# On Generalized Records and Spatial Conjunction in Role Logic 

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#### Abstract

We have previously introduced role logic as a notation for describing properties of relational structures in shape analysis, databases and knowledge bases. A natural fragment of role logic corresponds to two-variable logic with counting and is therefore decidable. We show how to use role logic to describe open and closed records, as well the dual of records, inverse records. We observe that the spatial conjunction operation of separation logic naturally models record concatenation. Moreover, we show how to eliminate the spatial conjunction of formulas of quantifier depth one in first-order logic with counting. As a result, allowing spatial conjunction of formulas of quantifier depth one preserves the decidability of two-variable logic with counting. This result applies to two-variable role logic fragment as well. The resulting logic smoothly integrates type system and predicate calculus notation and can be viewed as a natural generalization of the notation for constraints arising in role analysis and similar shape analysis approaches.


Keywords:. Records, Shape Analysis, Static Analysis, Program Verification, Two-Variable Logic with Counting, Description Logic, Types

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## 1 Introduction

In [36] we have introduced role logic, a notation for describing properties of relational structures in shape analysis, databases and knowledge bases. Role logic notation aims to combine the simplicity of role declarations [33] and the well-established first-order logic. Role logic is closed under all boolean operations and generalizes boolean shape analysis constraints [37]. Role logic formulas easily translate into the traditional first-order logic notation. Despite this generality, role logic enables the concise expression of common properties of data structures in imperative programs that manipulate complex data structures with mutable references. In [36, Section 4] we have established the decidability of the fragment $\mathrm{RL}^{2}$ of role logic by exhibiting a correspondence with two-variable logic with counting $C^{2}$ [22, 45].
Generalized records in role logic. In this paper we give a systematic account of field and slot declarations of role analysis [33] by introducing a set of role logic shorthands that allows concise description of records. Our basic idea is to generalize types to unary predicates on objects. Some of the aspects of our notion of records that indicate its generality are:

1. We allow building new records by taking the conjunction, disjunction, or negation of records.
2. In our notation, a record indicates a property of an object at a particular program point; objects can satisfy different record specifications at different program points. As a result, our records can express typestate changes such as object initialization $[16-18,55,56]$ and more general changes in relationships between objects such as movements of objects between data structures $[32,33,54]$.
3. We allow inverse records as a dual of records that specify incoming edges of an object in the graph of objects representing program heap. Inverse records allow the specification of aliasing properties of objects, generalizing unique pointers. Inverse records enable the convenient specification of movements of objects that participate in multiple data structures.
4. We allow the specification of both open and closed records. Closed records specify a complete set of outgoing and incoming edges of an object. Open records leave certain edges unspecified, which allows orthogonal data structures to be specified independently and then combined using logical conjunction.
5. We allow the concatenation of generalized records using a form of spatial conjunction of separation logic, while remaining within the decidable fragment of two-variable role logic.

Separation logic. Separation logic $[28,43,51,52]$ is a promising approach for specifying properties of programs in the presence of mutable data structures. One of the main uses of separation logic in previous approaches is dealing with frame conditions [5, 28]. In contrast, our paper identifies another use of spatial logic: expressing record concatenation. Although our approach is based on essentially
same logical operation of spatial conjunction, our use of spatial conjunction for records is more local, because it applies to the descriptions of the neighborhood of an object.

To remain within the decidable fragment of role logic, we give in Section 7 a construction that eliminates spatial conjunction when it connects formulas of quantifier depth one. This construction also illustrates that spatial conjunction is useful for reasoning about counting stars [22] of the two-variable logic with counting $C^{2}$. To our knowledge, this is the first result that combines two-variable logic with counting and a form of spatial conjunction.
Using the resulting logic. We can use specifications written in our notation to describe properties and relations between objects in programs with dynamically allocated data structures. These specifications can act as assertions, preconditions, postconditions, loop invariants or data structure invariants [33, 36, 39]. By selecting a finite-height lattice of properties for a given program fragment, abstract interpretation [15] can be used to synthesize properties of objects at intermediate program points $[2,3,24,33,49,50,54,58,59]$. Decidability and closure properties of our notation are essential for the completeness and predictability of the resulting static analysis [38].
Contributions. We summarize the main contributions of this paper as follows:

1. We present a logic which generalizes the concept of records in several directions (Section 5). These generalizations are useful for expressing properties of objects and memory cells in imperative programs, and go beyond standard type systems.
2. We identify a novel use of separation logic: modelling the concatenation of generalized records.
3. We show how to translate role constraints from role analysis [33] to role logic (Section 6).
4. We show that, under certain syntactic restrictions, we can translate spatial conjunction into other constructs of the decidable logic $\mathrm{RL}^{2}$ (Section 7). We therefore obtain a notation that extends $\mathrm{RL}^{2}$ with a convenient way of describing record concatenation, and remains decidable.
5 . We present a translation of first-order logic with spatial conjunction and inductive definitions into second-order logic (Section 8.2).

