Query Optimization

The common approach to (first-order) query optimization is via equivalence preserving transformations in relational algebra. E.g.:

- $\times$ is commutative and associative, hence applicable in any order
- Cascaded projections may be simplified: If the attributes $A_1, \ldots, A_n$ are among $B_1, \ldots, B_m$, then
  \[ \pi_{A_1, \ldots, A_n}(\pi_{B_1, \ldots, B_m}(E)) = \pi_{A_1, \ldots, A_n}(E) \]
- Cascaded selections might be merged:
  \[ \sigma_{c_1}(\sigma_{c_2}(E)) = \sigma_{c_1 \land c_2}(E) \]
- Commuting selection with join. If $c$ only involves attributes in $E_1$, then
  \[ \sigma_c(E_1 \times E_2) = \sigma_c(E_1) \times E_2 \]

We do not treat such transformations in this course.

Beyond Standard Equivalences

The known equivalences are not always sufficient:

- E.g.: none of the equivalences reduces the number of joins!
- For further optimization, the following decision problems are crucial:

**Definition (Query Equivalence and Containment)**

We say a query $Q_1$ is equivalent to a query $Q_2$ (in symbols, $Q_1 \equiv Q_2$) if $Q_1(D) = Q_2(D)$ for every database instance $D$. Similarly, we say $Q_1$ is contained in $Q_2$ (written $Q_1 \subseteq Q_2$) if $Q_1(D) \subseteq Q_2(D)$ for every $D$.

**QUERY-EQUIVALENCE**

INSTANCE: A pair $Q_1, Q_2$ of queries.
QUESTION: Does $Q_1 \equiv Q_2$ hold?

**QUERY-CONTAINMENT**

INSTANCE: A pair $Q_1, Q_2$ of queries.
QUESTION: Does $Q_1 \subseteq Q_2$ hold?
In the following we concentrate w.l.o.g. on query containment because

\[ Q_1 \equiv Q_2 \iff Q_1 \subseteq Q_2 \text{ and } Q_2 \subseteq Q_1 \text{ and } \]
\[ Q_1 \subseteq Q_2 \iff Q_1 \equiv (Q_1 \cap Q_2). \]

Observe that if \( Q_1, Q_2 \) are formulated in relational algebra, then deciding \( Q_1 \subseteq Q_2 \) (and thus also \( Q_1 \equiv Q_2 \)) is undecidable!

- Indeed, \( Q \) is empty over all databases \( \iff Q \subseteq \emptyset \).
- By Traktenbrots Theorem, checking emptiness is undecidable for RA!

Good news: \( Q_1 \subseteq Q_2 \) is decidable for conjunctive queries!

The decidability comes from the Homomorphism Theorem (see below).

The theorem also gives rise to optimization of conjunctive queries that reduces the number of joins.

---

### Datalog-like notation for CQs

Next we use Datalog notation for CQs!

E.g., the conjunctive query

\[ \{ \langle x, y \rangle \mid \exists z, w. B(x, y) \land R(y, z) \land R(y, w) \land R(w, y) \} \]

is written as the rule

\[ Q(x, y) \leftarrow B(x, y), R(y, z), R(y, w), R(w, y). \]

---

### Tableau homomorphisms

**Definition (Tableau homomorphism)**

A homomorphism of two tableaux \( f : T_1 \rightarrow T_2 \) is a mapping

\[ f : \{ \text{variables of } T_1 \} \rightarrow \{ \text{variables of } T_2 \} \cup \{ \text{constants} \} \]

such that:

- For every distinguished \( x \), \( f(x) = x \)
- For every relation \( R \) in \( T_1 \) and row \( \langle x_1, \ldots, x_k \rangle \) in \( R \), tuple \( \langle f(x_1), \ldots, f(x_k) \rangle \) is a row of \( R \) in \( T_2 \)

**Theorem (Homomorphism Theorem)**

Let \( Q_1, Q_2 \) be two conjunctive queries, and \( T_{Q_1}, T_{Q_2} \) their tableaux. Then

\[ Q_1 \subseteq Q_2 \iff \text{there exists a homomorphism } f : T_{Q_2} \rightarrow T_{Q_1}. \]
Applying the Homomorphism Theorem

- We first consider queries over a single relation:
  - \( Q_1(x, y) \) :– \( R(y, x), R(x, z) \)
  - \( Q_2(x, y) \) :– \( R(y, x), R(w, x), R(x, u) \)

Tableau for \( Q_1 \):

\[
\begin{array}{cc}
A & B \\
R: & y \\
& x \\
& x \\
& z \\
& x \\
& y \\
\end{array}
\]

Tableau for \( Q_2 \):

\[
\begin{array}{cc}
A & B \\
R: & y \\
& x \\
& w \\
& x \\
& u \\
& x \\
& y \\
\end{array}
\]

Take \( f \) such that:
- \( f(w) = y \),
- \( f(u) = z \),
- \( f(x) = x \) and \( f(y) = y \).
Take $f$ such that:
- $f(w) = y$,
- $f(u) = z$,
- $f(x) = x$ and $f(y) = y$.  
Hence $Q_1 \subseteq Q_2$!

Take $f$ such that:
- $f(z) = u$,
- $f(x) = x$ and $f(y) = y$.  
Hence $Q_2 \subseteq Q_1$!
Proof of the Homomorphism Theorem.

**Observation.** A tuple $\vec{c}$ is in the answer to a CQ $Q$ over a database $D$ if and only if there is a homomorphism $f$ from the tableau of $Q$ to the database $D$ such that $f(\vec{x}) = \vec{c}$, where $\vec{x}$ is the tuple of distinguished variables of $Q$.

