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Algorithms and Combinatorics on the Erdős–Pósa property

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Some (basic and necessary) definitions
Minors and models in graphs

\( H \) is a minor of \( G \): \( H \) occurs from a subgraph of \( G \) by edge contractions

\( H \)-model: any graph that contains \( H \) as a minor.

\( \mathcal{M}(H) \): the class of all minor models of \( H \).

\( H \)-minor free graphs: graphs that do not contain \( H \) as a minor.
**Treewidth**

- A vertex in $G$ is *simplicial* if its neighborhood induces a clique.
- A graph $G$ is a $k$-tree if one of the following holds:
  - $G = K_{k+1}$ or
  - the removal of $G$ of a simplicial vertex creates a $k$-tree.
- The treewidth of a graph $G$ is defined as follows:
  $$\text{tw}(G) = \min\{k \mid G \text{ is a subgraph of some } k\text{-tree}\}$$
### Main concepts
- Erdős-Pósa Theorem
- A more general setting
- Other variants

### Treewidth

```
1  2  3  4  5  6  7  8  9  10  11  12  13  14  15  16  17
```

#### A 3-tree

```
A 3-tree
```

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Algorithms and Combinatorics on the Erdős–Pósa property
A subgraph of a 3-tree: a graph with treewidth at most 3
Minor exclusion of a planar graph:

**Theorem (Robertson and Seymour – GM V)**

*For every planar graph $H$ there is a constant $c_H$ such that if a graph $G$ is $H$-minor free, then $\text{tw}(G) \leq c_H$.***
Erdős-Pósa Theorem
Theorem (Erdős & Pósa 1965)

There exists a function $f$ such that for every $k$, every graph $G$ has either $k$ vertex disjoint cycles or $f(k)$ vertices that meet all of its cycles.

Facts:

- **Gap**: $f(k) = O(k \cdot \log k)$

- In the same paper they show that the gap $f(k) = O(k \log k)$ is **tight**

According to Diestel’s monograph on graph theory:

- The same holds if we replace “vertices” by “edges”.

[Graph Theory, 3rd Edition, Corollary 12.4.10 and Ex. 39 of Chapter 12]
Lemma

Cycles have the E&P property on planar graphs with linear gap

Proof.

Let $G$ be a graph without any cycle packing of size $\geq k$.

- **Reduce**: We can assume that $G$ has no vertices of degree $\leq 2$.
- **Find**: A planar graph has always a face (cycle) of length $\leq 5$.

We build a cycle covering of $G$ by setting $C = \emptyset$ and repetitively

1. **Reduce** $G$ so that $\delta(G) \geq 3$.
2. **Find** a cycle of length $\leq 5$ and add its vertices to $C$.

The above finish after $\leq k$ rounds and creates a cycle cover $C$ of the input graph of at most $5k$ vertices.
Jones’ Conjecture:

Cycles have the E&P property on planar graphs with gap $2^k$.

► Wide Open (and famous)!

Why Jones'?
On October 29th, 2007 Anonymous says:

Does anyone know why this is called Jones' Conjecture?

Reply: Why Jones'?
On November 16th, 2007 Anonymous says:

I am Jones. My Taiwanese name is Chuan-Min Lee. This conjecture came up when I was working on it with Ton Kloks and Jiping Liu. I used the name "Jones" instead of my Taiwanese name for ease of communication.
**Fact:** Linear gap extends to $H$-minor free graphs

We will derive the **Fact** by the following **more general** statement of Erdős-Pósa Theorem:

**Theorem**

*For each graph $H$, cycles have the E&P property for $H$-minor free graphs with gap $O(k \cdot \log h)$, where $h = |V(H)|$.*

E&P follows as a graphs with no $k$-cycle packings are $K_{3k}$-minor free.
We give a proof using the following results:

**Theorem (Thomassen 1983)**

Given an integer \( r \), every graph \( G \) with \( \text{girth}(G) \geq 8r + 3 \) and \( \delta(G) \geq 3 \) has a minor \( J \) with \( \delta(J) \geq 2^r \).

