Review: Treewidth

Graphs of bounded treewidth as a generalisation of (undirected) trees:

- Trees have treewidth 1
- Graphs of higher treewidth resemble trees with “thicker branches”
- It is (in theory) not hard to check if a graph has treewidth \( \leq k \) for some \( k \)
- It is (in theory) not hard to answer BCQs whose primal graph has a bounded treewidth

Practically feasible only for lower treewidths

However, bounded treewidth does not generalise the notion of hypergraph acyclicity (acyclic families of hypergraphs may have unbounded treewidth)

Is there a better notion of tree-likeness for hypergraphs?

Query Width

Idea of Chekuri and Rajamaran [1997]:

- Create tree structure similar to tree decomposition
- But consider bags of query atoms instead of bags of variables
- Two connectedness conditions:
  1. Bags that refer to a certain variable must be connected
  2. Bags that refer to a certain query atom must be connected

Query width: least number of atoms needed in bags of a query decomposition

**Theorem 8.1:** Given a query decomposition for a BCQ, the query answering problem can be decided in time polynomial in the query width.

Problems with Query Width

**Theorem 8.2 (Gottlob et al. 1999):** Deciding if a query has query width at most \( k \) is NP-complete.

In particular, it is also hard to find a query decomposition

\(~ \Rightarrow \) Query answering complexity drops from NP to P . . .

\( \ldots \) but we need to solve another NP-hard problem first!
**Generalised Hypertree Width**

Gottlob, Leone, and Scarcello had another idea on defining tree-like hypergraphs:

**Intuition:**
- Combine key ideas of tree decomposition and query decomposition
- Start by looking at a tree decomposition
- But define the width based on query atoms:
  How many atoms do we need to cover all variables in a bag?

~ Generalised hypertree width
~ A technical condition is needed to get a simpler-to-check notion

**Hypertree Width**

**Definition 8.3:** Consider a hypergraph $G = \langle V, E \rangle$. A hypertree decomposition of $G$ is a tree structure $T$ where each node $n$ of $T$ is associated with a bag of variables $B_n \subseteq V$ and with a set of edges $G_n \subseteq E$, such that:

1. $T$ with $B_n$ yields a tree decomposition of the primal graph of $G$.
2. For each node $n$ of $T$:
   - The vertices used in the edges $G_n$ are a superset of $B_n$.
   - If a vertex $v$ occurs in an edge of $G_n$ and this vertex also occurs in $B_m$ for some node $m$ below $n$ in $T$, then $v \in B_n$.

The width to $T$ is the largest number of edges in a set $G_n$.

The hypertree width of $G$, $hw(G)$, is the least width of its hypertree decompositions.

((2) is the “special condition”: without it we get the generalised hypertree width)

**Hypertree Width: Example**

Special condition violated ~⇒ no hypertree decomposition
⇒ But generalised hypertree decomposition of width 2

Special condition satisfied ~⇒ hypertree decomposition of width 3
Hypertree Width: Observations

Observation 8.4: If \((T, (B_n), (G_n))\) is a hypertree decomposition for a hypergraph \((V, E)\), then the union of all sets \(G_n\) might be a proper subset of \(E\).

Proof: Indeed, we only require that every bag \(B_n\) is “covered” by the edges in \(G_n\), not that every edge in \(E\) is actually used for this purpose.

Observation 8.5: If \((T, (B_n), (G_n))\) is a hypertree decomposition for a hypergraph \((V, E)\), then, for every hyperedge \(e \in E\), there is a node \(n\) in \(T\) such that \(e \subseteq B_n\).

Proof: Since \(T, (B_n)\) is a tree decomposition of the primal graph, and every edge \(e \in E\) gives rise to a \(|e|\)-clique in this graph, the variables of \(e\) must occur together in one bag of the tree decomposition.

Complete Hypertree Decompositions

We can make sure that all atoms are in fact used in some set \(G_n\) of the decomposition:

Theorem 8.6: If \((T, (B_n), (G_n))\) is a (generalised) hypertree decomposition for a hypergraph \((V, E)\), then there is a (generalised) hypertree decomposition \((T', (B_n), (G_n'))\) of the same width and of size \(O(|T| + |E|)\) such that, for all \(e \in E\), there is a node \(n\) in \(T'\) with \(e \in G_n'\).

Proof: For every edge \(e \in E\) that does not appear in \((G_n)\) yet:

- extend \(T\) with a new node \(m\) that is a child of an existing node \(n\) with \(e \subseteq G_n\) (this must exist as just observed)
- define \(B_m = e\) and \(G_m = |e|\)

This establishes the claim for \(e\) and preserves all conditions in the definition of (generalised) hypertree decomposition.

Such hypertree decompositions are called complete.

Acyclic Hypergraphs and Hypertree Width (1)

Theorem 8.7: A hypergraph is acyclic if and only if it has hypertree width 1.

Proof: \((\Rightarrow)\) Recall that an acyclic hypergraph has a join tree:

- A tree structure \(T\)
- where each node is associated with a single edge
- such that, for any vertex \(v\), the nodes with edges that mention \(v\) are a subtree of \(T\)

This easily corresponds to a hypertree decomposition (using the same tree structure, singleton edge sets \(G_n = |e|\) and vertex bags \(B_n = e\) if \(n\) is associated with \(e\))

Proof: Indeed, a hypertree decomposition \((T, (B_n), (G_n))\) for a hypergraph \((V, E)\) with hypertree width \(1\) corresponds to a join tree:

- Each node is associated with a single edge
- no edge is associated with more than one node
- the vertices satisfy the connectedness condition for join trees

Hence the hypergraph has a join tree and is therefore acyclic.