Outline. Section 2 reviews the syntax and semantics of role logic. Section 3 defines spatial conjunction in role logic and motivates its use for describing record concatenation. Section 4 and Section 5 show how to use spatial conjunction in role logic to describe a generalization of records. Section 6 demonstrates that our notation is a generalization of the local constraints arising in role analysis [33] by giving a natural embedding of role constraints into our notation. Section 7 shows how to eliminate the spatial conjunction connective $\circledast$ from a spatial conjunction $F_{1} \circledast F_{2}$ of two formulas $F_{1}$ and $F_{2}$ when $F_{1}$ and $F_{2}$ have no nested counting quantifiers; this is the core technical result of this paper. A consequence of this is result is that we may allow certain uses of spatial conjunction in $\mathrm{RL}^{2}$ fragment of role logic while preserving the decidability property of $\mathrm{RL}^{2}$. Our
extension of role logic with spatial conjunction is therefore justified: it allows record-like specifications to be expressed in a more natural way, and it does not lead outside the decidable fragment. Section 8 contains remarks on preserving the satisfiability of formulas in the presence of spatial conjunction and shows how to encode the spatial conjunction (with inductive definitions) in second-order logic. Section 9 presents related work, and Section 10 concludes. Appendix contains the details of the correctness proof for the elimination of spatial conjunction from Section 7.

## 2 A Decidable Two-Variable Role Logic RL ${ }^{2}$

$$
\begin{array}{rlrl}
F:: & =A|f| \mathrm{EQ}\left|F_{1} \wedge F_{2}\right| \neg F\left|F^{\prime}\right| \sim F \mid \mathrm{card}{ }^{\geq k} F \\
e & :: & \{1,2\} \rightarrow D & \\
\llbracket A \rrbracket e & =\llbracket A \rrbracket(e 1) & \\
\llbracket \mathrm{EQ} \rrbracket e & =(e 2)=(e 1) & \\
\llbracket F_{1} \wedge F_{2} \rrbracket e & =\left(\llbracket F_{1} \rrbracket e\right) \wedge\left(\llbracket F_{2} \rrbracket e\right) & \llbracket \neg F \rrbracket e=\neg(\llbracket F \rrbracket e) \\
\llbracket F^{\prime} \rrbracket e & =\llbracket F \rrbracket(e[1 \mapsto(e 2)]) & \llbracket \sim F \rrbracket e=\llbracket F \rrbracket(e[1 \mapsto(e 2), 2 \mapsto(e 1)]) \\
\llbracket \mathrm{card}{ }^{\geq k} F \rrbracket e & =|\{d \in D \mid \llbracket F \rrbracket(e[1 \mapsto o, 2 \mapsto(e 1)])\}| \geq k \\
F_{1} \vee F_{2} & \equiv \neg\left(\neg F_{1} \wedge \neg F_{2}\right) \\
F_{1} \Rightarrow F_{2} & \equiv \neg F_{1} \vee F_{2} &
\end{array}
$$

Fig. 1. The Syntax and the Semantics of $\mathrm{RL}^{2}$

Figure 1 presents the two-variable role logic $\mathrm{RL}^{2}$ [36]. We have proved in [36] that $\mathrm{RL}^{2}$ has the same expressive power as two-variable logic with counting $C^{2}$. The logic $C^{2}$ is a first-order logic 1) extended with counting quantifiers $\exists^{\geq k} x . F(x)$, saying that there are at least $k$ elements $x$ satisfying formula $F(x)$ for some constant $k$, and 2) restricted to allow only two variable names $x, y$ in formulas. An example formula in two-variable logic with counting is

$$
\begin{equation*}
\forall x \cdot A(x) \Rightarrow\left(\forall y \cdot f(x, y) \Rightarrow \exists^{=1} x . g(x, y)\right) \tag{1}
\end{equation*}
$$

