

Joining Implications in Formal Contexts and Inductive Learning in a Horn Description Logic

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Abstract. A joining implication is a restricted form of an implication where it is explicitly specified which attributes may occur in the premise and in the conclusion, respectively. A technique for sound and complete axiomatization of joining implications valid in a given formal context is provided. In particular, a canonical base for the joining implications valid in a given formal context is proposed, which enjoys the property of being of minimal cardinality among all such bases. Background knowledge in form of a set of valid joining implications can be incorporated. Furthermore, an application to inductive learning in a Horn description logic is proposed, that is, a procedure for sound and complete axiomatization of Horn- \mathcal{M} concept inclusions from a given interpretation is developed. A complexity analysis shows that this procedure runs in deterministic exponential time.

Keywords: Inductive learning · Data mining · Axiomatization · Formal concept analysis · Joining implication · Horn description logic · Concept inclusion

1 Introduction

Formal Concept Analysis (abbrv. FCA) [10] is subfield of lattice theory that allows to analyze data-sets that can be represented as formal contexts. Put simply, such a formal context binds a set of objects to a set of attributes by specifying which objects have which attributes. There are two major techniques that can be applied in various ways for purposes of data mining, machine learning, knowledge management, knowledge visualization, etc. On the one hand, it is possible to describe the hierarchical structure of such a data-set in form of a formal concept lattice [10]. On the other hand, the theory of implications (dependencies between attributes) valid in a given formal context can be axiomatized in a sound and complete manner by the so-called canonical base [11], which furthermore contains a minimal number of implications w.r.t. the properties of soundness and completeness. So far, some variations of the canonical base have been developed, e.g., incorporation of valid background knowledge [29], constraining premises and conclusions in implications by some closure operator [3], and incorporation of arbitrary background knowledge [22], among others. The canonical base in its default form as well as its variations can be computed by the algorithm *NextClosures* [17,22] in a highly parallel way such the necessary computation time is almost inverse linear proportional to the number of available CPU cores.

Description Logic (abbrv. DL) [2] belongs to the field of knowledge representation and reasoning. DL researchers have developed a large family of logic-based languages, so-called *description logics* (abbrv. DLs). These logics allow their users to explicitly represent

knowledge as *ontologies*, which are finite sets of (human- and machine-readable) axioms, and provide them with automated inference services to derive implicit knowledge. The landscape of decidability and computational complexity of common reasoning tasks for various description logics has been explored in large parts: there is always a trade-off between expressibility and reasoning costs. It is therefore not surprising that DLs are nowadays applied in a large variety of domains [2]: agriculture, astronomy, biology, defense, education, energy management, geography, geoscience, medicine, oceanography, and oil and gas. Furthermore, the most notable success of DLs is that these constitute the logical underpinning of the *Web Ontology Language* (abbrv. OWL) [13] in the *Semantic Web*.

Within this document, we propose the new notion of so-called *joining implications* in FCA. More specifically, we assume that there are two distinct sets of attributes: the first one containing the attributes that may occur in premises of implications, while conclusions must only contain attributes from the second set. A canonical base for the joining implications valid in a given formal context is developed and it is proven that it has minimal cardinality among all such bases. Then, an application to inductive learning in a *Horn description logic* [24] is provided. Roughly speaking, such a Horn DL is obtained from some DL by disallowing any disjunctions. Reasoning procedures can then work deterministically, i.e., *reasoning by case* is not required [14]. Hornness is not a new notion: Horn clauses in first-order logic are disjunctions of an arbitrary number of negated atomic formulae and at most one non-negated atomic formula. It is easy to see that such Horn clauses have an implicative character, since $\neg\phi_1 \vee \dots \vee \neg\phi_n \vee \psi$ is equivalent to $\phi_1 \wedge \dots \wedge \phi_n \rightarrow \psi$. A *logic program* is a set of Horn clauses, and a *Datalog program* is a function-free logic program [7]. All commonly known Horn description logics can be translated into Datalog—more specifically, each *Horn-DL* TBox \mathcal{T} can be translated into some Datalog program \mathcal{D} such that, for each simple ABox \mathcal{A} , the ontology $\mathcal{T} \cup \mathcal{A}$ is satisfiable if, and only if, the Datalog program $\mathcal{D} \cup \mathcal{A}$ is satisfiable. For deeper insights please consider [12,15,24]. The most important advantage of Horn fragments is that these often have a significantly lower computational complexity. Using the canonical base of joining implications, we show how the *Horn-M* concept inclusions valid in a given interpretation can be axiomatized. This continues a line of research that combines FCA and DL for the sake of inductive learning, cf. [4,5,9,18,19,21,27] just to name a few.

Due to space constraints some technical lemmas and some proofs have been moved to a technical report [20].

2 Joining Implications in Formal Contexts

Throughout this section, assume that $\mathbb{K} := (G, M, I)$ is some *formal context*, that is, G is a set of *objects*, M is a set of *attributes*, and $I \subseteq G \times M$ is an *incidence relation*. If $(g, m) \in I$, then we say that g *has* m . It is well-known that the two mappings $\cdot^I: \wp(G) \rightarrow \wp(M)$ and $\cdot^I: \wp(M) \rightarrow \wp(G)$ defined below constitute a *Galois connection*, cf. [10].

$$\begin{aligned} A^I &:= \{ m \in M \mid (g, m) \in I \text{ for each } g \in A \} \quad \text{for any } A \subseteq G \\ B^I &:= \{ g \in G \mid (g, m) \in I \text{ for each } m \in B \} \quad \text{for any } B \subseteq M \end{aligned}$$

In particular, this means that the following statements hold true for any sets $A, C \subseteq G$ and $B, D \subseteq M$.

1. $A \subseteq B^I$ if, and only if, $B \subseteq A^I$ if, and only if, $A \times B \subseteq I$
2. $A \subseteq A^{II}$
3. $A^I = A^{III}$
4. $A \subseteq C$ implies $C^I \subseteq A^I$
5. $B \subseteq B^{II}$
6. $B^I = B^{III}$
7. $B \subseteq D$ implies $D^I \subseteq B^I$

An *implication* over M is a term $X \rightarrow Y$ where $X, Y \subseteq M$. It is valid in \mathbb{K} if $X^I \subseteq Y^I$ is satisfied, i.e., if each object that has all attributes in X also has all attributes in Y , and we shall then write $\mathbb{K} \models X \rightarrow Y$. A *model* of $X \rightarrow Y$ is a set $U \subseteq M$ such that $X \subseteq U$ implies $Y \subseteq U$, denoted as $U \models X \rightarrow Y$. An implication set \mathcal{L} *entails* an implication $X \rightarrow Y$ if any model of \mathcal{L} , i.e., any set that is a model of all implications in \mathcal{L} , is also a model of $X \rightarrow Y$, and we denote this by $\mathcal{L} \models X \rightarrow Y$.

We are now interested in a restricted form of implications. In particular, we restrict the sets of attributes that may occur in the *premise* X and in the *conclusion* Y , respectively, of every implication $X \rightarrow Y$. Thus, let further M_p be a set of *premise attributes* and let M_c be a set of *conclusion attributes* such that $M_p \cup M_c \subseteq M$ holds true. For each $x \in \{p, c\}$, we define the subcontext $\mathbb{K}_x := (G, M_x, I_x)$ where $I_x := I \cap (G \times M_x)$. Furthermore, we may also write X^x instead of X^{I_x} for subsets $X \subseteq G$ or $X \subseteq M_x$. Please note that then each pair (\cdot^x, \cdot^x) is a Galois connection between $(\wp(G), \subseteq)$ and $(\wp(M_x), \subseteq)$, that is, similar statements like above are valid.

Definition 1. A joining implication from M_p to M_c , or simply *pc-implication*, is an expression $X \rightarrow Y$ where $X \subseteq M_p$ and $Y \subseteq M_c$. It is valid in \mathbb{K} , written $\mathbb{K} \models X \rightarrow Y$, if $X^p \subseteq Y^c$ holds true.

