The Expander Hierarchy and its Applications in Dynamic Graph Algorithms

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Tree Cut Sparsifier

- given (undirected) graph \( G = (V, E) \)
- compute tree \( T = (V_T, E_T) \) with \( V_T \supseteq V \) that approximates cuts in \( G \)

Formally, for all subsets \( S \subseteq V \)

\[
\frac{1}{q} \text{mincut}_T(S, V \setminus S) \leq \text{cut}_G(S, V \setminus S) \leq \text{mincut}_T(S, V \setminus S)
\]

\( q \) is the quality of the \( T \)
Tree Cut Sparsifier

Graph $G$:

Tree $T$:
Tree Cut Sparsifier

**Motivation:**
Complicated cut-related problems can be (approximately) solved on $G$ by only considering the problem on $T$.

- Minimum Bisection
- Simultaneous Source Location
- $k$-multicut
- Min-max graph partitioning
- Online Multicut
Previous Work

▶ [R 02]
existence; quality $O(\log^3 n)$ (flow sparsifier)

▶ [Bienkowski, Korzeniowski, R 03]
polynomial time; quality $O(\log^4 n)$ (flow sparsifier)

▶ [Harrelson, Hildrum, Rao 03]
polynomial time; quality $O(\log^2 n \log \log n)$ (flow sparsifier)

▶ [R, Shah 14]
polynomial time; quality $O(\log^{1.5} n \log \log n)$ (cut sparsifier)
existence; quality $O(\log n \log \log n)$ (cut sparsifier)

▶ [R, Shah, Täubig 14]
early linear time; quality $O(\log^4 n)$ (flow sparsifier)
Main Result

dynamic construction of a tree cut sparsifier for unweighted graphs

- update time: $n^{o(1)}$
- quality: $n^{o(1)}$

fully dynamic, deterministic, can be deamortized...
Main Result

Consequences for Dynamic Graph Algorithms

- **s-t maxflow/mincut**
  - approx: $n^{o(1)}$, update time: $n^{o(1)}$, query time: $O(\log n)$

- **sparsest cut**
  - approx: $n^{o(1)}$, update time: $n^{o(1)}$, query time: $O(\log n)$

- **multicommodity flow, multi-cut**
  - approx: $n^{o(1)}$, update time: $kn^{o(1)}$, query time: $O(k \log n)$

- **treewidth-decomposition**
  - approx: $n^{o(1)}$, update time: $\text{tw} \cdot n^{o(1)}$

- **connectivity**
  - update time: $n^{o(1)}$, query time: $O(\log n)$
Proof Techniques of Existing Approaches

- leaf nodes of $T$ correspond to vertices in $G$
- a level of the tree induces a partitioning of $V$ into subsets

Graph $G$

Tree $T$
Proof Techniques of Existing Approaches

- an edge in the tree is assigned a capacity equal to the capacity of the corresponding cut in $G$

Graph $G$

Tree $T$
Proof Techniques of Existing Approaches

- equivalently a graph edge contributes to the capacity of every tree edge on the path between its endpoints in $T$
Proof Techniques of Existing Approaches

- this already guarantees that
  \[ \text{cut}_G(S, V \setminus S) \leq \text{mincut}_T(S, V \setminus S) \]
Proof Techniques of Existing Approaches

- let $P_i$ be the partitioning on level $i$; level 0 is the leaf level
- let $G_P$ be the graph obtained from $G$ by contracting subsets in $P$

Property I:
For a cluster $S$ on some level $i + 1$ the graph $G\{S\}_{P_i}$ must expand well

Property II:
The set $S$ must have good boundary-expansion in $G$
Property I

- cluster $S$ on level $i + 1$ partitioned into sub-clusters
- the graph $G\{S\}_{P_i}$ is obtained by
  - take induced subgraph $G[S]$ but turn edges leaving $S$ into self-loops
  - then contract subsets of $P_i$
- expands well means we can route an all-to-all flow problem between edges of $G\{S\}_{P_i}$ with small congestion ($C_i$)
Property II

- good boundary-expansion means we can route an all-to-all flow problem between boundary edges of $S$ with small congestion ($C_{II}$)
Proof

\[ q \cdot \text{cut}_G(S, V \setminus S) \geq \text{mincut}_T(S, V \setminus S) \]

- take any multicommodity flow that can be routed in \( T \) with congestion at most 1
- route it in \( G \) with congestion at most \( q \)
- demand for the multicommodity flow is between edges of \( G \)
- an edge sends/receives at most one unit of flow in this demand
Proof Techniques of Existing Approaches

▶ what does demand between edges mean?

