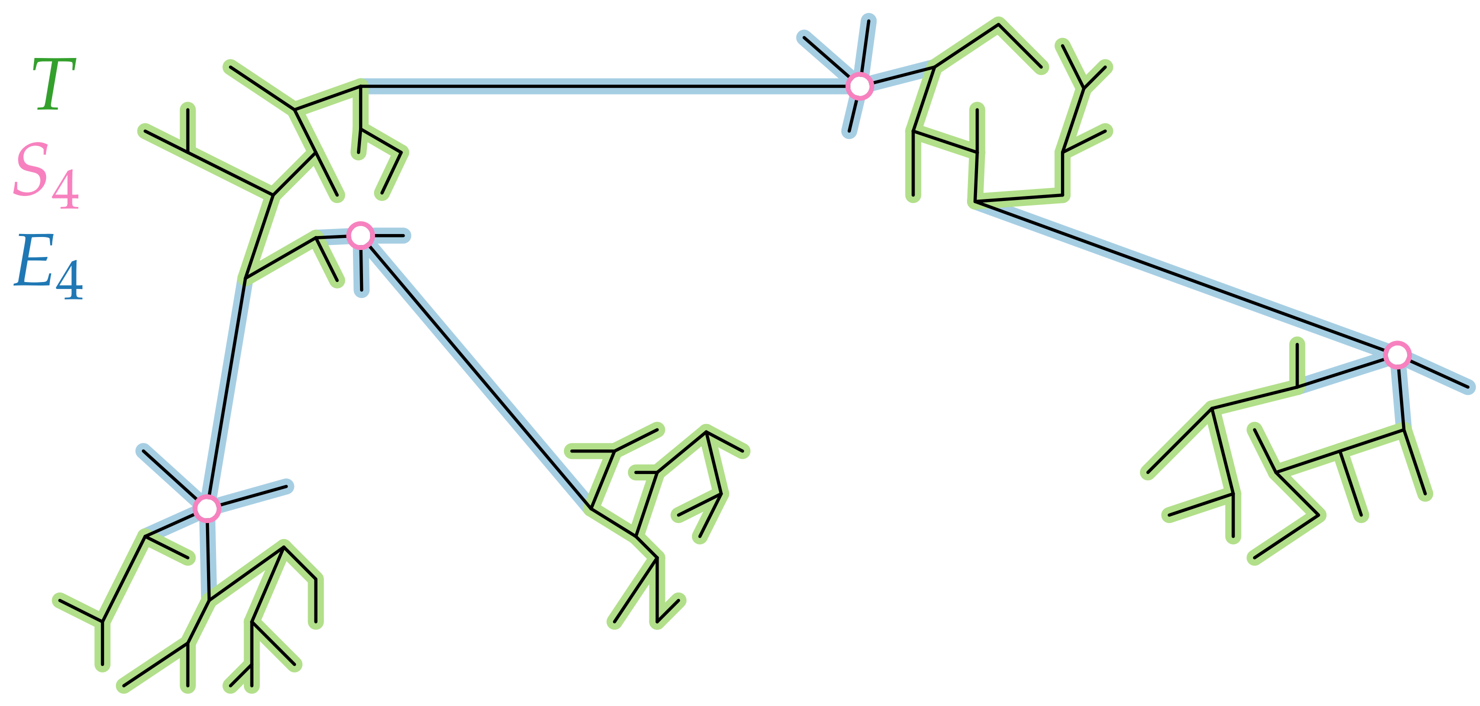

More Lemmas

Let S_i be the vertices v in T with $\deg_T(v) \geq i$.
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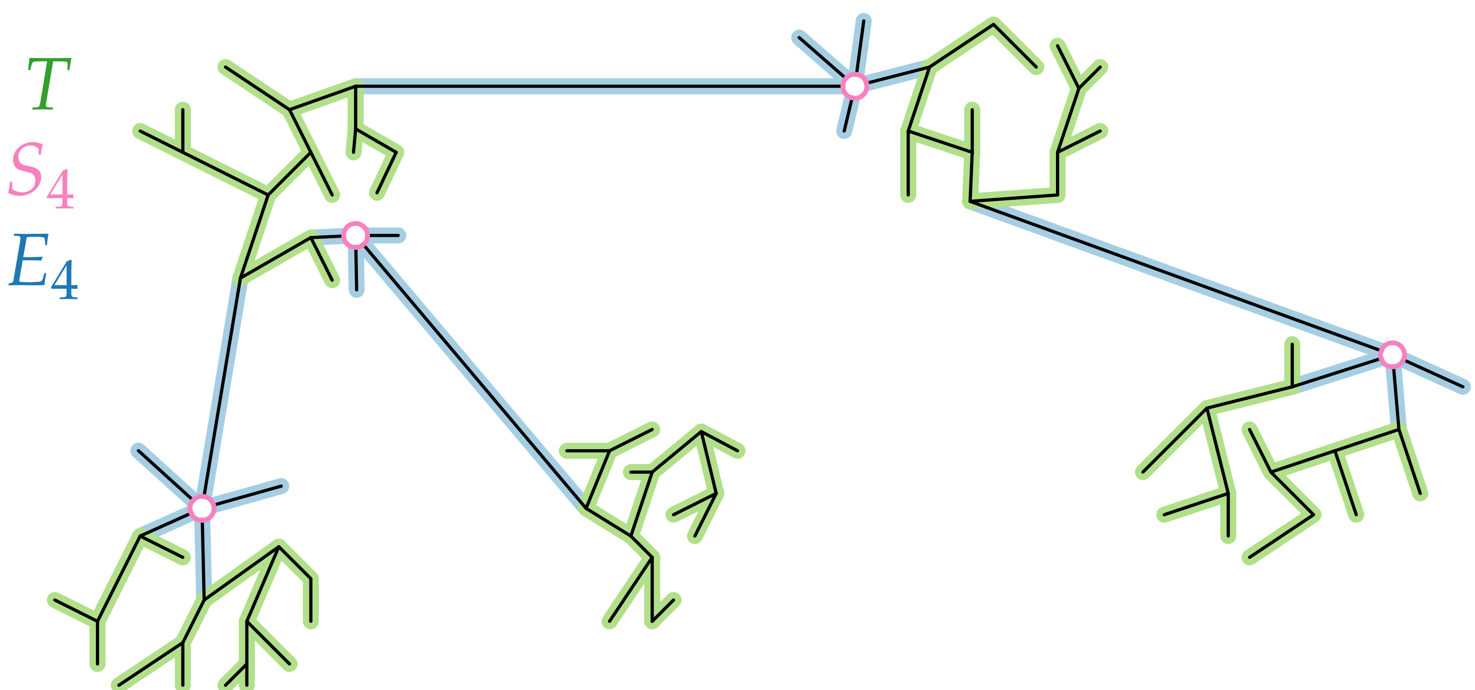
$\Rightarrow S_1 \supseteq S_2 \supseteq \dots$
$\Rightarrow S_1 = V(G)$
$\Rightarrow E_1 = E(T)$

Lemma 2. There is some $i \geq \Delta(T) - \ell + 1$ with $|S_{i-1}| \leq 2|S_i|$.



More Lemmas

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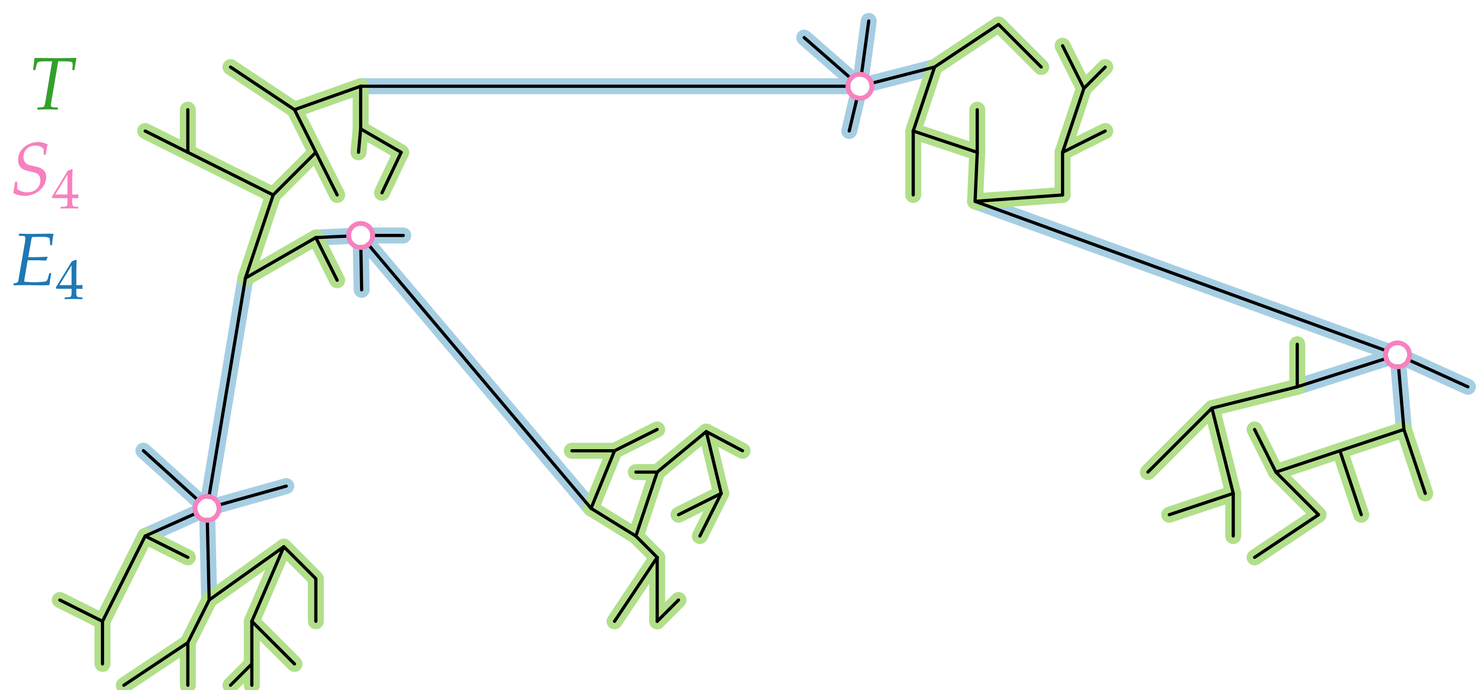
Proof. $|S_{\Delta(T)-\ell}| > 2^{\ell} |S_{\Delta(T)}|$



