Cuts and Connectivity in Graphs and Hypergraphs

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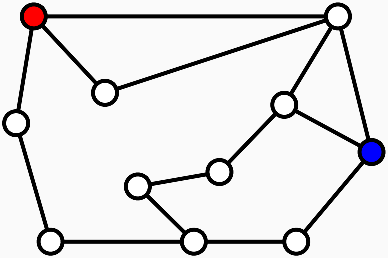
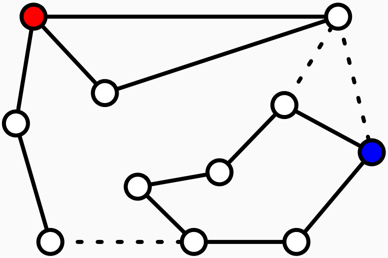
Min *st*-cut in graphs



Remove min number of edges to disconnect s from t.

Min st-cut in graphs



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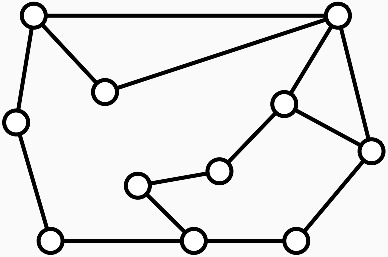

Remove min number of edges to disconnect some pair of vertices.

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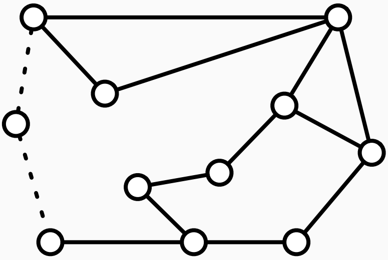

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Formal definition

Problem: Min *st*-cut

Input: $G = (V, E)$ and $s, t \in V$

Output: A 2-partition (S, T) of the vertices V, such that $s \in S$, $t \in T$, and the number of edges crossing S is minimized.

Problem: Min-cut

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Min *st*-cut problem is the fixed-terminal variant of min-cut problem, the global variant.

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Min *st*-cut problem is the fixed-terminal variant of min-cut problem, the global variant. The value of the min-cut is also called the (edge) connectivity, denoted λ.

Applications of min-cut and min-st-cut

- Disconnect railroad networks,
- Maximum cardinality bipartite matching,
- Image segmentation,
- ...

Algorithms for graph min-cut

- Finding a min-cut reduces to finding min-*st*-cut for each pair of s and t.
- $\tilde{O}(mn)$ time: Maximum adjacency ordering. [Stoer-Wagner 95].
- $\tilde{O}(m)$ time (randomized). [Karger 98]
- $\tilde{O}(m)$ time (simple, unweighted). [Kawarabayashi-Thorup 15, Henzinger-Rao-Wang 17]

The Thesis

- Efficient algorithms for min-cut and its generalizations in graphs and hypergraphs.
- Understand the complexity difference between global and fixed-terminal variants.

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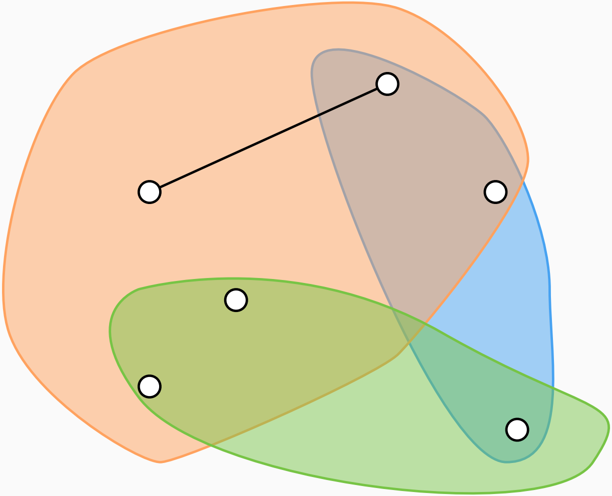
- Algorithms for hypergraph min-cut.
- Approximation for bicut.
- Hypergraph k-cut.
- Minimum violation.