- \( \text{girth}(G) \): minimum size of a cycle in \( G \)
- \( \delta(G) \): minimum degree of \( G \)
- \( J \) is a minor of \( G \): \( J \) occurs from a subgraph of \( G \) by edge contractions.

**Theorem (Kostochka 1982 & Thomason 1984)**

\[ \exists \alpha \; \forall h \; \delta(G) \geq \alpha h \sqrt{\log h} \Rightarrow G \text{ contains } K_h \text{ as a minor} \]
Proof.

Let $G$ be a $K_h$-free graph with no $k$-cycle packing

1. **Reduce**: $\delta(G) \geq 3$

As $G$ is $H$-minor free, from 2nd theorem every minor $F$ of $G$ has

$\delta(F) \leq \alpha h \sqrt{\log h}$

Let $r$ be such that $\alpha h \sqrt{\log h} < 2^r$

From 1st theorem contains a cycle of length $< 8r = O(\log h)$.

We build a cycle covering of $G$ by setting $C = \emptyset$ and repetitively

1. **Reduce** $G$ so that $\delta(G) \geq 3$.
2. **Find** a cycle of length $O(\log h)$ and add its vertices to $C$.

The above finish after $< k$ rounds and creates a cycle cover of the input graph of at most $O(k \log h)$ vertices.
Algorithmic Remarks:

- Both **Reduce** and **Find**, can be implemented in poly-time.

Therefore there is a polynomial algorithm that, for every $k$, returns one of the following:

- a set of $k$ disjoint cycles or

- a cycle cover of $O(k \cdot \log k)$ vertices.
Algorithmic Remarks:

- We just derived an $O(\log(OPT))$-approximation algorithm for both the maximum size of a vertex cycle packing and the minimum size of a vertex cycle covering.

Moreover:

All previous proofs, results, and algorithms extend directly to the edge variants of the above problems.
Algorithmic Remarks:

- We just derived an $O(\log(OPT))$-approximation algorithm for both the maximum size of a edge cycle packing and the minimum size of a edge cycle covering.

Moreover:

All previous proofs, results, and algorithms extend directly to the edge variants of the above problems.
Extensions on minor models
Let $\mathcal{G}$ and $\mathcal{C}$ be graph classes.

**Question (About $\mathcal{G}$ and $\mathcal{H}$)**

Is there a function $f$ such that, for every $k$, every graph $G \in \mathcal{G}$ has either $k$ vertex disjoint subgraphs in $\mathcal{C}$ or $f(k)$ vertices that meet all subgraphs in $\mathcal{C}$?

**Question (Optimizing the gap $f$)**

If the above question can be positively answered, what is the minimum $f$ for which this holds?

- We say that $\mathcal{C}$ has the Erdős & Pósa property on $\mathcal{G}$ with gap $f$.
- **Task**: detect such $\mathcal{C}$ and $\mathcal{G}$ and optimize the corresponding gap $f$.
- **Erdős & Pósa Theorem**:
  Cycles have the E&P property on all graphs with gap $O(k \log k)$. 

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Algorithms and Combinatorics on the Erdős–Pósa property
[Recall that $\mathcal{M}(H)$ is the graph class containing all $H$-models]

A vast generalization of Erdős-Pósa Theorem:

**Theorem (Robertson & Seymour)**

*Given a graph $H$, $\mathcal{M}(H)$ has the E&P-property on all graphs iff $H$ is planar.*

- Original Erdős-Pósa theorem: $H =$ “double edge”.
- “double edge” generalizes to any planar graph!!

We use $f_H$ for the gap of $\mathcal{M}(H)$
The proof of the general theorem

**Theorem (Robertson & Seymour)**

Given a graph $H$, $\mathcal{M}(H)$ has the E&P-property on all graphs iff $H$ is planar.