Assume a pair $Q_1, Q_2$ of CQs with variables $V_1, V_2$, respectively. Assume that $\vec{x}$ is the tuple of answer variables of $Q_1$ and $Q_2$.

Suppose there exists a homomorphism $f: T_{Q_2} \to T_{Q_1}$. Assume a database $D$ and an arbitrary tuple $\vec{c} \in Q_1(D)$. By the above observation there is a homomorphism $g$ from $T_{Q_1}$ to $D$ such that $g(\vec{c}) = \vec{c}$. Observe that the composition $h(\cdot) = g(f(\cdot))$ is a homomorphism from $T_{Q_1}$ to $D$ such that $h(\vec{x}) = \vec{c}$. Hence $\vec{c} \in Q_2(D)$.

Suppose $Q_1 \subseteq Q_2$. Then, by assumption, $Q_1(D) \subseteq Q_2(D)$ for all instances $D$. Take the tableau $T_{Q_2}$ as database instance $D$. Clearly, $\vec{x}$ is in the answer to $Q_1$ over $T_{Q_2}$. Then using the assumption we get $\vec{c} \in Q_2(T_{Q_2})$. By the observation above, then there is a homomorphism $f$ from $T_{Q_2}$ to $T_{Q_1}$ such that $f(\vec{x}) = \vec{c}$.

**CQ Containment and Equivalence: Complexity**

**Corollary**

Given two conjunctive queries $Q_1$ and $Q_2$, both deciding $Q_1 \subseteq Q_2$ and $Q_1 \equiv Q_2$ are NP-complete.

**Proof.**
The NP-completeness of CQ Containment follows immediately from the Homomorphism Theorem together with the above theorem. From this, we may conclude the NP-completeness of CQ Equivalence via the following equivalences:

\[ Q_1 \equiv Q_2 \iff Q_1 \subseteq Q_2 \text{ and } Q_2 \subseteq Q_1 \text{ and } Q_1 \subseteq Q_2 \iff Q_1 \equiv (Q_1 \cap Q_2). \]
Minimizing Conjunctive Queries

Goal: Given a conjunctive query $Q$, find an equivalent conjunctive query $Q'$ with the minimum number of joins.

More formally:

**Definition**

A conjunctive query $Q$ is **minimal** if there does not exist a conjunctive query $Q'$ such that
- $Q \equiv Q'$, and
- $Q'$ has fewer atoms than $Q$.

Minimization Procedure

Given a conjunctive query $Q$, transform it into the tableau $T_Q$.

Algorithm to obtain a minimal equivalent query:

- Given a conjunctive query $Q$, transform it into the tableau $T_Q$.
- **repeat until** no change
  - **choose a row** $t$ in $T'$;
  - if there is a homomorphism $f : T' \rightarrow T' \setminus \{t\}$
    - then $T' := T' \setminus \{t\}$
- **end**;
- **return** (the query defined by) $T'$;

**Note:** If a homomorphism $T' \rightarrow T' \setminus \{t\}$ exists, then $T'$, $T' \setminus \{t\}$ define equivalent queries, as a homomorphism from $T' \setminus \{t\}$ to $T'$ exists.

Minimization by Deletion (continued)

Consider CQs $Q$ and $Q'$ with $Q \equiv Q'$, s.t.
\[ Q(\vec{x}) := R_1(\vec{u}_1), \ldots, R_k(\vec{u}_k) \quad \text{and} \quad Q'(\vec{x}) := S_1(\vec{v}_1), \ldots, S_\ell(\vec{v}_\ell) \quad \text{and} \quad l < k. \]

By the Homomorphism Theorem, there exist homomorphisms $f : T_Q \rightarrow T_{Q'}$ and $g : T_{Q'} \rightarrow T_Q$. Clearly, for the image of $g$, we have $|\text{Im}(g)| \leq l$.

Let $\text{Im}(g) = \{R_1(\vec{u}_1), \ldots, R_m(\vec{u}_m)\}$ with $m \leq l$ and let $Q''(\vec{x}) := R_1(\vec{u}_1), \ldots, R_m(\vec{u}_m)$.

We claim that then $Q'' \equiv Q$ holds.

Again, we apply the Homomorphism Theorem: We have to show that there exist homomorphisms $f'' : T_Q \rightarrow T_{Q''}$ and $g'' : T_{Q''} \rightarrow T_Q$.

Actually, $g''$ trivially exists – just take the identity. Moreover, $f''$ can be obtained via composition: $f''(\cdot) = g(f(\cdot))$. □
Minimizing Conjunctive Queries: example

- Conjunctive query with one relation $R$ only:
  \[ Q(x, y, z) :\neg R(x, y, z_1), R(x_1, y, z), R(x, y, z), y = 4 \]

- Tableau $T_Q$ (relation $R$ omitted):
  \[
  \begin{array}{ccc}
  A & B & C \\
  x & 4 & z_1 \\
  x_1 & 4 & z \\
  x & 4 & z
  \end{array}
  \]

- Minimization, step 1: Is there a homomorphism from $T_Q$ to
  \[
  \begin{array}{ccc}
  A & B & C \\
  x_1 & 4 & z \\
  x & 4 & z
  \end{array}
  \]

- Answer: No. For any homomorphism $f$, $f(x) = x$ (why?), thus the image of the first row is not in the small tableau.