Graph $G$

Tree $T$
Route demand in $G$

- go top down level by level
Route demand in $G$

- go top down level by level
- route in the contracted graph (congestion $2C_l$)
- undo the contraction and fill the gaps (congestion $2C_lC_{ll}$)
For a bottom-up construction it is difficult to guarantee a good value for $C_{\Pi}$.

There is a (trivial) guarantee of $C_{i}^{h}$.
Bottom Up Construction

Property I:
For a cluster $S$ on some level $i + 1$ the graph $G\{S\}_{P_i}$ allows all-to-all routing between edges with congestion $C_i$

Property II′:
For a cluster $S$ on some level $i + 1$ the graph $G\{S\}_{P_i}$ allows all-to-all routing between boundary-edges with congestion $C_{II}'$

Then we guarantee Property II with $(C_{II}')^h$
Expander Decomposition

[Thatchaphol Saranurak, Di Wang 2019]
Given graph $G = (V, E)$, and parameter $\phi$ partition $V$ into disjoint pieces $U_1, U_2, \ldots$ s.t.

- $G\{U_i\}$ can route all-to-all on its edges with congestion $1/\phi$
- $\sum_i |E(U_i, V \setminus U_i)| \leq \tilde{O}(\phi m)$

This only gives something good for Property I...
Expander Decomposition

Given graph $G = (V, E)$, and parameter $\phi$ partition $V$ into disjoint pieces $U_1, U_2, \ldots$ s.t.

- $G[U_i]^{\alpha/\phi}$ can route all-to-all on its edges with congestion $\log m/\phi$
- $\sum_i |E(U_i, V \setminus U_i)| \leq \tilde{O}(\phi m)$

where $\alpha = \Omega(1 / \text{polylog } n)$.

$G[U_i]^{\alpha/\phi}$ is $G[U_i]$ where every outgoing edge is transformed into $\alpha/\phi$ many self-loops.

This means we get $C_{\parallel}' = \log m/\alpha$!!!
Existence

- give every edge money $\Phi \log |S|$ for each cluster $S$ of one of its end-points
- total amount of money handed out is $2\Phi m \log n$
- distribute money to cut-edges so that in the end every cut-edges has money at least one $\rightarrow$ small number of cut-edges
Existence

- congestion $\geq 2 \log n / \phi \Rightarrow \text{cut} \leq \log n \cdot \frac{1}{\text{congestion}} \cdot \text{vol}(S)$
- every edge incident to $S$ reduces its money by at least $\phi$
- money available: $\geq \phi \cdot \text{vol}(S)$
- every edge in the cut needs (at most)

$$1 + \alpha / \phi \cdot 2 \phi \log n \leq 2$$
Choosing Parameters

In each iteration the number of edges reduces by a factor of \( \phi \).

Height \( h \leq \log_{1/\phi} m \).

\[
C_I = \frac{1}{\phi} \log n
\]

\[
C_{II} = (\log m/\alpha)^h
\]

Quality: \( h \cdot C_I \cdot C_{II} \)

Choose \( \phi = 1/e^{\sqrt{\log n}} \)
Expander Pruning

- given $G$ and subset $U$ with $G[U]^{\alpha/\phi}$ a $\phi$-expander
- $(\leq \phi \ vol(U))$ edge-updates for which one endpoint is in $U$

We can maintain a pruned set $P$ such that

- $P_0 = \emptyset; \ P_i \subseteq P_{i+1}$
- $\ vol(P_i) \leq 32i/\phi$ and $|E(P_i, U \setminus P_i)| \leq 16i$
- $|E(P_i, V \setminus U)| \leq 16i/\alpha$
- $G[U]^{\alpha/\phi}$ is a $\phi/38$-expander
Maintaining the Expander Decomposition
Open Problems

- Better guarantee on the quality?
- Guarantees for vertex sparsifiers, i.e., sparsifiers w.r.t. a subset of vertices?