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Linear Programs with Conjunctive Queries

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Abstract

In this paper, we study the problem of optimizing a linear program whose variables are answers to a conjunctive query. For this we propose the language $LP(CQ)$ for specifying linear programs whose constraints and objective functions depend on the answer sets of conjunctive queries. We contribute an efficient algorithm for solving programs in a fragment of $LP(CQ)$. The naive approach constructs a linear program having as many variables as elements in the answer set of the queries. Our approach constructs a linear program having the same optimal value but fewer variables. This is done by exploiting the structure of the conjunctive queries using hypertree decompositions of small width to group elements of the answer set together. We illustrate the various applications of $LP(CQ)$ programs on three examples: optimizing deliveries of resources, minimizing noise for differential privacy, and computing the s -measure of patterns in graphs as needed for data mining.

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1 Introduction

When modeling optimization problems it often seems natural to separate the logical constraints from the relational data. This holds for linear programming with AMPL [7] and for constraint programming in MiniZinc [17]. It was also noticed in the context of database research, when using integer linear programming for finding optimal database repairs as proposed by Kolaitis, Pema and Tan [14], or when using linear optimization to explain the result of a database query to the user as proposed by Meliou and Suciu [16]. Moreover, tools like SolveDB [21] have been developed to better integrate mixed integer programming and thus linear programming into relational databases.

We also find it natural to define the relational data of linear optimization problems by database queries. For this reason, we propose the language of linear programs with conjunctive queries $LP(CQ)$ in the present paper. The objective is to become able to specify weightings of answer sets of database queries, that optimize a linear objective function subject to linear constraints. The optimal weightings of $LP(CQ)$ programs can be computed in a naive manner, by first answering the database queries, and then solving a linear program parametrized by the answer sets. We then approach the question – to our knowledge for the first time – of whether this can be done with lower complexity for subclasses of conjunctive queries such as the class of acyclic conjunctive queries.

As our main contribution we present a more efficient algorithm for computing the optimal value of a program in the fragment of so-called projecting $LP(CQ)$ programs for which we also bound the hypertree width of the queries. The particular case of width 1 covers the class of acyclic conjunctive queries. By using hypertree decompositions, our algorithm is based on a factorized interpretation of any projecting $LP(CQ)$ program over a database to a linear program without conjunctive queries. The factorized interpretation uses other linear program variables, that represent sums of the linear program variables in the naive interpretation. The number of linear program variables in the factorized interpretation depends only on the widths of the hypertree decompositions of the queries in the $LP(CQ)$ program, rather than on the number of query variables. In this manner, our more efficient algorithm can decrease



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46 the data complexity, i.e., the degree of the polynomial in the upper bound of the run time of
 47 the naive algorithm. With respect to the combined complexity, the special case of projecting
 48 $LP(CQ)$ programs with bounded quantifier depth becomes tractable for acyclic conjunctive
 49 queries, while it is NP -complete in general.

50 We prove the correctness of the factorized interpretation with respect to the naive
 51 interpretation. For this we have to show a correspondence between weightings of answer sets
 52 on the naive interpretation, and weightings of answer sets on the factorized interpretation.
 53 This correspondence can be seen as an independent contribution as it shows that one can
 54 reconstruct a relevant weighting of the answer set of a quantifier free conjunctive query by
 55 only knowing the value of the projected weighting on the bags of the tree decomposition.
 56 Conjunctive queries with existential quantifier are dealt with by showing that one can find
 57 an equivalent projecting $LP(CQ)$ program using only quantifier free conjunctive queries.

58 1.1 Applications

59 A wide range of applications of linear programs can benefit from conjunctive queries.

60 **Resource Delivery Optimization.** We consider a situation in logistics where a
 61 company received orders for specific quantities of resource objects. The objects must be
 62 produced at a factory then transported to a warehouse before being delivered to the buyer.
 63 The objective is to fulfill every order while minimizing the overall delivery costs and respecting
 64 the production capacities of the factories as well as the storing capacities of the warehouses.

65 Let F be the set of factories, O the set of objects, W the set of warehouses and B the set
 66 of buyers. We consider a database \mathbb{D} with elements in the domain $D = F \uplus O \uplus W \uplus B \uplus \mathbb{R}_+$.
 67 The elements $d \in D$ encoding a positive real number can be decoded back by applying the
 68 database's functions $\mathbf{num}^{\mathbb{D}}$, yielding the positive real number $\mathbf{num}^{\mathbb{D}}(d) \in \mathbb{R}_+$. The database
 69 \mathbb{D} has four tables. The first table $prod^{\mathbb{D}} \subseteq F \times O \times \mathbb{R}_+$ contains triples (f, o, q) stating that
 70 the factory f can produce up to q units of object o . The second table $order^{\mathbb{D}} : B \times O \times \mathbb{R}_+$
 71 contains triples (b, o, q) stating that the buyer b orders q units of object o . The third table
 72 $store^{\mathbb{D}} \subseteq W \times \mathbb{R}_+$ contains pairs (w, l) stating that the warehouse w has a storing limit of
 73 l . The fourth table $route^{\mathbb{D}} : (F \times W \times \mathbb{R}_+) \cup (W \times B \times \mathbb{R}_+)$ contains triples (f, w, c) stating
 74 that the transport from factory f to warehouse w costs c , and triples (w, b, c) stating that
 75 the transport from warehouse w to buyer b costs c . The query:

$$76 \quad dlr(f, w, b, o) = \exists q. \exists q'. \exists c \exists c'. prod(f, o, q) \wedge order(b, o, q') \wedge route(f, w, c) \wedge route(w, b, c')$$

77 selects from the database \mathbb{D} all tuples (f, w, b, o) such that the factory f can produce some
 78 objects o to be delivered to buyer b through the warehouse w . Let $Q = dlr(f', w', b', o')$. The
 79 question is to determine for each of these possible deliveries the quantity of the object that
 80 should actually be sent. These quantities are modelled by the unknown weights θ_Q^α of the query
 81 answers $\alpha \in sol^{\mathbb{D}}(Q)$. For any factory f and warehouse w the sum $\sum_{\alpha \in sol^{\mathbb{D}}(Q \wedge w' \doteq w \wedge f' \doteq f)} \theta_Q^\alpha$
 82 is described by the expression $\mathbf{weight}_{(f', w', b', o') : f' \doteq f \wedge w' \doteq w}(Q)$ when interpreted over \mathbb{D} .

83 We use the $LP(CQ)$ program in Figure 1 to describe the optimal weights that minimize
 84 the overall delivery costs. The weights depend on the interpretation of the program over the
 85 database, since \mathbb{D} specifies the production capacities of the factories, the stocking limits of
 86 the warehouses, etc. The program has the following constraints:

- 87 - for each $(f, o, q) \in prod^{\mathbb{D}}$ the overall quantity of object o produced by f is at most q .
- 88 - for each $(b, o, q) \in order^{\mathbb{D}}$ the overall quantity of objects o delivered to b is at least q .
- 89 - for each $(w, l) \in store^{\mathbb{D}}$ the overall quantity of objects stored in w is at most l .

$$\begin{aligned}
& \text{minimize} \\
& \sum_{(f,w,c):route(f,w,c)} \mathbf{num}(c) \mathbf{weight}_{(f',w',b',o'):f' \dot{=} f \wedge w' \dot{=} w}(Q) \\
& + \sum_{(w,b,c):route(w,b,c)} \mathbf{num}(c) \mathbf{weight}_{(f',w',b',o'):w' \dot{=} w \wedge b' \dot{=} b}(Q) \\
& \text{subject to} \\
& \forall (f,o,q):prod(f,o,q). \mathbf{weight}_{(f',w',b',o'):f' \dot{=} f \wedge o' \dot{=} o}(Q) \leq \mathbf{num}(q) \\
& \forall (b,o,q):order(b,o,q). \mathbf{weight}_{(f',w',b',o'):b' \dot{=} b \wedge o' \dot{=} o}(Q) \geq \mathbf{num}(q) \\
& \forall (w,l):store(w,l). \mathbf{weight}_{(f',w',b',o'):w' \dot{=} w}(Q) \leq \mathbf{num}(l)
\end{aligned}$$

■ **Figure 1** A $LP(CQ)$ program for the resource delivery optimization where $Q = dlr(f', w', b', o')$.

90 By answering the query Q on the database \mathbb{D} and introducing a linear program variable
91 θ_Q^α for each of the query answers α , we can interpret the $LP(CQ)$ program in Figure 1 as
92 a linear program. However the number of answers of Q and thus the number of variables
93 in this program could be cubic in the size of the database, which quickly grows too big.
94 Our factorized interpretation for the projecting $LP(CQ)$ program in Figure 1 produces a
95 linear program that only has a quadratic number of variables, since query Q has a hypertree
96 decomposition of width 2 as well as the whole $LP(CQ)$ program.

97 **Minimizing Noise for ε -Differential Privacy.** The strategy of differential privacy is to
98 add noise to the relational data before publication. Roughly speaking, the general objective
99 of ε -differential privacy [5] is to add as little noise as possible, without disclosing more
100 than an ε amount of information. We illustrate this with the example of a set of hospitals
101 which publish medical studies aggregating results of tests on patients, which are to be kept
102 confidential. We consider the problem of how to compute the optimal amount of noise to
103 be added to each separate piece of sensitive information (in terms of total utility of the
104 studies) while guaranteeing ε -differential privacy. We show that this question can be solved
105 (approximately) by computing the optimal solution of a projecting program in $LP(CQ)$
106 with a single conjunctive query that is acyclic, i.e., of hypertree with 1. While the naive
107 interpretation yields a linear program with a quadratic number of variables in the size of
108 the database, the factorized interpretation requires only a linear number. The example is
109 worked out in Appendix A.

110 **Computing the s-Measure for Graph Pattern Matching.** A matching of a subgraph
111 pattern in a graph is a graph homomorphism from the pattern to the graph. The s -measure
112 of Wang et al. [23] is used in data mining to measure the frequency of matchings of subgraph
113 patterns, while accounting for overlaps of different matchings. The idea is to find a maximal
114 weighting for the set of matchings, such that for any node of the subgraph pattern, the set of
115 matchings mapping it on the same graph node must have a overall weight less than 1. This
116 optimization problem can be expressed by a projecting $LP(CQ)$ program over a database
117 storing the graph. The conjunctive query of this program expresses the matching of the
118 subgraph pattern. The hypertree width of this conjunctive query is bounded by the hypertree
119 width of the subgraph pattern. Our factorized interpretation therefore reduces the size of
120 the linear program for subgraph patterns with small hypertree width. More information on
121 the $LP(CQ)$ program can be found in Appendix B.

122 **1.2 Related Work**

123 Our result builds on well-known techniques using dynamic programming on tree decomposi-
 124 tions of the hypergraph of conjunctive queries. This techniques were first introduced by
 125 Yannkakis [24] who observed that so-called acyclic conjunctive queries could be answered
 126 in linear time using dynamic programming on a tree whose nodes are in correspondence
 127 with the atoms of the query. Generalizations have followed in two directions: on the one
 128 hand, generalizations of acyclicity such as notions of hypertree width [9, 10, 11] have been
 129 introduced and on the other hand enumeration and aggregation problems have been shown
 130 to be tractable on these families of queries such as finding the size of the answer set [19]
 131 or enumerating it with small delay [1]. More recently, these tractability results have been
 132 explained by the mean of factorized databases [18], observing that the answer set of bounded
 133 width conjunctive queries could be succinctly represented by circuits enjoying interesting
 134 syntactic properties allowing to efficiently solve numerous aggregation problems on it in
 135 polynomial time in the size of the representation. While the complexity of several aggregation
 136 problems in databases have been studied on such structures [2, 20], our result is, to the best
 137 of our knowledge, the first one to exploit the structure of conjunctive queries to solve linear
 138 programs more efficiently. While our result could be made to work on factorized representa-
 139 tions of queries answer sets, we choose to directly work on tree decompositions because the
 140 semantic of the query is clearer in its conjunctive form than its factorized representation.
 141 Since one of our contribution is to offer a language to describe linear programs parametrized
 142 by the answer set of queries, this aspect is important to write intelligible linear programs.

143 **Organization of the paper.** Section 2 contains the necessary definitions to understand
 144 the paper. Section 3 presents the language $LP(CQ)$ of linear programs parametrized by
 145 conjunctive queries and gives its semantics. Section 4 defines a fragment of $LP(CQ)$ for
 146 which we propose a more efficient algorithm. Finally, Section 5 presents encouraging practical
 147 results on solving the delivery optimization problem using this algorithm. Due to space limit,
 148 most proofs and full details on applications to differential privacy and s-measure computation
 149 have been moved to the appendix.

150 **2 Preliminaries**

151 **Sets, Functions and Relations.** Let $\mathbb{B} = \{0, 1\}$ be the set of Booleans, \mathbb{N} the set of natural
 152 numbers including 0, \mathbb{R}_+ be the set of positive reals subsuming \mathbb{N} , and \mathbb{R} the set of all reals.

153 Given any set S and $n \in \mathbb{N}$ we denote by S^n the set all n -tuples over S and by $S^* = \cup_{n \in \mathbb{N}} S^n$
 154 the set of all words over S . A *weighting* on S is a (total) function $f : S \rightarrow \mathbb{R}_+$.

155 Given a set of (total) functions $A \subseteq D^S = \{f \mid f : S \rightarrow D\}$ and a subset $S' \subseteq S$, we
 156 define the set of restrictions $A_{|S'} = \{f_{|S'} \mid f \in A\}$. For any binary relation $R \subseteq S \times S$,
 157 we denote its transitive closure by $R^+ \subseteq S \times S$ and the reflexive transitive closure by
 158 $R^* = R^+ \cup \{(s, s) \mid s \in S\}$.

159 **Variable assignments.** We fix a countably infinite set of (query) variables \mathcal{X} . For any
 160 set D of database elements, an assignment of (query) variables to database elements is a
 161 function $\alpha : X \rightarrow D$ that maps elements of a finite subset of variables $X \subseteq \mathcal{X}$ to values of
 162 D . For any two sets of variable assignments $A_1 \subseteq D^{X_1}$ and $A_2 \subseteq D^{X_2}$ we define their join
 163 $A_1 \bowtie A_2 = \{\alpha_1 \cup \alpha_2 \mid \alpha_1 \in A_1, \alpha_2 \in A_2, \alpha_{1|I} = \alpha_{2|I}\}$ where $I = X_1 \cap X_2$.

164 We also use a few vector notations. Given a vector of variables $\mathbf{x} = (x_1, \dots, x_n) \in \mathcal{X}^n$ we
 165 denote by $set(\mathbf{x}) = \{x_1, \dots, x_n\}$ the set of the elements of \mathbf{x} . For any variable assignment

Linear sums	$S, S' \in Sum$	$::= c \mid \xi \mid cS \mid S + S'$
Linear constraints	$C, C' \in LC$	$::= S \leq S' \mid C \wedge C' \mid true$
Linear programs	$L \in LP$	$::= \mathbf{maximize} S \mathbf{subject to} C$

■ **Figure 2** The set of linear programs LP with variables $\xi \in \Xi$ and constants $c \in \mathbb{R}$.

Expressions	$E_1, \dots, E_n \in Ex_{\mathcal{C}}$	$::= x \mid a$
Conjunctive queries	$Q, Q' \in C_{Q\Sigma}$	$::= E_1 \doteq E_2 \mid r(E_1, \dots, E_n) \mid Q \wedge Q' \mid \exists x.Q \mid true$

■ **Figure 3** The set of conjunctive queries $C_{Q\Sigma}$ with schema $\Sigma = ((\mathcal{R}^{(n)})_{n \in \mathbb{N}}, \mathcal{C})$ where $x \in \mathcal{X}$, $a \in \mathcal{C}$, and $r \in \mathcal{R}^{(n)}$.

166 $\alpha : X \rightarrow D$ with $set(\mathbf{x}) \subseteq X$ we denote the application of the assignment α on \mathbf{x} by
 167 $\alpha(\mathbf{x}) = (\alpha(x_1), \dots, \alpha(x_n))$.

168 **Linear programs.** Let Ξ be a set of linear program variables. In Figure 2, we recall the
 169 definition of the sets of linear sums Sum , linear constraints LC , and linear programs LP
 170 with variables in Ξ . We consider the usual linear equations $S \doteq S'$ as syntactic sugar for the
 171 constraints $S \leq S' \wedge S' \leq S$. For any linear program $L = \mathbf{maximize} S \mathbf{subject to} C$ we call
 172 S the objective function of L and C the constraint of L . Note that $\mathbf{minimize} S \mathbf{subject to} C$
 173 can be expressed by $\mathbf{maximize} -1 S \mathbf{subject to} C$ up to negation.

174 The formal semantics of linear programs is recalled in Figure 10. Since we will only be
 175 interested in variables for positive real numbers – and do not want to impose positivity
 176 constraints all over – we restrict variables of linear programs to always be positive real
 177 numbers. For any weightings $\omega : \Xi \rightarrow \mathbb{R}_+$, the value of a sum $S \in Sum$ is the real number
 178 $\llbracket S \rrbracket_{\omega} \in \mathbb{R}$, and the value of a constraint $C \in LC$ is the truth value $\llbracket C \rrbracket_{\omega} \in \mathbb{B}$. The optimal
 179 solution $\llbracket L \rrbracket \in \mathbb{R}$ of a linear program L with objective function S and constraint C is
 180 $\llbracket L \rrbracket = \max\{\llbracket S \rrbracket_{\omega} \mid \omega : \Xi \rightarrow \mathbb{R}_+, \llbracket C \rrbracket_{\omega} = 1\}$. It is well-known that the optimal solution of a
 181 linear program can be computed in polynomial time [12].

182 **Rooted trees.** A digraph is a pair $(\mathcal{V}, \mathcal{E})$ with node set \mathcal{V} and edge sets $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$. A
 183 digraph is acyclic if there is no $v \in \mathcal{V}$ for which $(v, v) \in \mathcal{E}^+$. For any node $u \in \mathcal{V}$, we denote
 184 by $\downarrow u = \{v \in \mathcal{V} \mid (u, v) \in \mathcal{E}^*\}$ the set of nodes in \mathcal{V} reachable over some downwards path
 185 from u , and by $\uparrow u = \{v \in \mathcal{V} \mid (v, u) \in \mathcal{E}^*\}$ the set of nodes that are in the context of or equal
 186 to u . A *rooted tree* is an acyclic digraph where $(u, v), (u', v) \in \mathcal{E}$ implies $u = u'$, and there
 187 exists a node $r \in \mathcal{V}$ such that $\mathcal{V} = \downarrow(r)$. In this case, r is unique and called the root of the
 188 tree. Observe that in this tree, the paths are oriented from the root to the leaves of the tree.

