A Dichotomy Structure Theorem for the Resilience Problem

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joint with work Wolfgang Gatterbauer
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- Brains = Databases
- Opinions, beliefs = Query answer
- Delete memories = Delete tuples from the database

Resilience problem

Definition (Resilience)

Given a query q and database D, we say that $(D, k) \in \mathtt{RES}(q)$ if and only if $D \models q$ and there exists some $\Gamma \subseteq D$ such that $D - \Gamma \not\models q$ and $|\Gamma| \leq k$.

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$\texttt{RES}(q_{vc})$ *is* NP*-complete.*

- Conjunctive queries **without self-joins**
- Deleted tuples $\rightarrow$ Contingency set Γ
- Endogenous (changeable) vs exogenous (non changeable) tuples

Dual hypergraph

$q_{\triangle} \mathrel{:-} R(x, y), S(y, z), T(z, x)$ $\qquad$ $q_{\mathrm{T}} \mathrel{:-} A(x), B(y), C(z), W(x, y, z)$

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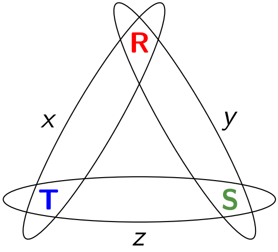
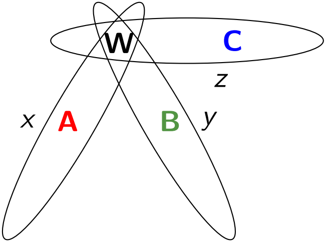


Triangle query

$q_{\mathrm{T}} :- A(x), B(y), C(z), W(x, y, z)$



Tripod query

Dual hypergraph

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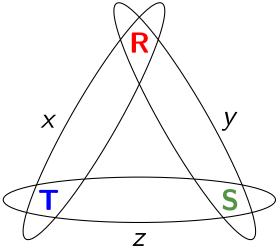

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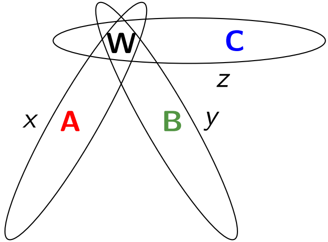


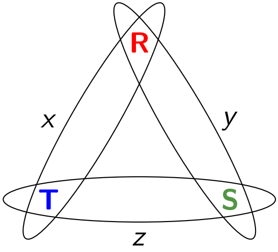
Tripod query

What is the complexity of resilience for those queries?

Dual hypergraph

$q_{\triangle}$:– $R(x, y), S(y, z), T(z, x)$

q_{T} :– $A(x), B(y), C(z), W(x, y, z)$



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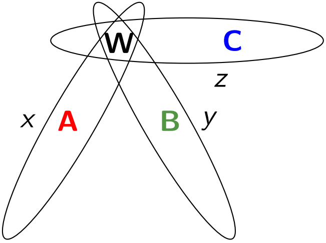

Tripod query

Lemma

$\mathtt{RES}(q_{\triangle})$ *and* $\mathtt{RES}(q_{\mathrm{T}})$ *are NP-complete.*

$\mathtt{RES}(q_\triangle)$ is NP-complete.

$3\text{SAT} \le \mathtt{RES}(q_\triangle)$. Let $\psi = C_1 \wedge \cdots \wedge C_m$ be a 3-CNF formula, $\text{var}(\psi) = \{v_1, \ldots, v_n\}$

Map $\psi \mapsto (D_\psi, k_\psi)$ s.t. $\quad \psi \in 3\mathrm{SAT} \Leftrightarrow (D_\psi, k_\psi) \in \mathtt{RES}(q_\triangle)$

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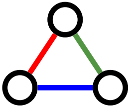
$$q_\triangle \coloneq R(x,y), S(y,z), T(z,x)$$