Algorithms for hypergraph min-cut

A hypergraph

A hypergraph $H = (V, E)$ consists of vertices V and edges E.

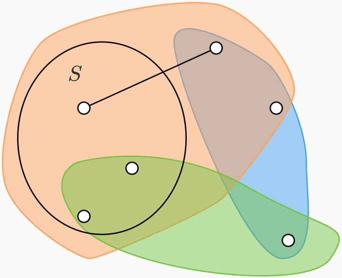


Cut function

- $\delta_H(S)$ is the set of all edges cross S
- The **cut function** $c : 2^V \to \mathbb{N}$

$$c_H(S) = |\delta_H(S)|$$

- A set of vertices $\emptyset \subsetneq S \subsetneq V$ is a min-cut if $c_H(S)$ is minimized.



Motivations for studying hypergraphs

- a natural generalization of graphs
- element connectivity [Chekuri-Rukkanchanunt-X 16]
- real life applications: VLIS, security, data mining, chemistry
  . . .

The min-cut problems

- Find a min-cut.
- Find all min-cuts.
- Find a $(1 + \epsilon)$-approximate min-cut.

Results on hypergraph cuts

	unweighted		weighted	
Problem	graph	hypergraph	graph	hypergraph
Min-cut	$O(m + \lambda n^2)$	$O(p + \lambda n^2)$	$\tilde{O}(mn)$	$\tilde{O}(pn)$
all min-cuts	$O(m + \lambda n^2)$	$O(p + \lambda n^2)$	$\tilde{O}(mn)$	$\tilde{O}(pn)$
$(1+\epsilon)$-min-cut	-	-	$O(m + n^2/\epsilon^2)$	$O(p + n^2 r^4/\epsilon^2)$

- n: # vertices.
- m: # edges.
- p: sum of the cardinality of the edges.
- λ: value of a min-cut.
- r: the rank.

Algorithms for hypergraph min-cut

Min-cut in unweighted hypergraphs

Min-cut in unweighted graphs

1. Find a sparse subgraph with $O(\lambda n)$ edges that preserves the min-cut in $O(m)$ time.
2. Apply the $O(mn)$ min-cut algorithm on the sparse subgraph.

Total running time: $O(m + \lambda n^2)$

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Subgraph H' a k-**certificate** of H if for all $S \subseteq V$

$$c_{H'}(S) \geq \min(c_H(S), k).$$

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Theorem ([Nagamochi-Ibaraki 92])
A graph has a k-certificate with $O(kn)$ edges, and can be found in $O(m)$ time.

Application of k-certificate

- finding the connectivity.

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- $(1+\epsilon)$-approximate min-cut.

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Running time $O(\lambda p + \lambda n^3)$.

Small size k-certificate

Theorem ([Chekuri-X 17])
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Consequence: $O(p + \lambda n^2)$ time algorithm for finding a min-cut.

Algorithms for hypergraph min-cut

All min-cuts

What does it mean to find all min-cuts?

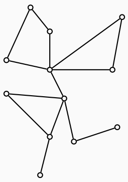
Find a small ($O(n)$-size) data structure that can quickly enumerate/count the number of min-cuts.

A representation

A graph(hypergraph) $G' = (V', E')$ is a representation of $G = (V, E)$, if there exists a function $\phi : V \to V'$ such that

1. S' is a min-cut in G' iff $\phi^{-1}(S')$ is a min-cut in G.
2. S is a min-cut in G, iff $\phi(S)$ is a min-cut in G'.

Graphs: Finding all min-cuts

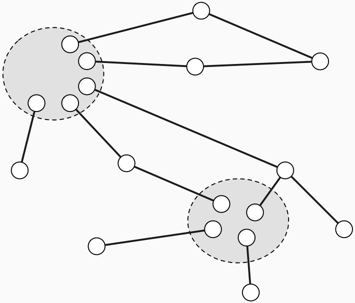


A cactus is a graph in which any two cycles are edge disjoint.

