# Games for Query Inseparability of Description Logic Knowledge Bases 

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#### Abstract

We consider conjunctive query inseparability of description logic knowledge bases with respect to a given signaturea fundamental problem in knowledge base versioning, module extraction, forgetting and knowledge exchange. We give a uniform game-theoretic characterisation of knowledge base conjunctive query inseparability and develop worst-  OWL 2 QL and $O W L 2 E L$. We also determine the data and combined complexity of deciding query inseparability. While query inseparability for all of these logics is P-complete for data complexity, the combined complexity ranges from P- to ExpTime- to 2ExpTime-completeness. We use these results to resolve two major open problems for OWL 2 QL by showing that TBox query inseparability and the membership problem for universal conjunctive query solutions in knowledge exchange are both ExpTime-complete for combined complexity. Finally, we introduce a more flexible notion of inseparability which compares answers to conjunctive queries in a given signature over a given set of individuals. In this case, checking query inseparability becomes NP-complete for data complexity, but the ExpTimeand 2ExpTime-completeness combined complexity results are preserved.


Keywords: Description logic, knowledge base, conjunctive query, query inseparability, games on graphs, computational complexity.

## 1. Introduction

A description logic (DL) knowledge base (KB) consists of a terminological box (TBox) and an assertion box (ABox). The TBox represents conceptual knowledge by providing a vocabulary for a domain of interest together with axioms that describe semantic relationships between the vocabulary items. To illustrate, consider the following toy TBox $\mathcal{T}_{a}$, which defines a vocabulary for the automotive industry:

```
        Minivan \sqsubseteq Automobile,
    Hybrid \sqsubseteq Automobile,
    Automobile \sqsubseteq \existspoweredBy.Engine,
    Hybrid \sqsubseteq \existspoweredBy.ElectricEngine }\sqcap\exists\mathrm{ poweredBy.InternalCombustionEngine,
    ElectricEngine \sqsubseteq Engine,
InternalCombustionEngine \sqsubseteq Engine.
```

The first two axioms say that minivans and hybrids are automobiles, the third one claims that every automobile is powered by an engine, and the fourth axiom states that every hybrid is powered by an electric engine and also by an internal combustion engine. Thus, the TBox introduces, among others, the concept names (sets) Minivan, Automobile and Engine, states that the concept Minivan is subsumed by the concept Automobile and uses the role name (binary

[^0]relation) poweredBy to say that automobiles are powered by engines. TBoxes, often called ontologies, are represented in many applications using the syntax of the Web Ontology Language OWL 2 (www.w3.org/TR/owl2-overview).

The ABox of a knowledge base is a set of facts storing data about the concept and role names introduced in the TBox. As an example ABox in the automotive domain, we will use the following set of assertions:

$$
\begin{aligned}
& \mathcal{A}_{a}=\{\text { Hybrid(toyota_highlander), Minivan(toyota_highlander), } \\
&\text { Minivan(nissan_note), poweredBy(nissan_note, hr15de), InternalCombustionEngine(hr15de) }\} .
\end{aligned}
$$

Typical applications of KBs in modern information systems use the semantics of the concepts and roles in the TBox to enable the user to query the data in the ABox. This is particularly useful if the data is incomplete or comes from heterogeneous data sources, which is the case, for example, in linked data applications [1] and large-scale data integration projects [2, 3], or if the data comprises the web content gathered by search engines using semantic markup [4].

As the data may be incomplete, the open world assumption is adopted when querying a KB $\mathcal{K}$ : a tuple $\boldsymbol{a}$ of individuals from $\mathcal{K}$ is a (certain) answer to a query $\boldsymbol{q}$ over $\mathcal{K}$ if $\boldsymbol{q}(\boldsymbol{a})$ is true in every model of $\mathcal{K}$. Since general firstorder queries are undecidable under the open-world semantics, the basic and most important querying instrument is conjunctive queries (CQs), which are ubiquitous in relational database systems and form the core of the Semantic Web query language SPARQL (www.w3.org/TR/sparql11-query). In our context, a CQ $\boldsymbol{q}(\boldsymbol{x})$ is a first-order formula $\exists \boldsymbol{y} \varphi(\boldsymbol{x}, \boldsymbol{y})$ such that $\varphi(\boldsymbol{x}, \boldsymbol{y})$ is a conjunction of atoms of the form $A\left(z_{1}\right)$ or $P\left(z_{1}, z_{2}\right)$, for a concept name $A$, a role name $P$, and variables $z_{1}, z_{2}$ from $\left.\boldsymbol{x}, \boldsymbol{y}\right]^{1}$ For example, to find minivans powered by electric engines, one can use the CQ

$$
\boldsymbol{q}(x)=\exists y(\operatorname{Minivan}(x) \wedge \operatorname{poweredBy}(x, y) \wedge \text { ElectricEngine }(y)),
$$

with toyota_highlander being the only certain answer to $\boldsymbol{q}(x)$ over $\left(\mathcal{T}_{a}, \mathcal{A}_{a}\right)$.
The problem of answering CQs over KBs has been the focus of significant research in the DL community: deep complexity results have been obtained for a broad range of DLs (see below), new DLs have been introduced with tractable (in data complexity) query answering [5, 6], a variety of query answering techniques have been invented [6, 7] and implemented in a number of powerful software systems (see, e.g., [8] and references therein).

Apart from developing query answering techniques, a major research problem is KB engineering and maintenance. In fact, with typically large data and often complex and tangled ontologies, tool support for transforming and comparing KBs is becoming indispensable for applications. To begin with, KBs are never static entities. Like most software artefacts, they are updated to incorporate new information, and distinct versions are introduced for different applications. Thus, developing support for KB versioning has become an important research problem [9, 10]. As dealing with a large and semantically tangled KB can be costly, one may want to extract from it a smaller module that is indistinguishable from the whole KB as far as the given application is concerned [11]. Another technique for extracting relevant information is forgetting, where the task is to replace a given KB with a new one, which uses only those concept and role names that are needed by the application but still provides the same information about those names as the original KB [12, 13]. Finally, the vocabulary of a given KB may not be convenient for a new application. In this case, similarly to data exchange in databases [14]-where data structured under a source schema is converted to data under a target schema-one may want to transform a KB in a source signature to a KB given in a more useful target signature and representing the original KB in an accurate way. This task is known as knowledge exchange [15, 16].

In this article, we investigate a relationship between KBs that is fundamental for all such tasks if querying the data via CQs is the main application. Let $\Sigma$ be a relational signature consisting of a finite set of concept and role names. We say that $\mathrm{KBs} \mathcal{K}_{1}$ and $\mathcal{K}_{2}$ are $\Sigma$-query inseparable and write $\mathcal{K}_{1} \equiv_{\Sigma} \mathcal{K}_{2}$ if any CQ formulated in $\Sigma$ has the same answers over $\mathcal{K}_{1}$ and $\mathcal{K}_{2}$. Note that even for $\Sigma$ containing all concept and role names in the KBs, $\Sigma$-query inseparability does not necessarily imply logical equivalence: for example, $(\emptyset,\{A(a)\})$ is $\{A, B\}$-query inseparable from $(\{B \sqsubseteq A\},\{A(a)\})$ but the two KBs are clearly not logically equivalent. Thus, if KBs are used for purposes other than querying data via CQs, then different notions of inseparability are required. We now discuss the applications of $\Sigma$-query inseparability for the tasks mentioned above in more detail.

[^1]Versioning. Version control systems for KBs provide a range of operations including, for example, computing the relevant differences between KBs, merging KBs and recovering KBs. All these operations rely on checking whether two versions, $\mathcal{K}_{1}$ and $\mathcal{K}_{2}$, of a KB are indistinguishable from the application point of view. If that application is querying the data via CQs in a given relational signature $\Sigma$, then $\mathcal{K}_{1}$ and $\mathcal{K}_{2}$ should be regarded as indistinguishable just in case they give the same answers to CQs formulated in $\Sigma$. Thus, the basic task for a query-centric approach to KB versioning is to check whether $\mathcal{K}_{1} \equiv_{\Sigma} \mathcal{K}_{2}$.

Modularisation. Modularisation and module extraction are major research topics in ontology engineering and maintenance. In module extraction, the problem is to find a (small) subset of the axioms of a given large KB that is indistinguishable from the KB with respect to the intended application. If that application is querying a $\mathrm{KB} \mathcal{K}$ using CQs in a relational signature $\Sigma$, then the problem is to find a small $\Sigma$-query module of $\mathcal{K}$, that is, a $\mathrm{KB} \mathcal{K}^{\prime} \subseteq \mathcal{K}$ with $\mathcal{K}^{\prime} \equiv_{\Sigma} \mathcal{K}$. Note that one can extract a minimal $\Sigma$-query module from a KB using a polynomial-time algorithm with the $\Sigma$-query inseparability check as an oracle (see, e.g., [17]). To illustrate the notion of $\Sigma$-query module, consider the automotive knowledge base $\mathcal{K}_{a}=\left(\mathcal{T}_{a}, \mathcal{A}_{a}\right)$ defined above and the relational signature $\Sigma_{m}=\{$ Automobile, Engine, poweredBy $\}$. Then $\mathcal{K}_{m}=\left(\mathcal{T}_{m}, \mathcal{A}_{m}\right)$ is a $\Sigma_{m}$-query module of $\mathcal{K}_{a}$, where

$$
\begin{aligned}
\mathcal{T}_{m} & =\{\text { Minivan } \sqsubseteq \text { Automobile, Automobile } \sqsubseteq \text { JpoweredBy.Engine, InternalCombustionEngine } \sqsubseteq \text { Engine }\}, \\
\mathcal{A}_{m} & =\{\text { Minivan(toyota_highlander), } \\
& \quad \text { Minivan(nissan_note), poweredBy(nissan_note, hr15de), InternalCombustionEngine(hrl5de) }\} .
\end{aligned}
$$

Knowledge Exchange. In knowledge exchange, we want to transform a $\mathrm{KB} \mathcal{K}_{1}$ in a relational signature $\Sigma_{1}$ to a KB $\mathcal{K}_{2}$ in a new signature $\Sigma_{2}$ connected to $\Sigma_{1}$ via a declarative mapping specification given by a TBox $\mathcal{T}_{12}$. Such mapping specifications between KBs are also known as ontology alignments or ontology matchings and have been studied extensively [18]. If, as above, we are interested in querying data via CQs, then the target $\mathrm{KB} \mathcal{K}_{2}$ should be a sound and complete representation of $\mathcal{K}_{1}$ with respect to answers to CQs, and so should satisfy the condition $\mathcal{K}_{1} \cup \mathcal{T}_{12} \equiv_{\Sigma_{2}} \mathcal{K}_{2}$, in which case it is called a universal CQ-solution. To illustrate, consider again the knowledge base $\mathcal{K}_{a}=\left(\mathcal{T}_{a}, \mathcal{A}_{a}\right)$ and let $\mathcal{T}_{a e}$ connect the relational signature $\Sigma_{a}$ of $\mathcal{K}_{a}$ to $\Sigma_{e}=\{$ Car, HybridCar, ElectricMotor, Motor, hasMotor $\}$ by means of the following axioms:

$$
\text { Automobile } \sqsubseteq \text { Car, } \quad \text { Hybrid } \sqsubseteq \text { HybridCar }, \quad \text { poweredBy } \sqsubseteq \text { hasMotor, }
$$

Then $\mathcal{K}_{e}=\left(\mathcal{T}_{e}, \mathcal{A}_{e}\right)$ is a universal CQ-solution, where

$$
\begin{aligned}
& \mathcal{T}_{e}=\{\text { ElectricMotor } \sqsubseteq \text { Motor, Car } \sqsubseteq \exists \text { hasMotor.Motor, HybridCar } \sqsubseteq \text { Car } \sqcap \exists \text { hasMotor.ElectricMotor }\}, \\
& \mathcal{A}_{e}=\{\text { HybridCar(toyota_highlander), Car(nissan_note), hasMotor(nissan_note,hr15de), Motor(hr15de) }\} .
\end{aligned}
$$

Forgetting. A $\mathrm{KB} \mathcal{K}^{\prime}$ is said to result from forgetting a relational signature $\Sigma$ in a $\mathrm{KB} \mathcal{K}$ if $\mathcal{K}^{\prime} \equiv \operatorname{sig}(\mathcal{K}) \backslash \Sigma \mathcal{K}$ and $\operatorname{sig}\left(\mathcal{K}^{\prime}\right) \subseteq \operatorname{sig}(\mathcal{K}) \backslash \Sigma$, where $\operatorname{sig}(\mathcal{K})$ is the relational signature of $\mathcal{K}$. Thus, the result of forgetting $\Sigma$ does not use $\Sigma$ and gives the same answers to CQs without symbols in $\Sigma$ as $\mathcal{K}$. The result of forgetting is also called a uniform interpolant for $\mathcal{K}$ with respect to $\operatorname{sig}(\mathcal{K}) \backslash \Sigma$. Forgetting is of interest in a number of scenarios. Typically, when reusing an existing KB in a new application, only a small number of its symbols is relevant, and so instead of reusing the whole KB , one can take a potentially smaller KB resulting from forgetting the extraneous symbols. Forgetting can also be used for predicate hiding: if a KB is to be published, but some part of it has to be concealed from the public, then this part can be removed by forgetting its symbols [19]. Finally, forgetting can be used for KB summary: the result of forgetting often provides a smaller and more focused KB that summarises what the original KB says about the retained symbols, potentially facilitating comprehension. To illustrate, the $\mathrm{KB} \mathcal{K}_{f}=\left(\mathcal{T}_{f}, \mathcal{A}_{f}\right)$ results from forgetting $\Sigma_{f}=\{$ Minivan, Hybrid, ElectricEngine, InternalCombustionEngine $\}$ in $\mathcal{K}_{a}$, where

$$
\begin{aligned}
\mathcal{T}_{f} & =\{\text { Automobile } \sqsubseteq \exists \text { poweredBy.Engine }\}, \\
\mathcal{A}_{f} & =\{\text { Automobile(toyota_highlander) }, \\
& \text { Automobile(nissan_note }), \text { poweredBy(nissan_note,hr15de), Engine(hr15de) }\} .
\end{aligned}
$$



Figure 1: Summary of the combined complexity results.

In this article, we develop worst-case optimal algorithms deciding $\Sigma$-query inseparability of KBs given in various fragments of the description logic Horn- $\mathcal{A} \mathcal{L C H} \mathcal{I}$ [20], which include $D L$-Lite ${ }_{\text {core }}^{\mathcal{H}}$ [6, 21] and $\mathcal{E} \mathcal{L} \mathcal{H}_{\perp}^{d r}$ [22] underlying the OWL 2 profiles OWL 2 QL and OWL 2EL (www.w3.org/TR/owl2-profiles). The algorithms are based on two characterisations of $\Sigma$-query inseparability, one of which is model-theoretic and the other game-theoretic. The former characterises $\Sigma$-query inseparability in terms of partial $\Sigma$-homomorphisms between materialisations, that is, interpretations $\mathcal{M}$ of KBs $\mathcal{K}$ such that the certain answers to any CQ $\boldsymbol{q}$ over $\mathcal{K}$ coincide with the answers to CQ $\boldsymbol{q}$ over $\mathcal{M}$. Any Horn- $\mathcal{A L C H} \mathcal{I}$ KB has a materialisation. While materialisations can be infinite, we show that one can always compute a finite generating structure from which a materialisation is obtained by unravelling. We then develop a game-theoretic machinery for checking the existence of partial $\Sigma$-homomorphisms between materialisations by playing two-player games on the corresponding finite generating structures. Thus, our algorithms consist of two components: computing finite generating structures for the given KBs and deciding the existence of winning strategies for the games on these structures.

We use the constructed algorithms to obtain optimal upper bounds for the data and combined complexity of deciding $\Sigma$-query inseparability for KBs given in all of the DLs mentioned above. $\Sigma$-query inseparability turns out to be P-complete for data complexity, which matches the complexity of CQ evaluation for all of our DLs lying outside the DL-Lite family. For combined complexity, the obtained tight complexity results are summarised in Fig. 1 . Most interesting are ExpTime-completeness of DL-Lite core $\mathcal{\mathcal { H }}$ and 2ExpTime-completeness of Horn- $\mathcal{A} \mathcal{L} C I$, which contrast with NP- and ExpTime-completeness of CQ evaluation for these logics. We note in passing that the 2ExpTime-hardness proof goes through for the fragment $\mathcal{E} \mathcal{L} \mathcal{I}$ of Horn- $\mathcal{A} \mathcal{L C I}$. For $D L$-Lite without role inclusions, $\mathcal{E} \mathcal{L}$ and $\mathcal{E} \mathcal{L} \mathcal{H}_{\perp}^{d r}, \Sigma$ query inseparability is P -complete, while CQ evaluation is NP-complete. In general, it is the combined presence of inverse roles and qualified existential restrictions (or role inclusions) that makes $\Sigma$-query inseparability hard. The matching lower bounds are established by a (rather involved) encoding of suitable alternating Turing machines.

We apply our complexity results for $\Sigma$-query inseparability to resolve two important open problems. First, we show that, in knowledge exchange, the membership problem for universal CQ-solutions for DL-Lite core KBs is ExpTime-complete for combined complexity, which settles an open question of [23], where only PSpace-hardness was established. Second, we show that deciding $\Sigma$-query inseparability of DL-Litecore ${ }_{\text {core }}^{\mathcal{H}}$ TBoxes (for arbitrary ABoxes) is ExpTime-complete, which closes the PSpace-ExpTime gap that was left open by Konev et al. [24].

In the definition of $\Sigma$-query inseparability above, we took account of all tuples of individuals in the KBs that could be certain answers to CQs. In some applications, however, we may be interested only in a specific set of individuals over which the certain answers should be compared. Let $\Gamma$ be an individual signature consisting of a finite set of individual names. For $\mathrm{KBs} \mathcal{K}_{1}, \mathcal{K}_{2}$ and a relational signature $\Sigma$, we say that $\mathcal{K}_{1}$ and $\mathcal{K}_{2}$ are $(\Sigma, \Gamma)$-query inseparable if any CQ formulated in $\Sigma$ has the same certain answers among the individuals in $\Gamma$ over both $\mathcal{K}_{1}$ and $\mathcal{K}_{2}$, in which case we write $\mathcal{K}_{1} \equiv_{\Sigma, \Gamma} \mathcal{K}_{2}$. Clearly, if $\Gamma$ contains all individuals in $\mathcal{K}_{1} \cup \mathcal{K}_{2}$, then $(\Sigma, \Gamma)$-query inseparability implies $\Sigma$-query inseparability. ( $\Sigma, \Gamma$ )-query inseparability can be used to refine $\Sigma$-query inseparability as a foundation for versioning, modularisation, forgetting and knowledge exchange.

For instance, a $\mathrm{KB} \mathcal{K}^{\prime}$ is a $(\Sigma, \Gamma)$-query module of a $\mathrm{KB} \mathcal{K}$ if $\mathcal{K}^{\prime} \subseteq \mathcal{K}$ and $\mathcal{K}^{\prime} \equiv_{\Sigma, \Gamma} \mathcal{K}$. Consider again the automo-
tive ontology $\mathcal{K}_{a}=\left(\mathcal{T}_{a}, \mathcal{A}_{a}\right)$ and the relational signature $\Sigma_{m}=\{$ Automobile, Engine, poweredBy $\}$. Unlike our example illustrating $\Sigma$-query modules, we now restrict the individual signature to $\Gamma_{m}=\{$ toyota_highlander, nissan_note $\}$ thereby leaving out $h r 15 d e$ from the set of individuals considered. Then the $\mathrm{KB} \mathcal{K}_{m}^{\prime}=\left(\mathcal{T}_{m}^{\prime}, \mathcal{A}_{m}^{\prime}\right)$ is a $\left(\Sigma_{m}, \Gamma_{m}\right)$-query module of $\mathcal{K}_{a}$, where

$$
\begin{aligned}
& \mathcal{T}_{m}^{\prime}=\{\text { Minivan } \sqsubseteq \text { Automobile, Automobile } \sqsubseteq \exists \text { poweredBy.Engine }\}, \\
& \mathcal{A}_{m}^{\prime}=\{\text { Minivan(toyota_highlander), Minivan(nissan_note) }\} .
\end{aligned}
$$

Thus, the restriction of the individual signature removes the two assertions with hr15de from $\mathcal{A}_{m}$ as well as an axiom from $\mathcal{T}_{m}$.

Similarly, a KB $\mathcal{K}^{\prime}$ results from forgetting $(\Sigma, \Gamma)$ in a $\mathrm{KB} \mathcal{K}$ if $\mathcal{K}^{\prime} \equiv_{\operatorname{sig}(\mathcal{K}) \backslash \Sigma, \operatorname{ind}(\mathcal{K}) \backslash \Gamma} \mathcal{K}, \operatorname{sig}\left(\mathcal{K}^{\prime}\right) \subseteq \operatorname{sig}(\mathcal{K}) \backslash \Sigma$ and $\operatorname{ind}\left(\mathcal{K}^{\prime}\right) \subseteq \operatorname{ind}(\mathcal{K}) \backslash \Gamma$, where $\operatorname{ind}(\mathcal{K})$ is the set of individuals in the ABox of $\mathcal{K}$. In this case, for $\Gamma_{f}=\{h r 15 d e\}$, the $\mathrm{KB} \mathcal{K}_{f}^{\prime}=\left(\mathcal{T}_{f}^{\prime}, \mathcal{H}_{f}^{\prime}\right)$ results from forgetting $\left(\Sigma_{f}, \Gamma_{f}\right)$ in $\mathcal{K}_{a}$, where

$$
\begin{aligned}
& \mathcal{T}_{f}^{\prime}=\{\text { Automobile } \sqsubseteq \exists \text { poweredBy.Engine }\}, \\
& \mathcal{A}_{f}^{\prime}=\{\text { Automobile(toyota_highlander), Automobile(nissan_note) }\} .
\end{aligned}
$$

In knowledge exchange, the refined notion of query inseparability can be used to represent a more flexible knowledge exchange model, which allows additional individuals in the target KB. These 'anonymous' individuals are similar to nulls in the standard approaches to incomplete databases [25]. Thus, we say that a $\mathrm{KB} \mathcal{K}_{2}$ with a relational signature $\Sigma_{2}$ is a universal CQ-solution with nulls for a $\mathrm{KB} \mathcal{K}_{1}$ and a mapping specification $\mathcal{T}_{12}$ if $\mathcal{K}_{1} \cup \mathcal{T}_{12} \equiv_{\Sigma_{2} \text {, ind }\left(\mathcal{K}_{1}\right)} \mathcal{K}_{2}$ (here, the individuals in ind $\left(\mathcal{K}_{2}\right) \backslash \operatorname{ind}\left(\mathcal{K}_{1}\right)$ play the role of nulls). To illustrate, we consider again the knowledge exchange example given above with the same $\Sigma_{e}$ and $\mathcal{T}_{a e}$. Observe first that $\mathcal{K}_{e}$ is also a universal CQ-solution with nulls. On the other hand, there are universal CQ-solutions with nulls that are not universal CQ-solutions. To illustrate, let $m_{1}$ be a fresh individual name. Then $\mathcal{K}_{e}^{\prime}=\left(\emptyset, \mathcal{A}_{e}^{\prime}\right)$ is a universal CQ-solution with nulls for $\mathcal{K}_{a}$ and $\mathcal{T}_{a e}$, where

$$
\begin{aligned}
& \mathcal{A}_{e}^{\prime}=\{\text { HybridCar }(\text { toyota_highlander }), \text { Car }(\text { toyota_highlander }), \\
& \text { hasMotor }\left(\text { toyota_highlander, } m_{1}\right), \text { ElectricMotor }\left(m_{1}\right), \operatorname{Motor}\left(m_{1}\right), \\
& \text { Car(nissan_note }), \text { hasMotor }(\text { nissan_note, } \text {,hr15de }), \text { Motor }(\text { hr15de })\} .
\end{aligned}
$$

Intuitively, $\mathcal{A}_{e}^{\prime}$ is a materialisation of all consequences of $\mathcal{K}_{a} \cup \mathcal{T}_{a e}$ in the relational signature $\Sigma_{e}$ and, among individuals of $\mathcal{K}_{a}$, it clearly gives rise to the same answers to all CQs formulated in $\Sigma_{e}$ (the additional individual, $m_{1}$, is not counted when comparing the CQ answers). The interested reader is referred to [23] for more explanations on the advantages of this notion.

We extend our algorithms deciding $\Sigma$-inseparability to algorithms deciding ( $\Sigma, \Gamma$ )-inseparability and investigate
 In contrast to $\Sigma$-query inseparability, which is P-complete for data complexity for all of those fragments, deciding ( $\Sigma, \Gamma$ )-query inseparability turns out to be NP-complete for data complexity. (In fact, it is NP-hard already for KBs without TBoxes since ( $\Sigma, \Gamma$ )-query inseparability is then equivalent to the problem of deciding the existence of a homomorphism from one relational structure to another, which is known to be NP-hard.) For combined complexity, $(\Sigma, \Gamma)$-query inseparability is exactly as hard as $\Sigma$-query inseparability whenever it is already NP-hard.

The remainder of the article is structured as follows. In Section 2, we introduce the syntax and semantics of the DLs considered in this article. In Section 3, we provide a model-theoretic characterisation of conjunctive query inseparability based on materialisations and introduce finite generating structures from which materialisations are obtained by unravelling. We also analyse our algorithms computing generating structures and their relevant properties, depending on the DLs considered. In Section 4, we develop games on generating structures and the corresponding algorithms for deciding inseparability, using which we obtain complexity upper bounds. Section 5 is devoted to proving matching lower complexity bounds. In Section 6, we refine $\Sigma$-inseparability by considering restricted sets of individuals in KBs and, in Section 7 . we discuss related work and how our results can be (or have been) applied to solve open problems in knowledge exchange, TBox inseparability and for the comparison of OBDA (ontology-based data access) specifications. We conclude with a discussion of future work in Section 8 .

## 2. Horn- $\mathcal{A} \mathcal{L C H I}$ and its Fragments

In this article, we investigate $\Sigma$ - and $(\Sigma, \Gamma)$-query inseparability of KBs given in DLs that are Horn fragment $\$^{2}$ of $\mathcal{A L C H I}$. To define these DLs, we fix sequences of individual names $a_{i}$, concept names $A_{i}$, and role names $P_{i}$, for $i<\omega$. A role is either a role name $P_{i}$ or an inverse role $P_{i}^{-}$; we assume that $\left(P_{i}^{-}\right)^{-}=P_{i} . \mathcal{A} \mathcal{L} C I$-concepts are defined by the grammar

$$
C::=A_{i}|\top| \perp|\neg C| C_{1} \sqcap C_{2}\left|C_{1} \sqcup C_{2}\right| \exists R . C \mid \forall R . C,
$$

( $\mathcal{A L C I})$
where $R$ is a role. $\mathcal{A} \mathcal{L} C$-concepts are those $\mathcal{A} \mathcal{L C I}$-concepts that do not contain inverse roles. $\mathcal{A} \mathcal{L C I}$-TBoxes and $\mathcal{A} \mathcal{L C}$-TBoxes are finite sets of concept inclusions of the form

$$
C_{1} \sqsubseteq C_{2},
$$

where the $C_{i}$ are $\mathcal{A} \mathcal{L C I}$ - or, respectively, $\mathcal{A} \mathcal{L C}$-concepts. $\mathcal{A L C H} I$-TBoxes are finite sets of concept inclusions in $\mathcal{A} \mathcal{L C I}$ and role inclusions of the form

$$
R_{1} \sqsubseteq R_{2},
$$

where the $R_{i}$ are roles. $\mathcal{A L C \mathcal { H }}$-TBoxes are $\mathcal{A} \mathcal{L C H} \mathcal{H}$-TBoxes that do not contain occurrences of inverse roles.
The DLs in the $\mathcal{E} \mathcal{L}$ and DL-Lite families are sub-Boolean fragments of $\mathcal{A} \mathcal{L C H} \mathcal{H}$. $\mathcal{E} \mathcal{L}$-concepts are defined by the grammar

$$
\begin{equation*}
C::=A_{i}|\top| C_{1} \sqcap C_{2} \mid \exists P_{i} . C . \tag{EL}
\end{equation*}
$$

In other words, they are $\mathcal{A} \mathcal{L} C$-concepts without $\perp, \sqcup, \neg$ and $\forall P_{i} . C$. Note that $\mathcal{E} \mathcal{L}$ does not have inverse roles. $\mathcal{E} \mathcal{L}$ TBoxes are finite sets of concepts inclusions in $\mathcal{E} \mathcal{L} . \mathcal{E} \mathcal{L} \mathcal{H}_{\perp}^{d r}$ is an extension of $\mathcal{E} \mathcal{L}$ with $\perp$, role inclusions and domain and range restrictions. Thus, $\mathcal{E} \mathcal{L} \mathcal{H}_{\perp}^{d r}$-concepts are defined similarly to $\mathcal{E} \mathcal{L}$-concepts but can also use $\perp$, and $\mathcal{E} \mathcal{L} \mathcal{H}_{\perp}^{d r}-$ TBoxes consist of a finite number of $\mathcal{E} \mathcal{L} \mathcal{H}_{\perp}^{d r}$-concept inclusions, role inclusions (without inverse roles), and range restrictions of the form

$$
\top \sqsubseteq \forall P_{i} . C
$$

(domain restrictions are expressible by means of concept inclusions $\exists P_{i} . T \sqsubseteq C$ ). Clearly, $\mathcal{E} \mathcal{L}$ and $\mathcal{E} \mathcal{L} \mathcal{H}_{\perp}^{d r}$ are sublanguages of $\mathcal{A L C}$ and $\mathcal{A} \mathcal{L C H}$, respectively.

Basic concepts in DL-Lite are defined by the following grammar:

$$
B::=A_{i}|\top| \perp \mid \exists R . \top
$$

(DL-Lite)
where $R$ is a (possibly inverse) role. Existential quantifiers $\exists R$. $\top$ are called unqualified, and we usually write $\exists R$ instead of $\exists R$.T. DL-Lite core $^{\text {-TBoxes }}$ are finite sets of concept inclusions of the form

$$
B_{1} \sqsubseteq B_{2} \quad \text { and } \quad B_{1} \sqcap B_{2} \sqsubseteq \perp
$$

where the $B_{i}$ are basic concepts. DL-Lite horn $_{\text {-TBoxes }}$ consist of a finite number of concept inclusions of the form

$$
B_{1} \sqcap \cdots \sqcap B_{k} \sqsubseteq B .
$$

DL-Lite core $_{\mathcal{H}}^{\mathcal{H}}$ and DL-Lite ${ }_{\text {horn }}^{\mathcal{H}}$-TBoxes contain, in addition, a finite number of role inclusions and role disjointness axioms of the form $R_{1} \sqcap R_{2} \sqsubseteq \perp$. Note that, unlike $\mathcal{E} \mathcal{L}$ and $\mathcal{E} \mathcal{L} \mathcal{H}_{\perp}^{d r}$, the DL-Lite logics do have inverse roles.

To introduce the Horn fragments of the DLs with the Booleans operators, we require the following (standard) recursive definition [5, 26]. We say that a concept $C$ occurs positively in $C$ itself and, if $C$ occurs positively (negatively) in $C^{\prime}$, then

[^2]- $C$ occurs positively (respectively, negatively) in $C^{\prime} \sqcup D, C^{\prime} \sqcap D, \exists R \cdot C^{\prime}, \forall R \cdot C^{\prime}, D \sqsubseteq C^{\prime}$, and
- $C$ occurs negatively (respectively, positively) in $\neg C^{\prime}$ and $C^{\prime} \sqsubseteq D$.

Now, we call a TBox $\mathcal{T}$ Horn if no concept of the form $C \sqcup D$ occurs positively in $\mathcal{T}$, and no concept of the form $\neg C$ or $\forall R . C$ occurs negatively in $\mathcal{T}$. Clearly, the $\mathcal{E} \mathcal{L}$ - and DL-Lite-TBoxes are Horn by definition. For any other DL $\mathcal{L}$ (e.g., $\mathcal{A} \mathcal{L C H} \mathcal{I}$ ), only Horn $\mathcal{L}$-TBoxes are allowed in the DL Horn- $\mathcal{L}$.

An ABox, $\mathcal{A}$, is a finite set of assertions of the form $A_{k}\left(a_{i}\right)$ or $P_{k}\left(a_{i}, a_{j}\right)$. An $\mathcal{L}$-TBox $\mathcal{T}$ and an ABox $\mathcal{A}$ together form an $\mathcal{L}$ knowledge base $(\mathrm{KB}) \mathcal{K}=(\mathcal{T}, \mathcal{A})$.

A relational signature is any non-empty finite set of concept and role names. An individual signature is a (possibly empty) finite set of individual names. We usually denote a relational signature by $\Sigma$, an individual signature by $\Gamma$, and sometimes call the pair $(\Sigma, \Gamma)$ simply a signature. The relational signature of a $\mathrm{KB} \mathcal{K}=(\mathcal{T}, \mathcal{A})$, which consists of the concept and role names occurring in $\mathcal{K}$, is denoted by $\operatorname{sig}(\mathcal{K})$. The individual signature of $\mathcal{K}$, comprising the individual names in $\mathcal{A}$, is denoted by ind $(\mathcal{K})$. In this article, we are not interested in KBs with empty ABoxes, and so both $\operatorname{sig}(\mathcal{K})$ and $\operatorname{ind}(\mathcal{K})$ are non-empty by definition. By a $\Sigma$-concept, $\Sigma$-role, $\Sigma$-ABox, etc. we understand any concept, role, ABox, etc. all of whose concept and role names are taken from $\Sigma$.

Let $(\Sigma, \Gamma)$ be a signature. In our interpretations, we adopt the standard name assumption in the sense that every individual name $a \in \Gamma$ is interpreted by itself. A $(\Sigma, \Gamma)$-interpretation is a pair $I=\left(\Delta^{I},{ }^{I}\right)$, where $\Delta^{I} \supseteq \Gamma$ is a nonempty set, the domain of $\mathcal{I}$, and ${ }^{I}$ is an interpretation function that assigns a subset $A^{\mathcal{I}} \subseteq \Delta^{I}$ to every concept name $A$ and a binary relation $P^{I} \subseteq \Delta^{I} \times \Delta^{I}$ to every role name $P$ in such a way that $A^{I}=\emptyset$ and $P^{I}=\emptyset$, for any $A \notin \Sigma$ and $P \notin \Sigma$. (Note that only the individual names from $\Gamma$ are interpreted in $\mathcal{I}$ and although the list of individual names is countably infinite, $\Delta^{I}$ may be finite. Note also that the concept and role names outside $\Sigma$ are always interpreted as $\emptyset$.) When we use the terms 'interpretation', ' $\Sigma$-interpretation' or ' $\Gamma$-interpretation' without specifying a full signature, we mean a $(\Sigma, \Gamma)$-interpretation for some suitable $(\Sigma, \Gamma)$; the same applies to other notions with the prefix $(\Sigma, \Gamma)$ to be introduced below.

Roles and complex concepts are interpreted in $I$ as follows:

$$
\begin{aligned}
\left(P_{i}^{-}\right)^{I} & =\left\{(v, u) \mid(u, v) \in P_{i}^{I}\right\}, \\
\perp^{I} & =\emptyset, \\
\left(C_{1} \sqcap C_{2}\right)^{I} & =C_{1}^{I} \cap C_{2}^{I} \\
(\exists R \cdot C)^{I} & =\left\{u \mid(u, v) \in R^{I} \text { and } v \in C^{I}\right\},
\end{aligned}
$$

$$
\begin{aligned}
\mathrm{T}^{I} & =\Delta^{I}, \\
(\neg C)^{I} & =\Delta^{I} \backslash C^{I}, \\
\left(C_{1} \sqcup C_{2}\right)^{I} & =C_{1}^{I} \cup C_{2}^{I}, \\
(\forall R \cdot C)^{I} & =\left\{u \mid v \in C^{I} \text { for all }(u, v) \in R^{I}\right\} .
\end{aligned}
$$

For an inclusion or assertion $\alpha$ (whose individual names belong to $\Gamma$ ), we define the truth-relation $\mathcal{I} \vDash \alpha$ by taking:

$$
\begin{aligned}
& I \vDash C_{1} \sqsubseteq C_{2} \quad \text { iff } \quad C_{1}^{I} \subseteq C_{2}^{I}, \quad I \vDash R_{1} \sqsubseteq R_{2} \quad \text { iff } \quad R_{1}^{I} \subseteq R_{2}^{I}, \\
& \mathcal{I} \vDash R_{1} \sqcap R_{2} \sqsubseteq \perp \quad \text { iff } \quad R_{1}^{\mathcal{I}} \cap R_{2}^{\mathcal{I}}=\emptyset, \\
& \mathcal{I} \vDash P_{k}\left(a_{i}, a_{j}\right) \quad \text { iff } \quad\left(a_{i}, a_{j}\right) \in P_{k}^{I} .
\end{aligned}
$$

Given a $\mathrm{KB} \mathcal{K}=(\mathcal{T}, \mathcal{A})$, a $\Gamma$-interpretation $\mathcal{I}$ is called a model of $\mathcal{K}$ if ind $(\mathcal{K}) \subseteq \Gamma$ and $\mathcal{I} \vDash \alpha$, for all $\alpha \in \mathcal{T} \cup \mathcal{A}$. In this case we write $\mathcal{I} \vDash \mathcal{K}$. We write $\mathcal{K} \vDash \alpha$, for an inclusion or assertion $\alpha$ that only uses individual names from $\operatorname{ind}(\mathcal{K})$, if $\mathcal{I} \vDash \alpha$ for all models $\mathcal{I}$ of $\mathcal{K}$. The notation $\mathcal{K} \vDash C(a)$, where $C$ is any concept and $a \in \operatorname{ind}(\mathcal{K})$, should be understood in the same way. Finally, $\mathcal{K}$ is consistent if it has a model.

A conjunctive query (CQ) $\boldsymbol{q}(\boldsymbol{x})$ is a formula $\exists \boldsymbol{y} \varphi(\boldsymbol{x}, \boldsymbol{y})$, where $\varphi$ is a conjunction of atoms of the form $A_{k}\left(z_{1}\right)$ or $P_{k}\left(z_{1}, z_{2}\right)$ with $z_{1}, z_{2}$ from $\boldsymbol{x}, \boldsymbol{y}$. Let $\mathcal{K}$ be a KB and $\boldsymbol{q}(\boldsymbol{x})$ a CQ. We call a tuple $\boldsymbol{a}$ of elements from ind $(\mathcal{K})$ (of the same length as $\boldsymbol{x})$ a certain answer to $\boldsymbol{q}(\boldsymbol{x})$ over $\mathcal{K}$ if $\mathcal{I} \vDash \boldsymbol{q}(\boldsymbol{a})$ for all models $\mathcal{I}$ of $\mathcal{K}$ (understood as first-order structures). In this case we write $\mathcal{K} \vDash \boldsymbol{q}(\boldsymbol{a})$. For $\boldsymbol{q}$ without free variables, the answer to $\boldsymbol{q}$ is 'yes' if $\mathcal{K} \vDash \boldsymbol{q}$ and 'no' otherwise. We slightly abuse notation and write $\boldsymbol{a} \subseteq \Gamma$ to say that all elements of the tuple $\boldsymbol{a}$ are in $\Gamma$.

We remind the reader that, for combined complexity, the problem ' $\mathcal{K} \vDash \boldsymbol{q}(\boldsymbol{a})$ ?' is NP-complete for the DL-Lite logics [6], $\mathcal{E} \mathcal{L}$ and $\mathcal{E} \mathcal{L} \mathcal{H}_{\perp}^{d r}$ [27], and ExpTime-complete for the remaining Horn DLs introduced above [28]. For data complexity (with fixed $\mathcal{T}$ and $\boldsymbol{q}$ ), this problem is in $\mathrm{AC}^{0}$ for the DL-Lite logics [6] and P-complete for the remaining DLs [27, 28].

## 3. $\Sigma$-Query Entailment, Materialisation and ( $\Sigma, \Gamma$ )-Homomorphism

We now define the central concepts of the article, $\Sigma$-query entailment and $\Sigma$-query inseparability, provide them with a semantic characterisation based on the notion of materialisation, and develop a theory of finitely generated materialisations.