189 **Relational Databases.** A *database schema* is a pair $\Sigma = (R, \mathcal{C})$ where \mathcal{C} a finite set of
 190 constants ranged over by a, b and $R = \cup_{n \in \mathbb{N}} \mathcal{R}^{(n)}$ is a finite set of relation symbols. The
 191 elements $r \in \mathcal{R}^{(n)}$ are called relation symbols of arity $n \in \mathbb{N}$.

192 A *database* $\mathbb{D} \in db_{\Sigma}$ is a tuple $\mathbb{D} = (\Sigma, D, \cdot^{\mathbb{D}})$, where Σ is a schema, D a finite set of
 193 database elements, and $r^{\mathbb{D}} \subseteq D^n$ a relation for any relation symbol $r \in \mathcal{R}^{(n)}$ and $a^{\mathbb{D}} \in D$ a
 194 database element for any constant $a \in \mathcal{C}$. We also define the database's domain $dom(\mathbb{D}) = D$.

195 A *database with real numbers* is a tuple $\mathbb{D} = (\Sigma, D, \cdot^{\mathbb{D}}, \mathbf{num}^{\mathbb{D}})$ such that $\mathbb{D} = (\Sigma, D, \cdot^{\mathbb{D}})$ is
 196 a relational database and $\mathbf{num}^{\mathbb{D}}$ a partial function from D to \mathbb{R} .

197 **Conjunctive Queries.** In Figure 3 we recall the notion of conjunctive queries on relational
 198 databases. An expression $E \in Ex_{\mathcal{C}}$ is either a (query) variable $x \in \mathcal{X}$ or a constant $a \in \mathcal{C}$.

XX:6 Linear Programs with Conjunctive Queries

199 The set of conjunctive queries $Q \in CQ_\Sigma$ is built from equations $E_1 \doteq E_2$, atoms $r(E_1, \dots, E_n)$,
 200 the logical operators of conjunction $Q \wedge Q'$ and existential quantification $\exists x.Q$. Given a
 201 vector $\mathbf{x} = (x_1, \dots, x_n) \in \mathcal{X}^n$ and a query Q , we write $\exists \mathbf{x}.Q$ instead of $\exists x_1. \dots \exists x_n.Q$.

202 The set of free variables $fv(Q) \subseteq \mathcal{X}$ are those variables that occur in Q outside the scope
 203 of an existential quantifier. A conjunctive query Q is said to be *quantifier free* if it does not
 204 contain any existential quantifier.

205 For any conjunctive query $Q \in CQ_\Sigma$, set $X \supseteq fv(Q)$ and database $\mathbb{D} \in db_\Sigma$ we define
 206 the answer set $sol_X^\mathbb{D}(Q)$ in Figure 11. It contains all those assignments $\alpha : X \rightarrow dom(\mathbb{D})$ for
 207 which Q becomes true on \mathbb{D} . We also write $sol^\mathbb{D}(Q)$ instead of $sol_{fv(Q)}^\mathbb{D}(Q)$. Observe that
 208 $sol^\mathbb{D}(\exists \mathbf{x}.Q) = sol^\mathbb{D}(Q)|_{fv(Q) \setminus set(\mathbf{x})}$.

209 **Hypertree Decompositions.** Hypertree decompositions of conjunctive queries are a
 210 way of laying out the structure of a conjunctive query in a tree. It allows to solve many
 211 aggregation problems (such as checking the existence of a solution, counting or enumerating
 212 the solutions etc.) on quantifier free conjunctive queries in polynomial time where the degree
 213 of the polynomial is given by the width of the decomposition.

214 **► Definition 1.** Let $X \subseteq \mathcal{X}$ be a finite set of variables. A decomposition tree T of X is a
 215 tuple $(\mathcal{V}, \mathcal{E}, \mathcal{B})$ such that:

- 216 - $(\mathcal{V}, \mathcal{E})$ is a finite directed rooted tree with edges from the root to the leaves,
- 217 - the bag function $\mathcal{B} : \mathcal{V} \rightarrow 2^X$ maps nodes to subsets of variables in X ,
- 218 - for all $x \in X$ the subset of nodes $\{u \in \mathcal{V} \mid x \in \mathcal{B}(u)\}$ is connected in the tree $(\mathcal{V}, \mathcal{E})$,
- 219 - each variable of X appears in some bag, that is $\bigcup_{u \in \mathcal{V}} \mathcal{B}(u) = X$.

220 Now a hypertree decomposition of a quantifier free conjunctive query is a decomposition
 221 tree where the variables of each atom of the query is covered by at least one bag:

222 **► Definition 2 (Hypertree width of quantifier free conjunctive queries).** Let $Q \in CQ_\Sigma$ be a
 223 quantifier free conjunctive query. A generalized hypertree decomposition of Q is a decomposi-
 224 tion tree $T = (\mathcal{V}, \mathcal{E}, \mathcal{B})$ of $fv(Q)$ such that for each atom $r(\mathbf{x})$ of Q there is a vertex $u \in \mathcal{V}$
 225 such that $set(\mathbf{x}) \subseteq \mathcal{B}(u)$. The width of T with respect to Q is the minimal number k such that
 226 every bag of T can be covered by the variables of k atoms of Q . The generalized hypertree
 227 width of a query Q is the minimal width of a tree decomposition of Q .

228 We call a conjunctive query α -acyclic if it has general hypertree width 1. The query
 229 $r(x, y) \wedge r(y, z)$ has the generalized hypertree decomposition $(\mathcal{V}, \mathcal{E}, \mathcal{B})$ with $\mathcal{V} = \{1, 2, 3\}$,
 230 $\mathcal{E} = \{(1, 2), (1, 3)\}$, and $\mathcal{B} = [1/\{x\}, 2/\{x, y\}, 3/\{y, z\}]$ of width 1, so it is α -acyclic.

231 Many problems can be solved efficiently on conjunctive queries having a small hypertree
 232 width. We will mainly be interested in the problem of efficiently computing $sol^\mathbb{D}(Q)$.

233 **► Lemma 3 (Folklore).** Given a tree decomposition $T = (\mathcal{V}, \mathcal{E}, \mathcal{B})$ of a quantifier free
 234 conjunctive query $Q \in CQ_\Sigma$ of width k and a database $\mathbb{D} \in db_\Sigma$, one can compute the
 235 collection of bag projections $(sol^\mathbb{D}(Q)|_{\mathcal{B}(u)})_{u \in \mathcal{V}}$ in time $O(|\mathbb{D}|^k \log(|\mathbb{D}|) \cdot |T|)$.

236 Lemma 3 is folklore and can be proven by computing the semi-join of every bag in a
 237 subtree in a bottom-up fashion, as it is done in [15, Theorem 6.25]. It gives a superset S_u of
 238 $sol^\mathbb{D}(Q)|_{\mathcal{B}(u)}$ for every u . Then, with a second top-down phase, one can remove tuples from
 239 S_u that cannot be extended to a solution of $sol^\mathbb{D}(Q)$.

240 Note that if Q contains n atoms, $sol^\mathbb{D}(Q)$ may be of size $O(|\mathbb{D}|^n)$ whereas $(sol^\mathbb{D}(Q)|_{\mathcal{B}(u)})_{u \in \mathcal{V}}$,
 241 that has size $O(|\mathbb{D}|^k \cdot |T|)$ where k is the width of T . In the particular case of α -acyclic
 242 conjunctive queries, where $n = 1$, the overall size of the projections is linear. It gives a
 243 succinct way of describing the set of solutions of Q that we exploit in this paper.

244 Parts of our result will be easier to describe on so-called normalized decomposition trees:

Constant numbers	$N \in Num_C$::=	$c \mid \mathbf{num}(E)$
Linear sums	$S, S' \in Sum_\Sigma$::=	$\mathbf{weight}_{\mathbf{x}:Q'}(Q) \mid \sum_{\mathbf{x}:Q} S \mid NS \mid S + S' \mid N$
Linear constraints	$C, C' \in LC_\Sigma$::=	$S \leq S' \mid C \wedge C' \mid true \mid \forall \mathbf{x}:Q.C$
Linear programs	$L \in LP_\Sigma$::=	$\mathbf{maximize} S \mathbf{subject\ to} C$ where $fv(S) = fv(C) = \emptyset$.

■ **Figure 4** $LP(CQ)$ programs $L \in LP_\Sigma$ where $c \in \mathbb{R}$, $E \in Ex_C$, $\mathbf{x} \in \mathcal{X}^*$ and $Q, Q' \in CQ_\Sigma$.

245 ▶ **Definition 4.** Let $T = (\mathcal{V}, \mathcal{E}, \mathcal{B})$ be a decomposition tree. We call a node $u \in \mathcal{V}$ of T :
 246 - **an extend node** if it has a single child u' and $\mathcal{B}(u) = \mathcal{B}(u') \cup \{x\}$ for some $x \in \mathcal{X} \setminus \mathcal{B}(u')$,
 247 - **a project node** if it has a single child u' and $\mathcal{B}(u) = \mathcal{B}(u') \setminus \{x\}$ for some $x \in \mathcal{X} \setminus \mathcal{B}(u)$,
 248 - **a join node** if it has $k \geq 1$ children u_1, \dots, u_k with $\mathcal{B}(u) = \mathcal{B}(u_1) = \dots = \mathcal{B}(u_k)$.
 249 We call T normalized if all its nodes in \mathcal{V} are either extend nodes, project nodes, join nodes,
 250 or leaves.¹

251 It is well-known that tree decompositions can always be normalized without changing the
 252 width. Thus normalization does not change the asymptotic complexity of the algorithms.

253 ▶ **Lemma 5** (Lemma of 13.1.2 of [13]). For every tree decomposition of $T = (\mathcal{V}, \mathcal{E}, \mathcal{B})$ of
 254 Q of width k , there exists a normalized tree decomposition $T' = (\mathcal{V}', \mathcal{E}', \mathcal{B}')$ having width k .
 255 Moreover, one can compute T' from T in polynomial time.

256 3 Linear Programs with Conjunctive Queries

257 3.1 Syntax

258 We want to assign weights to the answers of a conjunctive query on a database, such that
 259 they maximize a linear objective function subject to linear constraints. For this, we introduce
 260 the language $LP(CQ)$ of linear programs with conjunctive queries that we also call linear
 261 CQ -programs. Its syntax is given in Figure 4. Note that an example of an $LP(CQ)$ program
 262 for optimal warehouse selection was already given in Figure 1.

263 $LP(CQ)$ programs are interpreted as linear programs whose variables describe the solutions
 264 of conjunctive queries. As a consequence, they do *not* contain any explicit linear program
 265 variables. Instead, they may contain weight expressions $\mathbf{weight}_{\mathbf{x}:Q'}(Q)$ over conjunctive
 266 queries $Q, Q' \in CQ_\Sigma$. Intuitively, this expressions is interpreted as a linear sum over linear
 267 program variables representing a solution of $Q \wedge Q'$. Variables of Q and Q' however may be
 268 bound in the context, for example through universal quantifiers or Σ -operators. The query
 269 variables in \mathbf{x} are bound by the expression taking scope over Q and Q' . The free (query)
 270 variable of weight expressions must however be bound by the context, so that they will be
 271 instantiated to some database values before evaluation. Weight expressions without free
 272 variables reason about an unknown weighting of the answer set of query Q on the given
 273 database \mathbb{D} with the variables in $set(\mathbf{x})$. Its value is then the sum over the weights of tuples
 274 in answer set of $Q \wedge Q'$ on the database \mathbb{D} with variables in $set(\mathbf{x})$.

275 Beside weight expressions, linear sums in Sum_Σ may also contain expression $N \in Num_C$
 276 or NS where $S \in Sum_\Sigma$ and N is a constant number expression, which is either a real number

¹ In the literature this property is referred to as “nice” tree decompositions.

$$\begin{array}{ll}
fv(c) = \emptyset & fv(\mathbf{num}(E)) = fv(E) \\
fv(\mathbf{weight}_{\mathbf{x}:Q'}(Q)) = fv(Q) \cup fv(Q') \setminus set(\mathbf{x}) & fv(\sum_{\mathbf{x}:Q} S) = fv(S) \cup fv(Q) \setminus set(\mathbf{x}) \\
fv(NS) = fv(N) \cup fv(S) & fv(S \leq S') = fv(S) \cup fv(S') \\
fv(S + S') = fv(S) \cup fv(S') & fv(C \wedge C') = fv(C) \cup fv(C') \\
fv(\forall \mathbf{x}:Q. C) = fv(Q) \cup fv(C) \setminus \{\mathbf{x}\} & fv(true) = \emptyset \\
fv(\mathbf{maximize} S \text{ subject to } C) = \emptyset &
\end{array}$$

■ **Figure 5** Free variables of linear sums, constraints, and linear CQ -programs.

277 $c \in \mathbb{R}$ or a number expression $\mathbf{num}(E)$ with $E \in \mathcal{X} \cup \mathcal{C}$. An expression $\mathbf{num}(a)$ denotes the
278 real number $\mathbf{num}^{\mathbb{D}}(a^{\mathbb{D}})$ if this value is defined. Note that the real value of $\mathbf{num}(a)$ over \mathbb{D} is
279 constant from the perspective of the linear program once the database \mathbb{D} is fixed.

280 Linear constrains $C \in LC_{\Sigma}$ are conjunctions of inequalities $S \leq S'$ between linear sums
281 $S, S' \in Sum_{\Sigma}$, and universally quantified constraints $\forall \mathbf{x}:Q. C'$ requiring that C' must be
282 valid for all possible values of \mathbf{x} in the solution of Q over the database (after instantiation of
283 the free variables of the $\forall \mathbf{x}:Q. C'$). The bound variables in \mathbf{x} have scope over Q and C .

284 $LP(CQ)$ programs or equivalently linear CQ -programs $L \in LP_{\Sigma}$ are build from linear
285 sums in Sum_{Σ} and linear constraints in LP_{Σ} as one might expect. Note, however, that free
286 query variables are ruled out at this level, while being permitted in nested linear constraints
287 in LC_{Σ} and linear sums in Sum_{Σ} .

288 The sets of free variables of linear sums, constraints, and programs are formally defined
289 in Figure 5. For instance, the following linear constraint C from the warehouse example has
290 three free variables in $fv(C) = \{f, o, q\}$:

291
$$\mathbf{weight}_{(f', w', b', o'): f' \doteq f \wedge o' \doteq o}(\mathit{dlr}(f', w', b', o')) \leq \mathbf{num}(q)$$

292 The variables f', w', b', o' are bound by the weight expression. The free variables f, o, q
293 are bound by a quantifier in the context, which in the resource delivery example is the
294 universal quantifier $\forall(f, o, q): \mathit{prod}(f, o, q)$.

295 3.2 Semantics

296 We next define the semantics of a $LP(CQ)$ program $L \in LP_{\Sigma}$ with respect to a database
297 $\mathbb{D} \in db_{\Sigma}$ with real numbers by an interpretation to a linear program $\langle L \rangle^{\mathbb{D}} \in LP$, that we will
298 refer to as the naïve interpretation from now on.

299 For doing so, one step is to replace the free query variables of the $LP(CQ)$ programs by
300 elements from the database. For this we assume that we have constants for all elements of the
301 database domain, that is $dom(\mathbb{D}) \subseteq \mathcal{C}$ and define for any conjunctive query Q and variable
302 assignment $\gamma : Y \rightarrow D$ where $fv(Q) \subseteq Y$ a conjunctive query $sbs_{\gamma}(Q)$, by replacing in Q all
303 free occurrences of variables $y \in Y$ by $\gamma(y)$. The formal definition is given in Figure 12.

304 In order to define the semantics of a linear program L over a database \mathbb{D} we consider the
305 following set of linear program variables:

306
$$\Theta_L^{\mathbb{D}} = \{\theta_{sbs_{\gamma}(Q)}^{\alpha} \mid S = \mathbf{weight}_{\mathbf{x}:Q'}(Q) \text{ in } L, \alpha : set(\mathbf{x}) \rightarrow dom(\mathbb{D}), \gamma : fv(S) \rightarrow dom(\mathbb{D})\}$$

307 Let $S = \mathbf{weight}_{\mathbf{x}:Q'}(Q)$ be a weight expression and $\gamma : Y \rightarrow dom(\mathbb{D})$ a variable assignment
308 for the free variables $fv(S) \subseteq Y$ such that $set(\mathbf{x}) \cap Y = \emptyset$. The interpretation of the weight

$$\begin{array}{ll}
\langle \mathbf{weight}_{\mathbf{x}:Q'}(Q) \rangle^{\mathbb{D},\gamma} = \sum_{\alpha \in \text{sol}_{\text{set}(\mathbf{x})}^{\mathbb{D}}(\text{sbs}_{\tilde{\gamma}}(Q \wedge Q'))} \theta_{\text{sbs}_{\tilde{\gamma}}(Q)}^{\alpha} & \langle S_1 + S_2 \rangle^{\mathbb{D},\gamma} = \langle S_1 \rangle^{\mathbb{D},\gamma} + \langle S_2 \rangle^{\mathbb{D},\gamma} \\
\langle \forall \mathbf{x}:Q. C \rangle^{\mathbb{D},\gamma} = \bigwedge_{\gamma' \in \text{sol}_{\text{set}(\mathbf{x})}^{\mathbb{D}}(\text{sbs}_{\tilde{\gamma}}(Q))} \langle C \rangle^{\mathbb{D},\tilde{\gamma} \cup \gamma'} & \langle S_1 \leq S_2 \rangle^{\mathbb{D},\gamma} = \langle S_1 \rangle^{\mathbb{D},\gamma} \leq \langle S_2 \rangle^{\mathbb{D},\gamma} \\
\langle \sum_{\mathbf{x}:Q} S \rangle^{\mathbb{D},\gamma} = \sum_{\gamma' \in \text{sol}_{\text{set}(\mathbf{x})}^{\mathbb{D}}(\text{sbs}_{\tilde{\gamma}}(Q))} \langle S \rangle^{\mathbb{D},\tilde{\gamma} \cup \gamma'} & \langle C_1 \wedge C_2 \rangle^{\mathbb{D},\gamma} = \langle C_1 \rangle^{\mathbb{D},\gamma} \wedge \langle C_2 \rangle^{\mathbb{D},\gamma} \\
\langle NS \rangle^{\mathbb{D},\gamma} = \langle N \rangle^{\mathbb{D},\gamma} \langle S \rangle^{\mathbb{D},\gamma} & \langle \text{true} \rangle^{\mathbb{D},\gamma} = \text{true} \\
\langle \mathbf{num}(a) \rangle^{\mathbb{D},\gamma} = \mathbf{num}^{\mathbb{D}}(a^{\mathbb{D}}) \quad (\text{may be undefined}) & \langle c \rangle^{\mathbb{D},\gamma} = c
\end{array}$$

$$\langle \mathbf{maximize} S \text{ subject to } C \rangle^{\mathbb{D}} = \mathbf{maximize} \langle S \rangle^{\mathbb{D},\emptyset} \text{ subject to } \langle C \rangle^{\mathbb{D},\emptyset}$$

■ **Figure 6** Naïve interpretation of linear expressions (sums, constraints, programs) with conjunctive queries F over database \mathbb{D} as standard linear expression (sums, constraints, and respectively programs) $F^{\mathbb{D},\gamma}$, where $\gamma : Y \rightarrow \text{dom}(\mathbb{D})$ and $\text{fv}(F) \subseteq Y \subseteq \mathcal{X}$ and $\tilde{\gamma} = \gamma|_{Y \setminus \text{set}(\mathbf{x})}$.