$\mathbb{K}_{\text{illnesses}}$	Abrupt Onset	Fever	Aches	Chills	Fatigue	Sneezing	Cough	Stuffy Nose	Sore Throat	Headache	Cold	Flu
Bob	•	×	×	•	×	×	×	×	×	×	×	•
Alice	•	•	•	•	•	×	×	×	×	•	×	•
Tom	•	•	•	•	•	×	•	×	×	•	×	•
Julia	×	×	×	×	×	•	×	×	•	×	•	×
Keith	×	×	×	•	×	×	•	•	×	•	•	×
Wendy	×	×	×	×	×	×	×	•	•	×	•	×

M_p
 M_c

Figure 1. The formal context $\mathbb{K}_{\text{illnesses}}$.

Example. Consider the formal context $\mathbb{K}_{\text{illnesses}}$ in Figure 1. It considers six persons as objects and their symptoms and illnesses as attributes. Furthermore, we regard the symptoms as premise attributes and the illnesses as conclusion attributes. Note that, in general,

it is not required that the sets M_p and M_c form a partition of the attribute set. For other use cases both could overlap, one could be contained in the other, or their union could be a strict subset of the whole attribute set. The concept lattice is displayed in Figure 2.¹

The expression $\{\text{Cold}, \text{Cough}\} \rightarrow \{\text{Chills}\}$ is no pc-implication, since the attribute Cold must not occur in a premise and, likewise, the attribute Chills must not occur in a conclusion. The expression $\{\text{Sneezing}, \text{Cough}, \text{Stuffy Nose}\} \rightarrow \{\text{Cold}\}$ is a well-formed joining implication and it is valid in $\mathbb{K}_{\text{illnesses}}$, since $\{\text{Sneezing}, \text{Cough}, \text{Stuffy Nose}\}^p = \{\text{Bob}, \text{Alice}\}$ is a subset of $\{\text{Cold}\}^c = \{\text{Bob}, \text{Alice}, \text{Tom}\}$. Furthermore, the expression $\{\text{Abrupt Onset}\} \rightarrow \{\text{Cold}\}$ is a well-formed joining implication as well, but it is not valid in $\mathbb{K}_{\text{illnesses}}$, as $\{\text{Abrupt Onset}\}^p = \{\text{Julia}, \text{Keith}, \text{Wendy}\}$ is not a subset of $\{\text{Cold}\}^c = \{\text{Bob}, \text{Alice}, \text{Tom}\}$.

In the following, we shall characterize the set of all joining implications valid in \mathbb{K} . Of course, the pc-implication set

$$\text{Imp}_{\text{pc}}(\mathbb{K}) := \{X \rightarrow X^{\text{pc}} \mid X \subseteq M_p\}$$

contains only valid pc-implications and further entails any valid pc-implication, since $\mathbb{K} \models X \rightarrow Y$ is equivalent to $Y \subseteq X^{\text{pc}}$ and so $\{X \rightarrow X^{\text{pc}}\} \models X \rightarrow Y$.

Remark that a *closure operator* on M is some mapping $\phi: \wp(M) \rightarrow \wp(M)$ with the following properties for all subsets $X, Y \subseteq M$.

1. $X \subseteq \phi(X)$ *(extensive)*
2. $X \subseteq Y$ implies $\phi(X) \subseteq \phi(Y)$ *(monotonic)*
3. $\phi(\phi(X)) = \phi(X)$ *(idempotent)*

It is easy to verify that, for each Galois connection (f, g) , the compositions $f \circ g$ and $g \circ f$ are closure operators. It is well-known that each implication set \mathcal{L} induces a corresponding closure operator $\phi_{\mathcal{L}}$ such that the models of \mathcal{L} are exactly the closures of $\phi_{\mathcal{L}}$, cf. [10,22]: for each $U \subseteq M$, the closure $\phi_{\mathcal{L}}(U)$ is the smallest superset of U such that $X \subseteq \phi_{\mathcal{L}}(U)$ implies $Y \subseteq \phi_{\mathcal{L}}(U)$ for any implication $X \rightarrow Y$ in \mathcal{L} . In particular, we can readily verify the following.

$$\phi_{\mathcal{L}}(U) = U^{\mathcal{L}} := \bigcup \{U^{\mathcal{L},n} \mid n \in \mathbb{N}\}$$

$$\text{where } V^{\mathcal{L},n+1} := (V^{\mathcal{L},1})^{\mathcal{L},n}$$

$$\text{and } V^{\mathcal{L},1} := V \cup \{Y \mid X \rightarrow Y \in \mathcal{L} \text{ and } X \subseteq V\} \text{ for each } V \subseteq M$$

For the above joining implication set, we easily get that $\phi_{\mathbb{K}}^{\text{pc}} := \phi_{\text{Imp}_{\text{pc}}(\mathbb{K})}$ satisfies

$$\phi_{\mathbb{K}}^{\text{pc}}(X) = X \cup (X \cap M_p)^{\text{pc}}$$

for any $X \subseteq M$.

An implication $X \rightarrow Y$ is *valid* in a closure operator ϕ , written $\phi \models X \rightarrow Y$, if $Y \subseteq \phi(X)$ holds true, cf. [17]. Please note that this coincides with the notion of validity in a formal context \mathbb{K} if we consider the closure operator $\phi_{\mathbb{K}}: X \mapsto X^{II}$ and, likewise, entailment by an implication set \mathcal{L} is the same as validity in $\phi_{\mathcal{L}}$. Now consider an implication set \mathcal{L} . We say that \mathcal{L} is *sound* for ϕ if $\phi \models \mathcal{L}$ holds true, that is, if $\phi \models X \rightarrow Y$ is satisfied for each implication $X \rightarrow Y \in \mathcal{L}$. Furthermore, \mathcal{L} is *complete* for ϕ if, for any implication $X \rightarrow Y$, it holds true that $\phi \models X \rightarrow Y$ implies $\mathcal{L} \models X \rightarrow Y$.

¹ We have not introduced the notion of a concept lattice here, since it is not needed for our purposes; the interested reader is rather referred to [10].

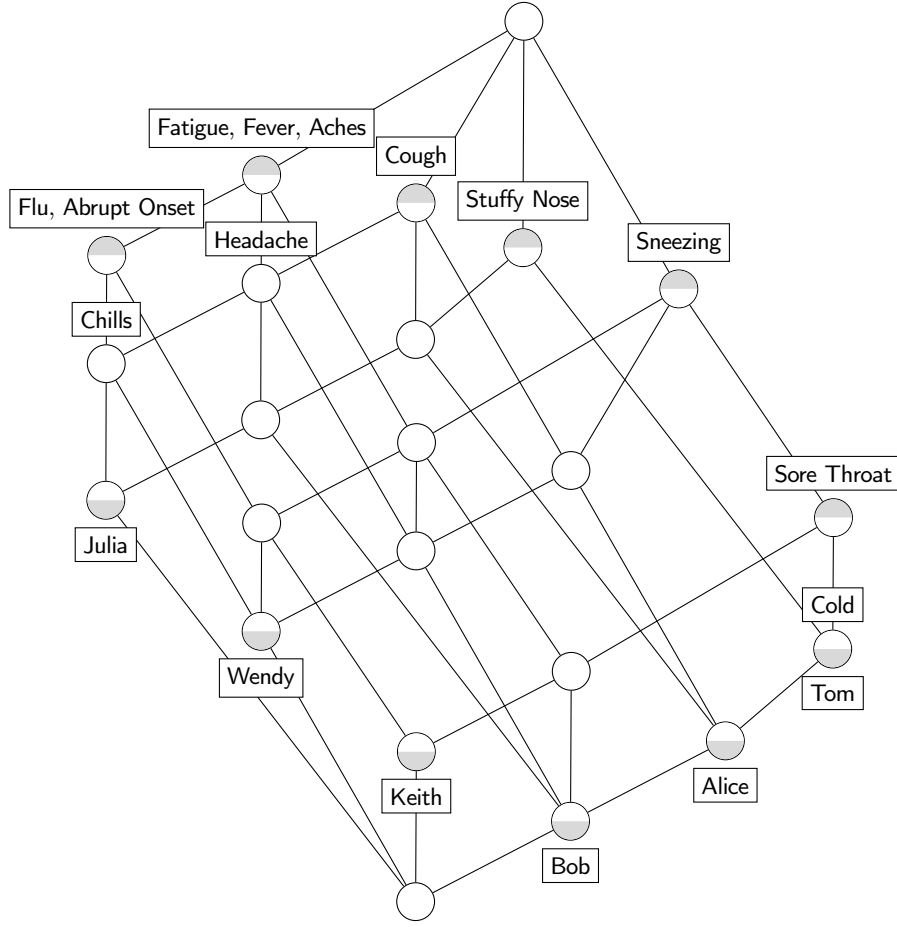


Figure 2. The concept lattice of $\mathbb{K}_{\text{illnesses}}$.