Definition 1. Let $\mathcal{K}_{1}$ and $\mathcal{K}_{2}$ be KBs and $\Sigma$ a relational signature. We say that $\mathcal{K}_{1} \Sigma$-query entails $\mathcal{K}_{2}$ if

$$
\mathcal{K}_{2} \vDash \boldsymbol{q}(\boldsymbol{a}) \text { implies } \boldsymbol{a} \subseteq \operatorname{ind}\left(\mathcal{K}_{1}\right) \text { and } \mathcal{K}_{1} \vDash \boldsymbol{q}(\boldsymbol{a}), \quad \text { for all } \Sigma \text {-CQs } \boldsymbol{q}(\boldsymbol{x}) \text { and all tuples } \boldsymbol{a} \subseteq \operatorname{ind}\left(\mathcal{K}_{2}\right) .
$$

Knowledge bases $\mathcal{K}_{1}$ and $\mathcal{K}_{2}$ are $\Sigma$-query inseparable if they $\Sigma$-query entail each other; in this case we write $\mathcal{K}_{1} \equiv_{\Sigma} \mathcal{K}_{2}$.
Remark 2. For KBs given in Horn DLs, $\Sigma$-query entailment for CQs implies $\Sigma$-query entailment for UCQs, that is, unions (or disjunctions) of conjunctive queries. This follows from the fact that, for any KB $\mathcal{K}$ in a Horn DL and any UCQ $\boldsymbol{q}(\boldsymbol{x})$, a tuple $\boldsymbol{a}$ is a certain answer to $\boldsymbol{q}(\boldsymbol{x})$ over $\mathcal{K}$ iff it is a certain answer to some CQ in $\boldsymbol{q}(\boldsymbol{x})$ over $\mathcal{K}$. Thus, our results for $\Sigma$-query entailment and inseparability apply to UCQs as well.

We first quickly consider $\Sigma$-query entailment for the degenerate case when one of the involved KBs is inconsistent so that in the remainder of the article we can focus on consistent KBs only. Clearly, an inconsistent $\mathcal{K}_{1} \Sigma$-query entails a KB $\mathcal{K}_{2}$ just in case $a \in \operatorname{ind}\left(\mathcal{K}_{1}\right)$ for all $a \in \operatorname{ind}\left(\mathcal{K}_{2}\right)$ with either $\mathcal{K}_{2} \vDash A(a)$ or $\mathcal{K}_{2} \vDash(\exists R)(a)$, for some $A \in \Sigma$ or $\Sigma$-role $R$. Now, suppose that $\mathcal{K}_{1}$ is consistent and $\mathcal{K}_{2}$ is inconsistent. Then $\mathcal{K}_{1} \Sigma$-query entails $\mathcal{K}_{2}$ iff $\mathcal{K}_{1} \vDash A(a)$ and $\mathcal{K}_{1} \vDash P(a, b)$, for all concept and role names $A, P \in \Sigma$ and all $a, b \in \operatorname{ind}\left(\mathcal{K}_{2}\right)$. Thus, deciding $\Sigma$-query entailment in this case reduces to checking certain answers for all atomic $\Sigma$-CQs. A simple example showing that a consistent KB $\mathcal{K}_{1}$ can $\Sigma$-query entail an inconsistent $\mathrm{KB} \mathcal{K}_{2}$ is given by $\mathcal{K}_{1}=(\emptyset,\{A(a)\})$ and $\mathcal{K}_{2}=(\{A \sqsubseteq \perp\},\{A(a)\})$ with $\Sigma=\{A\}$. From now on we assume that all our KBs are consistent.

Definition 3. Let $\mathcal{K}$ be a KB. A $(\operatorname{sig}(\mathcal{K})$, ind $(\mathcal{K}))$-interpretation $\mathcal{I}$ is called a materialisation of $\mathcal{K}$ if

$$
\mathcal{K} \vDash \boldsymbol{q}(\boldsymbol{a}) \quad \text { iff } \quad \boldsymbol{I} \vDash \boldsymbol{q}(\boldsymbol{a}), \quad \text { for all CQs } \boldsymbol{q}(\boldsymbol{x}) \text { and all tuples } \boldsymbol{a} \subseteq \operatorname{ind}(\mathcal{K}) .
$$

We say that $\mathcal{K}$ is materialisable if it has a materialisation. (Note that we do not require a materialisation of $\mathcal{K}$ to be a model of $\mathcal{K}$.)

Materialisations can be used to characterise $\Sigma$-query entailment by means of homomorphisms. Let ( $\Sigma, \Gamma$ ) be a signature. For an interpretation $I$, the atomic $\Sigma$-types $\boldsymbol{t}_{\Sigma}^{I}(u)$ and $\boldsymbol{r}_{\Sigma}^{I}(u, v)$ of $u, v \in \Delta^{I}$ are defined by taking:

$$
\boldsymbol{t}_{\Sigma}^{I}(u)=\left\{\Sigma \text {-concept name } A \mid u \in A^{I}\right\} \quad \text { and } \quad \boldsymbol{r}_{\Sigma}^{I}(u, v)=\left\{\Sigma \text {-role } R \mid(u, v) \in R^{I}\right\} .
$$

(It is to be emphasised that a $\Sigma$-role can be an inverse role even when we consider a language without role inverses.) We say that an element $u \in \Delta^{I}$ is $\Sigma$-participating in $\mathcal{I}$ if $\boldsymbol{t}_{\Sigma}^{I}(u) \neq \emptyset$ or $\boldsymbol{r}_{\Sigma}^{I}(u, v) \neq \emptyset$, for some $v \in \Delta^{I}$. The set of all individual names that are $\Sigma$-participating in $I$ is denoted by part ${ }_{\Sigma}^{I}$. Let $I_{i}$ be $\Gamma_{i}$-interpretations, for $i=1,2$, such that $\Gamma \cap \operatorname{part}_{\Sigma}^{I_{1}} \subseteq \Gamma_{2}$. A ( $\Sigma, \Gamma$ )-homomorphism $h$ from $I_{1}$ to $I_{2}$ is a function $h: \Delta^{I_{1}} \rightarrow \Delta^{I_{2}}$ such that
$-h(a)=a$, for every $a \in \Gamma \cap \operatorname{part}_{\Sigma}^{T_{1}}$,

- $\boldsymbol{t}_{\Sigma}^{I_{1}}(u) \subseteq \boldsymbol{t}_{\Sigma}^{I_{2}}(h(u))$ and $\boldsymbol{r}_{\Sigma}^{I_{1}}(u, v) \subseteq \boldsymbol{r}_{\Sigma}^{I_{2}}(h(u), h(v))$, for all $u, v \in \Delta^{I_{1}}$.

Example 4. For $\Gamma_{1}=\{a, b, c\}$, let $I_{1}$ be a $\Gamma_{1}$-interpretation with $\Delta^{I_{1}}=\{a, b, c\}, A^{I_{1}}=\{a\}, B^{I_{1}}=\{b\}$ and $C^{I_{1}}=\{c\}$. If $\Sigma=\{A\}$ then part ${ }_{\Sigma}^{T_{1}}=\{a\}$ as neither $b$ nor $c$ is $\Sigma$-participating in $I_{1}$. For $\Gamma_{2}=\{a, b, d\}$, let $I_{2}$ be a $\Gamma_{2}$-interpretation with $\Delta^{I_{2}}=\{a, b, d\}, A^{I_{2}}=\{a\}, B^{I_{2}}=\{d\}$ and $C^{I_{2}}=\{b\}$. In this case, any map $h: \Delta^{I_{1}} \rightarrow \Delta^{I_{2}}$ with $h(a)=a$ is a $(\{A\},\{a, b\})$-homomorphism from $I_{1}$ to $I_{2}$. However, there is no $(\{A, B\},\{a, b\})$-homomorphism from $I_{1}$ to $I_{2}$ because $\operatorname{part}_{\{A, B\}}^{I_{1}}=\{a, b\}$ but $\boldsymbol{t}_{\{A, B\}}^{I_{1}}(b) \nsubseteq \boldsymbol{t}_{\{A, B\}}^{I_{2}}(b)$.

We remind the reader of the following well-known link between certain answers to CQs and homomorphisms. Consider a CQ $\boldsymbol{q}(\boldsymbol{x})=\exists \boldsymbol{y} \varphi(\boldsymbol{x}, \boldsymbol{y})$, a $\Gamma^{\prime}$-interpretation $\mathcal{I}$, and a tuple $\boldsymbol{a} \subseteq \Gamma^{\prime}$ of the same length as $\boldsymbol{x}$. Let $\Sigma$ be the relational signature of $\boldsymbol{q}$, and let $\Gamma$ be the set of individuals in $\boldsymbol{a}$. We can regard $\varphi(\boldsymbol{a}, \boldsymbol{y})$ as a $(\Sigma, \Gamma)$-interpretation $I_{\varphi(\boldsymbol{a}, \boldsymbol{y})}$


Figure 2: Materialisations $I_{2}$ and $I_{1}$ from Example 5 (dotted lines indicate a partial homomorphism) and their generating structures, $\mathcal{G}_{2}$ and $\mathcal{G}_{1}$.
whose domain consists of the individuals in $\boldsymbol{a}$ and variables in $\boldsymbol{y}$, and $I_{\varphi(\boldsymbol{a}, \boldsymbol{y})} \vDash S(z)$ iff $S(z)$ is a conjunct of $\varphi(\boldsymbol{a}, \boldsymbol{y})$. In this case, we have $I \vDash \boldsymbol{q}(\boldsymbol{a})$ iff there is a $(\Sigma, \Gamma)$-homomorphism from $I_{\varphi(a, y)}$ to $I$.

Suppose $\mathcal{I}_{i}$ is a materialisation of $\mathcal{K}_{i}$, for $i=1,2$. Since a composition of homomorphisms is again a homomorphism, if there is a $\left(\Sigma, \operatorname{ind}\left(\mathcal{K}_{2}\right)\right)$-homomorphism from $\mathcal{I}_{2}$ to $I_{1}$, then $\mathcal{K}_{1} \Sigma$-query entails $\mathcal{K}_{2}$. The converse, however, does not necessarily hold, as shown by the following example.

Example 5. Consider the $\mathrm{KBs} \mathcal{K}_{i}=\left(\mathcal{T}_{i},\{A(a)\}\right)$, for $i=1$, 2, where

$$
\begin{aligned}
& \mathcal{T}_{1}=\left\{A \sqsubseteq \exists S, \exists S^{-} \sqsubseteq \exists T, \exists T^{-} \sqsubseteq \exists S, S \sqsubseteq Q, T \sqsubseteq Q, \exists Q^{-} \sqsubseteq \exists R\right\}, \\
& \mathcal{T}_{2}=\left\{A \sqsubseteq \exists P, \exists P^{-} \sqsubseteq \exists R^{-}, \exists R \sqsubseteq \exists S^{-} \sqcap \exists Q^{-}, \exists Q \sqsubseteq \exists Q^{-}, \exists S \sqsubseteq \exists T^{-}, \exists T \sqsubseteq \exists S^{-}\right\} .
\end{aligned}
$$

It is not hard to see (and it will be formally established below) that the interpretations $I_{1}$ and $I_{2}$ shown in Fig. 2 are materialisations of $\mathcal{K}_{1}$ and $\mathcal{K}_{2}$, respectively. Now, for $\Sigma=\{Q, R, S, T\}$, there is no $\left(\Sigma,\{a\}\right.$ )-homomorphism from $\mathcal{I}_{2}$ to $I_{1}$. Indeed, if we map $u$ to, say, $w$ then only the shaded part of $I_{2}$ can be mapped ( $\Sigma,\{a\}$ )-homomorphically to $I_{1}$. On the other hand, $I_{2} \vDash \boldsymbol{q}(\boldsymbol{a})$ implies $I_{1} \vDash \boldsymbol{q}(\boldsymbol{a})$, for any $\Sigma$-CQ $\boldsymbol{q}(\boldsymbol{x})$, because any finite subinterpretation of $I_{2}$ can be ( $\Sigma,\{a\}$ )-homomorphically mapped to $I_{1}$. This example motivates the following definitions.

A subinterpretation of a $(\Sigma, \Gamma)$-interpretation $I=\left(\Delta^{I}, I^{I}\right)$ is a $(\Sigma, \Gamma)$-interpretation $I^{\prime}=\left(\Delta^{I^{\prime}}, I^{I^{\prime}}\right)$ with $\Delta^{I^{\prime}} \subseteq \Delta^{I}$, $A^{I^{\prime}}=A^{I} \cap \Delta^{I^{\prime}}$ and $P^{I^{\prime}}=P^{I} \cap\left(\Delta^{I^{\prime}} \times \Delta^{I^{\prime}}\right)$, for all concept and role names $A$ and $P$. Now, given a signature $(\Sigma, \Gamma)$, we say that an interpretation $I_{2}$ is finitely $(\Sigma, \Gamma)$-homomorphically embeddable into an interpretation $I_{1}$ if, for every finite subinterpretation $I_{2}^{\prime}$ of $I_{2}$, there exists a $(\Sigma, \Gamma)$-homomorphism from $I_{2}^{\prime}$ to $I_{1}$.

In the proof of the following criterion of $\Sigma$-query entailment, we regard any finite subinterpretation of $I_{2}$ as a CQ whose variables are the elements of $\Delta^{I_{2}}$, with ind $\left(\mathcal{K}_{2}\right)$ being the answer variables.

Theorem 6. Suppose $\mathcal{K}_{i}$ is a KB with a materialisation $\mathcal{I}_{i}$, for $i=1$, 2. Then $\mathcal{K}_{1} \Sigma$-query entails $\mathcal{K}_{2}$ iff $\mathcal{I}_{2}$ is finitely $\left(\Sigma\right.$, ind $\left.\left(\mathcal{K}_{2}\right)\right)$-homomorphically embeddable into $\mathcal{I}_{1}$.

Proof. $(\Rightarrow)$ Suppose $\mathcal{K}_{1}$, -query entails $\mathcal{K}_{2}$. Let $\boldsymbol{a}=\left(a_{1}, \ldots, a_{n}\right)$ be an enumeration of the individual names in ind $\left(\mathcal{K}_{2}\right)$ that are $\Sigma$-participating in $I_{2}$. Take any finite subinterpretation $I_{2}^{\prime}$ of $I_{2}$ and let $u_{1}, \ldots, u_{n+m}$ be an enumeration of those elements of $\Delta^{I_{2}^{\prime}}$ that are $\Sigma$-participating in $I_{2}$ and such that $u_{i}=a_{i}$, for $i \leq n$. Consider a $\Sigma$-CQ

$$
\boldsymbol{q}\left(x_{1}, \ldots, x_{n}\right)=\exists x_{n+1} \ldots \exists x_{n+m} \varphi\left(x_{1}, \ldots, x_{n+m}\right), \quad \text { where } \varphi\left(x_{1}, \ldots, x_{n+m}\right)=\bigwedge_{\substack{i \leq n+m \\ A \in t_{\Sigma}^{I_{2}}\left(u_{i}\right)}} A\left(x_{i}\right) \wedge \bigwedge_{\substack{i, j \leq n+m \\ R \in r_{\Sigma}^{I 2}\left(u_{i}, u_{j}\right)}} R\left(x_{i}, x_{j}\right) .
$$

Since $I_{2} \vDash \varphi\left(u_{1}, \ldots, u_{n+m}\right)$, we have $\mathcal{I}_{2} \vDash \boldsymbol{q}(\boldsymbol{a})$ and, since $\mathcal{I}_{2}$ is a materialisation, $\mathcal{K}_{2} \vDash \boldsymbol{q}(\boldsymbol{a})$. As $\mathcal{K}_{1} \Sigma$-query entails $\mathcal{K}_{2}$, we have $\boldsymbol{a} \subseteq \operatorname{ind}\left(\mathcal{K}_{1}\right)$ and $\mathcal{K}_{1} \vDash \boldsymbol{q}(\boldsymbol{a})$. Since $I_{1}$ is a materialisation, $I_{1} \vDash \boldsymbol{q}(\boldsymbol{a})$, and so $I_{1} \vDash \varphi\left(\boldsymbol{a}, v_{n+1}, \ldots, v_{n+m}\right)$, for some $v_{n+1}, \ldots, v_{n+m} \in \Delta^{I_{1}}$. Define a map $h: \Delta^{I_{2}^{\prime}} \rightarrow \Delta^{I_{1}}$ by taking $h\left(a_{i}\right)=a_{i}$, for $i \leq n$, and $h\left(u_{n+i}\right)=v_{n+i}$, for $i \leq m$ (the rest of the domain of $I_{2}^{\prime}$ can be mapped arbitrarily as they are not $\Sigma$-participating in it). It can be readily seen that $h$ is a $(\Sigma, \Gamma)$-homomorphism from $I_{2}^{\prime}$ to $I_{1}$.
$(\Leftarrow)$ Suppose $I_{2}$ is finitely $\left(\Sigma\right.$, ind $\left(\mathcal{K}_{2}\right)$ )-homomorphically embeddable into $I_{1}$. Consider a $\Sigma$-CQ $\boldsymbol{q}(\boldsymbol{x})=\exists \boldsymbol{y} \varphi(\boldsymbol{x}, \boldsymbol{y})$ and let $\mathcal{K}_{2} \vDash \boldsymbol{q}(\boldsymbol{a})$, for some $\boldsymbol{a} \subseteq \operatorname{ind}\left(\mathcal{K}_{2}\right)$. Since $\mathcal{I}_{2}$ is a materialisation of $\mathcal{K}_{2}$, there is a tuple $\boldsymbol{u}=\left(u_{1}, \ldots, u_{m}\right)$ of elements in $\Delta^{I_{2}}$ such that $I_{2} \vDash \varphi(\boldsymbol{a}, \boldsymbol{u})$. Let $I_{2}^{\prime}$ be the subinterpretation of $I_{2}$ with $\Delta^{I_{2}^{\prime}}=\operatorname{ind}\left(\mathcal{K}_{2}\right) \cup\left\{u_{1}, \ldots, u_{m}\right\}$ and let $h$ be a $\left(\Sigma\right.$, ind $\left.\left(\mathcal{K}_{2}\right)\right)$-homomorphism from $I_{2}^{\prime}$ to $I_{1}$. Observe that each individual in $\boldsymbol{a}$ is $\Sigma$-participating in $I_{2}^{\prime}$, and so $h\left(a_{i}\right)=a_{i}$, for each $a_{i}$ in $\boldsymbol{a}$. We also have $I_{1} \vDash \varphi\left(\boldsymbol{a}, h\left(u_{1}\right), \ldots, h\left(u_{m}\right)\right)$, whence $\boldsymbol{a} \subseteq \operatorname{ind}\left(\mathcal{K}_{1}\right)$ and $\mathcal{K}_{1} \vDash \boldsymbol{q}(\boldsymbol{a})$.

One problem with applying Theorem6 is that materialisations are in general infinite for any of the DLs considered in this article. We address this problem by introducing finite representations of materialisations and showing that Horn- $\mathcal{A L C H} \mathcal{I}$ and all of its fragments defined above do have such finite representations.
Definition 7. Let $\mathcal{K}$ be a $\operatorname{KB}$ and let $\mathcal{G}=\left(\Delta^{\mathcal{G}},{ }^{\mathcal{G}}, \rightsquigarrow\right)$ be a finite structure such that
$-\Delta^{\mathcal{G}}=\operatorname{ind}(\mathcal{K}) \cup \Omega$, for some set $\Omega$ disjoint from ind $(\mathcal{K})$,

- $\left(\Delta^{\mathcal{G}},{ }^{\mathcal{G}}\right)$ is an interpretation with $P_{i}^{\mathcal{G}} \subseteq \operatorname{ind}(\mathcal{K}) \times \operatorname{ind}(\mathcal{K})$, for all role names $P_{i}$,
$-\left(\Delta^{\mathcal{G}}, \rightsquigarrow\right)$ is a directed graph (possibly containing loops) with nodes $\Delta^{\mathcal{G}}$ and arrows $\rightsquigarrow \subseteq \Delta^{\mathcal{G}} \times \Omega$, in which
- every $w \rightsquigarrow w^{\prime}$ is labelled with a set $\left(w, w^{\prime}\right)^{\mathcal{G}} \neq \emptyset$ of roles such that $\left(w_{1}, w^{\prime}\right)^{\mathcal{G}}=\left(w_{2}, w^{\prime}\right)^{\mathcal{G}}$ whenever $w_{i} \rightsquigarrow w^{\prime}$, for $i=1,2$,
- every $w \in \Omega$ is reachable by a path from $\operatorname{ind}(\mathcal{K})$,
where by a path, $\sigma$, we mean any sequence $w_{0} \cdots w_{n}$ with $w_{0} \in \operatorname{ind}(\mathcal{K})$ and $w_{i} \rightsquigarrow w_{i+1}$ for $i<n$.
Intuitively, $w \rightsquigarrow w^{\prime}$ means that $w$ generates $w^{\prime}$ to witness an existential restriction $\exists R . C$, and the label of $w \rightsquigarrow w^{\prime}$ consists of the super-roles of $R$. Hence, the labels on all incoming $\rightsquigarrow$-arrows of $w^{\prime}$ are required to coincide.

The unravelling $\mathcal{M}$ of $\mathcal{G}$ is a $(\operatorname{sig}(\mathcal{K})$, ind $(\mathcal{K}))$-interpretation $\left(\Delta^{\mathcal{M}},{ }^{\mathcal{M}}\right)$ such that

$$
\begin{aligned}
& \Delta^{\mathcal{M}} \text { is the set of paths in } \mathcal{G}, \\
& A^{\mathcal{M}}=\left\{\sigma \mid \text { tail }(\sigma) \in A^{\mathcal{G}}\right\}, \\
& P^{\mathcal{M}}=P^{\mathcal{G}} \cup\left\{(\sigma, \sigma w) \mid \operatorname{tail}(\sigma) \rightsquigarrow w, P \in(\operatorname{tail}(\sigma), w)^{\mathcal{G}}\right\}
\end{aligned}
$$

$$
A^{\mathcal{M}}=\left\{\sigma \mid \operatorname{tail}(\sigma) \in A^{\mathcal{G}}\right\}, \quad \text { for each concept name } A,
$$

$$
\cup\left\{(\sigma w, \sigma) \mid \operatorname{tail}(\sigma) \rightsquigarrow w, P^{-} \in(\operatorname{tail}(\sigma), w)^{\mathcal{G}}\right\}, \quad \text { for each role name } P,
$$

where tail $(\sigma)$ is the last element of a path $\sigma$. We call $\mathcal{G}$ a generating structure for $\mathcal{K}$ if its unravelling is a materialisation of $\mathcal{K}$. We say that a DL $\mathcal{L}$ has finitely generated materialisations if every $\mathcal{L}$-KB has a generating structure.

For instance, the materialisations $I_{2}$ and $I_{1}$ from Example 5 are isomorphic to the unravellings of the structures $\mathcal{G}_{2}$ and $\mathcal{G}_{1}$ in Fig. 2 respectively, and so $\mathcal{G}_{i}$ is a generating structure for the $\mathrm{KB} \mathcal{K}_{i}$ from that example, for $i=1,2$.

To construct generating structures for KBs, we first transform their TBoxes into normal form [20]. Let $\mathcal{L}$ be any of our DLs. An $\mathcal{L}$-TBox is said to be in normal form if its inclusions are of the following form:

$$
\begin{array}{rlr}
A_{1} \sqsubseteq A_{2}, & \top \sqsubseteq A, \\
A_{1} \sqsubseteq \forall R \cdot A_{2}, & \top \sqsubseteq \forall R \cdot A, \\
\exists R \cdot C \sqsubseteq A, & A \sqsubseteq \exists R . C, \\
A_{1} \sqcap A_{2} \sqsubseteq A, & R_{1} \sqsubseteq R_{2},
\end{array}
$$

where $A, A_{1}, A_{2}$ are concept names, $C$ is a concept name or T , and $R, R_{1}, R_{2}$ are roles. To describe the relationship between a TBox and its transformation into normal form, we introduce the notion of model inseparability. Let ( $\Sigma, \Gamma$ ) be a signature. We say that $\Gamma$-interpretations $I_{1}$ and $I_{2}$ coincide on $\Sigma$ if $\Delta^{I_{1}}=\Delta^{I_{2}}$ and $S^{I_{1}}=S^{I_{2}}$, for all $S \in \Sigma$; in this case we write $I_{1}=_{\Sigma} I_{2}$. KBs $\mathcal{K}_{1}$ and $\mathcal{K}_{2}$ with ind $\left(\mathcal{K}_{1}\right)=\operatorname{ind}\left(\mathcal{K}_{2}\right)$ are called $\Sigma$-model inseparable if, for every model $I_{1}$ of $\mathcal{K}_{1}$, there exists a model $I_{2}$ of $\mathcal{K}_{2}$ such that $I_{2}=\Sigma I_{1}$, and vice versa. The following was shown in [20, 28, 22]:

Theorem 8. Let $\mathcal{L}$ be any of our DLs. Given a consistent $\mathcal{L}-K B \mathcal{K}=(\mathcal{T}, \mathcal{A})$, one can construct in polynomial time an $\mathcal{L}-K B \mathcal{K}=\left(\mathcal{T}^{\prime}, \mathcal{A}\right)$ in normal form such that $\mathcal{K}$ and $\mathcal{K}^{\prime}$ are $\operatorname{sig}(\mathcal{T})$-model inseparable.
(Note that the 'negative' axioms of the form $A \sqsubseteq \perp, A_{1} \sqcap A_{2} \sqsubseteq \perp$ and $R_{1} \sqcap R_{2} \sqsubseteq \perp$ can be removed from a TBox if the knowledge base is known to be consistent.)

We show now how to define the generating structures. Suppose we are given a (consistent) KB $\mathcal{K}=(\mathcal{T}, \mathcal{A})$ with a Horn- $\mathcal{A} \mathcal{L C H} \mathcal{H}$ TBox $\mathcal{T}$ in normal form. For a role $R$, the equivalence class $[R]$ of $R$ with respect to $\mathcal{T}$ is defined by taking

$$
[R]=\{S \mid \mathcal{T} \vDash R \sqsubseteq S \text { and } \mathcal{T} \vDash S \sqsubseteq R\} .
$$

Denote by $\operatorname{con}(\mathcal{T})$ the set of

- concepts of the form $\top, A$ and $\exists R . A$ that occur in $\mathcal{T}$, as well as
- concepts of the form $\exists R^{-} . C$ such that $\mathcal{T}$ contains $C \sqsubseteq \forall R . A$.

The $\mathcal{T}$-type of $u \in \Delta^{I}$ in $\mathcal{I}$ is the set $\boldsymbol{\tau}_{\mathcal{T}}^{\mathcal{I}}(u)=\left\{C \in \operatorname{con}(\mathcal{T}) \mid u \in C^{I}\right\}$. We say that $\boldsymbol{\tau} \subseteq \operatorname{con}(\mathcal{T})$ is a $\mathcal{T}$-type if there exists a model $\mathcal{I}$ of $\mathcal{T}$ such that $\boldsymbol{\tau}=\boldsymbol{\tau}_{\mathcal{T}}^{\mathcal{I}}(u)$, for some $u \in \Delta^{I}$. Denote by type $(\mathcal{T})$ the set of all $\mathcal{T}$-types. It is well-known [29] that type $(\mathcal{T})$ can be computed in exponential time in $|\mathcal{T}|$. We can order $\mathcal{T}$-types by the set-theoretic inclusion $\subseteq$. Sometimes we use $\tau$ in concepts (say, $\exists R . \tau$ ), in which case it should be understood as an abbreviation for $\prod_{C \in \tau} C$.

Now, we define the generating relation $\rightsquigarrow$ on the set comprising $\operatorname{ind}(\mathcal{K})$ and $\Omega_{\mathcal{T}}$, which is the set of all pairs of the form $([R], \boldsymbol{\tau})$, for a role $R$ in $\mathcal{T}$ and $\boldsymbol{\tau} \in \operatorname{type}(\mathcal{T})$. For $a \in \operatorname{ind}(\mathcal{K})$ and $\left(\left[R_{1}\right], \tau_{1}\right),\left(\left[R_{2}\right], \tau_{2}\right) \in \Omega_{\mathcal{T}}$, we set

$$
\begin{gathered}
a \rightsquigarrow\left(\left[R_{2}\right], \boldsymbol{\tau}_{2}\right) \quad \text { iff } \quad \begin{array}{r}
\boldsymbol{\tau}_{2} \text { is a } \subseteq \text {-maximal } \mathcal{T} \text {-type such that } \mathcal{K} \vDash\left(\exists R_{2} . \boldsymbol{\tau}_{2}\right)(a) \text { and } \\
\mathcal{K} \not \models R_{2}(a, b), \text { for any } b \in \operatorname{ind}(\mathcal{K}) \text { with } \boldsymbol{\tau}_{2} \subseteq\{C \in \operatorname{con}(\mathcal{T}) \mid \mathcal{K} \vDash C(b)\} ; \\
\left(\left[R_{1}\right], \boldsymbol{\tau}_{1}\right) \rightsquigarrow\left(\left[R_{2}\right], \boldsymbol{\tau}_{2}\right) \quad \text { iff } \quad \boldsymbol{\tau}_{2} \text { is a } \subseteq \text {-maximal } \mathcal{T} \text {-type such that } \mathcal{T} \vDash \boldsymbol{\tau}_{1} \sqsubseteq \exists R_{2} . \boldsymbol{\tau}_{2} .
\end{array} .
\end{gathered}
$$

The generating structure $\mathcal{G}=\left(\Delta^{\mathcal{G}}, \cdot^{\mathcal{G}}, \rightsquigarrow\right)$ is defined as follows. Let $\Omega \subseteq \Omega_{\mathcal{T}}$ be the set of all $w$ such that there are $a \in \operatorname{ind}(\mathcal{K})$ and $w_{1}, \ldots, w_{n} \in \Omega_{\mathcal{T}}$ with $a \rightsquigarrow w_{1} \rightsquigarrow \cdots \rightsquigarrow w_{n}=w$; in other words, $\Omega$ is the subset of $\Omega_{\mathcal{T}}$ that is reachable from ind $(\mathcal{K})$ via $\rightsquigarrow$-arrows. Thus, $\Delta^{\mathcal{G}}=\operatorname{ind}(\mathcal{K}) \cup \Omega$. (The restriction of $\rightsquigarrow$ to $\Delta^{\mathcal{G}}$ will also be denoted by $\rightsquigarrow$.) Second, the interpretation function.$^{\mathcal{G}}$ and the labelling of the graph $\left(\Delta^{\mathcal{G}}, \rightsquigarrow\right)$ are defined by setting

$$
\begin{aligned}
A^{\mathcal{G}} & =\{a \in \operatorname{ind}(\mathcal{K}) \mid \mathcal{K} \vDash A(a)\} \cup\{([R], \boldsymbol{\tau}) \in \Omega \mid A \in \boldsymbol{\tau}\}, \\
P^{\mathcal{G}} & =\{(a, b) \mid R(a, b) \in \mathcal{A} \text { and } \mathcal{T} \vDash R \sqsubseteq P\}, \\
\left(w, w^{\prime}\right)^{\mathcal{G}} & =\{S \mid \mathcal{T} \vDash R \sqsubseteq S\}, \text { for every } w \rightsquigarrow w^{\prime} \text { with } w=([R], \boldsymbol{\tau})
\end{aligned}
$$

(here we assume that $P^{-}(b, a) \in \mathcal{A}$ if $\left.P(a, b) \in \mathcal{A}\right)$. In order to show that the constructed $\mathcal{G}=\left(\Delta^{\mathcal{G}},,^{\mathcal{G}}, \rightsquigarrow\right)$ is indeed a generating structure for $\mathcal{K}$, we need to establish that its unravelling is a materialisation.
Theorem 9. Let $\mathcal{K}=(\mathcal{T}, \mathcal{A})$ be a (consistent) KB with a Horn- $\mathcal{A} \mathcal{L C H} \mathcal{I}$ TBox in normal form. Let $\mathcal{G}$ be the structure defined above. Then the unravelling $\mathcal{M}$ of $\mathcal{G}$ is a materialisation of $\mathcal{K}$, and $\mathcal{G}$ is a generating structure for $\mathcal{K}$.

Proof. We require two lemmas. The proof of the first one is routine and can be found in Appendix A
Lemma 10. $\mathcal{M}$ is a model of $\mathcal{K}$. Moreover,

$$
\begin{aligned}
& -\boldsymbol{\tau}_{\mathcal{T}}^{\mathcal{M}}(a)=\{C \in \operatorname{con}(\mathcal{T}) \mid \mathcal{K} \vDash C(a)\}, \text { for all } a \in \operatorname{ind}(\mathcal{K}) \\
& -\boldsymbol{\tau}_{\mathcal{T}}^{\mathcal{M}}(\sigma)=\boldsymbol{\tau}, \text { for all } \sigma \in \Delta^{\mathcal{M}} \text { with } \text { tail }(\sigma)=([R], \boldsymbol{\tau})
\end{aligned}
$$

The second lemma says that $\mathcal{M}$ is a universal model of $\mathcal{K}$ in the following sense:
Lemma 11. For every model $\mathcal{I}$ of $\mathcal{K}$, there exists a $(\operatorname{sig}(\mathcal{K})$, $\operatorname{ind}(\mathcal{K}))$-homomorphism from $\mathcal{M}$ to $I$.

Proof. Let $\Sigma=\operatorname{sig}(\mathcal{K})$ and $\Gamma=\operatorname{ind}(\mathcal{K})$. By induction on the length of $\sigma \in \Delta^{\mathcal{M}}$, we define a function $h: \Delta^{\mathcal{M}} \rightarrow \Delta^{I}$ which satisfies the following properties implying that $h$ is a $(\Sigma, \Gamma)$-homomorphism:

$$
\begin{align*}
& h(a)=a  \tag{1}\\
& \boldsymbol{\tau}_{\mathcal{T}}^{\mathcal{M}}(\sigma) \subseteq \boldsymbol{\tau}_{\mathcal{T}}^{\mathcal{I}}(h(\sigma)),  \tag{2}\\
& \boldsymbol{r}_{\Sigma}^{\mathcal{M}}\left(\sigma, \sigma^{\prime}\right) \subseteq \boldsymbol{r}_{\Sigma}^{I}\left(h(\sigma), h\left(\sigma^{\prime}\right)\right), \tag{3}
\end{align*}
$$

$$
\begin{aligned}
& \text { for } a \in \Gamma \\
& \text { for } \sigma \in \Delta^{\mathcal{M}} \\
& \text { for } \sigma, \sigma^{\prime} \in \Delta^{\mathcal{M}} .
\end{aligned}
$$

(Note that (2) refers to the full $\mathcal{T}$-types comprising concepts of the form T, $A$ and $\exists R . B$ rather than the atomic $\Sigma$-types $t$ containing only concept names.)

First, for each $a \in \Gamma$, we set $h(a)=a$ in accordance with (1). Conditions (2) and (3) for $\sigma, \sigma^{\prime} \in \Gamma$ follow from Lemma 10, the fact that $\mathcal{I}$ is a model of $\mathcal{K}$, and the construction of $\mathcal{M}$.

Suppose now that $h(\sigma)$ has already been defined for $\sigma \cdot([S], \tau) \in \Delta^{\mathcal{M}}$. By the construction of $\mathcal{M}$, it follows that $\mathcal{K} \vDash(\exists S . \tau)(a)$ if $\sigma=a$, or $\mathcal{T} \vDash \tau^{\prime} \sqsubseteq \exists S . \tau$ if tail $(\sigma)=\left(\left[S^{\prime}\right], \tau^{\prime}\right)$. Since $\mathcal{I} \vDash \mathcal{K}$, by Lemma 10 and the induction hypothesis- $\boldsymbol{\tau}_{\mathcal{T}}^{\mathcal{M}}(\sigma) \subseteq \boldsymbol{\tau}_{\mathcal{T}}^{I}(h(\sigma))$-it follows that there exists $z \in \Delta^{I}$ such that $S \in \boldsymbol{r}_{\Sigma}^{I}(h(\sigma), z)$ and $\boldsymbol{\tau} \subseteq \boldsymbol{\tau}_{\mathcal{T}}^{\mathcal{I}}(z)$. We set $h(\sigma \cdot([S], \tau))=z$ and show that (2] and (3] hold. By Lemma 10, we have $\boldsymbol{\tau}_{\mathcal{T}}^{\mathcal{M}}(\sigma \cdot([S], \tau))=\boldsymbol{\tau}$, whence (2]. Next, observe that $R \in \boldsymbol{r}_{\Sigma}^{\mathcal{M}}(\sigma, \sigma \cdot([S], \boldsymbol{\tau}))$ follows from $\mathcal{T} \vDash S \sqsubseteq R$, and since $\mathcal{I}$ is a model of $\mathcal{T}$, we obtain $R \in \boldsymbol{r}_{\Sigma}^{I}(h(\sigma), z)$, thus proving (3).

We are now in a position to complete the proof of Theorem 9 . We show that $\mathcal{K} \vDash \boldsymbol{q}(\boldsymbol{a})$ if and only if $\mathcal{M} \vDash \boldsymbol{q}(\boldsymbol{a})$, for any CQ $\boldsymbol{q}(\boldsymbol{x})=\exists \boldsymbol{y} \varphi(\boldsymbol{x}, \boldsymbol{y})$ and $\boldsymbol{a} \subseteq \operatorname{ind}(\mathcal{K})$. If $\mathcal{K} \vDash \boldsymbol{q}(\boldsymbol{a})$ then, by Lemma 10, $\mathcal{M} \vDash \boldsymbol{q}(\boldsymbol{a})$. Conversely, suppose $\mathcal{M} \vDash \boldsymbol{q}(\boldsymbol{a})$. Then there exist a tuple $\boldsymbol{\sigma}=\left(\sigma_{1}, \ldots, \sigma_{m}\right)$ of elements in $\Delta^{\mathcal{M}}$ such that $\mathcal{M} \vDash \varphi(\boldsymbol{a}, \boldsymbol{\sigma})$. Let $\mathcal{I}$ be any model of $\mathcal{K}$. By Lemma 11, there exists a $(\operatorname{sig}(\mathcal{K}), \operatorname{ind}(\mathcal{K}))$-homomorphism $h$ from $\mathcal{M}$ to $\mathcal{I}$. But then we have $\mathcal{I} \vDash \varphi\left(\boldsymbol{a}, h\left(\sigma_{1}\right), \ldots, h\left(\sigma_{m}\right)\right)$, and so $\mathcal{I} \vDash \boldsymbol{q}(\boldsymbol{a})$.
 and Horn- $\mathcal{A} \mathcal{L C}$ TBoxes can contain exponentially many (in $|\mathcal{T}|$ ) elements in $\Omega$ (remember that $\Delta^{\mathcal{G}}=\operatorname{ind}(\mathcal{K}) \cup \Omega$ ); cf. Section 5 . Note also that if the TBox in $\mathcal{K}$ is in Horn- $\mathcal{A} \mathcal{L} \mathcal{H}$ (or one of its fragments Horn- $\mathcal{A} \mathcal{L} C, \mathcal{E} \mathcal{L} \mathcal{H}_{\perp}^{d r}$ or $\mathcal{E} \mathcal{L}$ ) then it contains no inverse roles, and so the labels $\left(w, w^{\prime}\right)^{\mathcal{G}}$ on arrows $w \rightsquigarrow w^{\prime}$ of the generating structure do not contain inverse roles either. We call such generating structures forward.

The generating structures of KBs with $\mathcal{E} \mathcal{L} \mathcal{H}_{\perp}^{d r}$ and $\mathcal{E} \mathcal{L}$ TBoxes $\mathcal{T}$ contain polynomially many elements in $\Omega$. Indeed, for every element $([R], \tau) \in \Omega$, we can find a single concept $\exists R . A$ in $\mathcal{T}$ such that

$$
\boldsymbol{\tau}=\left\{C \in \operatorname{con}(\mathcal{T}) \mid \mathcal{T} \vDash A \sqcap \prod_{\substack{\mathcal{T} \vDash R \subseteq S \\ T \subseteq Y \vee S . B \text { in } \mathcal{T}}} B \sqsubseteq C\right\} .
$$

(This is not the case for Horn- $\mathcal{A} \mathcal{L C}$ because of axioms of the form $A_{1} \sqsubseteq \forall R . A_{2}$ with $A_{1} \neq$ T.) We remark that the generating structures for $\mathcal{E} \mathcal{L}$ defined above were initially represented as pairs of functions by Brandt [30] and later called the canonical models; see, e.g., [31]. We prefer the term 'generating structure' to avoid confusion with the possibly infinite canonical model (materialisation).

Finally, the generating structures for KBs with DL-Lite TBoxes $\mathcal{T}$ also contain polynomially many elements in $\Omega$ because every $([R], \tau) \in \Omega$ is determined by the role $R$ :

$$
\boldsymbol{\tau}=\left\{C \in \operatorname{con}(\mathcal{T}) \mid \mathcal{T} \vDash \exists R^{-} \sqsubseteq C\right\} .
$$

Observe that if $\mathcal{T}$ does not contain role inclusions (which is the case for DL-Lite core and DL-Lite horn TBoxes) then, for any $w$ and $R$, there is at most one $w^{\prime}$ such that $w \rightsquigarrow w^{\prime}$ and $R \in\left(w, w^{\prime}\right)^{\mathcal{G}}$. Generating structures with this property will be called functional. We summarise these observations in the following theorem:

Theorem 12. Horn- $\mathcal{A} \mathcal{L C H} \mathcal{I}$ and all of its fragments defined above have finitely generated materialisations. Furthermore, there is a polynomial $p$ such that
(i) a generating structure $\mathcal{G}$ for any Horn- $\mathcal{A} \mathcal{L C H I} K B(\mathcal{T}, \mathcal{A})$ can be constructed in time $|\mathcal{A}| \cdot 2^{p(|\mathcal{T}|)}$;
(ii) a forward generating structure $\mathcal{G}$ for any Horn- $\mathcal{A} \mathcal{L C H} K B(\mathcal{T}, \mathcal{A})$ can be constructed in time $|\mathcal{A}| \cdot 2^{p(|\mathcal{T}|)}$;
(iii) a forward generating structure $\mathcal{G}$ for any $\mathcal{E} \mathcal{L} \mathcal{H}_{\perp}^{d r} K B(\mathcal{T}, \mathcal{A})$ can be constructed in time $|\mathcal{A}| \cdot p(|\mathcal{T}|)$;
(iv) a generating structure $\mathcal{G}$ for any $D L-L i t e_{\text {horn }}^{\mathcal{H}} K B(\mathcal{T}, \mathcal{A})$ can be constructed in time $|\mathcal{A}| \cdot p(|\mathcal{T}|)$;
(v) a functional generating structure $\mathcal{G}$ for any DL-Lite ${ }_{\text {horn }} K B(\mathcal{T}, \mathcal{A})$ can be constructed in time $|\mathcal{A}| \cdot p(|\mathcal{T}|)$.