309 expression $\langle S \rangle^{\mathbb{D},\gamma}$ is the overall weight of the solutions $\alpha \in \text{sol}_{\text{set}(\mathbf{x})}^{\mathbb{D}}(\text{sbs}_{\tilde{\gamma}}(Q' \wedge Q))$ where
310 $\tilde{\gamma} = \gamma|_{Y \setminus \text{set}(\mathbf{x})}$ in the table $\text{sol}_{\text{set}(\mathbf{x})}^{\mathbb{D}}(\text{sbs}_{\tilde{\gamma}}(Q))$. It is described by the following linear sum:

$$311 \quad \langle S \rangle^{\mathbb{D},\gamma} = \sum_{\alpha \in \text{sol}_{\text{set}(\mathbf{x})}^{\mathbb{D}}(\text{sbs}_{\tilde{\gamma}}(Q \wedge Q'))} \theta_{\text{sbs}_{\tilde{\gamma}}(Q)}^{\alpha}$$

312 The (naive) interpretations $\langle S \rangle^{\mathbb{D},\gamma}$ and $\langle C \rangle^{\mathbb{D},\gamma}$ of other kinds of linear sums $S \in \text{Sum}_{\Sigma}$ and
313 constraints $C \in \text{LC}_{\Sigma}$ over a database \mathbb{D} and an environment γ are rather obvious. Note that
314 $LP(CQ)$ program L can be interpreted as linear program $\langle L \rangle^{\mathbb{D}} \in LP$ without any environment
315 as they do not have free variables. The definitions are summarized in Figure 6.

316 We note that α -renaming the bound variables in weight expressions does *not* always
317 preserve the semantics of $LP(CQ)$ programs. It may make previously equal queries different,
318 so that different weights may be assigned to their answer sets.

319 3.3 Example from Resource Delivery Optimization

320 Reconsider the $LP(CQ)$ program L from Figure 1 with the following database \mathbb{D} :

$$321 \quad \begin{array}{ll} \text{prod}^{\mathbb{D}} = \{(F, O_1, 1.5), (F, O_2, 2.2)\} & \text{store}^{\mathbb{D}} = \{(W_1, 0.9), (W_2, 2.5)\} \\ \text{route}^{\mathbb{D}} = \{(F, W_1, 0.5), (F, W_2, 0.4), & \text{order}^{\mathbb{D}} = \{(B, O_1, 0.8), (B, O_2, 1.4)\} \\ & (W_1, B, 0.6), (W_2, B, 0.8)\} \end{array}$$

322 The answer set of query $Q = \text{dlr}(f', w', b', o')$ on \mathbb{D} is to be weighted. We denote every
323 answer $\alpha : \{f', w', b', o'\} \rightarrow \text{dom}(\mathbb{D})$ by $(\alpha(f'), \alpha(w'), \alpha(b'), \alpha(o'))$. Then:

$$324 \quad \text{sol}^{\mathbb{D}}(\text{dlr}) = \{(F, W_1, B, O_1), (F, W_2, B, O_1), (F, W_1, B, O_2), (F, W_2, B, O_2)\}$$

325 The naive interpretation $\langle L \rangle^{\mathbb{D}}$ is the following linear program with variables in $\Theta_L^{\mathbb{D}}$:

$$\begin{array}{ll}
\mathbf{minimize} & 0.5 (\theta_Q^{(F, W_1, B, O_1)} + \theta_Q^{(F, W_1, B, O_2)}) + 0.4 (\theta_Q^{(F, W_2, B, O_1)} + \theta_Q^{(F, W_2, B, O_2)}) \\
& + 0.6 (\theta_Q^{(F, W_1, B, O_1)} + \theta_Q^{(F, W_1, B, O_2)}) + 0.8 (\theta_Q^{(F, W_2, B, O_1)} + \theta_Q^{(F, W_2, B, O_2)}) \\
\mathbf{subject\ to} & \theta_Q^{(F, W_1, B, O_1)} + \theta_Q^{(F, W_2, B, O_1)} \leq 1.5 \quad \wedge \quad \theta_Q^{(F, W_1, B, O_2)} + \theta_Q^{(F, W_2, B, O_2)} \leq 2.2 \\
& \wedge \quad \theta_Q^{(F, W_1, B, O_1)} + \theta_Q^{(F, W_2, B, O_1)} \geq 0.8 \quad \wedge \quad \theta_Q^{(F, W_1, B, O_2)} + \theta_Q^{(F, W_2, B, O_2)} \geq 1.4 \\
& \wedge \quad \theta_Q^{(F, W_1, B, O_1)} + \theta_Q^{(F, W_1, B, O_2)} \leq 0.9 \quad \wedge \quad \theta_Q^{(F, W_2, B, O_1)} + \theta_Q^{(F, W_2, B, O_2)} \leq 2.5
\end{array}$$

327 The term $(\theta_Q^{(F, W_1, B, O_1)} + \theta_Q^{(F, W_1, B, O_2)})$ in the objective function of this linear program is
328 obtained by computing the value of the expression $\mathbf{weight}_{(f', w', b', o') : f' \doteq s \wedge w' \doteq e}(Q)$ with

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329 the environment $[f'/F, w'/W_1]$. Similarly the term $\theta_Q^{(F, W_1, B, O_1)} + \theta_Q^{(F, W_2, B, O_1)}$ in the first
 330 constraint is obtained by computing the value of $\mathbf{weight}_{(f', w', b', o'): f' \doteq f \wedge o' \doteq o}(Q)$ with the
 331 environment $[r/O_1, f/F]$. Observe that both weight expressions share the same linear
 332 program variable $\theta_Q^{(F, W_1, B, O_1)}$ so they are related semantically.

4 An Efficiently Solvable Fragment

334 We introduce a class of projecting $LP(CQ)$ programs and define a notion of width of linear
 335 CQ -program in this fragment through a collection of hypertree decompositions of the queries
 336 they contain. We then show one can find the optimal solution of such programs L more
 337 efficiently than by explicitly computing the interpretation over a database \mathbb{D} as a linear
 338 program $\langle L \rangle^{\mathbb{D}}$. For this we will present an alternative factorized interpretation of L to a
 339 linear program having fewer variables, while preserving the optimal solution.

4.1 Projecting $LP(CQ)$ Programs

341 We start with the definition of projecting $LP(CQ)$ programs, whose main restriction resides
 342 on how they can use conjunctive queries.

343 ► **Definition 6.** *The fragment $LP(CQ)_{proj}$ is the set of $LP(CQ)$ programs L such that:*
 344 *- for any subexpression $\mathbf{weight}_{\mathbf{x}:Q'}$ of L , we have that $set(\mathbf{x}) = fv(Q)$ and Q' is a*
 345 *projecting query of the form $\mathbf{x}' \doteq \mathbf{y}$ with $set(\mathbf{x}') \subseteq set(\mathbf{x})$ and $set(\mathbf{x}) \cap set(\mathbf{y}) = \emptyset$.*
 346 *- for any sum $\sum_{\mathbf{x}:Q} S$ and any universal quantifier $\forall \mathbf{x}:Q$. C of L , the query Q is of the*
 347 *form $\exists \mathbf{z}. r(\mathbf{y})$ for some relation symbol $r \in \mathcal{R}^{(n)}$, vector $\mathbf{y} \in \mathcal{X}^n$ and vector $\mathbf{z} \in \mathcal{X}^*$ such*
 348 *that $set(\mathbf{x}) \subseteq fv(Q)$.*

349 *We denote by $LP(CQ_{qf})_{proj}$ the subset of $LP(CQ)_{proj}$ where every conjunctive query Q*
 350 *appearing in a weight expression quantifier free.*

351 Any expression $\mathbf{weight}_{\mathbf{x}:Q'}(Q)$ of a projecting $LP(CQ)$ program is restricted to projection
 352 in Q' . Furthermore Q may not have any variables that are free in the weight expression.
 353 This condition ensures that the interpretation in environment γ of Q does not substitute any
 354 variables, that is $sbs_{\gamma}(Q) = Q$. Thus, it is interpreted as a sum over θ_Q^{α} variables where α
 355 are solutions of Q taking the same value $\gamma(\mathbf{y})$ on variables \mathbf{x}' . Our algorithm will exploit
 356 this fact by utilizing tree decompositions of Q to interpret $\mathbf{weight}_{\mathbf{x}:Q'}(Q)$ of $LP(CQ_{qf})_{proj}$
 357 with one variable instead of $|sol^{\mathbb{D}}(Q \wedge Q')|$ needed in the naive interpretation.

358 Another restriction of $LP(CQ)_{proj}$ is that universal quantifiers and sums are guarded by
 359 a database relation. Our algorithm does not exploit the structure of conjunctive queries in
 360 universal quantifiers and sums so we interpret these expressions in the same way as in Figure 6.
 361 To avoid a blow up in the number of constraints, we chose to guard these constructions.

362 **Hypertree Width of Projecting $LP(CQ)$ Programs.** We next lift the concept of generalized
 363 hypertree width from quantifier free conjunctive queries to $LP(CQ_{qf})_{proj}$ programs. The
 364 complexity of our algorithm will depend thereof.

365 For any program L in $LP(CQ)_{proj}$, we define the set of queries $cqs(L)$ that are weighted
 366 when interpreting L as $cqs(L) = \{Q \mid \mathbf{weight}_{\mathbf{x}:Q'}(Q) \text{ is a subexpression of } L\}$. Observe that
 367 the resource delivery problem L is in $LP(CQ)_{proj}$ with $cqs(L) = \{dlr(f', w', b', o')\}$.

368 ► **Definition 7.** *Let L be an $LP(CQ_{qf})_{proj}$ program and $\mathcal{T} = (T_Q)_{Q \in cqs(L)}$ a collection of*
 369 *decomposition trees. We call \mathcal{T} a tree decomposition of L if for any expression $\mathbf{weight}_{\mathbf{x}:Q'}(Q)$*
 370 *in L , $T_Q = (\mathcal{V}_Q, \mathcal{E}_Q, \mathcal{B}_Q)$ is a tree decomposition of Q and there is a node u of T_Q such that*

$$\begin{aligned}
\rho^{\mathcal{T},\mathbb{D},\gamma}(\forall \mathbf{x}:r(\mathbf{x}).C) &= \bigwedge_{\gamma' \in \text{sol}^{\mathbb{D}}(r(\mathbf{x}))} \rho^{\mathcal{T},\mathbb{D},\gamma \cup \gamma'}(C) & \rho^{\mathcal{T},\mathbb{D},\gamma}(S_1 + S_2) &= \rho^{\mathcal{T},\mathbb{D},\gamma}(S_1) + \rho^{\mathcal{T},\mathbb{D},\gamma}(S_2) \\
\rho^{\mathcal{T},\mathbb{D},\gamma}(\sum_{\mathbf{x}:r(\mathbf{x})} S) &= \sum_{\gamma' \in \text{sol}^{\mathbb{D}}(r(\mathbf{x}))} \rho^{\mathcal{T},\mathbb{D},\gamma \cup \gamma'}(S) & \rho^{\mathcal{T},\mathbb{D},\gamma}(S_1 \leq S_2) &= \rho^{\mathcal{T},\mathbb{D},\gamma}(S_1) \leq \rho^{\mathcal{T},\mathbb{D},\gamma}(S_2) \\
\rho^{\mathcal{T},\mathbb{D},\gamma}(NS) &= \rho^{\mathcal{T},\mathbb{D},\gamma}(N) \rho^{\mathcal{T},\mathbb{D},\gamma}(S) & \rho^{\mathcal{T},\mathbb{D},\gamma}(C_1 \wedge C_2) &= \rho^{\mathcal{T},\mathbb{D},\gamma}(C_1) \wedge \rho^{\mathcal{T},\mathbb{D},\gamma}(C_2) \\
\rho^{\mathcal{T},\mathbb{D},\gamma}(\mathbf{num}(a)) &= \mathbf{num}^{\mathbb{D}}(a^{\mathbb{D}}) & \rho^{\mathcal{T},\mathbb{D},\gamma}(\text{true}) &= \text{true} \\
& & & \rho^{\mathcal{T},\mathbb{D},\gamma}(c) = c \\
& & & \text{(may be undefined)}
\end{aligned}$$

$$\rho^{\mathcal{T},\mathbb{D},\gamma}(\mathbf{weight}_{\mathbf{x}:\mathbf{x}'=\mathbf{y}}(Q)) = \begin{cases} \xi_{Q,u,\beta} & \text{if } \beta = [\mathbf{x}'/\gamma(\mathbf{y})] \in \text{sol}^{\mathbb{D}}(Q)|_{\mathcal{B}_Q(u)} \\ 0 & \text{else} \end{cases}$$

where u is a node of T_Q such that $\text{set}(\mathbf{x}') = \mathcal{B}_Q(u)$.

$$\begin{aligned}
\rho^{\mathcal{T},\mathbb{D}}(\mathbf{maximize } S \text{ subject to } C) \\
= \mathbf{maximize } \rho^{\mathcal{T},\mathbb{D},\emptyset}(S) \text{ subject to } \rho^{\mathcal{T},\mathbb{D},\emptyset}(C) \wedge \bigwedge_{Q \in \text{cqs}(L)} \text{lsc}^{\mathcal{T},\mathbb{D}}(Q)
\end{aligned}$$

■ **Figure 7** \mathcal{T} -factorized interpretation of $LP(CQ_{\text{qf}})_{\text{proj}}$ programs L with respect to a database \mathbb{D} .

371 $\mathcal{B}_Q(u) = \text{set}(\mathbf{x}')$. We define the width of \mathcal{T} to be the maximal width of T_Q for $Q \in \text{cqs}(L)$.
372 The size of \mathcal{T} is defined to be $|\mathcal{T}| = \sum_{Q \in \text{cqs}(L)} |\mathcal{V}_Q|$.

373 The rest of the section is dedicated to proving the following theorem:

374 ► **Theorem 8 (Main).** Let L be a $LP(CQ_{\text{qf}})_{\text{proj}}$ program, \mathcal{T} a decomposition of L of width
375 k and \mathbb{D} a database. There exists an interpretation $\rho^{\mathcal{T},\mathbb{D}}(L)$ of L having the same value as
376 $\langle L \rangle^{\mathbb{D}}$ and $O(|\mathcal{T}||\mathbb{D}|^k)$ variables.

377 Observe that the number of variables of $\langle L \rangle^{\mathbb{D}}$ is roughly the total number of solutions
378 of the conjunctive queries in $\text{cqs}(L)$, which may be up to $O(|\mathbb{D}|^n)$, where n is the number
379 of atoms in the conjunctive queries. In Theorem 8, the degree of the polynomial now only
380 depends on the width of the queries, which may be much smaller, resulting in a more succinct
381 linear program that is easier to solve. In the resource optimization example, this allows to
382 go from a cubic number of variables to a quadratic one, but the improvement may be much
383 better on queries having many atoms and small width.

384 4.2 Factorized Interpretation

385 Based on hypertree decompositions we present an alternative factorized interpretation to
386 smaller linear program having the same optimal value.

387 In this section, we explain how we can exploit tree decompositions of projecting $LP(CQ)$
388 programs with quantifier free conjunctive queries to find a smaller interpretation. We fix a
389 program L of $LP(CQ_{\text{qf}})_{\text{proj}}$. Let $\mathcal{T} = (T_Q)_{Q \in \text{cqs}(L)}$ be a tree decomposition of L of width k
390 where $T_Q = (\mathcal{V}_Q, \mathcal{E}_Q, \mathcal{B}_Q)$. The \mathcal{T} -factorized interpretation $\rho^{\mathcal{T},\mathbb{D}}(L)$ of L is formally defined
391 in Figure 7. It mainly mirrors the naïve interpretation of Figure 6 but significantly differs in
392 two places: the first one is the way $\mathbf{weight}_{\mathbf{x}:\mathbf{x}'=\mathbf{y}}(Q)$ is interpreted and one can observe the
393 addition *local soundness constraints* $\text{lsc}^{\mathcal{T},\mathbb{D}}(Q)$ to the program.

394 The set of linear program variables for the factorized interpretation $\rho^{\mathcal{T},\mathbb{D}}(L)$ is defined by:

$$395 \Xi_L^{\mathcal{T},\mathbb{D}} = \{\xi_{Q,u,\beta} \mid Q \in \text{cqs}(L), u \in \mathcal{V}_Q, \beta \in \text{sol}^{\mathbb{D}}(Q)|_{\mathcal{B}_Q(u)}\}.$$

396 Observe that since T_Q is a tree decomposition of Q of width at most k , $\text{sol}^{\mathbb{D}}(Q)|_{\mathcal{B}_Q(u)}$ is of
397 size at most $|\mathbb{D}|^k$. Thus we have at most $|\mathcal{T}||\mathbb{D}|^k$ variables in $\rho^{\mathcal{T},\mathbb{D}}(L)$, as stated in Theorem 8.

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398 One can see that given a context γ such that $\rho^{\mathcal{T}, \mathbb{D}, \gamma}(\mathbf{weight}_{\mathbf{x}: \mathbf{x}' \doteq \mathbf{y}}(Q)) = \xi_{Q, u, \beta}$, the
 399 usual interpretation would have been $\langle \mathbf{weight}_{\mathbf{x}: \mathbf{x}' \doteq \mathbf{y}}(Q) \rangle^{\mathbb{D}, \gamma} = \sum_{\alpha \in \text{sol}_{\text{set}(\mathbf{x})}^{\mathbb{D}}(Q): \alpha|_{\mathbf{x}' = \mathbf{y}} \theta_Q^\alpha$, that
 400 is, intuitively, $\xi_{Q, u, \beta}$ represents the linear sum of variables θ_Q^α in the naive interpretation
 401 with α compatible with β .