Definition 2. An implication set is join-sound or pc-sound if it is sound for $\phi_{\mathbb{K}}^{\text{pc}}$, and it is join-complete or pc-complete if it is complete for $\phi_{\mathbb{K}}^{\text{pc}}$. Fix some pc-sound implication set \mathcal{S} . A pc-implication set is called joining implication base or pc-implication base relative to \mathcal{S} if it is pc-sound and its union with \mathcal{S} is pc-complete.

Obviously, the above $\text{Imp}_{\text{pc}}(\mathbb{K})$ is a joining implication base relative to \emptyset .

Further fix some implication set \mathcal{S} as well as a closure operator ϕ such that $\phi \models \mathcal{S}$. Now remark that a pseudo-closure of ϕ relative to \mathcal{S} is a set $P \subseteq M$ such that $P \neq \phi(P)$ and $P \models \mathcal{S}$ (i.e., $P = \phi_{\mathcal{S}}(P)$) hold true and $Q \subsetneq P$ implies $\phi(Q) \subseteq P$ for each pseudo-closure Q of ϕ relative to \mathcal{S} . We shall denote the set of all pseudo-closures of ϕ relative to \mathcal{S} as $\text{PsClo}(\phi, \mathcal{S})$. Then, the canonical implication base of ϕ relative to \mathcal{S} is defined as $\text{Can}(\phi, \mathcal{S}) := \{P \rightarrow \phi(P) \mid P \in \text{PsClo}(\phi, \mathcal{S})\}$, and it is sound for ϕ and is further complete for ϕ relative to \mathcal{S} , i.e., $\phi \models X \rightarrow Y$ if, and only if, $\text{Can}(\phi, \mathcal{S}) \cup \mathcal{S} \models X \rightarrow Y$

for each implication $X \rightarrow Y$, cf. [11,17,29]. It is easy to see that we can replace each implication $P \rightarrow \phi(P)$ by $P \rightarrow \phi(P) \setminus P$ to get an equivalent implication set.

Our aim for the sequel of this section is to find a *canonical* representation of the valid joining implications of some formal context, i.e., we shall provide a joining implication base that has *minimal* cardinality among all joining implication bases. For this purpose, we consider the canonical implication base of the above closure operator $\phi_{\mathbb{K}}^{\text{pc}}$ and show how we can modify it to get a *canonical joining implication base*. We start with showing that we can rewrite any join-sound and join-complete implication set into a joining implication base in a certain normal form. For the remainder of this section, fix some arbitrary join-sound joining implication set \mathcal{S} that is used as background knowledge.

Lemma 3. *Fix some join-sound implication set \mathcal{L} over M . Further assume that $\mathcal{L} \cup \mathcal{S}$ is join-complete, and define the following set of joining implications.*

$$\mathcal{L}_{\text{pc}} := \{ X \cap M_{\mathfrak{p}} \rightarrow (X \cap M_{\mathfrak{p}})^{\text{pc}} \mid X \rightarrow Y \in \mathcal{L} \}$$

Then, \mathcal{L}_{pc} is a joining implication base relative to \mathcal{S} .

Proof. Since $\mathcal{L}_{\text{pc}} \subseteq \text{Imp}_{\text{pc}}(\mathbb{K})$ obviously holds true, we know that \mathcal{L}_{pc} is join-sound. For join-completeness we show that $\mathcal{L}_{\text{pc}} \cup \mathcal{S} \models \text{Imp}_{\text{pc}}(\mathbb{K})$. Thus, consider some $Z \subseteq M_{\mathfrak{p}}$. As $\mathcal{L} \cup \mathcal{S}$ is join-complete, it must hold true that $\mathcal{L} \cup \mathcal{S} \models Z \rightarrow Z^{\text{pc}}$, that is, there are implications $X_1 \rightarrow Y_1, \dots, X_n \rightarrow Y_n$ in $\mathcal{L} \cup \mathcal{S}$ such that the following statements are satisfied.

$$\begin{aligned} X_1 &\subseteq Z \\ X_2 &\subseteq Z \cup Y_1 \\ X_3 &\subseteq Z \cup Y_1 \cup Y_2 \\ &\vdots \\ X_n &\subseteq Z \cup Y_1 \cup Y_2 \cup \dots \cup Y_{n-1} \\ Z^{\text{pc}} &\subseteq Z \cup Y_1 \cup Y_2 \cup \dots \cup Y_{n-1} \cup Y_n \end{aligned}$$

Let $L := \{ k \mid k \in \{1, \dots, n\} \text{ and } X_k \rightarrow Y_k \in \mathcal{L} \setminus \mathcal{S} \}$ and $S := \{1, \dots, n\} \setminus L$. Since \mathcal{L} is join-sound, we have $Y_k \subseteq X_k \cup (X_k \cap M_{\mathfrak{p}})^{\text{pc}}$ for each index $k \in L$. Define $X_{n+1} := Z^{\text{pc}}$. An induction on $k \in \{1, \dots, n+1\}$ shows the following.

$$\begin{aligned} X_k &\subseteq Z \cup \bigcup \{ Y_i \mid i \in \{1, \dots, k-1\} \cap S \} \\ &\quad \cup \bigcup \{ (X_i \cap M_{\mathfrak{p}})^{\text{pc}} \mid i \in \{1, \dots, k-1\} \cap L \} \end{aligned}$$

Of course, $X_k \cap M_{\mathfrak{p}} \subseteq X_k$ is satisfied for any index $k \in L$. We conclude that $\{ X_k \rightarrow Y_k \mid k \in S \} \cup \{ X_k \cap M_{\mathfrak{p}} \rightarrow (X_k \cap M_{\mathfrak{p}})^{\text{pc}} \mid k \in L \}$ entails $Z \rightarrow Z^{\text{pc}}$ and we are done. \square

The transformation from Lemma 3 can now immediately be applied to the canonical implication base of the closure operator $\phi_{\mathbb{K}}^{\text{pc}}$ to obtain a joining implication base, which we call *canonical*. This is due to fact that, by definition, $\text{Can}(\phi_{\mathbb{K}}^{\text{pc}})$ is both *pc-sound* and *pc-complete*.

Proposition 4. *The following is a joining implication base relative to \mathcal{S} and is called canonical joining implication base or canonical pc-implication base of \mathbb{K} relative to \mathcal{S} .*

$$\text{Can}_{\text{pc}}(\mathbb{K}, \mathcal{S}) := \{ P \cap M_{\mathfrak{p}} \rightarrow (P \cap M_{\mathfrak{p}})^{\text{pc}} \mid P \in \text{PsClo}(\phi_{\mathbb{K}}^{\text{pc}}, \mathcal{S}) \}$$

Proof. Remark that $\phi_{\mathbb{K}}^{\text{pc}}(P) = P \cup (P \cap M_p)^{\text{pc}}$ holds true and, consequently, the canonical implication base for $\phi_{\mathbb{K}}^{\text{pc}}$ relative to \mathcal{S} evaluates to

$$\text{Can}(\phi_{\mathbb{K}}^{\text{pc}}, \mathcal{S}) = \{ P \rightarrow (P \cap M_p)^{\text{pc}} \mid P \in \text{PsClo}(\phi_{\mathbb{K}}^{\text{pc}}, \mathcal{S}) \}.$$