Acyclic Hypergraphs and Hypertree Width (2)

Theorem 8.7: A hypergraph is acyclic if and only if it has hypertree width 1.

Proof: \((\Leftarrow)\) For a hypergraph \((V, E)\), consider a hypertree decomposition \((T, (B_n), (G_n))\) of width 1 that is complete (w.l.o.g.).

We modify the decomposition so that, for every edge \(e \in E\), there is exactly one node \(n_e\) in \(T\) such that \(G_{n_e} = |e|\) and \(B_{n_e} = e\):

- Choose an arbitrary total order < on the nodes of \(T\)
- For each \(e \in E\):
  - Find the <-least node \(n_e\) of \(T\) with \(G_{n_e} = |e|\) and \(B_{n_e} = e\)
  - For every node \(n\) with \(G_n = |e|\): re-attach all children of \(n\) to \(n_e\) and delete \(n\)

The modified hypertree decomposition corresponds to a join tree:

- each node is associated with a single edge
- no edge is associated with more than one node
- the vertices satisfy the connectedness condition for join trees

Hence the hypergraph has a join tree and is therefore acyclic.
Efficient Query Answering

**Theorem 8.8:** For a BCQ of (generalised) hypertree width $k$, query answering can be decided in polynomial time (actually in LOGCFL).

**Proof:** Consider a BCQ $q$, a width-$k$ hypertree decomposition $(T, (B_n), (G_n))$ of the hypergraph of $q$, and a database instance $I$.

We first construct a modified BCQ $q'$, hypertree decomposition $(T, (B_n), (G'_n))$ of $q'$, and a database instance $I'$, such that $I \models q$ iff $I' \models q'$ and $\bigcup G'_n = B_n$ for all nodes $n$ of $T$:

- For each node $n$ and atom $r(\vec{x}) \in G_n$
- create a new relation $r'$ and let $\vec{y}$ be a list of all variables in $\vec{x} \cap B_n$
- replace $r(\vec{x}) \in G_n$ by $r'(\vec{y}) \in G'_n$
- define $r'^I$ as the projection of $r'$ to $\vec{y}$

BCQ $q'$, hypertree decomposition $(T, (B_n), (G'_n))$, and database instance $I'$ are of size polynomial in the input.

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Efficient Query Answering

**Theorem 8.9:** For a BCQ of (generalised) hypertree width $k$, query answering can be decided in polynomial time (actually in LOGCFL).

**Proof:** We claim that $I \models q$ iff $I' \models q'$.

$(\Rightarrow)$ Every match of $q$ on $I$ is also a match of $q'$ on $I'$ since

- each atom in $q'$ is just a restriction of an atom in $q$, and
- the corresponding relation in $I'$ is a projection of the corresponding relation in $I$

$(\Leftarrow)$ Every match of $q'$ in $I'$ is also a match of $q$ in $I$ since

- For every atom $r(\vec{x})$ of $q$, there is a node $n$ of $T$ with $\vec{x} \subseteq B_n$ (observed before)
- so $r(\vec{x})$ is an atom of $q'$ as well

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Hypertree Width: Results

- Relationships of hypergraph tree-likeness measures:
  - generalised hypertree width $\leq$ hypertree width $\leq$ query width
  (both inequalities might be $<$ in some cases)
- Acyclic graphs have hypertree width 1
- Deciding “query width $< k$?” is NP-complete
- Deciding “generalised hypertree width $< k$?” is NP-complete
- Deciding “hypertree width $< k$?” is polynomial (LOGCFL)
- Hypertree decompositions can be computed in polynomial time if $k$ is fixed

**Theorem 8.9:** For a BCQ of (generalised) hypertree width $k$, query answering can be decided in polynomial time, and is complete for LOGCFL.

...but the degree of the polynomial time bound is greater than $k$
Hypertree Width via Games

There is also a game characterisation of (generalised) hypertree width.

The Marshals-and-Robber Game
- The game is played on a hypergraph
- There are \( k \) marshals, each controlling one hyperedge, and one robber located at a vertex
- Otherwise similar to cops-and-robber game
- Special condition: Marshals must shrink the space that is left for the robber in every turn!

Hypertree width \( \leq k \) if and only if \( k \) marshals have a winning strategy
\[ \Rightarrow \text{hypergraph is acyclic iff 1 marshal has a winning strategy} \]

Hypertree Width via Logic

There is also a logical characterisation of hypertree width.

Loosely \( k \)-Guarded Logic
- Fragment of FO with \( \exists \) and \( \land \)
- Special form for all \( \exists \) subexpressions:
\[ \exists x_1, \ldots, x_n (G_1 \land \ldots \land G_k \land \varphi) \]
where \( G_i \) are atoms ("guards") and every variable that is free in \( \varphi \) occurs in one such atom \( G_i \).

A query has hypertree width \( \leq k \) if and only if it can be expressed as a loosely \( k \)-guarded formula
\[ \Rightarrow \text{tree queries correspond to loosely 1-guarded formulae} \]
("loosely 1-guarded" logic is better known as guarded logic and widely studied)

Summary and Outlook

Besides tree queries, there are other important classes of CQs that can be answered in polynomial time:
- Bounded treewidth queries
- Bounded hypertree width queries

General idea: decompose the query in a tree structure

Other possible characterisations via games and logic

Open questions:
- What else is there besides query answering? \( \Rightarrow \text{optimisation} \)
- Measure expressivity rather than just complexity