The formula (1) means that all nodes that satisfy $A(x)$ point along the field $f$ to nodes that have exactly one incoming $g$ edge. Note that the variables $x$ and $y$ may be reused via quantifier nesting, and that formulas of the form $\exists^{=k} x . F(x)$ and $\exists \leq k x . F(x)$ are expressible as boolean combination of formulas of the form $\exists^{\geq k} x . F(x)$. The logic $C^{2}$ was shown decidable in [22] and the complexity for the $C_{1}^{2}$ fragment of $C^{2}$ (with counting up to one) was established in [45]. We can view role logic as a variable-free version of $C^{2}$. Variable-free logical notations are attractive as generalizations of type systems because traditional type systems
are often variable-free. The formula (1) can be written in role logic as $[A \Rightarrow$ $\left[f \Rightarrow\right.$ card $\left.^{\geq 1} \sim g\right]$ ] where the construct $[F]$ is a shorthand for $\neg$ card $^{\geq 1} \neg F$ and corresponds to the universal quantifier. The expression $\sim g$ denotes the inverse of relation $g$. This paper focuses on the use of role logic to describe generalized records, see [36] for further examples of using role logic and [6] for advantages of variable-free notation in general.

## 3 Spatial Conjunction

$$
\begin{aligned}
& \llbracket F_{1} \circledast F_{2} \rrbracket e=\exists e_{1}, e_{2} \text {. split } e\left[e_{1} e_{2}\right] \wedge \llbracket F_{1} \rrbracket e_{1} \wedge \llbracket F_{2} \rrbracket e_{2} \\
& \text { split } e\left[e_{1} e_{2}\right]= \\
& \quad \forall A \in \mathcal{A} . \forall d \in D .(e A) d \Longleftrightarrow\left(e_{1} A\right) d \vee\left(e_{2} A\right) d \wedge \neg\left(\left(e_{1} A\right) d \wedge\left(e_{2} A\right) d\right) \wedge \\
& \quad \forall f \in \mathcal{F} . \forall d_{1}, d_{2} \in D . \\
& \quad(e f) d_{1} d_{2} \Longleftrightarrow\left(e_{1} f\right) d_{1} d_{2} \vee\left(e_{2} f\right) d_{1} d_{2} \wedge \neg\left(\left(e_{1} f\right) d_{1} d_{2} \wedge\left(e_{2} f\right) d_{1} d_{2}\right) \\
& \text { emp } \left.\equiv \llbracket\left[\wedge_{A \in \mathcal{A}} \neg A \wedge \wedge_{f \in \mathcal{F}} \neg f\right]\right] \\
& \text { priority: } \wedge \text { binds strongest, then } \circledast, \text { then } \vee \\
& F \sim G \text { means } \forall e . \llbracket F \rrbracket e=\llbracket G \rrbracket e \\
& \left(F_{1} \circledast F_{2}\right) \circledast F_{3} \sim F_{1} \circledast\left(F_{2} \circledast F_{3}\right) \\
& F \circledast \text { emp } \sim \text { emp } \circledast F \sim F \\
& F_{1} \circledast F_{2} \sim F_{2} \circledast F_{1} \\
& F_{1} \circledast\left(F_{2} \vee F_{3}\right) \sim F_{1} \circledast F_{2} \vee F_{1} \circledast F_{3}
\end{aligned}
$$

Fig. 2. Semantics and Properties of Spatial Conjunction $\circledast$.

Figure 2 shows our semantics of spatial conjunction $\circledast$. To motivate our use of spatial conjunction, we first illustrate how role logic supports the description of simple properties of objects in a concise way. Indeed, one of the design goals of role logic is to have a logic-based specification language where simple properties of objects are as convenient to write as type declarations in a language like Java.

Example 1. The formula $[f \Rightarrow A$ ] is true for an object whose every $f$-fields points to an $A$ object, $[g \Rightarrow B]$ means that every $g$-field points to a $B$ object, so

$$
[f \Rightarrow A] \wedge[g \Rightarrow B]
$$

denotes the objects that has both $f$ pointing to an $A$ object and $g$ pointing to a $B$ object. Such specification is as concise as the following Java class declaration

```
class C { A f; B g; }
```