As a final remark, we note that the generating structures $\mathcal{G}=\left(\Delta^{\mathcal{G}},{ }^{\mathcal{G}}, \rightsquigarrow\right)$ defined above can often be simplified. For example, in the case of DL-Lite KBs, we can impose the following additional restrictions on the generating relation $\rightsquigarrow$ :
(lite ${ }_{1}$ ) if $u \rightsquigarrow([R], \boldsymbol{\tau})$ then $[R]$ is $\leq_{\mathcal{T}}$-minimal, where $[S] \leq_{\mathcal{T}}[T]$ iff $\mathcal{T} \vDash S \sqsubseteq T$;
(lite $2_{2}$ ) if $\left(\left[R_{1}\right], \tau_{1}\right) \rightsquigarrow\left(\left[R_{2}\right], \tau_{2}\right)$ then $\left[R_{2}^{-}\right] \neq\left[R_{1}\right]$.
It is easily seen that these simplifications do not affect the proof of Theorem 9 (the branches of the unravelling that are pruned as a result of these restrictions can be homomorphically mapped to other branches; for a more detailed argument, see the proof of Theorem 5 in the full version of [24]). The generating structure $\mathcal{G}_{1}$ in Fig. 2 as well as the generating structures in all our examples from Section 4 are constructed with these extra restrictions in mind.

So far we have only considered $\Sigma$-query entailment because $\Sigma$-query inseparability can be reduced to two $\Sigma$-query entailment checks. The following result shows that, conversely, one can reduce $\Sigma$-query entailment in LogSpace to $\Sigma$-query inseparability, for all DLs considered in this article except DL-Lite core and DL-Lite horn $^{3}$

Theorem 13. Let $\mathcal{L}$ be any of our DLs that contains $\mathcal{E} \mathcal{L}$ or has role inclusions. Then $\Sigma$-query entailment of consistent $\mathcal{L}$-KBs is LogSpace-reducible to $\Sigma$-query inseparability of $\mathcal{L}$-KBs.

The proof of Theorem 13 is given in Appendix A and is based on the notions and results introduced in this section: the materialisations of KBs constructed to prove Theorem [12, the normal form of Theorem 8, and the semantic characterisation of $\Sigma$-query entailment given in Theorem6. The underlying idea is to construct modifications $\mathcal{K}_{1}^{\prime}$ and $\mathcal{K}_{2}^{\prime}$ of the given $\mathrm{KBs} \mathcal{K}_{1}$ and $\mathcal{K}_{2}$ such that $\mathcal{K}_{1} \Sigma$-query entails $\mathcal{K}_{2}$ iff $\mathcal{K}_{1}$ and $\mathcal{K}_{1}^{\prime} \cup \mathcal{K}_{2}^{\prime}$ are $\Sigma$-query inseparable. Note that modifications of $\mathcal{K}_{1}$ and $\mathcal{K}_{2}$ are, in general, necessary: let $\mathcal{K}_{1}=(\emptyset,\{A(a)\}), \mathcal{K}_{2}=(\{A \sqsubseteq B\},\{C(a)\})$ and $\Sigma=\{A, B\}$; then $\mathcal{K}_{1} \Sigma$-query entails $\mathcal{K}_{2}$ but $\mathcal{K}_{1}$ does not $\Sigma$-query entail $\mathcal{K}_{1} \cup \mathcal{K}_{2}$ since $\mathcal{K}_{1} \cup \mathcal{K}_{2} \vDash B(a)$.

## 4. Finite $\boldsymbol{\Sigma}$-homomorphic Embeddability by Games

In this section, we show that, for a DL $\mathcal{L}$ having finitely generated materialisations, the problem of checking finite $\Sigma$-homomorphic embeddability between materialisations of KBs can be reduced to the problem of finding a winning strategy in a game played on the generating structures for these KBs.

We begin by giving a brief abstract description of the games we need. Every game $G$ is played by two players, player 1 and player 2 , and defined by a set $\mathfrak{S}$ of states, a set $\mathfrak{C}$ of challenges, and two functions $\chi: \mathfrak{S} \rightarrow 2^{\mathbb{C}}$ and $\rho: \mathfrak{S} \times \mathfrak{C} \rightarrow 2^{\mathfrak{G}}$, where $\chi(\mathfrak{s})$ is the set of challenges player 2 can choose from in any state $\mathfrak{s}$ and $\rho(\mathfrak{s}, \mathfrak{c})$ is the set of responses available to player 1 in order to reply to any challenge c made by player 2 in the state $\mathfrak{s}$. The game starts in an initial state $\mathfrak{s}_{0} \in \mathfrak{S}$ and is played in rounds. In each round $i, i>0$, the current state is $\mathfrak{s}_{i-1} \in \mathfrak{G}$. If $\chi\left(\mathfrak{s}_{i-1}\right)=\emptyset$, then player 2 loses. Otherwise, player 2 challenges player 1 by choosing $\mathfrak{c}_{i} \in \chi\left(\mathfrak{s}_{i-1}\right)$. If $\rho\left(\mathfrak{s}_{i-1}, \mathfrak{c}_{i}\right)=\emptyset$, then player 1 loses. Otherwise, player 1 responds with $\mathfrak{s}_{i} \in \rho\left(\mathfrak{s}_{i-1}, \mathfrak{c}_{i}\right)$, which becomes the current state for the next round $i+1$. A play of length $n$ starting from $\mathfrak{s}_{0} \in \mathfrak{S}$ is any sequence $\mathfrak{s}_{0}, \ldots, \mathfrak{s}_{n}$ of states obtained as described above. For any ordinal $\lambda \leq \omega$, we say that player 1 has a $\lambda$-winning strategy in the game $G$ starting from $\mathfrak{s}_{0}$ if, for any play $\mathfrak{s}_{0}, \ldots, \mathfrak{s}_{n}$ with $n<\lambda$ that is played according to this strategy, player 1 has a response to any challenge of player 2 in the final state $\mathfrak{s}_{n}$. The following proposition can be proved by a straightforward translation of the games introduced above into reachability games and using the known results [32, 33]:

[^3]Proposition 14. Given a finite game $G=(\mathfrak{S}, \mathfrak{C}, \chi, \rho)$ defined above and a state $\mathfrak{s}_{0} \in \mathfrak{S}$, it can be checked in time polynomial in the size of $\mathfrak{\subseteq}$ and $\mathfrak{C}$ whether player 1 has an $\omega$-winning strategy from $\mathfrak{s}_{0}$.

We now reformulate the definition of finite $\Sigma$-homomorphic embedding in game-theoretic terms. Let $\mathcal{M}_{1}$ and $\mathcal{M}_{2}$ be the materialisations for (consistent) KBs $\mathcal{K}_{1}$ and $\mathcal{K}_{2}$, respectively. The states of the game $G_{\Sigma}\left(\mathcal{M}_{2}, \mathcal{M}_{1}\right)$ are of the form $(\pi \mapsto \sigma)$, where $\pi \in \Delta^{\mathcal{M}_{2}}$ and $\sigma \in \Delta^{\mathcal{M}_{1}}$. Intuitively, $(\pi \mapsto \sigma)$ means that ' $\pi$ is to be $\Sigma$-homomorphically mapped to $\sigma^{\prime}$. The game is played by player 1 and player 2 starting from some initial state $\left(\pi_{0} \mapsto \sigma_{0}\right)$. The aim of player 1 is to demonstrate that there exists a $\Sigma$-homomorphism from (a finite subinterpretation of) $\mathcal{M}_{2}$ into $\mathcal{M}_{1}$ with $\pi_{0}$ mapped to $\sigma_{0}$, while player 2 wants to show that there is no such homomorphism. In each round $i>0$ of the game, player 2 challenges player 1 with some $\pi_{i} \in \Delta^{\mathcal{M}_{2}}$ such that $\boldsymbol{r}_{\Sigma}^{\mathcal{M}_{2}}\left(\pi_{i-1}, \pi_{i}\right) \neq \emptyset$. Player 1 , in turn, has to respond with some $\sigma_{i} \in \Delta^{\mathcal{M}_{1}}$ such that the already constructed partial $\Sigma$-homomorphism can be extended with $\pi_{i} \mapsto \sigma_{i}$ :
$-\sigma_{i}=\pi_{i}, \quad$ if $\pi_{i} \in \operatorname{part}_{\Sigma}^{\mathcal{H}_{2}}$,
$-\boldsymbol{t}_{\Sigma}^{\mathcal{M}_{2}}\left(\pi_{i}\right) \subseteq \boldsymbol{t}_{\Sigma}^{\mathcal{M}_{1}}\left(\sigma_{i}\right)$ and $\boldsymbol{r}_{\Sigma}^{\mathcal{M}_{2}}\left(\pi_{i-1}, \pi_{i}\right) \subseteq \boldsymbol{r}_{\Sigma}^{\mathcal{M}_{1}}\left(\sigma_{i-1}, \sigma_{i}\right) ;$
remember that part $\Sigma^{\mathcal{H}_{2}} \subseteq \operatorname{ind}\left(\mathcal{K}_{2}\right)$. It is easy to see that if,

- for any $\pi_{0} \in \Delta^{\mathcal{M}_{2}}$, there exists $\sigma_{0} \in \Delta^{\mathcal{M}_{1}}$ such that player 1 has an $\omega$-winning strategy in the game $G_{\Sigma}\left(\mathcal{M}_{2}, \mathcal{M}_{1}\right)$ starting from $\left(\pi_{0} \rightarrow \sigma_{0}\right)$,
then there exists a $\Sigma$-homomorphism from $\mathcal{M}_{2}$ into $\mathcal{M}_{1}$, and the other way round. That $\mathcal{M}_{2}$ is finitely $\Sigma$-homomorphically embeddable into $\mathcal{M}_{1}$ is equivalent to the following condition:
- for any $\pi_{0} \in \Delta^{\mathcal{M}_{2}}$ and any $n<\omega$, there exists $\sigma_{0} \in \Delta^{\mathcal{M}_{1}}$ such that player 1 has an $n$-winning strategy in the game $G_{\Sigma}\left(\mathcal{M}_{2}, \mathcal{M}_{1}\right)$ starting from $\left(\pi_{0} \rightarrow \sigma_{0}\right)$.
This criterion, however, does not immediately yield any algorithm to decide finite $\Sigma$-homomorphic embeddability because both $\mathcal{M}_{2}$ and $\mathcal{M}_{1}$ can be infinite. Our aim now is to show that the existence of $n$-winning strategies for player 1 in this simple infinite game $G_{\Sigma}\left(\mathcal{M}_{2}, \mathcal{M}_{1}\right)$ is equivalent to the existence of winning strategies in a more involved game played on the finite generating structures for $\mathcal{M}_{2}$ and $\mathcal{M}_{1}$. First, in Section 4.1 we replace $\mathcal{M}_{2}$ with its finite generating structure $\mathcal{G}_{2}$, in which player 2 can only make challenges indicated by the generating relation $\rightsquigarrow \Sigma_{2}^{\Sigma}$. Replacing $\mathcal{M}_{1}$ with $\mathcal{G}_{1}$ is not so easy because player 1 can respond not only in the 'forward' direction (according to $\rightsquigarrow{\underset{1}{\Sigma}}^{\Sigma}$ ), but also in the 'backward' direction (because the label of $\rightsquigarrow{ }_{2}^{\Sigma}$ can be included in the inverse of the label of $\rightsquigarrow{ }_{1}^{\Sigma}$ ). In the latter case, we have to ensure that all the responses of player 1 stay on the same branch of $\mathcal{M}_{1}$, which obviously complicates the game. In Section 4.2, we consider the forward strategies that are suitable for DLs without inverse roles. The general strategies are formulated in Section 4.5. To make the exposition more transparent, we decompose these strategies into backward strategies defined in Section 4.3, and start-bounded ones analysed in Section 4.4 .

We require the following notation throughout this section. Suppose a $\operatorname{DL} \mathcal{L}$ has finitely generated materialisations. Let $\mathcal{K}$ be an $\mathcal{L}$-KB and $\mathcal{G}$ its generating structure. For a relational signature $\Sigma$, the $\Sigma$-types $\boldsymbol{t}_{\Sigma}^{\mathcal{G}}(w)$ and $\boldsymbol{r}_{\Sigma}^{\mathcal{G}}\left(w, w^{\prime}\right)$ of $w, w^{\prime} \in \Delta^{\mathcal{G}}$ are defined by:

$$
\boldsymbol{t}_{\Sigma}^{\mathcal{G}}(w)=\left\{\Sigma \text {-concept name } A \mid w \in A^{\mathcal{G}}\right\}, \quad \boldsymbol{r}_{\Sigma}^{\mathcal{G}}\left(w, w^{\prime}\right)= \begin{cases}\left\{\Sigma \text {-role } R \mid\left(w, w^{\prime}\right) \in R^{\mathcal{G}}\right\}, & \text { if } w, w^{\prime} \in \operatorname{ind}(\mathcal{K}) \\ \left\{\Sigma \text {-role } R \mid R \in\left(w, w^{\prime}\right)^{\mathcal{G}}\right\}, & \text { if } w \rightsquigarrow w^{\prime} \\ \emptyset, & \text { otherwise }\end{cases}
$$

where $\left(P^{-}\right)^{\mathcal{G}}$ is the inverse of $P^{\mathcal{G}}$. We also define $\overline{\boldsymbol{r}}_{\Sigma}^{\mathcal{G}}\left(w, w^{\prime}\right)$ to contain the inverses of the roles in $\boldsymbol{r}_{\Sigma}^{\mathcal{G}}\left(w, w^{\prime}\right)$. Note that $\overline{\boldsymbol{r}}^{\mathcal{G}}(a, b)=\boldsymbol{r}^{\mathcal{G}}(b, a)$, for $a, b \in \operatorname{ind}(\mathcal{K})$ but, in general, $\overline{\boldsymbol{r}}_{\Sigma}^{\mathcal{G}}\left(w, w^{\prime}\right)$ is not the same as $\boldsymbol{r}_{\Sigma}^{\mathcal{G}}\left(w^{\prime}, w\right)$ as shown by the $T^{-}, S^{-}$-cycle in Fig. 2] We also write

$$
w \rightsquigarrow^{\Sigma} w^{\prime} \quad \text { if } \quad w \rightsquigarrow w^{\prime} \quad \text { and } \quad r_{\Sigma}^{\mathcal{G}}\left(w, w^{\prime}\right) \neq \emptyset,
$$

that is, if $w$ generates $w^{\prime}$ with a non-empty $\Sigma$-label of $w \rightsquigarrow w^{\prime}$ in $\mathcal{G}(\rightsquigarrow$-arrows with empty $\Sigma$-labels are irrelevant for $\Sigma$-homomorphisms).

For the rest of the section, we fix consistent $\mathcal{L}$-KBs $\mathcal{K}_{1}$ and $\mathcal{K}_{2}$, and a relational signature $\Sigma$. Let $\mathcal{G}_{i}=\left(\Delta^{\mathcal{G}_{i}}, \mathcal{G}_{i}, \rightsquigarrow_{i}\right)$ be a generating structure for $\mathcal{K}_{i}$ and let $\mathcal{M}_{i}$ be its unravelling; $\mathcal{G}_{i}^{\Sigma}$ and $\mathcal{M}_{i}^{\Sigma}$ denote the restrictions of $\mathcal{G}_{i}$ and $\mathcal{M}_{i}$ to $\Sigma$. We first define the game played on the finite generating structure $\mathcal{G}_{2}^{\Sigma}$ and the possibly infinite materialisation $\mathcal{M}_{1}^{\Sigma}$.

### 4.1. Infinite Game $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$

The states of this game are of the form $\mathfrak{s}_{i}=\left(u_{i} \mapsto \sigma_{i}\right)$, for $i \geq 0, u_{i} \in \Delta^{\mathcal{G}_{2}}$ and $\sigma_{i} \in \Delta^{\mathcal{M}_{1}}$, such that
( $\left.\mathrm{s}_{1}\right) \boldsymbol{t}_{\Sigma}^{\mathcal{G}_{2}}\left(u_{i}\right) \subseteq \boldsymbol{t}_{\Sigma}^{\mathcal{M}_{1}}\left(\sigma_{i}\right)$.
The game starts in a state $\mathfrak{s}_{0}=\left(u_{0} \mapsto \sigma_{0}\right)$ with
$\left(\mathbf{s}_{0}\right) \sigma_{0}=u_{0}$ in case $u_{0} \in \operatorname{part}_{\Sigma}^{\mathcal{N}_{2}}$.
In each round $i>0$, player 2 challenges player 1 with some $u_{i} \in \Delta^{\mathcal{G}_{2}}$ such that $u_{i-1} \rightsquigarrow_{2}^{\Sigma} u_{i}$. Player 1 has to respond with a $\sigma_{i} \in \Delta^{\mathcal{M}_{1}}$ satisfying ( $\mathbf{s}_{1}$ ) and
( $\left.\mathbf{s}_{2}\right) \boldsymbol{r}_{\Sigma}^{\mathcal{G}_{2}}\left(u_{i-1}, u_{i}\right) \subseteq \boldsymbol{r}_{\Sigma}^{\mathcal{M}_{1}}\left(\sigma_{i-1}, \sigma_{i}\right)$.
This gives the next state $\mathfrak{s}_{i}=\left(u_{i} \mapsto \sigma_{i}\right)$. Note that of all the $u_{i}$ only $u_{0}$ may be an ABox individual from $\operatorname{ind}\left(\mathcal{K}_{2}\right)$; however, there is no such a restriction on the $\sigma_{i}$. As the game $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ is not played on the individuals of $\mathcal{K}_{2}$, we need to make sure that the ABox part of $\mathcal{M}_{2}$ is $\left(\Sigma\right.$, ind $\left.\left(\mathcal{K}_{2}\right)\right)$-homomorphically embeddable into the ABox part of $\mathcal{M}_{1}$. Thus, we require an additional condition:
(abox) $\operatorname{part}_{\Sigma}^{\mathcal{M}_{2}} \subseteq \operatorname{ind}\left(\mathcal{K}_{1}\right)$ and $\boldsymbol{t}_{\Sigma}^{\mathcal{M}_{2}}(a) \subseteq \boldsymbol{t}_{\Sigma}^{\mathcal{M}_{1}}(a)$ and $\boldsymbol{r}_{\Sigma}^{\mathcal{M}_{2}}(a, b) \subseteq \boldsymbol{r}_{\Sigma}^{\mathcal{M}_{1}}(a, b)$, for any $a, b \in \operatorname{part}_{\Sigma}^{\mathcal{M}_{2}}$.
The following theorem gives a game-theoretic flavour to the criterion of Theorem6
Theorem 15. (i) $\mathcal{M}_{2}$ is finitely $\Sigma$-homomorphically embeddable into $\mathcal{M}_{1}$ if and only if (abox) and the following condition hold:
(win) for any $u_{0} \in \Delta^{\mathcal{G}_{2}}$ and $n<\omega$, there exists $\sigma_{0} \in \Delta^{\mathcal{M}_{1}}$ such that player 1 has an $n$-winning strategy in the game $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from $\left(u_{0} \mapsto \sigma_{0}\right)$.
(ii) There exists a $\Sigma$-homomorphism from $\mathcal{M}_{2}$ to $\mathcal{M}_{1}$ if and only if (abox) and the following condition hold:
( $\omega$-win) for any $u_{0} \in \Delta^{\mathcal{G}_{2}}$, there is $\sigma_{0} \in \Delta^{\mathcal{M}_{1}}$ such that player 1 has an $\omega$-winning strategy in the game $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from $\left(u_{0} \mapsto \sigma_{0}\right)$.

Proof. We only prove (i) and leave (ii) to the reader.
$(\Rightarrow)$ Suppose $\mathcal{M}_{2}$ is finitely $\Sigma$-homomorphically embeddable into $\mathcal{M}_{1}$. Then (abox) holds by the definition of $\Sigma$ homomorphism. To show that ( $\mathbf{w i n}$ ) holds, suppose $u_{0} \in \Delta^{\mathcal{G}_{2}}$ and $n<\omega$ are given. Take a finite subinterpretation $\mathcal{M}_{02}$ of $\mathcal{M}_{2}$ that contains $\sigma u_{0}$, for some (say, the shortest) word $\sigma$, and all those elements of $\mathcal{M}_{2}$ whose distance from $\sigma u_{0}$ does not exceed $n\left(\mathcal{M}_{02}\right.$ also contains all individual names of $\left.\mathcal{M}_{2}\right)$. Let $h: \mathcal{M}_{02} \rightarrow \mathcal{M}_{1}$ be a $\left(\Sigma\right.$, ind $\left.\left(\mathcal{K}_{2}\right)\right)$ homomorphism. Take $\sigma_{0}=h\left(\sigma u_{0}\right)$. Clearly, $u_{0}$ and $\sigma_{0}$ satisfy ( $\mathbf{s}_{0}$ ) and ( $\mathbf{s}_{1}$ ). We show that player 1 has an $n$-winning strategy in the game $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from $\left(u_{0} \mapsto \sigma_{0}\right)$. Suppose player 2 picks $u_{0} \rightsquigarrow \Sigma_{2}^{\Sigma} u_{1}$. Then $\sigma u_{0} u_{1}$ is an element of $\mathcal{M}_{02}$, and player 1 responds with $\sigma_{1}=h\left(\sigma u_{0} u_{1}\right)$. Conditions ( $\mathbf{s}_{1}$ ) and ( $\mathbf{s}_{2}$ ) hold because $h$ is a $\Sigma$ homomorphism. In the same way player 1 uses $h$ to respond to all challenges of player 2 in any round $k<n$ of the game $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$.
$(\Leftarrow)$ Let $\mathcal{M}_{02}$ be a finite subinterpretation of $\mathcal{M}_{2}$. We enumerate elements of the domain of $\mathcal{M}_{02}$ in such a way that $\sigma$ appears in the list before $\sigma^{\prime}$ whenever $\sigma^{\prime}=\sigma u$, for some $u$. We define, by induction, a ( $\Sigma$, ind $\left(\mathcal{K}_{2}\right)$ )-homomorphism $h: \mathcal{M}_{02} \rightarrow \mathcal{M}_{1}$ as follows. Let $n$ be the number of elements in the domain of $\mathcal{M}_{02}$. Pick the first (in the order described above) element $\sigma$ that has not been mapped to $\mathcal{M}_{1}$ yet. There are two possible options.

- Suppose first that there is no $\sigma_{0} \in \Delta^{\mathcal{M}_{02}}$ such that $\sigma=\sigma_{0} u$ and tail $\left(\sigma_{0}\right) \rightsquigarrow{ }_{2}^{\Sigma} u$, for some $u$. Then, by (win), there is $\sigma^{\prime} \in \Delta^{\mathcal{M}_{1}}$ such that player 1 has an $n$-winning strategy in the game $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from (tail $\left.(\sigma) \mapsto \sigma^{\prime}\right)$. We set $h(\sigma)=\sigma^{\prime}$. Note that if $\sigma=a$, for some $a \in \operatorname{part}_{\Sigma}^{\mathcal{H}_{2}}$, then, by $\left(\mathbf{s}_{0}\right), h(a)=a$.
- Otherwise, we consider the longest sequence $u_{1}, \ldots, u_{k}, k \geq 1$, such that tail $\left(\sigma_{0}\right) \rightsquigarrow_{2}^{\Sigma} u_{1} \rightsquigarrow_{2}^{\Sigma} \ldots \rightsquigarrow_{2}^{\Sigma} u_{k}$ and $\sigma_{m}=\sigma_{0} u_{1} \cdots u_{m} \in \Delta^{\mathcal{M}_{02}}$, for all $m<k$, with $\sigma=\sigma_{k}$. By the definition of the order, $\sigma_{0}, \ldots, \sigma_{k-1}$ have already been mapped by $h$. By construction and (win), player 1 has an $n$-winning strategy from (tail $\left(\sigma_{0}\right) \mapsto h\left(\sigma_{0}\right)$ ). Therefore, player 1 has a response $\sigma^{\prime}$ to the challenge tail $\left(\sigma_{k-1}\right) \rightsquigarrow_{2}^{\Sigma}$ tail $\left(\sigma_{k}\right)$. So, we set $h(\sigma)=\sigma^{\prime}$.


Figure 3: (a) Example $16 n$-winning strategy in $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ from $(a \mapsto a)$. (b) Example 17 4-winning strategy in $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ from $\left(u_{0} \mapsto \sigma_{4}\right)$.

It is readily seen that, by (abox), $\left(\mathbf{s}_{1}\right)$ and $\left(\mathbf{s}_{2}\right)$, the constructed $h$ is a $\left(\Sigma, \operatorname{ind}\left(\mathcal{K}_{2}\right)\right)$-homomorphism from $\mathcal{M}_{02}$ to $\mathcal{M}_{1}$.
Example 16. Consider $\mathcal{G}_{2}^{\Sigma}$ and $\mathcal{M}_{1}^{\Sigma}$ shown in Fig. 3 a, where $\Sigma=\{Q, R\}$. An $n$-winning strategy for player 1 in $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from $(a \mapsto a)$ is shown by dotted lines with the rounds of the game indicated by the numbers on the dotted lines. In the state ( $a \mapsto a$ ), player 2 has two possible challenges: $a \rightsquigarrow \frac{\Sigma}{2} u$ and $a \rightsquigarrow \frac{\Sigma}{2} u^{\prime}$. In response to the former, player 1 maps $u$ to $a$ and the successive challenges to the elements of the chain that begins with $R Q$ (indicated by indices $1,2, \ldots$ ). In response to the latter challenge, player 1 maps $u^{\prime}$ and all the successive challenges to the same element $a$ (indices $1^{\prime}, 2^{\prime}, \ldots$ ). Note that in all but the starting state, player 2 has only one possible challenge.

Example 17. Consider now $\mathcal{G}_{2}^{\Sigma}$ and $\mathcal{M}_{1}^{\Sigma}$ in Fig. 3 b , where $\Sigma=\{Q, R, S, T\}$ (see also Example 5 . A 4 -winning strategy for player 1 in $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from $\left(u_{0} \mapsto \sigma_{4}\right)$ is shown in Fig. 3 b by dotted lines (again, rounds of the game are indicated by the numbers). In contrast to Example 16, where player 1 either stays in the ABox or always moves away from it, the winning strategy for player 1 now is to move in the opposite direction, towards the ABox. (Note that in round 2, player 2 has two possible challenges, $u_{1} \rightsquigarrow{ }_{2}^{\Sigma} u_{2}$ and $u_{1} \rightsquigarrow{ }_{2}^{\Sigma} v$.) In fact, for any $n>0$, player 1 has an $n$-winning strategy starting from any $\left(u_{0} \mapsto \sigma_{m}\right)$ provided that $m$ is even and $m \geq n$.

The criterion of Theorem 15 does not seem to be a big improvement on Theorem 6 as we still have to deal with an infinite materialisation. Note that, for some DLs such as $\mathcal{E L}$, Horn- $\mathcal{A} \mathcal{L C}$ and DL-Lite horn , it is enough to play the same game as defined above but on the finite generating structures $\mathcal{G}_{2}$ and $\mathcal{G}_{1}$. We denote this naïve reformulation of $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$-in which $\sigma_{i}$ and $\mathcal{M}_{1}$ are replaced with $w_{i}$ and $\mathcal{G}_{1}$, respectively-by $G_{\Sigma}^{n}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ and invite the reader to prove that, in the case of, say DL-Lite ${ }_{\text {horn }}$, Theorem 15 will continue to hold if we replace (win) with the following condition, which can be checked in polynomial time in $O\left(\left|\mathcal{G}_{2}\right| \times\left|\mathcal{G}_{1}\right|\right)$ : for any $u_{0} \in \Delta^{\mathcal{G}_{2}}$, there exists $w_{0} \in \Delta^{\mathcal{G}_{1}}$ such that player 1 has an $\omega$-winning strategy in the game $G_{\Sigma}^{n}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ starting from $\left(u_{0} \mapsto w_{0}\right)$. (We shall obtain this result later as a consequence of a more general theorem.) Unfortunately, the existence of an $\omega$-winning strategy in this naïve game does not imply $\Sigma$-homomorphic embeddability of $\mathcal{M}_{2}$ into $\mathcal{M}_{1}$ for DLs such as DL-Litecore or Horn- $\mathcal{A} \mathcal{L} C I$.

In the remainder of this section, we show that condition (win) in the infinite game $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ can be checked by analysing a much more complex game on the finite generating structures $\mathcal{G}_{2}$ and $\mathcal{G}_{1}$. We consider four types of strategies in $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ : forward, backward, start-bounded and general. For each strategy type, $\theta$, we define a game $G_{\Sigma}^{\theta}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ such that the following conditions are equivalent:
(win- $\boldsymbol{\theta}$ ) for any $u_{0} \in \Delta^{\mathcal{G}_{2}}$ and $n<\omega$, there is $\sigma_{0} \in \Delta^{\mathcal{M}_{1}}$ such that player 1 has an $n$-winning $\theta$-strategy in the infinite game $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from $\left(u_{0} \mapsto \sigma_{0}\right)$;


Figure 4: The forward game $G_{\Sigma}^{f}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ from $(a \mapsto a)$ in Example 18 (a) an $\omega$-winning strategy for player 1 ; (b) the infinite graph $\mathfrak{I}$ for extracting $\omega$-winning strategies.
( $\omega$-win ${ }^{\theta}$ ) for any $u_{0} \in \Delta^{\mathcal{G}_{2}}$, player 1 has an $\omega$-winning strategy in the finite game $G_{\Sigma}^{\theta}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ starting from some state depending on $u_{0}$ and $\theta$.

We begin by considering 'forward' winning strategies (such as in Example 16) that are sufficient for the DLs without inverse roles.

### 4.2. Forward Strategy and Game $G_{\Sigma}^{f}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$

We say that a $\lambda$-strategy $(\lambda \leq \omega)$ for player 1 in the game $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ is forward if, for any play of length $i-1<\lambda$, which conforms with this strategy, and any challenge $u_{i-1} \rightsquigarrow_{2}^{\Sigma} u_{i}$ by player 2, the response $\sigma_{i}$ of player 1 is such that either $\sigma_{i-1}, \sigma_{i} \in \operatorname{ind}\left(\mathcal{K}_{1}\right)$ or $\sigma_{i}=\sigma_{i-1} w$, for some $w \in \Delta^{\mathcal{G}_{1}}$. For instance, if the generating structures $\mathcal{G}_{i}, i=1,2$, are forward then every strategy in $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ is forward, and so (win) coincides with (win-f). By Theorem 12 (ii) and (iii), this is the case for Horn- $\mathcal{A} \mathcal{L C H}$, Horn- $\mathcal{A} \mathcal{L C}, \mathcal{E} \mathcal{L} \mathcal{H}_{\perp}^{d r}$ and $\mathcal{E} \mathcal{L}$.

The existence of a forward $\lambda$-winning strategy for player 1 in $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ is equivalent to the existence of a $\lambda$ winning strategy in the game $G_{\Sigma}^{f}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ whose states, initial states, challenges of player 2 and responses of player 1 are defined in the table below:

| forward game $G_{\Sigma}^{f}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ |  |
| :---: | :--- |
| states, $i \geq 0$ | $\left(u_{i} \mapsto w_{i}\right)$ with $u_{i} \in \Delta^{\mathcal{G}_{2}}, w_{i} \in \Delta^{\mathcal{G}_{1}}$ <br> and $\boldsymbol{t}_{\Sigma}^{\mathcal{G}_{2}}\left(u_{i}\right) \subseteq \boldsymbol{t}_{\Sigma}^{\mathcal{G}_{1}}\left(w_{i}\right)$ |
| initial state | $\left(u_{0} \mapsto w_{0}\right)$ such that $w_{0}=u_{0}$ in case $u_{0} \in \operatorname{part}_{\Sigma}^{\mathcal{M}_{2}}$ |
| challenges, $i>0$ | $u_{i-1} \rightsquigarrow_{2}^{\Sigma} u_{i}$ |
| responses, $i>0$ | $w_{i}$ such that either $w_{i-1} \rightsquigarrow_{1} w_{i}$ or $w_{i-1}, w_{i} \in \operatorname{ind}\left(\mathcal{K}_{1}\right)$ <br> and $\boldsymbol{r}_{\Sigma}^{\mathcal{G}_{2}}\left(u_{i-1}, u_{i}\right) \subseteq \boldsymbol{r}_{\Sigma}^{\mathcal{G}_{1}}\left(w_{i-1}, w_{i}\right)$ |

Note again that of all $u_{i}$ only $u_{0}$ may belong to $\operatorname{ind}\left(\mathcal{K}_{2}\right)$.
Example 18. Consider $\mathcal{G}_{2}^{\Sigma}$ and $\mathcal{G}_{1}^{\Sigma}$ shown in Fig. 4 , where $\mathcal{G}_{1}^{\Sigma}$ is a generating structure that can be unravelled into $\mathcal{M}_{1}^{\Sigma}$ from Example 16. It is not hard to see that, for any $u_{0} \in \Delta^{\mathcal{G}_{2}}$, there is $w_{0} \in \Delta^{\mathcal{G}_{1}}$ such that player 1 has an $\omega$-winning strategy in $G_{\Sigma}^{f}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ starting from $\left(u_{0} \mapsto w_{0}\right)$. Such a strategy starting from $(a \mapsto a)$ is depicted by dotted lines.

The reader may find more elegant proofs of the following lemma. However, the constructions we use will be required for the proofs of other lemmas, in particular, a more general Lemma 30 .

Lemma 19. Conditions (win-f) and ( $\omega$ - $\boldsymbol{w i n}^{f}$ ) are equivalent. More precisely, for any $u_{0} \in \Delta^{G_{2}}$ and $\sigma_{0} \in \Delta^{\mathcal{M}_{1}}$, the following are equivalent:
(a) player 1 has an $\omega$-winning forward strategy in the game $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from $\left(u_{0} \mapsto \sigma_{0}\right)$;
(b) for every $n<\omega$, player 1 has an n-winning forward strategy in the game $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from $\left(u_{0} \mapsto \sigma_{0}\right)$;
(c) player 1 has an $\omega$-winning strategy in the game $G_{\Sigma}^{f}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ starting from $\left(u_{0} \mapsto \operatorname{tail}\left(\sigma_{0}\right)\right)$.

Proof. $(a) \Rightarrow(b)$ is trivial.
$(b) \Rightarrow(c)$ We construct a (possibly infinite) directed graph $\mathfrak{I}$ whose nodes are of the form $(u \mapsto \delta)$, where $u \in \Delta^{\mathcal{G}_{2}}$ and $\delta$ is a suffix of some element in $\Delta^{\mathcal{M}_{1}}$, and whose arrows are labelled with $u \rightsquigarrow{ }_{2}^{\Sigma} u^{\prime}$ so that the following conditions hold:
(1) $\mathfrak{I}$ contains an initial node $\left(u_{0} \mapsto \operatorname{tail}\left(\sigma_{0}\right)\right)$;
(2) $\boldsymbol{t}_{\Sigma}^{\mathcal{G}_{2}}(u) \subseteq \boldsymbol{t}_{\Sigma}^{\mathcal{G}_{1}}$ (tail $(\delta)$ ), for every node $(u \mapsto \delta)$ in $\mathfrak{I}$;
(3) for any $u \rightsquigarrow{ }_{2}^{\Sigma} u^{\prime}$, every node $\left(u \mapsto \delta\right.$ ) in $\mathfrak{I}$ has exactly one ( $u \rightsquigarrow{ }_{2}^{\Sigma} u^{\prime}$ )-successor, which can be of the following forms:
(3.1) $\left(u^{\prime} \mapsto \delta w^{\prime}\right)$ if $\operatorname{tail}(\delta)=w, w w_{1} w^{\prime}$ and $\boldsymbol{r}_{\Sigma}^{\mathcal{G}_{2}}\left(u, u^{\prime}\right) \subseteq r_{\Sigma}^{\mathcal{G}_{1}}\left(w, w^{\prime}\right)$;
(3.2) $\left(u^{\prime} \mapsto b\right)$ if $\delta=a \in \operatorname{ind}\left(\mathcal{K}_{1}\right), \quad b \in \operatorname{ind}\left(\mathcal{K}_{1}\right)$ and $r_{\Sigma}^{\mathcal{G}_{2}}\left(u, u^{\prime}\right) \subseteq r_{\Sigma}^{\mathcal{G}_{1}}(a, b)$.
(The infinite graph $\mathfrak{I}$ for the winning strategy in Example 18 is depicted in Fig. 4 b.)
Such a graph $\mathfrak{I}$ (if it exists) gives rise to the required $\omega$-winning strategy for player 1 in $G_{\Sigma}^{f}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$. Indeed, consider the function $s$ mapping the nodes of $\mathfrak{I}$ to states in the game $G_{\Sigma}^{f}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ and defined by taking

$$
\mathbf{s}(u \mapsto \delta)=(u \mapsto \operatorname{tail}(\delta)) ;
$$

in particular, the initial node $\mathfrak{n}_{0}$ of $\mathfrak{I}$ is mapped to the starting state: $\mathrm{s}\left(\mathfrak{n}_{0}\right)=\left(u_{0} \mapsto\right.$ tail $\left.\left(\sigma_{0}\right)\right)$. Now, when challenged by player 2 with $u \rightsquigarrow \sum_{2}^{\Sigma} u^{\prime}$ in a state $\mathrm{s}(\mathfrak{n})$, player 1 picks a unique $u \rightsquigarrow{ }_{2}^{\Sigma} u^{\prime}$-successor $\mathfrak{n}^{\prime}$ of any $\mathfrak{r}$ in $\mathfrak{I}$ such that $\mathrm{s}(\mathfrak{r})=\mathrm{s}(\mathfrak{r})$, and responds to the challenge with $\mathrm{s}\left(\mathrm{n}^{\prime}\right)$. Note that although nodes are not uniquely determined by the states, any choice of $r$ as above results in an $\omega$-winning strategy for player 1 .

We now show that $\mathfrak{I}$ exists. Let $\mathbb{S}_{0}$ be the given set of $n$-winning forward strategies for player 1 in $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from $\left(u_{0} \mapsto \sigma_{0}\right)$. Let $w_{0}=\operatorname{tail}\left(\sigma_{0}\right)$. Define $\mathfrak{I}_{0}$ to be the graph with the single initial node $\left(u_{0} \mapsto w_{0}\right)$. Clearly it satisfies (1) and (2) above. If it also satisfies (3), then we are done. Otherwise, we take all the challenges $u_{0} \rightsquigarrow \Sigma_{2}^{\Sigma} u_{1}^{1}, \ldots, u_{0} \rightsquigarrow_{2}^{\Sigma} u_{1}^{k}$ by player 2 and use the pigeonhole principle and the fact that the number of roles in $\mathcal{K}_{1}$ is finite to find $w_{1}^{1}, \ldots, w_{1}^{k} \in \Delta^{\mathcal{G}_{1}}$ and a subset $\mathbb{S}_{1} \subseteq \mathbb{S}_{0}$ such that, for any challenge $u_{0} \rightsquigarrow_{2}^{\Sigma} u_{1}^{i}$, every strategy $\mathcal{S} \in \mathbb{S}_{1}$ gives a response ( $u_{1}^{i} \mapsto \sigma_{1}^{i}$ ) with tail $\left(\sigma_{1}^{i}\right)=w_{1}^{i}$. If $w_{1}^{i} \in \operatorname{ind}\left(\mathcal{K}_{1}\right)$ then we add to $\mathfrak{I}_{0}$ the node ( $u_{1}^{i} \mapsto w_{1}^{i}$ ); and if $w_{1}^{i} \notin \operatorname{ind}\left(\mathcal{K}_{1}\right)$ then we add to $\mathfrak{I}_{0}$ the node ( $u_{1}^{i} \mapsto w_{0} w_{1}^{i}$ ); we also add a $u_{0} \rightsquigarrow_{2}^{\Sigma} u_{1}^{i}$ arc connecting ( $u_{0} \mapsto w_{0}$ ) with the newly introduced node. This gives us the graph $\mathfrak{I}_{1}$. We proceed in the same way and construct a sequence of directed graphs $\mathfrak{I}_{0} \subseteq \mathfrak{I}_{1} \subseteq \ldots$ until we either reach some $\mathfrak{I}_{k}$ satisfying (1)-(3) or obtain an infinite sequence and take $\mathfrak{I}=\bigcup_{k<\omega} \mathfrak{I}_{k}$, which obviously satisfies (1)-(3).
$(c) \Rightarrow(a)$ The given $\omega$-winning strategy in $G_{\Sigma}^{f}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ starting from ( $u_{0} \mapsto$ tail $\left(\sigma_{0}\right)$ ) is mirrored by an obvious $\omega$-winning forward strategy in $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from $\left(u_{0} \mapsto \sigma_{0}\right)$.
Example 20. Consider again $\mathcal{G}_{2}^{\Sigma}$ and $\mathcal{G}_{1}^{\Sigma}$ in Fig. 4a. Figure 5 depicts the full graph of the game $G_{\Sigma}^{f}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$, in which rectangles represent the states and circles the challenges of player 2 . Note that it contains two dead-ends reachable from $(a \mapsto a)$-the challenges $u^{\prime} \rightsquigarrow \Sigma_{2}^{\Sigma} u^{\prime}$ in the state $\left(u^{\prime} \mapsto w\right)$ and $u \rightsquigarrow_{2}^{\Sigma} v$ in $(u \mapsto w)$ of player 2 to which player 1 has no response (the dead-ends are indicated by double circles). The $\omega$-winning strategy for player 1 in this graph is, therefore, to avoid these dead-ends; it is indicated by the shaded states.