More Lemmas

Let S_i be the vertices v in T with $\deg_T(v) \geq i$.
Let E_i be the edges in T incident to S_i.

$\Rightarrow S_1 \supseteq S_2 \supseteq \dots$
$\Rightarrow S_1 = V(G)$
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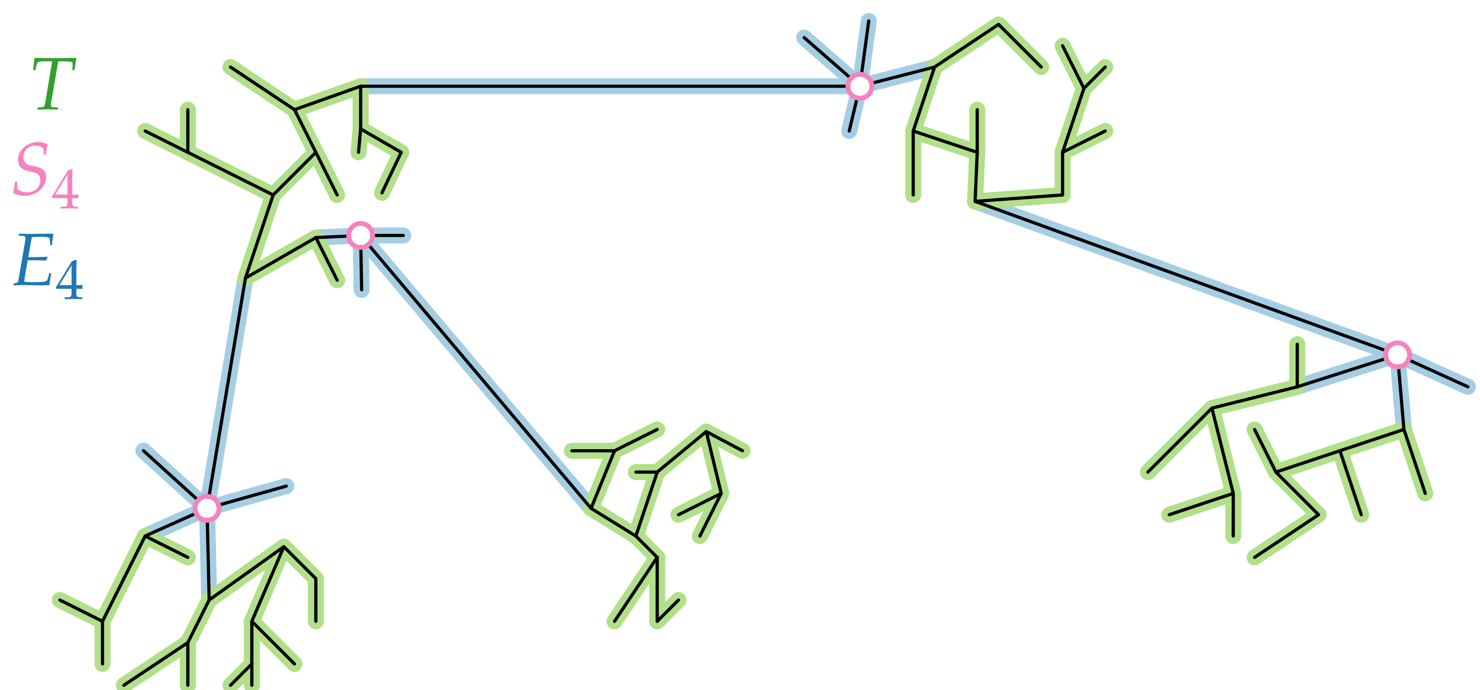
Lemma 2. There is some $i \geq \Delta(T) - \ell + 1$ with $|S_{i-1}| \leq 2|S_i|$.

Proof. $|S_{\Delta(T)-\ell}| > 2^{\ell}|S_{\Delta(T)}| = 2^{\lceil \log_2 n \rceil}|S_{\Delta(T)}|$

$\ell = \lceil \log_2 n \rceil$



More Lemmas

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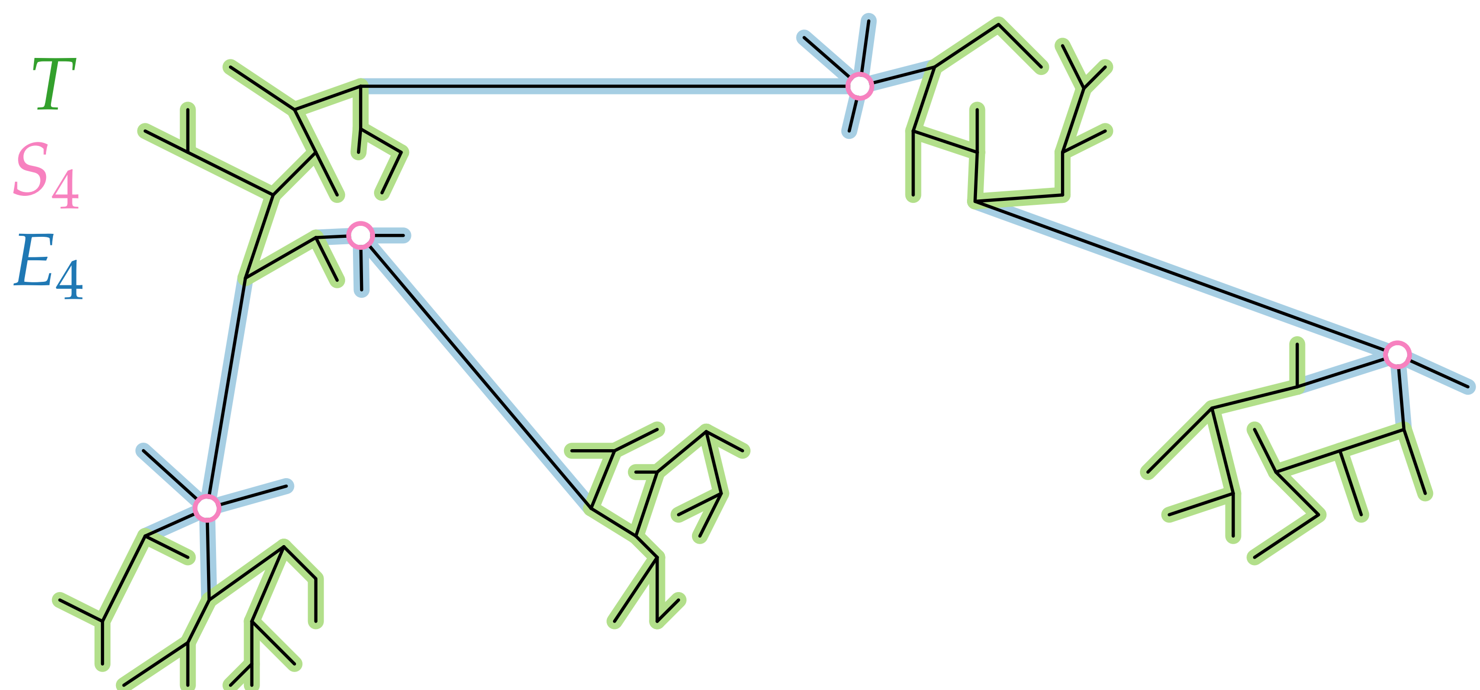