$(D_\psi, k_\psi) \in \texttt{RES}(q_\triangle) \Leftrightarrow \exists \Gamma\ (|\Gamma| = k_\psi) \wedge (D_\psi - \Gamma)$ has no 

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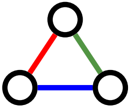
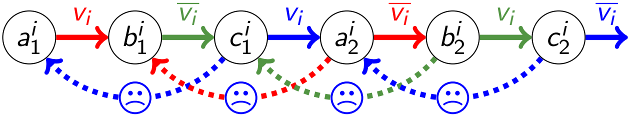
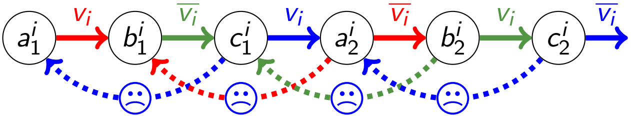


D_ψ has one circular gadget G_i for each variable v_i.




a_1^i
v_i
b_1^i
$\overline{v_i}$
c_1^i
v_i
a_2^i
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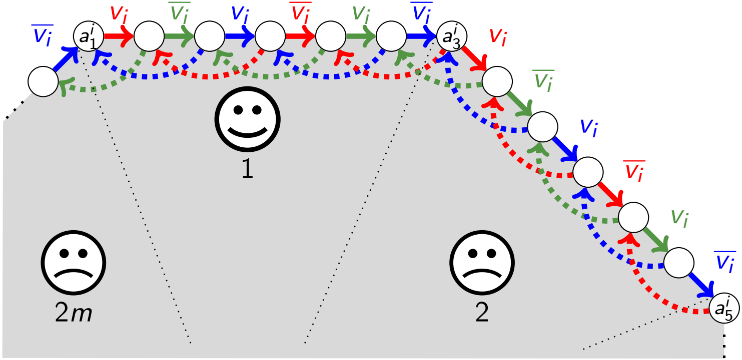
$\overline{v_i}$
a_1^i
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v_i
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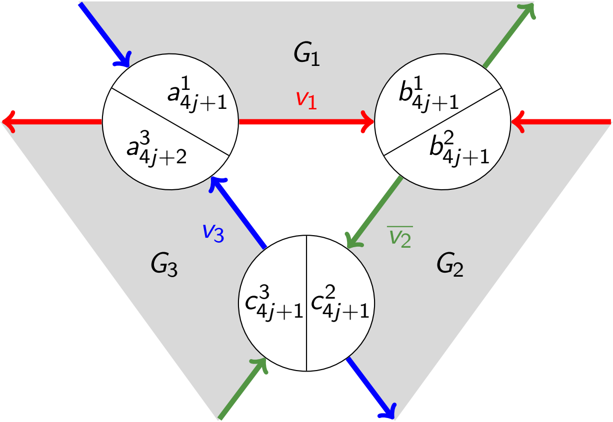
v_i
$\overline{v_i}$
a_3^i
v_i
$\overline{v_i}$
v_i
$\overline{v_i}$
v_i
$\overline{v_i}$
a_5^i
1
$2m$
2

For each clause, e.g., $C_j = (v_1 \vee \overline{v_2} \vee v_3)$, pick the jth occurrences of $v_1 \in G_1$, $\overline{v_2} \in G_2$ and $v_3 \in G_3$. Identify head of v_1 with tail of $\overline{v_2}$, head of $\overline{v_2}$ with tail of v_3, head of v_3 with tail of v_1



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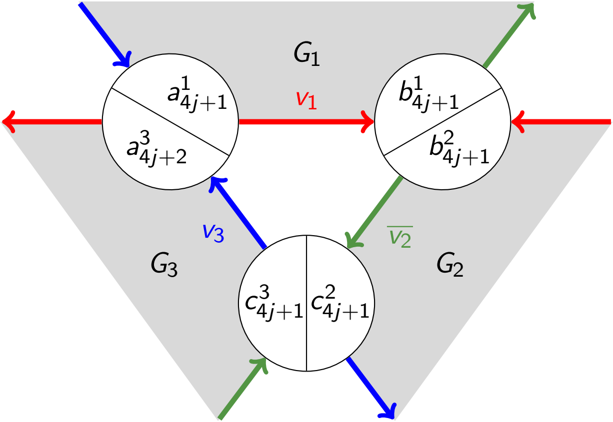