Step 2: Is $T_Q$ equivalent to

\[
\begin{array}{ccc}
  A & B & C \\
  x & 4 & z_1 \\
  x & 4 & z
  \end{array}
  \]

- Answer: Yes. Homomorphism $f$: $f(z_2) = z$, all other variables stay the same.

- The new tableau is not equivalent to
  \[
  \begin{array}{ccc}
  A & B & C \\
  x_1 & 4 & z \\
  x & 4 & z
  \end{array}
  \]

Because $f(x) = x, f(z) = z$, and the image of one of the rows is not present.

Complexity of Minimization (1)

**Theorem**

Given a tableau $T$ and a tuple $t$ in $T$, checking whether there is a homomorphism from $T$ to $T \setminus \{t\}$ is NP-complete.

**Proof.**

Membership in NP is immediate. For the hardness part, we provide a reduction from 3-COLORABILITY. We exploit a well-known trick: a graph is 3-colorable iff it can be homomorphically embedded into a “triangle”. Assume a graph $G = (V, E)$, where $V = \{1, \ldots, n\}$. W.l.o.g., $G$ is assumed to be connected. Take the Boolean CQ $Q_G$ with the following atoms and test if atom $V_i(x_i)$ is “redundant”:

1. $V_1(x_1), \ldots, V_n(x_n)$,
2. $E(x_i, x_j)$ for each edge $(i, j) \in E$,
3. $R(y)$, $G(y_g), B(y_b)$,
4. $E(y_r, y_g), E(y_g, y_r), E(y_g, y_b), E(y_b, y_g)$ and $E(y_r, y_b), E(y_b, y_r)$,
5. $V_i(y_c)$ for all $i \in V$ and $c \in \{r, g, b\}$.
Proof (continued).

It remains to show that $G$ is 3-colorable iff there is a homomorphism from $T_{Q_c}$ to $T_{Q_c} \setminus \{ V_i(x_1) \}$.

$(\Rightarrow)$ Assume $G$ is 3-colorable with $\mu : V \to \{ r, g, b \}$ a witnessing coloring. Then the following function $f$ is a homomorphism from $T_{Q_c}$ to $T_{Q_c} \setminus \{ V_i(x_1) \}$:

- $f(x_i) = y_{\mu(i)}$, for all $i \in V$,
- $f(y_c) = y_c$, for all $c \in \{ r, g, b \}$.

$(\Leftarrow)$ Assume there is a homomorphism $f$ from $T_{Q_c}$ to $T_{Q_c} \setminus \{ V_i(x_1) \}$. Then $f(x_1) \in \{ y_r, y_g, y_b \}$ due to the atom $V_i(x_1)$ of $Q_c$. Since $G$ is connected, we must also have $f(x_1) \in \{ y_r, y_g, y_b \}$ for all $i \in V$.

Take the function $\mu : V \to \{ r, g, b \}$ such that (a) $\mu(i) = r$ if $f(x_i) = y_r$, (b) $\mu(i) = g$ if $f(x_i) = y_g$, and (c) $\mu(i) = b$ if $f(x_i) = y_b$.

We claim that $\mu$ is a valid 3-coloring of $G$. Let $(i,j)$ be an arbitrary edge in $E$. Then $E(x_i, x_j)$ is an atom in $Q_c$. Since $f$ is a homomorphism, we have $(f(x_i), f(x_j))$ in the relation $E$ of $T_{Q_c} \setminus \{ V_i(x_1) \}$. Then by construction of $Q_c$, we have $f(x_1) \neq f(x_j)$ and thus $\mu(i) \neq \mu(j)$.

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Complexity of Minimization (2)

Theorem

Given a conjunctive query $Q$, checking whether $Q$ is minimal is co-NP-complete.

Proof.

We prove by showing that checking whether a query is not minimal is NP-complete. NP-Membership of the latter problem is immediate. For the hardness part, we observe that the query $Q_G$ obtained from $G$ in the previous proof can be reused. We show below that $G$ is 3-colorable iff $Q_G$ is not minimal.

$(\Rightarrow)$ Assume $G$ is 3-colorable with $\mu : V \to \{ r, g, b \}$ a witnessing coloring. Then the following function $f$ (also used in the previous proof) is a homomorphism from $T_{Q_c}$ to $T_{Q_c} \setminus \{ V_i(x_1) \}$:

- $f(x_i) = y_{\mu(i)}$, for all $i \in V$,
- $f(y_c) = y_c$, for all $c \in \{ r, g, b \}$.

Hence, $Q_G$ is not minimal.

Uniqueness of Minimal Queries

A natural question: does the order in which we remove tuples from the tableaux matter? The answer is "no" by the following theorem.

Theorem

If $Q_1, Q_2$ are two minimal queries equivalent to a query $Q$, then the tableaux $T_{Q_1}$ and $T_{Q_2}$ are isomorphic.

Proof.

The proof proceeds in several steps.

Homomorphisms. By the equivalences $Q_1 \equiv Q \equiv Q_2$, there exists a homomorphism $f : T_{Q_1} \to T_{Q_2}$ and a homomorphism $g : T_{Q_2} \to T_{Q_1}$. Let $h = g \circ f$. Clearly, $h : T_{Q_1} \to T_{Q_1}$ is also a homomorphism.