In view of Theorem 12 (ii) and (iii) and Proposition 14, we then obtain:
Theorem 21. For combined complexity, checking $\Sigma$-query entailment is in P for $\mathcal{E} \mathcal{L}$ and $\mathcal{E} \mathcal{L} \mathcal{H}_{\perp}^{d r} K B s$, and in ExpTime for Horn- $\mathcal{A L C}$ and Horn- $\mathcal{A L C \mathcal { H }}$ KBs. For data complexity, it is in P for all these DLs.

In comparison to forward strategies, the winning strategies used in Example 17 can be described as 'backward'.





Figure 5: The full graph of the game $G_{\Sigma}^{f}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ in Example 16

### 4.3. Backward Strategy and Game $G_{\Sigma}^{b}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$

A $\lambda$-strategy for player 1 in $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ is backward if, for any play of length $i-1<\lambda$, which conforms with this strategy, and any challenge $u_{i-1} \rightsquigarrow{ }_{2}^{\Sigma} u_{i}$ by player 2 , the response $\sigma_{i}$ of player 1 is the immediate predecessor of $\sigma_{i-1}$ in $\mathcal{M}_{1}$ in the sense that $\sigma_{i-1}=\sigma_{i} w$, for some $w \in \Delta^{\mathcal{G}_{1}}$ (player 1 loses in case $\sigma_{i-1} \in \operatorname{ind}\left(\mathcal{K}_{1}\right)$ ). Note that, since $\mathcal{M}_{1}$ is tree-shaped, the response of player 1 to any different challenge $u_{i-1} \rightsquigarrow{ }_{2}^{\Sigma} u_{i}^{\prime}$ must be the same $\sigma_{i}$; cf. Example 17. That is why the states of the game $G_{\Sigma}^{b}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ are of the form $\mathfrak{s}_{i}=\left(\Xi_{i} \mapsto w_{i}\right)$, where $\Xi_{i}$ is a non-empty subset of $\Delta^{\mathcal{G}_{2}}$ and $w_{i} \in \Delta^{\mathcal{G}_{1}}$. For each $i>0$, player 2 always challenges player 1 with the set $\Xi_{i}=\Xi_{i-1}^{\rightsquigarrow}$, where

$$
\Xi^{\rightsquigarrow}=\left\{v \in \Delta^{\mathcal{G}_{2}} \mid u \rightsquigarrow \sum_{2}^{\Sigma} v \text {, for some } u \in \Xi\right\} \text {, }
$$

provided that it is not empty (otherwise, player 2 loses). Player 1 responds with $w_{i} \in \Delta^{\mathcal{G}_{1}}$ such that $w_{i} \rightsquigarrow_{1} w_{i-1}$. More formally, the states, challenges of player 2 and responses by player 1 are defined as follows:

| backward game $G_{\Sigma}^{b}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ |  |
| :---: | :--- |
| states, $i \geq 0$ | $\left(\Xi_{i} \mapsto w_{i}\right)$ with $\Xi_{i} \subseteq \Delta^{\mathcal{G}_{2}}, \Xi_{i} \neq \emptyset, w_{i} \in \Delta^{\mathcal{G}_{1}}$ <br> and $\boldsymbol{t}_{\Sigma}^{\mathcal{G}_{2}}(u) \subseteq \boldsymbol{t}_{\Sigma}^{\mathcal{G}_{1}}\left(w_{i}\right)$, for all $u \in \Xi_{i}$ |
| initial state | $\left(\left\{u_{0}\right\} \mapsto w_{0}\right)$ such that $w_{0}=u_{0}$ in case $u_{0} \in$ part $_{\Sigma}^{\mathcal{M}_{2}}$ |$|$| challenges, $i>0$ | $\Xi_{i}=\Xi_{i-1}^{\rightsquigarrow}$ provided that $\Xi_{i} \neq \emptyset$ |
| :---: | :--- |
| responses, $i>0$ | $w_{i}$ such that $w_{i} \rightsquigarrow_{1} w_{i-1}$ <br> and $\boldsymbol{r}_{\Sigma}^{\mathcal{G}_{2}}(u, v) \subseteq \bar{r}_{\Sigma}^{\mathcal{G}_{1}}\left(w_{i}, w_{i-1}\right)$, for all $u \in \Xi_{i-1}$ and $v \in \Xi_{i}$ |

Note that, by definition, $\Xi_{0}$ is a singleton and the sets $\Xi_{i}$, for $i>0$, contain no individuals from ind $\left(\mathcal{K}_{2}\right)$.
Example 22. Figure 6 a shows an $\omega$-winning strategy for player 1 in $G_{\Sigma}^{b}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ starting from $\left(\left\{u_{0}\right\} \mapsto w_{0}\right)$, where $\mathcal{G}_{1}$ is a generating structure that can be unravelled into $\mathcal{M}_{1}$ in Example 17. Figure 6 p presents the corresponding fragment of the full game graph (shaded nodes form an $\omega$-winning strategy and the non-shaded node leads to a dead-end, where player 1 loses).

Lemma 23. Conditions (win-b) and ( $\boldsymbol{\omega}$-win ${ }^{\boldsymbol{b}}$ ) are equivalent. More precisely, for any $u_{0} \in \Delta^{\mathcal{G}_{2}}$ and $w_{0} \in \Delta^{\mathcal{G}_{1}}$, the following are equivalent:
(a) for every $n<\omega$, there is $\sigma_{0} \in \Delta^{\mathcal{M}_{1}}$ with tail $\left(\sigma_{0}\right)=w_{0}$ such that player 1 has an $n$-winning backward strategy in the game $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from $\left(u_{0} \mapsto \sigma_{0}\right)$;
(b) player 1 has an $\omega$-winning strategy in the game $G_{\Sigma}^{b}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ starting from $\left(\left\{u_{0}\right\} \mapsto w_{0}\right)$.


Figure 6: The backward game $G_{\Sigma}^{b}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ from $\left(\left\{u_{0}\right\} \mapsto w_{0}\right)$ in Example 22 (a) an $\omega$-winning strategy for player 1; (b) a fragment of the full game graph; (c) the infinite tree $\mathfrak{I}$ for extracting $\omega$-winning strategies.

Proof. (a) $\Rightarrow(b)$ We begin by constructing a possibly infinite directed tree $\mathfrak{I}$ with nodes of the form $(u \mapsto w, i)$, where $u \in \Delta^{\mathcal{G}_{2}}, w \in \Delta^{\mathcal{G}_{1}}$ and $0 \leq i<\omega$, whose arrows are labelled with $u \rightsquigarrow_{2}^{\Sigma} u^{\prime}$ so that the following conditions hold:
(1) the root of $\mathfrak{I}$ is of the form $\left(u_{0} \mapsto w_{0}, 0\right)$;
(2) $\boldsymbol{t}_{\Sigma}^{\mathcal{G}_{2}}(u) \subseteq \boldsymbol{t}_{\Sigma}^{\mathcal{G}_{1}}(w)$, for every node $(u \mapsto w, i)$ in $\mathfrak{I}$;
(3) for any $u \rightsquigarrow{ }_{2}^{\Sigma} u^{\prime}$, every node ( $u \mapsto w, i$ ) in $\mathfrak{I}$ has exactly one ( $u \rightsquigarrow{ }_{2}^{\Sigma} u^{\prime}$ )-successor in $\mathfrak{I}$, which is of the form $\left(u^{\prime} \mapsto w^{\prime}, i+1\right)$ and satisfies $w^{\prime} \rightsquigarrow 1 w$ and $\boldsymbol{r}_{\Sigma}^{\mathcal{G}_{2}}\left(u, u^{\prime}\right) \subseteq \overline{\boldsymbol{r}}_{\Sigma}^{\mathcal{G}_{1}}\left(w^{\prime}, w\right)$.
(4) for any nodes $(u \mapsto w, i)$ and $\left(u^{\prime} \mapsto w^{\prime}, i\right)$ in $\mathfrak{I}$, we have $w=w^{\prime}$.
(The infinite tree $\mathfrak{I}$ for the winning strategy in Example 22 is depicted in Fig. 6.)
Such a tree $\mathfrak{I}$ defines an $\omega$-winning strategy for player 1 in $G_{\Sigma}^{b}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ starting from $\left(\left\{u_{0}\right\} \mapsto w_{0}\right)$. In detail, let $w_{0}, w_{1}, \ldots$ be the longest (and so possibly infinite) sequence of elements of $\Delta^{\mathcal{G}_{1}}$ such that, for each $w_{i}$, there exists $u$ with ( $u \mapsto w_{i}, i$ ) a node in $\mathfrak{I}$. Note that, by (4), every $w_{i}$ (if it exists) is uniquely determined. We set

$$
\Xi_{i}=\left\{u \mid\left(u \mapsto w_{i}, i\right) \in \mathfrak{I}\right\}
$$

and observe that $\Xi_{0}=\left\{u_{0}\right\}$ and $\Xi_{i}=\Xi_{i-1}^{\aleph}$ and $\Xi_{i} \neq \emptyset$, for all $i>0$. Take the maximal $m<\omega$ such that $w_{m}$ exists and $w_{i} \neq w_{m}$ for all $i<m$ (in other words, $w_{m}$ is the first repeating element in the sequence). Now the strategy of player 1 is as follows: when challenged by player 2 with some $u \rightsquigarrow \frac{\Sigma}{2} u^{\prime}$ in state $\left(\Xi_{i} \mapsto w_{i}\right)$ with $i \leq m$, player 1 responds with $w_{i+1}$ if $i<m$ and with the uniquely determined $w_{k}$, for $k \leq m$ and $w_{k}=w_{m+1}$, if $i=m$.

We now show that $\mathfrak{I}$ exists. Let $\mathbb{S}_{0}$ be the given set of $n$-winning backward strategies for player 1 in $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from $\left(u_{0} \mapsto \sigma_{0}\right)$, for $\sigma_{0} \in \Delta^{\mathcal{M}_{1}}$ with tail $\left(\sigma_{0}\right)=w_{0}$. Define $\mathfrak{I}_{0}$ to be the tree with the single node $\left(u_{0} \mapsto w_{0}, 0\right)$. Clearly, it satisfies (1), (2) and (4). If it also satisfies (3), then we are done. Otherwise, we take a challenge $u_{0} \leadsto{ }_{2}^{\Sigma} u_{1}$ by player 2 and use the pigeonhole principle to find $w_{1} \in \Delta^{\mathcal{G}_{1}}$ and a subset $\mathbb{S}_{1} \subseteq \mathbb{S}_{0}$ such that, for any challenge $u_{0} \rightsquigarrow \Sigma_{2}^{\Sigma} u^{\prime}$, every strategy $\mathcal{S} \in \mathbb{S}_{1}$ gives a response $\left(u^{\prime} \mapsto \sigma^{\prime}\right)$ with tail $\left(\sigma^{\prime}\right)=w_{1}$. We add to $\mathfrak{I}_{0}$ the nodes $\left(u^{\prime} \mapsto w_{1}, 1\right)$, for any challenge $u_{0} \rightsquigarrow \Sigma_{2} u^{\prime}$. We also add a $u_{0} \rightsquigarrow \Sigma_{2}^{\Sigma} u^{\prime}$ arc connecting ( $u_{0} \mapsto w_{0}, 0$ ) with the newly introduced nodes. This gives us the tree $\mathfrak{I}_{1}$ satisfying (1), (2) and (4). We proceed in this way and construct a sequence of trees $\mathfrak{I}_{0} \subseteq \mathfrak{I}_{1} \subseteq \ldots$ until we either reach some $\mathfrak{I}_{k}$ satisfying (1)-(4) or obtain an infinite sequence and take $\mathfrak{I}=\bigcup_{k<\omega} \mathfrak{I}_{k}$, which obviously satisfies (1)-(4).
$(b) \Rightarrow(a)$ Suppose player 1 has an $\omega$-winning strategy $\mathcal{S}$ starting from $\left(\left\{u_{0}\right\} \mapsto w_{0}\right)$ in the game $G_{\Sigma}^{b}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ and let $n<\omega$. Recall that, for each state $(\Xi \mapsto w)$, there is (at most) one challenge $\Xi^{\prime}=\Xi^{\rightsquigarrow}$. Thus, the first $n$ rounds of a


Figure 7: $\mathcal{M}_{2}^{\Sigma}$ and $\mathcal{M}_{1}^{\Sigma}$ for $\varphi=c_{1} \wedge c_{2} \wedge c_{3}$, where $c_{1}=p_{1} \vee p_{2}, c_{2}=\neg p_{1} \vee p_{2}$ and $c_{3}=\neg p_{2}$. The $T / \perp$ symbols on the arrows of $\mathcal{M}_{2}^{\Sigma}$ indicate the truth value of the respective variable. Only one branch of $\mathcal{M}_{1}^{\Sigma}$ is shown in full detail, with the index of the missing role $C_{i}$ in the black circle next to the arrow.
play according to $\mathcal{S}$ starting from $\left(\left\{u_{0}\right\} \mapsto w_{0}\right)$ are given by a sequence $\left(\Xi_{0} \mapsto w_{0}\right),\left(\Xi_{1} \mapsto w_{1}\right), \ldots,\left(\Xi_{k} \mapsto w_{k}\right)$, where $\Xi_{0}=\left\{u_{0}\right\}$ and either $k=n$ or $k<n$ and $\Xi_{k}^{\rightsquigarrow}=\emptyset$. Take any $\sigma \in \Delta^{\mathcal{M}_{1}}$ with tail $(\sigma)=w_{k}$ and let $\sigma_{0}=\sigma w_{k-1} \cdots w_{0}$. Clearly, player 1 has an $n$-winning backward strategy in $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from ( $u_{0} \mapsto \sigma_{0}$ ).

Although Lemmas 19 and 23 look similar, the game $G_{\Sigma}^{b}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ turns out to be more complex than $G_{\Sigma}^{f}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ because the full game graph is exponential in the size of $\Delta^{\mathcal{G}_{2}} \backslash$ ind $\left(\mathcal{K}_{2}\right)$. The following lemma explains this fact using very simple DL-Lite core $_{\mathcal{H}}^{\mathcal{H}}$ KBs:

Lemma 24. Checking whether player 1 has an $\omega$-winning strategy in $G_{\Sigma}^{b}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ is coNP-hard.
Proof. The proof is by reduction of the unsatisfiability problem for 3CNFs $\varphi=\bigwedge_{i=1}^{m} c_{i}$, where $c_{i}=l_{i 1} \vee l_{i 2} \vee l_{i 3}$ and each $l_{i j}$ is either one of the propositional variables $p_{1}, \ldots p_{k}$ or a negation of such a variable.

Let $N_{1}, \ldots, N_{k}$ be the first $k$ prime numbers (observe that $1<N_{k} \leq k^{2}$ ). We take a role name $R$, a role name $C_{i}$, for each clause $c_{i}$ in $\varphi$, and a role name $S_{j \ell}$, for each $1 \leq j \leq k$ and $1 \leq \ell \leq N_{j}$. Now we define a KB $\mathcal{K}_{2}=\left(\mathcal{T}_{2},\{A(a)\}\right)$, where $\mathcal{T}_{2}$ contains $A \sqsubseteq \exists R$, the following inclusions, for $1 \leq j \leq k$ and $1 \leq \ell<N_{j}$,

$$
\exists R^{-} \sqsubseteq \exists S_{j 1}, \quad \exists S_{j \ell}^{-} \sqsubseteq \exists S_{j \ell+1}, \quad \exists S_{j N_{j}}^{-} \sqsubseteq \exists S_{j 1}
$$

and the following inclusions, for $1 \leq j \leq k$ and $1 \leq i \leq m$ :

$$
\begin{array}{ll}
S_{j 1} \sqsubseteq C_{i}, & \text { if } p_{j} \text { is a literal of } c_{i}, \\
S_{j 2} \sqsubseteq C_{i}, & \text { if } \neg p_{j} \text { is a literal of } c_{i} .
\end{array}
$$

Intuitively, $\mathcal{M}_{2}$ is a tree with $k$ branches having a common root arrow $R$. The $j$ th branch is obtained by unravelling a loop of $N_{j}$ arrows $S_{j 1}, \ldots, S_{j N_{j}}$ : the first arrow, $S_{j 1}$, corresponds to $p_{j}$ being true (under an assignment) and the second arrow, $S_{j 2}$, to $p_{j}$ being false (other arrows do not encode truth values). Therefore, $N_{1} \times N_{2} \times \cdots \times N_{k}$ layers (the layer $i$ consists of all arrows from points at distance $i$ from the root) contain representations of all possible assignments to $p_{1}, \ldots, p_{k}$ (for $k=2$, see Fig. 7 ]on the left). The last two types of role inclusions make sure that the roles $C_{1}, \ldots, C_{m}$, which constitute the signature $\Sigma$, mark those assignments under which $\varphi$ is true.


Figure 8: Example 25 (a) an $\omega$-winning start-bounded strategy in $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ from ( $u_{2} \mapsto \sigma_{0}$ ); (b) an $\omega$-winning strategy in $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ from $\left(\emptyset,\left\{u_{2}, u_{9}\right\} \mapsto w_{0}\right) ;(\mathrm{c})$ the respective fragment of the game graph of $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right) ;(\mathrm{d})$ the graph $\mathfrak{I}$ for extracting $\omega$-winning strategies in $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$.

We now take $\mathcal{K}_{1}=\left(\mathcal{T}_{1},\{A(a)\}\right)$, where $\mathcal{T}_{1}$ contains the following inclusions:

$$
\begin{array}{rll}
A \sqsubseteq \exists T_{i} \quad \text { and } \quad \exists T_{i}^{-} \sqsubseteq A, & \text { for } 1 \leq i \leq m \\
T_{i} \sqsubseteq C_{i^{\prime}}^{-}, & & \text {for } 1 \leq i \neq i^{\prime} \leq m .
\end{array}
$$

In $\mathcal{M}_{1}$, the path from each point to the root contains arrows that are labelled by all of $C_{1}, \ldots, C_{m}$ but one (for $m=3$, see Fig. 7 on the right). Note that the $C_{i}$ arrows point towards the root, in the opposite direction to the $C_{i}$ arrows of $\mathcal{M}_{2}$. Thus, there is a finite $(\Sigma,\{a\})$-homomorphism from $\mathcal{M}_{2}$ into $\mathcal{M}_{1}$ if and only if one of the clauses is false under each of the assignments (that is, iff $\varphi$ is unsatisfiable).

The generating structure $\mathcal{G}_{1}$ is essentially a set of loops each of which is missing precisely one of the $C_{i}$. Thus, the responses of player 1 correspond to the choices of the missing $C_{i}$. The challenges by player 2 , on the other hand, correspond to the subsets of $C_{1}, \ldots, C_{m}$ in the layers of $\mathcal{M}_{2}$, the number of which may be exponential in $k$. So player 2 can go through a sequence of exponentially many distinct challenges (assignments), to each of which player 1 will have to find a clause that is false under the assignment. The sequence repeats itself after $N_{1} \times \cdots \times N_{k}$ steps.

A general strategy for player 1 in $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ is a combination of a backward strategy and a number of startbounded strategies to be defined next.

### 4.4. Start-bounded Strategy and Game $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$

A strategy for player 1 in the game $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from $\left(u_{0} \mapsto \sigma_{0}\right)$ is called start-bounded if it never leads to a state $\left(u_{i} \mapsto \sigma_{i}\right)$ such that $\sigma_{0}=\sigma_{i} w$, for some $w \in \Delta^{\mathcal{G}_{1}}$ and $i>0$. In other words, player 1 cannot use those elements of $\mathcal{M}_{1}$ that are located closer to the ABox than $\sigma_{0}$; the ABox individuals in $\mathcal{M}_{1}$ can only be used if $\sigma_{0} \in \operatorname{ind}\left(\mathcal{K}_{1}\right)$.

Example 25. The strategy starting from $\left(u_{2} \mapsto \sigma_{0}\right)$ and shown in Fig. 8 by dotted lines is start-bounded, with the numbers indicating the rounds of the game: the responses $\sigma_{0}, \sigma_{1}, \sigma_{2}$ of player 1 move away from the ABox, after which player 1 retraces his steps back to $\sigma_{0}$ (in order to avoid clutter, we omitted the ABox part from the generating structure $\mathcal{G}_{2}$ in the picture).

The states of $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ are of the form $\left(\Theta_{i}, \Xi_{i} \mapsto w_{i}\right), i \geq 0$, where $\Theta_{i}, \Xi_{i} \subseteq \Delta^{\mathcal{G}_{2}}, \Xi_{i} \neq \emptyset$ and $w_{i} \in \Delta^{\mathcal{G}_{1}}$. (Intuitively, $\Xi_{i}$ is the set of elements of $\Delta^{G_{2}}$ that are mapped to $w_{i}$, while $\Theta_{i}$ identifies illegitimate challenges for player 2 , that is, the $\rightsquigarrow \Sigma_{2}^{\Sigma}$-successors that have already been mapped to $w_{i-1}$.) The initial state is of the form ( $\left.\emptyset, \Xi_{0} \mapsto w_{0}\right)$. In each round $i>0$, player 2 challenges player 1 with some $u \rightsquigarrow_{2}^{\Sigma} v$ such that $u \in \Xi_{i-1}$ and

$$
\text { if } v \in \Theta_{i-1} \text { then } \boldsymbol{r}_{\Sigma}^{\mathcal{G}_{2}}(u, v) \nsubseteq \overline{\boldsymbol{r}}_{\Sigma}^{\mathcal{G}_{1}}\left(w_{i-2}, w_{i-1}\right) \text {. }
$$

(no-backward)
(Player 2 loses if there is no challenge satisfying this condition.) Player 1 'guesses' some $\Xi_{i}$ and $w_{i}$ such that $\Xi_{i}$ contains $v, r_{\Sigma}^{\mathcal{G}_{2}}(u, v) \subseteq \boldsymbol{r}_{\Sigma}^{\mathcal{G}_{1}}\left(w_{i-1}, w_{i}\right)$ and responds with a state $\left(\Theta_{i}, \Xi_{i} \mapsto w_{i}\right)$, where $\Theta_{i}$ is determined by $\Xi_{i-1}$ and $w_{i}$ : $\Theta_{i}=\Xi_{i-1}$ if $w_{i} \notin \operatorname{ind}\left(\mathcal{K}_{1}\right)$ and $\Theta_{i}=\emptyset$, otherwise. We make challenges $u \rightsquigarrow_{2}^{\Sigma} v$, for which

$$
u \in \Xi_{i-1}, \quad v \in \Theta_{i-1} \quad \text { and } \quad \boldsymbol{r}_{\Sigma}^{\mathcal{G}_{2}}(u, v) \subseteq \overline{\boldsymbol{r}}_{\Sigma}^{\mathcal{G}_{1}}\left(w_{i-2}, w_{i-1}\right),
$$

'illegitimate' because, by the choice of $\Xi_{i-2}$, the element $w_{i-2}$ was supposed to be used as a response; note that the last two conditions above are the complement of no-backward. Because of this, player 1 always moves 'forward' in $\mathcal{G}_{1}$, but has to guess appropriate sets $\Xi_{i}$ in advance. The states, initial states, challenges by player 2 and responses of player 1 are summarised in the table below:

| start-bounded game $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ |  |
| :---: | :---: |
| states, $i \geq 0$ | $\left(\Theta_{i}, \Xi_{i} \mapsto w_{i}\right)$ with $\Theta_{i}, \Xi_{i} \subseteq \Delta^{\mathcal{G}_{2}}, \Xi_{i} \neq \emptyset, w_{i} \in \Delta^{\mathcal{G}_{1}}$ and $\boldsymbol{t}_{\Sigma}^{\mathcal{G}_{2}}(u) \subseteq t_{\Sigma}^{\mathcal{G}_{1}}\left(w_{i}\right)$, for all $u \in \Xi_{i}$ |
| initial state | $\left(\emptyset, \Xi_{0} \mapsto w_{0}\right)$ such that $w_{0}=u$ in case $u \in \Xi_{0} \cap \operatorname{part}_{\Sigma}^{\mathcal{M}_{2}}$ and $\Xi_{0} \cap \operatorname{ind}\left(\mathcal{K}_{2}\right)$ contains at most one element |
| challenges, $i>0$ | $u \rightsquigarrow_{2}^{\Sigma} v$ such that $u \in \Xi_{i-1}$ and if $v \in \Theta_{i-1}$, for $i>1$, then $\boldsymbol{r}_{\Sigma}^{\mathcal{G}_{2}}(u, v) \nsubseteq \overline{\boldsymbol{r}}_{\Sigma}^{\mathcal{G}_{1}}\left(w_{i-2}, w_{i-1}\right)$ |
| responses, $i>0$ | $\left(\Theta_{i}, \Xi_{i} \mapsto w_{i}\right)$ such that $v \in \Xi_{i}$ and $\Xi_{i} \cap \operatorname{ind}\left(\mathcal{K}_{2}\right)=\emptyset$, either $w_{i-1} \rightsquigarrow_{1} w_{i}$ and $\Theta_{i}=\Xi_{i-1}$ or $w_{i-1}, w_{i} \in \operatorname{ind}\left(\mathcal{K}_{1}\right)$ and $\Theta_{i}=\emptyset$, and $\boldsymbol{r}_{\Sigma}^{\mathcal{G}_{2}}(u, v) \subseteq \boldsymbol{r}_{\Sigma}^{\mathcal{G}_{1}}\left(w_{i-1}, w_{i}\right)$ |

Note that of all $\Xi_{i}$ only $\Xi_{0}$ may contain (at most one) individual from ind $\left(\mathcal{K}_{2}\right) ; \Theta_{0}=\emptyset$ and of all $\Theta_{i}$ only $\Theta_{1}$ may contain an individual.

Example 26. Consider $\mathcal{G}_{2}^{\Sigma}$ and $\mathcal{G}_{1}^{\Sigma}$ in Fig. 8p. In the game $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$, player 1 will have to guess all the points of $\mathcal{G}_{2}$ that are mapped to the same point of $\mathcal{M}_{1}$. We show that player 1 has an $\omega$-winning strategy in $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ starting from ( $\emptyset,\left\{u_{2}, u_{9}\right\} \mapsto w_{0}$ ). Player 2 challenges with $u_{2} \rightsquigarrow_{2}^{\Sigma} u_{6}$, and player 1 responds with ( $\left.\left\{u_{2}, u_{9}\right\},\left\{u_{6}, u_{8}\right\} \mapsto w_{1}\right)$. Then player 2 picks $u_{6} \rightsquigarrow_{2}^{\Sigma} u_{7}$ and player 1 responds with $\left(\left\{u_{6}, u_{8}\right\},\left\{u_{7}\right\} \mapsto w_{2}\right)$, where the game ends because player 2 has no challenge available. Observe that this strategy involves only 3 rounds in contrast to the 5 rounds of the corresponding strategy in $G\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ shown in Fig. 8 a. The strategy in $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ is indicated by the shaded states of the fragment of the game graph in Fig. $8_{8}$. Note the crucial guesses $\left\{u_{2}, u_{9}\right\} \mapsto w_{0}$ and $\left\{u_{6}, u_{8}\right\} \mapsto w_{1}$ made by player 1. For example, if player 1 responded with $\left(\left\{u_{2}, u_{9}\right\},\left\{u_{6}\right\} \mapsto w_{1}\right)$ (and failed to guess that $u_{8}$ must also be mapped to $w_{1}$ ), then after the challenge $u_{6} \rightsquigarrow_{2}^{\Sigma} u_{7}$ and the only possible response ( $\left\{u_{6}\right\},\left\{u_{7}\right\} \mapsto w_{2}$ ), player 2 would pick $u_{7} \rightsquigarrow{ }_{2}^{\Sigma} u_{8}$ to which player 1 would not have a response; see the non-shaded states in Fig. 8.
Lemma 27. Conditions (win-s) and ( $\omega$ - $\boldsymbol{w i n}^{s}$ ) are equivalent. More precisely, for any $u_{0} \in \Delta^{\mathcal{G}_{2}}$ and $\sigma_{0} \in \Delta^{\mathcal{M}_{1}}$, the following are equivalent:
(a) player 1 has an $\omega$-winning start-bounded strategy in the game $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from $\left(u_{0} \mapsto \sigma_{0}\right)$;
(b) for every $n<\omega$, player 1 has an n-winning start-bounded strategy in $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from $\left(u_{0} \mapsto \sigma_{0}\right)$;
(c) player 1 has an $\omega$-winning strategy in the game $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ starting from $\left(\emptyset, \Xi_{0} \mapsto\right.$ tail $\left.\left(\sigma_{0}\right)\right)$, for some $\Xi_{0} \ni u_{0}$.

Proof. $(a) \Rightarrow(b)$ is trivial.
$(b) \Rightarrow(c)$ We define a (possibly infinite) directed graph $\mathfrak{I}$ whose nodes are of the form $(u \mapsto \delta)$, where $u \in \Delta^{\mathcal{G}_{2}}$ and $\delta$ is a suffix of some element in $\Delta^{\mathcal{M}_{1}}$, and whose arrows are labelled with $u \rightsquigarrow{ }_{2}^{\Sigma} u^{\prime}$ so that the following conditions hold:
(1) $\mathfrak{I}$ contains an initial node $\left(u_{0} \mapsto \operatorname{tail}\left(\sigma_{0}\right)\right)$;
(2) $\boldsymbol{t}_{\Sigma}^{\mathcal{G}_{2}}(u) \subseteq t_{\Sigma}^{\mathcal{G}_{1}}(\operatorname{tail}(\delta))$, for every node $(u \mapsto \delta)$ in $\mathfrak{I}$;
(3) for any $u \rightsquigarrow{ }_{2}^{\Sigma} u^{\prime}$, every node $(u \mapsto \delta)$ in $\mathfrak{I}$ has exactly one ( $u \rightsquigarrow{ }_{2}^{\Sigma} u^{\prime}$ )-successor in $\mathfrak{I}$, which can be of the following forms:
(3.1) $\left(u^{\prime} \mapsto \delta w^{\prime}\right)$, if tail $(\delta)=w, w \rightsquigarrow_{1} w^{\prime}$ and $\boldsymbol{r}_{\Sigma}^{\mathcal{G}_{2}}\left(u, u^{\prime}\right) \subseteq \boldsymbol{r}_{\Sigma}^{\mathcal{G}_{1}}\left(w, w^{\prime}\right)$;
(3.2) $\left(u^{\prime} \mapsto b\right), \quad$ if $\delta=a \in \operatorname{ind}\left(\mathcal{K}_{1}\right), b \in \operatorname{ind}\left(\mathcal{K}_{1}\right)$ and $\boldsymbol{r}_{\Sigma}^{\mathcal{G}_{2}}\left(u, u^{\prime}\right) \subseteq \boldsymbol{r}_{\Sigma}^{\mathcal{G}_{1}}(a, b)$;
(3.3) $\left(u^{\prime} \mapsto \delta^{\prime}\right)$, if $\delta=\delta^{\prime} w$, tail $\left(\delta^{\prime}\right)=w^{\prime}, w^{\prime} \rightsquigarrow_{1} w$ and $r_{\Sigma}^{\mathcal{G}_{2}}\left(u, u^{\prime}\right) \subseteq \bar{r}_{\Sigma}^{\mathcal{G}_{1}}\left(w^{\prime}, w\right)$.

Observe that these conditions coincide with the conditions given in the proof of Lemma 19 except that now (3.3) provides a possibility of going backward. The graph $\mathfrak{I}$ for the winning strategy in Example 25 is depicted in Fig. 8 d .

We show that the graph $\mathfrak{I}$ (if it exists) gives rise to the required $\omega$-winning strategy for player 1 in $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$. Consider the function s mapping the nodes in $\mathfrak{I}$ to states in the game $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ and defined by taking

$$
\mathrm{s}(u \mapsto \delta)= \begin{cases}\left(\Xi_{\delta^{\prime}}, \Xi_{\delta} \mapsto \operatorname{tail}(\delta)\right), & \text { if } \delta=\delta^{\prime} w, \\ \left(\emptyset, \Xi_{\delta} \mapsto \delta\right), & \text { otherwise (that is, if } \left.\delta=\operatorname{tail}\left(\sigma_{0}\right) \text { or } \delta \in \operatorname{ind}\left(\mathcal{K}_{1}\right)\right),\end{cases}
$$

where $\Xi_{\delta}=\{u \mid(u \mapsto \delta)$ a node in $\mathfrak{I}\}$. In particular, the initial node $\mathfrak{n}_{0}$ in $\mathfrak{I}$ is mapped to the initial state: $\mathbf{s}\left(\mathfrak{n}_{0}\right)=\left(\emptyset, \Xi_{\text {tail }\left(\sigma_{0}\right)} \mapsto \operatorname{tail}\left(\sigma_{0}\right)\right)$. (Note that only $\mathfrak{n}_{0}$ may refer to an individual from ind $\left(\mathcal{K}_{2}\right)$, and so $\mathbf{s}\left(\mathfrak{n}_{0}\right)$ is a properly defined initial state.) In order to define the $\omega$-winning strategy of player 1 in $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ from $s\left(n_{0}\right)$, we show that, for all $\mathfrak{n}$ in $\mathfrak{I}$,
if player 2 has a challenge $u \rightsquigarrow_{2}^{\Sigma} u^{\prime}$ in $\mathrm{s}(\mathfrak{n})$, then there is $\mathrm{r}_{u}$ and a $\left(u \rightsquigarrow_{2}^{\Sigma} u^{\prime}\right)$-successor $\mathfrak{n}^{\prime}$ of $\mathrm{r}_{u}$ in $\mathfrak{I}$

$$
\text { such that } \mathbf{s}\left(\mathfrak{r}_{u}\right)=\mathbf{s}(\mathfrak{n}) \text { and } \mathbf{s}\left(\mathfrak{n}^{\prime}\right) \text { is a valid response by player } 1 \text { to } u \rightsquigarrow_{2}^{\Sigma} u^{\prime} \text { in } \mathbf{s}(\mathfrak{n})
$$

Indeed, if $u \rightsquigarrow_{2}^{\Sigma} u^{\prime}$ is a challenge in $\mathbf{s}(\mathfrak{n})$ then $\mathbf{s}(\mathfrak{n})$ is of the form $\left(\Theta, \Xi_{\delta} \mapsto\right.$ tail $(\delta)$ ), for some $\delta$ and $u \in \Xi_{\delta}$. By definition, $\mathfrak{I}$ contains a node $\mathfrak{r}_{u}=(u \mapsto \delta)$ and $\mathrm{s}\left(\mathfrak{r}_{u}\right)=\mathrm{s}(\mathfrak{n})$; moreover, $\mathrm{r}_{u}$ has a $\left(u \rightsquigarrow_{2}^{\Sigma} u^{\prime}\right)$-successor $\mathfrak{n}^{\prime}$ in $\mathfrak{I}$. (Observe that, by the definition of s , for two distinct nodes $\mathfrak{n}=(v \mapsto \delta)$ and $\mathfrak{r}_{u}=(u \mapsto \delta)$, we may have $\mathrm{s}(\mathfrak{r})=\mathrm{s}\left(\mathfrak{r}_{u}\right)=\left(\Theta, \Xi_{\delta} \mapsto\right.$ tail $\left.(\delta)\right)$ and $\{u, v\} \subseteq \Xi_{\delta}$, and so $\mathfrak{I}$ may contain a node $n$ that has no $u \rightsquigarrow{ }_{2}^{\Sigma} u^{\prime}$ successor for a valid challenge $u \rightsquigarrow_{2}^{\Sigma} u^{\prime}$ in $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ from $\mathrm{s}(\mathfrak{r})$. Similarly to the proof of Lemma 19 , the choice of a particular $\mathrm{r}_{u}$ is not essential.) It remains to show that $\mathrm{s}\left(\mathfrak{n}^{\prime}\right)$ is a valid response by player 1 to $u \rightsquigarrow_{2}^{\Sigma} u^{\prime}$ from $\mathrm{s}(\mathfrak{n})$. Consider all possible cases:

- If $\mathrm{r}_{u}=(u \mapsto w)$ and $\mathfrak{n}^{\prime}=\left(u^{\prime} \mapsto w w^{\prime}\right)$ then $\mathbf{s}(\mathfrak{n})=\left(\emptyset, \Xi_{w} \mapsto w\right)$ and $\mathbf{s}\left(\mathfrak{n}^{\prime}\right)=\left(\Xi_{w}, \Xi_{w w^{\prime}} \mapsto w^{\prime}\right)$. By item (3.1) of the definition of $\mathfrak{I}, \mathrm{s}\left(\mathrm{n}^{\prime}\right)$ is as required.
- If $\mathfrak{r}_{u}=(u \mapsto \delta w)$ and $\mathfrak{n}^{\prime}=\left(u^{\prime} \mapsto \delta w w^{\prime}\right)$ then $\mathbf{s}(\mathfrak{n})=\left(\Xi_{\delta}, \Xi_{\delta w} \mapsto w\right)$ and $\mathbf{s}\left(\mathfrak{n}^{\prime}\right)=\left(\Xi_{\delta w}, \Xi_{\delta w w^{\prime}} \mapsto w^{\prime}\right)$. By (3.1), $\mathbf{s}\left(\mathfrak{n}^{\prime}\right)$ is as required.
- If $\mathfrak{r}_{u}=(u \mapsto w)$ and $\mathfrak{n}^{\prime}=\left(u^{\prime} \mapsto w^{\prime}\right)$ then $w, w^{\prime} \in \operatorname{ind}\left(\mathcal{K}_{1}\right), \mathbf{s}(\mathfrak{n})=\left(\emptyset, \Xi_{w} \mapsto w\right)$ and $\mathbf{s}\left(\mathfrak{n}^{\prime}\right)=\left(\emptyset, \Xi_{w^{\prime}} \mapsto w^{\prime}\right)$. By (3.2), $\mathrm{s}\left(\mathfrak{r}^{\prime}\right)$ is as required.
- If $\mathfrak{r}_{u}=\left(u \mapsto \delta w^{\prime} w\right)$ and $\mathfrak{n}^{\prime}=\left(u^{\prime} \mapsto \delta w^{\prime}\right)$ then $\mathbf{s}(\mathfrak{n})=\left(\Xi_{\delta w^{\prime}}, \Xi_{\delta w^{\prime} w} \mapsto w\right)$ and $u^{\prime} \in \Xi_{\delta w^{\prime}}$, which is impossible because, in view of (3.3), we have $\boldsymbol{r}_{\Sigma}^{\mathcal{G}_{2}}\left(u, u^{\prime}\right) \subseteq \overline{\boldsymbol{r}}_{\Sigma}^{\mathcal{G}_{1}}\left(w^{\prime}, w\right)$ contrary to the fact that $u \rightsquigarrow_{2}^{\Sigma} u^{\prime}$ is a challenge in $\mathrm{s}(\mathfrak{r})$; see no-backward.