More Lemmas

Let S_i be the vertices v in T with $\deg_T(v) \geq i$.
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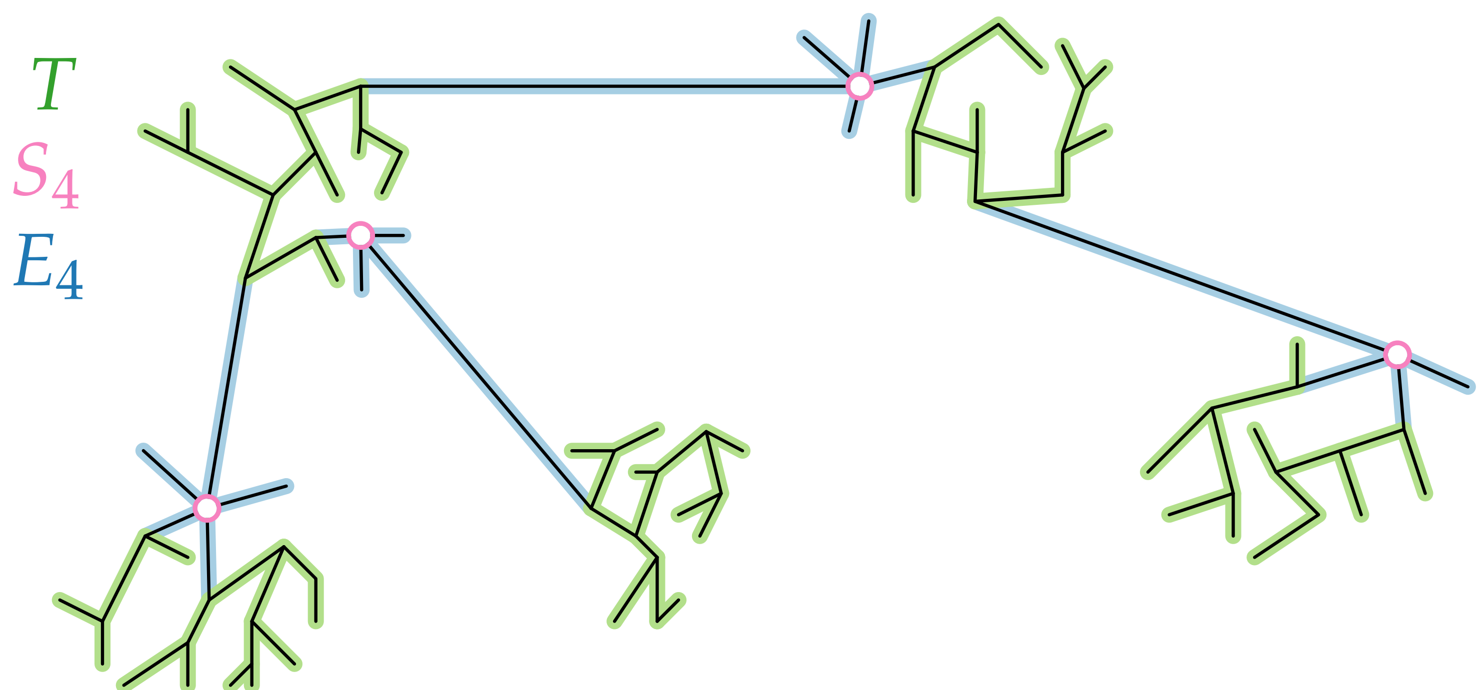
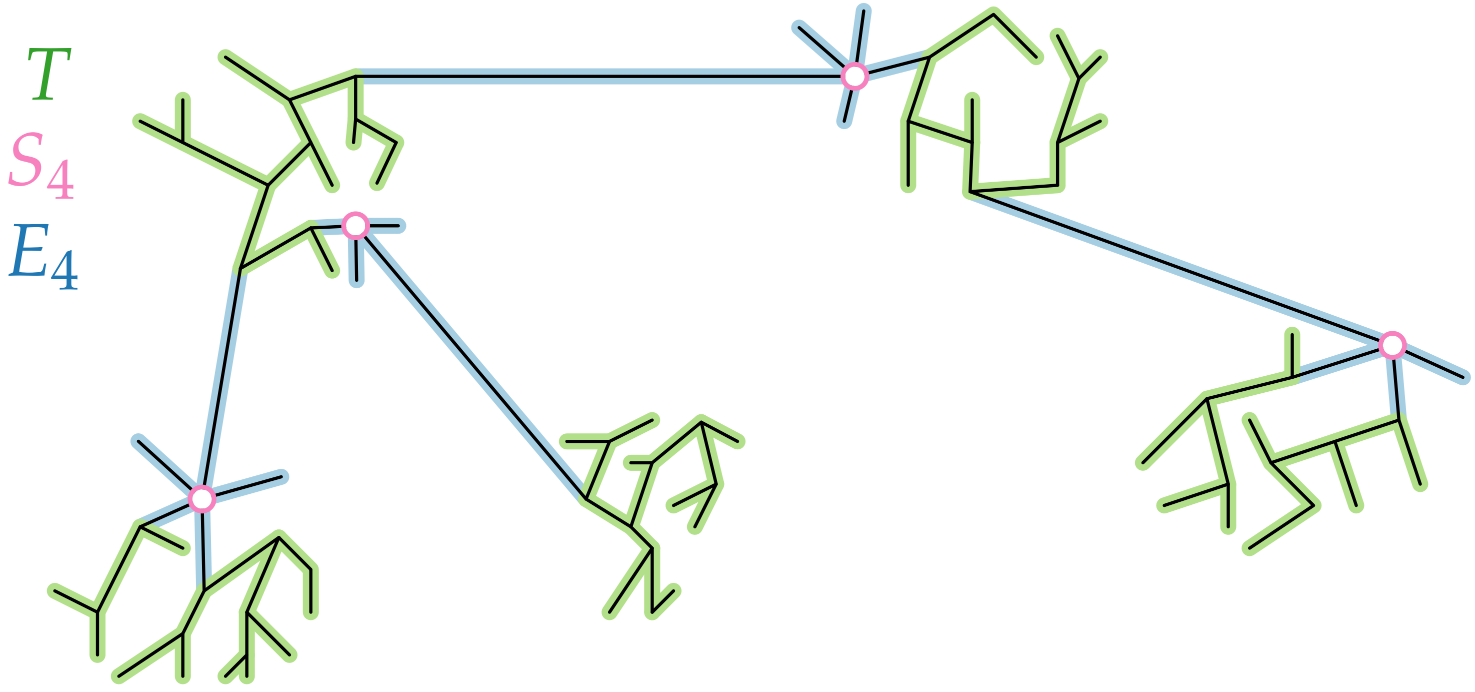


More Lemmas

Lemma 3. For $i \geq \Delta(T) - \ell + 1$,



More Lemmas

Lemma 3. For $i \geq \Delta(T) - \ell + 1$,
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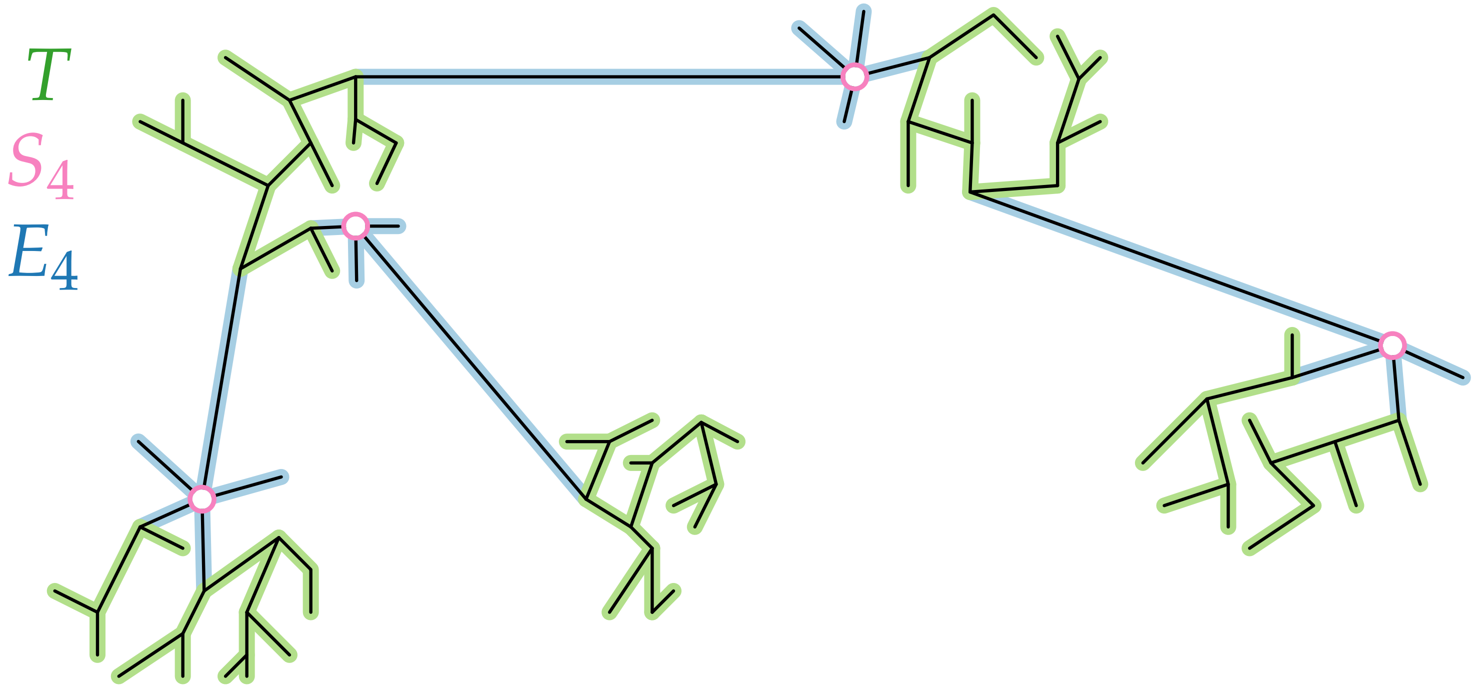