$|T_{Q_1}| = |T_{Q_1}|$. Suppose that $|T_{Q_1}| < |T_{Q_1}|$ (the case $|T_{Q_1}| < |T_{Q_1}|$ is symmetric). Then $h(T_{Q_1}) < |T_{Q_1}|$ and, hence, $h(T_{Q_1}) \subset T_{Q_1}$. Thus the query corresponding to $h(T_{Q_1})$ is strictly smaller than $Q_1$. This contradicts the assumption that $Q_1$ is a minimal CQ equivalent to $Q$. 

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Join Tree - Example

**Example**

\[ Q(x_1, x_2, x_3, x_4, x_5, x_6) :- \\
R_3(x_3) \land R_4(x_2, x_4, x_3) \land R_1(x_1, x_2, x_3) \land R_2(x_2, x_3) \land R_2(x_5, x_6) \]

**Acyclic Conjunctive Queries**

- Many CQs in practice enjoy the so-called **acyclicity** property.
- Acyclic CQs can be evaluated efficiently (in polynomial time).

**Definition**

A conjunctive query \( Q \) is acyclic if it has a join tree.

**Definition (Join Tree)**

Let \( Q(x) : R_1(z_1), \ldots, R_n(z_n) \) be a CQ.

A **join tree** \( T = (V, E) \) is a tree where

- \( V = \{ R_1(z_1), \ldots, R_n(z_n) \} \), i.e., \( V \) is the set of atoms in \( Q \).
- \( E \) satisfies for all variables \( z \) of \( Q \):
  \[ \{ R_j(z_j) \in V \mid z \text{ occurs in } R_j(z_j) \} \text{ induces a connected subtree in } T \]
Join Tree – Example

**Example**

\[ Q(x_1, x_2, x_3, x_4, x_5, x_6) :– \]

\[ R_3(x_3) \land R_4(x_2, x_4, x_3) \land R_1(x_1, x_2, x_3) \land R_2(x_2, x_3) \land R_2(x_5, x_6) \]

Join Tree – Example

**Example**

\[ Q(x_1, x_2, x_3, x_4, x_5, x_6) :– \]

\[ R_3(x_3) \land R_4(x_2, x_4, x_3) \land R_1(x_1, x_2, x_3) \land R_2(x_2, x_3) \land R_2(x_5, x_6) \]
Join Tree – Example

Example

\[ Q(x_1, x_2, x_3, x_4, x_5, x_6) :\]
\[ R_3(x_3) \land R_4(x_2, x_4, x_3) \land R_1(x_1, x_2, x_3) \land R_2(x_2, x_3) \land R_2(x_5, x_6) \]

Finding Join Trees

Remarks:
- Existence of a join tree can be efficiently decided
- Join tree can be efficiently computed (if one exists)

\[ \rightarrow \text{GYO-reduction (Graham, Yu, and Ozsoyoglu)} \]

- Tests for acyclicity of hypergraphs
- Reduction sequence allows to build a join tree efficiently
- Easy to identify a query with a hypergraph
- Two equivalent definitions exist

Define
- Atom \( R(\vec{z}) \) is empty if \( |\vec{z}| = 0 \), and
- Atom \( R_i(\vec{z}_1) \) is contained in atom \( R_j(\vec{z}_2) \) if \( \vec{z}_1 \subseteq \vec{z}_2 \)
**GYO-Reduction**

**Definition (GYO/GYO'-reduction)**

Let \( Q(x_1, x_2, x_3, x_4, x_5, x_6) \) be a CQ. Apply the following rules until no longer possible.

- **GYO-reduction:**
  - Eliminate variables that are contained in at most one atom.
  - Eliminate atoms that are empty or contained in another atom.

- **GYO'-reduction:**
  - Eliminate atoms that share no variables with other atoms.
  - Eliminate atoms \( R \) if there exists a witness \( R' \) s.t. each variable in \( R \) either appears in \( R \) only, or also appears in \( R' \).

**Theorem**

- \( GYO'(Q) = \emptyset \) iff \( GYO(Q) = \emptyset \)
- \( GYO'(Q) = \emptyset \) iff \( Q \) has a join tree (iff \( Q \) is acyclic)

---

**GYO-reduction: Example**

**Example**

Consider again \( Q(x_1, x_2, x_3, x_4, x_5, x_6) \):

\[
R_3(x_3) \land R_4(x_2, x_3, x_4) \land R_1(x_1, x_2, x_3) \land R_2(x_2, x_3) \land R_2(x_5, x_6)
\]

\[
\begin{align*}
R_1(x_1, x_2, x_3) & \quad R_2(x_2, x_3) \\
R_3(x_3) & \quad R_4(x_2, x_3, x_4) \\
R_5(x_5, x_6) & \quad R_2(x_2, x_3)
\end{align*}
\]

---

**GYO-reduction: Proof**

**Proof.**

We only prove the second equivalence:

- **GYO'(Q) = \emptyset \Rightarrow Q has a join tree:** Consider the sequence \((R_1, \ldots, R_n)\) of atoms removed during the reduction. Create a join tree as follows:
  - Whenever \( R_j \) was the witness for \( R_i \), then make \( R_j \) a child node of \( R_i \).
  - Merge the resulting forest to a tree "arbitrarily".

It is easy to check that this indeed gives a valid join tree.

- **Q has a join tree \Rightarrow GYO'(Q) = \emptyset:** Consider a join tree \( T \) for \( Q \).