402 To prove that $\rho^{\mathcal{T}, \mathbb{D}}(L)$ has the same optimal value as $\langle L \rangle^{\mathbb{D}}$, we will reconstruct a solution
 403 to $\langle L \rangle^{\mathbb{D}}$ from a solution to $\rho^{\mathcal{T}, \mathbb{D}}(L)$ such that the value of $\xi_{Q, u, \beta}$ indeed corresponds to the sum
 404 of the values of variables θ_Q^α with α compatible with β and vice-versa. To ensure that this is
 405 always possible, we have to be careful that variables $\xi_{Q, u, \beta}$ and $\xi_{Q, v, \beta'}$ are compatible with
 406 one another because they may correspond to two sums on θ_Q^α variables having a non-empty
 407 intersection. We ensure this through *local soundness constraints* $\text{lsc}^{\mathcal{T}, \mathbb{D}}(Q)$ for every query
 408 $Q \in \text{cqs}(L)$ (where $A = \text{sol}^{\mathbb{D}}(Q)$):

$$409 \quad \text{lsc}^{\mathcal{T}, \mathbb{D}}(Q) = \bigwedge_{(u, v) \in \mathcal{E}_Q} \bigwedge_{\gamma \in A|_{\mathcal{B}_Q(u)} \cap \mathcal{B}_Q(v)} \sum_{\beta \in A|_{\mathcal{B}_Q(u)}, \beta|_{\mathcal{B}_Q(v)} = \gamma} \xi_{Q, u, \beta} \doteq \sum_{\beta' \in A|_{\mathcal{B}_Q(v)}, \beta'|_{\mathcal{B}_Q(u)} = \gamma} \xi_{Q, v, \beta'}.$$

410 Observe we added at most $|\mathbb{D}|^k |\mathcal{E}_Q|$ constraints for each $Q \in \mathcal{Q}$. Moreover constructing
 411 $\rho^{\mathcal{T}, \mathbb{D}}(L)$ from L and \mathbb{D} mainly relies on being able to compute $\text{sol}^{\mathbb{D}}(Q)|_{\mathcal{B}(u)}$ for every node u
 412 of T_Q . This is possible in polynomial time by dynamic programming on T_Q , see Lemma 3.

413 4.3 Correctness

414 **Weightings on Tree Decompositions.** One can observe that the key idea in the definition
 415 of $\rho^{\mathcal{T}, \mathbb{D}}(L)$ is to introduce linear program variables that will intuitively encode the sum of
 416 several linear program variables in the naive interpretation $\langle L \rangle^{\mathbb{D}}$. A solution to $\langle L \rangle^{\mathbb{D}}$ maps a
 417 variable θ_Q^α to a non-negative real number where $\alpha \in \text{sol}^{\mathbb{D}}(Q)$. In other words, it assigns a
 418 weight $\omega(\alpha) \in \mathbb{R}_+$ to every $\alpha \in \text{sol}^{\mathbb{D}}(Q)$ for every $Q \in \text{cqs}(L)$. A solution to $\rho^{\mathcal{T}, \mathbb{D}}(L)$ maps a
 419 variable $\xi_{Q, u, \beta}$ to a non-negative real number where $\beta \in \text{sol}^{\mathbb{D}}(Q)|_{\mathcal{B}_Q(u)}$. In other words, it
 420 assigns a weight W_u to every β that is in $\text{sol}^{\mathbb{D}}(Q)|_{\mathcal{B}(u)}$ for every node u of T_Q .

421 To reconstruct a solution of $\langle L \rangle^{\mathbb{D}}$ from a solution W of $\rho^{\mathcal{T}, \mathbb{D}}(L)$, we need to be able to
 422 reconstruct a weighting ω of $\text{sol}^{\mathbb{D}}(Q)$ such that $\sum_{\alpha|_{\mathcal{B}_Q(u)} = \beta} \omega(\alpha) = W_u(\beta)$. In this section,
 423 we explain that this is always possible as long as the W_u are compatible with one another,
 424 which is ensured by local soundness constraints $\text{lsc}^{\mathcal{T}, \mathbb{D}}(Q)$ in $\rho^{\mathcal{T}, \mathbb{D}}(L)$.

425 The technique is not specifically tied to the fact that the weights are assigned to the
 426 solutions of a quantifier free conjunctive query, thus we formulate our result in a more general
 427 setting by considering weightings on a set $A \subseteq D^X = \{\alpha \mid \alpha : X \rightarrow D\}$ for a finite set
 428 of variables X . Intuitively however, one can think of A as $\text{sol}^{\mathbb{D}}(Q)$ for a **quantifier-free**
 429 **conjunctive query** Q .

430 We start by introducing a few notations. Let $X' \subseteq X \subseteq \mathcal{X}$. For any $\alpha' : X' \rightarrow D$ we
 431 define the set of its extensions into A by $A[\alpha'] = \{\alpha \in A \mid \alpha|_{X'} = \alpha'\}$. Moreover, given a
 432 weighting $\omega : A \rightarrow \mathbb{R}_+$ of A , we define the projection $\pi_{X'}(\omega) : A|_{X'} \rightarrow \mathbb{R}_+$ such that for all
 433 $\alpha' \in A|_{X'}$: $\pi_{X'}(\omega)(\alpha') = \sum_{\alpha \in A[\alpha']} \omega(\alpha)$.

434 We now fix $T = (\mathcal{V}, \mathcal{E}, \mathcal{B})$ a decomposition tree for X . Given two nodes $u, v \in \mathcal{V}$ we
 435 denote the intersection of their bags by $\mathcal{B}^{uv} = \mathcal{B}(u) \cap \mathcal{B}(v)$.

436 **► Definition 9.** A family $W = (W_v)_{v \in \mathcal{V}}$ is a weighting collection on T for A if it satisfies
 437 the following conditions for any two nodes $u, v \in \mathcal{V}$:

- 438 - W_u is a weighting of $A|_{\mathcal{B}(u)}$, i.e., $W_u : A|_{\mathcal{B}(u)} \rightarrow \mathbb{R}_+$.
- 439 - W_u is sound for T at $\{u, v\}$, i.e., $\pi_{\mathcal{B}^{uv}}(W_u) = \pi_{\mathcal{B}^{uv}}(W_v)$.

440 Intuitively, the soundness of a weighting collection on T is a minimal requirement for the
 441 existence of a weighting ω of A such that W_u is the projection of ω on the bag $\mathcal{B}(u)$ of T ,
 442 that is $W_u = \pi_{\mathcal{B}(u)}(\omega)$ since we have the following:

443 ► **Proposition 10.** *For any weighting $\omega : A \rightarrow \mathbb{R}_+$, the family $(\pi_{\mathcal{B}(v)}(\omega))_{v \in \mathcal{V}}$ is a weighting
 444 collection on T for A .*

445 What is more interesting is the other way around, that is, given $(W_u)_{u \in \mathcal{V}}$ a weighting
 446 collection on T , whether we can find a weighting ω of A such that $W_u = \pi_{\mathcal{B}(u)}(\omega)$ for every
 447 u . It turns out that soundness is not enough to ensure the existence of such a weighting.
 448 However it becomes possible when A is conjunctively decomposed:

449 ► **Definition 11.** *Let $T = (\mathcal{V}, \mathcal{E}, \mathcal{B})$ be a decomposition tree of $X \subseteq \mathcal{X}$. We call a subset
 450 of variable assignments $A \subseteq D^X$ conjunctively decomposed by T if for all $u \in \mathcal{V}$ and
 451 $\beta \in A|_{\mathcal{B}(u)} : \{\alpha_1 \cup \alpha_2 \mid \alpha_1 \in A|_{\mathcal{B}(\uparrow u)}[\beta], \alpha_2 \in A|_{\mathcal{B}(\downarrow u)}[\beta]\} \subseteq A[\beta]$ where $\mathcal{B}(V) = \bigcup_{v \in V} \mathcal{B}(v)$
 452 for any $V \subseteq \mathcal{V}$.*

453 Note that the inverse inclusion holds in general. Of course, this property holds if A is the
 454 answer set of a conjunctive queries and the tree is a tree decompositions of Q :

455 ► **Proposition 12.** *For any tree decomposition T of a quantifier free conjunctive query
 456 $Q \in CQ_\Sigma$ and database $\mathbb{D} \in db_\Sigma$, the answer set $sol^{\mathbb{D}}(Q)$ is conjunctively decomposed by T .*

457 Proposition 12 does not hold when Q is not quantifier free. It explains why the technique
 458 only works for the fragment $LP(CQ_{gf})_{proj}$. We however explain how one can use the same
 459 technique on $LP(CQ)_{proj}$ in Section 4.4.

460 Soundness and conjunctive decomposition are enough to prove this correspondence
 461 theorem that allows us to transform solutions of $\rho^{\mathcal{T}, \mathbb{D}}(L)$ to solutions of $\langle L \rangle^{\mathbb{D}}$ and vice-versa.

462 ► **Theorem 13 (Correspondence).** *Let $T = (\mathcal{V}, \mathcal{E}, \mathcal{B})$ be a normalized decomposition tree of
 463 $X \subseteq \mathcal{X}$ and $A \subseteq D^X$ be a set of variable assignment that is conjunctively decomposed by T .*

- 464 1. *For every weighting ω of A , $(\pi_{\mathcal{B}(u)}(\omega))_{u \in \mathcal{V}}$ is a weighting collection on T for A .*
- 465 2. *For any weighting collection W on T for A there exists a weighting ω of A such that
 466 $\forall u : W_u = \pi_{\mathcal{B}(u)}(\omega)$.*

467 While the first item of Theorem 13 follows by Proposition 10 and can be proven by a simple
 468 calculation, the second item is harder to prove. We present here one way of constructing ω
 469 from $(W_u)_{u \in \mathcal{V}}$. The proof of correctness of this construction can be found Appendix C.

470 Let $T = (\mathcal{V}, \mathcal{E}, \mathcal{B})$ be a normalized decomposition tree of X and $W = (W_u)_{u \in \mathcal{V}}$ a weighting
 471 collection on T for $A \subseteq D^X$. For any node $u \in \mathcal{V}$, we inductively construct $\omega_u : A|_{\mathcal{B}(\downarrow u)} \rightarrow \mathbb{R}_+$.

472 **If u is a leaf of T ,** we define ω_u such that for all $\alpha \in A|_{\mathcal{B}(\downarrow u)}$, $\omega_u(\alpha) := W_u(\alpha)$.

473 Now, assume $\omega_{u'}$ is defined for all children u' of u . Let $\alpha \in A|_{\mathcal{B}(\downarrow u)}$ and denote by
 474 $\beta = \alpha|_{\mathcal{B}(u)}$. We define $\omega_u(\alpha)$ as follows:

475 **If u is an extend node** with a child v then $\omega_u(\alpha) := \frac{W_u(\beta)}{W_v(\alpha|_{\mathcal{B}(v)})} \omega_v(\alpha|_{\mathcal{B}(\downarrow v)})$ if $W_v(\alpha|_{\mathcal{B}(v)}) >$
 476 0 and $\omega_u(\alpha) := 0$ otherwise.

477 **If u is a project node** with a child v then $\omega_u(\alpha) := \omega_v(\alpha|_{\mathcal{B}(\downarrow v)})$.

478 **If u is a join node** with children v_1, \dots, v_k then $\omega_u(\alpha) := \frac{\prod_{i=1}^k \omega_{v_i}(\alpha|_{\mathcal{B}(\downarrow v_i)})}{W_u(\beta)^{k-1}}$ if $W_u(\beta) > 0$
 479 and $\omega_u(\alpha) := 0$ otherwise.

480 Finally, we let ω be ω_r where r is the root of T . The proof that $\forall u : W_u = \pi_{\mathcal{B}(u)}(\omega)$ is
 481 done via two inductions. The first one is a bottom-up induction to prove that $W_u = \pi_{\mathcal{B}(u)}(\omega)$
 482 for every node u in the tree decomposition. Then, by top-down induction, one can prove that

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483 $\omega_u = \pi_{\mathcal{B}(\downarrow u)}(\omega_r)$. The proof is tedious and mainly rely on calculations and careful analysis
 484 on how A is decomposed along T .

485 **Correctness Proof.** We are now ready to prove that, given a tree decomposition \mathcal{T} of a
 486 linear CQ -program L of $LP(CQ_{qf})_{proj}$, $\rho^{\mathcal{T}, \mathbb{D}}(L)$ and $\langle L \rangle^{\mathbb{D}}$ have the same optimal value.

487 For any weighting $\dot{\omega}: \Theta_L \rightarrow \mathbb{R}_+$ we define a weighting $\Pi(\dot{\omega}): \Xi_L^{\mathcal{T}, \mathbb{D}} \rightarrow \mathbb{R}_+$ such that for all
 488 $\xi_{Q,u,\beta} \in \Xi_L^{\mathcal{T}, \mathbb{D}}: \Pi(\dot{\omega})(\xi_{Q,u,\beta}) = \sum_{\alpha \in \text{sol}^{\mathbb{D}}(Q)[\beta]} \dot{\omega}(\theta_{\alpha}^Q)$.

489 Observe that $\dot{\omega}$ can be seen as a collection of weightings of $\text{sol}^{\mathbb{D}}(Q)$ for $Q \in \text{cqs}(L)$. It
 490 turns out that evaluating linear sums and constraints of $\langle L \rangle^{\mathbb{D}}$ with $\dot{\omega}$ returns the same value
 491 as the evaluation of linear sums and constraints of $\rho^{\mathcal{T}, \mathbb{D}}(L)$ with $\Pi(\dot{\omega})$:

492 ► **Lemma 14.** *For any \mathcal{T} -projecting sum $S \in \text{Sum}_{\Sigma}$ and environment $\gamma: X \rightarrow \text{dom}(\mathbb{D})$
 493 where $\text{fv}(S) \subseteq X$ it holds that $\llbracket \langle S \rangle^{\mathbb{D}, \gamma} \rrbracket_{\dot{\omega}} = \llbracket \rho^{\mathcal{T}, \mathbb{D}, \gamma}(S) \rrbracket_{\Pi(\dot{\omega})}$.*

494 ► **Lemma 15.** *For any constraint $C \in LC_{\Sigma}$ that is \mathcal{T} -projecting and environment $\gamma: X \rightarrow$
 495 $\text{dom}(\mathbb{D})$ where $\text{fv}(C) \subseteq X$: $\llbracket \langle C \rangle^{\mathbb{D}, \gamma} \rrbracket_{\dot{\omega}} = \llbracket \rho^{\mathcal{T}, \mathbb{D}, \gamma}(C) \rrbracket_{\Pi(\dot{\omega})}$.*

496 Lemma 14 and Lemma 15 rely on Proposition 10. It is easy to see that they imply that if
 497 $\dot{\omega}$ is a solution of $\langle L \rangle^{\mathbb{D}}$ (the fact that it respects the local soundness constraints follows from
 498 Proposition 10), then $\Pi(\dot{\omega})$ is a solution of $\rho^{\mathcal{T}, \mathbb{D}}(L)$ with the same value. Thus, the optimal
 499 value of $\rho^{\mathcal{T}, \mathbb{D}}(L)$ is greater or equal than the optimal value of $\langle L \rangle^{\mathbb{D}}$.

500 To prove the equality, it remains to prove that the optimal value of $\langle L \rangle^{\mathbb{D}}$ is greater or
 501 equal than the optimal value of $\rho^{\mathcal{T}, \mathbb{D}}(L)$. To this end, consider a solution of $\rho^{\mathcal{T}, \mathbb{D}}(L)$. It is a
 502 weighting \dot{W} of $\Xi_L^{\mathcal{T}, \mathbb{D}}$ which respects the local soundness constraints. By Theorem 13, we
 503 will be able to reconstruct a weighting $\dot{\omega}$ of Θ_L which respects the constraint of $\langle L \rangle^{\mathbb{D}}$. It is
 504 formalized in the following lemma whose proof can be found in the appendix.

505 ► **Lemma 16.** *For any weighting \dot{W} of $\Xi_L^{\mathcal{T}, \mathbb{D}}$ such that $\llbracket \bigwedge_{Q \in \mathcal{Q}} \text{lsc}^{\mathcal{T}, \mathbb{D}}(Q) \rrbracket_{\dot{W}} = 1$, there exists
 506 a weighting $\dot{\omega}$ of $\Theta_{\mathcal{Q}}$ such that $\dot{W} = \Pi(\dot{\omega})$.*

507 ► **Proposition 17.** *Let \mathbb{D} be a database and \mathcal{T} a collection of decomposition tree. Any
 508 \mathcal{T} -projecting $LP(CQ)$ program $L = (\text{maximize } S \text{ subject to } C) \in LP_{\Sigma}$ satisfies that:*

- 509 1. *For any solution $\dot{\omega}$ of $\langle L \rangle^{\mathbb{D}}$ there is a solution \dot{W} of $\rho^{\mathcal{T}, \mathbb{D}}(L)$ s.t. $\llbracket \langle S \rangle^{\mathbb{D}, \emptyset} \rrbracket_{\dot{\omega}} = \llbracket \rho^{\mathcal{T}, \mathbb{D}}(S) \rrbracket_{\dot{W}}$.*
- 510 2. *For any solution \dot{W} of $\rho^{\mathcal{T}, \mathbb{D}}(L)$ there is a solution $\dot{\omega}$ of $\langle L \rangle^{\mathbb{D}}$ s.t. $\llbracket \langle S \rangle^{\mathbb{D}, \emptyset} \rrbracket_{\dot{\omega}} = \llbracket \rho^{\mathcal{T}, \mathbb{D}}(S) \rrbracket_{\dot{W}}$.*

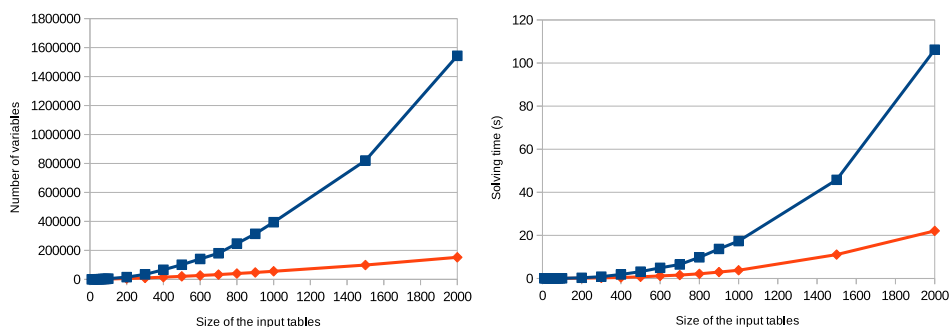
511 4.4 Treatment of Existential Quantifiers

512 The previous method of factorized interpretation only works for the $LP(CQ_{qf})_{proj}$ fragment,
 513 where conjunctive queries are supposed to be quantifier free. It turns out that one can
 514 similarly solve linear programs of $LP(CQ)_{proj}$ programs by applying a simple transformation.