This new RGB triangle is automatically removed iff one of the literals in C_j is chosen true. $\square$

$\texttt{RES}(q_{\mathrm{T}})$ is NP-complete.

$$q_{\mathrm{T}} \ :\!-\ A(x), B(y), C(z), W(x, y, z)$$

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A **dominates** W.

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Proposition

If A dominates W, then we can assume that W is **exogenous**, i.e., rewrite as W^{x}, tuples from W^{x} are **never chosen**.

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$$q_{\mathrm{T}} \ :- \ A(x), B(y), C(z), W^{\times}(x, y, z)$$

$\mathtt{RES}(q_{\mathrm{T}})$ is NP-complete.

$$\begin{aligned} q_{\triangle} &:- \quad R(x,y), S(y,z), T(z,x) \\ q_{\mathrm{T}} &:- \quad A(x), B(y), C(z), W^{x}(x,y,z) \end{aligned}$$

Show $\mathtt{RES}(q_{\triangle}) \leq \mathtt{RES}(q_{\mathrm{T}})$

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Let (D,k) be an instance of $\mathtt{RES}(q_{\triangle})$.

$(D,k) \mapsto (D',k) \qquad D' \stackrel{\mathrm{def}}{=} (A,B,C,W^{\times})$

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$$\begin{aligned} A &= \left\{ \langle ab \rangle \;\middle|\; R(a,b) \in D \right\} \\ B &= \left\{ \langle bc \rangle \;\middle|\; S(b,c) \in D \right\} \\ C &= \left\{ \langle ca \rangle \;\middle|\; T(c,a) \in D \right\} \\ W^{\times} &= \left\{ (\langle ab \rangle, \langle bc \rangle, \langle ca \rangle) \;\middle|\; a,b,c \in \mathrm{dom}(D) \right\} \end{aligned}$$

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\end{aligned}
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Claim

$$(D,k) \in \mathtt{RES}(q_\triangle) \quad \Leftrightarrow \quad (D',k) \in \mathtt{RES}(q_{\mathrm{T}}). \qquad \square$$

Triads

What do the triangle query and the tripod query have in common?

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Definition (triad)

A **triad** is a set of three *endogenous atoms*, $\mathcal{T} = \{S_0, S_1, S_2\}$ such that for every pair i, j, there is a path from S_i to S_j that uses no variable occurring in the other atom of $\mathcal{T}$.

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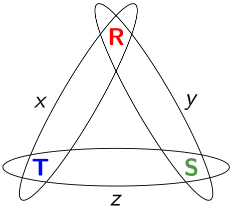

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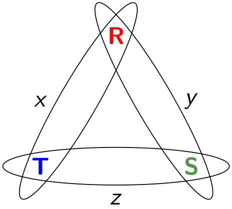

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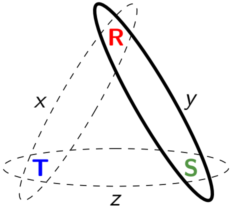

Where is the triad?
Path from R to S.

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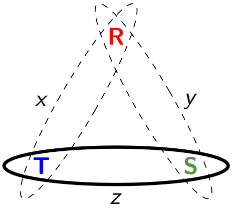

Where is the triad?
Path from S to T.

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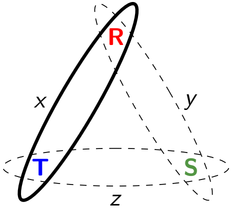

Where is the triad?
Path from T to R.