The proof of the “only if” is a corollary of the planar exclusion theorem:

**Theorem (Robertson and Seymour – GM V)**

For every planar graph $H$ there is a constant $c_H$ such that if a graph $G$ is $H$-minor free, then $\text{tw}(G) \leq c_H$.

**Ideas of proof:**

- if a graph $G$ does not contain any packing of $k$ models of $H$, then it excludes their disjoint union as a minor (that is planar).
- Therefore, $\text{tw}(G) \leq f(k, H) = w$.
- Let $G$ be a subgraph of a $w$-tree $R$
The graph is “tree-like”:
Theorem (Robertson and Seymour – GM V)

For every planar graph $H$ there is a constant $c_H$ such that if a graph $G$ is $H$-minor free, then $\text{tw}(G) \leq c_H$.

Ideas of the “if” proof: (we describe the case where $H = K_5$)
The proof of the general theorem

\[ H = K_5 \]

A \( \sqrt{n} \times \sqrt{n} \) triangulated toroidal grid \( \Gamma_n \):

\[
\begin{array}{cccccc}
a & 1 & 2 & 3 & 4 & 5 \\
b & 1 & 2 & 3 & 4 & 5 \\
c & 1 & 2 & 3 & 4 & 5 \\
d & 1 & 2 & 3 & 4 & 5 \\
e & 1 & 2 & 3 & 4 & 5 \\
f & 1 & 2 & 3 & 4 & 5 \\
a & 1 & 2 & 3 & 4 & 5 \\
\end{array}
\]

\[
\text{pack}_H(G) = 1 \quad \text{but} \quad \text{cover}_H(G) = \Theta(\sqrt{n})
\]
The proof of the general theorem

\[ H = K_5 \]

\[ A \sqrt{n} \times \sqrt{n} \] triangulated toroidal grid \( \Gamma_n \):

\[ \text{pack}_H(G) = 1 \quad \text{but} \quad \text{cover}_H(G) = \Theta(\sqrt{n}) \]
Therefore, the result of Robertson and Seymour is best possible.
Theorem (Robertson & Seymour)

Given a graph $H$, $\mathcal{M}(H)$ has the E&P-property on all graphs iff $H$ is planar.

What about the “gap” $f_H$ in the above theorem?

Lower bound:

If $H$ is not acyclic, then $f_H(k) = \Omega_H(k \log(k))$

Proof:

Let $G$ be an $n$-vertex cubic graph where

$tw(G) = \Omega(n)$ and

$girth(G) = \Omega(\log n)$

Such graphs are well-known to exist: Ramanujan Graphs (expanders).
We use the fact that $\text{tw}(G) = \Omega(n)$:

- Assume that $C$ covers all models of $H$ in $G$.
- Then $G^- = G \setminus C$ is $H$-minor free.
- As $H$ is planar, $\text{tw}(G^-) \leq c_H$.
- A removal of a vertex reduces treewidth at most by one.
- As $\text{tw}(G) = \Omega(n)$ and $\text{tw}(G^-) \leq c_H$, we have that $|C| = \Omega_h(n)$. 
We use the fact that \( \text{girth}(G) = \Omega(\log n) \):

- Let \( \mathcal{P} \) be a packing of models of \( H \) in \( G \)
- As \( H \) contains a cycle and \( \text{girth}(G) = \Omega(\log n) \), each graph in \( \mathcal{P} \) contains at least \( \Omega_h(\log n) \) vertices.
- Therefore \( |\mathcal{P}| = O_h(n/\log n) \)

**Conclusion:** for every packing \( \mathcal{P} \) of models of \( H \) in \( G \) and every covering \( \mathcal{C} \) of models of \( H \) in \( G \) it holds that \( |\mathcal{C}| = \Omega_h(|\mathcal{P}| \log |\mathcal{P}|) \)

**Therefore:** \( f_H(k) = \Omega_H(k \log(k)) \)
When can we do better than $O_h(k \log k)$?

- If $H$ is acyclic, then the gap is linear, i.e., $f_H(k) = O_H(k)$
  
  [Fiorini, Joret, & Wood, 2013]

- Let $\mathcal{R}$ be a non trivial minor-closed graph class.
  Then for every planar graph $H$, $\mathcal{M}(H)$ has the E&P-property on $\mathcal{R}$ with linear gap $O_\mathcal{R}(k)$.
  