More Lemmas

Lemma 3. For $i \geq \Delta(T) - \ell + 1$,
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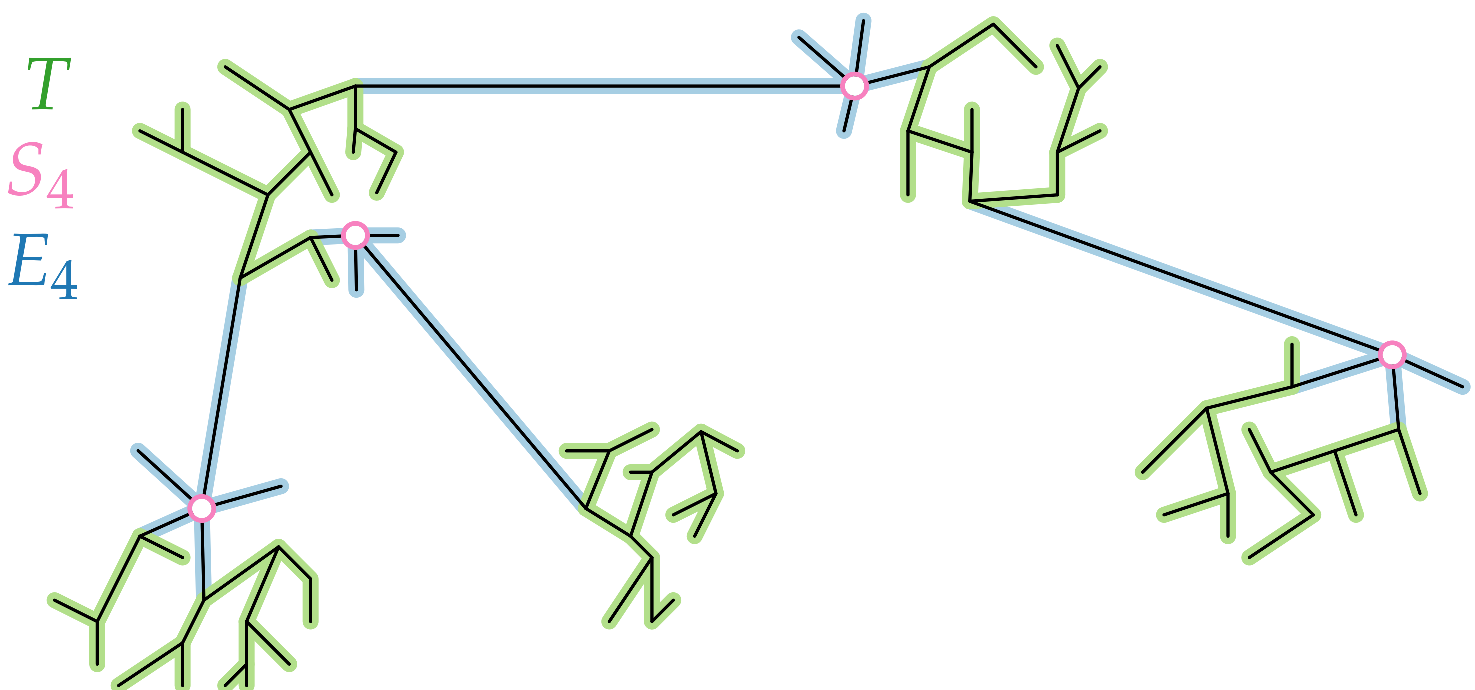

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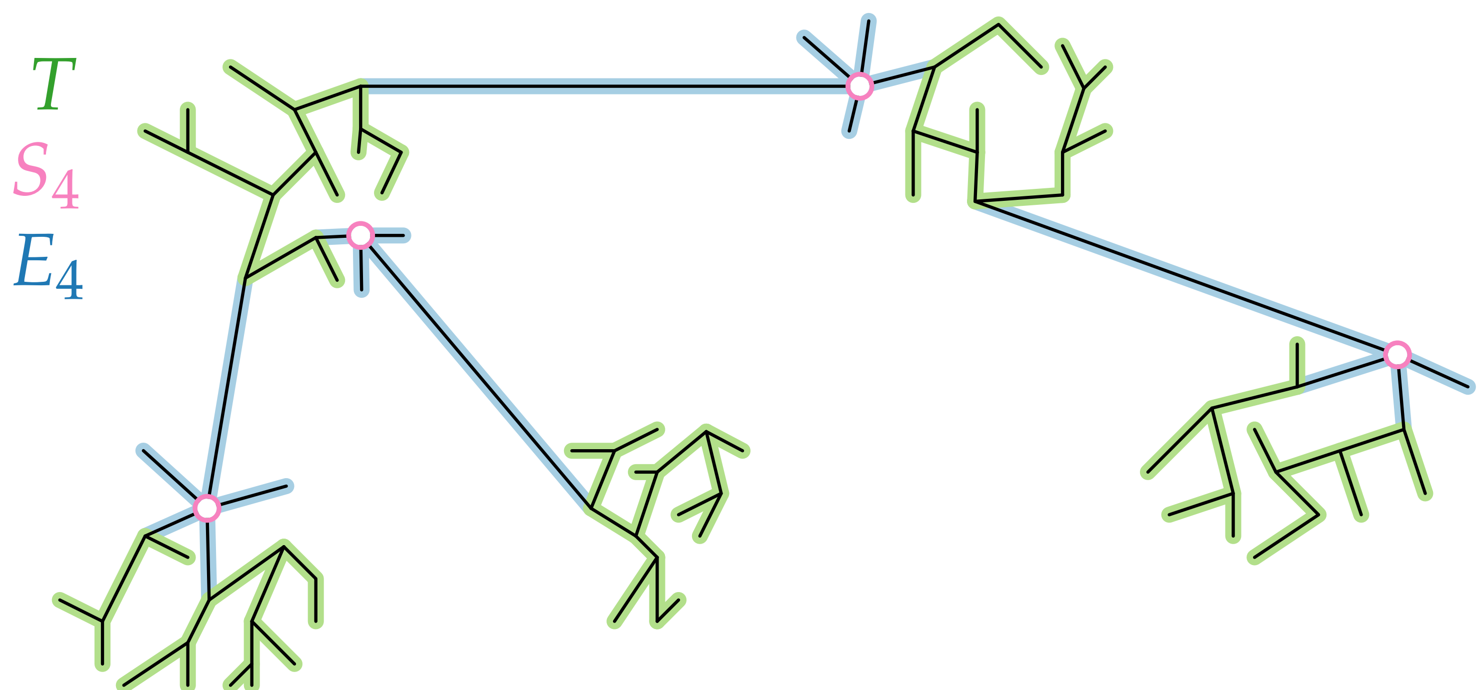
Proof. (i) $|E_i| \geq$



More Lemmas

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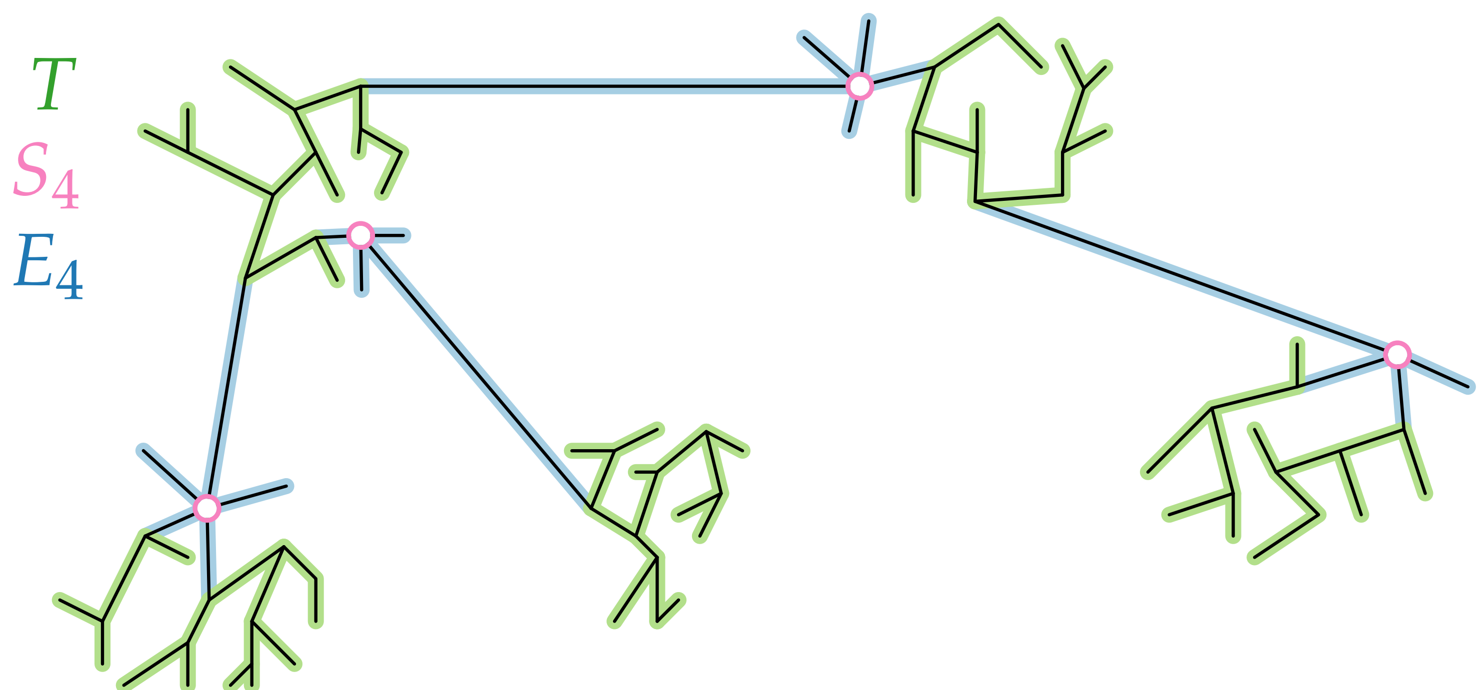
Proof. (i) $|E_i| \geq i|S_i|$