We already know that $\text{Can}(\phi_{\mathbb{K}}^{\text{pc}}, \mathcal{S})$ is join-sound and its union with \mathcal{S} is join-complete. Since $(\text{Can}(\phi_{\mathbb{K}}^{\text{pc}}, \mathcal{S}))_{\text{pc}} = \text{Can}_{\text{pc}}(\mathbb{K}, \mathcal{S})$ holds true, an application of Lemma 3 shows that $\text{Can}_{\text{pc}}(\mathbb{K}, \mathcal{S})$ is indeed a joining implication base relative to \mathcal{S} . \square

Example. We continue with investigating our exemplary formal context $\mathbb{K}_{\text{illnesses}}$. In order to compute the canonical joining implication base of it (relative to \emptyset), we first need to construct the canonical base of the closure operator $\phi_{\mathbb{K}_{\text{illnesses}}}^{\text{pc}}$.²

$$\text{Can}(\phi_{\mathbb{K}_{\text{illnesses}}}^{\text{pc}}, \emptyset) = \left\{ \begin{array}{l} \{\text{Headache, Sore Throat}\} \rightarrow \{\text{Cold}\} \\ \{\text{Abrupt Onset}\} \rightarrow \{\text{Flu}\} \\ \{\text{Sore Throat, Stuffy Nose}\} \rightarrow \{\text{Cold}\} \\ \{\text{Flu, Sore Throat, Chills}\} \rightarrow \{\text{Cold}\} \\ \{\text{Stuffy Nose, Sneezing}\} \rightarrow \{\text{Cold}\} \\ \{\text{Chills}\} \rightarrow \{\text{Flu}\} \\ \{\text{Sore Throat, Cough}\} \rightarrow \{\text{Cold}\} \end{array} \right\}$$

Now applying the transformation from Lemma 3 yields the following set of joining implications, which is the canonical joining implication base. In particular, only the fourth implication is altered.

$$\text{Can}_{\text{pc}}(\mathbb{K}_{\text{illnesses}}, \emptyset) = \left\{ \begin{array}{l} \{\text{Headache, Sore Throat}\} \rightarrow \{\text{Cold}\} \\ \{\text{Abrupt Onset}\} \rightarrow \{\text{Flu}\} \\ \{\text{Sore Throat, Stuffy Nose}\} \rightarrow \{\text{Cold}\} \\ \{\text{Sore Throat, Chills}\} \rightarrow \{\text{Flu, Cold}\} \\ \{\text{Stuffy Nose, Sneezing}\} \rightarrow \{\text{Cold}\} \\ \{\text{Chills}\} \rightarrow \{\text{Flu}\} \\ \{\text{Sore Throat, Cough}\} \rightarrow \{\text{Cold}\} \end{array} \right\}$$

The canonical base of $\mathbb{K}_{\text{illnesses}}$, which coincides with the canonical base of the induced closure operator $\phi_{\mathbb{K}_{\text{illnesses}}}$, is as follows. Note that it is sound and complete for *all* implications valid in $\mathbb{K}_{\text{illnesses}}$, i.e., no constraints on premises and conclusions are imposed.

$$\text{Can}(\mathbb{K}_{\text{illnesses}}, \emptyset) =$$

² The result has not been obtained by hand, but instead the implementation of the algorithm *NextClosures* [17] in *ConceptExplorer FX* [16] has been utilized. Thus, no intermediate computation steps are provided.

$$\left\{ \begin{array}{l}
\{\text{Fever}\} \rightarrow \{\text{Fatigue, Aches}\} \\
\{\text{Sore Throat}\} \rightarrow \{\text{Sneezing}\} \\
\{\text{Chills}\} \rightarrow \left\{ \begin{array}{l} \text{Headache, Flu, Fatigue, Cough,} \\ \text{Fever, Aches, Abrupt Onset} \end{array} \right\} \\
\{\text{Cold}\} \rightarrow \{\text{Sore Throat, Stuffy Nose, Sneezing}\} \\
\{\text{Headache}\} \rightarrow \{\text{Fatigue, Cough, Fever, Aches}\} \\
\left\{ \begin{array}{l} \text{Headache, Flu, Fatigue, Cough,} \\ \text{Fever, Aches, Abrupt Onset} \end{array} \right\} \rightarrow \{\text{Chills}\} \\
\{\text{Aches}\} \rightarrow \{\text{Fatigue, Fever}\} \\
\{\text{Stuffy Nose, Sneezing}\} \rightarrow \{\text{Sore Throat, Cold}\} \\
\{\text{Fatigue}\} \rightarrow \{\text{Fever, Aches}\} \\
\{\text{Sore Throat, Sneezing, Cough}\} \rightarrow \{\text{Stuffy Nose, Cold}\} \\
\{\text{Fatigue, Stuffy Nose, Fever, Aches}\} \rightarrow \{\text{Headache, Cough}\} \\
\{\text{Fatigue, Cough, Fever, Aches}\} \rightarrow \{\text{Headache}\} \\
\{\text{Abrupt Onset}\} \rightarrow \{\text{Flu, Fatigue, Fever, Aches}\} \\
\{\text{Flu}\} \rightarrow \{\text{Fatigue, Fever, Aches, Abrupt Onset}\}
\end{array} \right\}$$

If we apply the transformation from Lemma 3 to $\text{Can}(\mathbb{K}_{\text{illnesses}}, \emptyset)$, then we obtain the following set of joining implications. Obviously, it is not complete, since it does not entail the valid joining implication $\{\text{Headache, Sore Throat}\} \rightarrow \{\text{Cold}\}$.

$$\left\{ \begin{array}{l}
\{\text{Chills}\} \rightarrow \{\text{Flu}\} \\
\{\text{Stuffy Nose, Sneezing}\} \rightarrow \{\text{Cold}\} \\
\{\text{Sore Throat, Sneezing, Cough}\} \rightarrow \{\text{Cold}\} \\
\{\text{Abrupt Onset}\} \rightarrow \{\text{Flu}\}
\end{array} \right\}$$

We close this section with two further important properties of the canonical joining implication base. On the one hand, we shall show that it has minimal cardinality among all joining implication bases or, more generally, even among all join-sound, join-complete implication bases. On the other hand, we investigate the computational complexity of actually computing the canonical joining implication base.

Proposition 5. *The canonical joining implication base $\text{Can}_{\text{pc}}(\mathbb{K}, \mathcal{S})$ has minimal cardinality among all implication sets that are join-sound and have a union with \mathcal{S} that is join-complete.*

Proof. Consider some implication set \mathcal{L} such that $\mathcal{L} \cup \mathcal{S}$ is join-sound and join-complete. According to Lemma 3, we can assume that—without loss of generality— $\mathcal{L} \subseteq \text{Imp}_{\text{pc}}(\mathbb{K})$ holds true. In particular, note that $|\mathcal{L}_{\text{pc}}| \leq |\mathcal{L}|$ is always true.

Join-soundness and join-completeness of $\mathcal{L} \cup \mathcal{S}$ yield that $\mathcal{L} \cup \mathcal{S}$ and $\text{Can}(\phi_{\mathbb{K}}^{\text{pc}}, \mathcal{S}) \cup \mathcal{S}$ are equivalent. It is well-known [11,29] that $\text{Can}(\phi_{\mathbb{K}}^{\text{pc}}, \mathcal{S})$ has minimal cardinality among all implication bases for $\phi_{\mathbb{K}}^{\text{pc}}$ relative to \mathcal{S} , and so it follows that $|\mathcal{L}| \geq |\text{Can}(\phi_{\mathbb{K}}^{\text{pc}}, \mathcal{S})|$.

Clearly, the choice $\mathcal{L} := \text{Can}_{\text{pc}}(\mathbb{K}, \mathcal{S})$ implies $|\text{Can}_{\text{pc}}(\mathbb{K}, \mathcal{S})| \geq |\text{Can}(\phi_{\mathbb{K}}^{\text{pc}}, \mathcal{S})|$. It is further apparent that $|\text{Can}_{\text{pc}}(\mathbb{K}, \mathcal{S})| \leq |\text{Can}(\phi_{\mathbb{K}}^{\text{pc}}, \mathcal{S})|$ holds true and we infer that, in particular, $\text{Can}_{\text{pc}}(\mathbb{K}, \mathcal{S})$ and $\text{Can}(\phi_{\mathbb{K}}^{\text{pc}}, \mathcal{S})$ must contain the same number of implications. \square

The next proposition shows that computing the canonical joining implication base is not more expensive than computing the canonical implication base where no constraints on the premises and conclusions must be satisfied. It uses the fact that canonical implication bases of closure operators can be computed using the algorithm *NextClosures* [17].