515 For any $LP(CQ)_{proj}$ program L we can move the existential quantifiers of the con-
 516 junctive query into the weight expression as follows, yielding an $LP(CQ_{qf})_{proj}$ program
 517 $\text{mvq}(L)$: we replace every subexpression $\text{weight}_{\mathbf{x}:Q'}(\exists \mathbf{z}.Q)$ of L , where Q is quantifier free,
 518 by $\text{weight}_{\mathbf{xz}:Q'}(Q)$ where \mathbf{xz} is the concatenation of vectors \mathbf{x} and \mathbf{z} . We have:

519 ► **Theorem 18 (Removing Existential Quantifiers).** *For any projecting $LP(CQ)$ program, the
 520 $LP(CQ_{qf})_{proj}$ program $\text{mvq}(L)$ has the same optimal value as L .*

521 Observe that we can use this technique for the resource delivery problem L . In $\text{mvq}(L)$,
 522 there is only one query on variables $(f', o', q, q', b', w', c, c')$. It is easy to see that it has
 523 hypertree width 2 since we can construct a tree decomposition having two connected bags
 524 $\mathcal{B}(u) = \{f', o', b', q, q'\}$ and $\mathcal{B}(v) = \{f', w', b', c, c'\}$. $\mathcal{B}(u)$ is covered by the first two atoms



■ **Figure 8** Number of variables and performances of GLPK for naive (blue) and factorized (red) interpretation of the resource delivery problem with respect to table size.

525 and $\mathcal{B}(v)$ by the last two. Now, because of the weight expressions, we also need to add a
 526 bag for $\{f', w'\}$, $\{w'\}$ and $\{w', b'\}$ which can safely be connected to v , and for $\{f', o'\}$ and
 527 $\{b', o'\}$ which can safely be connected to u . It gives a decomposition of L of width 2, showing
 528 that factorized interpretation will have less variables than the naive interpretation.

529 **5 Preliminary Experimental Results**

530 The practical performances of our idea heavily depends on how linear solvers perform on
 531 factorized interpretation. We compared the performances of GLPK on both the naive
 532 interpretation and the factorized interpretation of the resource delivery problem from the
 533 introduction using some synthetic data. We used Python and the Pulp library to build the
 534 linear programs. The tree-decomposition of the *dlr* query is hard-coded. The tests were run
 535 on an office laptop by making the number of tuples in the randomly filled *prod*, *order* and
 536 *route* tables vary. A summary of our experiments is displayed on Figure 8.

537 As expected when comparing both linear programs we observed a larger number of
 538 constraints (due to the soundness constraints) and a smaller number of variables in the
 539 factorized interpretation. While building the naive interpretation quickly became slower
 540 than building the factorized interpretation, we do not analyze this aspect further since we
 541 are not using a database engine to build the naive interpretation and solve it directly from
 542 the tree decomposition, which may not be the fastest method without further optimizations.
 543 Most interestingly solving the factorized interpretation was faster than solving the naive
 544 interpretation in spite of the increased number of constraints thanks to the decrease in the
 545 number of variables. In particular for an instance with an input size of 2000 lines per table,
 546 the naive interpretation had roughly 1.5 million variables while the factorized interpretation
 547 had only roughly 150000. The solving time was also noticeably improved at 22s for the
 548 factorized case against 106s for the naive one.

549 **Conclusion and Future Work** Our preliminary experiments seem to confirm the efficiency
 550 of factorized interpretation, in accordance with our complexity results. More thorough
 551 benchmarking is needed to evaluate the practical relevance though. Another direction to
 552 explore would be to better integrate our approach into a database engine, in the way it is
 553 done by *SolveDB* for example. Finally, other optimization problems may benefit from this
 554 approach such as convex optimization or integer linear programming. It would be interesting
 555 to define languages analogous to $LP(CQ)$ for these optimization problems and study how
 556 conjunctive query decompositions could help to improve the efficiency.

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617 **A** Minimizing Noise in ϵ -Differential Privacy

618 The strategy of differential privacy is to add noise to the relational data before publication.
 619 Roughly speaking, the general objective of ϵ -differential privacy [5] is to add as few noise as
 620 possible, without disclosing more than an ϵ amount of information. We illustrate this with
 621 the example of a set of hospitals which publish medical studies aggregating results of tests on
 622 patients, which are to be kept confidential. We consider the problem of how to compute the
 623 optimal amount of noise to be added to each separate piece of sensitive information (in terms
 624 of total utility of the studies) while guaranteeing ϵ -differential privacy. We show that this
 625 question can be solved (approximately) by computing the optimal solution of a projecting
 626 $LP(CQ)$ program with an acyclic conjunctive query.

627 **A.1 Hospital Database about Medical Studies on Patient Tests**

628 We consider a database \mathbb{D} with signature $\Sigma = \{H, Test, St, Priv, Sens\}$ whose domain provides
 629 patients, hospitals, studies, and positive real numbers. The relations of \mathbb{D} are the following:

- 630 ■ $(pat, hosp) \in H^{\mathbb{D}}$: the patient pat is in the hospital $hosp$.
- 631 ■ $(pat, st) \in Test^{\mathbb{D}}$: the patient pat participates in the study st .
- 632 ■ $(st, test) \in St^{\mathbb{D}}$: the test $test$ is used in the study st .
- 633 ■ $(obj, \epsilon) \in Priv^{\mathbb{D}}$: the object obj is either a patient or a hospital. The positive real number
 634 ϵ indicates the privacy budget for obj .
- 635 ■ $(st, test, val) \in Sens^{\mathbb{D}}$: the value (in terms of study results) of a patient participating in
 636 a study and contributing a unit of information on their result on test $test$.

The following query defines the sensitive information that will be revealed to the researchers performing the medical studies. It selects all pairs of patients pat and tests $test$, such pat did the $test$ which was then used by some study st .

$$InStudy(pat, test) = \exists st. Test(pat, test) \wedge St(test, st)$$

More precisely, the sensitive information is the answer set of this query over the database \mathbb{D} . We want to assign a weight to all the pairs in the answer set. The weight of a sensitive pair states the amount of information that may be disclosed about the pair after the addition of the noise. The needed amount of noise for the pair is then inversely proportional to the amount of information that may be disclosed, i.e, the weight of the pair, which is also called its privacy budget. The weight of a patient pat and a test $test$ is specified by the weight expression:

$$\mathbf{weight}_{(pat', test') : test' \doteq test \wedge pat' \doteq pat} (InStudy(pat', test'))$$

In an environment γ for the global variables pat and $test$ this weight expression is interpreted as the linear program variable:

$$\theta_{InStudy(pat', test')}^{[pat' / \gamma(pat), test' / \gamma(test)]}$$

The overall weight of all sensitive tests of the same patient pat is described by the weight expression:

$$\mathbf{weight}_{(pat', test') : pat' \doteq pat} (InStudy(pat', test'))$$

In an environment γ for the global variable pat this weight expression is interpreted as the following sum of linear program variables:

$$\sum_{\alpha \in sol^{\mathbb{D}}(InStudy(pat', test') \wedge pat' = \gamma(pat))} \theta_{InStudy(pat', test')}^{[pat' / \gamma(pat), test' / \alpha(test')]}$$

Queries

$$InStudy(pat, test) = \exists st. Test(pat, test) \wedge St(st, test)$$

Constraints

$$\begin{aligned} C_{PAT} &= \forall(pat, \varepsilon): Priv(pat, \varepsilon). \\ &\quad \mathbf{weight}_{(pat', test'): pat' \doteq pat}(Q(pat', test')) \leq \mathbf{num}(\varepsilon) \\ C_{HOSP} &= \forall(hosp, \varepsilon): Priv(hosp, \varepsilon). \sum_{(pat): H(pat, hosp)} \\ &\quad \mathbf{weight}_{(pat', test'): pat' \doteq pat}(InStudy(pat', test')) \leq \mathbf{num}(\varepsilon) \end{aligned}$$

Program

$$\begin{aligned} &\mathbf{maximize} \sum_{(st, test, val): Sens(st, test, val)} \\ &\quad \mathbf{num}(val) \mathbf{weight}_{(pat', test'): test' \doteq test}(InStudy(pat', test')) \\ &\mathbf{subject\ to} C_{PAT} \wedge C_{HOSP} \end{aligned}$$

■ **Figure 9** An $LP(CQ)_{proj}$ program for differential privacy when publishing medical studies aggregating patient tests in hospitals.

637 This sum may be represented more compactly in factorized interpretation avoiding the
638 enumeration of the answer set for the database \mathbb{D} .

639 The $LP(CQ)$ program for this example is given in Figure 9. The linear privacy constraints
640 that are to be satisfied are C_{PAT} and C_{HOSP} . Constraint C_{PAT} states that for all patients pat
641 with privacy requirement ε , i.e., $\forall(pat, \varepsilon) : Priv(pat, \varepsilon)$, the sum of all weights of all sensitive
642 pairs $(pat, test')$ in $InStudy$ must be bounded by ε . This constraint is motivated by the
643 composition rule of differential privacy (DP). Suppose we have sensitive pairs $p_i = (pat_i, test_i)$.
644 If p_i is ε_i -DP for $1 \leq i \leq n$, then $\{p_1 \dots p_n\}$ is $(\sum_{i=1}^n \varepsilon_i)$ -DP.

645 Similarly, constraint C_{HOSP} states that for all hospitals $hosp$ with privacy requirement
646 ε , i.e., $\forall(hosp, \varepsilon) : Priv(hosp, \varepsilon)$, the sum of all weights of all sensitive pairs $(pat, test)$ in
647 $InStudy$ where pat is a patient of $hosp$ must be bounded by ε . Finally, the objective function
648 is to maximize the sum over all triples $(st, test, val)$ in $Sens$ of the weights of pairs $(pat', test)$
649 in $InStudy$ but multiplied with $\mathbf{num}(val)$, the utility of the information for the study.

650 This program is projecting, so it is a member of $LP(CQ)_{proj}$. Furthermore, a hypertree
651 decomposition of width 1 is available. While the naive interpretation over a database yields
652 a linear program with a quadratic number of variables (in the size of the database), the
653 factorized interpretation yields a linear program with a linear number of variables.

654 Please note that the approach presented above is only approximate. For example, summing
655 over noise variance in the objective function would be more accurate but would only lead
656 to a convex program, which motivates us to extend beyond linear programs in future work.
657 Also, the composition rule for DP is only approximate, more advanced composition rules
658 have been studied but they are more complex and still approximate.

659 **B** Computing the s -Measure for Graph Pattern Matching

660 The s -measure has been introduced by Wang et al. [23] to evaluate the frequency of matchings
661 of a subgraph pattern in a larger graph. Here, we consider pattern matches as graph
662 homomorphism, but we could also restrict them to graph isomorphisms.

663 A naive way of evaluating this frequency is to use the number of pattern matches as the
664 frequency measure. Using this value as a frequency measure is problematic since different

665 pattern matches may overlap, and as such they share some kind of dependencies that is
 666 relevant from a statistical point of view. More importantly, due to the overlaps, this measure
 667 fails to be anti-monotone, meaning that a subpattern may be counter-intuitively matched less
 668 frequently than the pattern itself. Therefore, the finding of better anti-monotonic frequency
 669 measures – also known as *support measures* – has received a lot of attention in the data
 670 mining community [3, 4, 6]. A first idea is to count the maximal number of non-overlapping
 671 patterns [22]. However, finding such a maximal subset of patterns essentially boils down to
 672 finding a maximal independent set in a graph, a notorious NP-complete problem [8].

The s -measure is a relaxation of this idea where the frequency of pattern matches is computed as the maximum of the sum of the weights that can be assigned to each pattern match, under the constraint that for any node v of the graph and node v' in the subgraph pattern that the sum of the weights of the matchings mapping v' to v is at most 1. More formally, given two digraphs $G = (V_G, E_G)$ and $P = (V_P, E_P)$, we define a matching of the pattern P in graph G as a graph homomorphism $h : V_P \rightarrow V_G$. Recall that a graph homomorphism requires for all $(v, v') \in E_P$ that $(h(v), h(v')) \in E_G$. We denote by $hom(P, G)$ the set of matchings of P in G . The s -measure of P in G is then defined as the optimal value of the following linear program with variables in $\{\theta_h \mid h \in hom(P, G)\}$ for positive real numbers:

$$\begin{array}{ll} \text{maximize} & \sum_{h \in hom(P, G)} \theta_h \\ \text{subject to} & \forall v \in V_G. \forall v' \in V_P. \sum_{\substack{h \in hom(P, G) \\ h(v')=v}} \theta_h \leq 1 \end{array}$$

673

674 We can consider each graph G as a database \mathbb{D} with signature $\Sigma = \{node, edge\}$, domain
 675 $dom(\mathbb{D}_G) = V_G$ and relations $node^{\mathbb{D}} = V_G$ and $edge^{\mathbb{D}} = E_G$. Since the names of the nodes
 676 of the pattern do not care for pattern matching, we can assume without loss of generality
 677 that $V_P = \{1, \dots, \ell\}$ for some $\ell \in \mathbb{N}$. We can then define a matching of a pattern P by a
 678 conjunctive query $match_P(x_1, \dots, x_\ell)$:

$$679 \quad match_P(x_1, \dots, x_\ell) = \bigwedge_{(i,j) \in E_P} edge(x_i, x_j)$$

It is clear that $\alpha \in sol^{\mathbb{D}}(match_P(x_1, \dots, x_\ell))$ if and only if $\alpha \circ [1/x_1, \dots, \ell/x_\ell]$ is a pattern matching in $hom(P, Q)$. One can thus rewrite the previous linear program as $LP(CQ)$ program as follows:

$$\begin{array}{ll} \text{maximize} & \sum_{(x):node(x)} \text{weight}_{(x_1, \dots, x_n):x_1 \dot{=} x}(match_P(x_1, \dots, x_n)) \\ \text{subject to} & \forall (x) : node(x) : \bigwedge_{i=1}^{\ell} \text{weight}_{(x_1, \dots, x_n):x_i \dot{=} x}(match_P(x_1, \dots, x_n)) \leq 1. \end{array}$$

680 Moreover, the hypertree width of the conjunctive query $match_P(x_1, \dots, x_\ell)$ is at most
 681 the (hyper)tree width of the pattern graph P . By our main Theorem 8, the factorized
 682 interpretation yields a linear program with at most $(|V_G| + |E_G|)^k$ variables, where k is
 683 the (hyper)tree width of pattern P . The original linear program could have been of size
 684 $\binom{|V_G|}{\ell}$ which is bounded by $|V_G|^\ell$. So the factorized interpretation will pay off if the
 685 (hyper)tree width k of the pattern is considerably smaller than the number ℓ of its nodes.

686 C Weightings

687 C.1 Projections of weightings

688 Let $X' \subseteq X \subseteq \mathcal{X}$ and $A \subseteq D^X = \{\alpha \mid \alpha : X \rightarrow D\}$ be a set of variable assignments. For any
 689 $\alpha' : X' \rightarrow D$ we define the set of its extensions into A by $A[\alpha'] = \{\alpha \in A \mid \alpha|_{X'} = \alpha'\}$.

690 ▶ **Lemma 19.** For any two $\alpha_1, \alpha_2 \in A_{|X'}$, if $\alpha_1 \neq \alpha_2$ then $A[\alpha_1] \cap A[\alpha_2] = \emptyset$.

691 **Proof.** If $\alpha_1 \neq \alpha_2 \in A_{|X'}$, then there exists $x' \in X'$ such that $\alpha_1(x') \neq \alpha_2(x')$, so if
692 $\gamma_1 \in A[\alpha_1]$ and $\gamma_2 \in A[\alpha_2]$ then $\gamma_1(x') = \alpha_1(x') \neq \alpha_2(x') = \gamma_2(x')$. ◀

693 ▶ **Lemma 20.** For $A \subseteq D^X$, $X'' \subseteq X' \subseteq X$, $\alpha'' \in A_{|X''}$: $A[\alpha''] = \bigsqcup_{\alpha' \in A_{|X'}[\alpha'']} A[\alpha']$.

694 **Proof.** First note that the union on the right is disjoint by Lemma 19.

695 For the inclusion from the left to the right, let $\alpha \in A[\alpha'']$ and $\alpha' = \alpha_{|X'}$. By definition,
696 $\alpha' \in A_{|X'}$ so $\alpha \in A[\alpha']$. Furthermore, $\alpha' \in A_{|X'}[\alpha'']$ so $\alpha \in \bigsqcup_{\tilde{\alpha}' \in A_{|X'}[\alpha'']} A[\tilde{\alpha}']$.

697 For the inclusion from the right to the left, let $\alpha \in \bigsqcup_{\alpha' \in A_{|X'}[\alpha'']} A[\alpha']$ and let $\alpha' \in A_{|X'}[\alpha'']$
698 be such that $\alpha \in A[\alpha']$. By definition, $\alpha_{|X'} = \alpha'$ and $\alpha'_{|X''} = \alpha''$. Since $X'' \subseteq X'$,
699 $\alpha_{|X''} = \alpha'_{|X''} = \alpha''$. Thus $\alpha \in A[\alpha'']$. ◀

For any weighting ω of A and subset of variables $X' \subseteq X$, we define the projection
 $\pi_{X'}(\omega) : A_{|X'} \rightarrow \mathbb{R}_+$ such that for all $\alpha' \in A_{|X'}$:

$$\pi_{X'}(\omega)(\alpha') = \sum_{\alpha \in A[\alpha']} \omega(\alpha)$$

700 ▶ **Proposition 21.** For $A \in D^X$, $\omega : A \rightarrow \mathbb{R}_+$, $X'' \subseteq X' \subseteq X$: $\pi_{X''}(\omega) = \pi_{X''}(\pi_{X'}(\omega))$.

701 **Proof sketch.** This is a consequence of the disjoint decomposition of Lemma 20. ◀

702 **Proof.** Indeed, let $\alpha'' \in A_{|X''}$. We have:

$$\begin{aligned} 703 \quad \pi_{X''}(\omega)(\alpha'') &= \sum_{\alpha \in A[\alpha'']} \omega(\alpha) && \text{by definition} \\ 704 \quad &= \sum_{\alpha' \in A_{|X'}[\alpha'']} \sum_{\alpha \in A[\alpha']} \omega(\alpha) && \text{by Lemma 20} \\ 705 \quad &= \sum_{\alpha' \in A_{|X'}[\alpha'']} \pi_{X'}(\omega)(\alpha') && \text{by definition of } \pi_{X'}(\omega) \\ 706 \quad &= \pi_{X''}(\pi_{X'}(\omega))(\alpha'') && \text{by definition of } \pi_{X''}(\pi_{X'}(\omega)). \end{aligned}$$

708 The last equality is well defined since $\alpha'' \in A_{|X''} = (A_{|X'})_{|X''}$. ◀

709 C.2 Weighting collections on decomposition trees

Let $X \subseteq \mathcal{X}$ be a finite set of variables and $T = (\mathcal{V}, \mathcal{E}, \mathcal{B})$ a decomposition tree of X . Given
two nodes $u, v \in \mathcal{V}$ we denote the intersection of their bags by:

$$\mathcal{B}^{uv} = \mathcal{B}(u) \cap \mathcal{B}(v)$$

710 ▶ **Definition 22.** Let $A \subseteq D^X$ and let $T = (\mathcal{V}, \mathcal{E}, \mathcal{B})$ be a decomposition tree for X . We call
711 a family $W = (W_v)_{v \in \mathcal{V}}$ a weighting collection on T for A if it satisfies the following two
712 conditions for any two nodes $u, v \in \mathcal{V}$:

- 713 - W_u is a weighting of $A_{|\mathcal{B}(u)}$, i.e., $W_u : A_{|\mathcal{B}(u)} \rightarrow \mathbb{R}_+$.
- 714 - W_u is sound for T at $\{u, v\}$, i.e., $\pi_{\mathcal{B}^{uv}}(W_u) = \pi_{\mathcal{B}^{uv}}(W_v)$.