The $\omega$-winning strategy of player 1 in $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ from $\mathrm{s}\left(\mathfrak{n}_{0}\right)$ is then defined naturally.
Now we show that $\mathfrak{I}$ exists. The construction is similar to the proof of Lemma 19. Let $\mathbb{S}_{0}$ be the given set of $n$-winning start-bounded strategies in $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ starting from $\left(u_{0} \mapsto \sigma_{0}\right)$ and let $w_{0}=\operatorname{tail}\left(\sigma_{0}\right)$. Define $\mathfrak{I}_{0}$ to be the graph with the single initial node ( $u_{0} \mapsto w_{0}$ ). Clearly, it satisfies (1) and (2) above. If it also satisfies (3), then we are done. Otherwise, as in the proof of Lemma 19 , we take all the challenges $u_{0} \rightsquigarrow \Sigma_{2}^{\Sigma} u_{1}^{1}, \ldots, u_{0} \rightsquigarrow \Sigma_{2}^{\Sigma} u_{1}^{k}$ by player 2 and using the pigeonhole principle find $w_{1}^{1}, \ldots, w_{1}^{\mathcal{L}} \in \Delta^{\mathcal{G}_{1}}$ and a set $\mathbb{S}_{1} \subseteq \mathbb{S}_{0}$ such that, for any challenge $u_{0} \rightsquigarrow_{2}^{\Sigma} u_{1}^{i}$, every strategy $\mathcal{S} \in \mathbb{S}_{1}$ gives a response ( $u_{1}^{i} \mapsto \sigma_{1}^{i}$ ) with tail $\left(\sigma_{1}^{i}\right)=w_{1}^{i}$. If $w_{1}^{i} \in \operatorname{ind}\left(\mathcal{K}_{1}\right)$ then we add the node ( $u_{1}^{i} \mapsto w_{1}^{i}$ ) to $\mathfrak{I}_{0}$, and if $w_{1}^{i} \notin \operatorname{ind}\left(\mathcal{K}_{1}\right)$ then we add the node $\left(u_{1}^{i} \mapsto w_{0} w_{1}^{i}\right)$ to $\mathfrak{I}_{0}$; we also add an $u_{0} \rightsquigarrow_{2}^{\Sigma} u_{1}^{i}$ arrow connecting $\left(u_{0} \mapsto w_{0}\right)$ with the newly introduced node. This gives us the graph $\mathfrak{I}_{1}$. To illustrate the construction of $\mathfrak{I}$ in the case of a backward step (which is impossible in round 1), consider now a challenge $u_{1} \rightsquigarrow_{2}^{\Sigma} u_{2}$ by player 2 for some $u_{1} \in\left\{u_{1}^{1}, \ldots, u_{1}^{k}\right\}$ such that the response according to $\mathcal{S}$ was $\left(u_{1} \mapsto \sigma_{0} w_{1}\right)$ and ( $u_{1} \mapsto w_{0} w_{1}$ ) is a node in $\mathfrak{I}_{1}$. Then, using the pigeonhole principle, we find either

- $w_{2} \in \Delta^{\mathcal{G}_{1}}$ and a subset $\mathbb{S}_{2} \subseteq \mathbb{S}_{1}$ such that every strategy $\mathcal{S} \in \mathbb{S}_{2}$ gives a response of the form $\left(u_{2} \mapsto \sigma_{0} w_{1} w_{2}\right)$,
- or a subset $\mathbb{S}_{2} \subseteq \mathbb{S}_{1}$ such that every strategy $\mathcal{S} \in \mathbb{S}_{2}$ gives a response of the form $\left(u_{2} \mapsto \sigma_{0}\right)$.

In the former case we add the node $\left(u_{2} \mapsto w_{0} w_{1} w_{2}\right)$ to $\mathfrak{I}_{1}$ and in the latter case we add $\left(u_{2} \mapsto w_{0}\right)$ to $\mathfrak{I}_{1}$. We also add an $u_{1} \rightsquigarrow_{2}^{\Sigma} u_{2}$ arrow connecting $\left(u_{1} \mapsto w_{0} w_{1}\right)$ and the new node to $\mathfrak{I}_{1}$. This defines $\mathfrak{I}_{2}$. We proceed in the same way and construct a sequence of graphs $\mathfrak{I}_{0} \subseteq \mathfrak{I}_{1} \subseteq \ldots$ until we either reach some $\mathfrak{I}_{k}$ satisfying (1)-(3) or obtain an infinite sequence and take $\mathfrak{I}=\bigcup_{k<\omega} \mathfrak{I}_{k}$, which obviously satisfies (1)-(3).
$(c) \Rightarrow(a)$ Suppose that player 1 has an $\omega$-winning strategy $\mathcal{S}$ in $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ starting from $\left(\emptyset, \Xi_{0} \mapsto\right.$ tail $\left.\left(\sigma_{0}\right)\right)$ with $u_{0} \in \Xi_{0}$. We transform the strategy $\mathcal{S}$ into an $\omega$-winning start-bounded strategy $\mathcal{S}^{\prime}$ in $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from $s_{0}=\left(u_{0} \mapsto \sigma_{0}\right)$. We associate with any (possibly infinite) sequence $u_{0} \rightsquigarrow_{2}^{\Sigma} u_{1} \rightsquigarrow_{2}^{\Sigma} \cdots \rightsquigarrow_{2}^{\Sigma} u_{i} \rightsquigarrow_{2}^{\Sigma} \cdots$ of challenges by player 2 in $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from the state $\mathfrak{s}_{0}$ a sequence $\mathfrak{s}_{1}=\left(u_{1} \mapsto \sigma_{1}\right), \ldots, \mathfrak{s}_{i}=\left(u_{i} \mapsto \sigma_{i}\right), \ldots$ of responses by player 1 which are start-bounded (that is, $\sigma_{0} \neq \sigma_{i} w$, for any $w \in \Delta^{\mathcal{G}_{1}}$ ). To this end, we also define a sequence of states $\mathfrak{s b}_{0}=\left(\Theta_{0}, \Xi_{0} \mapsto w_{0}\right), \ldots, \mathfrak{s b}_{i}=\left(\Theta_{i}, \Xi_{i} \mapsto w_{i}\right), \ldots$ in $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ such that $u_{i} \in \Xi_{i}$ and tail $\left(\sigma_{i}\right)=w_{i}$ for all $i$. To keep track of 'backward moves' we also define a sequence $\pi_{0}, \ldots, \pi_{i}, \ldots$ of sequences of states in $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ such that each $\pi_{i}$ has length $\left|\sigma_{i}\right|+1-\left|\sigma_{0}\right|$ and its first state is of the form $(\emptyset, \Xi \mapsto w)$. Finally, we require that

$$
\begin{equation*}
\text { if } \pi_{i}=\pi_{j} \cdot\left(\Theta^{1}, \Xi^{1} \mapsto w^{1}\right) \cdots\left(\Theta^{m}, \Xi^{m} \mapsto w^{m}\right) \text { then } \sigma_{i}=\sigma_{j} w^{1} \cdots w^{m} \tag{4}
\end{equation*}
$$

For $i=0$, we set $\mathfrak{s b}_{0}=\left(\emptyset, \Xi_{0} \mapsto w_{0}\right)$ and $\pi_{0}=\mathfrak{s b}_{0}$, which clearly has the required properties. Now assume that $\mathfrak{s}_{0}, \ldots, \mathfrak{s}_{i-1}, \mathfrak{s b}_{0}, \ldots, \mathfrak{s b}_{i-1}$ and $\pi_{0}, \ldots, \pi_{i-1}$, for $i>0$, are defined as above. Consider a challenge $u_{i-1} \rightsquigarrow_{2}^{\Sigma} u_{i}$ in state $\mathfrak{s}_{i-1}$. We distinguish the following two cases.

- If $u_{i-1} \rightsquigarrow{ }_{2}^{\Sigma} u_{i}$ is a valid challenge in $\mathfrak{s b}_{i-1}$ then we define $\mathfrak{s b}_{i}=\left(\Theta_{i}, \Xi_{i} \mapsto w_{i}\right)$ as the response of player 1 in $\mathfrak{s b}_{i-1}$ according to $\mathcal{S}$. If $w_{i} \notin \operatorname{ind}\left(\mathcal{K}_{1}\right)$ then we set $\pi_{i}=\pi_{i-1} \cdot \mathfrak{s b}_{i}$ and $\mathfrak{s}_{i}=\left(u_{i} \mapsto \sigma_{i-1} w_{i}\right)$. Otherwise, $\Theta_{i}=\emptyset$ and we set $\pi_{i}=\mathfrak{s b}_{i}$ and $\mathfrak{s}_{i}=\left(u_{i} \mapsto w_{i}\right)$. Obviously, the conditions above hold for the resulting sequences.
- If $u_{i-1} \rightsquigarrow_{2}^{\Sigma} u_{i}$ is not a valid challenge from $\mathfrak{s b}_{i-1}$ then $\Theta_{i-1} \neq \emptyset, u_{i} \in \Theta_{i-1}$ and $\boldsymbol{r}_{\Sigma}^{\mathcal{G}_{2}}\left(u_{i-1}, u_{i}\right) \subseteq \bar{r}_{\Sigma}^{\mathcal{G}_{1}}\left(w, w_{i-1}\right)$ for the predecessor $w$ of $w_{i-1}$ in $\sigma_{i-1}$. Let $\pi_{i}$ be the result of removing the final state from $\pi_{i-1}$; let $\mathfrak{s b}_{i}$ be the final element of $\pi_{i}$; and let $\mathfrak{s}_{i}=\left(u_{i} \mapsto \sigma_{i}\right)$, where $\sigma_{i}$ is obtained from $\sigma_{i-1}$ by removing its final element. Clearly, (4) is satisfied. We show that $\mathfrak{s}_{i}$ is a valid response. First, observe that there exists $j \leq i-2$ such that $\pi_{j}=\pi_{i}$ and $\pi_{j+1}=\pi_{i-1}$ for which $\mathfrak{s b}_{j+1}$ is the response to the challenge $u_{j} \rightsquigarrow{ }_{2}^{\Sigma} u_{j+1}$ from $\mathfrak{s b}_{j}$. By 44, $\sigma_{j+1}=\sigma_{i-1}$ and $\sigma_{j+1}=\sigma_{j} w_{j}$. By the construction of $\sigma_{i}, \sigma_{i}=\sigma_{j}$. Second, it remains to observe that $\Theta_{j+1}=\Theta_{i-1}$ and $\Theta_{j+1}=\Xi_{j}$, i.e., $u_{i} \in \Xi_{j}$ and $\boldsymbol{t}_{\Sigma}^{\mathcal{G}_{2}}\left(u_{i}\right) \subseteq \boldsymbol{t}_{\Sigma}^{\mathcal{G}_{1}}\left(w_{j}\right)=\boldsymbol{t}_{\Sigma}^{\mathcal{M}_{1}}\left(\sigma_{i}\right)$ (recall that, by no-backward, $\left.\boldsymbol{r}_{\Sigma}^{\mathcal{G}_{2}}\left(u_{i-1}, u_{i}\right) \subseteq \boldsymbol{r}_{\Sigma}^{\mathcal{M}_{1}}\left(\sigma_{i-1}, \sigma_{i}\right)\right)$.

By repeating these steps, we obtain an $\omega$-winning start-bounded strategy in $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from $\left(u_{0} \mapsto \sigma_{0}\right)$.
Similarly to $G_{\Sigma}^{f}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$, player 1 has an $\omega$-winning strategy in $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ starting from a state $\mathfrak{s}$ if and only if player 2 does not have a winning strategy in the reachability game on the full graph of $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ starting from $\mathfrak{s}$. However, now the size of the game graph is exponential in the size of $\mathcal{G}_{2}$. More precisely, each $\Theta_{i}$ and $\Xi_{i}$ is a subset of $\Delta^{\mathcal{G}_{2}}$ with at most one individual name, which results in $O\left(\left(\left|\operatorname{ind}\left(\mathcal{K}_{2}\right)\right| \times 2^{\mid \Delta^{\mathcal{G}_{2}} \backslash \text { ind }\left(\mathcal{K}_{2}\right) \mid}\right)^{2} \times\left|\Delta^{\mathcal{G}_{1}}\right|\right)$ states in $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$. The
number of vertices in the graph for the reachability game is then cubic in the number of states in $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ because no-backward) involves three states. So the existence of the required $\omega$-winning strategy for player 1 can be checked in time polynomial in $\mathcal{G}_{1}$ but exponential in $\mathcal{G}_{2}$. Moreover, as we shall see in Section 5 , this problem is ExpTime-hard.

### 4.5. General Strategies and Game $G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$

A general winning strategy in the game $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ can be composed of one backward and a number of startbounded strategies.

Example 28. Consider $\mathcal{G}_{2}^{\Sigma}$ and $\mathcal{M}_{1}^{\Sigma}$ shown in Fig. 9 . Starting from $\left(u_{1} \mapsto \sigma_{3}\right)$, player 1 can respond to the challenges $u_{1} \rightsquigarrow_{2}^{\Sigma} u_{2} \rightsquigarrow_{2}^{\Sigma} u_{3}$ according to the backward strategy; the challenges $u_{2} \rightsquigarrow_{2}^{\Sigma} u_{6} \rightsquigarrow_{2}^{\Sigma} u_{7} \rightsquigarrow_{2}^{\Sigma} u_{8} \rightsquigarrow_{2}^{\Sigma} u_{9}$ according to the start-bounded strategy as in Example 25 , the challenges $u_{3} \rightsquigarrow_{2}^{\Sigma} u_{4} \rightsquigarrow_{2}^{\Sigma} u_{5}$ also according to the obvious start-bounded strategy; finally, the challenge $u_{9} \rightsquigarrow \sum_{2}^{2} u_{10}$ needs a response according to the backward strategy. We will combine the two backward strategies into a single one, but keep the start-bounded ones separate.

The states, initial states, challenges and responses in the general game $G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ are defined in the table below:

| general game $G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ |  |
| :---: | :---: |
| states, $i \geq 0$ | ( $\Xi_{i} \mapsto w_{i}, \Psi_{i}$ ) such that $\Xi_{i} \subseteq \Delta^{\mathcal{G}_{2}}, \Xi_{i} \neq \emptyset, w_{i} \in \Delta^{\mathcal{G}_{1}}, \Psi_{i} \subseteq \Xi_{i}^{\rightsquigarrow}$, <br> $\boldsymbol{t}_{\Sigma}^{\mathcal{G}_{2}}(u) \subseteq \boldsymbol{t}_{\Sigma}^{\mathcal{G}_{1}}\left(w_{i}\right)$, for all $u \in \Xi_{i}$, <br> $\Psi_{i}=\emptyset$ if $w_{i} \in \operatorname{ind}\left(\mathcal{K}_{1}\right)$, <br> and player 1 has an $\omega$-winning strategy in the start-bounded game $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ <br> from $\left(\emptyset, \Xi_{i} \mapsto w_{i}\right)$ with the first challenge $u \rightsquigarrow \Sigma_{2}^{\Sigma} v$ by player 2 satisfying $v \in \Xi_{i}^{\rightsquigarrow} \backslash \Psi_{i}$ |
| initial state | $\left(\Xi_{0} \mapsto w_{0}, \Psi_{0}\right)$ such that $w_{0}=u$ in case $u \in \Xi_{0} \cap \operatorname{part}_{\Sigma}^{\mathcal{N}_{2}}$, $\Xi_{0} \cap \operatorname{ind}\left(\mathcal{K}_{2}\right)$ contains at most one element |
| challenges, $i>0$ | $\Psi_{i-1}$ provided that $\Psi_{i-1} \neq \emptyset$ |
| responses, $i>0$ | $\left(\Xi_{i} \mapsto w_{i}, \Psi_{i}\right)$ such that $w_{i} \rightsquigarrow_{1} w_{i-1}, \Xi_{i} \supseteq \Psi_{i-1}$ with $\Xi_{i} \cap \operatorname{ind}\left(\mathcal{K}_{2}\right)=\emptyset$, $\boldsymbol{r}_{\Sigma}^{\mathcal{G}_{2}}(u, v) \subseteq \overline{\boldsymbol{r}}_{\Sigma}^{\mathcal{G}_{1}}\left(w_{i}, w_{i-1}\right)$, for all $u \in \Xi_{i-1}$ and $v \in \Xi_{i}$. |

Thus, in every round $i>0$ of the game, player 1 chooses a set $\Xi_{i} \supseteq \Psi_{i-1}$ and partitions the elements of $\Xi_{i}^{\rightsquigarrow}$ into those that will be mapped according to the backward strategy in round $i+1$ (the set $\Psi_{i}$ ) and those that will be mapped according to the start-bounded strategy (the set $\Xi_{i}^{\leadsto} \backslash \Psi_{i}$ ). Note the additional condition that player 1 must have an $\omega$-winning strategy in the start-bounded game $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ from $\left(\emptyset, \Xi_{i} \mapsto w_{i}\right)$ where the first challenge by player 2 is restricted to $\Xi_{i}^{\rightsquigarrow} \backslash \Psi_{i}$.

Example 29. Figure 9 p shows an $\omega$-winning strategy for player 1 in $G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ starting from $\left(\left\{u_{1}\right\} \mapsto w_{3},\left\{u_{2}\right\}\right)$, where $\mathcal{G}_{1}^{\Sigma}$ looks like $\mathcal{M}_{1}^{\Sigma}$ but with $w_{i}$ in place of $\sigma_{i}$. The dashed transitions represent two launches of start-bounded games: one from the state $\left(\emptyset,\left\{u_{2}, u_{9}\right\} \mapsto w_{0}\right)$ with the initial challenge $u_{2} \rightsquigarrow_{2}^{\Sigma} u_{6}$, and the other from the state $\left(\emptyset,\left\{u_{3}, u_{10}\right\} \mapsto a\right)$ with the initial challenge $u_{3} \rightsquigarrow_{2}^{\Sigma} u_{4}$.

Lemma 30. Conditions (win), (win-g) and $\left(\omega-\right.$ win $\left.^{g}\right)$ are equivalent. More precisely, for any $u_{0} \in \Delta^{\mathcal{G}_{2}}$ and $w_{0} \in \Delta^{\mathcal{G}_{1}}$, the following are equivalent:
(a) for every $n<\omega$, there is $\sigma_{0} \in \Delta^{\mathcal{M}_{1}}$ such that tail $\left(\sigma_{0}\right)=w_{0}$ and player 1 has an n-winning strategy in the game $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from $\left(u_{0} \mapsto \sigma_{0}\right)$;
(b) player 1 has an $\omega$-winning strategy in $G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ starting from $\left(\Xi_{0} \mapsto w_{0}, \Psi_{0}\right)$, for some $\Xi_{0} \ni u_{0}$ and $\Psi_{0}$.

Proof. $(a) \Rightarrow(b)$ As before, we construct a (possibly infinite) directed graph $\mathfrak{I}$ whose nodes are of the form $(u \mapsto \delta, i)$, where $u \in \Delta^{\mathcal{G}_{2}}, \delta$ is a suffix of some element in $\Delta^{\mathcal{M}_{1}}$ and $0 \leq i<\omega$ or $i=*$, and whose arrows are labelled with $u \rightsquigarrow{ }_{2}^{\Sigma} u^{\prime}$ and such that the following conditions hold:
(1) the initial node of $\mathfrak{I}$ is of the form $\left(u_{0} \mapsto w_{0}, 0\right)$;


Figure 9: Example 28 (a) an $\omega$-winning general strategy in the infinite game $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ from ( $u_{1} \mapsto \sigma_{3}$ ); (b) the respective fragment of the game graph of $G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ with graphs of the start-bounded games.


Figure 10: The graph $\mathfrak{I}$ for extracting $\omega$-winning strategies in $G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ from Example 28
(2) $\boldsymbol{t}_{\Sigma}^{\mathcal{G}_{2}}(u) \subseteq \boldsymbol{t}_{\Sigma}^{\mathcal{G}_{1}}($ tail $(\delta))$, for any node $(u \mapsto \delta, k)$ in $\mathfrak{I}$;
(3) for any $u \rightsquigarrow_{2}^{\Sigma} u^{\prime}$, every node ( $u \mapsto \delta, i$ ) in $\mathfrak{I}$ has exactly one ( $u \rightsquigarrow_{2}^{\Sigma} u^{\prime}$ )-successor in $\mathfrak{I}$, which can be of the following forms:
(3.1) $\left(u^{\prime} \mapsto \delta w^{\prime}, i\right)$, if tail $(\delta)=w, w \rightsquigarrow 1 w^{\prime}$ and $\boldsymbol{r}_{\Sigma}^{\mathcal{G}_{2}}\left(u, u^{\prime}\right) \subseteq \boldsymbol{r}_{\Sigma}^{\mathcal{G}_{1}}\left(w, w^{\prime}\right)$;
(3.2) $\left(u^{\prime} \mapsto b, *\right)$, if $\delta=a \in \operatorname{ind}\left(\mathcal{K}_{1}\right), b \in \operatorname{ind}\left(\mathcal{K}_{1}\right) \quad$ and $r_{\Sigma}^{\mathcal{G}_{2}}\left(u, u^{\prime}\right) \subseteq r_{\Sigma}^{\mathcal{G}_{1}}(a, b)$;
(3.3) $\left(u^{\prime} \mapsto \delta^{\prime}, i\right)$, if $\delta=\delta^{\prime} w$, tail $\left(\delta^{\prime}\right)=w^{\prime}, w^{\prime} \rightsquigarrow 1 w$ and $\boldsymbol{r}_{\Sigma}^{\mathcal{G}_{2}}\left(u, u^{\prime}\right) \subseteq \overline{\boldsymbol{r}}_{\Sigma}^{\mathcal{G}_{1}}\left(w^{\prime}, w\right)$;
(3.4) $\left(u^{\prime} \mapsto w^{\prime}, i+1\right)$, if $\delta=w \in \Delta^{\mathcal{G}_{1}}, w^{\prime} \rightsquigarrow 1 w$ and $r_{\Sigma}^{\mathcal{G}_{2}}\left(u, u^{\prime}\right) \subseteq \overline{\boldsymbol{r}}_{\Sigma}^{\mathcal{G}_{1}}\left(w^{\prime}, w\right)$.
(4) for any nodes $(u \mapsto w, i)$ and $\left(u^{\prime} \mapsto w^{\prime}, i\right)$ in $\mathfrak{I}$ with $w, w^{\prime} \in \Delta^{\mathcal{G}_{1}}$ and $i \neq *$, we have $w=w^{\prime}$.

Note that the conditions on $\mathfrak{I}$ combine the conditions given in the proofs of Lemma 23(backward strategies, cf. (3.4) and (4)) and Lemma 27 (start-bounded strategies, cf. (3.1)-(3.3)). The graph $\mathfrak{I}$ for the $\omega$-winning strategy in Example 28 is depicted in Fig. 10

We show first that such a graph $\mathfrak{I}$ exists. Let $\mathbb{S}_{0}$ be the given set of $n$-winning strategies of player 1 in $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from $\left(u_{0} \mapsto \sigma_{0}\right)$. Define $\mathfrak{I}_{0}$ to be the graph with the single initial node ( $u_{0} \mapsto w_{0}, 0$ ). In the sequel, we slightly
abuse notation and use $\varepsilon$ for the empty word so that $\varepsilon a$ is regarded to be the same as $a$, an element of $\operatorname{ind}\left(\mathcal{K}_{1}\right)$. We say that a strategy $\mathcal{S} \in \mathbb{S}_{0}$ respects $\mathfrak{I}$ if there exists a sequence $\sigma_{0}^{\mathcal{S}}, \sigma_{1}^{\mathcal{S}}, \ldots$ of elements of $\Delta^{\mathcal{M}_{1}} \cup\{\varepsilon\}$ such that

- each $\sigma_{i}^{\mathcal{S}}$ satisfies $\sigma_{i-1}^{\mathcal{S}}=\sigma_{i}^{\mathcal{S}} w$, for some $w \in \Delta^{\mathcal{G}_{1}}$, with $\sigma_{-1}^{\mathcal{S}}=\sigma_{0}$, and
- if $\left(u^{\prime} \mapsto \delta^{\prime}, i^{\prime}\right)$ is a ( $u \rightsquigarrow_{2}^{\Sigma} u^{\prime}$ )-successor of $(u \mapsto \delta, i)$ in $\mathfrak{I}$ then, according to $\mathcal{S}$, player 1 responds to the challenge $u \rightsquigarrow{ }_{2}^{\Sigma} u^{\prime}$ of player 2 in the state $\left(u \mapsto \sigma_{i}^{\mathcal{S}} \delta\right.$ ) with ( $u^{\prime} \mapsto \sigma_{i^{\prime}}^{\mathcal{S}} \delta^{\prime}$ ),
where $\sigma_{*}^{\mathcal{S}}=\varepsilon$. (Intuitively, $\sigma_{i}^{\mathcal{S}}$ is the $\sigma_{i-1}^{\mathcal{S}}$ without the last element, and so the sequence $\sigma_{0}^{\mathcal{S}} w_{0}, \sigma_{1}^{\mathcal{S}} w_{1}, \sigma_{2}^{\mathcal{S}} w_{2}, \ldots$, with $w_{i}=\operatorname{tail}\left(\sigma_{i-1}^{\mathcal{S}}\right)$, are the responses to the challenges of the strategy.) Clearly, all strategies in $\mathbb{S}_{0}$ respect $\mathfrak{I}_{0}$. Suppose we have already constructed $\mathfrak{I}_{k}$ and $\mathbb{S}_{k}$ such that every $\mathcal{S} \in \mathbb{S}_{k}$ respects $\mathfrak{I}_{k}$. If $\mathfrak{I}_{k}$ satisfies (3), then we are done. Otherwise, $\mathfrak{I}_{k}$ contains a node $(u \mapsto \delta, i)$ without a $\left(u \rightsquigarrow{ }_{2}^{\Sigma} u^{\prime}\right)$-successor, for some $u \rightsquigarrow_{2}^{\Sigma} u^{\prime}$. (We take such a node to be closest to the initial node.) Using the pigeonhole principle, we can find $\delta^{\prime}, i^{\prime}$ and a subset $\mathbb{S}_{k+1} \subseteq \mathbb{S}_{k}$ such that one of the following four options holds for all strategies $\mathcal{S} \in \mathbb{S}_{k+1}$ simultaneously: the response of player 1 according to $\mathcal{S}$ to the challenge $\left(u \not{ }_{2}^{\Sigma} u^{\prime}\right)$ in state $\left(u \mapsto \sigma_{i}^{\mathcal{S}} \delta\right)$ is of the form

$$
\begin{align*}
& \left(u^{\prime} \mapsto \sigma_{i}^{\mathcal{S}} \delta^{\prime}\right) \text { with } \delta^{\prime}=\delta w^{\prime} \text { and } i^{\prime}=i,  \tag{r.1}\\
& \left(u^{\prime} \mapsto \delta^{\prime}\right) \text { with } \sigma_{i}^{\mathcal{S}}=\varepsilon, \delta, \delta^{\prime} \in \operatorname{ind}\left(\mathcal{K}_{1}\right) \text { and } i^{\prime}=*,  \tag{r.2}\\
& \left(u^{\prime} \mapsto \sigma_{i}^{\mathcal{S}} \delta^{\prime}\right) \text { with } \delta=\delta^{\prime} w \text { and } i^{\prime}=i,  \tag{r.3}\\
& \left(u^{\prime} \mapsto \sigma_{i}^{\mathcal{S}}\right) \text { with } \delta \in \Delta^{\mathcal{G}_{1}}, \delta^{\prime}=\operatorname{tail}\left(\sigma_{i}^{\mathcal{S}}\right) \text { and } i^{\prime}=i+1 ; \tag{r.4}
\end{align*}
$$

see also items (3.1)-(3.4) above. In each of the four cases, we define $\mathfrak{I}_{k+1}$ by extending $\mathfrak{I}_{k}$ with $\left(u^{\prime} \mapsto \delta^{\prime}, i^{\prime}\right)$ as a ( $u \rightsquigarrow{ }_{2}^{\Sigma} u^{\prime}$ )-successor of ( $u \mapsto \delta, i$ ). Observe also that all $\mathcal{S} \in \mathbb{S}_{k+1}$ clearly respect $\mathfrak{I}_{k+1}$. We proceed in the same way and construct sequences $\mathfrak{I}_{0} \subseteq \mathfrak{I}_{1} \subseteq \ldots$ and $\mathbb{S}_{0} \supseteq \mathbb{S}_{1} \supseteq \mathbb{S}_{2}, \ldots$ until we either reach some $\mathfrak{I}_{n}$ satisfying (1)-(4) or obtain infinite sequences and take $\mathfrak{I}=\bigcup_{n<\omega} \mathfrak{I}_{n}$, which obviously satisfies (1)-(4).

Now we show that $\mathfrak{I}$ defines an $\omega$-winning strategy for player 1 in $G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ starting from some $\left(\Xi_{0} \mapsto w_{0}, \Psi_{0}\right)$. Let $w_{0}, w_{1}, \ldots$ be the longest (and possibly infinite) sequence of elements of $\Delta^{\mathcal{G}_{1}}$ such that, for each $w_{i}$, there exists $u$ with ( $u \mapsto w_{i}, i$ ) a node in $\mathfrak{I}$. Note that, by (4), every $w_{i}$ (if it exists) is uniquely determined. For each $i \geq 0$ with $w_{i}$ defined, set

$$
\Xi_{i}=\left\{u \mid\left(u \mapsto w_{i}, i\right) \text { in } \mathfrak{I}\right\} \quad \text { and } \quad \Psi_{i}=\left\{u^{\prime} \mid u \rightsquigarrow_{2}^{\Sigma} u^{\prime},\left(u \mapsto w_{i}, i\right) \text { and }\left(u^{\prime} \mapsto w_{i+1}, i+1\right) \text { are in } \mathfrak{I}\right\}
$$

and observe that $u_{0} \in \Xi_{0}, \Xi_{i} \neq \emptyset$ and $\Psi_{i} \subseteq \Xi_{i}^{\rightsquigarrow}, \Psi_{i} \subseteq \Xi_{i+1}$, for all $i \geq 0$ such that the sets are defined. Note also that if the sequence $w_{0}, w_{1}, \ldots$ is finite then the last $\Psi_{k}$ is empty. Similarly to the proof of Lemma 23, take the maximal $m<\omega$ such that $w_{m}$ exists and $w_{i} \neq w_{m}$ for all $i<m$.

To show that each $\left(\Xi_{i} \mapsto w_{i}, \Psi_{i}\right)$, for $0 \leq i \leq m$, is a valid state in the game $G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$, we have to define an $\omega$-winning strategy for the start-bounded game $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ from $\left(\emptyset, \Xi_{i} \mapsto w_{i}\right)$ with the first-round challenges $u \rightsquigarrow{ }_{2}^{\Sigma} v$ such that $v \notin \Psi_{i}$. Fix $i$ and define a graph $\mathfrak{I}_{i}$ containing the nodes $(u \mapsto \delta)$, for $(u \mapsto \delta, i)$ in $\mathfrak{I}$, and all the nodes $(u \mapsto \delta)$ such that $(u \mapsto \delta, *)$ is reachable from some ( $u^{\prime} \mapsto \delta^{\prime}, i$ ) in $\mathfrak{I}$ by a path not containing any ( $u^{\prime \prime} \mapsto \delta^{\prime \prime}, i+1$ ). The arrows and their labels in $\mathfrak{I}_{i}$ are induced in the obvious way by the arrows of $\mathfrak{I}$. Observe that $\mathfrak{I}_{i}$ satisfies (1) and (2) of Lemma 27 and satisfies (3) except, perhaps, in nodes ( $u \mapsto w_{i}$ ) with $u \rightsquigarrow{ }_{2}^{\Sigma} v$ and $v \in \Psi_{i}$. It can now be shown in the same way as in Lemma 27 that player 1 has an $\omega$-winning strategy in the start-bounded game $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ from $\left(\emptyset, \Xi_{i} \mapsto w_{i}\right)$ provided that the challenge $u \rightsquigarrow{ }_{2}^{\Sigma} v$ in the first round satisfies $v \notin \Psi_{i}$.

Now, by (3.4), the states $\left(\Xi_{i} \mapsto w_{i}, \Psi_{i}\right), i \leq m$, clearly define an $\omega$-winning strategy for player 1 in the game $G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ starting from $\left(\Xi_{0} \mapsto w_{0}, \Psi_{0}\right)$ : if player 2 challenges (with $\Psi_{i}$ ) in some state ( $\Xi_{i} \mapsto w_{i}, \Psi_{i}$ ), then player 1 responds with $\left(\Xi_{i+1} \mapsto w_{i+1}, \Psi_{i+1}\right)$ if $i<m$, and by the uniquely determined $\left(\Xi_{k} \mapsto w_{k}, \Psi_{k}\right)$ with $w_{k}=w_{m+1}$ if $i=m$. $(b) \Rightarrow(a)$ Suppose player 1 has an $\omega$-winning strategy $\mathcal{S}$ starting from $\mathfrak{a}_{0}=\left(\Xi_{0} \mapsto w_{0}, \Psi_{0}\right)$ in $G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ with $u_{0} \in \Xi_{0}$ and let $n<\omega$. Consider any play in $G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ starting from $\mathfrak{a}_{0}$ and conforming with $\mathcal{S}$. One can represent the play as a sequence

$$
\left(\mathfrak{a}_{0}, u_{0}^{0} \rightsquigarrow{ }_{2}^{\Sigma} v_{0}^{0}, \ldots, u_{k_{0}}^{0} \rightsquigarrow{ }_{2}^{\Sigma} v_{k_{0}}^{0}\right), \quad\left(\mathfrak{a}_{1}, u_{0}^{1} \rightsquigarrow{ }_{2}^{\Sigma} v_{0}^{1}, \ldots, u_{k_{1}}^{1} \rightsquigarrow{ }_{2}^{\Sigma} v_{k_{1}}^{1}\right),
$$

where each $\mathfrak{a}_{i}$ is a response of player 1 (a state of the game $G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ ) to the (uniquely determined) challenge in $\mathfrak{a}_{i-1}$, and $u_{0}^{i} \rightsquigarrow \sum_{2}^{\Sigma} v_{0}^{i}, \ldots, u_{k_{i}}^{i} \rightsquigarrow{ }_{2}^{\Sigma} v_{k_{i}}^{i}$ are the challenges of player 2 in the start-bounded game $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ from $\mathfrak{a}_{i}$ (in
which case player 1 has an $\omega$-winning strategy). Similarly to the backward game, the sequence $\mathfrak{a}_{0}, \mathfrak{a}_{1}, \ldots$ does not depend on the challenges of player 2 but only on $\mathfrak{a}_{0}$ and $\mathcal{S}$. So we fix the sequence $\mathfrak{a}_{0}, \mathfrak{a}_{1}, \ldots, \mathfrak{a}_{k}$, where either $k=n$ or $k<n$ is the maximal number of states reached in any play starting from $\mathfrak{a}_{0}$ according to $\mathcal{S}$. This sequence induces a sequence $w_{0}, w_{1}, \ldots, w_{k}$ of elements of $\Delta^{\mathcal{G}_{1}}$ given by the states $\mathfrak{a}_{i}=\left(\Xi_{i} \mapsto w_{i}, \Psi_{i}\right)$. We take any element $\sigma \in \Delta^{\mathcal{M}_{1}}$ with $\operatorname{tail}(\sigma)=w_{k}$ and let $\sigma_{0}=\sigma w_{k-1} \ldots w_{0}$. In addition to the $\omega$-winning strategy $\mathcal{S}$, we also fix the $\omega$-winning strategies for player 1 in the start-bounded games for $G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ from $\mathfrak{a}_{i}$ with the appropriate challenge in the first round.

Now, for any sequence $u_{0} \rightsquigarrow_{2}^{\Sigma} u_{1} \rightsquigarrow_{2}^{\Sigma} \cdots \rightsquigarrow_{2}^{\Sigma} u_{m-1} \rightsquigarrow_{2}^{\Sigma} u_{m}, m \leq n$, of challenges by player 2 in the game $G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)$ starting from $\mathfrak{s}_{0}=\left(u_{0} \mapsto \sigma_{0}\right)$, we construct a sequence of responses $\mathfrak{s}_{1}=\left(u_{1} \mapsto \sigma_{1}\right), \ldots, \mathfrak{s}_{m}=\left(u_{m} \mapsto \sigma_{m}\right)$ of player 1 . In order to do this, we define inductively a sequence $\pi_{0}, \ldots, \pi_{m}$ (of non-empty sequences) such that the following hold for each $i \leq m$ :
$-\pi_{i}$ begins with one of the states $\mathfrak{a}_{0}, \ldots, \mathfrak{a}_{k}$, and all other elements in $\pi_{i}$ are states $(\Theta, \Xi \mapsto w)$ of the respective start-bounded game;

- if $\pi_{i}=\pi_{j} \cdot\left(\Theta^{1}, \Xi^{1} \mapsto w^{1}\right) \cdots\left(\Theta^{\ell}, \Xi^{\ell} \mapsto w^{\ell}\right)$ then $\sigma_{i}=\sigma_{j} w^{1} \cdots w^{\ell}$.

For $i=0$, we set $\pi_{0}=\mathfrak{a}_{0}=\left(\Xi_{0} \mapsto w_{0}, \Psi_{0}\right)$, which clearly has the required properties. Now suppose that $\mathfrak{s}_{0}, \ldots, \mathfrak{s}_{i-1}$ and $\pi_{0}, \ldots, \pi_{i-1}$ have already been defined, for $1 \leq i \leq m$. Consider a challenge $u_{i-1} \rightsquigarrow \frac{\Sigma}{2} u_{i}$ in the state $\mathfrak{s}_{i-1}$. Two cases are possible.

- If $\pi_{i-1}$ consists of a single state $(\Xi \mapsto w, \Psi)$ then it coincides with some $\mathfrak{a}_{j-1}$, for $j \leq k$. Recall that $u_{i-1} \in \Xi$ and tail $\left(\sigma_{i-1}\right)=w$. We have the following two options.
- If $u_{i} \in \Psi$ then we set $\pi_{i}=\mathfrak{a}_{j}$ and obtain $\sigma_{i}$ from $\sigma_{i-1}$ by removing its final element, $w$.
- Otherwise, $u_{i} \in \Xi^{\leadsto \backslash} \backslash \Psi$ and we launch the start-bounded game $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ from $(\emptyset, \Xi \mapsto w)$ and set $\pi_{i}=\pi_{i-1} \cdot\left(\Theta^{\prime}, \Xi^{\prime} \mapsto w^{\prime}\right)$ and $\sigma_{i}=\sigma_{i-1} w^{\prime}$, where $\left(\Theta^{\prime}, \Xi^{\prime} \mapsto w^{\prime}\right)$ is the response of player 1 to $u_{i-1} \rightsquigarrow \frac{\Sigma}{2} u_{i}$ according to the $\omega$-winning strategy in the start-bounded game.
- Otherwise, the final element of $\pi_{i-1}$ is a state of the start-bounded game, and we follow the construction from the proof of $(c) \Rightarrow(a)$ in Lemma 27.

This completes the proof of the lemma.
Similarly to the start-bounded game, the size of the game graph for $G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ is exponential in the size of $\mathcal{G}_{2}$ as it contains $O\left(\left(\left|\operatorname{ind}\left(\mathcal{K}_{2}\right)\right| \times 2^{\mid \Delta^{G_{2}} \backslash \text { ind }\left(\mathcal{K}_{2}\right) \mid}\right)^{2} \times\left|\Delta^{\mathcal{G}_{1}}\right|\right)$ states. Note, however, that when constructing the graph, we have to check that for each of its states player 1 has an $\omega$-winning strategy in the corresponding start-bounded game. As observed in Section 4.4, this can also be done in time exponential in $\Delta^{\mathcal{G}_{2}} \backslash \operatorname{ind}\left(\mathcal{K}_{2}\right)$ and polynomial in both ind $\left(\mathcal{K}_{2}\right)$ and $\Delta^{\mathcal{G}_{1}}$. In view of Theorem 12 (i) and (iv) and Proposition 14 , we then obtain:

Theorem 31. For combined complexity, $\Sigma$-query entailment is in 2ExpTime for Horn- $\mathcal{A L C H} \mathcal{I}$ and Horn- $\mathcal{A L C I}$ KBs, and in ExpTime for DL-Lite $\mathcal{h o r n}_{\mathcal{H}}$ and DL-Lite core $\mathcal{\mathcal { H }}$ KBs. For data complexity, these problems are all in P .

For DL-Lite core and $D L$-Lite $_{\text {horn }} \mathrm{KBs}$, the general game $G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ can be significantly simplified. Note first that the start-bounded game $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ in this case can be reduced to the forward game $G_{\Sigma}^{f}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$. Indeed, by (lite ${ }_{2}$ ) and the fact that $(u, v)^{\mathcal{G}}$ is always a singleton set in the generating structures for DL-Lite ${ }_{\text {horn }}$, player 2 cannot challenge player 1 in any round $i>0$ of $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ with $u \rightsquigarrow{ }_{2}^{\Sigma} v$ such that $\boldsymbol{r}_{\Sigma}^{\mathcal{G}_{2}}(u, v) \subseteq \overline{\boldsymbol{r}}_{\Sigma}^{\mathcal{G}_{1}}\left(w_{i-2}, w_{i-1}\right)$. Thus, (nobackward) holds for any set $\Theta_{i}$, and so we obtain: for any $u_{0} \in \Delta^{\mathcal{G}_{2}}$ and $w_{0} \in \Delta^{\mathcal{G}_{1}}$, player 1 has an $\omega$-winning strategy in $G_{\Sigma}^{s}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ with an initial state $\left(\emptyset, \Xi_{0} \mapsto w_{0}\right)$ and $u_{0} \in \Xi_{0}$ if and only if player 1 has an $\omega$-winning strategy in $G_{\Sigma}^{f}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ with the initial state $\left(u_{0} \mapsto w_{0}\right)$.