Theorem ([Dinitz et. al. 76, Karzanov & Timofeev 86])
For each graph G there exist a representation G' where G' is a cactus.

A cactus representation can be found

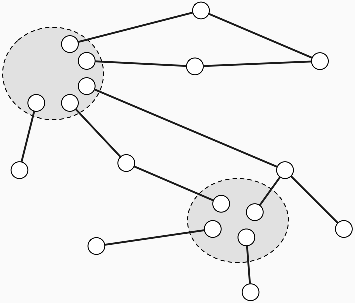
- in $\tilde{O}(nm)$ time [Nagamochi et. al. 03]
- in (randomized) $\tilde{O}(m)$ time [Karger & Panigrahi 09]



Theorem ([Cheng 99, Fleiner & Jordan 99])

For each hypergraph H there exist a representation H' where H' is a hypercactus.

Hypergraphs: Finding all min-cuts



Theorem ([Cheng 99, Fleiner & Jordan 99])

For each hypergraph H there exist a representation H' where H' is a hypercactus.

Expensive to construct, in the order of $O(n^4 p)$.

Hypergraphs: Finding all min-cuts

Theorem ([Chekuri & X 17])

A hypercactus representation can be found in $\tilde{O}(np)$ time.

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Approach: Using the decomposition framework [Cunningham 93].

Hypergraphs: Finding all min-cuts

Theorem ([Chekuri & X 17])

A hypercactus representation can be found in $\tilde{O}(np)$ *time.*

Approach: Using the decomposition framework [Cunningham 93].

Matches the result in graphs. Conceptually simpler algorithm.

Algorithms for hypergraph min-cut

$(1+\epsilon)$-approximate min-cut

Finding an $(1+\epsilon)$-approximate min-cut

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1. Find a sparse subgraph that approximately preserves all min-cuts.
2. Find a min-cut in the sparse subgraph.

Cut-sparsifiers

A graph G is a $(1 \pm \epsilon)$-**cut-sparsifier** of H if
$(1-\epsilon)c_G(A) \leq c_H(A) \leq (1+\epsilon)c_G(A)$ for all $A \subseteq V$.

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Cut-sparsifiers in hypergraphs

Theorem ([Kogan-Krauthgamer 14])

There exists a $(1 \pm \epsilon)$-cut-sparsifier of $\tilde{O}(\frac{nr}{\epsilon^2})$ edges, and can be constructed in $\tilde{O}(n^2 p)$ time with high probability.

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Too slow.

Fast cut-sparsifiers in hypergraphs

Theorem ([Chekuri-X 17])

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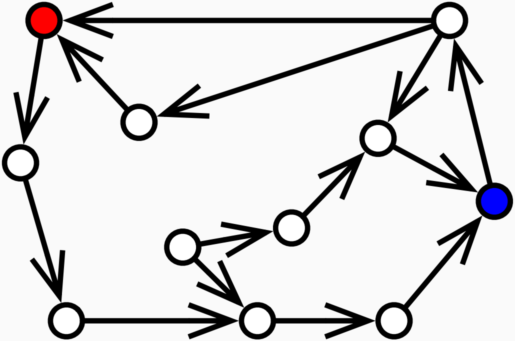
Near-linear time when the hypergraph is dense.

Summary: Fast hypergraph cut algorithms that match their state-of-the-art graph counterparts.