715 ▶ **Proposition 23.** Let $A \subseteq D^X$ and let $T = (\mathcal{V}, \mathcal{E}, \mathcal{B})$ be a decomposition tree for X . For
716 any weighting $\omega : A \rightarrow \mathbb{R}_+$, the family $(\pi_{\mathcal{B}(v)}(\omega))_{v \in \mathcal{V}}$ is a weighting collection on T for A .

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717 **Proof.** For any $u \in \mathcal{V}$ let $W_u = \pi_{\mathcal{B}(u)}(\omega)$. The first condition on weighting projections holds
 718 trivially so we only have to show that the soundness constraint holds. By definition of W_u ,
 719 $\pi_{\mathcal{B}^{uv}}(W_u) = \pi_{\mathcal{B}^{uv}}(\pi_{\mathcal{B}(u)}(\omega))$. Observe that $\mathcal{B}^{uv} \subseteq \mathcal{B}(u)$ so by Proposition 21 $\pi_{\mathcal{B}^{uv}}(W_u) =$
 720 $\pi_{\mathcal{B}^{uv}}(\omega)$. Similarly $\pi_{\mathcal{B}^{uv}}(W_v) = \pi_{\mathcal{B}^{uv}}(\omega)$. \blacktriangleleft

721 We next show that the global soundness at any subset of nodes $\{u, v\} \subseteq \mathcal{V}$ follows from
 722 the local soundness at all subsets $\{u, v\}$ such that $(u, v) \in \mathcal{E}$.

723 **► Lemma 24.** *If W is sound for T at $\{u, v\}$ for all edges $(u, v) \in \mathcal{E}$ then W is sound for T*
 724 *at all subsets $\{u, v\} \subseteq \mathcal{V}$.*

725 **Proof.** We show by induction on $k \geq 0$ for all pairs of nodes $(u, v) \in (\mathcal{E} \cup \mathcal{E}^{-1})^k$ that
 726 $\pi_{\mathcal{B}^{uv}}(W_u) = \pi_{\mathcal{B}^{uv}}(W_v)$.

The base case where $k = 0$ is obvious. We now show the induction step from k to $k + 1$.
 Let $(u, v) \in (\mathcal{E} \cup \mathcal{E}^{-1})^{k+1}$ be arbitrary. Then there exists $w \in \mathcal{V}$ such that $(u, w) \in (\mathcal{E} \cup \mathcal{E}^{-1})^k$
 and $(v, w) \in \mathcal{E} \cup \mathcal{E}^{-1}$. By induction hypothesis, we have $\pi_{\mathcal{B}^{uw}}(W_u) = \pi_{\mathcal{B}^{uw}}(W_w)$. We need
 to show that $\pi_{\mathcal{B}^{uv}}(W_u) = \pi_{\mathcal{B}^{uv}}(W_v)$. We first observe that $\mathcal{B}^{uv} \subseteq \mathcal{B}(w)$ by connectedness of
 T which implies that $\mathcal{B}^{uv} \subseteq \mathcal{B}^{uw}$ and $\mathcal{B}^{uv} \subseteq \mathcal{B}^{vw}$. Therefore, we can conclude as follows:

$$\begin{aligned}
 \pi_{\mathcal{B}^{uv}}(W_u) &= \pi_{\mathcal{B}^{uv}}(\pi_{\mathcal{B}^{uw}}(W_u)) && \text{by Proposition 21 and } \mathcal{B}^{uv} \subseteq \mathcal{B}^{uw} \\
 &= \pi_{\mathcal{B}^{uv}}(\pi_{\mathcal{B}^{uw}}(W_w)) && \text{by induction hypothesis} \\
 &= \pi_{\mathcal{B}^{uv}}(W_w) && \text{by Proposition 21 and } \mathcal{B}^{uv} \subseteq \mathcal{B}^{uw} \\
 &= \pi_{\mathcal{B}^{uv}}(\pi_{\mathcal{B}^{vw}}(W_w)) && \text{by Proposition 21 and } \mathcal{B}^{uv} \subseteq \mathcal{B}^{vw} \\
 &= \pi_{\mathcal{B}^{uv}}(\pi_{\mathcal{B}^{vw}}(W_v)) && \text{by local soundness at } \{v, w\} \\
 &= \pi_{\mathcal{B}^{uv}}(W_v) && \text{by Proposition 21 and } \mathcal{B}^{uv} \subseteq \mathcal{B}^{vw}
 \end{aligned}$$

727 \blacktriangleleft

728 If T is normalized then the local soundness constraint (22) of W at $(u, v) \in \mathcal{E}$ can be
 729 rewritten equivalently into a simpler form as follows:

- 730 \blacksquare if u is an extend node with unique child v then: $\forall \beta \in A_{|\mathcal{B}(v)} : \sum_{\beta' \in A_{|\mathcal{B}(u)}[\beta]} W_u(\beta') =$
 731 $W_v(\beta)$,
- 732 \blacksquare if u is a project node with unique child v then $\forall \beta \in A_{|\mathcal{B}(u)} : W_u(\beta) = \sum_{\beta' \in A_{|\mathcal{B}(v)}[\beta]} W_v(\beta')$,
- 733 \blacksquare if u is a join node with child v then $\forall \beta \in A_{|\mathcal{B}(u)} : W_u(\beta) = W_v(\beta)$.

734 C.3 Conjunctive decomposition

We need to restrict ourselves to particular subsets of variable assignments, including answer
 sets of acyclic conjunctive queries. More generally, we define what it means for a subset
 of variable assignments to be conjunctively decomposed by a decomposition tree. For any
 decomposition tree $T = (\mathcal{V}, \mathcal{E}, \mathcal{B})$ and subset $V \subseteq \mathcal{V}$ we define the set of variables:

$$\mathcal{B}(V) = \bigcup_{v \in V} \mathcal{B}(v)$$

735 In particular, this defines for any $v \in \mathcal{V}$ the union $\mathcal{B}(\uparrow v)$ of bags of vertices in-the-context-
 736 or-equal-to v , and the union $\mathcal{B}(\downarrow v)$ of bags of vertices that are descendants-or-equal-to
 737 v .

738 **► Definition 25.** *Let $T = (\mathcal{V}, \mathcal{E}, \mathcal{B})$ be a decomposition tree of $X \subseteq \mathcal{X}$. We call a subset of*
 739 *variable assignments $A \subseteq D^X$ conjunctively decomposed by T if for all $u \in \mathcal{V}$ and $\beta \in A_{|\mathcal{B}(u)}$:*

$$740 \quad \{\alpha_1 \cup \alpha_2 \mid \alpha_1 \in A_{|\mathcal{B}(\uparrow u)}[\beta], \alpha_2 \in A_{|\mathcal{B}(\downarrow u)}[\beta]\} \subseteq A[\beta]$$

741 Note that the inverse inclusion holds in general. To see this let $\beta \in A|_{\mathcal{B}(u)}$. If $\alpha \in A[\beta]$
 742 then $\alpha \in A$ and $\beta = \alpha|_{\mathcal{B}(u)}$. Hence, $\alpha = \alpha|_{\mathcal{B}(\uparrow u)} \cup \alpha|_{\mathcal{B}(\downarrow u)}$, so we can define $\alpha_1 = \alpha|_{\mathcal{B}(\uparrow u)}$ and
 743 $\alpha_2 = \alpha|_{\mathcal{B}(\downarrow u)}$.

744 ► **Proposition 26.** *For any tree decomposition T of a quantifier free conjunctive query*
 745 *$Q \in C_{Q\Sigma}$ and database $\mathbb{D} \in db_\Sigma$, the answer set $sol^{\mathbb{D}}(Q)$ is conjunctively decomposed by T .*

746 **Proof.** Let u be a node of T . The proof is based on the following observation: given an atom
 747 $R(\mathbf{x})$ of Q , either $\mathbf{x} \subseteq \mathcal{B}(\downarrow u)$ or $\mathbf{x} \subseteq \mathcal{B}(\uparrow u)$. Thus Q can be written as $Q_1 \wedge Q_2$ with the
 748 variables of Q_1 included in $\mathcal{B}(\downarrow u)$ and the variables of Q_2 includes in $\mathcal{B}(\uparrow u)$. Moreover, recall
 749 that $\mathcal{B}(u) = \mathcal{B}(\downarrow u) \cap \mathcal{B}(\uparrow u)$. Thus, given an assignment β of $\mathcal{B}(u)$ and $\alpha|_1 \in sol^{\mathbb{D}}(Q_1)[\beta]$ and
 750 $\alpha|_2 \in sol^{\mathbb{D}}(Q_2)[\beta]$, we have that $\alpha = \alpha_1 \cup \alpha_2 \in sol^{\mathbb{D}}(Q)[\beta]$. That is, $sol^{\mathbb{D}}(Q)$ is conjunctively
 751 decomposed by T . ◀

► **Lemma 27.** *Let T be a decomposition tree of X , u an extend node of T with child v , and*
 $A \subseteq D^X$ a subset of variable assignments. If A is conjunctively decomposed by T then any
assignment $\beta \in A|_{\mathcal{B}(u)}$ satisfies:

$$A|_{\mathcal{B}(\downarrow u)}[\beta]|_{\mathcal{B}(\downarrow v)} = A|_{\mathcal{B}(\downarrow v)}[\beta|_{\mathcal{B}(v)}]$$

752 **Proof.** For the inclusion from the left to the right let $\alpha \in A|_{\mathcal{B}(\downarrow u)}[\beta]|_{\mathcal{B}(\downarrow v)}$. Since $\alpha \in A|_{\mathcal{B}(\downarrow u)}$
 753 and $\alpha|_{\mathcal{B}(v)} = \beta|_{\mathcal{B}(v)}$ it follows that $\alpha \in A|_{\mathcal{B}(\downarrow v)}[\beta|_{\mathcal{B}(v)}]$.

754 For the inclusion from the right to the left let $\alpha \in A|_{\mathcal{B}(\downarrow v)}[\beta|_{\mathcal{B}(v)}]$. Let $\gamma \in A|_{\mathcal{B}(\uparrow v)}[\beta]$ be
 755 arbitrary and $\tau = \gamma \cup \alpha$.

756 Note that $(\tau|_{\mathcal{B}(\downarrow u)})|_{\mathcal{B}(\downarrow v)} = \alpha$, so it is sufficient to show $\tau|_{\mathcal{B}(\downarrow u)} \in A|_{\mathcal{B}(\downarrow u)}[\beta]$.

757 Since u is an extend node with child v it follows that $\mathcal{B}(\uparrow u) = \mathcal{B}(\uparrow v)$, and thus $\gamma \in$
 758 $A|_{\mathcal{B}(\uparrow v)}[\beta]$. By conjunctive decomposition of A by T it follows that $\tau \in A[\beta]$. Hence,
 759 $\tau|_{\mathcal{B}(\downarrow u)} \in A|_{\mathcal{B}(\downarrow u)}[\beta]$ as required. ◀

760 ► **Lemma 28.** *Let T be a decomposition tree of X , u a join node of T with children v_1, \dots, v_k*
 761 *where $k \geq 1$, and $A \subseteq D^X$ a subset of variable assignments. If A is conjunctively decomposed*
 762 *by T then any $\beta \in A|_{\mathcal{B}(u)}$ satisfies:*

$$A|_{\mathcal{B}(\downarrow u)}[\beta] = A|_{\mathcal{B}(\downarrow v_1)}[\beta] \bowtie \dots \bowtie A|_{\mathcal{B}(\downarrow v_k)}[\beta]$$

763 **Proof.** The inclusion from the left to the right is obvious by projecting an element of
 764 $A|_{\mathcal{B}(\downarrow u)}[\beta]$ to $\mathcal{B}(\downarrow v_1) \dots \mathcal{B}(\downarrow v_k)$.

765 For the inclusion from the right to the left let $\alpha_1 \in A|_{\mathcal{B}(\downarrow v_1)}[\beta], \dots, \alpha_k \in A|_{\mathcal{B}(\downarrow v_k)}[\beta]$. We
 766 show by induction that $\forall p \in [1, k], \tau_p = \alpha_1 \bowtie \dots \bowtie \alpha_p \in A|_{Y_p}[\beta]$ where $Y_p = \bigcup_{i=1}^p \mathcal{B}(\downarrow v_i)$.

767 **Base case** $p = 1$: Obvious.

768 **Inductive case:** Recall that by induction $\tau_p \in A|_{Y_p}[\beta]$ and observe that $Y_p \subseteq \mathcal{B}(\uparrow v_{p+1})$ so
 769 there exists $\gamma \in \mathcal{B}(\uparrow v_{p+1})[\beta]$ such that $\gamma|_{Y_p} = \tau_p$.

770 By conjunctive decomposition on v_{p+1} , $\alpha = \gamma \bowtie \alpha_{p+1} \in A$. Finally we have $\alpha|_{Y_{p+1}} =$
 771 $(\gamma \bowtie \alpha_{p+1})|_{Y_p \cup \mathcal{B}(\downarrow v_{p+1})} = \gamma|_{Y_p} \bowtie \alpha_{p+1}|_{\mathcal{B}(\downarrow v_{p+1})} = \tau_p \bowtie \alpha_{p+1} = \tau_{p+1}$ so $\tau_{p+1} \in A|_{Y_{p+1}}$.
 772 Thus $\tau_{p+1} \in Y_p[\beta]$ because $\tau_{p+1}|_{\mathcal{B}(u)} = \beta$.

773 ◀

774 **C.4 Weightings correspondence**

775 We are now ready to prove the main correspondence between weightings of A and weighting
776 collection on T :

777 **► Theorem 29.** *Let $T = (\mathcal{V}, \mathcal{E}, \mathcal{B})$ be a normalized decomposition tree of $X \subseteq \mathcal{X}$ and $A \subseteq D^X$
778 be a set of variable assignment that is conjunctively decomposed by T .*

- 779 1. *For every weighting ω of A , $(\pi_{\mathcal{B}(u)}(\omega))_{u \in \mathcal{V}}$ is a weighting collection on T for A .*
780 2. *For any weighting collection W on T for A there exists a weighting ω of A such that
781 $\forall u : W_u = \pi_{\mathcal{B}(u)}(\omega)$.*

782 **► Definition 30.** *Let $T = (\mathcal{V}, \mathcal{E}, \mathcal{B})$ be a normalized decomposition tree of X and $W =$
783 $(W_u)_{u \in \mathcal{V}}$ a weighting collection on T for $A \subseteq D^X$.*

784 *For any node $u \in \mathcal{V}$, $\omega_u : A_{|\mathcal{B}(\downarrow u)} \rightarrow \mathbb{R}_+$ is a weighting defined by induction on well-
785 founded order on the nodes of tree T .*

For the base case where u is a leaf of T , we define ω_u such that for all $\alpha \in A_{|\mathcal{B}(\downarrow u)}$:

$$\omega_u(\alpha) = W_u(\alpha)$$

786 *For the induction step we suppose that $\omega_{u'}$ is defined for all children u' of u . With
787 $\beta = \alpha_{|\mathcal{B}(u)}$ we define $\omega_u(\alpha)$ for all $\alpha \in A_{|\mathcal{B}(\downarrow u)}$.*

788 *If u is an extend node with a child v then:*

$$789 \quad \omega_u(\alpha) = \begin{cases} \frac{W_u(\beta)}{W_v(\alpha_{|\mathcal{B}(v)})} \omega_v(\alpha_{|\mathcal{B}(\downarrow v)}) & \text{if } W_v(\alpha_{|\mathcal{B}(v)}) > 0 \\ 0 & \text{otherwise.} \end{cases}$$

If u is a project node with a child v then

$$\omega_u(\alpha) = \omega_v(\alpha_{|\mathcal{B}(\downarrow v)}).$$

790 *Observe that $\mathcal{B}(u) = \mathcal{B}(v)$ so $\mathcal{B}(\downarrow u) = \mathcal{B}(\downarrow v)$ thus $\omega_v(\alpha_{|\mathcal{B}(\downarrow v)}) = \omega_v(\alpha)$.*

791 *If u is a join node with children v_1, \dots, v_k then*

$$792 \quad \omega_u(\alpha) = \begin{cases} \frac{\prod_{i=1}^k \omega_{v_i}(\alpha_{|\mathcal{B}(\downarrow v_i)})}{W_u(\beta)^{k-1}} & \text{if } W_u(\beta) > 0 \\ 0 & \text{otherwise.} \end{cases}$$

793 **► Proposition 31.** *For all $u \in \mathcal{V}$, $W_u = \pi_{\mathcal{B}(u)}(\omega_u)$.*

794 **Proof.** We show by bottom-up induction on the nodes of T that for all $u \in \mathcal{V}$ and $\beta \in A_{|\mathcal{B}(u)}$,
795 $\sum_{\alpha \in A_{|\mathcal{B}(\downarrow u)}[\beta]} \omega_u(\alpha) = W_u(\beta)$.

796 The base case is clearly true by the definition of ω_u when u is a leaf.

797 **Case 1** u is an extend node with v its only child.

798 Let $\beta \in A_{|\mathcal{B}(u)}$ and $\beta' = \beta_{|\mathcal{B}(v)}$.

799 **Case 1.1** $W_v(\beta') = 0$.

800 By definition $\forall \alpha \in A_{|\mathcal{B}(\downarrow u)}[\beta], \omega_u(\alpha) = 0$.

801 Recall that by soundness $\sum_{\beta'' \in A_{|\mathcal{B}(u)}[\beta']} W_u(\beta'') = W_v(\beta') = 0$. Observe that $\beta \in$

802 $A_{|\mathcal{B}(u)}[\beta']$ so $W_u(\beta) = 0 = \sum_{\alpha \in A_{|\mathcal{B}(\downarrow u)}[\beta]} \omega_u(\alpha)$.