Second, since having a start-bounded $\omega$-winning strategy with an initial state $(\emptyset, \Xi \mapsto w)$ is equivalent to having forward $\omega$-winning strategies for all initial states $(u \mapsto w)$ with $u \in \Xi$, for any general $\omega$-winning strategy player 1 can choose $\Xi_{i}$ as small as possible: $\Xi_{i}=\left\{u_{0}\right\}$ in the initial state and $\Xi_{i}=\Psi_{i-1}$, for $i>0$. Also observe that in the general game, if $\Xi_{i-1}$ contains at most one element, then player 1 has to choose for $\Psi_{i}$ a set containing at most one element (if player 1 chooses a set with at least two elements, then he will not have a response to the challenge $\Psi_{i}$
since the generating structures for $D L$-Lite $_{\text {horn }}$ KBs are functional). It follows by induction that if player 1 has an $\omega$-winning strategy in the general game then player 1 has an $\omega$-winning strategy in which all states are of the form $\left(\Xi_{i} \mapsto w_{i}, \Psi_{i}\right)$, where $\Xi_{i}$ is a singleton set, $\Psi_{i}$ has at most one element, and $\Xi_{i}=\Psi_{i-1}$. The number of states in this game is polynomial, and so the existence of an $\omega$-winning strategy can be checked in P. Note also that this strategy corresponds to the winning strategy in the naïve game $G_{\Sigma}^{n}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)$ sketched in Section 4.1 .
Theorem 32. $\Sigma$-query entailment for DL-Lite core and $D L-L i t e_{\text {horn }} K B s$ is in P for both combined and data complexity.

## 5. Lower Bounds

In this section, we show that the upper complexity bounds obtained in Section 4 are optimal. Throughout the section we assume that the materialisations of the KBs we deal with are the unravellings of the generating structures for those KBs constructed as described in Section 3 .

As we have seen in the previous section, the problems of $\Sigma$-query entailment and inseparability for all of our DLs are in P for data complexity. The next theorem establishes a matching lower bound:

Theorem 33. For data complexity, $\Sigma$-query entailment and inseparability are P -hard for DL-Lite core and $\mathcal{E} \mathcal{L} K B s$.
Proof. The proof is by reduction of the P-complete entailment problem for acyclic Horn ternary clauses: given a conjunction $\varphi$ of clauses of the form $p_{i}$ and $p_{i} \wedge p_{i^{\prime}} \rightarrow p_{j}$, with $i, i^{\prime}<j$, decide whether $p_{n}$ is true in every model of $\varphi$. Consider a DL-Lite core TBox $\mathcal{T}$ containing the following concept inclusions:

$$
V \sqsubseteq \exists S, \quad \exists S^{-} \sqsubseteq \exists R_{k} \text { and } \exists R_{k}^{-} \sqsubseteq V, \text { for } k=1,2,
$$

and let an ABox $\mathcal{A}$ consist of $F\left(p_{n}\right)$ and

$$
\begin{array}{ll}
S\left(p_{i}, p_{i}\right), R_{1}\left(p_{i}, p_{i}\right), R_{2}\left(p_{i}, p_{i}\right), & \text { for each clause } p_{i} \text { in } \varphi, \\
S\left(p_{j}, c\right), R_{1}\left(c, p_{i}\right), R_{2}\left(c, p_{i^{\prime}}\right), & \text { for each clause } c=p_{i} \wedge p_{i^{\prime}} \rightarrow p_{j} \text { in } \varphi .
\end{array}
$$

Set $\Sigma=\left\{F, S, R_{1}, R_{2}\right\}, \mathcal{K}_{1}=(\emptyset, \mathcal{A})$ and $\mathcal{K}_{2}=\left(\mathcal{T}, \mathcal{A} \cup\left\{V\left(p_{n}\right)\right\}\right)$. Obviously, $\mathcal{K}_{2} \Sigma$-query entails $\mathcal{K}_{1}$. On the other hand, the materialisation of $\mathcal{K}_{2}$ is (finitely) $\Sigma$-homomorphically embeddable in the materialisation of $\mathcal{K}_{1}$ iff $\varphi$ derives $p_{n}$. Indeed, the materialisation $\mathcal{M}_{2}$ of $\mathcal{K}_{2}$ is infinite, while the materialisation $\mathcal{M}_{1}$ of $\mathcal{K}_{1}$ is finite. So, the only way to embed finite prefixes of $\mathcal{M}_{2}$ of arbitrary depth into $\mathcal{M}_{1}$ is by mapping subtrees of unbounded depth into the loops in $\mathcal{M}_{1}$ for unary clauses $p_{i}$ in $\varphi$, which is only possible if there is a tree of clauses of the form $p_{i} \wedge p_{i^{\prime}} \rightarrow p_{j}$ with root $p_{n}$ and leaves among the clauses $p_{i}$ of $\varphi$ (that is, if there is a derivation of $p_{n}$ from $\varphi$ ).

For $\mathcal{E} \mathcal{L}$, we take $\mathcal{T}=\left\{V \sqsubseteq \exists S .\left(\exists R_{1} . V \sqcap \exists R_{2} . V\right)\right\}$. The remainder of the proof is the same as above.
For combined complexity, ExpTime-hardness of $\Sigma$-query inseparability for Horn- $\mathcal{A} \mathcal{L C}$ can be proved by reduction of the subsumption problem: we have $\mathcal{T} \vDash A \sqsubseteq B$ if and only if $(\mathcal{T},\{A(a)\})$ and $(\mathcal{T} \cup\{A \sqsubseteq B\},\{A(a)\})$ are $\{B\}$-query inseparable. We now establish the remaining lower bounds for the combined complexity.

Theorem 34. For combined complexity, the problems of $\Sigma$-query entailment and inseparability are ExpTime-hard for DL-Lite core ${ }^{\mathcal{H}}$ KBs.

Proof. The proof is by encoding alternating Turing machines (ATMs) with polynomial tape and using the fact that APSpace $=$ ExpTime; see, e.g. [34].

Let $M=\left(\Lambda, Q, q_{0}, q_{1}, \delta\right)$ be an ATM with a tape alphabet $\Lambda$, a set of states $Q$ partitioned into existential $Q_{\exists}$ and universal $Q_{\Downarrow}$ states, an initial state $q_{0} \in Q_{\exists}$, an accepting state $q_{1} \in Q$, and a transition function

$$
\delta:\left(Q \backslash\left\{q_{1}\right\}\right) \times \Lambda \times\{1,2\} \rightarrow Q \times \Lambda \times\{-1,0,+1\}
$$

which, for a state $q$ and symbol $a$, gives two instructions, $\delta(q, a, 1)$ and $\delta(q, a, 2)$. We assume that existential and universal states strictly alternate: any transition from an existential state leads to a universal state, and vice versa. We extend $\delta$ with the instructions $\delta\left(q_{1}, a, j\right)=\left(q_{1}, a, 0\right)$, for $a \in \Lambda$ and $j=1,2$, which go into an infinite loop if $M$


Figure 11: Encoding the initial configuration by a block.
reaches the accepting state $q_{1}$. Thus, assuming that $M$ terminates on every input, it accepts an input $\boldsymbol{w}$ if and only if the modified ATM $M^{\prime}$ has a run on $\boldsymbol{w}$ all branches of which are infinite.

Given $M^{\prime}$ and an input $\boldsymbol{w}$, our aim is to construct TBoxes $\mathcal{T}_{1}$ and $\mathcal{T}_{2}$ and a signature $\Sigma$ such that $M^{\prime}$ has a run with only infinite branches if and only if the materialisation $\mathcal{M}_{2}$ of $\left(\mathcal{T}_{2}, \mathcal{A}\right)$ is finitely $\Sigma$-homomorphically embeddable into the materialisation $\mathcal{M}_{1}$ of $\left(\mathcal{T}_{1}, \mathcal{A}\right)$, where $\mathcal{A}$ is an ABox with a single assertion $A(c)$. Let $f$ be a polynomial such that, on any input of length $m, M^{\prime}$ uses at most $n=f(m)$ cells, which are numbered from 1 to $n$, and throughout any computation the head remains to the right of cell 0 , which contains a special marker $b \in \Lambda$.

The construction proceeds in four steps. In the definition of the TBoxes $\mathcal{T}_{1}$ and $\mathcal{T}_{2}$, we use concept inclusions of the form $B \sqsubseteq \exists R .\left(C_{1} \sqcap \cdots \sqcap C_{k}\right)$ as an abbreviation for

$$
B \sqsubseteq \exists R_{0}, \quad R_{0} \sqsubseteq R \quad \text { and } \quad \exists R_{0}^{-} \sqsubseteq C_{i}, \text { for } 1 \leq i \leq k,
$$

where $R_{0}$ is a fresh role name. If $C_{i}$ is a complex concept then $\exists R_{0}^{-} \sqsubseteq C_{i}$ is also treated as an abbreviation for the respective concept and role inclusions.
Step 1. First we encode configurations and transitions of $M^{\prime}$ using $\mathcal{T}_{1}$. We represent a configuration (that is, the content of every cell on the tape, the state and the position of the head) by a sequence of $n+2$ domain elements in $\mathcal{M}_{1}$, which will be called a block. The first element in each block is used to distinguish the type of the block, whereas the remaining elements are assigned indexes from 0 to $n$ : if the element with index $i$ belongs to $C_{a}$, for some $a \in \Lambda$, then the $i$ th cell of the tape is assumed to contain $a$ in the configuration defined by the block as shown in Fig. 11 (the first element of the block has index -1 ). The first block represents the initial configuration, that is, symbols $a_{1}, \ldots, a_{n}$ written in the $n$ cells of the tape (the input $\boldsymbol{w}$ padded with $\smile$ ) and the initial state $q_{0}$, which is achieved by the following inclusion in $\mathcal{T}_{1}$ :

$$
\begin{equation*}
A \sqsubseteq \exists P .\left(C_{b} \sqcap \exists P .\left(C_{a_{1}} \sqcap \exists P .\left(C_{a_{2}} \sqcap \exists P .\left(\ldots \exists P .\left(C_{a_{n}} \sqcap Z_{q_{0}, a_{1}, 1}^{0, n}\right) \ldots\right)\right)\right)\right) . \tag{1}
\end{equation*}
$$

Step 2. The current state $q \in Q$, the position $k$ of the head and the content $a \in \Lambda$ of the active cell scanned by the head are recorded in the concept $Z_{q, a, k}^{0, n}$ that contains the last element of the block. At the end of the block we branch out one block for each of the two instructions and propagate via the $Z_{q, a, k}^{1, i}$ and the $Z_{q, a, k}^{2, i}$ the current state, head position and symbol in the active cell: for $q \in Q, a \in \Lambda$ and $1 \leq k \leq n$, we add to $\mathcal{T}_{1}$ the inclusions

$$
\begin{equation*}
Z_{q, a, k}^{0, n} \sqsubseteq \prod_{j=1,2} \exists P .\left(X_{j} \sqcap Z_{q, a, k}^{j,-1}\right), \tag{1}
\end{equation*}
$$

where $X_{1}$ and $X_{2}$ are two fresh concept names (which specify the type of the block).
The acceptance condition for $M^{\prime}$ is enforced by means of $\mathcal{T}_{2}$. For the initial block representing the initial configuration we take

$$
\begin{equation*}
A \sqsubseteq \exists P . \underbrace{\exists P \cdots \exists P}_{n \text { times }} \prod_{j=1,2} \exists P \cdot X_{j} . \tag{2}
\end{equation*}
$$

The two concept names, $X_{1}$ and $X_{2}$, are used to distinguish between the two blocks for universal successor states and one more concept name, $X_{3}$, marks both blocks for existential state successors. These blocks are arranged into an infinite tree-like structure: the initial block is the root from which an $X_{1^{-}}$and an $X_{2}$-blocks branch out (recall that successors of the initial state $q_{0}$ are universal). Each of them is followed by an $X_{3}$-block, which branches out an $X_{1-}$


Figure 12: The structure of $\Sigma$-homomorphisms from $\mathcal{M}_{2}$ to $\mathcal{M}_{1}$ : note that $A, X_{1}, X_{2} \in \Sigma$ but $X_{3} \notin \Sigma$.
and an $X_{2}$-block, and so on. This is achieved by adding to $\mathcal{T}_{2}$ the following inclusions:

$$
\begin{align*}
& X_{3} \sqsubseteq \exists P \cdot \underbrace{\exists P .(G \sqcap \exists P .(\cdots \exists P \cdot(G \sqcap}_{n \text { times }} \prod_{j=1,2} \exists P \cdot X_{j}))),  \tag{2}\\
& X_{j} \sqsubseteq \exists P \cdot \underbrace{\exists P .(G \sqcap \exists P \cdot(\cdots \exists P \cdot(G \sqcap}_{n \text { times }} \exists P \cdot X_{3}))), \tag{2}
\end{align*}
$$

$$
\text { for } j=1,2
$$

where $G$ is a fresh concept name (which marks every cell of the tape). If $\Sigma=\left\{A, X_{1}, X_{2}, P\right\}$ then there is a unique $\Sigma$ homomorphism from the initial block in $\mathcal{M}_{2}$ to the block of the initial configuration in $\mathcal{M}_{1}$. Next, signature concepts $X_{1}$ and $X_{2}$ ensure that the $X_{1}$ - and $X_{2}$-blocks are $\Sigma$-homomorphically mapped (in a unique way) into the respective blocks in $\mathcal{M}_{1}$, which reflects the acceptance condition of universal states. The following $X_{3}$-block, however, contains no signature marker ( $X_{1}$ or $X_{2}$ ) and can be mapped to either of the blocks in $\mathcal{M}_{1}$, which reflects the choice in existential states; see Fig. 12, where possible $\Sigma$-homomorphisms are shown by thick dashed arrows.
Step 3. Recall that the $Z_{q, a, k}^{j, i}$, for $-1 \leq i \leq n$, specify the position $k$ of the head on the tape. Let the active cell in the previous configuration be $k$. Then, until the cell $k-2$ is reached in the current configuration, the following inclusions in $\mathcal{T}_{1}$ propagate its current state $(q \in Q)$, the symbol in the active cell $(a \in \Lambda)$, the head position $(1 \leq k \leq n)$ and the block type $(j=1,2)$ along the domain elements constituting the block: for $-1<i \leq n$ with $i \neq k-1$,

$$
\begin{equation*}
Z_{q, a, k}^{j, i-1} \sqsubseteq \prod_{b \in \Lambda} \exists P \cdot\left(C_{b} \sqcap Z_{q, a, k}^{j, i}\right) \tag{1}
\end{equation*}
$$

(for each $b \in \Lambda$, these concept inclusions also generate a branch in $\mathcal{M}_{1}$ to represent the same cell but with a different symbol, $b$, tentatively assigned to the cell—Step 4 will ensure that the correct branch and symbol are selected to match the cell contents in the preceding configuration). We point out that, since the size of the tape is polynomial in the length of the input, we can use the subscripts of the $Z_{q, a, k}^{j, i}$ to specify the head position, $k$, and the cell number, $i$. When the cell $k-2$ is reached, the contents of the active cell, the information from the subscripts of the $Z_{q, a, k}^{j, i}$ is used to perform the instruction according to $\delta$ :

$$
Z_{q, a, k}^{j, k-2} \sqsubseteq \begin{cases}\prod_{b \in \Lambda} \exists P \cdot\left(C_{b} \sqcap \exists P \cdot\left(F_{a^{\prime}} \sqcap Z_{q^{\prime}, b, k-1}^{0, k}\right)\right), & \text { if } \delta(q, a, j)=\left(q^{\prime}, a^{\prime},-1\right),  \tag{1}\\ \prod_{b \in \Lambda} \exists P \cdot\left(C_{b} \sqcap \exists P \cdot\left(F_{a^{\prime}} \sqcap Z_{q^{\prime}, a^{\prime}, k}^{0, k}\right)\right), & \text { if } \delta(q, a, j)=\left(q^{\prime}, a^{\prime}, 0\right), \\ \prod_{b \in \Lambda} \exists P \cdot\left(C_{b} \sqcap \exists P \cdot\left(F_{a^{\prime}} \sqcap \prod_{b^{\prime} \in \Lambda} \exists P \cdot\left(C_{b^{\prime}} \sqcap Z_{q^{\prime}, b^{\prime}, k+1}^{0, k+1}\right)\right)\right), & \text { if } \delta(q, a, j)=\left(q^{\prime}, a^{\prime},+1\right) .\end{cases}
$$

Specifically, the symbol in the active cell, $k$, is changed according to the instruction and the cell is marked by concept $F_{a^{\prime}}$. Then the current state, symbol in the active cell of the successive configuration and the new head position are


Figure 13: Executing the instructions of $M^{\prime}$.
recorded in the subscripts of the concepts $Z_{q, a, k}^{0, i}$; note that the block type marker, $j=1,2$, is replaced by 0 . These three situations are depicted in Fig. 13, where the hatched nodes denote domain elements two cells before the active cell of the configuration (where inclusion ( $\mathcal{T}_{1}-4$ ) becomes 'active) and the filled black and grey nodes denote domain elements for the active cell. (Note that the element corresponding to the cell $k-1$ has only one $P$-successor, which encodes the new symbol, $a^{\prime}$, in that cell; see explanations below.) Then the new state and the symbol in the active cell of the successive configurations are propagated further along the tape using $\left(\mathcal{T}_{1}-3\right)$ with $j=0$ and $i>k-1$.
Step 4. The inclusions $\left(\mathcal{T}_{1}-3\right)-\left(\mathcal{T}_{1}-4\right)$ generate a separate $P$-successor for each $b \in \Lambda$, thus not preserving the contents of the tape between transitions. We now add a number of inclusions to both TBoxes so that wrong branches would be ignored by any finite $\Sigma$-homomorphism, $h$, from $\mathcal{M}_{2}$ to $\mathcal{M}_{1}$, where

$$
\begin{equation*}
\Sigma=\left\{A, P, X_{1}, X_{2}\right\} \cup\left\{D_{a} \mid a \in \Lambda\right\} . \tag{5}
\end{equation*}
$$

Suppose $h\left(d_{2}\right)=d_{1}$ and $d_{2}$ belongs to $G$ in $\mathcal{M}_{2}$ (and therefore, it represents a cell in a non-initial configuration). We add the following two inclusions to $\mathcal{T}_{2}$ :

$$
\begin{align*}
G & \sqsubseteq \prod_{b \in \Lambda} G_{b},  \tag{2}\\
G_{b} & \sqsubseteq \exists P^{-} \cdot \underbrace{\exists P^{-} \ldots \exists P^{-}}_{n \text { times }} \cdot \exists P^{-} \cdot D_{b}, \tag{T-1}
\end{align*}
$$

$$
\text { for } b \in \Lambda
$$

Then, for each symbol $b \in \Lambda$, the element $d_{2}$ generates a block of $n+2$-many $P^{-}$-connected elements that ends in the concept $D_{b}$; we call it a $D_{b}$-block of $d_{2}$. Recall from Step 3 that, for $a \in \Lambda$, if $d_{1} \in F_{a}^{\mathcal{M}_{1}}$ then it represents a cell whose content is changed to $a$ (in which case $d_{1}$ has no 'siblings', that is, the $P$-predecessor of $d_{1}$ has a single $P$-successor, $d_{1}$ ). However, if $d_{1} \in C_{a}^{\mathcal{M}_{1}}$ then the content of the cell represented by $d_{1}$ must be copied from the previous configuration). This is achieved by adding $\left(\mathcal{T}-1\right.$ and the following inclusions to $\mathcal{T}_{1}$ :

$$
\begin{align*}
& F_{a} \sqsubseteq D_{a} \sqcap \prod_{b \in \Lambda} G_{b},  \tag{1}\\
& C_{a} \sqsubseteq D_{a} \sqcap \prod_{b \in \Lambda \backslash\{a\}} G_{b} . \tag{1}
\end{align*}
$$

So, if $d_{1} \in F_{a}^{\mathcal{M}_{1}}$ then $d_{1}$ has a $D_{b}$-block for any $b \in \Lambda$ and, by the choice of $\Sigma$, each of the $D_{b}$-blocks of $d_{2}$ in $\mathcal{M}_{2}$ can be mapped by $h$ to the respective $D_{b}$-block of $d_{1}$ in $\mathcal{M}_{1}$. On the other hand, if $d_{1} \in C_{a}^{\mathcal{M}_{1}}$ then $d_{1}$ has a $D_{b}$-block only for $b \in \Lambda$ with $b \neq a$. So, all $D_{b}$-blocks of $d_{2}$ with $b \neq a$ can still be mapped by $h$ to the respective $D_{b}$-blocks of $d_{1}$ in $\mathcal{M}_{1}$. The remaining $D_{a}$-block of $d_{2}$ could be mapped in the reverse order along the 'main' branch in $\mathcal{M}_{1}$ but only


Figure 14: Ensuring succession of $M^{\prime}$ configurations.
if the cell contains $a$ in the preceding configuration (that is, the element that is $n+2$ steps closer to the root of $\mathcal{M}_{1}$ belongs to $D_{a}$ ); see Fig. 14 .

One can show now that $\mathcal{T}_{1}$ and $\mathcal{T}_{2}$ are as required: $M^{\prime}$ has a run with only infinite branches if and only if the materialisation $\mathcal{M}_{2}$ of $\left(\mathcal{T}_{2}, \mathcal{A}\right)$ is finitely $\Sigma$-homomorphically embeddable into the materialisation $\mathcal{M}_{1}$ of $\left(\mathcal{T}_{1}, \mathcal{A}\right)$. It remains to use Theorem 6 and the fact that APSpace $=$ ExpTime. It follows, by Theorem 13 , that deciding $\Sigma$-query inseparability is also ExpTime-hard.

Theorem 35. For combined complexity, the problems of $\Sigma$-query entailment and inseparability are 2ExpTime-hard for Horn- $\mathcal{A L C I}$ KBs.

Proof. The proof is by encoding alternating Turing machines (ATMs) with exponential tape and using the fact that AExpSpace $=2$ ExpTime.

As in the proof of Theorem 34, let $M=\left(\Lambda, Q, q_{0}, q_{1}, \delta\right)$ be an ATM and let $M^{\prime}$ be the ATM obtained from $M$ by extending it with two instructions that go into an infinite loop if $M$ reaches the accepting state. Given $M^{\prime}$ and an input $\boldsymbol{w}$, our aim is to construct two TBoxes, $\mathcal{T}_{1}^{\prime}$ and $\mathcal{T}_{2}^{\prime}$, and a signature $\Sigma$ such that $M^{\prime}$ has a run with only infinite branches if and only if the materialisation $\mathcal{M}_{2}$ of $\left(\mathcal{T}_{2}^{\prime}, \mathcal{A}\right)$ is finitely $\Sigma$-homomorphically embeddable into the materialisation $\mathcal{M}_{1}$ of $\left(\mathcal{T}_{1}^{\prime}, \mathcal{A}\right)$, where $\mathcal{A}=\{A(c)\}$. Let $f$ be a polynomial such that, on any input of length $m, M$ uses at most $2^{n}-2$ tape cells, with $n=f(m)$, which are numbered from 1 to $2^{n}-2$, and throughout any computation the head remains to the right of cell 0 , which contains a special marker $b \in \Lambda$. The construction proceeds in five steps (steps $1-4$ are similar to steps 1-4 in the proof of Theorem 34.
Step 0. We use tuples of $2 n$ concept names to represent distances of up to $2^{n}$ between the cells on the tape in consecutive configurations. We refer to a tuple $Y_{n-1}, \bar{Y}_{n-1}, \ldots, Y_{0}, \bar{Y}_{0}$ of concept names as $Y$ and assume that the TBox contains the following concept inclusions to encode an $n$-bit $R$-counter on $Y$ :

$$
\begin{array}{ll}
\bar{Y}_{k} \sqcap Y_{k-1} \sqcap \cdots \sqcap Y_{0} \sqsubseteq \forall R .\left(Y_{k} \sqcap \bar{Y}_{k-1} \sqcap \cdots \sqcap \bar{Y}_{0}\right), & \text { for } n>k \geq 0, \\
\bar{Y}_{i} \sqcap \bar{Y}_{k} \sqsubseteq \forall R . \bar{Y}_{i}, & \text { for } n>i>k, \\
Y_{i} \sqcap \bar{Y}_{k} \sqsubseteq \forall R . Y_{i}, & \text { for } n>i>k .
\end{array}
$$

(Note that we will need $P$-counters as well as $P^{-}$-counters.) We use the expression end ${ }^{Y}$ on the left-hand side of concept inclusions to say that the $Y$-value is $2^{n}-1$ (which is a shortcut for $Y_{n-1} \sqcap \cdots \sqcap Y_{0}$ ); we also use not-end ${ }^{Y}$ on the left-hand side of concept inclusions for the complementary statement (which is a shortcut for $n$ concept inclusions with not-end ${ }^{Y}$ replaced by each of $\bar{Y}_{n-1}, \ldots, \bar{Y}_{0}$ ). Finally, we use reset ${ }^{Y}$ on the right-hand side of concept inclusions for the reset command (which is equivalent to $\bar{Y}_{n-1} \sqcap \cdots \sqcap \bar{Y}_{0}$ ). Note that the counter stops at $2^{n}-1$ : the $R$-successors of a domain element in end ${ }^{Y}$ do not have to encode any value.
Step 1. First we encode configurations and transitions of $M^{\prime}$ using $\mathcal{T}_{1}^{\prime}$. We represent a configuration by a block, which is a sequence of $2^{n}+1$ domain elements connected by a role $P$. As in Theorem 34 the first element distinguishes the


Figure 15: Encoding the initial configuration by a block.
blocks for the two alternative instructions; using a $P$-counter on a tuple $T$, we assign indices from 0 to $2^{n}-1$ to all other elements in each block. The element with index 0 is needed for padding. Each of the remaining $2^{n}-1$ elements belongs to a concept $C_{a}$, for some $a \in \Lambda$ : if the element with index $i+1$ is in $C_{a}$, then the cell $i$ is assumed to contain $a$ in the configuration represented by the block (in particular, the element with index 1 contains $b$ for cell 0 ) as shown in Fig. 15