Example 1 illustrates how the presence of conjunction $\wedge$ in role logic enables combination of orthogonal properties such as constraints on distinct fields. However, not all properties naturally compose using conjunction.
Example 2. Consider a program that contains three fields, modelled as binary relations $f, g, h$. The formula $P_{f} \equiv\left(\operatorname{card}^{=1} f\right) \wedge\left(\operatorname{card}^{=0}(g \vee h)\right)$ means that the object has only one outgoing $f$-edge and no other edges. The formula $P_{g} \equiv$ $\left(\operatorname{card}^{=1} g\right) \wedge\left(\operatorname{card}^{=0}(f \vee h)\right)$ means that the object has only one outgoing $g$-edge and no other edges. If we "physically join" two records, each of which has one field, we obtain a record that has two fields, and is described by the formula

$$
P_{f g} \equiv\left(\operatorname{card}^{=1} f\right) \wedge\left(\operatorname{card}^{=1} g\right) \wedge\left(\operatorname{card}^{=0} h\right)
$$

Note that it is not the case that $P_{f g} \sim P_{f} \wedge P_{g}$. More generally, no boolean combination of $P_{f}$ and $P_{g}$ yields $P_{f g}$.
Example 2 prompts the question: is there an operation that allows joining specifications that will allow us to combine $P_{f}$ and $P_{g}$ into $P_{f g}$ ? Moreover, can we define such an operation on records viewed as arbitrary formulas in role logic?

It turns out that there is a natural way to describe the set of models of formula $P_{f g}$ in Example 2 as the result of "physically merging" the edges (relations) of the models of $P_{f}$ and models of $P_{g}$. The merging of disjoint models of formulas is the idea behind the definition of spatial conjunction $\circledast$ in Figure 2. The predicate (split $e\left[e_{1} e_{2}\right]$ ) is true iff the relations of the model (environment) $e$ can be split into $e_{1}$ and $e_{2}$ and the notation generalizes to splitting into any number of environments.

Example 3. For $P_{f}, P_{g}$, and $P_{f g}$ of Example 2, we have $P_{f g}=P_{f} \circledast P_{g}$.
Note that the operation $\circledast$ is associative and commutative. The formula emp, which asserts that all predicates are false, is the unit for $\circledast$. Moreover, $\circledast$ distributes over $\vee$.
A note on relationship with [28]. The semantics of spatial conjunction in Figure 2 match the semantics of [28], with two differences.

A small technical difference is that Figure 2 splits the edges of the model (the tuples of the relations), whereas [28] splits the domain. The difference arises because the elements of the domain in [28] are locations, whereas the elements of our models are objects. To represent a location in our view, we would use a tuple $\langle o, f\rangle$ where $o$ is an element of the domain and $f$ is a field name.

A higher-level difference is that the use of spatial logic we propose in this paper is the notation for records (Section 5), as opposed to the description of global heap properties. When used for formulas of quantifier depth one (Section 7), spatial conjunction does not even change the set of definable relations of two-variable logic with counting.

## 4 Field Complement

As a step towards record calculus in role logic, this section introduces the notion of a field complement, which makes it easier to describe records in role logic.

Example 4. Consider the formula $P_{f} \equiv\left(\operatorname{card}^{=1} f\right) \wedge\left(\operatorname{card}^{=0}(g \vee h)\right)$ from Example 2 , stating the property that an object has only one outgoing $f$-edge and no other edges. Property $P_{f}$ has little to do with $g$ or $h$, yet $g$ and $h$ explicitly occur in $P_{f}$. Moreover, we need to know the entire set of relations in the language to write $P_{f}$; if the language contains an additional field $i$, the property $P_{f}$ would become $P_{f} \equiv\left(\operatorname{card}^{=1} f\right) \wedge\left(\operatorname{card}^{=0}(g \vee h \vee i)\right)$. Note also that $\neg f$ is not the same as $g \vee h \vee i$, because $\neg f$ computes the complement of the value of the relation $f$ with respect to the universal set, whereas $g \vee h \vee i$ is the union of all relations other than $f$.

To address the notational problem illustrated in Example 4, we introduce the symbol edges, which denotes the union of all binary relations, and the notation $-f$ (field complement of $f$ ), which denotes the union of all relations other than $f$.

$$
\text { edges } \equiv \bigvee_{g} g \quad-f \equiv \bigvee_{g \neq f} g
$$

This additional notation allows us to avoid explicitly listing all fields in the language when stating properties like $P_{f}$.

Example 5. Formula $P_{f}$ from Example 4 can be written as $P_{f} \equiv\left(\operatorname{card}^{=1} f\right) \wedge$ (card ${ }^{=0}-f$ ), which mentions only $f$. Even when the language is extended with additional relations, $P_{f}$ still denotes the intended property. Similarly, to denote the property of an object that has outgoing fields given by $P_{f}$ and has no incoming fields, we use the predicate $P_{f} \wedge$ card $^{=0} \sim$ edges.