803 **Case 1.2** $W_v(\beta') > 0$.

$$\begin{aligned}
& \sum_{\alpha \in A_{|\mathcal{B}(\downarrow u)}[\beta]} \omega_u(\alpha) \\
&= \sum_{\alpha \in A_{|\mathcal{B}(\downarrow u)}[\beta]} \frac{W_u(\beta)}{W_v(\beta')} \omega_v(\alpha_{|\mathcal{B}(\downarrow v)}) && \text{by definition} \\
&= \frac{W_u(\beta)}{W_v(\beta')} \sum_{\alpha \in A_{|\mathcal{B}(\downarrow u)}[\beta]} \omega_v(\alpha_{|\mathcal{B}(\downarrow v)}) \\
&= \frac{W_u(\beta)}{W_v(\beta')} \sum_{\alpha' \in A_{|\mathcal{B}(\downarrow v)}[\beta']} \omega_v(\alpha') && \text{by Lemma 27} \\
&= \frac{W_u(\beta)}{W_v(\beta')} W_v(\beta') && \text{by induction} \\
&= W_u(\beta)
\end{aligned}$$

804 **Case 2** u is a project node with only child v .

$$\begin{aligned}
& \sum_{\alpha \in A_{|\mathcal{B}(\downarrow u)}[\beta]} \omega_u(\alpha) \\
&= \sum_{\alpha \in A_{|\mathcal{B}(\downarrow u)}[\beta]} \omega_u(\alpha) && \text{by definition} \\
&= \sum_{\beta' \in A_{|\mathcal{B}(v)}[\beta]} \sum_{\alpha' \in A_{|\mathcal{B}(\downarrow u)}[\beta']} \omega_v(\alpha') && \text{by Proposition 21 and } \mathcal{B}(v) \subseteq \mathcal{B}(\downarrow u) \\
&= \sum_{\beta' \in A_{|\mathcal{B}(v)}[\beta]} W_v(\beta') && \text{by induction and } \mathcal{B}(\downarrow u) = \mathcal{B}(\downarrow v) \\
&= W_u(\beta) && \text{by soundness at } (u, v)
\end{aligned}$$

805 **Case 3** u is a join node with children v_1, \dots, v_k .

806 Let $\beta \in A_{|\mathcal{B}(u)}$.

807 **Case 3.1** $W_u(\beta) = 0$.

808 By definition $\forall \alpha \in A_{|\mathcal{B}(\downarrow u)}[\beta], \omega_u(\alpha) = 0$.

809 Thus $\sum_{\alpha \in A_{|\mathcal{B}(\downarrow u)}[\beta]} \omega_u(\alpha) = 0 = W_u(\beta)$.

810 **Case 3.2** $W_u(\beta) > 0$.

$$\begin{aligned}
& \sum_{\alpha \in A_{|\mathcal{B}(\downarrow u)}[\beta]} \omega_u(\alpha) \\
&= \sum_{\alpha \in A_{|\mathcal{B}(\downarrow u)}[\beta]} \frac{\prod_{i=1}^k \omega_{v_i}(\alpha_{|\mathcal{B}(\downarrow v_i)})}{W_u(\beta)^{k-1}} && \text{by definition} \\
&= \sum_{\alpha_1 \in A_{|\mathcal{B}(\downarrow v_1)}[\beta]} \dots \sum_{\alpha_k \in A_{|\mathcal{B}(\downarrow v_k)}[\beta]} \frac{\prod_{i=1}^k \omega_{v_i}(\alpha_i)}{W_u(\beta)^{k-1}} && \text{by Lemma 28} \\
&= \frac{\prod_{i=1}^k \sum_{\alpha_i \in A_{|\mathcal{B}(\downarrow v_i)}[\beta]} \omega_{v_i}(\alpha_i)}{W_u(\beta)^{k-1}} \\
&= \frac{\prod_{i=1}^k W_{v_i}(\beta)}{W_u(\beta)^{k-1}} && \text{by induction} \\
&= \frac{W_u(\beta)^k}{W_u(\beta)^{k-1}} && \text{by soundness at } (u, v_i) \\
&= W_u(\beta)
\end{aligned}$$

811

► **Lemma 32.** Let v be the child of an extend node u , $\forall \alpha \in A_{|\mathcal{B}(\downarrow v)}$ with $\beta = \alpha_{|\mathcal{B}(v)}$:

$$A[\alpha] = \bigsqcup_{\beta' \in A_{|\mathcal{B}(u)}[\beta]} A[\alpha \cup \beta']$$

812 **Proof.** For the inclusion from the left to the right, let $\tau \in A[\alpha]$ and $\beta' = \tau_{|\mathcal{B}(u)}$. Observe
813 that $\beta' \in A_{|\mathcal{B}(u)}[\beta]$. Moreover $\mathcal{B}(\downarrow u) = \mathcal{B}(\downarrow v) \cup \mathcal{B}(u)$ so $\tau_{|\mathcal{B}(\downarrow u)} = \alpha \cup \beta'$ so $\tau \in A[\alpha \cup \beta']$.

814 For the inclusion from the right to the left, let $\tau \in \bigsqcup_{\beta' \in A_{|\mathcal{B}(u)}[\beta]} A[\alpha \cup \beta']$. By definition
815 $\tau \in A$ and $\tau_{|\mathcal{B}(\downarrow v)} = \alpha$ so $\tau \in A[\alpha]$. ◀

816 ► **Lemma 33.** Given a join node u and its children v_1, \dots, v_k , let $\alpha \in A_{|\mathcal{B}(\downarrow v_1)}$ and $\beta = \alpha_{|\mathcal{B}(u)}$.

$$A_{|\mathcal{B}(\downarrow u)}[\alpha] = \{\alpha\} \bowtie A_{|\mathcal{B}(\downarrow v_2)}[\beta] \bowtie \dots \bowtie A_{|\mathcal{B}(\downarrow v_k)}[\beta]$$

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817 **Proof.** Clearly $A_{|\mathcal{B}(\downarrow u)}[\alpha] = \{\tau \in A_{|\mathcal{B}(\downarrow u)}[\beta] \mid \tau_{|\mathcal{B}(\downarrow v_1)} = \alpha\}$ because $\beta = \alpha_{|\mathcal{B}(u)}$.

818 Thus by Lemma 28, $A_{|\mathcal{B}(\downarrow u)}[\alpha] = \{\tau \in A_{|\mathcal{B}(\downarrow v_1)}[\beta] \bowtie \dots \bowtie A_{|\mathcal{B}(\downarrow v_k)}[\beta] \mid \tau_{|\mathcal{B}(\downarrow u)} = \alpha\} =$
 819 $\{\alpha\} \bowtie A_{|\mathcal{B}(\downarrow v_2)}[\beta] \bowtie \dots \bowtie A_{|\mathcal{B}(\downarrow v_k)}[\beta]$ \blacktriangleleft

820 **► Proposition 34.** For all $u \in \mathcal{V}$, $\omega_u = \pi_{\mathcal{B}(\downarrow u)}(\omega_r)$.

821 **Proof.** We show by top-down induction on the nodes of T that for all $v \in \mathcal{V}$ and $\alpha \in A_{|\mathcal{B}(\downarrow v)}$,
 822 $\sum_{\tau \in A[\alpha]} \omega_r(\tau) = \omega_v(\alpha)$.

823 The base case is clearly true when v is the root r of T .

824 In the following we consider a given $\alpha \in A_{|\mathcal{B}(\downarrow v)}$. and we let $\beta = \alpha_{|\mathcal{B}(v)}$

825 **Case 1** v is the only child of an extend node u .

826 By Lemma 32, $\sum_{\tau \in A[\alpha]} \omega_r(\tau) = \sum_{\beta' \in A_{|\mathcal{B}(u)}[\beta]} \sum_{\tau \in A[\alpha \cup \beta']} \omega_r(\tau)$. By induction this is
 827 equal to $\sum_{\beta' \in A_{|\mathcal{B}(u)}[\beta]} \omega_u(\alpha \bowtie \beta')$.

828 **Case 1.1** $W_v(\beta) = 0$.

829 By definition of ω_u , $\sum_{\beta' \in A_{|\mathcal{B}(u)}[\beta]} \omega_u(\alpha \bowtie \beta') = 0$.

830 Observe that by Proposition 31, $\sum_{\alpha' \in A_{|\mathcal{B}(\downarrow u)}[\beta]} \omega_v(\alpha') = W_v(\beta) = 0$. However ω_v is
 831 non-negative so $\omega_v(\alpha) = 0 = \sum_{\tau \in A[\alpha]} \omega_r(\tau)$.

832 **Case 1.2** $W_v(\beta) > 0$.

$$\begin{aligned} & \sum_{\beta' \in A_{|\mathcal{B}(u)}[\beta]} \omega_u(\alpha \bowtie \beta') \\ &= \sum_{\beta' \in A_{|\mathcal{B}(u)}[\beta]} \frac{W_u(\beta')}{W_v(\beta)} \omega_v((\alpha \bowtie \beta')_{|\mathcal{B}(\downarrow v)}) \quad \text{by definition} \\ &= \frac{\sum_{\beta' \in A_{|\mathcal{B}(u)}[\beta]} W_u(\beta')}{W_v(\beta)} \omega_v(\alpha) \\ &= \omega_v(\alpha) \quad \text{by soundness at } (u, v) \end{aligned}$$

833 **Case 2** v is the only child of a project node u .

834 Observe that $\mathcal{B}(\downarrow u) = \mathcal{B}(\downarrow v)$ because u is a project node so by induction $\sum_{\tau \in A[\alpha]} \omega_r(\tau) =$
 835 $\omega_u(\alpha) = \omega_v(\alpha)$.

836 **Case 3** v is the child of a join node u .

837 Let v_1, \dots, v_n be the children of u , we assume wlog that v is v_1 .

838 By Proposition 21, $\sum_{\tau \in A[\alpha]} \omega_r(\tau) = \sum_{\alpha' \in A_{|\mathcal{B}(\downarrow u)}[\alpha]} \sum_{\tau \in A[\alpha']} \omega_r(\tau)$.

839 By induction we obtain $\sum_{\alpha' \in A_{|\mathcal{B}(\downarrow u)}[\alpha]} \omega_u(\alpha')$.

840 **Case 3.1** $W_u(\beta) = 0$.

841 By definition of ω_u , $\sum_{\alpha' \in A_{|\mathcal{B}(\downarrow u)}[\alpha]} \omega_u(\alpha') = 0$.

842 Recall that because u is a join node, $W_v(\beta) = W_u(\beta) = 0$ so similarly to Case 1.2,
 843 $\omega_v(\alpha) = 0 = \sum_{\tau \in A[\alpha]} \omega_r(\tau)$.

844 **Case 3.2** $W_v(\beta) > 0$.

845 By definition of ω_u , $\sum_{\alpha' \in A_{|\mathcal{B}(\downarrow u)}[\alpha]} \omega_u(\alpha') = \sum_{\alpha' \in A_{|\mathcal{B}(\downarrow u)}[\alpha]} \frac{\prod_{i=1}^k \omega_{v_i}(\alpha'_{|\mathcal{B}(\downarrow v_i)})}{W_u(\beta)^{k-1}}$. Moreover
 846 by Lemma 33 we can split α' into $\alpha \times \alpha_2 \times \dots \times \alpha_k$ and the sum into

847 $\sum_{\alpha_2 \in A_{|\mathcal{B}(\downarrow v_2)}[\beta]} \dots \sum_{\alpha_k \in A_{|\mathcal{B}(\downarrow v_k)}[\beta]} \frac{\prod_{i=1}^k \omega_{v_i}(\alpha'_{|\mathcal{B}(\downarrow v_i)})}{W_u(\beta)^{k-1}}$. Observe that each term in the
 848 product only depends on α_i (or α for $i = 1$) and that the denominator only depends
 849 on the fixed β so we can rewrite the formula into the following $\omega_v(\alpha) \cdot$
 850 $\frac{\prod_{i=2}^k \sum_{\alpha_i \in A_{|\mathcal{B}(\downarrow v_i)}[\beta]} \omega_{v_i}(\alpha_i)}{W_u(\beta)^{k-1}}$ which is equal to $\omega_v(\alpha) \cdot \frac{\prod_{i=2}^k W_{v_i}(\beta)}{W_u(\beta)^{k-1}}$ by Proposition 31.

851 Finally observe that by soundness, $\prod_{i=2}^k W_{v_i}(\beta) = W_u(\beta)^{k-1}$.


852 Thus $\sum_{\tau \in A[\alpha]} \omega_r(\tau) = \omega_v(\alpha)$.

853



854 **of Theorem 29.** The first item follows directly from Proposition 23.

855 For the second item we know by Proposition 31 that $W_u = \pi_{\mathcal{B}(u)}(\omega_u)$ which is equal to

856 $\pi_{\mathcal{B}(u)}(\pi_{\mathcal{B}(\downarrow u)}(\omega_r))$ by Proposition 34. Thus $W_u = \pi_{\mathcal{B}(u)}(\omega_r)$ by Proposition 21. 



$$\begin{aligned}
\llbracket c \rrbracket_\omega &= c \\
\llbracket \xi \rrbracket_\omega &= \omega(\xi) \\
\llbracket cS \rrbracket_\omega &= c \cdot \llbracket S \rrbracket_\omega \\
\llbracket S + S' \rrbracket_\omega &= \llbracket S \rrbracket_\omega + \llbracket S' \rrbracket_\omega \\
\llbracket true \rrbracket_\omega &= 1 \\
\llbracket S \leq S' \rrbracket_\omega &= \begin{cases} 1 & \text{if } \llbracket S \rrbracket_\omega \leq \llbracket S' \rrbracket_\omega \\ 0 & \text{otherwise.} \end{cases} \\
\llbracket C \wedge C' \rrbracket_\omega &= \llbracket C \rrbracket_\omega \wedge \llbracket C' \rrbracket_\omega \\
\llbracket \text{maximize } S \text{ subject to } C \rrbracket &= \max(\{\llbracket S \rrbracket_\omega \mid \omega : \Xi \rightarrow \mathbb{R}_+, \llbracket C \rrbracket_\omega = 1\})
\end{aligned}$$

■ **Figure 10** Evaluation of linear sums, constraints and programs.

$$\begin{aligned}
eval^{\mathbb{D},\alpha}(x) &= \alpha(x) \\
eval^{\mathbb{D},\alpha}(a) &= a^{\mathbb{D}} \\
sol_X^{\mathbb{D}}(E_1 \doteq E_2) &= \{\alpha : X \rightarrow D \mid eval^{\mathbb{D},\alpha}(E_1) = eval^{\mathbb{D},\alpha}(E_2)\} \\
sol_X^{\mathbb{D}}(r(E_1, \dots, E_n)) &= \{\alpha : X \rightarrow D \mid (eval^{\mathbb{D},\alpha}(E_1), \dots, eval^{\mathbb{D},\alpha}(E_n)) \in r^{\mathbb{D}}\} \\
sol_X^{\mathbb{D}}(Q_1 \wedge Q_2) &= sol_X^{\mathbb{D}}(Q_1) \cap sol_X^{\mathbb{D}}(Q_2) \\
sol_X^{\mathbb{D}}(\exists x.Q) &= \{\alpha|_X \mid \alpha \in sol_{X \cup \{x\}}^{\mathbb{D}}(Q)\} \quad \text{if } x \notin X \\
sol_X^{\mathbb{D}}(true) &= X^{dom(\mathbb{D})}
\end{aligned}$$

■ **Figure 11** Answer sets of conjunctive queries.

857 **A** Proofs for Section 2 (Preliminaries)

858 **B** Proofs for Section 3 (Linear Programs with Conjunctive Queries)

859 **B.1** α -Renaming may change the semantics of linear CQ -programs.

To illustrate this let $\mathbf{x} = (x_1, x_2)$ and L be the following linear CQ -program:

$$\text{maximize weight}_{\mathbf{x}:x_2 \doteq a}(r(\mathbf{x})) \text{ subject to weight}_{\mathbf{x}}(r(\mathbf{x})) \leq 1.$$

Let \mathbb{D} be a database with signature $\Sigma = \{r^{(2)}\}$ and interpretation $r^{\mathbb{D}} = \{(0, 0), (0, 1)\}$. If Q is the query $r(\mathbf{x})$ then the semantics of this linear CQ -program $\langle L \rangle^{\mathbb{D}}$ is the linear program:

$$\text{maximize } \theta_Q^{(0,1)} \text{ subject to } \theta_Q^{(0,0)} + \theta_Q^{(0,1)} \leq 1$$

The optimal value $\langle L \rangle^{\mathbb{D}}$ is $\llbracket \langle L \rangle^{\mathbb{D}} \rrbracket = 1$ since $\theta_Q^{(0,0)} + \theta_Q^{(0,1)} \leq 1$ and $\theta_Q^{(0,0)} \geq 0$. Now let us α -rename the second occurrence of \mathbf{x} in L apart to $\mathbf{x}' = (x'_1, x'_2)$ yielding the following linear CQ -program L' :

$$\text{maximize weight}_{\mathbf{x}:x_2 \doteq a}(r(\mathbf{x})) \text{ subject to weight}_{\mathbf{x}'}(r(\mathbf{x}')) \leq 1.$$

The semantics $\langle L' \rangle^{\mathbb{D}}$ is the following linear program where Q' is $r(\mathbf{x}')$ and Q is $r(\mathbf{x})$:

$$\text{maximize } \theta_{Q'}^{(0,1)} \text{ subject to } \theta_{Q'}^{(0,0)} + \theta_{Q'}^{(0,1)} \leq 1$$

860 The optimal value of $\langle L' \rangle^{\mathbb{D}}$ is ∞ since $\theta_{Q'}^{(0,1)}$ is no more constrained: the renaming made
861 the variables of Q and Q' different, so that the variable assignments answering these queries

$$\begin{aligned}
sbs_\gamma(Q \wedge Q') &= sbs_\gamma(Q) \wedge sbs_\gamma(Q') \\
sbs_\gamma(\exists x.Q) &= \exists x.sbs_{\gamma|_{dom(\gamma) \setminus \{x\}}}(Q) \\
sbs_\gamma(r(t_1, \dots, t_n)) &= r(sbs_\gamma(t_1), \dots, sbs_\gamma(t_n)) \\
sbs_\gamma(x) &= \begin{cases} \gamma(x) & \text{if } x \in dom(\gamma) \\ x & \text{otherwise} \end{cases} \\
sbs_\gamma(a) &= a
\end{aligned}$$

■ **Figure 12** Lifting substitutions $\gamma : fv(Q) \rightarrow \mathcal{C}$ to queries Q .

862 become different too. Therefore, different weights may be assigned to them. In other word
863 the tables of answers of Q and Q' are different, since their columns are named by differently,
864 by \mathbf{x} and respectively \mathbf{x}' .

865 **C** Proofs for Section 4 (An Efficiently Solvable Fragment)

866 ► **Lemma 14.** For any \mathcal{T} -projecting sum $S \in Sum_\Sigma$ and environment $\gamma : X \rightarrow dom(\mathbb{D})$
867 where $fv(S) \subseteq X$ it holds that $\llbracket \langle S \rangle^{\mathbb{D}, \gamma} \rrbracket_{\dot{\omega}} = \llbracket \rho^{\mathcal{T}, \mathbb{D}, \gamma}(S) \rrbracket_{\Pi(\dot{\omega})}$.