Proposition 6. *The canonical joining implication base can be computed in exponential time, and there exist formal contexts for which the canonical joining implication base cannot be encoded in polynomial space.*

Proof. The canonical implication base of the closure operator $\phi_{\mathbb{K}}^{\text{pc}}$ relative to some background implication set \mathcal{S} can be computed in exponential time by means of the algorithm *NextClosures*, cf. [5,17], which is easy to verify. The transformation of $\text{Can}(\phi_{\mathbb{K}}^{\text{pc}}, \mathcal{S})$ into $\text{Can}_{\text{pc}}(\mathbb{K}, \mathcal{S})$ as described in Lemma 3 can be done in polynomial time.

Kuznetsov and Obiedkov have shown in [26, Theorem 4.1] that the number of implications in the canonical implication base $\text{Can}(\mathbb{K})$ of a formal context $\mathbb{K} := (G, M, I)$ can be exponential in $|G| \cdot |M|$. Clearly, if we let $\mathcal{S} := \emptyset$ and set both M_p and M_c to M , then $\text{Can}(\mathbb{K})$ and $\text{Can}_{\text{pc}}(\mathbb{K}, \mathcal{S})$ coincide. \square

We have seen in the running example that the canonical pc-implication base can be used to characterize implications between symptoms and diagnoses/illnesses. A further application is, for instance, formal contexts encoding observations between attributes satisfied *yesterday* and *today*, i.e., we could construct the canonical base of pc-implications and then use it as a forecast stating which combinations of attributes being satisfied *today* would imply which combinations of attributes being satisfied *tomorrow*. In general, we could think of the premise attributes as *observable attributes* and the conclusion attributes as *goal/decision attributes*. By constructing the canonical pc-implication base from some formal context in which the goal/decision attributes have been manually assessed, we would obtain a set of rules with which we could analyze new data sets for which only the observable attributes are specified.

3 The Description Logic Horn- \mathcal{M}

A *Horn description logic* [12,15,24] is some description logic that, basically, does not allow for any usage of disjunction. While Hornness decreases expressiveness, it often also significantly lowers the computational complexity of some common reasoning tasks, e.g., *instance checking* or *query answering*. These are, thus, of importance in practical applications where computation times and costs must not be too high.

In the sequel of this section, we introduce the description logic *Horn- \mathcal{M}* , which is the Horn variant of $\mathcal{M} := \mathcal{ALQ}^{\geq} \mathcal{N}^{\leq}(\text{Self})$ [18]. Restrictions are imposed on concept inclusions only and, generally speaking, premises must always be $\mathcal{EL}^* := \mathcal{EL}^{\perp}(\text{Self})$ concept descriptions while conclusions may be arbitrary $\mathcal{M}^{\leq 1} := \mathcal{ALQ}^{\geq} \mathcal{N}^{\leq 1}(\text{Self})$ concept descriptions, that is, \mathcal{M} concept descriptions except that in unqualified smaller-than restrictions $\exists \leq n. r$ only the case $n = 1$ is allowed. More specifically, a *Horn- \mathcal{M} concept inclusion* is an expression $C \sqsubseteq D$ where the *concept descriptions* C and D are built by means of the following grammar. Beforehand, fix some *signature* Σ , which is a disjoint union of a set Σ_I of *individual names*, a set Σ_C of *concept names*, and a set Σ_R of *role names*. In the below grammar, A can be replaced by an arbitrary concept name from Σ_C and, likewise, r can be replaced by an arbitrary role name from Σ_R .

$$C := \perp \mid \top \mid A \mid C \sqcap C \mid \exists r. C \mid \exists r. \text{Self}$$

$$D := \perp \mid \top \mid A \mid \neg A \mid D \sqcap D \mid \exists \geq n. r. D \mid \exists \leq 1. r \mid \forall r. D \mid \exists r. \text{Self}$$

As usual, we denote by $\mathcal{DL}(\Sigma)$ the set of all \mathcal{DL} concept descriptions over Σ for each description logic \mathcal{DL} . The *role depth* $\text{rd}(E)$ of a concept description E is the maximal number of nestings of restrictions within E .³ We then further denote by $\mathcal{DL}_d(\Sigma)$ the set of all \mathcal{DL} concept descriptions over Σ with a role depth not greater than d . Note that the above syntactic characterization follows easily from the results in [12,15,24]. A finite set of concept inclusions is called *terminological box* (abbrv. TBox).

As it has already been pointed out in [15], the following properties can be expressed in a sufficiently strong Horn DL, e.g., in $\text{Horn-}\mathcal{M}$.

Inclusion of Simple Concepts. $A \sqsubseteq B$ states that each individual being A is also B .
Concept Disjointness. $A \sqcap B \sqsubseteq \perp$ states that there are no individuals that are both A and B .

Domain Restrictions. $\exists r. \top \sqsubseteq A$ states that each individual having an r -successor must be an A .

Range Restrictions. $\top \sqsubseteq \forall r. A$ states that each individual being an r -successor must be an A .

Functionality Restrictions. $\top \sqsubseteq \exists \leq 1. r$ states that each individual has at most one r -successor.

Participation Constraints. $A \sqsubseteq \exists r. B$ states that each individual that is an A has an r -successor that is a B .

A *concept assertion* is an expression $a \sqsubseteq E$ where a is an individual name from Σ_I and E is some concept description, and further a *role assertion* is an expression $(a, b) \sqsubseteq r$ where $a, b \in \Sigma_I$ and r is some role name from Σ_R . A finite set of concept and role assertions is called *assertional box* (abbrv. ABox). The union of a terminological and an assertional box yields an *ontology*. We often call the assertional part of an ontology the *data* and the terminological part of an ontology the *schema*. If a question of the form $\mathcal{O} \models \alpha$? is to be decided, then we also call the axiom α the *query*.

An *interpretation* \mathcal{I} is a pair $(\Delta^{\mathcal{I}}, \cdot^{\mathcal{I}})$ consisting of a non-empty set $\Delta^{\mathcal{I}}$ of *objects*, called *domain*, and an *extension mapping* $\cdot^{\mathcal{I}}$ such that $a^{\mathcal{I}} \in \Delta^{\mathcal{I}}$ for $a \in \Sigma_I$, $A^{\mathcal{I}} \subseteq \Delta^{\mathcal{I}}$ for each $A \in \Sigma_C$, and $r^{\mathcal{I}} \subseteq \Delta^{\mathcal{I}} \times \Delta^{\mathcal{I}}$ for each $r \in \Sigma_R$. The extension mapping is then extended to all concept descriptions in the following recursive manner; the names of these concept descriptions are shown in the right column.

$$\begin{aligned} \perp^{\mathcal{I}} &:= \emptyset && \text{(bottom concept description)} \\ \top^{\mathcal{I}} &:= \Delta^{\mathcal{I}} && \text{(top concept description)} \\ (\neg A)^{\mathcal{I}} &:= \Delta^{\mathcal{I}} \setminus A^{\mathcal{I}} && \text{(negated concept name)} \\ (E \sqcap F)^{\mathcal{I}} &:= E^{\mathcal{I}} \cap F^{\mathcal{I}} && \text{(conjunction)} \\ (\exists r. E)^{\mathcal{I}} &:= \{ \delta \mid (\delta, \epsilon) \in r^{\mathcal{I}} \text{ and } \epsilon \in E^{\mathcal{I}} \text{ for some } \epsilon \} && \text{(existential restriction)} \\ (\exists \geq n. r. E)^{\mathcal{I}} &:= \{ \delta \mid |\{ \epsilon \mid (\delta, \epsilon) \in r^{\mathcal{I}} \text{ and } \epsilon \in E^{\mathcal{I}} \}| \geq n \} && \text{(qualified at-least restr.)} \\ (\exists \leq 1. r)^{\mathcal{I}} &:= \{ \delta \mid |\{ \epsilon \mid (\delta, \epsilon) \in r^{\mathcal{I}} \}| \leq 1 \} && \text{(local functionality restriction)} \end{aligned}$$