We use the notation edges and $-f$ to build the notation for records and inverse records in Section 5 below.
A note on ternary relation interpretation. It is possible to provide a notation for relations that generalizes the notation edges and $-f$. The idea of this generalization is to change the definition of the model (environment). Instead of a model that specifies a binary relation for each field, the model specifies the value of one ternary relation $H$ and a unary tag-predicate for each field name. For example, instead of the model that provides interpretations $f_{I}$ and $g_{I}$ for two binary relations $f$ and $g$, we could use the model that provides interpretation of $\llbracket H \rrbracket$, where

$$
\begin{aligned}
\llbracket H \rrbracket o_{1} o_{2} n= & \left(n=f_{0} \wedge f_{I} o_{1} o_{2}\right) \vee \\
& \left(n=g_{0} \wedge f_{I} o_{1} o_{2}\right)
\end{aligned}
$$

and the interpretation of unary tag-predicates $f$ and $g$. Here $f_{0}$ is an element of the domain that tags tuples coming from $\llbracket f \rrbracket$, whereas $g_{0}$ tags tuples coming from $\llbracket g \rrbracket$. We interpret $f$ as a predicate that is true only on the element $f_{0}$, and similarly $g$ as a predicate true only on the element $g_{0}$. We then introduce the following dereferencing shorthand:

$$
\begin{equation*}
\uparrow F \equiv\{H \wedge F\} \tag{2}
\end{equation*}
$$

The expression $\uparrow f$ now denotes the original interpretation of $f$, that is, $\llbracket \uparrow f \rrbracket=f_{I}$. Moreover, $\uparrow \neg f$ corresponds to field complement $-f$, and $\uparrow$ True corresponds to
edges. Note that the expressions of the form $\uparrow(\neg f \wedge \neg g)$ are now also available. Let $B$ be a boolean combination of unary predicates denoting fields. These unary predicates are disjoint, so transforming $B$ into disjunctive normal form and applying the property

$$
\uparrow\left(B_{1} \vee B_{2}\right)=\uparrow B_{1} \vee \uparrow B_{2}
$$

which follows from (2), allows transforming $\uparrow B$ into a boolean combination of expressions of the form $\uparrow f$ and $\uparrow g$. This means that we obtain no additional expressive power using expressions of the form $\uparrow B$ where $B$ is a boolean combination of unary predicates denoting fields, so for simplicity we do not consider such "ternary relation interpretation" further in this paper.

## 5 Records and Inverse Records

In this section we use role logic with spatial conjunction and field complement from Section 4 to introduce a notation for records. We also introduce inverse records, which are dual to records, and correspond to slot constraints in role analysis [33].

```
multifield: \(f \xrightarrow{*} A \equiv\) card \(^{=0}(-f \vee(f \wedge \neg A))\)
    field: \(f \xrightarrow{s} A \equiv \operatorname{card}^{s}(A \wedge f) \wedge f \xrightarrow{*} A\)
            \(s\) of the form \(=k, \leq k\), or \(\geq k\), for \(k \in\{0,1,2, \ldots\}\)
        \(f \rightarrow A \equiv f \xrightarrow{=1} A\)
multislot: \(A \stackrel{*}{\leftarrow} f \equiv \operatorname{card}^{=0}(\sim-f \vee(\sim f \wedge \neg A))\)
    slot: \(A \stackrel{s}{\leftarrow} f \equiv \operatorname{card}^{s}(A \wedge \sim f) \wedge A \stackrel{*}{\leftarrow} f\)
            \(s\) of the form \(=k, \leq k\), or \(\geq k\), for \(k \in\{0,1,2, \ldots\}\)
        \(A \leftarrow f \equiv A \stackrel{\bar{\leftarrow}}{\leftarrow} f\)
            \(\mathrm{fm}::=\) field \(\mid\) multifield
        closedRecord \(::=\mathrm{fm} \mid\) closedRecord \(\circledast \mathrm{fm}\)
        openRecord \(::=\) closedRecord \(\circledast\) True
            sm ::= slot \(\mid\) multislot
        closedlnvRecord \(::=\mathrm{sm} \mid\) closedInvRecord \(\circledast\) sm
        openInvRecord \(::=\) closedInvRecord \(\circledast\) True
```