Removing leaf nodes from \( T \) in arbitrary order gives a sequence of valid GYO'-reduction steps that eliminates all atoms:

  - Either a leaf node shares no variable with its parent \( \Rightarrow \) First rule
  - All variables occuring not only in the leaf node must be contained in the parent node (connectedness condition) \( \Rightarrow \) parent node is witness

---

**Example**

Consider again \( Q(x_1, x_2, x_3, x_4, x_5, x_6) \):

\[
R_3(x_3) \land R_4(x_2, x_3, x_4) \land R_1(x_1, x_2, x_3) \land R_2(x_2, x_3) \land R_2(x_5, x_6)
\]

\[
\begin{align*}
R_1(x_1, x_2, x_3) & \quad R_2(x_2, x_3) \\
R_3(x_3) & \quad R_4(x_2, x_3, x_4) \\
R_5(x_5, x_6) & \quad R_2(x_2, x_3)
\end{align*}
\]

\( A_0 = \{ r_1, r_2, r_3, r_4, r_5 \} \)
Consider again $Q(x_1, x_2, x_3, x_4, x_5, x_6)$:

\[
R_3(x_3) \land R_2(x_2, x_4, x_3) \land R_1(x_1, x_2, x_3) \land R_2(x_2, x_3) \land R_2(x_5, x_6)
\]

\[A_0 = \{r_1, r_2, r_3, r_4, r_5\}\]

\[A_1 = \{r_1, r_2, r_3, r_4\}\]

\[A_2 = \{r_2, r_3, r_4\}\]

\[A_3 = \{r_3, r_4\}\]

\[A_4 = \{r_4\}\]
GYO-reduction: Example

Consider again $Q(x_1, x_2, x_3, x_4, x_5, x_6)$:

$$R_3(x_3) \land R_2(x_2, x_4, x_3) \land R_1(x_1, x_2, x_3) \land R_2(x_2, x_5) \land R_2(x_5, x_6)$$

Let $T = (V, E)$ be a join tree of a query $Q$.

**Algorithm by Yannakakis**

Let $T = (V, E)$ be a join tree of a query $Q$.

Given database instance $D$, decide $Q(D) = \emptyset$ as follows:

1. Assign to each $R_j(x_j) \in V$ the corresponding relation $R_j^D$ of $D$.
2. In a bottom up traversal of $T$: compute semijoins of $R_j^D$.
3. If the resulting relation at root node is empty, then $Q(D) = \emptyset$.
   nonempty, then $Q(D) \neq \emptyset$.

**Theorem**

For ACQs $Q$:

- **Deciding** $Q(D) = \emptyset$ is **feasible in polynomial time**.
- **Computing** $Q(D)$ can be done in output polynomial time.
Yannakakis Algorithm – Example

t_1 : R_2(x_2, x_3)
  x_2  x_3
c_1  c_2

\[ \rightarrow \]

\begin{align*}
  t_2 & : R_2(x_3, x_5) \\
  x_3 & \quad x_5 \\
  c_1 & \quad c_2 \quad b_2 \quad b_5 \\
  c_4 & \quad b_6
\end{align*}

\[ \rightarrow \]

\begin{align*}
  t_3 & : R_3(x_5, x_6) \\
  x_5 & \quad x_6 \\
  c_1 & \quad c_2 \quad b_2 \\
  c_4 & \quad b_6
\end{align*}

\[ \rightarrow \]

\begin{align*}
  t_4 & : R_4(x_6, x_7) \\
  x_6 & \quad x_7 \\
  b_3 & \quad x_8 \\
  c_1 & \quad c_2 \\
  c_4 & \quad b_6
\end{align*}

\[ \rightarrow \]

\begin{align*}
  t_5 & : R_5(x_7, x_8) \\
  x_7 & \quad x_8 \\
  c_1 & \quad c_2 \\
  c_4 & \quad b_6
\end{align*}
Database Theory 6. Conjunctive Queries 6.4. Acyclic Conjunctive Queries

Yannakakis Algorithm – Example

```
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<tr>
<td>x3</td>
</tr>
<tr>
<td>c1</td>
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<tr>
<td>b2</td>
</tr>
<tr>
<td>c4</td>
</tr>
<tr>
<td>b6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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</thead>
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<tr>
<td>b6</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>t3: R1(x1, x2, x3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x1</td>
</tr>
<tr>
<td>x2</td>
</tr>
<tr>
<td>x3</td>
</tr>
<tr>
<td>c1</td>
</tr>
<tr>
<td>b2</td>
</tr>
<tr>
<td>c4</td>
</tr>
<tr>
<td>b6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>t4: R3(x3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x3</td>
</tr>
<tr>
<td>b2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>t5: R4(x2, x4, x3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x2</td>
</tr>
<tr>
<td>x4</td>
</tr>
<tr>
<td>x3</td>
</tr>
<tr>
<td>c1</td>
</tr>
<tr>
<td>a1</td>
</tr>
<tr>
<td>b1</td>
</tr>
<tr>
<td>c2</td>
</tr>
<tr>
<td>a2</td>
</tr>
</tbody>
</table>
```