³ Formally, the *role depth* is recursively defined as follows: $\text{rd}(\perp) := \text{rd}(\top) := \text{rd}(A) := \text{rd}(\neg A) := 0$, and $\text{rd}(E \sqcap F) := \text{rd}(E) \vee \text{rd}(F)$, and $\text{rd}(\exists r. E) := \text{rd}(\exists \geq n. r. E) := \text{rd}(\forall r. E) := 1 + \text{rd}(E)$, and $\text{rd}(\exists \leq 1. r) := \text{rd}(\exists r. \text{Self}) := 1$.

$$\begin{aligned}
(\exists r. \text{Self})^{\mathcal{I}} &:= \{ \delta \mid (\delta, \delta) \in r^{\mathcal{I}} \} && \text{(existential self-restriction)} \\
(\forall r. E)^{\mathcal{I}} &:= \{ \delta \mid (\delta, \epsilon) \in r^{\mathcal{I}} \text{ implies } \epsilon \in E^{\mathcal{I}} \text{ for each } \epsilon \} && \text{(value restriction)}
\end{aligned}$$

Now a concept inclusion $C \sqsubseteq D$ is *valid* in \mathcal{I} if $C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$ holds true, written $\mathcal{I} \models C \sqsubseteq D$. A concept assertion $a \in E$ is *valid* in \mathcal{I} if $a^{\mathcal{I}} \in E^{\mathcal{I}}$ is satisfied, and we shall denote this as $\mathcal{I} \models a \in E$. Likewise, a role assertion $(a, b) \in r$ is *valid* in \mathcal{I} if $(a^{\mathcal{I}}, b^{\mathcal{I}}) \in r^{\mathcal{I}}$ holds true, and we symbolize this as $\mathcal{I} \models (a, b) \in r$. If \mathcal{O} is an ontology, then \mathcal{I} is a *model* of \mathcal{O} if $\mathcal{I} \models \alpha$ holds true for each axiom $\alpha \in \mathcal{O}$, and we shall denote this as $\mathcal{I} \models \mathcal{O}$. Furthermore, an ontology \mathcal{O}_1 *entails* another ontology \mathcal{O}_2 , written $\mathcal{O}_1 \models \mathcal{O}_2$, if each model of \mathcal{O}_1 is a model of \mathcal{O}_2 too. In case $\mathcal{O} \models \{\alpha\}$ for some single axiom α , we shall omit set parenthesis and simply write $\mathcal{O} \models \alpha$. Note that, if $x * y$ is an axiom and \mathcal{Z} is either an interpretation or an ontology, then we sometimes write $x *_Z y$ instead of $\mathcal{Z} \models x * y$.

There are several standard reasoning tasks as follows.

Knowledge Base Consistency. Given an ontology \mathcal{O} , is there a model of \mathcal{O} ?

Concept Satisfiability. Given a concept description E and an ontology \mathcal{O} , is there a model of \mathcal{O} in which E has a non-empty extension?

Concept Subsumption. Given two concept descriptions C and D and an ontology \mathcal{O} , does \mathcal{O} entail $C \sqsubseteq D$?

Instance Checking. Given an individual a , a concept description E , and an ontology \mathcal{O} , does \mathcal{O} entail $a \in E$?

There are two approaches to determining the computational complexity of the above tasks.

Combined Complexity. This is the default. Necessary time and space for solving the reasoning problem is measured as a function in the size of the whole input. For instance, if $a \in_{\mathcal{O}} E$ is to be decided, then time and space requirements are measured as a function of $\|a \in E\| + \|\mathcal{O}\|$.

Data Complexity. Determining data complexity is more meaningful for practical purposes, as in most cases the size of the stored data easily outgrows the size of the schema and query. In particular, time and space needed for solving the reasoning problem is measured as a function in the size of the ABox only. If, e.g., $a \in_{\mathcal{O}} E$ is to be decided where \mathcal{O} is the union of an ABox \mathcal{A} and some TBox \mathcal{T} , then necessary time and space is only measured as a function of $\|\mathcal{A}\|$.

So far, the computational complexity of reasoning in \mathcal{M} and its sibling Horn- \mathcal{M} has not been determined and, thus, we shall catch up on this here. Since for a large variety of description logics complexity results have been obtained, we can immediately find the following results for $\mathcal{M}^- := \mathcal{ALQ}^{\geq} \mathcal{N}^{\leq}$, the sublogic of \mathcal{M} in which we disallow existential self-restrictions $\exists r. \text{Self}$. Note that we always consider the case of a *general* TBox, i.e., where no restrictions are imposed on the concept inclusions (except those possibly implied by Hornness).

*Concept subsumption in \mathcal{M}^- is **EXP**-complete (combined complexity).* Since \mathcal{M}^- is a sublogic of *SHIQ* and concept subsumption in *SHIQ* is in **EXP** [28,30], it follows that concept subsumption in \mathcal{M}^- is in **EXP** as well. Furthermore, \mathcal{FL}_0 is a sublogic of \mathcal{M}^- in which concept subsumption is **EXP**-hard [1]. We conclude that concept subsumption in \mathcal{M}^- must be **EXP**-hard too.

*Concept subsumption in $\text{Horn-}\mathcal{M}^-$ is **EXP**-complete (combined complexity).* $\text{Horn-}\mathcal{M}^-$ is a sublogic of Horn-SHIQ and for the latter concept subsumption is known to be in **EXP** [24]. Thus, concept subsumption in $\text{Horn-}\mathcal{M}^-$ is also in **EXP**. Since \mathcal{ELF} is a sublogic of $\text{Horn-}\mathcal{M}^-$ in which concept subsumption is **EXP**-hard [1], we infer that the same problem in $\text{Horn-}\mathcal{M}^-$ must be **EXP**-hard too.

*Instance checking in \mathcal{M}^- is **coNP**-complete (data complexity).* Instance checking in SHIQ is in **coNP** (data complexity) [14] and since \mathcal{M}^- is a sublogic of SHIQ , it follows that instance checking in \mathcal{M}^- is also in **coNP** (data complexity). Furthermore, \mathcal{EL}^{kf} is a sublogic of \mathcal{M}^- in which instance checking is **coNP**-hard (data complexity) [23], and this result immediately transfers to \mathcal{M}^- .

*Instance checking in $\text{Horn-}\mathcal{M}^-$ is **P**-complete (data complexity).* As instance checking in Horn-SHIQ is in **P** (data complexity) [14] and $\text{Horn-}\mathcal{M}^-$ is a sublogic of Horn-SHIQ , we conclude that the similar problem in $\text{Horn-}\mathcal{M}^-$ is in **P** (data complexity) as well. Furthermore, \mathcal{EL} is a sublogic of $\text{Horn-}\mathcal{M}^-$ and instance checking in \mathcal{EL} is **P**-hard (data complexity) [6]. Consequently, instance checking in $\text{Horn-}\mathcal{M}^-$ is **P**-hard as well.

We see that terminological reasoning in $\text{Horn-}\mathcal{M}^-$ is not cheaper than in \mathcal{M}^- , but that assertional reasoning with knowledge bases containing both a schema (TBox) and data (ABox) is considerably cheaper in $\text{Horn-}\mathcal{M}^-$ than in \mathcal{M}^- if we only take into account the size of the ABox (data complexity), unless **P** = **NP**. It is obvious that the hardness results transfer from \mathcal{M}^- to \mathcal{M} and accordingly for the Horn variants. Furthermore, since \mathcal{M} and $\text{Horn-}\mathcal{M}$ can each be seen as a sublogic of μALCQ in which concept subsumption is **EXP**-complete [8,25], we can infer that concept subsumption in \mathcal{M} as well as in $\text{Horn-}\mathcal{M}$ is **EXP**-complete (combined complexity) as well. Unfortunately, the author cannot provide sharp upper bounds for the data complexity of instance checking in \mathcal{M} and $\text{Horn-}\mathcal{M}$. If one takes a closer look on the proofs in [15], one could get the impression that it might suffice to include the case $\pi_y(\exists R. \text{Self}, X) := R(X, X)$ for the translation of concept descriptions into first-order logic. While the author conjectures that this extended translation allows for obtaining the same complexity results, it is necessary to check whether all later steps in the proof indeed work as before.