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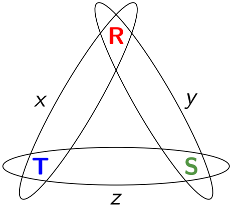

Where is the triad?
$\mathcal{T} = \{R, S, T\}$

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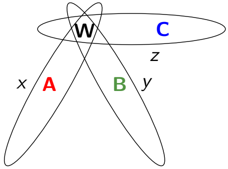

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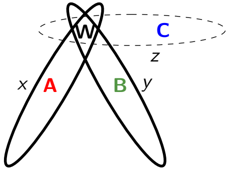

Where is the triad?
Path from A to B.

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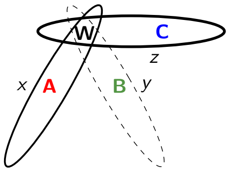

Where is the triad?
Path from A to C.

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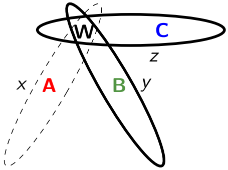

Where is the triad?
Path from B to C.

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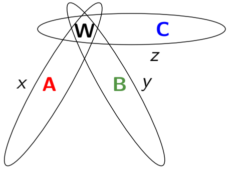

Where is the triad?
$\mathcal{T} = \{A, B, C\}$

Triads → hardness

Lemma

If q has a triad, then $\texttt{RES}(q)$ *is* NP*-complete.*

Triads $\rightarrow$ hardness

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Important remark

It is easy to check if a query has a triad!

Triads → hardness

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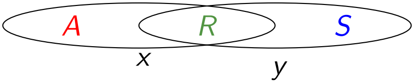
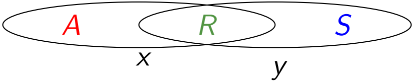
What if a query does not have a triad?

Linear queries



$$q :- A(x), R(x, y), S(y)$$

Linear queries

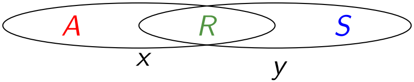


$$q :\!- A(x), R(x,y), S(y)$$

Definition

A query q is **linear** if its atoms may be arranged in a linear order such that each variable occurs in a contiguous sequence of atoms.

Linear queries



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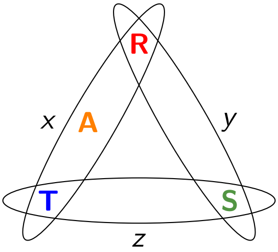
Definition

A query q is **linear** if its atoms may be arranged in a linear order such that each variable occurs in a contiguous sequence of atoms.

Fact [Meliou et.al., VLDB10]

For any linear sj-free CQ q, $\texttt{RES}(q)$ is in P. (Reduction to network flow.)

Is there a triad in the following query?



$$q_{\mathrm{rats}} :- A(x), R(x,y), S(y,z), T(z,x)$$

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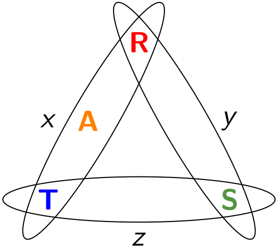

$$q_{\mathrm{rats}} \coloneq A(x), R(x, y), S(y, z), T(z, x)$$

$\mathtt{RES}(q_{\mathrm{rats}})$ is in P!

Domination

T and R are **dominated** by A in q_{rats}. This guarantees we don't need tuples from R, T in a minimum contingency set.

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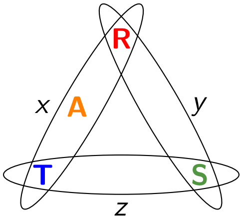

$$q_{\mathrm{rats}} :\!-\, A(x), R^x(x,y), S(y,z), T^x(z,x)$$

No triads $\rightarrow$ easy

Lemma

If q is a query in normal form with no triads, we can transform it into a linear query q', such that $\texttt{RES}(q) \leq \texttt{RES}(q')$. Therefore $\texttt{RES}(q)$ is in P.