Yannakakis Algorithm – Example

```
<table>
<thead>
<tr>
<th>t1: R2(x2, x3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x2</td>
</tr>
<tr>
<td>x3</td>
</tr>
<tr>
<td>c1</td>
</tr>
<tr>
<td>b2</td>
</tr>
<tr>
<td>c4</td>
</tr>
<tr>
<td>b6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>t2: R2(x3, x6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x6</td>
</tr>
<tr>
<td>x3</td>
</tr>
<tr>
<td>c1</td>
</tr>
<tr>
<td>b5</td>
</tr>
<tr>
<td>c4</td>
</tr>
<tr>
<td>b6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>t3: R1(x1, x2, x3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x1</td>
</tr>
<tr>
<td>x2</td>
</tr>
<tr>
<td>x3</td>
</tr>
<tr>
<td>c1</td>
</tr>
<tr>
<td>b2</td>
</tr>
<tr>
<td>c4</td>
</tr>
<tr>
<td>b6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>t4: R3(x3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x3</td>
</tr>
<tr>
<td>b2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>t5: R4(x2, x4, x3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x2</td>
</tr>
<tr>
<td>x4</td>
</tr>
<tr>
<td>x3</td>
</tr>
<tr>
<td>c1</td>
</tr>
<tr>
<td>a1</td>
</tr>
<tr>
<td>b1</td>
</tr>
<tr>
<td>c2</td>
</tr>
<tr>
<td>a2</td>
</tr>
</tbody>
</table>
```
Yannakakis Algorithm – Example

\[ t_1 : R_2(x_2, x_3) \]
\[ x_2 \quad x_3 \]
\[ c_1 \quad b_2 \]
\[ c_4 \quad b_5 \]

\[ t_2 : R_3(x_2, x_4, x_5) \]
\[ x_2 \quad x_4 \quad x_5 \]
\[ c_1 \quad b_2 \quad b_3 \]
\[ c_6 \quad b_7 \quad b_8 \]

\[ t_3 : R_1(x_1, x_2, x_3) \]
\[ x_1 \quad x_2 \quad x_3 \]
\[ c_1 \quad a_1 \quad b_1 \]
\[ c_1 \quad a_2 \quad b_2 \]

\[ t_4 : R_4(x_2, x_3) \]
\[ x_2 \quad x_3 \]
\[ c_1 \quad b_2 \]
\[ c_4 \quad b_5 \]

\[ t_5 : R_3(x_2, x_4, x_5) \]
\[ x_2 \quad x_3 \quad x_4 \quad x_5 \]
\[ c_1 \quad a_1 \quad a_2 \quad b_2 \]
\[ b_6 \]

Yannakakis Algorithm – Example

\[ t_1 : R_2(x_2, x_3) \]
\[ x_2 \quad x_3 \]
\[ c_1 \quad b_2 \]
\[ c_4 \quad b_5 \]

\[ t_2 : R_3(x_2, x_4, x_5) \]
\[ x_2 \quad x_4 \quad x_5 \]
\[ c_1 \quad b_2 \quad b_3 \]
\[ c_6 \quad b_7 \quad b_8 \]

\[ t_3 : R_1(x_1, x_2, x_3) \]
\[ x_1 \quad x_2 \quad x_3 \]
\[ c_1 \quad a_1 \quad b_1 \]
\[ c_1 \quad a_2 \quad b_2 \]

\[ t_4 : R_3(x_2, x_3) \]
\[ x_2 \quad x_3 \]
\[ c_1 \quad b_2 \]
\[ c_4 \quad b_5 \]

\[ t_5 : R_3(x_2, x_4, x_5) \]
\[ x_2 \quad x_3 \quad x_4 \quad x_5 \]
\[ c_1 \quad a_1 \quad a_2 \quad b_2 \]
\[ b_6 \]
Yannakakis Algorithm – Example

t_1 : R_2 (x_2, x_3)  
  x_2  x_3  
  c_1  b_2  
  c_2  b_2  
  c_3  b_2  
  c_4  b_2  

t_2 : R_3 (x_2, x_3)  
  x_2  x_3  
  b_2  c_1  
  c_1  x_2  
  c_2  x_3  
  c_3  b_2  

t_3 : R_4 (x_1, x_2, x_3)  
  x_1  x_2  x_3  
  c_1  c_2  b_1  
  c_1  b_2  b_1  
  c_1  b_2  c_3  
  c_1  b_2  c_4  

t_4 : R_5 (x_2)  
  x_2  
  c_1  
  b_2  

Yannakakis Algorithm – Example

t_1 : R_2 (x_2, x_3)  
  x_2  x_3  
  c_1  b_2  
  c_2  b_2  
  c_3  b_2  
  c_4  b_2  

t_2 : R_3 (x_2, x_3)  
  x_2  x_3  
  b_2  c_1  
  c_1  x_2  
  c_2  x_3  
  c_3  b_2  

t_3 : R_4 (x_1, x_2, x_3)  
  x_1  x_2  x_3  
  c_1  c_2  b_1  
  c_1  b_2  b_1  
  c_1  b_2  c_3  
  c_1  b_2  c_4  

t_4 : R_5 (x_2)  
  x_2  
  c_1  
  b_2  

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Yannakakis Algorithm – Example

\[
\begin{align*}
&\text{t}_1 : R_2(x_1, x_2) \\
&x_1 & x_2 \\
&c_1 & b_2 \\
&c_2 & b_2 \\
&c_3 & b_2 \\
&b_1 & b_2 \\
\end{align*}
\]

\[
\begin{align*}
&\text{t}_2 : R_2(x_3, x_4) \\
&x_3 & x_4 \\
&c_1 & b_2 \\
&c_2 & b_2 \\
&c_3 & b_2 \\
&c_4 & b_2 \\
\end{align*}
\]

\[
\begin{align*}
&\text{t}_3 : R_1(x_1, x_2, x_3) \\
&x_1 & x_2 & x_3 \\
&c_1 & c_2 & b_2 \\
&c_1 & c_2 & b_2 \\
&c_1 & c_2 & b_2 \\
&c_1 & c_2 & b_2 \\
&c_1 & c_2 & b_2 \\
\end{align*}
\]

\[
\begin{align*}
&\text{t}_4 : R_3(x_5) \\
&x_5 \\
&c_1 & b_2 \\
&c_2 & b_2 \\
&c_3 & b_2 \\
&c_4 & b_2 \\
\end{align*}
\]

\[
\begin{align*}
&\text{t}_5 : R_4(x_2, x_4, x_3) \\
&x_2 & x_4 & x_3 \\
&c_1 & c_2 & b_2 \\
&c_1 & c_2 & b_2 \\
&c_1 & c_2 & b_2 \\
&c_1 & c_2 & b_2 \\
&c_1 & c_2 & b_2 \\
\end{align*}
\]