Henceforth, it makes sense to use a $\text{Horn-}\mathcal{M}$ TBox as the schema for *ontology-based data access* (abbrv. OBDA) applications. This motivates the development of a procedure that can learn $\text{Horn-}\mathcal{M}$ concept inclusions from observations in form of an interpretation.

The next section makes use of the notion of a *model-based most specific concept description*, which we shall define now. Fix some description logic \mathcal{DL} , an interpretation \mathcal{I} , a subset $X \subseteq \Delta^{\mathcal{I}}$, as well as some role-depth bound $d \in \mathbb{N}$. The *model-based most specific concept description* (abbrv. MMSC) of X in \mathcal{I} is then some \mathcal{DL} concept description E that satisfies the following conditions.

1. $\text{rd}(E) \leq d$
2. $X \subseteq E^{\mathcal{I}}$
3. $X \subseteq F^{\mathcal{I}}$ implies $E \sqsubseteq_{\emptyset} F$ for each \mathcal{DL} concept description F satisfying $\text{rd}(F) \leq d$.

Since MMSCs are unique up to equivalence, we shall denote these as $X^{\mathcal{I}^{\mathcal{DL}}_d}$. In [18] the author has shown how MMSCs can be computed in the description logic \mathcal{M} . For any sublogic of \mathcal{M} , the computation method can suitably be adapted by simply ignoring unsupported concept constructors.

It is easy to see that this MMSC mapping $\cdot^{\mathcal{I}_d^{\mathcal{D}\mathcal{L}}}: \wp(\Delta^{\mathcal{I}}) \rightarrow \mathcal{D}\mathcal{L}_d(\Sigma)$ is the *adjoint* of the extension mapping $\cdot^{\mathcal{I}}: \mathcal{D}\mathcal{L}_d(\Sigma) \rightarrow \wp(\Delta^{\mathcal{I}})$, that is, the pair of both constitutes a galois connection just like it is the case for the pair of derivation operators \cdot^I induced by a formal context. This implies that the following statements hold true, where X and Y are arbitrary subsets of the domain $\Delta^{\mathcal{I}}$, and E and F are any $\mathcal{D}\mathcal{L}$ concept descriptions with a role depth of at most d .

1. $X \subseteq E^{\mathcal{I}}$ if, and only if, $X^{\mathcal{I}_d^{\mathcal{D}\mathcal{L}}} \sqsubseteq_{\emptyset} E$
2. $X \subseteq X^{\mathcal{I}_d^{\mathcal{D}\mathcal{L}\mathcal{I}}}$
3. $X^{\mathcal{I}_d^{\mathcal{D}\mathcal{L}}} = X^{\mathcal{I}_d^{\mathcal{D}\mathcal{L}}\mathcal{I}\mathcal{I}_d^{\mathcal{D}\mathcal{L}}}$
4. $X \subseteq Y$ implies $X^{\mathcal{I}_d^{\mathcal{D}\mathcal{L}}} \sqsubseteq_{\emptyset} Y^{\mathcal{I}_d^{\mathcal{D}\mathcal{L}}}$
5. $E^{\mathcal{I}\mathcal{I}_d^{\mathcal{D}\mathcal{L}}} \sqsubseteq_{\emptyset} E$
6. $E^{\mathcal{I}} \equiv_{\emptyset} E^{\mathcal{I}\mathcal{I}_d^{\mathcal{D}\mathcal{L}}\mathcal{I}}$
7. $E \sqsubseteq_{\emptyset} F$ implies $E^{\mathcal{I}} \subseteq F^{\mathcal{I}}$

Compared to the FCA setting, we have replaced intent descriptions using sets of attributes by intent descriptions using $\mathcal{D}\mathcal{L}$ concept descriptions.

4 Inductive Learning in Horn- \mathcal{M}

Now fix some finitely representable interpretation \mathcal{I} over a signature Σ , and further let $d \in \mathbb{N}$ be a role-depth bound. Similarly to [5,9,18], we define the *induced formal context* $\mathbb{K}_{\mathcal{I},d} := (\Delta^{\mathcal{I}}, M, I)$ where $M := M_p \cup M_c$, the premise attribute set is defined by

$$M_p := \{\perp\} \cup \Sigma_C \cup \{\exists r. \text{Self} \mid r \in \Sigma_R\} \cup \{\exists r. X^{\mathcal{I}_d^{\mathcal{E}\mathcal{L}^*}} \mid r \in \Sigma_R \text{ and } \emptyset \neq X \subseteq \Delta^{\mathcal{I}}\}$$

while the conclusion attribute set is given as

$$M_c := \{\perp\} \cup \{A, \neg A \mid A \in \Sigma_C\} \cup \{\exists r. \text{Self}, \exists \leq 1. r, \forall r. \perp \mid r \in \Sigma_R\} \\ \cup \left\{ \mathfrak{D} r. X^{\mathcal{I}_d^{\mathcal{M}^{\leq 1}}} \mid \mathfrak{D} \in \{\exists \geq n \mid 1 \leq n \leq |\Delta^{\mathcal{I}}|\} \cup \{\forall\}, \right. \\ \left. r \in \Sigma_R, \text{ and } \emptyset \neq X \subseteq \Delta^{\mathcal{I}} \right\},$$

and $(\delta, C) \in I$ if $\delta \in C^{\mathcal{I}}$. Our interest is to axiomatize the Horn- \mathcal{M} concept inclusions valid in \mathcal{I} . Of course, it holds true that $\prod \mathbf{X} \sqsubseteq \prod \mathbf{Y}$ is a Horn- \mathcal{M} concept inclusion for each subset $\mathbf{X} \subseteq M_p$ and each subset $\mathbf{Y} \subseteq M_c$. As in [5,9,18], such a concept inclusion is valid in \mathcal{I} if, and only if, the joining implication $\mathbf{X} \rightarrow \mathbf{Y}$ is valid in the induced formal context $\mathbb{K}_{\mathcal{I},d}$. As we are only interested in axiomatizing these concept inclusions that are valid in \mathcal{I} and are no tautologies, we define the following joining implication set that we shall use as background knowledge on the FCA side.

$$\mathcal{S} := \{\{C\} \rightarrow \{D\} \mid C \in M_p, D \in M_c, \text{ and } C \sqsubseteq_{\emptyset} D\} \\ \cup \{\{C, \exists r. \text{Self}\} \rightarrow \{D\} \mid C \in M_p, r \in \Sigma_R, D \in M_c, \text{ and } C \sqcap \exists r. \text{Self} \sqsubseteq_{\emptyset} D\}$$

We will see at the end of this section that the model-based most specific concept descriptions $X^{\mathcal{I}_d}$ can have an exponential size w.r.t. $|\Delta^{\mathcal{I}}|$ and d in $\mathcal{M}^{\leq 1}$. Since the problem of deciding subsumption in Horn- \mathcal{M} is **EXP**-complete, we infer that a naïve approach of computing \mathcal{S} needs double exponential time. However, a more sophisticated analysis yields that most concept inclusions cannot be valid. In particular, a concept description from M_p only contains concept names and existential (self-)restrictions and,

thus, these can never be subsumed (w.r.t. \emptyset) by a concept description from M_c containing a negated concept name, a local functionality restriction, a qualified at-least restriction where $n > 1$, or a value restriction. Thus, we conclude from the characterization in [18, Section 8] that \mathcal{S} does not contain any implication $\{C\} \rightarrow \{D\}$ or $\{C, \exists r. \text{Self}\} \rightarrow \{D\}$ except for the trivial cases where $C = \perp$, $C = D$, or $D = \exists r. \text{Self}$ (only for the second form), and it can hence be computed in single exponential time. Even in the case where the tautological TBox \mathcal{S} is not that simple, e.g., for another description logic where subsumption is also **EXP**-complete and model-based most specific concept descriptions can have exponential sizes, we could also dispense with the expensive computation of \mathcal{S} , since the canonical base can then still be computed in single exponential time with the only drawback that it could contain tautologies.