Min-cut in directed graphs: Bicut

st-cut



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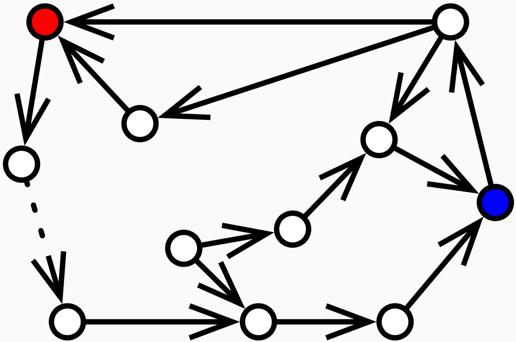
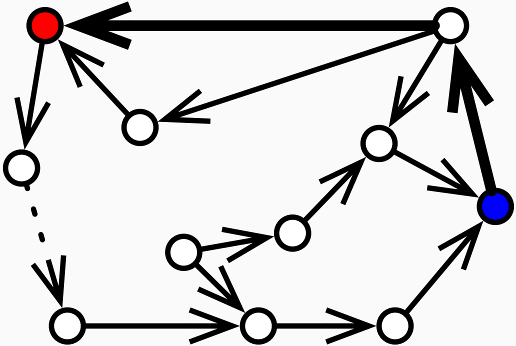
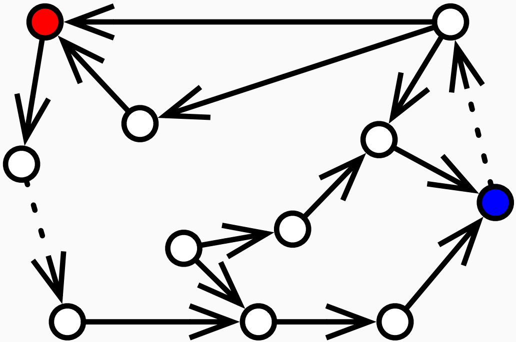




st-bicut



Bicut: Generalization of min-cut in directed graphs

- *st*-bicut: A set of edges such that its removal disconnect s and t in both direction.
- bicut: A *st*-bicut for some s and t.

Hardness: min-st-bicut

A special case of multicut in directed graphs.

- Trivial 2-approximation. Union of min-st-cut and min-ts-cut [Dahlhaus et. al. 1994].
- $(2-\epsilon)$-inapproximable under UGC. [Chekuri & Madan 16, Lee 16]

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A hardness separation between fixed-terminal and global bicut!

Vertex based interpretation of bicut

A and B are uncomparable if $A \setminus B \neq \emptyset$ and $B \setminus A \neq \emptyset$.

Theorem

The min-bicut problem is equivalent to two uncomparable sets $A, B \subseteq V$ with minimum $|\delta^{in}(A) \cup \delta^{in}(B)|$.

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Approach: Find multiple relaxations such that one of them is a $(2 - \delta)$-approximation.

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Approach: Find multiple relaxations such that one of them is a $(2-\delta)$-approximation.
Example: Find uncomparable sets A and B such that $|\delta^{in}(A)|+|\delta^{in}(B)|$ is minimized. If it is not a $(2-\delta)$-approximation, then most edges in the optimal bi-cut are going into $A \cap B$.

Summary: A hardness gap between global and fixed-terminal bicut.

k-cut in hypergraphs

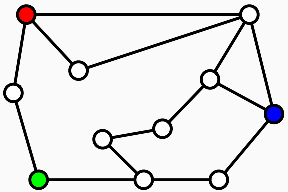
k-way-cut in graphs

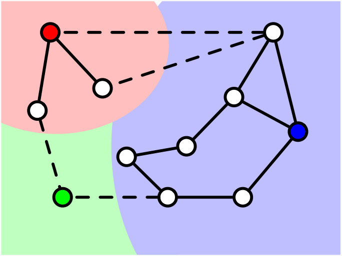
Problem: Min k-way cut

Input: G and $v_1, \ldots, v_k \in V(G)$

Output: A k-partition $(V_1, \ldots, V_k)$, such that $v_i \in V_i$ for all i, and the number of edges crossing the partition classes is minimized.

A min-k-cut is the minimum over all k-way-cut.





Global vs. Fixed-terminal

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  - Divide and conquer: $O(n^{(4+o(1))k})$ [Kamidoi-Yoshida-Nagamochi 07].
  - Divide and conquer: $O(n^{(4-o(1))k})$ [Xiao 08].

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  - Divide and conquer: $O(n^{(4-o(1))k})$ [Xiao 08].
  - Tree packing: $\tilde{O}(n^{2k})$ [Thorup 08].

What about hypergraphs?

Previous works on HYPERGRAPH k-cut

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Main question: Hypergraph k-cut for $k \geq 4$ in arbitrary rank hypergraphs?