The first block represents the initial configuration: the input $\boldsymbol{w}=a_{1} \ldots a_{m}$ is followed by $2^{n}-m-2$ blank symbols $\lrcorner$ and the head is positioned over cell 1 , which is indicated by the 0 value of the $P$-counter on a tuple $H$. This is achieved by the following concept inclusions in the TBox $\mathcal{T}_{1}^{\prime}$ :

```
\(A \sqsubseteq \exists P .\left(\right.\) reset \(^{T} \sqcap \exists P .\left(C_{b} \sqcap \exists P .\left(C_{a_{1}} \sqcap \operatorname{reset}^{H} \sqcap \exists P .\left(C_{a_{2}} \sqcap \exists P .\left(\ldots \exists P .\left(C_{a_{m}} \sqcap I\right) \ldots\right)\right)\right)\right)\),
not-end \({ }^{T} \sqcap I \sqsubseteq \exists P .\left(I \sqcap C_{\llcorner }\right)\),
\(\left(\mathcal{T}_{1}^{\prime}-2\right)\)
end \(^{T} \sqcap I \sqsubseteq Z_{q_{0} a_{1}}^{0}\),
where \(I\) is a fresh concept name that is used only for padding of the input with \(\lrcorner\); cf. \(\mathcal{T}_{1}-1\).
Step 2. Similarly to the proof of Theorem 34, the current state \(q \in Q\) and the content \(a \in \Lambda\) of the active cell scanned by the head is recorded in the subscripts of concepts \(Z_{q a}^{0}\) that contain the last element of the block; note, however, that the position of the head must now be specified using the \(P\)-counter on \(H\). At the end of the block, when the \(T\)-value reaches \(2^{n}-1\), we branch out one block for each of the two transitions, reset the \(P\)-counter on \(T\), and propagate, via \(Z_{q a}^{1}\) and \(Z_{q a}^{2}\), the current state and symbol in the active cell: for \(q \in Q\) and \(a \in \Lambda\), we add to \(\mathcal{T}_{1}^{\prime}\) the concept inclusion
\[
\begin{equation*}
\text { end }^{T} \sqcap Z_{q a}^{0} \sqsubseteq \prod_{j=1,2} \exists P .\left(X_{j} \sqcap \exists P .\left(\text { reset }^{T} \sqcap Z_{q a}^{j}\right)\right), \tag{1}
\end{equation*}
\]
where \(X_{1}\) and \(X_{2}\) are two fresh concept names that distinguish the type of the block; cf. ( \(\left.\mathcal{T}_{1-2}\right)\).
As in the proof of Theorem 34, the acceptance condition for \(M^{\prime}\) is enforced by means of \(\mathcal{T}_{2}^{\prime}\), which uses four types of blocks. In this proof, however, we need to use \(P\)-counters to reach the end of the block. The \(P\)-counter on a tuple \(T\) creates the initial block for the initial configuration:
\[
\begin{align*}
& A \sqsubseteq \exists P .\left(\text { reset }^{T} \sqcap B_{0}\right),  \tag{2}\\
& \text { not-end }{ }^{T} \sqcap B_{0} \sqsubseteq \exists P . B_{0}, \tag{2}
\end{align*}
\]
where \(B_{0}\) is a fresh concept, an indicator of the initial block. We use \(X_{1}\) - and \(X_{2}\)-blocks for universal states (these blocks are indicated by concepts \(B_{1}\) and \(B_{2}\), respectively) and \(X_{3}\)-blocks for existential states (indicated by concept \(B_{3}\) ). The tree-like structure of the blocks is achieved by adding to \(\mathcal{T}_{2}^{\prime}\) the following inclusions:
\[
\begin{aligned}
\text { end }^{T} \sqcap B_{k} & \sqsubseteq \prod_{j=1,2} \exists P .\left(X_{j} \sqcap \exists P .\left(\text { reset }^{T} \sqcap B_{j}\right)\right), & \text { for } k=0,3, & \left(\mathcal{T}_{2}^{\prime}-3\right) \\
\text { end }^{T} \sqcap B_{j} & \sqsubseteq \exists P .\left(X_{3} \sqcap \exists P .\left(\text { reset }^{T} \sqcap B_{3}\right)\right), & \text { for } j=1,2, & \left(\mathcal{T}_{2}^{\prime}-4\right) \\
\text { not-end }^{T} \sqcap B_{j} & \sqsubseteq \exists P .\left(G \sqcap B_{j}\right), & \text { for } j=1,2 \text { and 3, } & \left(\mathcal{T}_{2}^{\prime}-5\right)
\end{aligned}
\]
where \(G\) is a fresh concept name; cf. \(\left(\mathcal{T}_{2}-2\right)\) and \(\left(\mathcal{T}_{2}-3\right)\); see also Fig. 12 (Note that \(\left(\widetilde{\mathcal{T}_{2}^{\prime}-3}\right.\) with \(k=0\) is required as a replacement of part of \(\left(\mathcal{T}_{2}-1\right)\).)
Step 3. Recall that the \(P\)-counter on \(H\) measures the distance from the head: if the active cell in the current configuration has index \(k\), then its \(H\)-value is 0 and the \(H\)-value of the cell with index \(k-2\) in a successor configuration is


Figure 16: Encoding the transitions of \(M^{\prime}\) in \(\mathcal{M}_{1}\).
\(2^{n}-1\) (note that since the head never visits cells with indexes 0 and 1 , the \(P\)-counter on \(T\) is ahead of the \(P\)-counter on \(H\) at least by 2 , whence \(k-2 \geq 0\) ). So, until the \(H\)-counter reaches \(2^{n}-1\), the following concept inclusions in \(\mathcal{T}_{1}^{\prime}\) propagate the state and symbol in the active cell along the elements constituting the blocks: for \(q \in Q, a \in \Lambda\) and \(j=0,1,2\),
\[
\begin{equation*}
\text { not-end }^{T} \sqcap \text { not-end }^{H} \sqcap Z_{q a}^{j} \sqsubseteq \prod_{b \in \Lambda} \exists P .\left(C_{b} \sqcap Z_{q a}^{j}\right) ; \tag{1}
\end{equation*}
\]
cf. \(\mathcal{T}_{1}-3\); note that not-end \({ }^{T}\) means that this concept inclusion is not 'applicable' to the last and the first elements of each block (with indexes \(2^{n}-1\) and -1 , respectively). When the distance from the last head position is \(2^{n}-2\), the contents of the cell and the current state are changed according to \(\delta\) : for \(q \in Q, a \in \Lambda\) and \(j=1,2\),
\[
\operatorname{end}^{H} \sqcap Z_{q a}^{j} \sqsubseteq\left\{\begin{array} { l l } 
{ \prod _ { b \in \Lambda } \exists P . ( C _ { b } \sqcap \operatorname { r e s e t } ^ { H } \sqcap Z _ { q ^ { \prime } b } ^ { 0 } \sqcap \exists P . F _ { a ^ { \prime } } ) , } & { \text { if } \delta ( q , a , j ) = ( q ^ { \prime } , a ^ { \prime } , - 1 ) , } \\
{ \prod _ { b \in \Lambda } \exists P . ( C _ { b } \sqcap \exists P \cdot ( F _ { a ^ { \prime } } \sqcap \operatorname { r e s e t } ^ { H } \sqcap Z _ { q ^ { \prime } a ^ { \prime } } ^ { 0 } ) ) , } & { \text { if } \delta ( q , a , j ) = ( q ^ { \prime } , a ^ { \prime } , 0 ) , }
\end{array} \quad \left(\mathcal{T}_{\left.1^{\prime}-6\right)}^{\prod_{b \in \Lambda} \exists P .\left(C_{b} \sqcap \exists P \cdot\left(F_{a^{\prime}} \sqcap \prod_{b^{\prime} \in \Lambda} \exists P .\left(C_{b^{\prime}} \sqcap \operatorname{reset}^{H} \sqcap Z_{q^{\prime} b^{\prime}}^{0}\right)\right),\right.} \begin{array}{l}
\text { if } \delta(q, a, j)=\left(q^{\prime}, a^{\prime},+1\right)
\end{array}\right.\right.
\]
(the symbol in the active cell is changed according to the instruction, and the current state and symbol in the active cell of a successive configuration are then recorded in the subscripts of the \(Z_{q a}^{0}\) ). These three situations are depicted in Fig. 16, where hatched nodes denote domain elements with \(H\)-values of \(2^{n}-1\) and grey and black nodes with \(H\)-values of 0 . (Again, the element corresponding to the cell \(k-1\) has only one \(P\)-successor, which encodes the updated symbol, \(a^{\prime}\), in that cell.) Then, the current state and the symbol in the active cell are propagated along the tape using \(\sqrt[\mathcal{T}_{1}^{\prime}-5]{ }\) with \(j=0\).
Step 4. The concept inclusions \(\overline{\mathcal{T}_{1}^{\prime}-5}-\sqrt{\mathcal{T}_{1}^{\prime}-6}\) generate a separate \(P\)-successor for each \(b \in \Lambda\). As in the proof of Theorem 34, the correct one is chosen by a finite \(\Sigma\)-homomorphism, \(h\), from \(\mathcal{M}_{2}\) to \(\mathcal{M}_{1}\) for \(\Sigma\) defined by (5). We add \(\mathcal{T}_{2}-4\) from the proof of Theorem 34 along with the following replacement of \(\mathcal{T}-1\), to \(\mathcal{T}_{2}^{\prime}\) :
\[
\begin{align*}
& G_{b} \sqsubseteq \exists P^{-} .\left(S_{b} \sqcap \operatorname{reset}^{E}\right), \\
& \text { not-end } \\
& \text { end }^{E} \sqcap S_{b} \sqsubseteq \exists P_{b} . S_{b} \\
& \sqsubseteq \exists P^{-} . D_{b},
\end{align*}
\]
where we use a \(P^{-}\)-counter on a tuple \(E\) (unlike \(P\)-counters in all other cases) and a concept \(S_{b}\) to propagate \(b\) along the whole block, which will be called a \(D_{b}\)-block; see Fig. 17. Like in the proof of Theorem 34 the length of any \(D_{b}\)-block, \(2^{n}+1\), matches the length of blocks representing configurations and the last element of a \(D_{b}\)-block belongs


Figure 17: A \(D_{b}\)-block is generated using a \(P^{-}\)-counter on a tuple \(E\).
to concept \(D_{b}\). We also add \(\left(\mathcal{T}_{1}-5\right)-\left(\mathcal{T}_{1}-6\right)\) from the proof of Theorem 34 and \(\left(\mathcal{T}^{\prime}-1\right)-\left(\mathcal{T}^{\prime}-3\right)\) to \(\mathcal{T}_{1}^{\prime}\), which generate \(D_{b}\)-blocks for all \(b \neq a\) from every domain element in \(C_{a}\) and \(D_{b}\)-blocks for all \(b \in \Lambda\) from domain elements in \(F_{a}\). The rest of the argument is as in the proof of Theorem 34, see Fig. 14

One can show that \(M^{\prime}\) has a run with only infinite branches if and only if \(\left(\mathcal{T}_{1}^{\prime}, \mathcal{A}\right) \Sigma\)-query entails \(\left(\mathcal{T}_{2}^{\prime}, \mathcal{A}\right)\). By Theorem [13, \(\Sigma\)-query inseparability is also 2ExpTime-hard.

\section*{6. Query Inseparability for Restricted Sets of Individuals}

In the definition of \(\Sigma\)-query entailment and inseparability discussed so far we considered all tuples of individuals in the KBs that are certain answers to CQs. In this section, we refine this notion by allowing the user to define the set of individuals he is interested in. This leads to the following generalisation of Definition 1 .

Definition 36. Let \(\mathcal{K}_{1}\) and \(\mathcal{K}_{2}\) be \(\mathrm{KBs}, \Sigma\) a relational signature and \(\Gamma\) an individual signature. We say that \(\mathcal{K}_{1}(\Sigma, \Gamma)\) query entails \(\mathcal{K}_{2}\) if
\[
\mathcal{K}_{2} \vDash \boldsymbol{q}(\boldsymbol{a}) \text { implies } \boldsymbol{a} \subseteq \operatorname{ind}\left(\mathcal{K}_{1}\right) \text { and } \mathcal{K}_{1} \vDash \boldsymbol{q}(\boldsymbol{a}), \quad \text { for all } \Sigma \text {-CQs } \boldsymbol{q}(\boldsymbol{x}) \text { and all tuples } \boldsymbol{a} \text { in ind }\left(\mathcal{K}_{2}\right) \cap \Gamma \text {. }
\]

KBs \(\mathcal{K}_{1}\) and \(\mathcal{K}_{2}\) are \((\Sigma, \Gamma)\)-query inseparable if they \((\Sigma, \Gamma)\)-query entail each other, in which case we write \(\mathcal{K}_{1} \equiv_{\Sigma, \Gamma} \mathcal{K}_{2}\).
By definition, \(\mathcal{K}_{1} \Sigma\)-query entails \(\mathcal{K}_{2}\) if and only if \(\mathcal{K}_{1}(\Sigma, \Gamma)\)-query entails \(\mathcal{K}_{2}\) for all individual signatures \(\Gamma\). Also, if \(\Gamma \supseteq \operatorname{ind}\left(\mathcal{K}_{2}\right)\) then \(\mathcal{K}_{1} \Sigma\)-query entails \(\mathcal{K}_{2}\) in case \(\mathcal{K}_{1}(\Sigma, \Gamma)\)-query entails \(\mathcal{K}_{2}\). As only the intersection ind \(\left(\mathcal{K}_{2}\right) \cap \Gamma\) is relevant for \((\Sigma, \Gamma)\)-query entailment, in what follows without loss of generality we assume that \(\Gamma \subseteq \operatorname{ind}\left(\mathcal{K}_{2}\right)\).

One can analyse ( \(\Sigma, \Gamma\) )-query entailment between KBs, one of which is inconsistent, in a way similar to \(\Sigma\)-query entailment. So, in the sequel we only focus on consistent KBs without mentioning this explicitly. The main difference between \(\Sigma\)-query entailment and ( \(\Sigma, \Gamma\) )-query entailment can already be seen on KBs with empty TBoxes and empty individual signature \(\Gamma\). Note that for KBs with empty TBoxes, \(\Sigma\)-query entailment is trivial as \(\mathcal{K}_{1}=\left(\emptyset, \mathcal{A}_{1}\right) \Sigma\)-query entails \(\mathcal{K}_{2}=\left(\emptyset, \mathcal{A}_{2}\right)\) if and only if, for all \(a, b \in \operatorname{ind}\left(\mathcal{K}_{2}\right)\) with \(A(a) \in \mathcal{A}_{2}, A \in \Sigma\), or \(P(a, b) \in \mathcal{A}_{2}, P \in \Sigma\), it follows that \(A(a) \in \mathcal{A}_{1}\) or \(P(a, b) \in \mathcal{A}_{1}\), respectively. Note also that \((\Sigma, \emptyset)\)-query entailment between any KBs \(\mathcal{K}_{1}\) and \(\mathcal{K}_{2}\) means that all Boolean \(\Sigma\)-CQs entailed by \(\mathcal{K}_{2}\) are entailed by \(\mathcal{K}_{1}\) as well.

Theorem 37. Checking \((\Sigma, \emptyset)\)-query entailment and \((\Sigma, \emptyset)\)-inseparability of \(K B s\) with empty TBoxes are both NP-hard for data complexity.

Proof. Let \(\mathcal{K}_{i}=\left(\emptyset, \mathcal{A}_{i}\right)\), for \(i=1,2\). Clearly, \(\mathcal{K}_{1}(\Sigma, \emptyset)\)-query entails \(\mathcal{K}_{2}\) if and only if there exists a \((\Sigma, \emptyset)\)-homomorphism from (the interpretation corresponding to) \(\mathcal{A}_{2}\) to \(\mathcal{A}_{1}\). The latter problem is the standard homomorphism problem for relational structures which is known to be NP-hard [35]. To show NP-hardness of \((\Sigma, \emptyset)\)-query inseparability, observe that there is a \((\Sigma, \emptyset)\)-homomorphism from \(\mathcal{A}_{2}\) to \(\mathcal{A}_{1}\) if and only if \(\left(\emptyset, \mathcal{A}_{1} \uplus \mathcal{A}_{2}\right)\) and \(\left(\emptyset, \mathcal{A}_{1}\right)\) are \((\Sigma, \emptyset)\)-query inseparable, where \(\mathcal{A}_{1} \uplus \mathcal{A}_{2}\) is the disjoint union of \(\mathcal{A}_{1}\) and \(\mathcal{A}_{2}\).

We now show that checking the existence of a homomorphism between ABoxes is the only additional source of complexity for \((\Sigma, \Gamma)\)-query entailment compared to \(\Sigma\)-query entailment. In particular, for data complexity, checking \((\Sigma, \Gamma)\)-query entailment is in NP for all of our DLs; for combined complexity, it is either NP-complete or harder than NP, in which case it is of the same complexity as \(\Sigma\)-query entailment. We begin by generalising the semantic characterisation of \(\Sigma\)-query entailment via finite \(\Sigma\)-homomorphic embeddability of materialisations:

Theorem 38. Suppose \(\mathcal{K}_{i}\) is a \(K B\) with a materialisation \(\mathcal{I}_{i}\), for \(i=1,2, \Sigma\) is a relational signature, and \(\Gamma \subseteq \operatorname{ind}\left(\mathcal{K}_{2}\right)\). Then \(\mathcal{K}_{1}(\Sigma, \Gamma)\)-query entails \(\mathcal{K}_{2}\) if and only if \(I_{2}\) is finitely \((\Sigma, \Gamma)\)-homomorphically embeddable into \(I_{1}\).

(a)

(b)

(c)

(d)

Figure 18: (a) Generating structure \(\mathcal{G}\), (b) its unravelling \(\mathcal{M}\), (c) the unravelling \(\mathcal{M}^{\{a\}}\) of the extended generating structure \(\mathcal{G}^{\{a\}}\), and (d) the extended generating structure \(\mathcal{G}^{\{a\}}\left(\Pi_{\{a\}}\right.\) is shaded \()\).

Proof. A straightforward extension of the proof of Theorem 6
Now we generalise the game-theoretic characterisation provided by Theorem 15 Let \(\mathcal{M}_{1}\) and \(\mathcal{M}_{2}\) be materialisations obtained by unravelling finite generating structures \(\mathcal{G}_{1}\) and \(\mathcal{G}_{2}\) for KBs \(\mathcal{K}_{1}\) and \(\mathcal{K}_{2}\), respectively, and let \(\mathcal{M}_{2}^{\text {ind }}\) be the subinterpretation of \(\mathcal{M}_{2}\) with domain \(\operatorname{ind}\left(\mathcal{K}_{2}\right)\).

Theorem 39. Let \(\Gamma \subseteq \operatorname{ind}\left(\mathcal{K}_{2}\right)\). Then \(\mathcal{M}_{2}\) is finitely \((\Sigma, \Gamma)\)-homomorphically embeddable into \(\mathcal{M}_{1}\) if and only if the following conditions are satisfied:
( \(\boldsymbol{w i n}_{\text {wit }}\) ) for any \(u \in \Delta^{\mathcal{G}_{2}} \backslash \operatorname{ind}\left(\mathcal{K}_{2}\right)\) and \(n<\omega\), there exists \(\sigma \in \Delta^{\mathcal{M}_{1}}\) such that player 1 has an \(n\)-winning strategy in the game \(G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)\) starting from \((u \mapsto \sigma)\);
\(\left(\mathbf{h}+\right.\) win \(\left._{\text {ind }}\right)\) for any \(n<\omega\), there is a \((\Sigma, \Gamma)\)-homomorphism \(h_{n}: \mathcal{M}_{2}^{\text {ind }} \rightarrow \mathcal{M}_{1}\) such that, for every \(a \in \operatorname{ind}\left(\mathcal{K}_{2}\right)\), player 1 has an \(n\)-winning strategy in the game \(G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)\) starting from \(\left(a \mapsto h_{n}(a)\right)\).

Proof. A straightforward modification of the proof of Theorem 15
Condition ( \(\boldsymbol{w i n}_{\text {wit }}\) ) is the restriction of (win) in Theorem 15 to \(u \in \Delta^{\mathcal{G}_{2}} \backslash \operatorname{ind}\left(\mathcal{K}_{2}\right)\), and so can be reduced, by Lemma 30, to conditions for games on the finite generating structures \(\mathcal{G}_{1}\) and \(\mathcal{G}_{2}\). We now show that ( \(\mathbf{h}+\mathbf{w i n} \mathbf{n}_{\text {ind }}\) ) can also be reduced to certain conditions on \(\mathcal{G}_{1}\) and \(\mathcal{G}_{2}\). In contrast to the case where one could not restrict the set of individuals and individuals were mapped to themselves (cf. (abox)), we now require a ( \(\Sigma, \Gamma\) )-homomorphism \(h\) from \(\mathcal{M}_{2}^{\text {ind }}\) to an extension of \(\mathcal{G}_{1}\), which is obtained by a partial unravelling of \(\mathcal{G}_{1}\) defined as follows.

Consider \(\mathcal{G}=\left(\Delta^{\mathcal{G}}, .^{\mathcal{G}}, \rightsquigarrow\right)\) and let \(X \subseteq \Delta^{\mathcal{G}}\), where either \(X \subseteq \operatorname{ind}(\mathcal{K})\) or \(X=\{w\}\) for some \(w \in \Delta^{\mathcal{G}} \backslash \operatorname{ind}(\mathcal{K})\). We associate with \(X\) a finite prefix-closed set \(\Pi_{X}\) of paths \(\pi\) of the form \(w_{0} \cdots w_{n}\) such that \(w_{0} \in X\) and \(w_{i} \rightsquigarrow w_{i+1}\), for \(i<n\) (cf. Definition 7). The structure \(\mathcal{G}^{X}=\left(\Delta^{\mathcal{G}^{X}}, \cdot \mathcal{G}^{X}, \rightsquigarrow^{X}\right)\) is defined by first taking \(\Delta^{\mathcal{G}^{X}}=\Delta^{\mathcal{G}} \cup \Pi_{X}\),
\[
\begin{array}{rll}
\pi \rightsquigarrow^{X} w & \text { if } & \pi \in \Delta^{\mathcal{G}} \cup \Pi_{X}, \operatorname{tail}(\pi) \rightsquigarrow w \text { but } \pi w \notin \Pi_{X}, \\
\pi \rightsquigarrow^{X} \pi w & \text { if } & \pi, \pi w \in \Pi_{X},
\end{array}
\]
\(A^{\mathcal{G}^{X}}=A^{\mathcal{G}} \cup\left\{\pi \in \Pi_{X} \mid\right.\) tail \(\left.(\pi) \in A^{\mathcal{G}}\right\}\), for each concept name \(A\), \(P^{\mathcal{G}^{X}}=P^{\mathcal{G}}\), for each role name \(P\), and \(\left(\pi, \pi^{\prime}\right)^{\mathcal{G}^{X}}=\) (tail \((\pi)\), tail \(\left.\left(\pi^{\prime}\right)\right)^{\mathcal{G}}\), for each arrow \(\pi \rightsquigarrow^{X} \pi^{\prime}\). Then we remove all 'disconnected' elements from \(\mathcal{G}^{X}\) to make sure that each \(\Delta^{\mathcal{G}^{X}} \backslash \operatorname{ind}(\mathcal{K})\) is reachable from ind \((\mathcal{K})\) via a path of \(\rightsquigarrow\) arrows. (Note that \(\mathcal{G}^{X}\) depends on \(\Pi_{X}\), which will always be clear from the context.)

Observe that the unravelling \(\mathcal{M}^{X}\) of \(\mathcal{G}^{X}\) is isomorphic to the unravelling \(\mathcal{M}\) of \(\mathcal{G}\). We denote the natural isomorphism from \(\mathcal{M}^{X}\) onto \(\mathcal{M}\) by \(g\). Note that if \(X \subseteq \operatorname{ind}(\mathcal{K})\) then, on \(g^{-1}\left(\Pi_{X}\right)\), the function \(g\) coincides with tail; otherwise, if \(X=\left\{w_{0}\right\}\) then \(g\left(\delta \cdot w_{0}\right)=g(\delta) w_{0}\), for \(\delta \cdot w_{0} \in \Delta^{\mathcal{M}^{X}}\), and \(g(\delta \cdot \pi \cdot \pi w)=g(\delta \cdot \pi) w\), for \(\delta \cdot \pi \in \Delta^{\mathcal{M}^{X}}\) and \(\pi, \pi w \in \Pi_{X}\).


Figure 19: (a) Generating structure \(\mathcal{G}_{1}\), (b) its unravelling \(\mathcal{M}_{1}\), (c) the unravelling \(\mathcal{M}_{1}^{\{w\}}\) of the extended generating structure \(\mathcal{G}_{1}^{\{w\}}\), and (d) the extended generating structure \(\mathcal{G}_{1}^{\{w\}}\left(\Pi_{\{w\}}\right.\) is shaded \()\).

Example 40. Consider the generating structure \(\mathcal{G}\) depicted in Fig. 181. The extended generating structure \(\mathcal{G}^{\{a\}}\), with \(\Pi_{\{a\}}=\left\{a, a w, a w w_{1}\right\}\), is shown in Fig. 18A. Observe that the shaded part, \(\Pi_{\{a\}}\), of \(\mathcal{G}^{\{a\}}\) coincides with the shaded part of the unravelling \(\mathcal{M}\) of \(\mathcal{G}\) and that the unravelling \(\mathcal{M}^{\{a\}}\) of \(\mathcal{G}^{\{a\}}\) is isomorphic to \(\mathcal{M}\) so that, on the shaded area, the natural isomorphism \(g\) coincides with tail: for example, \(g\left(a \cdot a w \cdot a w w_{1}\right)=a w w_{1}=\operatorname{tail}\left(a \cdot a w \cdot a w w_{1}\right)\), as shown by the dotted line in Fig. 18 .

Next, consider the generating structure \(\mathcal{G}_{1}\) depicted in Fig. 19a. The extended generating structure \(\mathcal{G}_{1}^{[w]}\), with \(\Pi_{\{w\}}=\left\{w, w w^{\prime}\right\}\), is shown in Fig. 19d. Note that \(w^{\prime}\) does not belong to \(\mathcal{G}_{1}^{\{w\}}\) because it would not be connected to any other domain element. Observe again that the unravelling \(\mathcal{M}_{1}^{\{w\}}\) of \(\mathcal{G}_{1}^{\{\omega\}}\) is isomorphic to the unravelling \(\mathcal{M}_{1}\) of \(\mathcal{G}_{1}\) : the natural isomorphism \(g\) is such that \(g\left(c \cdot w_{i} \cdot w\right)=c w_{i} w\) and \(g\left(c \cdot w_{i} \cdot w \cdot w w^{\prime}\right)=g\left(c \cdot w_{i} \cdot w\right) w^{\prime}\), for \(i=1,2\). Note also that both unravellings contain two isomorphic copies of \(\Pi_{\{w\}}\) from \(\mathcal{G}_{1}^{\{w\}}\) (shaded in Fig. 19d): for example, the elements \(c w_{1} \pi\) and \(c w_{2} \pi\) in \(\mathcal{M}_{1}\) are copies of \(\pi \in \Pi_{\{w\}}\).

It will be convenient to consider \(h\)-images of maximal \(\Sigma\)-connected components of \(\mathcal{M}_{2}^{\text {ind }}\) separately. A subset \(\Delta_{0}\) of the domain \(\Delta^{\mathcal{M}}\) of an interpretation \(\mathcal{M}\) is called \(\Sigma\)-connected if, for any \(u, u^{\prime} \in \Delta_{0}\), there are \(u_{0}, \ldots, u_{n}\) such that \(u_{0}=u, u_{n}=u^{\prime}\) and, for each \(i<n\), there exists a \(\Sigma\)-role \(R\) with \(\left(u_{i}, u_{i+1}\right) \in R^{\mathcal{M}}\).
Theorem 41. Condition \(\left(\mathbf{h}+\mathbf{w i n}_{\text {ind }}\right)\) holds if and only if, for every maximal \(\Sigma\)-connected component \(\Delta_{0}\) of \(\mathcal{M}_{2}^{\text {ind }}\), there are \(X \subseteq \Delta^{\mathcal{G}_{1}}\), a structure \(\mathcal{G}_{1}^{X}\) and a map \(h: \Delta_{0} \rightarrow \Delta^{\mathcal{G}_{1}^{X}}\) such that either \(X \subseteq \operatorname{ind}\left(\mathcal{K}_{1}\right)\) or \(X=\left\{w_{0}\right\}\) for \(w_{0} \in \Delta^{\mathcal{G}_{1}} \backslash \operatorname{ind}\left(\mathcal{K}_{1}\right)\), and \(h\left(\Delta_{0}\right)=\Pi_{X}\),
\(\left(\mathbf{h}^{\Gamma}\right) h(a)=a\), for any \(a \in \Delta_{0} \cap \Gamma \cap \operatorname{part}_{\Sigma}^{\mathcal{M}_{2}}\), and \(\boldsymbol{t}_{\Sigma}^{\mathcal{M}_{2}}(a) \subseteq \boldsymbol{t}_{\Sigma}^{\mathcal{G}_{1}^{X}}(h(a))\) and \(\boldsymbol{r}_{\Sigma}^{\mathcal{M}_{2}}(a, b) \subseteq r_{\Sigma}^{G_{1}^{X}}(h(a), h(b))\), for any \(a, b \in \Delta_{0}\),
\(\left(\mathbf{h}+\mathbf{w i n}_{X}\right)\) for each \(\pi \in \Pi_{X}\), there exists a state \(\mathfrak{a}_{\pi}=\left(\Xi_{\pi} \mapsto \pi, \Psi_{\pi}\right)\) such that \(\Xi_{\pi} \supseteq h^{-1}(\pi)\), player 1 has an \(\omega\)-winning strategy in \(G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}^{X}\right)\) from \(\mathfrak{a}_{\pi}\), and if \(X=\left\{w_{0}\right\}\) then the \(\mathfrak{a}_{\pi}\) are co-ordinated in the following sense:
\[
\begin{equation*}
\mathfrak{a}_{\pi} \text { is a valid response to the challenge } \Psi_{\pi w} \text { in the state } \mathfrak{a}_{\pi w} \text { in } G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}^{X}\right) \text {, for any } \pi, \pi w \in \Pi_{X} . \tag{6}
\end{equation*}
\]

Proof. \((\Rightarrow)\) Let \(\Delta_{0}\) be a maximal \(\Sigma\)-connected component of \(\mathcal{M}_{2}^{\text {ind }}\). For any \(n<\omega\), take a \((\Sigma, \Gamma)\)-homomorphism \(h_{n}\) from \(\mathcal{M}_{2}^{\text {ind }}\) to \(\mathcal{M}_{1}\) such that, for every \(a \in \operatorname{ind}\left(\mathcal{K}_{2}\right)\), player 1 has an \(n\)-winning strategy in the game \(G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)\) starting from \(\left(a \mapsto h_{n}(a)\right)\). Two cases are possible now.
- If \(h_{n}\left(\Delta_{0}\right) \cap \operatorname{ind}\left(\mathcal{K}_{1}\right) \neq \emptyset\) for infinitely many \(n<\omega\) then, since \(h_{n}\left(\Delta_{0}\right)\) is \(\Sigma\)-connected, the number of distinct sets \(h_{n}\left(\Delta_{0}\right)\) with \(h_{n}\left(\Delta_{0}\right) \cap \operatorname{ind}\left(\mathcal{K}_{1}\right) \neq \emptyset\) is finite. Thus, by the pigeonhole principle, there is an infinite set \(\mathbb{H}\) of natural numbers \(n\) with \(h_{n}\left(\Delta_{0}\right) \cap \operatorname{ind}\left(\mathcal{K}_{1}\right) \neq \emptyset\) such that the restrictions of all \(h_{n}\) to \(\Delta_{0}\) coincide. Let \(h\) be the restriction of some \(h_{n}\), for \(n \in \mathbb{H}\), to \(\Delta_{0}\). We set \(X=h\left(\Delta_{0}\right) \cap \operatorname{ind}\left(\mathcal{K}_{1}\right)\) and \(\Pi_{X}=h\left(\Delta_{0}\right)\). Using the map \(h\), one can now construct the required starting states and \(\omega\)-winning strategies in \(G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}^{X}\right)\) in exactly the same way as in the proof of \((a) \Rightarrow(b)\) in Lemma 30 .
- Otherwise, \(h_{n}\left(\Delta_{0}\right) \cap \operatorname{ind}\left(\mathcal{K}_{1}\right)=\emptyset\) for infinitely many \(n<\omega\) and, as \(\Delta_{0}\) is \(\Sigma\)-connected, by the pigeonhole principle there exists \(w_{0} \in \Delta^{\mathcal{G}_{1}} \backslash \operatorname{ind}\left(\mathcal{K}_{1}\right)\) such that, for infinitely many \(n<\omega, h_{n}\left(\Delta_{0}\right)\) is a tree with root \(\sigma^{n} w_{0} \in \Delta^{\mathcal{M}_{1}}\). We set \(X=\left\{w_{0}\right\}\) and can define, again by the pigeonhole principle, \(\Pi_{X}\) in such a way that there is an infinite set \(\mathbb{H}\) of natural numbers \(n\) such that \(h_{n}\left(\Delta_{0}\right)=\left\{\sigma^{n} \pi \mid \pi \in \Pi_{X}\right\}\). Then, for every \(a \in \Delta_{0}\), there is \(h(a) \in \Pi_{X}\) such that \(h_{n}(a)=\sigma^{n} h(a)\), for all \(n \in \mathbb{H}\). Using the map \(h\), one can now construct the required starting states satisfying (6), and \(\omega\)-winning strategies in \(G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}^{X}\right)\) in exactly the same way as in the proof of \((a) \Rightarrow(b)\) in Lemma 30 .
\((\Leftarrow)\) Let \(\Delta_{0}\) be a maximal \(\Sigma\)-connected component of \(\mathcal{M}_{2}^{\text {ind }}\). Set \(\Gamma^{\prime}=\Gamma \cap \Delta_{0}\). It is sufficient to show that ( \(\mathbf{h}+\boldsymbol{w i n} \mathbf{w i n d}_{\text {ind }}\) ) holds for \(\Delta_{0}\) in place of ind \(\left(\mathcal{K}_{2}\right)\), i.e., for any \(n<\omega\), there exists a \(\left(\Sigma, \Gamma^{\prime}\right)\)-homomorphism \(h_{n}\) from \(\mathcal{M}_{\Delta_{0}}\) to \(\mathcal{M}_{1}\) such that player 1 has an \(n\)-winning strategy in the game \(G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)\) starting from \(\left(a \mapsto h_{n}(a)\right)\) for all \(a \in \Delta_{0}\), where \(\mathcal{M}_{\Delta_{0}}\) is the interpretation \(\mathcal{M}_{2}\) relativised to the domain \(\Delta_{0}\). Let \(X \subseteq \Delta^{\mathcal{G}_{1}}, h: \Delta_{0} \rightarrow \Delta^{\mathcal{G}_{1}^{X}}\), and \(n<\omega\) be given, where \(X\) and \(h\) satisfy the conditions of the theorem.
- If \(X \subseteq \operatorname{ind}\left(\mathcal{K}_{1}\right)\) then we set \(h_{n}(a)=h(a)\) for all \(a \in \Delta_{0}\). It is readily checked that \(h_{n}\) is a \(\left(\Sigma, \Gamma^{\prime}\right)\)-homomorphism from \(\mathcal{M}_{\Delta_{0}}\) to \(\mathcal{M}_{1}\). For each \(a \in \Delta_{0}\), by Lemma 30, player 1 has an \(n\)-winning strategy in the game \(G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}^{X}\right)\) from some \((a \mapsto \delta)\) with tail \((\delta)=h(a)\). Then the natural isomorphism \(g\) from \(\mathcal{M}_{1}^{X}\) onto \(\mathcal{M}_{1}\) translates this strategy into an \(n\)-winning strategy in the game \(G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)\) from \((a \mapsto h(a))\).
- Otherwise, \(X=\left\{w_{0}\right\}\) for \(w_{0} \in \Delta^{\mathcal{G}_{1}} \backslash \operatorname{ind}\left(\mathcal{K}_{1}\right)\). Since \(\Xi_{w_{0}} \supseteq h^{-1}\left(w_{0}\right)\), by Lemma 30, for each \(a \in h^{-1}\left(w_{0}\right)\), player 1 has an \(n\)-winning strategy in \(G_{\Sigma}\left(\mathcal{G}_{1}, \mathcal{M}_{1}^{X}\right)\) from some \((a \mapsto \delta)\) with tail \((\delta)=\sigma w_{0} \in \Delta^{\mathcal{M}_{1}}\). Then the natural isomorphism \(g\) from \(\mathcal{M}_{1}^{X}\) onto \(\mathcal{M}_{1}\) translates each such strategy into an \(n\)-winning strategy in \(G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)\) from ( \(a \mapsto \sigma w_{0}\) ).
We set \(h_{n}(a)=\sigma \pi\), for each \(a \in h^{-1}(\pi)\) and \(\pi \in \Pi_{X}\). Then \(h_{n}\) is a \(\left(\Sigma, \Gamma^{\prime}\right)\)-homomorphism from \(\mathcal{M}_{\Delta_{0}}\) to \(\mathcal{M}_{1}\). We show by induction that, for all \(\pi \in \Pi_{X}\),
player 1 has an \(n\)-winning strategy in \(G_{\Sigma}\left(\mathcal{G}_{2}, \mathcal{M}_{1}\right)\) from \(\left(a \mapsto h_{n}(a)\right)\), for each \(a \in h^{-1}(\pi)\).
For \(\pi=w\), this holds by the definition of \(\sigma\). Now assume that 77 has been proved for \(\pi\) and let \(\pi w \in \Pi_{X}\). By the induction hypothesis and the proof of Lemma 30, it suffices to show that \(\mathfrak{a}_{\pi}\) is a response of player 1 to the challenge \(\Psi_{\pi w}\) in the state \(\mathfrak{a}_{\pi w}\) of \(G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}^{X}\right)\), which is guaranteed by (6).

This completes the proof of the theorem.
Condition (6) is necessary for co-ordinating the starting states of the games when \(X=\left\{w_{0}\right\}\), for \(w_{0} \in \Delta^{\mathcal{G}_{1}} \backslash\) ind \(\left(\mathcal{K}_{1}\right)\). On the other hand, if \(\Gamma \supseteq\) ind \(\left(\mathcal{K}_{2}\right)\) then all \(\Sigma\)-participating individuals in ind \(\left(\mathcal{K}_{2}\right)\) must be mapped to themselves, and so condition (6) is not applicable in this case. The following example shows that without (6) we cannot guarantee that ( \(\mathbf{h}+\) win \(_{\text {ind }}\) ) holds, and so \(\mathcal{M}_{2}\) may not be finitely \((\Sigma, \Gamma)\)-homomorphically embeddable into \(\mathcal{M}_{1}\).

Example 42. Consider \(\mathrm{KBs} \mathcal{K}_{2}\) and \(\mathcal{K}_{1}\) and a relational signature \(\Sigma\) such that \(\operatorname{ind}\left(\mathcal{K}_{2}\right)=\{a, b\}\), ind \(\left(\mathcal{K}_{1}\right)=\{c\}\) and their generating structures \(\mathcal{G}_{2}^{\Sigma}\) and \(\left(\mathcal{G}_{1}^{\{w\}}\right)^{\Sigma}\) are as in Fig. 20a, with \(\Pi_{\{w\}}=\left\{w, w w^{\prime}\right\}\) (see also Figs. 19 and d for \(\mathcal{G}_{1}\) and \(\mathcal{G}_{1}^{\{w\}}\), respectively). Let \(\Gamma=\emptyset\) and suppose that \(h(a)=w\) and \(h(b)=w w^{\prime}\) (see the dashed lines in Fig. 20a). Player 1 has \(\omega\)-winning strategies in \(G_{\Sigma}^{g}\left(\mathcal{G}_{2}, \mathcal{G}_{1}^{X}\right)\) from the states \(\mathfrak{a}_{a}=\left(\{a\} \mapsto w,\left\{v_{1}\right\}\right)\) and \(\mathfrak{a}_{b}=\left(\{b\} \mapsto w w^{\prime},\left\{u_{1}\right\}\right)\) : see the dotted lines in Fig. 20a and the game graph in Fig. 20p. However, the two starting states, \(\mathfrak{a}_{a}\) and \(\mathfrak{a}_{b}\), do not satisfy the co-ordination condition (6). In fact, the map they induce is not a ( \(\Sigma, \Gamma\) )-homomorphism from \(\mathcal{M}_{2}\) to \(\mathcal{M}_{1}\) because it sends \(a\) to \(c w_{2} w\) and \(b\) to \(c w_{1} w w^{\prime}\), which are not connected by the role \(T\) in \(\mathcal{M}_{1}\). Moreover, it is not hard to see that there is no \((\Sigma, \Gamma)\)-homomorphism from \(\mathcal{M}_{2}\) to \(\mathcal{M}_{1}\). Indeed, our co-ordination condition means that we have to choose appropriate starting states for each of the elements in \(\Pi_{X}\). So, we can pick \(\mathfrak{a}_{b}\) for \(w w^{\prime}\), from which, as we noted above, player 1 has an \(\omega\)-winning strategy. We cannot, however, choose \(\mathfrak{a}_{a}\) for \(w\) because \(\Psi_{w w^{\prime}}=\left\{u_{1}\right\}\), and so, by (6), \(\Xi_{w}\) must contain \(u_{1}\) (along with \(a\) ) but the 'uncoordinated' starting state \(\mathfrak{a}_{a}\) does not include \(u_{1}\). Thus, we have to take \(\mathfrak{a}_{a}^{\prime}=\left(\left\{u_{1}, a\right\} \mapsto w,\left\{u_{2}, v_{1}\right\}\right)\) for \(w\), from which player 1 has no \(\omega\)-winning strategy: see the graph in Fig. 20p, where all the paths from \(\mathfrak{a}_{a}^{\prime}\) lead to dead-ends.

Finally, we obtain the following tight complexity results for \(\mathrm{KB}(\Sigma, \Gamma)\)-query entailment and inseparability.


Figure 20: Co-ordination of starting states: (a) generating structure \(\mathcal{G}_{2}^{\Sigma}\) and extended generating structure \(\left(\mathcal{G}_{1}^{X}\right)^{\Sigma}\) with \(\Pi_{X}=\left\{w, w w^{\prime}\right\}\); (b) the relevant fragment of the game graph.

Theorem 43. For combined complexity, both \(K B(\Sigma, \Gamma)\)-query entailment and inseparability are 2ExpTime-complete for Horn- \(\mathcal{A L C H} \mathcal{H}\) and Horn- \(\mathcal{A} \mathcal{L C I}\); ExpTime-complete for Horn- \(\mathcal{A} \mathcal{L C H}\), Horn- \(\mathcal{A} \mathcal{L C}\), DL-Lite \(\mathcal{h o r n}^{\mathcal{H}}\) and DL-Lite core ; and NP -complete for \(\mathcal{E} \mathcal{L} \mathcal{H}_{\perp}^{d r}, \mathcal{E} \mathcal{L}, D L-\) Lite \(_{\text {horn }}\) and DL-Lite core . For data complexity, these problems are NP-complete.

Proof. Note first that the size of \(X\) and \(\Pi_{X}\) is bounded by the size of ind \(\left(\mathcal{K}_{2}\right)\), so the size of \(\mathcal{G}_{1}^{X}\) is polynomial in the size of \(\mathcal{G}_{1}\) and \(\operatorname{ind}\left(\mathcal{K}_{2}\right)\). Note also that if \(\mathcal{G}_{1}\) is a forward generating structure then so is \(\mathcal{G}_{1}^{X}\); if \(\mathcal{G}_{1}\) is a functional generating structure then so is \(\mathcal{G}_{1}^{X}\); and if \(\mathcal{G}_{1}\) satisfies \(\left(\right.\) lite \(\left._{1}\right)\) and (lite \({ }_{2}\) ) then so does \(\mathcal{G}_{1}^{X}\).

We start with an NP algorithm for data complexity. Let \(\mathcal{G}_{i}\) be a generating structure for a \(\mathrm{KB} \mathcal{K}_{i}, i=1,2\). For each maximal \(\Sigma\)-connected component \(\Delta_{0}\) of \(\mathcal{M}_{2}^{\text {ind }}\), the algorithm performs two NP steps: (i) it guesses sets \(X, \Pi_{X}\) and a map \(h\) from \(\Delta_{0}\) onto \(\Pi_{X}\), computes \(\mathcal{G}_{1}^{X}\), and checks whether \(\left(\mathbf{h}^{\Gamma}\right)\) is satisfied; then (ii) it guesses sets \(\Xi_{\pi}\) and \(\Psi_{\pi}\) satisfying (6) if \(X \nsubseteq \operatorname{ind}\left(\mathcal{K}_{1}\right)\), for each \(\pi \in \Pi_{X}\), and finally checks whether ( \(\mathbf{h}+\boldsymbol{w} \mathbf{w i n}_{X}\) ) holds. It is not hard to see both (i) and (ii) can be done in polynomial time in the size of ind \(\left(\mathcal{K}_{1}\right)\) and ind \(\left(\mathcal{K}_{2}\right)\).

It is easy to see that for \(\mathcal{E} \mathcal{L} \mathcal{H}_{\perp}^{d r}\) and \(D L\)-Lite \(_{\text {horn }}\) KBs, the algorithm above provides an NP upper bound for the combined complexity as well. For the more expressive DLs, the upper bounds for combined complexity stay the same as before because there is at most an exponential number of distinct sets \(\Pi_{X}\), maps \(h\) and states \(\mathfrak{a}_{\pi}\). The ExpTimeand 2ExpTime-hardness results also carry over from \(\Sigma\)-query inseparability and \(\Sigma\)-query entailment, and NP-hardness follows from Theorem 37

\section*{7. Related Work and Applications}

In this section, we discuss the relationship between \((\Sigma, \Gamma)\)-query inseparability and knowledge exchange, TBox inseparability, and query-based comparison of OBDA specifications. \(\Sigma\)-query inseparability of KBs has not been investigated systematically before. Note, however, that the polynomial upper bound for \(\mathcal{E} \mathcal{L}\) was established as a preliminary step to study \(\Sigma\)-query inseparability of TBoxes [31], and that this notion was also used to study forgetting in DL-Lite \({ }_{\text {bool }}^{\mathcal{N}}\) [36].

\subsection*{7.1. Knowledge Exchange}

For the motivation of studying knowledge exchange between KBs and illustrating examples, we refer the reader to Section 1. Here we establish a tight link between deciding \(\Sigma\)-query inseparability and deciding the membership problem for universal CQ-solutions. We also consider the connection between ( \(\Sigma, \Gamma\) )-query inseparability and the membership problem for universal CQ-solutions with nulls.

Assume (without loss of generality) that \(\mathcal{K}_{1}\) and \(\mathcal{K}_{2}\) are KBs given in disjoint relational signatures \(\Sigma_{1}\) and \(\Sigma_{2}\). Suppose also that \(\mathcal{T}_{12}\) consists of inclusions of the form \(S_{1} \sqsubseteq S_{2}\) such that the \(S_{i}\) are concept or role names in \(\Sigma_{i}\). Then the problem of deciding whether \(\mathcal{K}_{1} \cup \mathcal{T}_{12} \equiv_{\Sigma_{2}} \mathcal{K}_{2}\) is called the membership problem for universal CQ-solutions. For
any of our DLs \(\mathcal{L}\) with role inclusions, the problem whether \(\mathcal{K}_{1} \cup \mathcal{T}_{12} \equiv_{\Sigma_{2}} \mathcal{K}_{2}\) is a \(\Sigma_{2}\)-query inseparability problem in \(\mathcal{L}\), and so the upper complexity bounds for \(\Sigma\)-query inseparability can be applied directly to obtain upper bounds for the membership problem for universal CQ-solutions. The following result establishes the converse:
Theorem 44. \(\Sigma\)-query entailment for any of our DLs \(\mathcal{L}\) is LoGSpace-reducible to the membership problem for universal CQ-solutions in \(\mathcal{L}\).

The proof uses the construction from the proof of Theorem 13 and is given in Appendix A. As a consequence of Theorems 44,31 and 35 we obtain the following:

Theorem 45. For combined complexity, the membership problem for universal CQ-solutions is 2ExpTime-complete for Horn- \(\mathcal{A L C H} \mathcal{I}\) and Horn- \(\mathcal{A} \mathcal{L C I}\); ExpTime-complete for Horn- \(\mathcal{A} \mathcal{L C H}\), Horn- \(\mathcal{A} \mathcal{L C}, D L\)-Lite \({ }_{\text {horn }}^{\mathcal{H}}\) and DL-Lite core ; and P -complete for \(\mathcal{E} \mathcal{L} \mathcal{H}_{\perp}^{d r}\) and \(\mathcal{E} \mathcal{L}\). For data complexity, all these problems are P -complete.