868 **Proof.** By induction on the structure of S .

869 **Case** $S = \mathbf{weight}_{\mathbf{x}, \mathbf{x}' \doteq \mathbf{y}}(Q)$ where $set(\mathbf{x}') \subseteq set(\mathbf{x}) = fv(Q)$, $set(\mathbf{y}) \cap set(\mathbf{x}) = \emptyset$ and
870 $set(\mathbf{x}') = \mathcal{B}_Q(u)$ for some node u of T_Q .

871 Let $\beta = [\mathbf{x}' / \gamma(\mathbf{y})]$.

$$\begin{aligned}
\llbracket \langle S \rangle^{\mathbb{D}, \gamma} \rrbracket_{\dot{\omega}} &= \llbracket \sum_{\alpha \in sol_{set(\mathbf{x})}^{\mathbb{D}}(Q \wedge sbs_\gamma(Q'))} \theta_Q^\alpha \rrbracket_{\dot{\omega}} \\
&= \llbracket \sum_{\alpha \in sol_{set(\mathbf{x})}^{\mathbb{D}}(Q \wedge \bigwedge_{j=1}^m x'_j = \gamma(y_j))} \theta_Q^\alpha \rrbracket_{\dot{\omega}} \\
&= \llbracket \sum_{\alpha \in sol_{set(\mathbf{x})}^{\mathbb{D}}(Q)} \theta_Q^\alpha \rrbracket_{\dot{\omega}} && \text{since } set(\mathbf{x}') = \mathcal{B}_Q(u) \\
&\quad \alpha|_{\mathcal{B}(u)} = \beta \\
&= \sum_{\alpha \in sol_{set(\mathbf{x})}^{\mathbb{D}}(Q)} \dot{\omega}(\theta_Q^\alpha) \\
&\quad \alpha|_{\mathcal{B}(u)} = \beta \\
&= \sum_{\alpha \in sol^{\mathbb{D}}(Q)[\beta]} \dot{\omega}(\theta_Q^\alpha)
\end{aligned}$$

872 We distinguish two cases depending on whether $\beta \in sol^{\mathbb{D}}(Q)|_{\mathcal{B}(u)}$:

– If $\beta \notin sol^{\mathbb{D}}(Q)|_{\mathcal{B}(u)}$ then by definition of $\rho^{\mathcal{T}, \mathbb{D}, \gamma}(S)$:

$$\llbracket \langle S \rangle^{\mathbb{D}, \alpha} \rrbracket_{\dot{\omega}} = \sum_{\alpha \in sol^{\mathbb{D}}(Q)[\beta]} \dot{\omega}(\theta_Q^\alpha) = \sum_{\alpha \in \emptyset} \dot{\omega}(\theta_Q^\alpha) = 0 = \rho^{\mathcal{T}, \mathbb{D}, \gamma}(S)$$

873 .

– If $\beta \in sol^{\mathbb{D}}(Q)|_{\mathcal{B}(u)}$ then $\xi_{Q, u, \beta} \in \Xi_L^{\mathcal{T}, \mathbb{D}}$ and thus by definition of $\rho^{\mathcal{T}, \mathbb{D}, \gamma}(S)$:

$$\begin{aligned}
\llbracket \langle S \rangle^{\mathbb{D}, \gamma} \rrbracket_{\dot{\omega}} &= \sum_{\gamma \in sol^{\mathbb{D}}(Q)[\beta]} \dot{\omega}(\theta_Q^\gamma) \\
&= \Pi(\dot{\omega})(\xi_{Q, u, \beta}) && \text{by definition of } \Pi \\
&= \llbracket \xi_{Q, u, \beta} \rrbracket_{\Pi(\dot{\omega})} \\
&= \llbracket \rho^{\mathcal{T}, \mathbb{D}, \gamma}(S) \rrbracket_{\Pi(\dot{\omega})}
\end{aligned}$$

874 **Case** $S = N$.

875 Straightforward.

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876 Case $S = \sum_{\mathbf{x}:Q} S'$.

$$\begin{aligned}
 877 \quad \llbracket \langle S \rangle^{\mathbb{D}, \gamma} \rrbracket_{\dot{\omega}} &= \llbracket \sum_{\gamma' \in \text{sol}_{\text{set}(\mathbf{x})}^{\mathbb{D}}(\text{sbs}_{\gamma}(Q))} \langle S' \rangle^{\mathbb{D}, \gamma \cup \gamma'} \rrbracket_{\dot{\omega}} \\
 878 \quad &= \sum_{\gamma' \in \text{sol}_{\text{set}(\mathbf{x})}^{\mathbb{D}}(\text{sbs}_{\gamma}(Q))} \llbracket \langle S' \rangle^{\mathbb{D}, \gamma \cup \gamma'} \rrbracket_{\dot{\omega}} \\
 879 \quad &= \sum_{\gamma' \in \text{sol}_{\text{set}(\mathbf{x})}^{\mathbb{D}}(\text{sbs}_{\gamma}(Q))} \llbracket \rho^{\mathcal{T}, \mathbb{D}, \gamma \cup \gamma'}(S') \rrbracket_{\Pi(\dot{\omega})} \quad \text{by induction hyp.} \\
 880 \quad &= \llbracket \sum_{\gamma' \in \text{sol}_{\text{set}(\mathbf{x})}^{\mathbb{D}}(\text{sbs}_{\gamma}(Q))} \rho^{\mathcal{T}, \mathbb{D}, \gamma \cup \gamma'}(S') \rrbracket_{\Pi(\dot{\omega})} \\
 881 \quad &= \llbracket \rho^{\mathcal{T}, \mathbb{D}, \gamma}(S) \rrbracket_{\Pi(\dot{\omega})} \\
 882 \quad &
 \end{aligned}$$

883 Case $S = NS$. Straightforward.

884 Case $S = S' + S''$.

885 Straightforward.

886

887 ► **Lemma 15.** For any constraint $C \in LC_{\Sigma}$ that is \mathcal{T} -projecting and environment $\gamma : X \rightarrow$
 888 $\text{dom}(\mathbb{D})$ where $\text{fv}(C) \subseteq X$: $\llbracket \langle C \rangle^{\mathbb{D}, \gamma} \rrbracket_{\dot{\omega}} = \llbracket \rho^{\mathcal{T}, \mathbb{D}, \gamma}(C) \rrbracket_{\Pi(\dot{\omega})}$.

889 **Proof.** By induction on the structure of C .

890 **Base case 1** $C = \text{true}$ Obvious.

891 **Base case 2** $C = S \leq S'$ Straightforward using Lemma 14.

892 **Induction step 1** $C = C' \wedge C''$

893 Straightforward.

894 **Induction step 2** $C = \forall \mathbf{x}:r(\mathbf{x}).C$

$$\begin{aligned}
 895 \quad \llbracket \langle C \rangle^{\mathbb{D}, \gamma} \rrbracket_{\dot{\omega}} &= \llbracket \langle \forall \mathbf{x}:r(\mathbf{x}).C' \rangle^{\mathbb{D}, \gamma} \rrbracket_{\dot{\omega}} \\
 896 \quad &= \llbracket \bigwedge_{\gamma' \in \text{sol}_{\text{set}(\mathbf{x})}^{\mathbb{D}}(r(\mathbf{x}))} \langle C' \rangle^{\mathbb{D}, \gamma \cup \gamma'} \rrbracket_{\dot{\omega}} \\
 897 \quad &= \bigwedge_{\gamma' \in \text{sol}_{\text{set}(\mathbf{x})}^{\mathbb{D}}(r(\mathbf{x}))} \llbracket \langle C' \rangle^{\mathbb{D}, \gamma \cup \gamma'} \rrbracket_{\dot{\omega}} \\
 898 \quad &= \sum_{\gamma' \in \text{sol}_{\text{set}(\mathbf{x})}^{\mathbb{D}}(r(\mathbf{x}))} \llbracket \rho^{\mathcal{T}, \mathbb{D}, \gamma \cup \gamma'}(C') \rrbracket_{\Pi(\dot{\omega})} \quad \text{by induction} \\
 899 \quad &= \llbracket \bigwedge_{\gamma' \in \text{sol}^{\mathbb{D}}(r(\mathbf{x}))} \rho^{\mathcal{T}, \mathbb{D}, \gamma \cup \gamma'}(C') \rrbracket_{\Pi(\dot{\omega})} \\
 900 \quad &= \llbracket \rho^{\mathcal{T}, \mathbb{D}, \gamma}(\forall \mathbf{x}:r(\mathbf{x}).C') \rrbracket_{\Pi(\dot{\omega})} \\
 901 \quad &= \llbracket \rho^{\mathcal{T}, \mathbb{D}, \gamma}(C) \rrbracket_{\Pi(\dot{\omega})} \\
 902 \quad &
 \end{aligned}$$

903

904 ► **Lemma 16.** For any weighting \dot{W} of $\Xi_L^{\mathcal{T}, \mathbb{D}}$ such that $\llbracket \bigwedge_{Q \in \mathcal{Q}} \text{lsc}^{\mathcal{T}, \mathbb{D}}(Q) \rrbracket_{\dot{W}} = 1$, there exists
 905 a weighting $\dot{\omega}$ of $\Theta_{\mathcal{Q}}$ such that $\dot{W} = \Pi(\dot{\omega})$.

906 **Proof.** For each $Q \in \mathcal{Q}$, let $W^Q = (W_u^Q)_{u \in T_Q}$ where $W_u^Q(\beta) = \dot{W}(\xi_{Q,u,\beta})$ for each $\xi_{Q,u,\beta} \in$
 907 $\Xi_L^{\mathcal{T}, \mathbb{D}}$.

908 Observe that it follows from the hypothesis that $\llbracket \text{lsc}^{\mathcal{T}, \mathbb{D}}(Q) \rrbracket_{\dot{W}} = 1$ so given a pair of nodes
 909 (u, v) in T_Q and a $\gamma \in \text{sol}^{\mathbb{D}}(Q)|_{\mathcal{B}^{uv}}$ then $\llbracket \sum_{\beta \in A_{|\mathcal{B}(u)}[\gamma]} \xi_{Q,u,\beta} \rrbracket_{\dot{W}} = \llbracket \sum_{\beta' \in A_{|\mathcal{B}(v)}[\gamma]} \xi_{Q,v,\beta'} \rrbracket_{\dot{W}}$.
 910 By definition of W^Q we then have $\sum_{\beta \in A_{|\mathcal{B}(u)}[\gamma]} W_u^Q(\beta) = \sum_{\beta' \in A_{|\mathcal{B}(v)}[\gamma]} W_u^Q(\beta')$. By definition
 911 of the projection of weightings it follows that $\pi_{\mathcal{B}^{uv}}(W_u^Q) = \pi_{\mathcal{B}^{uv}}(W_v^Q)$ so W^Q is a weighting
 912 collection on T_Q . Thus by Theorem 13 for each $Q \in \mathcal{Q}$, there is a weighting $\omega_Q : \text{sol}^{\mathbb{D}}(Q) \rightarrow \mathbb{R}_+$
 913 such that $W_Q = (\pi_{\mathcal{B}(u)}(\omega_Q))_{u \in \mathcal{V}}$. Finally we define a weighting $\dot{\omega} : \Theta_{\mathcal{Q}} \rightarrow \mathbb{R}_+$ such that
 914 $\dot{\omega}(\theta_Q^\alpha) = \omega_Q(\alpha)$ for each $\theta_Q^\alpha \in \Theta_{\mathcal{Q}}$.

915 We fix a $\xi_{Q,u,\beta} \in \Xi_L^{\mathcal{T}, \mathbb{D}}$. By definition $W(\xi_{Q,u,\beta}) = W_u^Q(\beta) = (\pi_{\mathcal{B}(u)}(\omega_Q))(\beta) =$
 916 $\sum_{\alpha \in \text{sol}^{\mathbb{D}}(Q)|_{\beta}} \omega_Q(\alpha)$. Thus $W(\xi_{Q,u,\beta}) = \Pi(\dot{\omega})(\xi_{Q,u,\beta})$ by definition of Π . ◀

917 ▶ **Proposition 17.** *Let \mathbb{D} be a database and \mathcal{T} a collection of decomposition tree. Any*
 918 *\mathcal{T} -projecting $LP(CQ)$ program $L = (\text{maximize } S \text{ subject to } C) \in LP_{\Sigma}$ satisfies that:*

- 919 1. *For any solution $\dot{\omega}$ of $\langle L \rangle^{\mathbb{D}}$ there is a solution \dot{W} of $\rho^{\mathcal{T}, \mathbb{D}}(L)$ s.t. $\llbracket \langle S \rangle^{\mathbb{D}, \emptyset} \rrbracket_{\dot{\omega}} = \llbracket \rho^{\mathcal{T}, \mathbb{D}}(S) \rrbracket_{\dot{W}}$.*
- 920 2. *For any solution \dot{W} of $\rho^{\mathcal{T}, \mathbb{D}}(L)$ there is a solution $\dot{\omega}$ of $\langle L \rangle^{\mathbb{D}}$ s.t. $\llbracket \langle S \rangle^{\mathbb{D}, \emptyset} \rrbracket_{\dot{\omega}} = \llbracket \rho^{\mathcal{T}, \mathbb{D}}(S) \rrbracket_{\dot{W}}$.*

921 **Proof.** Let $\mathcal{Q} = \text{cqs}(L)$.

922 **Case 1** Consider a solution $\dot{\omega}$ of $\langle L \rangle^{\mathbb{D}}$.

923 Let \dot{W} be a weighting of $\Theta_{\mathcal{Q}}$ such that $\dot{W} = \Pi(\dot{\omega})$. By hypothesis $\llbracket \langle C \rangle^{\mathbb{D}, \emptyset} \rrbracket_{\dot{\omega}} = 1$ so
 924 $\llbracket \rho^{\mathcal{T}, \mathbb{D}}(C) \rrbracket_{\dot{W}} = 1$ by Lemma 15. Thus \dot{W} is a solution of $\rho^{\mathcal{T}, \mathbb{D}}(L)$. Moreover $\llbracket \langle S \rangle^{\mathbb{D}, \emptyset} \rrbracket_{\dot{\omega}} =$
 925 $\llbracket \rho^{\mathcal{T}, \mathbb{D}}(S) \rrbracket_{\dot{W}}$ by Lemma 14.

926 **Case 2** Fixed solution \dot{W} of $\rho^{\mathcal{T}, \mathbb{D}}(L)$

927 By Lemma 16 there is a weighting $\dot{\omega}$ of $\Theta_{\mathcal{Q}}$ such that $\dot{W} = \Pi(\dot{\omega})$ By hypothesis
 928 $\llbracket \rho^{\mathcal{T}, \mathbb{D}}(C) \rrbracket_{\dot{W}} = 1$ so $\llbracket \langle C \rangle^{\mathbb{D}, \emptyset} \rrbracket_{\dot{\omega}} = 1$ by Lemma 15. Thus \dot{W} is a solution of $\rho^{\mathcal{T}, \mathbb{D}}(L)$.
 929 Moreover $\llbracket \langle S \rangle^{\mathbb{D}, \emptyset} \rrbracket_{\dot{\omega}} = \llbracket \rho^{\mathcal{T}, \mathbb{D}}(S) \rrbracket_{\dot{W}}$ by Lemma 14. ◀

931 ▶ **Theorem 18 (Removing Existential Quantifiers).** *For any projecting $LP(CQ)$ program, the*
 932 *$LP(CQ_{\text{qf}})_{\text{proj}}$ program $mvq(L)$ has the same optimal value as L .*

933 **Proof.** It is clear that every Q appearing in a subexpression $\text{weight}_{\mathbf{x}, \mathbf{z}, Q}(Q)$ of $mvq(L)$ is
 934 quantifier free by definition. Now, since L is in $LP(CQ)_{\text{proj}}$, Q' is of the form $\mathbf{x}' = \mathbf{y}$ where
 935 \mathbf{x}' only contains free variables of $\exists \mathbf{z}.Q$. Since $\text{fv}(\exists \mathbf{z}.Q) \subseteq \text{fv}(Q)$, we have that \mathbf{x}' only contains
 936 free variables of Q . Moreover, the other condition of $LP(CQ)_{\text{proj}}$ concerning the sum and
 937 universal quantification are still respected in $mvq(L)$, thus L is in $LP(CQ_{\text{qf}})_{\text{proj}}$.

938 Now, let $\dot{\omega} : \Theta_L^{\mathbb{D}} \rightarrow \mathbb{R}_+$ be a solution of L . We define $\dot{\omega}' : \Theta_{mvq(L)}^{\mathbb{D}} \rightarrow \mathbb{R}_+$ as follows:
 939 $\dot{\omega}'(\theta_Q^\alpha) = \frac{1}{N} \dot{\omega}(\theta_{\exists \mathbf{z}.Q}^{\alpha|U})$ where $U = \text{fv}(\exists \mathbf{z}.Q)$ and $N = \#\{\beta : \mathbf{z} \rightarrow \text{dom} \mid \alpha \cup \beta \in \text{sol}^{\mathbb{D}}(Q)\}$. It
 940 is readily verified that the value $\llbracket \text{weight}_{\mathbf{x}, Q'}(\exists \mathbf{z}.Q) \rrbracket_{\dot{\omega}}$ is the same as $\llbracket \text{weight}_{\mathbf{x}, \mathbf{z}, Q'}(Q) \rrbracket_{\dot{\omega}'}$
 941 and thus that $\dot{\omega}'$ is a solution of $mvq(L)$ and $\llbracket L \rrbracket_{\dot{\omega}} = \llbracket mvq(L) \rrbracket_{\dot{\omega}'}$.

942 For the other way around, given $\dot{\omega}' : \Theta_{mvq(L)}^{\mathbb{D}} \rightarrow \mathbb{R}_+$ a solution of $mvq(L)$, we construct
 943 $\dot{\omega} : \Theta_L^{\mathbb{D}} \rightarrow \mathbb{R}_+$ as $\dot{\omega}(\theta_{\exists \mathbf{z}.Q}^\alpha) = \sum_{\beta \mid \alpha \cup \beta \in \text{sol}^{\mathbb{D}}(Q)} \dot{\omega}'(\theta_Q^{\alpha \cup \beta})$. Again, it is readily verified that the
 944 value $\llbracket \text{weight}_{\mathbf{x}, Q'}(\exists \mathbf{z}.Q) \rrbracket_{\dot{\omega}}$ is the same as $\llbracket \text{weight}_{\mathbf{x}, \mathbf{z}, Q'}(Q) \rrbracket_{\dot{\omega}'}$ and thus that $\dot{\omega}$ is a solution
 945 of L and $\llbracket L \rrbracket_{\dot{\omega}} = \llbracket mvq(L) \rrbracket_{\dot{\omega}'}$. ◀