vertex-deg



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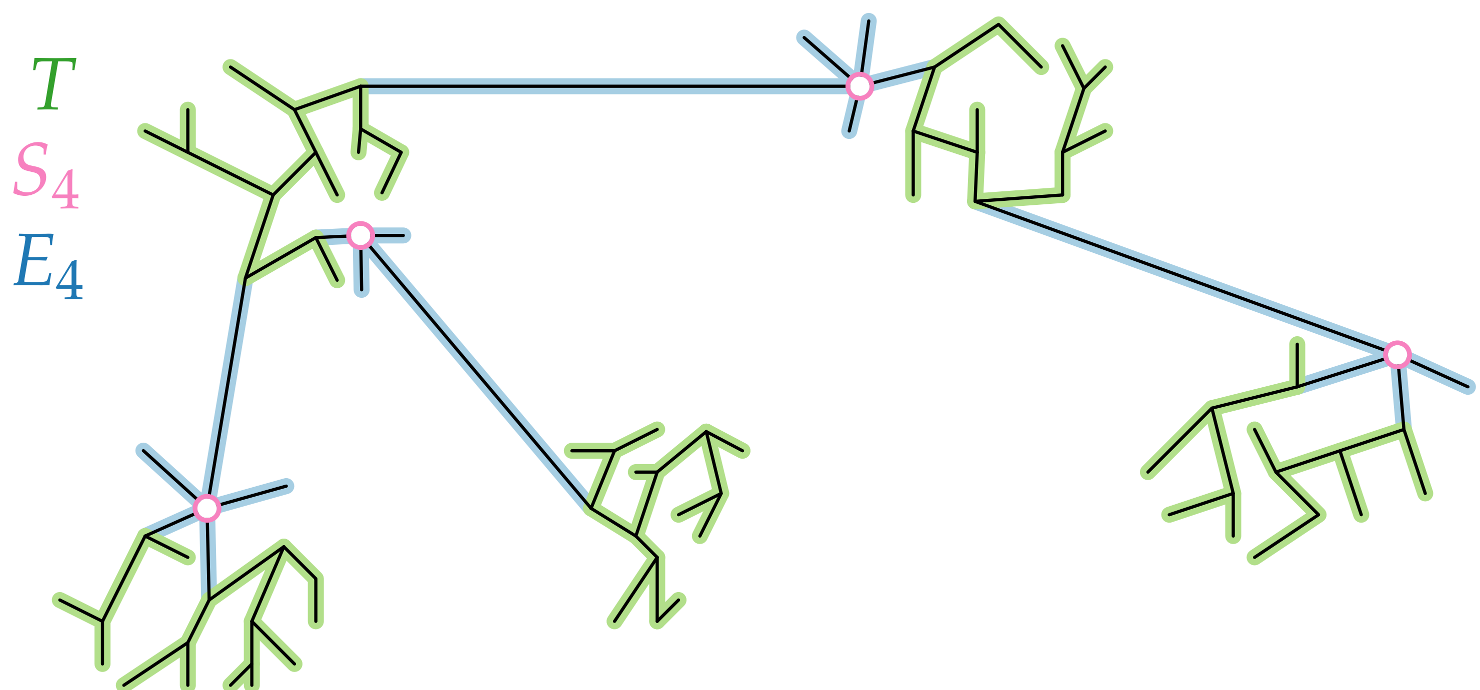
Proof. (i) $|E_i| \geq i|S_i| - (|S_i| - 1)$

vertex-deg counted twice?



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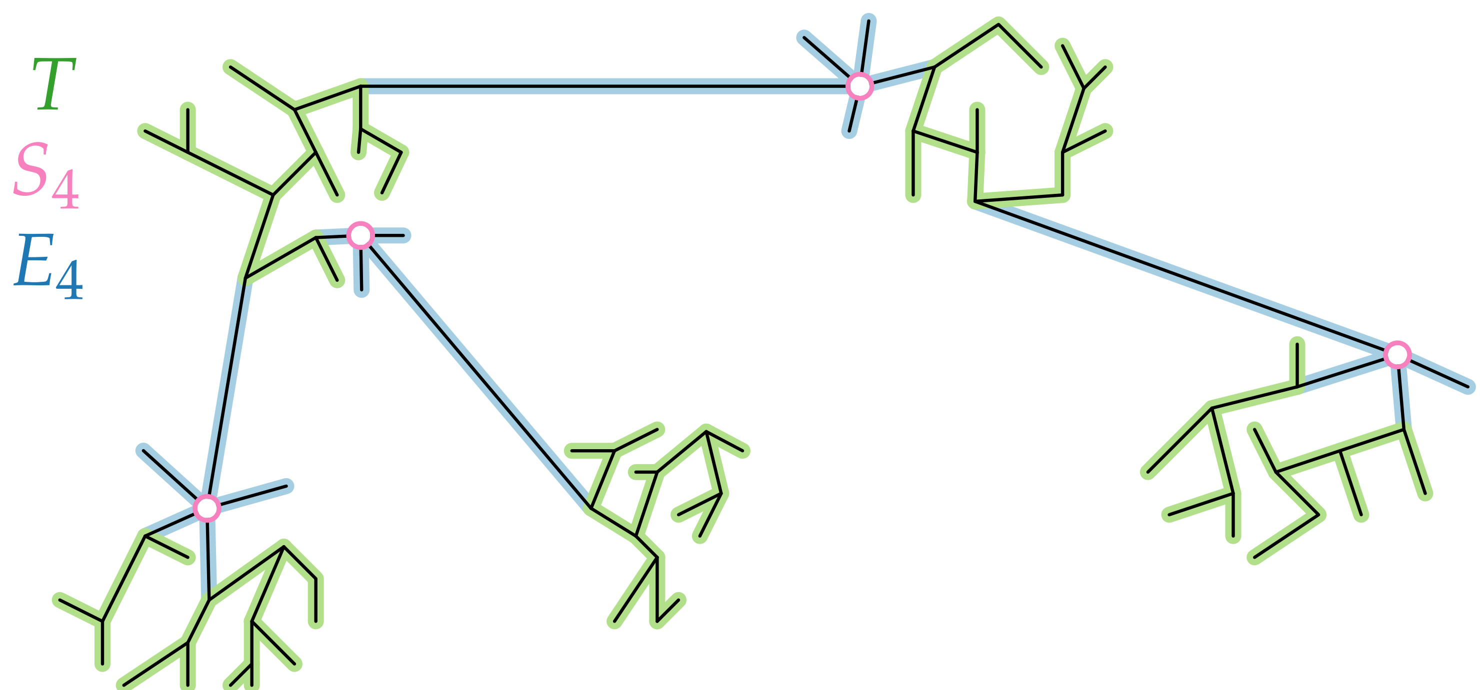
vertex-deg   counted twice?