  [Fomin, Saurabh, Thilikos 2011]
What about **matching** (or approaching) the lower bound?

- If $H$ is not acyclic, then $f_H(k) = O_H(k \ \text{polylog}(k))$

  [Chekuri & Chuzhoy, 2013]

- **Most general existing tight bound:**

  If $H = \theta_h = \quad \text{(diagram)}$ then $f_H(k) = O_h(k \ \log k)$ on all graphs.

  [Fiorini, Joret, & Sau, 2013] and  
  [Chatzidimitriou, Florent, Sau, & Thilikos, 2015]
Open problem:

Prove or disprove:

▶ Given a planar graph $H$, $M(H)$ has the vertex-Erdős–Pósa property on all graphs with (optimal) gap $f_H(k) = O_H(k \log k)$
<table>
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Other variants of Erdős–Pósa properties
Edge variants:

For every $r$, $\mathcal{M}(\theta_r)$ has the edge-Erdős-Pósa property with (optimal) gap $O(k \log k)$.

(An $O(\log OPT)$-approximation also exists)

[Chatzidimitriou, Florent, Sau, & Thilikos, 2015]
Open problem:

Prove or disprove:

Given a planar graph $H$, $\mathcal{M}(H)$ has the edge–Erdős–Pósa property on all graphs

and, if this is correct, prove that the gap is optimal $f_H(k) = O_H(k \log k)$
Minor models of cliques:

\[ \mathcal{M}(K_h) \text{ have the edge Erdős-Pósa property on } \Omega(k \cdot h)\text{-connected graphs} \]

[Diestel, Kawarabayashi, Wollan JCTSB 2012]
Immersions:

$I(H)$: Immersion models

$\forall H, \ I(H)$ have the edge Erdős-Pósa property on 4-edge connected graphs

[Chun-Hung Liu, May 2015]
Topological Minors:

\( \mathcal{T}(H) \): Topological Minor models

There is a class \( C \) (completely characterized) such that

\( \mathcal{T}(H) \) has the vertex Erdős-Pósa property iff \( H \in C \).

[Chun-Hung Liu, 2015]
Odd cycles: odd cycles have vertex Erdős-Pósa property on 576-connected graphs with linear gap

[Rautenbach & Reed, 1999]

Odd cycles have vertex/edge Erdős-Pósa property on graphs embeddable in orientable surfaces

[Kawarabayashi, Nakamoto, 2007]

Odd cycles have edge Erdős-Pósa property on 4-edge connected graphs

[Kawarabayashi, Kobayashi, STACS 2012]
Long cycles:

\( \mathcal{M}(C_r) \) has the vertex Erdős-Pósa property with gap

\[ f(k, \ell) = O(\ell \cdot k \cdot \log k). \]

[Fiorini & Herinckx, JGT 2013]
Cycles through a set of vertices:

We consider a graph $G$ with terminals $T \subseteq V(G)$

$T$-cycle: a cycle intersecting $T$.

Cycles intersecting $T$ have the vertex/edge Erdős-Pósa property with (optimal) gap $f(k) = O(k \cdot \log k)$.

[Pontecorvia & Wollan, JCTSB 2012]
Directed cycles in directed graphs:

Directed cycles have the vertex Erdős-Pósá property.

[Reed, Robertson, Seymour, & Thomas, Combinatorica 1996]
Matroids:

[Geelen, Gerards, Whittle, JCTSB 2003]

[Geelen, Kabell JCTSB 2009]
Najlepša hvála

Thank you!
Diego Velázquez - El Triunfo de Baco o Los Borrachos

(Museo del Prado, 1628-29)