Note that the combined complexity of the membership problem for universal CQ-solutions remains open for \(D L\) Lite \(_{\text {core }}\) and DL-Lite \({ }_{\text {horn }}\).

In the case of DL-Lite \({ }_{\text {core }}^{\mathcal{H}}\), we also obtain an ExpTime algorithm for checking the existence and computing universal CQ-solutions. Indeed, given a \(\mathrm{KB} \mathcal{K}_{1}\), a target signature \(\Sigma_{2}\) and a mapping \(\mathcal{T}_{12}\), we first compute the \(\Sigma_{2}\)-ABox over \(\operatorname{ind}\left(\mathcal{K}_{1}\right)\) that is implied by \(\mathcal{K}_{1}\) and \(\mathcal{T}_{12}\), and then check whether at least one \(\mathrm{KB} \mathcal{K}_{2}\) in \(\Sigma_{2}\) with this ABox is a universal CQ -solution (there are at most \(O\left(2^{\left|\Sigma_{2}\right|}\right)\) such KBs). This gives an ExpTime upper bound for the non-emptiness problem for universal CQ-solutions in DL-Lite core [23].

A more flexible knowledge exchange model allows the target KB to use additional individuals (i.e., not only the individuals in \(\mathcal{K}_{1}\) ), which however cannot be returned as certain answers [23]. These 'anonymous' individuals are similar to nulls in the standard approaches to incomplete databases, and intuitively represent objects the existence of which is implied by \(\mathcal{K}_{1} \cup \mathcal{T}_{12}\). The reader can find an illustrating example in Section 11. Formally, we say that a KB \(\mathcal{K}_{2}\) with a relational signature \(\Sigma_{2}\) is a universal CQ-solution with nulls for a \(\mathrm{KB} \mathcal{K}_{1}\) and a mapping specification \(\mathcal{T}_{12}\) if \(\mathcal{K}_{1} \cup \mathcal{T}_{12} \equiv_{\Sigma_{2} \text {, ind }\left(\mathcal{K}_{1}\right)} \mathcal{K}_{2}\) (which is equivalent to the definition given in [23]). Thus we obtain the following result:

Theorem 46. For combined complexity, the membership problem for universal CQ-solutions with nulls is 2ExpTimecomplete for Horn- \(\mathcal{A} \mathcal{L C H} \mathcal{I}\) and Horn- \(\mathcal{A} \mathcal{L C I}\); ExpTime-complete for Horn- \(\mathcal{A} \mathcal{L C H}\), Horn- \(\mathcal{A} \mathcal{L C}\), DL-Lite \(\mathcal{H}_{\text {horn }}\) and DL-Lite core; and NP-complete for \(\mathcal{E} \mathcal{L} \mathcal{H}_{\perp}^{d r}\) and \(\mathcal{E} \mathcal{L}\). For data complexity, all these problems are NP-complete.
Proof. The upper bounds follow from Theorem 43. The ExpTime and 2ExpTime lower bounds follow from Theorem 45 , and the NP lower bound can be obtained from the proof of Theorem 37 by a straightforward modification.

Again, the combined complexity of the membership problem for universal CQ-solutions with nulls remains open for DL-Lite core and DL-Lite \(_{\text {horn }}\).

\subsection*{7.2. TBox Inseparability and OBDA Specifications}

We remind the reader that, for a relational signature \(\Sigma\), TBoxes \(\mathcal{T}_{1}\) and \(\mathcal{T}_{2}\) are called \(\Sigma\)-query inseparable if, for all \(\Sigma\)-ABoxes \(\mathcal{A}\), the \(\operatorname{KBs}\left(\mathcal{T}_{1}, \mathcal{A}\right)\) and \(\left(\mathcal{T}_{2}, \mathcal{A}\right)\) are \(\Sigma\)-query inseparable. TBox \(\Sigma\)-query inseparability has been extensively studied; see, e.g., [17, 31, 24, 10]. TBox and KB inseparabilities have different applications. The former supports ontology engineering when data is not known or changes frequently: one can equivalently replace one TBox with another only if they return the same answers to queries for every \(\Sigma\)-ABox. In contrast, KB inseparability is useful in applications where data is stable-such as knowledge exchange or variants of module extraction and forgetting with fixed data-in order to use the KB in a new application or as a compilation step to make CQ answering more efficient.

For many DLs, TBox \(\Sigma\)-query inseparability is harder than KB query inseparability. For \(D L\)-Lite \({ }_{h o r n}\), the space of relevant \(\Sigma\)-ABox counterexamples is of exponential size and, in fact, \(\Sigma\)-query inseparability of TBoxes is NPhard [17], while \(\Sigma\)-query inseparability of KBs is in P. Similarly, we have seen that \(\Sigma\)-query inseparability of \(\mathcal{E} \mathcal{L}\) KBs is in P , while \(\Sigma\)-query inseparability of \(\mathcal{E} \mathcal{L}\) TBoxes is ExpTime-complete [31]. The complexity of TBox \(\Sigma\)-query inseparability for Horn-DLs extending Horn- \(\mathcal{A} \mathcal{L C}\) is not known.

The complexity of \(\Sigma\)-query inseparability of DL-Litecore \({ }_{\text {cores }}^{\mathcal{H}}\) TBoxes was known to sit between PSpace and ExpTime [24]. Using the fact that witness \(\Sigma\)-ABoxes for \(\Sigma\)-query inseparability of DL-Lite core TBoxes can always be chosen among the singleton \(\Sigma\)-ABoxes [24, Theorem 8], one can easily modify the proof of Theorem 34 to improve the PSpace lower bound:

Theorem 47. TBox \(\Sigma\)-query inseparability of DL-Lite core \(_{\mathcal{H}}^{\text {Hexes }}\) TBox ExpTime-complete.
For work on other notions of TBox inseparability and the corresponding notions of modules and forgetting, we refer the reader to [37, 12, 38, 39, 40, 41, 42, 43].

In ontology-based data access (OBDA), a TBox \(\mathcal{T}\) provides a vocabulary for user queries, which is connected by a declarative mapping \(\mathcal{M}\) to a data source schema \(S\) (see, e.g., [2, 44]). The pair \(\mathcal{S}=(\mathcal{T}, \mathcal{M})\) is called an OBDA specification (sometimes, it also includes integrity constraints of the data source). For example, \(\mathcal{M}\) can consist of implications \(\forall \boldsymbol{x y}(\varphi(\boldsymbol{x}, \boldsymbol{y}) \rightarrow \psi(\boldsymbol{x}))\), where \(\varphi(\boldsymbol{x}, \boldsymbol{y})\) is a conjunction of atoms over \(S\) and \(\psi(\boldsymbol{x})\) is a conjunction of atoms over the signature of \(\mathcal{T}\) (in which case \(\mathcal{M}\) is called a GAV mapping). For a data instance \(D\) over \(S\) and a CQ \(\boldsymbol{q}(\boldsymbol{x})\), the certain answers to \(\boldsymbol{q}(\boldsymbol{x})\) over \(D\) under the OBDA specification \(\mathcal{S}\) are defined in the obvious way. In [45], the following generalisation of TBox \(\Sigma\)-query entailment is introduced to support the static analysis of OBDA specifications. Say that an OBDA specification \(\mathcal{S}_{1}\) query entails an OBDA specification \(\mathcal{S}_{2}\) if, for every CQ \(\boldsymbol{q}(\boldsymbol{x})\) and every data instance \(D\) over \(S\), the certain answers to \(\boldsymbol{q}(\boldsymbol{x})\) over \(D\) under \(\mathcal{S}_{2}\) are contained in the certain answers to \(\boldsymbol{q}(\boldsymbol{x})\) over \(D\) under \(\mathcal{S}_{1}\). It was shown [45] that the complexity of query entailment between OBDA specifications is closely linked to the complexity of \(\Sigma\)-query entailment. In fact, for GLAV, GAV, and linear mappings \(\mathcal{M}\), and DL-Lite core \(_{\mathcal{H}}^{\mathcal{H}}\) TBoxes \(\mathcal{T}\), the tight complexity results obtained in this article for \(\Sigma\)-query entailment are used to obtain the same complexity for deciding query entailment between OBDA specifications.

\section*{8. Future Work}

In this article, we have been concerned with algorithms deciding whether two KBs are \((\Sigma, \Gamma)\)-query inseparable. Depending on the applications of \((\Sigma, \Gamma)\)-query inseparability, other reasoning problems may also become important. We discuss them below for the four applications described in Section 1 .

For \(K B\) versioning, it is often not sufficient to learn that two KBs give different answers to some CQs in the signature \((\Sigma, \Gamma)\). In addition, a description of the relevant differences between the KBs should be given. Our algorithms compute a CQ witnessing ( \(\Sigma, \Gamma\) )-query separability, if one exists, which can be presented to the user. However, this CQ can be unnecessarily large, and it might not be a comprehensive representation of the differences between the two KBs. It would thus be of interest to develop additional algorithms that search for small witness CQs of \((\Sigma, \Gamma)\)-query separability, provide a comprehensive list of such witnesses, and link them to assertions in the KBs that explain them. Similar problems have been addressed in TBox versioning [10].

In knowledge exchange, we often do not have a candidate KB for the role of universal CQ-solution, but are rather interested in deciding whether a universal CQ-solution exists and computing it. We have seen above that our decision algorithms give a solution to this problem in the case of \(D L\)-Lite \(\mathcal{c o r e}^{\mathcal{H}}\), but seem to require significant extensions for more expressive DLs; see also [23].

In forgetting, the situation is similar to knowledge exchange: we are usually interested in deciding whether a uniform interpolant exists and computing it. For TBoxes, these problems have been investigated within one approach to uniform interpolants with respect to subsumptions [41, 46]. However, little is known about uniform interpolants for KBs with respect to answering CQs. Again, for DL-Lite core one can adapt our algorithm to compute uniform interpolants, but in general the ideas presented in this article will have to be significantly extended and/or modified.

Our algorithms can be directly used to decide whether a subset of a KB is its \((\Sigma, \Gamma)\)-query module. One of the most important problems in modularisation is the extraction of a minimal (with respect to set inclusion) module from a given KB. It is straightforward to design a polynomial-time algorithm extracting a ( \(\Sigma, \Gamma\) )-query module that calls an inseparability checker as an oracle: exhaustively remove assertions \(\alpha\) from a given \(\mathrm{KB} \mathcal{K}\) such that \(\mathcal{K} \backslash\{\alpha\}\) and \(\mathcal{K}\) are \((\Sigma, \Gamma)\)-query inseparable. Without any additional optimisations, however, only the algorithms based on forward strategies for \(\Sigma\)-inseparability in DLs without inverse roles can have acceptable performance. Interestingly, one can apply the same algorithms to compute approximations of minimal \(\Sigma\)-query modules for DLs with inverse roles: one can extract a \(\Sigma\)-query module of a given \(\mathrm{KB} \mathcal{K}\) by exhaustively removing from \(\mathcal{K}\) those inclusions and assertions \(\alpha\) for which player 1 has a winning strategy in the game \(G_{\Sigma}^{f}\left(\mathcal{G}_{2}, \mathcal{G}_{1}\right)\) on generating structures \(\mathcal{G}_{2}\) and \(\mathcal{G}_{1}\) for \(\mathcal{K}\) and \(\mathcal{K} \backslash\{\alpha\}\), respectively. The resulting KB is a module that approximates a minimal one. Efficiency of a similar approach to module extraction from TBoxes was shown in experiments [24].

As far as \((\Sigma, \Gamma)\)-query inseparability itself is concerned, it would be of interest to consider more expressive HornDLs than Horn- \(\mathcal{A} \mathcal{L C H} \mathcal{H}\), for example, those with (qualified) number restrictions, transitive roles, or nominals. We
conjecture that extensions of our game-theoretic approach can be applied to most (if not all) of those Horn-DLs. Finally, nothing is known about the complexity (and algorithms) for query inseparability for non-Horn DLs. Observe that in this case inseparability for CQs does not coincide anymore with inseparability for UCQs. For example, for \(\Sigma=\{A, B, E\}\), the KBs \(\mathcal{K}_{1}=(\{\top \sqsubseteq A \sqcup B\},\{E(a)\})\) and \(\mathcal{K}_{2}=(\emptyset,\{E(a)\})\) are \(\Sigma\)-inseparable for CQs but not \(\Sigma\) inseparable for UCQs. It seems appropriate to start an investigation of inseparability (for CQs and UCQs) with weak non-Horn DLs such as the DL underpinning Schema.org [47, 48] or other fragments of DL-Lite \({ }_{\text {bool }}\) and then move to more expressive DLs such as \(\mathcal{A} \mathcal{L} C\). We conjecture that the game-theoretic approach can be applied to those DLs as well.

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\section*{Appendix A. Proofs}

Lemma 10. Let \(\mathcal{K}=(\mathcal{T}, \mathcal{A})\) be a consistent \(K B\) with a Horn- \(\mathcal{A} \mathcal{L C H} \mathcal{I}\) TBox in normal form and \(\mathcal{M}\) the unravelling of \(\mathcal{G}\). Then \(\mathcal{M}\) is a model of \(\mathcal{K}\). Moreover,
\(-\boldsymbol{\tau}_{\mathcal{T}}^{\mathcal{M}}(a)=\{C \in \operatorname{con}(\mathcal{T}) \mid \mathcal{K} \vDash C(a)\}\), for all \(a \in \operatorname{ind}(\mathcal{K})\),
\(-\boldsymbol{\tau}_{\mathcal{T}}^{\mathcal{M}}(\sigma)=\boldsymbol{\tau}\), for all \(\sigma \in \Delta^{\mathcal{M}}\) with \(\operatorname{tail}(\sigma)=([S], \boldsymbol{\tau})\).
Proof. First, we show that \(a \in C^{\mathcal{M}}\) iff \(\mathcal{K} \vDash C(a)\), for all \(a \in \operatorname{ind}(\mathcal{K})\), and \(\sigma \in C^{\mathcal{M}}\) iff \(C \in \tau\), for all \(\sigma \in \Delta^{\mathcal{M}}\) with \(\operatorname{tail}(\sigma)=([S], \tau)\). We consider the following two cases for \(C\) :
1: \(C=A\). For \(a \in \operatorname{ind}(\mathcal{K})\), we clearly have \(a \in A^{\mathcal{M}} \operatorname{iff} a \in A^{\mathcal{G}}\) iff \(\mathcal{K} \vDash A(a)\). Similarly, for any \(\sigma \in \Delta^{\mathcal{M}}\) with tail \((\sigma)=([S], \boldsymbol{\tau})\), we have \(\sigma \in A^{\mathcal{M}}\) iff \(([S], \tau) \in A^{\mathcal{G}}\) iff \(A \in \boldsymbol{\tau}\).
2: \(C=\exists R . B\). Let \(a \in(\exists R . B)^{\mathcal{M}}\). If there is \(b \in \operatorname{ind}(\mathcal{K})\) with \((a, b) \in R^{\mathcal{M}}\) and \(b \in B^{\mathcal{M}}\) then, by the construction of \(\mathcal{M}\) and \(\mathcal{G}\), there is some \(P\) with \(P(a, b) \in \mathcal{A}\) and \(\mathcal{T} \vDash P \sqsubseteq R\), whence \(\mathcal{K} \vDash R(a, b)\). On the other hand, by item \(\mathbf{1}\), \(\mathcal{K} \vDash B(b)\), whence \(\mathcal{K} \vDash(\exists R . B)(a)\). If there is no \(b \in \operatorname{ind}(\mathcal{K})\) with \((a, b) \in R^{\mathcal{M}}\) and \(\mathcal{K} \vDash B(b)\), then \(a \rightsquigarrow([R], \tau)\), for some \(\mathcal{T}\)-type \(\boldsymbol{\tau}\) such that \(\mathcal{K} \vDash(\exists R . \tau)(a)\) and \(B \in \boldsymbol{\tau}\), whence \(\mathcal{K} \vDash(\exists R . B)(a)\).
Conversely, let \(\mathcal{K} \vDash(\exists R . B)(a)\). If there is \(b \in \operatorname{ind}(\mathcal{K})\) with \(P(a, b) \in \mathcal{A}, \mathcal{T} \vDash P \sqsubseteq R\) and \(\mathcal{K} \vDash B(b)\) then, by construction, \((a, b) \in R^{\mathcal{M}}\) and, by item \(\mathbf{1}, b \in B^{\mathcal{M}}\), whence \(a \in(\exists R . B)^{\mathcal{M}}\). Otherwise, let \(\boldsymbol{\tau}\) be a maximal \(\mathcal{T}\)-type such that \(\mathcal{K} \vDash(\exists R . \boldsymbol{\tau})(a)\) and \(B \in \boldsymbol{\tau}\). Then \(a \rightsquigarrow([R], \boldsymbol{\tau})\) and, by the construction of \(\mathcal{G}\) and \(\mathcal{M},(a, a \cdot([R], \boldsymbol{\tau})) \in R^{\mathcal{M}}\) and, by item \(\mathbf{1}, a \cdot([R], \tau) \in B^{\mathcal{M}}\), whence \(a \in(\exists R . B)^{\mathcal{M}}\).
Now, suppose \(\sigma \in(\exists R . B)^{\mathcal{M}}\). Then there is \(\sigma^{\prime}\) such that \(\left(\sigma, \sigma^{\prime}\right) \in R^{\mathcal{M}}\) and \(\sigma^{\prime} \in B^{\mathcal{M}}\). By construction, the following three options are possible.
- If \(\sigma^{\prime}=\sigma \cdot\left(\left[S^{\prime}\right], \boldsymbol{\tau}^{\prime}\right)\) then \(\mathcal{T} \vDash \boldsymbol{\tau} \sqsubseteq \exists S^{\prime} . \boldsymbol{\tau}^{\prime}, \mathcal{T} \vDash S^{\prime} \sqsubseteq R\) and \(B \in \boldsymbol{\tau}^{\prime}\), whence \(\mathcal{T} \vDash \boldsymbol{\tau} \sqsubseteq \exists R . B\), and so, as \(\boldsymbol{\tau}\) is a \(\mathcal{T}\)-type, \(\exists R . B \in \tau\).
- If \(\sigma=\sigma^{\prime} \cdot([S], \boldsymbol{\tau})\) with tail \(\left(\sigma^{\prime}\right)=\left(\left[S^{\prime}\right], \boldsymbol{\tau}^{\prime}\right)\) then \(\mathcal{T} \vDash \boldsymbol{\tau}^{\prime} \sqsubseteq \exists S . \tau, \mathcal{T} \vDash S \sqsubseteq R^{-}\)and \(B \in \boldsymbol{\tau}^{\prime}\). It follows that we have \(\mathcal{T} \vDash \boldsymbol{\tau}^{\prime} \sqsubseteq \exists R^{-} \cdot \tau\) and \(B \in \boldsymbol{\tau}^{\prime}\). Since \(\boldsymbol{\tau}\) is maximal, it must contain \(\exists R . B\) (for otherwise \(\tau^{\prime} \sqcap \exists R^{-} .(\tau \sqcap \forall R . \neg B)\) would be consistent).
- If \(\sigma=\sigma^{\prime} \cdot([S], \tau)\) with \(\sigma^{\prime}=a \in \operatorname{ind}(\mathcal{K})\) then \(\mathcal{K} \vDash(\exists S . \tau)(a), \mathcal{T} \vDash S \sqsubseteq R^{-}\)and, by item \(\mathbf{1}, \mathcal{K} \vDash B(a)\). Thus, we have \(\mathcal{K} \vDash\left(\exists R^{-} . t\right)(a)\) and \(\mathcal{K} \vDash B(a)\). Again, since \(\boldsymbol{\tau}\) is maximal it must contain \(\exists R\).B.

Conversely, let \(\exists R . B \in \boldsymbol{\tau}\). Then, by construction, \(([S], \tau) \rightsquigarrow\left([R], \tau^{\prime}\right)\), for some \(\mathcal{T}\)-type \(\boldsymbol{\tau}^{\prime}\) with \(B \in \boldsymbol{\tau}^{\prime}\). It follows then that \(\left(\sigma, \sigma \cdot\left([R], \boldsymbol{\tau}^{\prime}\right)\right) \in R^{\mathcal{M}}\) and, by item \(\mathbf{1},\left(\sigma \cdot\left([R], \boldsymbol{\tau}^{\prime}\right)\right) \in B^{\mathcal{M}}\), whence \(\sigma \in(\exists R . B)^{\mathcal{M}}\).

Next, we show that \(\mathcal{M}\) is a model of \((\mathcal{T}, \mathcal{A})\). Clearly, \(\mathcal{M}\) is a model of \(\mathcal{A}\). That \(\mathcal{M} \vDash\left(C_{1} \sqsubseteq C_{2}\right)\), for each \(C_{1} \sqsubseteq C_{2} \in \mathcal{T}\), follows immediately from the two properties of \(\boldsymbol{\tau}_{\mathcal{T}}^{\mathcal{M}}\), the fact that \(\mathcal{T}\)-types are closed under the concept inclusions in \(\mathcal{T}\), and that \(C \sqsubseteq \forall R . A\) is equivalent to \(\exists R^{-} . C \sqsubseteq A\).

Consider now \(R_{1} \sqsubseteq R_{2} \in \mathcal{T}\). Let \(\left(\sigma, \sigma^{\prime}\right) \in R_{1}^{\mathcal{M}}\). If \(\sigma=a \in \operatorname{ind}(\mathcal{K})\) and \(\sigma=b \in \operatorname{ind}(\mathcal{K})\) then \(\mathcal{K} \vDash R_{1}(a, b)\). Since \(R_{1} \sqsubseteq R_{2} \in \mathcal{T}\), we obtain \(\mathcal{K} \vDash R_{2}(a, b)\), whence \(\left(\sigma, \sigma^{\prime}\right) \in R_{2}^{\mathcal{M}}\). If \(\sigma^{\prime}=\sigma \cdot([R], \tau)\), for some \(R\) and \(\boldsymbol{\tau}\), then, by the construction of \(R_{1}^{\mathcal{M}}, \mathcal{T} \vDash R \sqsubseteq R_{1}\). Thus \(\mathcal{T} \vDash R \sqsubseteq R_{2}\), and so \(\left(\sigma, \sigma^{\prime}\right) \in R_{2}^{\mathcal{M}}\). The case of \(\sigma=\sigma^{\prime} \cdot([R], \tau)\) is the mirror image.

Theorem 13. Let \(\mathcal{L}\) be any of our DLs that contains \(\mathcal{E} \mathcal{L}\) or has role inclusions. Then \(\Sigma\)-query entailment for consistent \(\mathcal{L}\)-KBs is LogSpace-reducible to \(\Sigma\)-query inseparability for \(\mathcal{L}\)-KBs.

Proof. Let \(\mathcal{K}_{i}=\left(\mathcal{T}_{i}, \mathcal{A}_{i}\right), i=1,2\), be consistent \(\mathcal{L}\)-KBs and \(\Sigma\) a relational signature. We want to decide whether \(\mathcal{K}_{1}\) \(\Sigma\)-query entails \(\mathcal{K}_{2}\) assuming that we know how to decide \(\Sigma\)-query inseparability. Without loss of generality, we may assume that \(\Sigma=\operatorname{sig}\left(\mathcal{K}_{1}\right)=\operatorname{sig}\left(\mathcal{K}_{1}\right) \cap \operatorname{sig}\left(\mathcal{K}_{2}\right)\). To show this, we note first that we can add trivial concept inclusions \(A \sqsubseteq A\) and \(\exists P . \top \sqsubseteq \exists P . \top\) to KBs to ensure that \(\Sigma \subseteq \operatorname{sig}\left(\mathcal{K}_{1}\right)=\operatorname{sig}\left(\mathcal{K}_{1}\right) \cap \operatorname{sig}\left(\mathcal{K}_{2}\right)\). For symbols \(S \in \operatorname{sig}\left(\mathcal{K}_{1}\right) \cap \operatorname{sig}\left(\mathcal{K}_{2}\right)\) that are not in \(\Sigma\), we introduce a fresh \(S^{*}\) and replace \(S\) by \(S^{*}\) in \(\mathcal{K}_{2}\). Denote the resulting KB by \(\mathcal{K}_{2}^{*}\). Then \(\mathcal{K}_{1} \Sigma\)-query entails \(\mathcal{K}_{2}\) iff \(\mathcal{K}_{1} \Sigma^{*}\)-query entails \(\mathcal{K}_{2}^{*}\) for \(\Sigma^{*}=\operatorname{sig}\left(\mathcal{K}_{1}\right)\), as required.

Case 1: \(\mathcal{L}\) has role inclusions.
Case 1.1: Assume that the trivial interpretation \(I_{\emptyset}\) with \(\left|\Delta^{I_{0}}\right|=1\) and \(S^{I_{0}}=\emptyset\), for any symbol \(S\), is a model of the \(\mathcal{T}_{i}\) for \(i=1,2\) (we show how the \(\mathrm{KBs} \mathcal{K}_{1}\) and \(\mathcal{K}_{2}\) can be modified to ensure that this assumption holds in Case 1.2). Let \(\mathcal{K}_{i}^{i}\) be a copy of \(\mathcal{K}_{i}\) in which all symbols \(S\) are replaced by fresh symbols \(S_{i}\), and let \(\mathcal{K}_{i}^{\prime}\) be the extension of \(\mathcal{K}_{i}^{i}\) with \(S_{i} \sqsubseteq S\), for all \(S \in \Sigma\). The purpose of this construction is to avoid the interaction between the symbols used in \(\mathcal{K}_{1}\) and the symbols used in \(\mathcal{K}_{2}\) (as shown in Section 3 after the formulation of the theorem). We show that
\[
\mathcal{K}_{1} \Sigma \text {-query entails } \mathcal{K}_{2} \quad \text { iff } \quad \mathcal{K}_{1} \text { and } \mathcal{K}_{1}^{\prime} \cup \mathcal{K}_{2}^{\prime} \text { are } \Sigma \text {-query inseparable. }
\]

The interesting direction is to show that if \(\mathcal{K}_{1} \Sigma\)-query entails \(\mathcal{K}_{2}\) then \(\mathcal{K}_{1} \Sigma\)-query entails \(\mathcal{K}_{1}^{\prime} \cup \mathcal{K}_{2}^{\prime}\). Suppose that \(\mathcal{K}_{1} \Sigma\)-query entails \(\mathcal{K}_{2}\). Then \(\mathcal{K}_{1} \Sigma\)-query entails both \(\mathcal{K}_{1}^{\prime}\) and \(\mathcal{K}_{2}^{\prime}\). We use the following construction to 'merge' materialisations of the \(\mathcal{K}_{i}^{\prime}\). Let \(\mathcal{M}_{1}\) be a materialisation of \(\mathcal{K}_{1}\) and, for \(i=1\), 2, let \(\mathcal{U}_{i}\) be a materialisation of \(\mathcal{K}_{i}^{\prime}\) obtained by unravelling a generating structure for \(\mathcal{K}_{i}^{\prime}\). By Lemma \(10, \mathcal{U}_{i}\) is a model of \(\mathcal{K}_{i}^{\prime}\). It should be clear that we can also assume that
\[
\begin{equation*}
\Delta^{\mathcal{U}_{1}} \cap \Delta^{\mathcal{U}_{2}}=\operatorname{ind}\left(\mathcal{K}_{1}\right) \cap \operatorname{ind}\left(\mathcal{K}_{2}\right) \tag{A.1}
\end{equation*}
\]

Denote by \(\mathcal{U}\) the union of \(\mathcal{U}_{1}\) and \(\mathcal{U}_{2}\) defined by setting \(\Delta^{\mathcal{U}}=\Delta^{\mathcal{U}_{1}} \cup \Delta^{\mathcal{U}_{2}}\) and \(S^{\mathcal{U}}=S^{\mathcal{U}_{1}} \cup S^{\mathcal{U}_{2}}\) for all concept and role names \(S\). We show that
(i) \(\mathcal{U}\) is a model of \(\mathcal{K}_{1}^{\prime} \cup \mathcal{K}_{2}^{\prime}\), and
(ii) \(\mathcal{U}\) is finitely \(\left(\Sigma, \operatorname{ind}\left(\mathcal{K}_{1}\right) \cup \operatorname{ind}\left(\mathcal{K}_{2}\right)\right)\)-homomorphically embeddable into \(\mathcal{M}_{1}\).

It will then follow, by Theorem 6 , that \(\mathcal{K}_{1} \Sigma\)-query entails \(\mathcal{K}_{1}^{\prime} \cup \mathcal{K}_{2}^{\prime}\). Indeed, let \(\mathcal{M}^{\prime}\) be a materialisation of \(\mathcal{K}_{1}^{\prime} \cup \mathcal{K}_{2}^{\prime}\). Since, by (i), \(\mathcal{U}\) is a model of \(\mathcal{K}_{1}^{\prime} \cup \mathcal{K}_{2}^{\prime}\), by Lemma 11 , there is a homomorphism from (any finite subinterpretation of) \(\mathcal{M}^{\prime}\) to \(\mathcal{U}\), and so, by (ii), from any finite subinterpretation of \(\mathcal{M}^{\prime}\) to \(\mathcal{M}_{1}\).

Now, for item (i), recall that, for both \(i=1,2\), the trivial interpretation is a model of the TBox of \(\mathcal{K}_{3-i}^{\prime}\), which does not contain any negative occurrences of the symbols of \(\mathcal{K}_{i}^{\prime}\), and \(\mathcal{U}_{i}\) is a model of \(\mathcal{K}_{i}^{\prime}\); therefore, \(\mathcal{U}\) is a model of \(\mathcal{K}_{i}^{\prime}\). For (ii), consider a finite subinterpretation \(\mathcal{U}_{0}\) of \(\mathcal{U}\) and, for \(i=1,2\), let \(\mathcal{U}_{0 i}\) be the respective finite subinterpretation of \(\mathcal{U}_{i}\). Since \(\mathcal{K}_{1} \Sigma\)-query entails both \(\mathcal{K}_{1}^{\prime}\) and \(\mathcal{K}_{2}^{\prime}\), by Theorem6, we have \(\left(\Sigma\right.\), ind \(\left(\mathcal{K}_{i}^{\prime}\right)\) )-homomorphisms \(h_{i}\) from \(\mathcal{U}_{0 i}\) to \(\mathcal{M}_{1}\), for \(i=1,2\). Define \(h\) by taking \(h(u)=h_{1}(u)\), for all \(u \in \Delta^{\mathcal{U}_{01}}\), and \(h(u)=h_{2}(u)\), for all \(u \in \Delta^{\mathcal{U}_{02}} \backslash \Delta^{\mathcal{U}_{01}}\). Since A.1) and \(h_{1}(a)=h_{2}(a)\), for all \(a \in \operatorname{part}_{\Sigma}^{\mathcal{U}_{1}} \cap \operatorname{part} \boldsymbol{\mathcal { U }}_{\Sigma}\), the function \(h\) is a \(\left(\Sigma, \operatorname{ind}\left(\mathcal{K}_{1}\right) \cup \operatorname{ind}\left(\mathcal{K}_{2}\right)\right)\)-homomorphism from \(\mathcal{U}_{0}\) to \(\mathcal{M}_{1}\), as required.
Case 1.2: Suppose that the trivial interpretation is not a model of \(\mathcal{T}_{i}\), for some \(i \in\{1,2\}\). We construct \(\mathcal{K}_{i}^{\prime \prime}=\left(\mathcal{T}_{i}^{\prime \prime}, \mathcal{A}_{i}^{\prime \prime}\right)\), \(i=1,2\), such that the trivial interpretation is a model of \(\mathcal{T}_{i}^{\prime \prime}\), for \(i=1,2\), and \(\mathcal{K}_{1} \Sigma\)-query entails \(\mathcal{K}_{2}\) iff \(\mathcal{K}_{1}^{\prime \prime} \Sigma\)-query entails \(\mathcal{K}_{2}^{\prime \prime}\) (this will reduce Case 1.2 to Case 1.1). The construction is by careful relativisation. We assume that the TBoxes \(\mathcal{T}_{i}\) are in normal form (see Theorem 8 . If the \(\mathcal{T}_{i}\) do not contain inclusions of the form \(T \sqsubseteq A\) then the trivial
interpretation is a model of the TBoxes and we are done. Otherwise, for \(i=1,2\), let \(D^{i}\) be fresh concept names: \(D^{i}\) will replace \(T\) in the inclusion \(T \sqsubseteq A\) in \(\mathcal{T}_{i}\), which will ensure that the trivial interpretation is a model of the resulting TBox. In addition, we have to ensure that \(D^{i}\) contains all domain elements of the materialisation. To deal with the individual names in the ABox \(\mathcal{A}_{i}\), we take \(\mathcal{A}_{i}^{\prime \prime}=\mathcal{A}_{i} \cup \mathcal{A}_{i}^{D_{i}}\), where
\[
\begin{equation*}
\mathcal{A}_{i}^{D_{i}}=\left\{D^{i}(a) \mid a \in \operatorname{ind}\left(\mathcal{K}_{i}\right)\right\} . \tag{A.2}
\end{equation*}
\]

The TBoxes \(\mathcal{T}_{i}^{\prime \prime}\) are obtained from \(\mathcal{T}_{i}\) by replacing
- any inclusion \(T \sqsubseteq A\) with \(D^{i} \sqsubseteq A\);
- any inclusion \(A \sqsubseteq \exists R . C\) with
\(-A \sqsubseteq \exists R\) and \(\exists R^{-} \sqsubseteq D^{i}\), if the \(\mathcal{T}_{i}\) are members of the DL-Lite family ( \(C=\top\) in this case), and
\(-A \sqsubseteq \exists R .\left(D^{i} \sqcap C\right)\), otherwise.
The remaining inclusions are not modified and the modification of inclusions of the form \(A \sqsubseteq \exists R . C\) ensures that \(D^{i}\) holds in all generated domain elements of the materialisations constructed to prove Theorem 12 Note that if \(\mathcal{T}_{i}\) is an \(\mathcal{L}\)-TBox, then \(\mathcal{T}_{i}^{\prime \prime}\) is an \(\mathcal{L}\)-TBox as well, for any of our DLs. We show that the \(\mathcal{K}_{i}^{\prime \prime}=\left(\mathcal{T}_{i}^{\prime \prime}, \mathcal{A}_{i}^{\prime \prime}\right)\), for \(i=1,2\), are as required. First, by construction, the trivial interpretation \(\mathcal{I}_{\emptyset}\) is a model of \(\mathcal{T}_{i}^{\prime \prime}\). Second, let \(\mathcal{M}_{i}\) be the unravelling of a generating structure for \(\mathcal{K}_{i}\). By Theorem \(9, \mathcal{M}_{i}\) is a materialisation of \(\mathcal{K}_{i}\). Observe that the interpretation \(\mathcal{U}_{i}\) obtained from \(\mathcal{M}_{i}\) by interpreting \(D^{i}\) as the domain of \(\mathcal{M}_{i}\) is a materialisation of \(\mathcal{K}_{i}^{\prime \prime}\). Thus, by Theorem \(6 \mathcal{K}_{1} \Sigma\)-query entails \(\mathcal{K}_{2}\) iff \(\mathcal{K}_{1}^{\prime \prime} \Sigma\)-query entails \(\mathcal{K}_{2}^{\prime \prime}\), as required.
Case 2: \(\mathcal{L}\) contains \(\mathcal{E} \mathcal{L}\) and has no role inclusions (that is, \(\mathcal{L} \in\{\mathcal{E} \mathcal{L}\), Horn- \(\mathcal{A} \mathcal{L} C\), Horn- \(\mathcal{A} \mathcal{L} C \mathcal{I}\}\) ). We construct \(\mathcal{K}_{1}^{\prime}=\left(\mathcal{T}_{1}^{\prime}, \mathcal{A}_{1}^{\prime}\right)\) and \(\mathcal{K}_{2}^{\prime}=\left(\mathcal{T}_{2}^{\prime}, \mathcal{F}_{2}^{\prime}\right)\) such that
\[
\begin{equation*}
\mathcal{K}_{1} \Sigma \text {-query entails } \mathcal{K}_{2} \quad \text { iff } \quad \mathcal{K}_{1} \text { and } \mathcal{K}_{1}^{\prime} \cup \mathcal{K}_{2}^{\prime} \text { are } \Sigma \text {-query inseparable. } \tag{A.3}
\end{equation*}
\]

First, we make sure that \(\mathcal{K}_{1}\) is role-compatible with \(\mathcal{K}_{2}\), that is, for all \(a, b \in \operatorname{ind}\left(\mathcal{K}_{2}\right)\), if \(R(a, b) \notin \mathcal{A}_{2}\), then \(R(a, b) \notin \mathcal{A}_{1}\). Remove from \(\mathcal{A}_{1}\) all assertions \(R(a, b)\), for \(a, b \in \operatorname{ind}\left(\mathcal{K}_{2}\right)\), that are not in \(\mathcal{A}_{2}\), and denote the resulting ABox by \(\mathcal{A}_{1}^{-}\). Define \(\mathcal{A}_{1}^{\star}\) by adding a disjoint copy of \(\mathcal{A}_{1}\) to \(\mathcal{A}_{1}^{-}\)(in which the copy of an individual \(a\) is denoted by \(\left.a^{\star}\right)\) and also adding the assertions \(R\left(a, b^{\star}\right)\) and \(R\left(a^{\star}, b\right)\) for every \(R(a, b) \in \mathcal{A}_{1}\).

Then \(\mathcal{K}_{1}^{\star}=\left(\mathcal{T}_{1}, \mathcal{A}_{1}^{\star}\right) \Sigma\)-query entails \(\mathcal{K}_{2}\) iff \(\mathcal{K}_{1} \Sigma\)-query entails \(\mathcal{K}_{2}\). This follows directly from the fact that Horn\(\mathcal{A} \mathcal{L C I}\) is unravelling-tolerant [49], which implies that in the unravellings \(\mathcal{M}_{1}\) and \(\mathcal{M}_{1}^{\star}\) of the generating structures for \(\mathcal{K}_{1}\) and \(\mathcal{K}_{1}^{\star}\), we have that the subtrees \(\mathcal{I}_{a}, I_{a}^{\star}\), and \(I_{a^{\star}}^{\star}\) of \(\mathcal{M}_{1}, \mathcal{M}_{1}^{\star}\) and \(\mathcal{M}_{1}^{\star}\) rooted at \(a, a\) and \(a^{\star}\), respectively, are isomorphic for any \(a \in \operatorname{ind}\left(\mathcal{K}_{1}\right)\).

Second, assume that \(\mathcal{K}_{1}\) is role-compatible with \(\mathcal{K}_{2}\). We employ relativisation again. Let \(D^{i}\) be fresh concept names, for \(i=1,2\). In this case, apart from ensuring that \(D^{i}\) contains all domain elements of the materialisation of \(\mathcal{K}_{i}\) we have to ensure that merging the materialisations of \(\mathcal{K}_{1}\) and \(\mathcal{K}_{2}\) does not lead to additional domain elements. Let \(\mathcal{A}_{i}^{\prime}=\mathcal{A}_{i} \cup \mathcal{A}_{i}^{D_{i}}\), for \(i=1,2\), where \(\mathcal{A}_{i}^{D_{i}}\) is defined by A.2). Assume the TBoxes \(\mathcal{T}_{i}\) are in normal form and define \(\mathcal{T}_{i}^{\prime}\) by replacing
- any inclusion \(\top \sqsubseteq A\) with \(D^{i} \sqsubseteq A\);
- any inclusion \(A_{1} \sqsubseteq A_{2}\) with \(A_{1} \sqcap D^{i} \sqsubseteq A_{2}\);
- any inclusion \(A_{1} \sqcap A_{2} \sqsubseteq A\) with \(A_{1} \sqcap A_{2} \sqcap D^{i} \sqsubseteq A\);
- any inclusion \(\exists R . C \sqsubseteq A\) with \(\exists R .\left(C \sqcap D^{i}\right) \sqcap D^{i} \sqsubseteq A ;\)
- any inclusion \(A \sqsubseteq \exists R . C\) with \(A \sqcap D^{i} \sqsubseteq \exists R .\left(D^{i} \sqcap C\right)\);
- any inclusion \(A_{1} \sqsubseteq \forall R . A_{2}\) with \(A_{1} \sqcap D^{i} \sqsubseteq \forall R .\left(\neg D^{i} \sqcup A_{2}\right)\).

Note that \(\mathcal{T}_{i}^{\prime}\) is not necessarily in normal form, but it is an \(\mathcal{L}\)-TBox, which can then be transformed to normal form by Theorem 8 .

We show A.3). The interesting direction is 'if \(\mathcal{K}_{1} \Sigma\)-query entails \(\mathcal{K}_{2}\) then \(\mathcal{K}_{1} \Sigma\)-query entails \(\mathcal{K}_{1}^{\prime} \cup \mathcal{K}_{2}^{\prime}\) '. Suppose \(\mathcal{K}_{1} \Sigma\)-query entails \(\mathcal{K}_{2}\). Then \(\mathcal{K}_{1} \Sigma\)-query entails both \(\mathcal{K}_{1}^{\prime}\) and \(\mathcal{K}_{2}^{\prime}\) (as \(\mathcal{K}_{1} \Sigma\)-query entails both \(\mathcal{K}_{1}\) and \(\mathcal{K}_{2}\) ). Let \(\mathcal{M}_{1}\) be a materialisation of \(\mathcal{K}_{1}\) and, for \(i=1,2\), let \(\mathcal{U}_{i}\) be a materialisation of \(\mathcal{K}_{i}^{\prime}\) obtained by unravelling a generating structure for \(\mathcal{K}_{i}^{\prime}\). We proceed as in Case 1.1: we construct \(\mathcal{U}\) by merging \(\mathcal{U}_{1}\) and \(\mathcal{U}_{2}\) and show that conditions (i) and (ii) hold. It will then follow that \(\mathcal{K}_{1} \Sigma\)-query entails \(\mathcal{K}_{1}^{\prime} \cup \mathcal{K}_{2}^{\prime}\).

For item (i), observe that (a) since \(\mathcal{K}_{1}\) is role-compatible with \(\mathcal{K}_{2}\), if an assertion \(A(a)\), for \(a \in \operatorname{ind}\left(\mathcal{K}_{2}\right)\), can be derived in \(\mathcal{K}_{1}^{\prime} \cup \mathcal{K}_{2}^{\prime}\) by the \(\mathcal{T}_{2}^{\prime}\) axioms of the form \(\exists R .\left(D^{2} \sqcap C\right) \sqcap D^{2} \sqsubseteq A\) or \(A_{1} \sqcap D^{2} \sqsubseteq \forall R .\left(\neg D^{2} \sqcup A\right)\), then the same assertion can be already derived in \(\mathcal{K}_{2}\) by the axioms \(\exists R . C \sqsubseteq A\) and \(A_{1} \sqsubseteq \forall R . A\); (b) for \(i=1,2\), the trivial interpretation \(\mathcal{I}_{\emptyset}\) is a model of \(\mathcal{T}_{i}^{\prime}\); and (c) every inclusion of \(\mathcal{T}_{i}^{\prime}\) is relativised to \(D^{i}\) : it is 'applicable' only to elements in \(D_{i}\) and 'generates' only elements in \(D_{i}\) again. In particular, the \(\mathcal{T}_{2}^{\prime}\) axioms of the form \(\exists R .\left(D^{2} \sqcap C\right) \sqcap D^{2} \sqsubseteq A\) or \(A_{1} \sqcap D^{2} \sqsubseteq \forall R .\left(\neg D^{2} \sqcup A\right)\) are not 'applicable' to \(a \in \operatorname{ind}\left(\mathcal{K}_{1}\right) \backslash \operatorname{ind}\left(\mathcal{K}_{2}\right)\). Thus, \(\mathcal{U}\) is a model of \(\mathcal{K}_{1}^{\prime} \cup \mathcal{K}_{2}^{\prime}\). The argument for item (ii) is analogous to Case 1.1, which completes the proof.

Theorem 44. \(\Sigma\)-query entailment for any of our DLs \(\mathcal{L}\) is LogSpace-reducible to the membership problem for universal \(\mathbb{C Q}\)-solutions in \(\mathcal{L}\).

Proof. We use the proof of Theorem 13 Suppose \(\mathcal{L} \mathrm{KBs} \mathcal{K}_{1}, \mathcal{K}_{2}\), and a signature \(\Sigma\) are given. We want to reduce the problem to decide whether \(\mathcal{K}_{1} \Sigma\)-query entails \(\mathcal{K}_{2}\) to the membership problem for universal CQ-solutions in \(\mathcal{L}\). As argued in the proof of Theorem 13, we may assume that \(\Sigma=\operatorname{sig}\left(\mathcal{K}_{1}\right)=\operatorname{sig}\left(\mathcal{K}_{1}\right) \cap \operatorname{sig}\left(\mathcal{K}_{2}\right)\).

For the reduction to the membership problem for universal CQ -solutions in \(\mathcal{L}\), we do not have to consider the case that \(\mathcal{L}\) does not have role inclusions since they can always be used in the mapping \(\mathcal{T}_{12}\). Thus, we follow the proof of Case 1 in the in the proof of Theorem 13 and first assume that the trivial interpretation \(\mathcal{I}_{\emptyset}\) is a model of \(\mathcal{T}_{i}\), for \(i=1,2\). Recall the definition of \(\mathcal{K}_{i}^{i}\) : \(\mathcal{K}_{i}^{i}\) is obtained from \(\mathcal{K}_{i}\) by replacing every symbol \(S\) in \(\mathcal{K}_{i}\) with a fresh symbol \(S_{i}\). Then it is shown in the proof of Theorem 13 (Case 1.1) that \(\mathcal{K}_{1} \Sigma\)-query entails \(\mathcal{K}_{2}\) iff \(\mathcal{K}_{1}^{\prime} \cup \mathcal{K}_{2}^{\prime} \cup \mathcal{T}_{12}\) and \(\mathcal{K}_{1}\) are \(\Sigma\)-query inseparable, where \(\mathcal{T}_{12}=\left\{S_{i} \sqsubseteq S \mid S \in \Sigma\right\}\). But the latter problem is a membership problem for universal CQ-solutions since we assume that \(\Sigma=\operatorname{sig}\left(\mathcal{K}_{1}\right)\).

We complete the proof by considering the case when \(I_{\emptyset}\) is not a model of \(\mathcal{T}_{i}\) for some \(i \in\{1,2\}\). We reduce this case to the previous one by constructing \(\mathrm{KBs} \mathcal{K}_{i}^{\prime \prime}=\left(\mathcal{T}_{i}^{\prime \prime}, \mathcal{A}_{i}^{\prime \prime}\right)\) such that \(\mathcal{I}_{\emptyset}\) is a model of \(\mathcal{T}_{i}^{\prime \prime}\) and \(\mathcal{K}_{1} \Sigma\)-query entails \(\mathcal{K}_{2}\) iff \(\mathcal{K}_{1}^{\prime \prime} \Sigma\)-query entails \(\mathcal{K}_{2}^{\prime \prime}\). But KBs \(\mathcal{K}_{i}^{\prime \prime}\) with these properties have been constructed in the proof of Theorem 13 (Case 1.2) already (observe that no role inclusions are introduced in the construction of \(\mathcal{K}_{i}^{\prime \prime}\), and so \(\mathcal{K}_{i}^{\prime \prime}\) is an \(\mathcal{L}\)-KB if \(\mathcal{K}_{i}\) is an \(\mathcal{L}\)-KB for any of our DLs \(\mathcal{L}\) ).

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[^1]:    ${ }^{1}$ Since we consider Horn DLs, the results of this article actually apply to unions of CQs (known as UCQs), see Remark 2 below. For simplicity, however, we consider CQs only.

[^2]:    ${ }^{2}$ Strictly speaking, DL-Lite core $\mathcal{\mathcal { H }}$ and DL-Lite ${ }_{\text {horn }}^{\mathcal{H}}$ are not fragments of $\mathcal{A} \mathcal{L C H} \mathcal{I}$ because it does not have role disjointness constraints. However, these constraints play no essential part in our constructions, and the techniques we develop for $\mathcal{A} \mathcal{L C H} \mathcal{I}$ are also applicable to the logics in the DL-Lite family.

[^3]:    ${ }^{3}$ Note that, by Theorems 33 and $32 \Sigma$-query entailment and inseparability are P-complete for DL-Lite ${ }_{\text {core }}$ and DL-Lite ${ }_{\text {horn }}$ in both combined and data complexity. DL-Lite core and DL-Lite horn are omitted from Theorem 13 since we have not found a direct LogSpace-reduction of $\Sigma$-query entailment to $\Sigma$-query inseparability.