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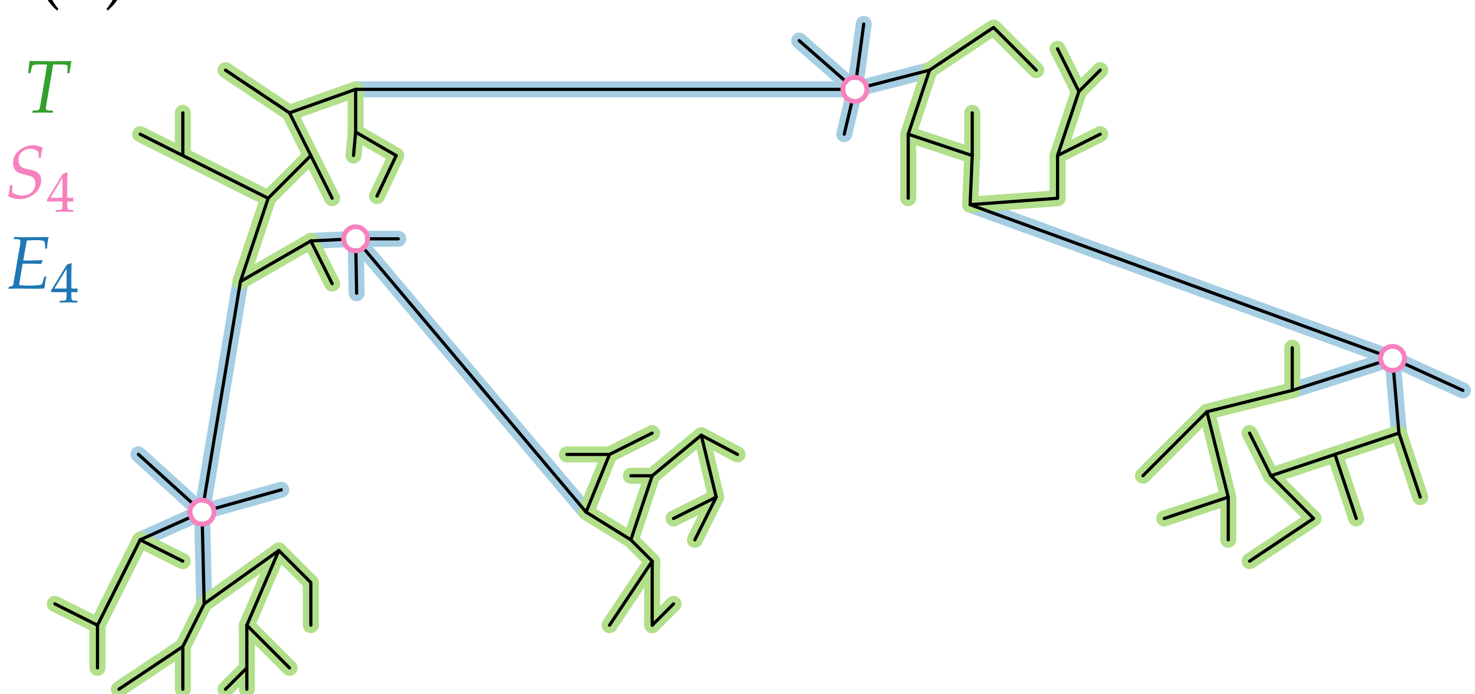
vertex-deg counted twice?

(ii)



More Lemmas

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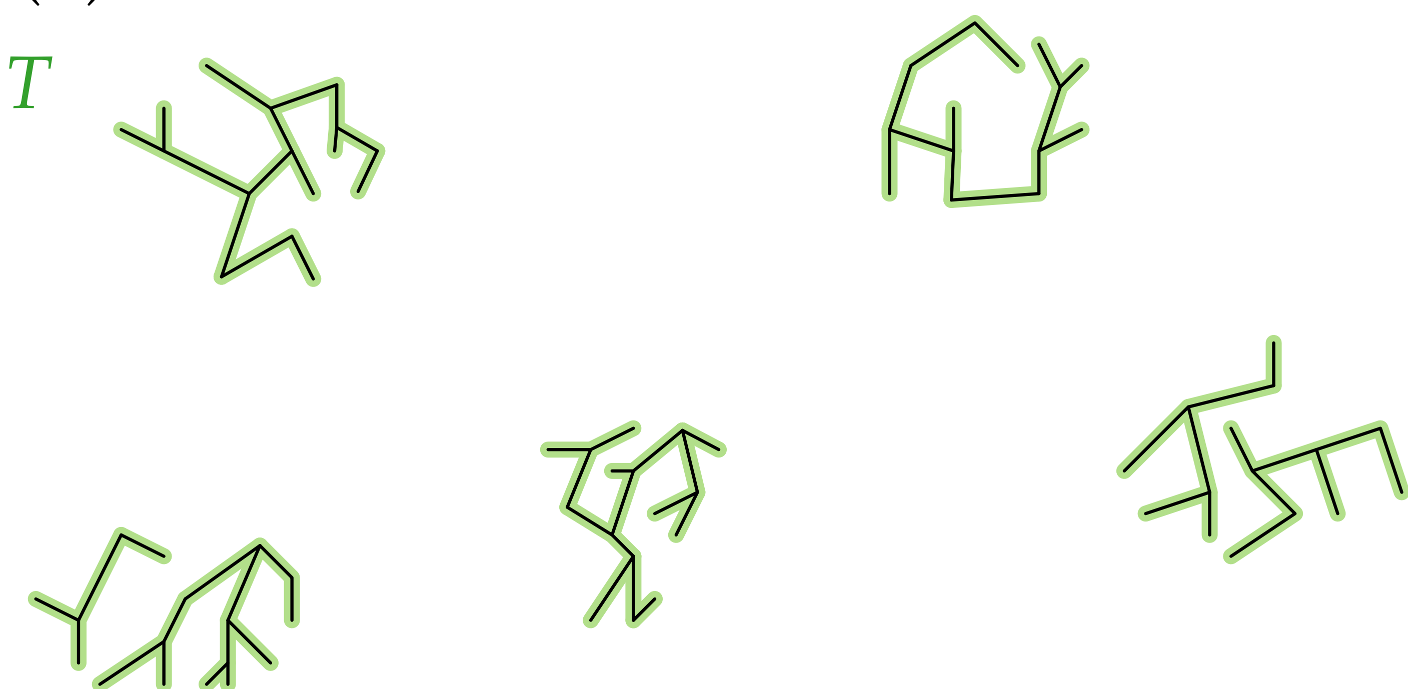

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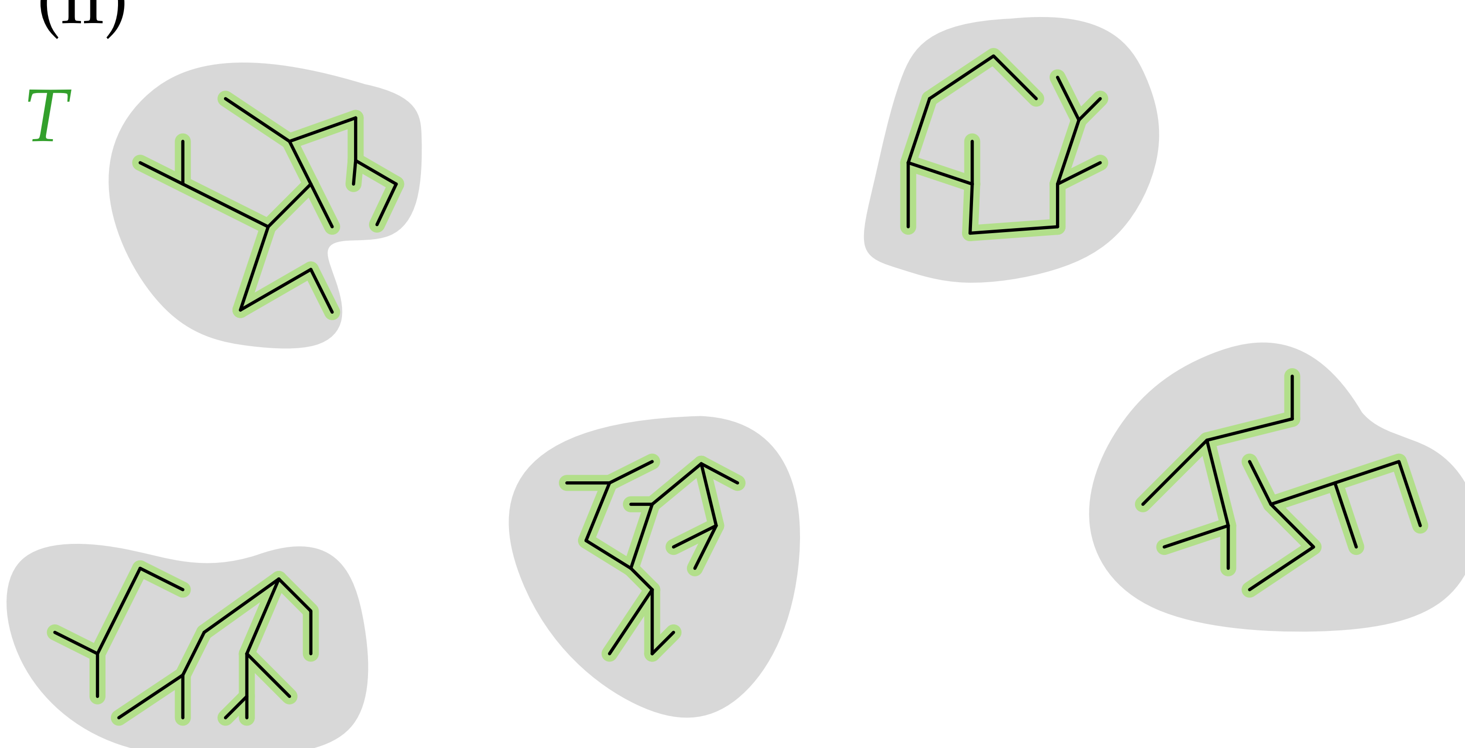