Fixed-terminal vs. global complexity gap?

Our result

Theorem ([Chandrasekaran-X-Yu 18])
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Theorem ([Chandrasekaran-X-Yu 18])
There are $O(n^{2(k-1)})$ distinct min-k-cuts in a hypergraph.

Summary: There is a global vs. fixed-terminal complexity gap for hypergraph k-cut.

Minimum violation

Violation

A map from $G = (V, E)$ to $H = (U, F)$ is a function $f : V \to U$.

H is the pattern graph.

An edge $uv \in E$ is a violating edge, if $f(u)f(v) \notin F$.

The violation of f is the number of violating edges.

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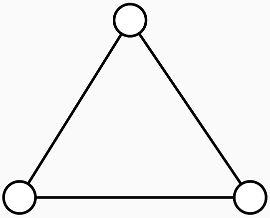
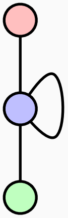


G



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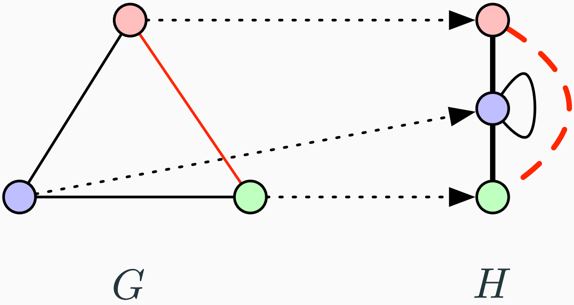
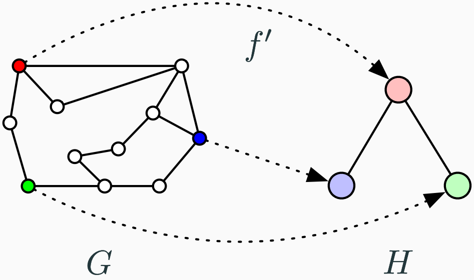


Minimum violation retraction. RVio(H)

Input: graph G and a bijection $f' : V' \to U$ for some $V' \subseteq V(G)$

Output: A map f from G to H such that $f|_{V'} = f'$ and the violation is minimized.

Vertices in V' are fixed vertices.

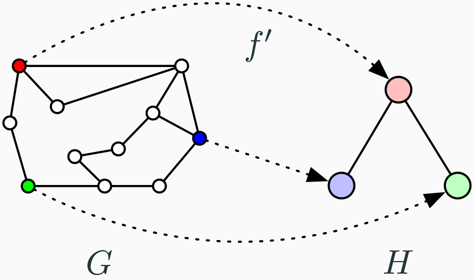


Minimum violation retraction. RVio(H)

Input: graph G and a bijection $f' : V' \to U$ for some $V' \subseteq V(G)$

Output: A map f from G to H such that $f|_{V'} = f'$ and the violation is minimized.

Vertices in V' are fixed vertices.

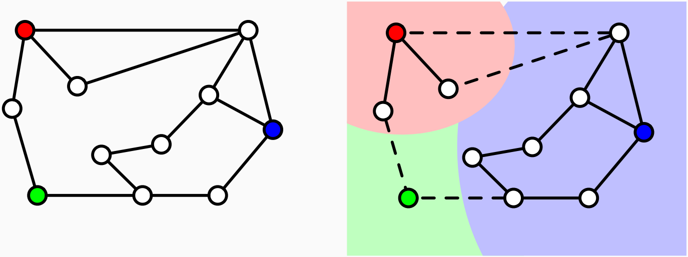


H is r-tractable if **RVio**(H) is tractable.