Dichotomy for Resilience - sj-free CQ

Theorem

Let q be an sj-free CQ and $\texttt{nf}(q)$ its normal form.

- *If* $\texttt{nf}(q)$ *has a triad, then* $\texttt{RES}(q)$ *is* NP*-complete*
- *If* $\texttt{nf}(q)$ *does* **not** *have a triad, then* $\texttt{RES}(q)$ *is in* P.

Adding functional dependencies

$q_{\mathrm{T}} :- A(x), B(y), C(z), W(x, y, z)$

A

	X
a_1	1
a_2	3

B

	Y
b_1	2
b_2	4

C

	Z
c_1	5
c_2	6

W

	X	Y	Z
w_1	1	2	5
w_2	1	2	6
w_3	3	4	5
w_4	1	4	5

Adding functional dependencies

$q_{\mathrm{T}} :- A(x), B(y), C(z), W(x, y, z)$,$\texttt{fd} = W : x \to y$

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- FDs constrain the databases we can consider
- FDs can reduce the complexity of resilience

Adding functional dependencies

Transform the query based on FDs

Adding functional dependencies

Transform the query based on FDs $\rightarrow$ *induced rewrites*

Adding functional dependencies

Transform the query based on FDs $\rightarrow$ *induced rewrites*

$$q_{\mathrm{T}} = A(x), B(y), C(z), W(x, y, z), W : x \rightarrow y$$

$$\downarrow$$

$$q^*_{\mathrm{T}} = \mathbf{A}'(\mathbf{x}, \mathbf{y}), B(y), C(z), W(x, y, z), W : x \rightarrow y$$

$$\downarrow$$

$$q^*_{\mathrm{T}} = A'(x, y), B(y), C(z), W(x, y, z)$$

Adding functional dependencies

Transform the query based on FDs $\rightarrow$ *induced rewrites*

$$q_{\mathrm{T}} = A(x), B(y), C(z), W(x,y,z), W : x \rightarrow y$$

$$\downarrow$$

$$q_{\mathrm{T}}^{*} = \mathbf{A}'(\mathbf{x}, \mathbf{y}), B(y), C(z), W(x,y,z), W : x \rightarrow y$$

$$\downarrow$$

$$q_{\mathrm{T}}^{*} = A'(x,y), B(y), C(z), W(x,y,z)$$

$\texttt{RES}(q_{\mathrm{T}}, \varphi)$ is in P.

Adding functional dependecies

Induced rewrites

Let q be a query and $\overline{v} \to u \in \Phi$ be a functional dependency. We write $(q; \Phi) \rightsquigarrow (q'; \Phi)$ to mean that q' is the result of adding the dependent variable u to some relation that contains all the determinant variables $\overline{v}$. After applying all possible rewrites, we obtain query q^*, which we call **closed query**.

Adding functional dependecies

Induced rewrites

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Lemma

Let q^* be q after all possible induced rewrites have been applied. Then $\mathrm{RES}(q; \Phi) \equiv \mathrm{RES}(q^*; \Phi) \equiv \mathrm{RES}(q^*)$.

Dichotomy for resilience - sj-free CQ + FD

Theorem

Let $(q; \Phi)$ be a sf-free CQ with functional dependencies. Let (q^*, Φ) be its closure under induced rewrites, and such that all dominated atoms of q^* are exogenous.

- *If q^* has a triad then $\mathtt{RES}(q; \Phi)$ is NP-complete.*
- *If q^* does* **not** *have a triad, then $\mathtt{RES}(q; \Phi)$ is in P.*

Future Directions

- Resilience for CQ with self-joins - (q_{vc})
- Deletion propagation: view side-effects for CQ with self-joins
  - Dichotomy results for CQ without self-joins [Kimelfeld et.al., PODS11]
  - Extended to functional dependencies [Kimelfeld, PODS12]
- Characterize the complexity of the parts of the problem that are in P, cf. [Allender, et. al.]