Yannakakis Algorithm – Example

\[
\begin{align*}
&\text{t}_1 : R_2(x_1, x_2) \\
&x_1 & x_2 \\
&c_1 & b_2 \\
&c_2 & b_2 \\
&c_3 & b_2 \\
&b_1 & b_2 \\
\end{align*}
\]

\[
\begin{align*}
&\text{t}_2 : R_2(x_3, x_4) \\
&x_3 & x_4 \\
&c_1 & b_2 \\
&c_2 & b_2 \\
&c_3 & b_2 \\
&c_4 & b_2 \\
\end{align*}
\]

\[
\begin{align*}
&\text{t}_3 : R_1(x_1, x_2, x_3) \\
&x_1 & x_2 & x_3 \\
&c_1 & c_2 & b_2 \\
&c_1 & c_2 & b_2 \\
&c_1 & c_2 & b_2 \\
&c_1 & c_2 & b_2 \\
&c_1 & c_2 & b_2 \\
\end{align*}
\]

\[
\begin{align*}
&\text{t}_4 : R_3(x_5) \\
&x_5 \\
&c_1 & b_2 \\
&c_2 & b_2 \\
&c_3 & b_2 \\
&c_4 & b_2 \\
\end{align*}
\]

\[
\begin{align*}
&\text{t}_5 : R_4(x_2, x_4, x_3) \\
&x_2 & x_4 & x_3 \\
&c_1 & c_2 & b_2 \\
&c_1 & c_2 & b_2 \\
&c_1 & c_2 & b_2 \\
&c_1 & c_2 & b_2 \\
&c_1 & c_2 & b_2 \\
\end{align*}
\]
Yannakakis Algorithm – Example

\[ t_1 : R_2(x_2, x_3) \]
\[ x_2 \quad x_3 \]
\[ c_1 \quad b_2 \\
 c_1 \quad b_3 \\
 c_4 \quad b_2 \]

\[ t_2 : R_2(x_2, x_3) \]
\[ x_2 \quad x_3 \]
\[ c_1 \quad b_2 \\
 c_1 \quad b_3 \\
 c_4 \quad b_2 \]

\[ t_3 : R_1(x_1, x_2, x_3) \]
\[ x_1 \quad x_2 \quad x_3 \]
\[ c_1 \quad c_2 \quad b_2 \\
 c_1 \quad c_3 \quad b_2 \\
 c_4 \quad b_2 \]

\[ t_4 : R_3(x_3) \]
\[ x_3 \]
\[ b_2 \]

\[ t_5 : R_4(x_2, x_4, x_3) \]
\[ x_2 \quad x_4 \quad x_3 \]
\[ c_1 \quad a_1 \quad b_2 \\
 c_1 \quad a_1 \quad b_2 \\
 c_1 \quad a_1 \quad b_2 \\
 c_4 \quad b_2 \]

\[ t_6 : R_4(x_2, x_4, x_3) \]
\[ x_2 \quad x_4 \quad x_3 \]
\[ c_1 \quad a_1 \quad b_2 \\
 c_1 \quad a_1 \quad b_2 \\
 c_1 \quad a_1 \quad b_2 \\
 c_4 \quad b_2 \]
Yannakakis Algorithm – Example

t_1 : \text{R}_2(x_2, x_3)
\begin{array}{c}
\begin{array}{c}
\text{c}_1 \\
\text{c}_4
\end{array}
\end{array}
\begin{array}{c}
\begin{array}{c}
\text{b}_1 \\
\text{b}_2
\end{array}
\end{array}
\begin{array}{c} x_2 \end{array}
\begin{array}{c} x_3 \end{array}

t_2 : \text{R}_2(x_3, x_4)
\begin{array}{c}
\begin{array}{c}
\text{c}_1 \\
\text{c}_4
\end{array}
\end{array}
\begin{array}{c} x_3 \end{array}
\begin{array}{c} x_4 \end{array}
\begin{array}{c} \text{b}_2 \\
\text{b}_2
\end{array}
\begin{array}{c} \text{b}_2 \\
\text{b}_1
\end{array}

t_3 : \text{R}_1(x_1, x_2, x_3)
\begin{array}{c}
\begin{array}{c}
\text{c}_1 \\
\text{c}_2
\end{array}
\end{array}
\begin{array}{c} x_1 \end{array}
\begin{array}{c} x_2 \end{array}
\begin{array}{c} x_3 \end{array}
\begin{array}{c} \text{b}_2 \\
\text{b}_2
\end{array}
\begin{array}{c} \text{b}_2 \\
\text{b}_1
\end{array}

\text{t_4 : R_3(x_3)}
\begin{array}{c}
\begin{array}{c}
\text{c}_1 \\
\text{c}_4
\end{array}
\end{array}
\begin{array}{c} x_3 \end{array}
\begin{array}{c} x_3 \end{array}
\begin{array}{c} \text{b}_2 \\
\text{b}_2
\end{array}
\begin{array}{c} \text{b}_2 \\
\text{b}_1
\end{array}