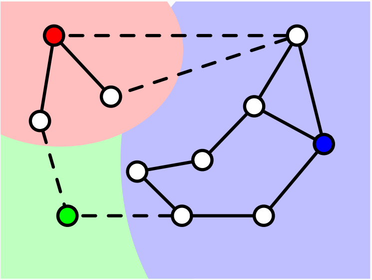
Problem: Min k-way cut

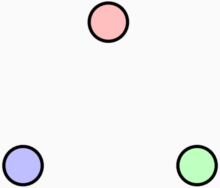
Input: G and $v_1, \ldots, v_k \in V(G)$

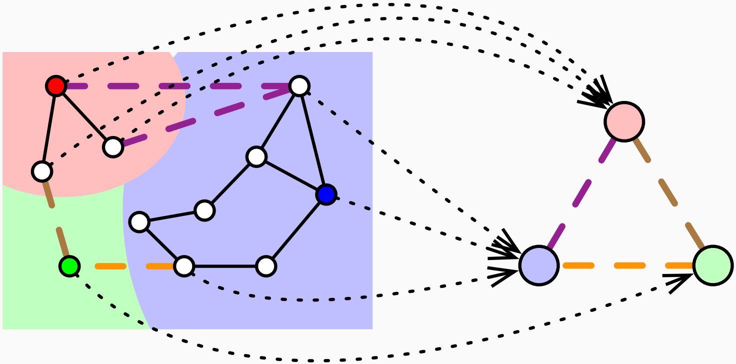
Output: A k-partition $(V_1, \ldots, V_k)$, such that $v_i \in V_i$ for all i, and the number of edges crossing the partition classes is minimized.



3-way cut







Surjective Minimum Violation. SVio(H)

Input: $G = (V, E)$.

Output: A surjective map from G to H with minimum violation.

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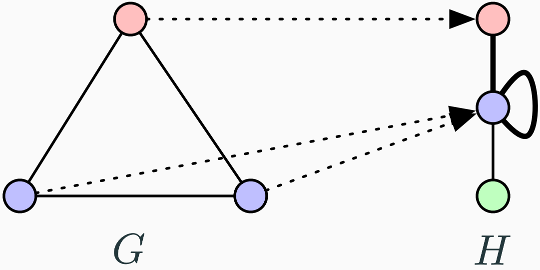

NOT SURJECTIVE!

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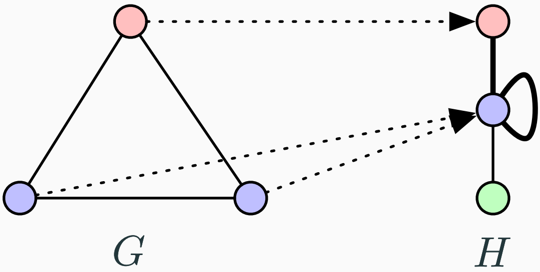

NOT SURJECTIVE! H is s-tractable if **SVio**(H) is tractable.

Why minimum violation?

Complete classification of r-tractable/s-tractable graphs implies complexity of various cut problems.

Why minimum violation?

Complete classification of r-tractable/s-tractable graphs implies complexity of various cut problems.

Classification of s-tractable graphs and r-tractable graphs was studied under the name "G_c-cut". [Elem-Hassin-Monnot 13]

Goal: classify the s-tractable and r-tractable graphs.

Classification of r-tractable (directed) graphs

Theorem ([Kawarabayashi-X unpublished])
There exists a polynomial time algorithm that decides if a (directed) graph is r-tractable.

Classification of r-tractable graphs

v dominates u if $N(u) \subsetneq N(v)$.

A graph $G = (V, E)$ is a double-clique, if $G = G[A] \cup G[B]$ for some clique $A, B \subseteq V$.

Theorem ([Kawarabayashi-X unpublished])
A reflexive graph G is r-tractable if and only if $G[U]$ is a double-clique, where U is the set of non-dominated vertices.

A theorem on s-tractable graphs

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A reflexive graph H is s-tractable if and only if each of its component is s-tractable.

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Consequences:

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A theorem on s-tractable graphs

Theorem ([Kawarabayashi-X unpublished])
A reflexive graph H is s-tractable if and only if each of its component is s-tractable.

Consequences:

- k-cut is solvable in polynomial time.
- Size-constrained k-cut: each partition class has at least c (a constant) vertices is solvable in polynomial time.

Thank you!