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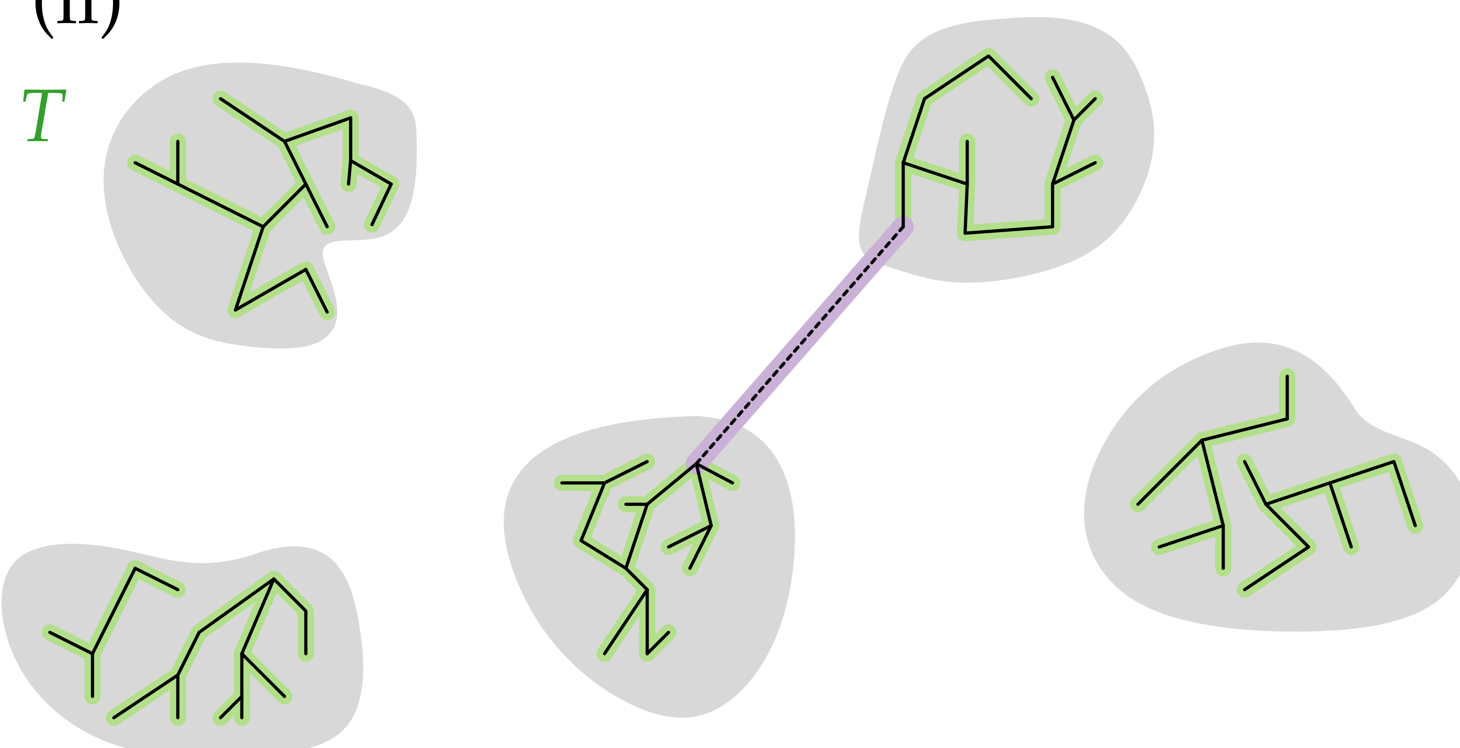
Proof. (i) $|E_i| \geq i|S_i| - (|S_i| - 1) = (i-1)|S_i| + 1$

vertex-deg counted twice?

(ii)



More Lemmas

Lemma 3. For $i \geq \Delta(T) - \ell + 1$,
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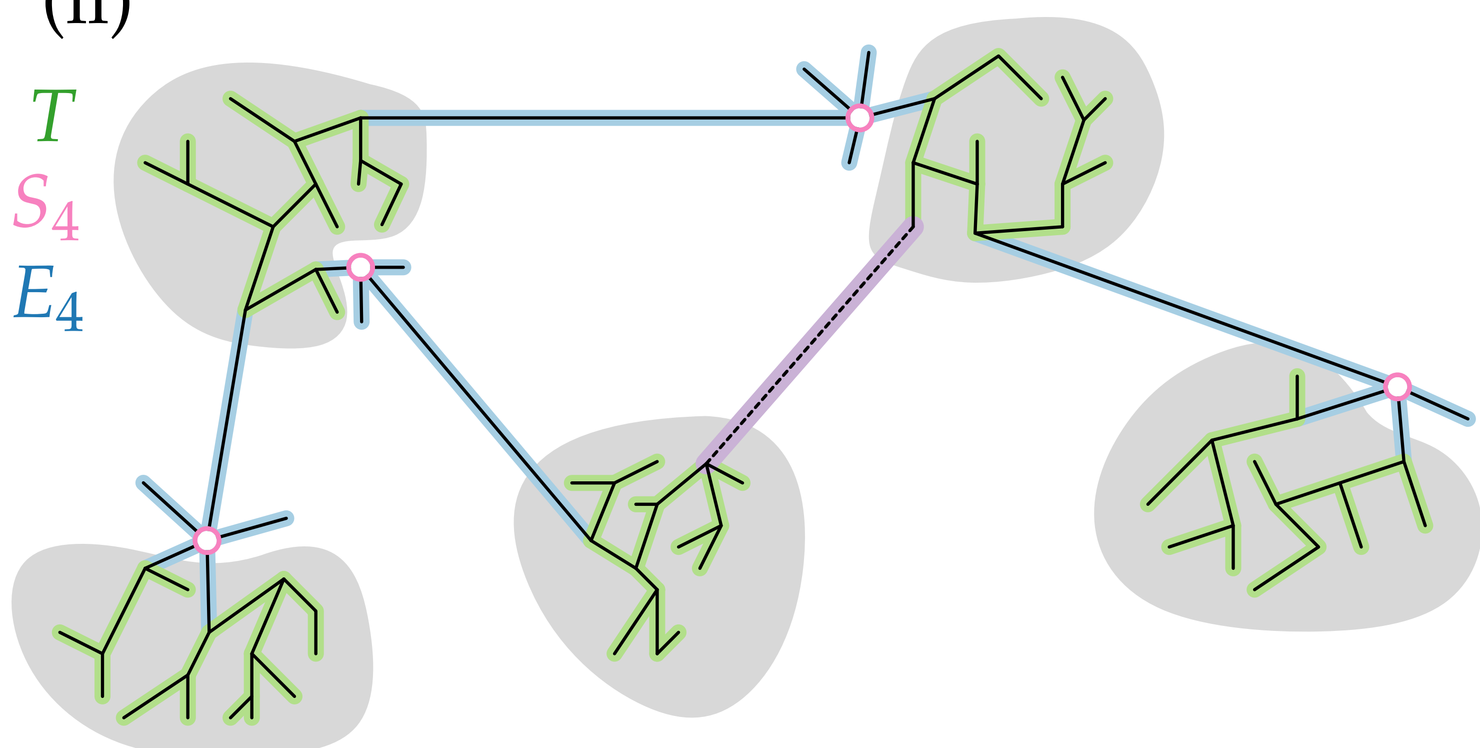