\text{t_5 : R_4(x_2, x_4, x_3)}
\begin{array}{c}
\begin{array}{c}
\text{c}_1 \\
\text{c}_4
\end{array}
\end{array}
\begin{array}{c} x_2 \end{array}
\begin{array}{c} x_4 \end{array}
\begin{array}{c} x_3 \end{array}
\begin{array}{c} \text{b}_2 \\
\text{b}_2
\end{array}
\begin{array}{c} \text{b}_2 \\
\text{b}_1
\end{array}

\text{t_6 : R_4(x_2, x_4, x_3)}
\begin{array}{c}
\begin{array}{c}
\text{c}_1 \\
\text{c}_4
\end{array}
\end{array}
\begin{array}{c} x_2 \end{array}
\begin{array}{c} x_4 \end{array}
\begin{array}{c} x_3 \end{array}
\begin{array}{c} \text{b}_2 \\
\text{b}_2
\end{array}
\begin{array}{c} \text{b}_2 \\
\text{b}_1
\end{array}
Yannakakis Algorithm – Example

\[ t_1 : R_2(\mathbf{x}_2, \mathbf{x}_3) \]
\[ x_2 \quad x_3 \]
\[ c_1 \quad b_2 \]
\[ c_1 \quad b_2 \]
\[ c_4 \quad b_6 \]

\[ t_2 : R_2(\mathbf{x}_3, \mathbf{x}_4) \]
\[ x_3 \quad x_4 \]
\[ c_1 \quad b_2 \]
\[ c_1 \quad b_2 \]
\[ c_4 \quad b_6 \]

\[ t_3 : R_1(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3) \]
\[ x_1 \quad x_2 \quad x_3 \]
\[ c_1 \quad b_2 \]
\[ c_1 \quad b_2 \]
\[ c_4 \quad b_6 \]

\[ t_4 : R_3(\mathbf{x}_3) \]
\[ x_3 \]
\[ b_2 \]
\[ c_1 \quad a_1 \quad b_1 \]
\[ c_1 \quad a_1 \quad b_1 \]

\[ t_5 : R_6(\mathbf{x}_2, \mathbf{x}_4, \mathbf{x}_5) \]
\[ x_2 \quad x_4 \quad x_5 \]
\[ b_2 \]
\[ c_1 \quad a_1 \quad b_1 \]
\[ c_1 \quad a_1 \quad b_1 \]
Yannakakis Algorithm – Enumeration

Two additional traversals allow us to enumerate all answers.

**Theorem**

Let $Q$ be an acyclic conjunctive query. Given some database instance $D$, $Q(D)$ can be computed in output polynomial time, i.e., in time $O\left(|D| + |Q(D)|^k\right)$ for some constant $k \geq 1$.

**Enumeration Algorithm**

Given a join tree of query $Q$; a database instance $D$. Compute $Q(D)$:

1. 1st bottom-up traversal: semijoins as before (upwards propagation)
2. top-down traversal: “reverse” semijoins (downwards propagation)
3. 2nd bottom-up traversal: compute solutions using joins.

Yannakakis Algorithm – Proof

**Proof sketch.**

Correctness of the algorithm follows from the following propositions:

Given join tree $T$, for $t \in V(T)$ let $T_t$ be the subtree of $T$ rooted at $t$, $R_t$ the relation computed by semijoins and $R_t'$ the one by joins:

1. After the 1st bottom-up traversal:
   \[ R_t = \pi_{\text{vars}(t)}(\bigland_{v \in V(T_t)} v) \text{ for each } t \in T \]

2. After the top-down traversal:
   \[ R_t = \pi_{\text{vars}(t)}(\bigland_{v \in V(T_t)} v) \text{ for each } t \in T \]
Yannakakis Algorithm – Proof

Proof sketch.
Correctness of the algorithm follows from the following propositions:
Given join tree $T$, for $t \in V(T)$ let $T_t$ be the subtree of $T$ rooted at $t$, $R_t$ the relation computed by semijoins and $R'_t$ the one by joins:
1. After the 1st bottom-up traversal:
   
   \[ R_t = \pi_{\text{vars}(t)}(\land_{v \in V(T_t)} \nu) \text{ for each } t \in T \]
2. After the top-down traversal:
   \[ R_t = \pi_{\text{vars}(t)}(\land_{v \in V(T)} \nu) \text{ for each } t \in T \]
3. After the 2nd bottom-up traversal:
   \[ R'_t = \pi_{\text{vars}(T_t)}(\land_{v \in V(T)} \nu) \text{ for each } t \in T \]

$\Rightarrow R'_r$ at root $r$ contains all results

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Enumeration – Example

Example

1. We have already performed the 1st bottom-up traversal

2. Top-down semijoins

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6.4. Acyclic Conjunctive Queries

Example

1. We have already performed the 1st bottom-up traversal
2. Top-down semijoins

Compute result in 2nd bottom-up traversal

Example

1. We have already performed the 1st bottom-up traversal
2. Top-down semijoins
We have already performed the 1st bottom-up traversal
Top-down semijoins
Compute result in 2nd bottom-up traversal
Enumeration – Example

Learning Objectives

- The notions of query equivalence and containment,
- The Homomorphism Theorem,
- The complexity of query equivalence and containment,
- Minimization of conjunctive queries,
- Acyclic conjunctive queries,
- The Yannakakis algorithm.