In the remainder of this section, we show how the techniques from Section 2 can be applied to axiomatize Horn- \mathcal{M} concept inclusions valid in \mathcal{I} . Note that the proofs are suitable adaptations of those for the \mathcal{EL}^\perp case [5] or of those for the \mathcal{M} case [18]. We first show that the TBox consisting of the concept inclusions $C \sqsubseteq C^{\mathcal{II}_d^{\mathcal{M}^{\leq 1}}}$ for all \mathcal{EL}^* concept descriptions C with a role depth not exceeding d is sound and complete. As a further step, we prove by means of structural induction that also the TBox containing the concept inclusions $\prod \mathbf{C} \sqsubseteq (\prod \mathbf{C})^{\mathcal{II}_d^{\mathcal{M}^{\leq 1}}}$ where \mathbf{C} is a subset of M_p is sound and complete. Furthermore, when computing the MMSC of a conjunction $\prod \mathbf{C}$ where $\mathbf{C} \subseteq M_p$ we do not have to do this on the DL side, which is expensive, but it suffices to compute the result \mathbf{C}^{pc} on the FCA side by applying the derivation operators \cdot^p and \cdot^c . The conjunction $\prod \mathbf{C}^{\text{pc}}$ is then (equivalent to) the MMSC in the DL $\mathcal{M}^{\leq 1}$. The proofs for the three aforementioned statements can be found in the technical report [20].

The main result for inductive learning of Horn- \mathcal{M} concept inclusions is as follows. It states that (the premises of) each pc-implication base of the induced context $\mathbb{K}_{\mathcal{I},d}$ give rise to a base of Horn- \mathcal{M} concept inclusions for \mathcal{I} .

Proposition 7. *If \mathcal{L} is a joining implication base for $\mathbb{K}_{\mathcal{I},d}$ relative to \mathcal{S} , then the following TBox is sound and complete for the Horn- \mathcal{M} concept inclusions that are valid in \mathcal{I} and have role depths not exceeding d .*

$$\{ \prod \mathbf{C} \sqsubseteq (\prod \mathbf{C})^{\mathcal{II}_d^{\mathcal{M}^{\leq 1}}} \mid \mathbf{C} \rightarrow \mathbf{D} \in \mathcal{L} \}$$

Instantiating the previous proposition with the canonical pc-implication base now yields the following corollary.

Corollary 8. *The following Horn- \mathcal{M} TBox, called canonical Horn- \mathcal{M} concept inclusion base for \mathcal{I} and d , is sound and complete for the Horn- \mathcal{M} concept inclusions that are valid in \mathcal{I} and have role depths at most d .*

$$\text{Can}_{\text{Horn-}\mathcal{M}}(\mathcal{I}, d) := \{ \prod (P \cap M_p) \sqsubseteq \prod (P \cap M_p)^{\text{pc}} \mid P \in \text{PsClo}(\phi_{\mathcal{I},d}^{\text{Horn-}\mathcal{M}}, \mathcal{S}) \}$$

The closure operator $\phi_{\mathcal{I},d}^{\text{Horn-}\mathcal{M}}: \wp(M) \rightarrow \wp(M)$ is defined by $X \mapsto X \cup (X \cap M_p)^{\text{pc}}$.

In the sequel of this section, we investigate the computational complexity of computing the canonical Horn- \mathcal{M} concept inclusion base. As it turns out, the complexity is the same as for computing the canonical pc-implication base—both can be obtained in exponential time. Afterwards, we investigate whether we can show that the canonical Horn- \mathcal{M} concept inclusion base has minimal cardinality.

Proposition 9. *The canonical Horn- \mathcal{M} concept inclusion base for a finitely representable interpretation \mathcal{I} and role depth bound $d \geq 1$ can be computed in exponential time with respect to d and the cardinality of the domain $\Delta^{\mathcal{I}}$, and further there exist finitely representable interpretations \mathcal{I} for which the canonical Horn- \mathcal{M} concept inclusion base cannot be encoded in polynomial space.*

Note that in order to save space for representing the model-based most specific concept descriptions, we could also represent them in the form $X^{\mathcal{I}} \upharpoonright_d$ where $X^{\mathcal{I}}$ is the model-based most specific concept description without any bound on the role depth and $E \upharpoonright_d$ denotes the *unraveling* of some concept description E (formulated in a DL with greatest fixed-point semantics) up to role depth d . In general, these unbounded MMSCs $X^{\mathcal{I}}$ only exist in extensions of the considered DL with greatest fixed-point semantics. The advantage is that then the size of $X^{\mathcal{I}} \upharpoonright_d$ is exponential only in $|\Delta^{\mathcal{I}}|$ but not in d .

The author conjectures that, for each finitely representable interpretation \mathcal{I} , the canonical Horn- \mathcal{M} concept inclusion base $\text{Can}_{\text{Horn-}\mathcal{M}}(\mathcal{I}, d)$ has *minimal cardinality* among all Horn- \mathcal{M} concept inclusion bases for \mathcal{I} and d . However, it is not immediately possible to suitably adapt the minimality proof for the \mathcal{EL} case described in [5,9], since not all notions from \mathcal{EL} are available in more expressive description logics. The crucial point is that we need the validity of the following claim, which resembles [9, Lemma 5.16] or [5, Lemma A.9], respectively, for our case of Horn- \mathcal{M} .

Claim. Fix some Horn- \mathcal{M} TBox $\mathcal{T} \cup \{C \sqsubseteq D\}$ in which all occurring concept descriptions have role depths not exceeding d . Further assume that \mathcal{I} is a finitely representable model of \mathcal{T} such that, for each subconcept $\exists r. X$ of C , the filler X is (equivalent to) some model-based most specific concept description of \mathcal{I} in the description logic \mathcal{EL}^* ; more specifically, we assume that $Y \equiv Y^{TT_{d-1}^{\mathcal{EL}^*}}$ is satisfied for each $\exists r. Y \in \text{Conj}(C)$. If $C \not\sqsubseteq_{\emptyset} D$ and $C \sqsubseteq_{\mathcal{T}} D$, then $C \sqsubseteq_{\emptyset} E$ and $C \not\sqsubseteq_{\emptyset} F$ holds true for some concept inclusion $E \sqsubseteq F$ contained in \mathcal{T} .

However, the author has just developed a computation procedure for so-called most specific consequences, cf. [19,21, Definition 3], in a description logic that is more expressive than \mathcal{EL}^{\perp} . A proof of the above claim can then be obtained as a by-product. This will be subject of a future publication.

5 Conclusion

In Formal Concept Analysis, a restricted form of implications has been introduced: so-called *joining implications*. From the underlying attribute set M two subsets M_p and M_c are declared, and then only those implications are considered in which the premises only contain attributes from M_p and in which the conclusions only contain attributes from M_c . A canonical base for the joining implications valid in some given formal context has been devised, and it has been proven that it has minimal cardinality and can be computed in deterministic exponential time.

The former results have then been applied to the problem of inductive learning in the Horn description logic Horn- \mathcal{M} . More specifically, we have proposed a canonical base for the Horn- \mathcal{M} concept inclusions valid in a given interpretation. While the author conjectures that it has minimal cardinality, it has been demonstrated that it can be computed in deterministic exponential time.

Future research could deliver the proof for the claimed minimality of the canonical Horn- \mathcal{M} concept inclusion base, or could investigate means that allow for the integration of existing knowledge to make incremental learning possible. The author believes that both tasks can be tackled as soon as computation procedures for most specific consequences in Horn- \mathcal{M} are available. This will be subject of future publications.

Eventually, the author wants to point out that incremental learning from a sequence of interpretations [19,21, Section 8.4 for the \mathcal{EL}^\perp case] is probably more practical than *model exploration* or *ABox exploration* [9], since new observations that could show invalidity of concept inclusions are not requested from the expert at a certain time point, but are rather processed upon availability (*“push instead of pull”*). However, completeness of the eventual result for the considered domain of interest is only achieved if *all* typical individuals occur in the sequence at some time point.

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