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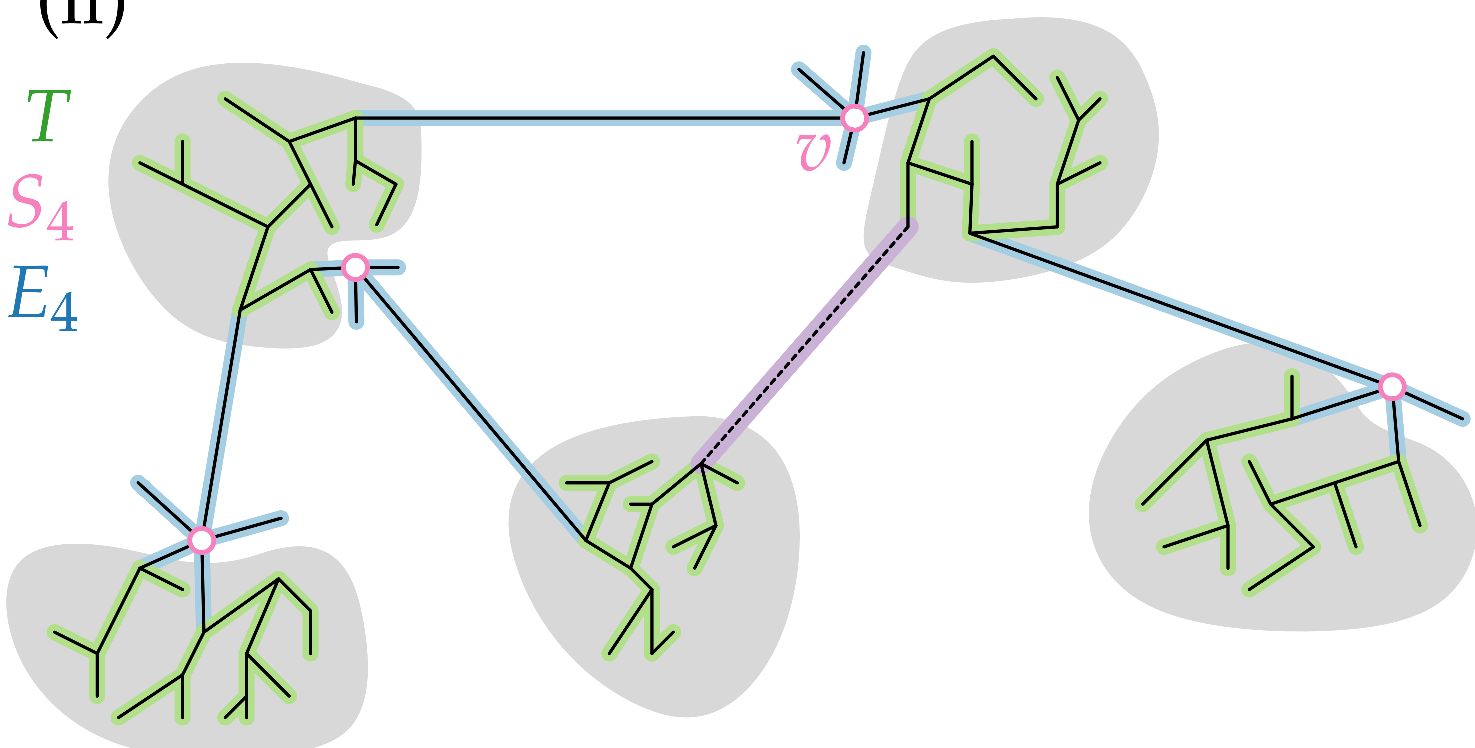

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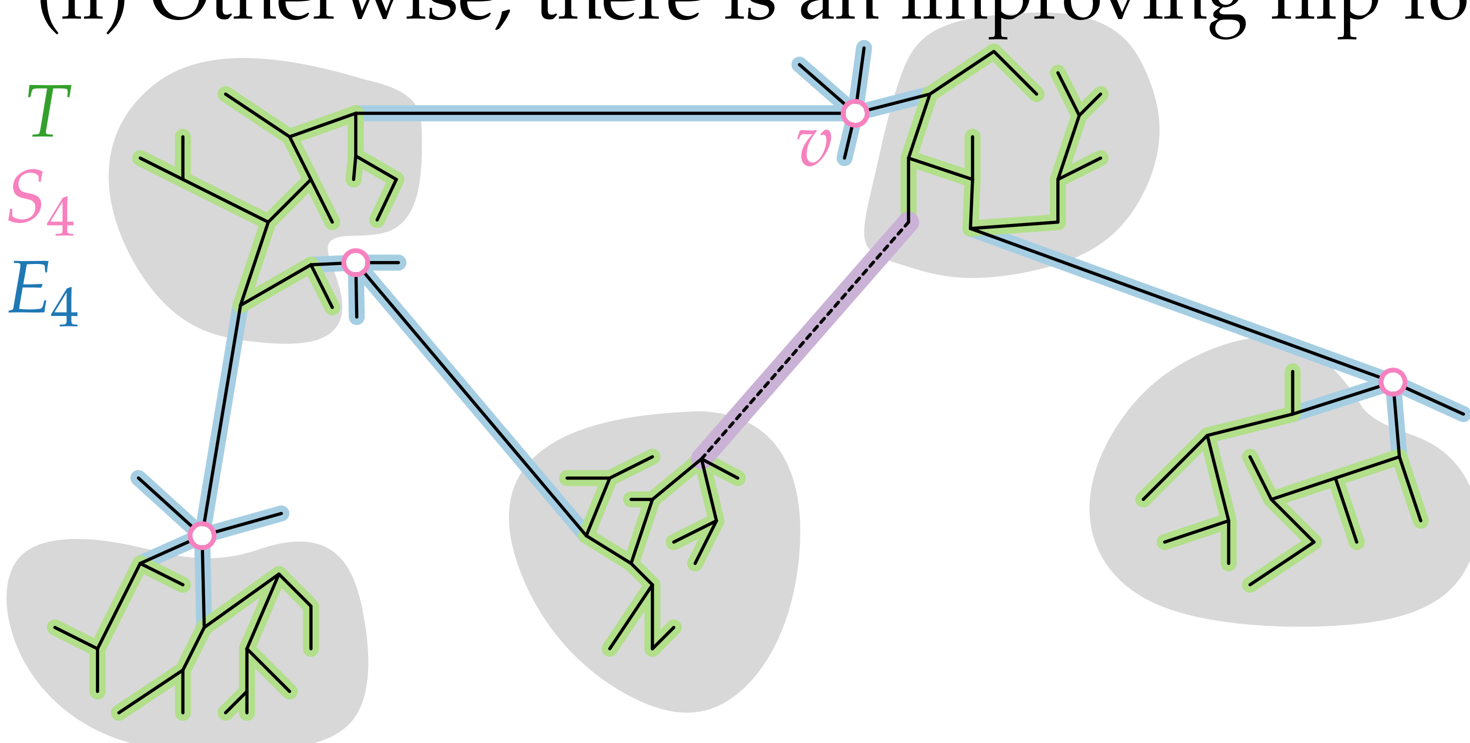
(ii) Otherwise, there is an improving flip for $v \in S_i$.



Approximation Algorithms

Lecture 9:
Minimum-Degree Spanning Tree via Local Search

Part V:
Approximation Factor

Philipp Kindermann

Summer Semester 2020

Approximation Factor

Approximation Factor

[Fürer & Raghavachari: SODA'92, JA'94]

Theorem. Let T be a locally optimal spanning tree.
Then $\Delta(T) \leq 2 \cdot \mathrm{OPT} + \ell$, where $\ell = \lceil \log_2 n \rceil$.

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$\mathrm{OPT} \geq \frac{k}{|S|}$ (Lemma 1)

Approximation Factor

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$\square$

Approximation Algorithms

Lecture 9: Minimum-Degree Spanning Tree via Local Search

Part VI: Termination, Running Time & Extensions

Philipp Kindermann

Summer Semester 2020

Termination and Running Time

Theorem. The algorithm finds a locally optimal spanning tree efficiently.

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Termination and Running Time

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- the function is bounded both from above and below.

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- each iteration decreases the potential of a solution.
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- executing $f(n)$ iterations would exceed this lower bound.

Termination and Running Time

Theorem. The algorithm finds a locally optimal spanning tree after at most $f(n)$ iterations.

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Proof. Via potential function $\Phi(T)$ measuring the value of a solution where (hopefully):

$\Phi(T) = \sum_{v \in V(G)} 3^{\deg_T(v)}$

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Lemma. After each flip $T \to T'$, $\Phi(T') \leq (1 - \frac{2}{27n^3})\Phi(T)$.

Homework

- the function is bounded both from above and below.

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Goal: After $f(n)$ iterations: $\Phi(T) = n < 3n$

Termination and Running Time

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Lemma. For each spanning tree T, $\Phi(T) \in [3n, n3^n]$.

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  Let $f(n) = \frac{27}{2} n^4 \cdot \ln 3$. How does $\Phi(T)$ change?

  decreases by: $(1 - \frac{2}{27n^3})^{f(n)} \leq (e^{-\frac{2}{27n^3}})^{f(n)}$

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Goal: After $f(n)$ iterations: $\Phi(T) = n < 3n$ $\square$

Termination and Running Time

Theorem. The algorithm finds a locally optimal spanning tree after $O(n^4)$ iterations.

Proof. Via potential function $\Phi(T)$ measuring the value of a solution where (hopefully): $\Phi(T) = \sum_{v \in V(G)} 3^{\deg_T(v)}$

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Extensions

[Fürer & Raghavachari: SODA'92, JA'94]

Corollary. For any constant $b > 1$ and $\ell = \lceil \log_b n \rceil$, the local search algorithm runs in polynomial time and produces a spanning tree T with $\Delta(T) \leq b \cdot \mathrm{OPT} + \lceil \log_b n \rceil$.

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Proof. Similar to previous pages. Homework $\square$

Extensions

[Fürer & Raghavachari: SODA'92, JA'94]

Corollary. For any constant $b > 1$ and $\ell = \lceil \log_b n \rceil$, the local search algorithm runs in polynomial time and produces a spanning tree T with $\Delta(T) \leq b \cdot \mathrm{OPT} + \lceil \log_b n \rceil$.

Proof. Similar to previous pages. Homework $\square$

Theorem. There is a local search algorithm that runs in $O(EV\alpha(E,V)\log V)$ time and produces a spanning tree T with $\Delta(T) \leq \mathrm{OPT} + 1$.