Fig. 3. Record Notation

Figure 3 presents the notation for records and inverse records. A field predicate $f \rightarrow A$ is true for an object whose only outgoing edge in the graph (model) is an $f$-edge terminating at $A$. Dually, a slot predicate $A \leftarrow f$ is true for an object whose only incoming edge in the graph is an $f$-edge originating at $A$. A multifield predicate $f \xrightarrow{*} A$ is true iff the object has any number of outgoing $f$-edges terminating at $A$, and no other edges. Dually, a multislot predicate $A \stackrel{*}{\leftarrow} f$ is true iff the object has any number of incoming $f$-edges originating from $A$, and no other edges. We also allow notation $f \xrightarrow{s} A$ where $s$ is an expression of the form $=k$, $\leq k$, or $\geq k$. This notation gives a bound on the number of outgoing edges, and implies that there are no other outgoing edges. We similarly introduce $A \stackrel{s}{\leftarrow} f$. A closed record is a spatial conjunction of fields and multifields. An open record is a spatial conjunction of a closed record with True. While a closed record allows only the listed fields, an open record allows any number of additional fields. Inverse records are dual to records, and we similarly distinguish open and closed inverse records.

Example 6. To describe a closed record whose only fields are $f$ and $g$ where $f$-fields point to objects in the set $A$ and $g$-fields point to objects in the set $B$, we use the predicate $P_{1} \equiv f \rightarrow A \circledast g \rightarrow B$. The definition of $P_{1}$ lists all fields of the object. To specify an open record which certainly has fields $f$ and $g$ but may or may not have other fields, we write $P_{2} \equiv f \rightarrow A \circledast g \rightarrow B \circledast$ True. Neither $P_{1}$ nor $P_{2}$ restrict incoming references of an object. To specify that the only incoming references of an object are from the field $h$, we conjoin $P_{2}$ with the closed inverse record consisting of a single multislot True $\stackrel{*}{\leftarrow} h$, yielding the predicate $P_{3} \equiv P_{2} \wedge \operatorname{True}^{*}{ }_{\leftarrow} h$. To specify that an object has exactly one incoming reference, and that the incoming reference is from the $h$ field and originates from an object belonging to the set $C$, we use $P_{4} \equiv P_{2} \wedge C \leftarrow h$. Note that specifications $P_{3}$ and $P_{4}$ go beyond most standard type systems in their ability to specify the incoming (in addition to the outgoing) references of objects.

## 6 Role Constraints

Role constraints were introduced in $[30,31,33]$. In this section we show that role logic is a natural generalization of role constraints by giving a translation from role constraints to role logic. A logical view of role constraints is also suggested in $[35,35]$. A role is a set of objects that satisfy a conjunction of the following four kinds of constraints: field constraints, slot constraints, identities, acyclicities. In this paper we show that role logic naturally models field constraints, slot constraints, and identities. ${ }^{1}$
Roles describing complete sets of fields and slots. Figure 4 shows the translation of role constraints [33, Section 3] into role logic formulas. The simplicity of the translation is a consequence of the notation for records that we have developed in this paper.

[^1]$\mathcal{C} \llbracket$ fields $F$ ；slots $S ;$ identities $I ;$ acyclic $A \rrbracket=\mathcal{C} \llbracket$ fields $F \rrbracket \wedge \mathcal{C} \llbracket$ slots $S \rrbracket \wedge$【identities $I$ 】 $\wedge$ acyclic $A \rrbracket$
\[

$$
\begin{aligned}
\mathcal{C} \llbracket \text { fields } f_{1}: S_{1}, \ldots, f_{n}: S_{n} \rrbracket & =f_{1} \rightarrow S_{1} \circledast \ldots \circledast f_{n} \rightarrow S_{n} \\
\mathcal{C} \llbracket \text { slots } S_{1} \cdot f_{1}, \ldots, S_{n} \cdot f_{n} \rrbracket & =S_{1} \leftarrow f_{1} \circledast \ldots \circledast S_{n} \leftarrow f_{n} \\
\llbracket \text { identities } f_{1} \cdot g_{1}, \ldots, f_{n} \cdot g_{n} \rrbracket & =\bigwedge_{i=1}^{n}\left[f_{i} \Rightarrow \sim g_{i}\right] \\
\llbracket \operatorname{acyclic} f_{1}, \ldots, f_{n} \rrbracket & =\operatorname{acyclic}\left(\bigvee_{i=1}^{n} f_{i}\right)
\end{aligned}
$$
\]

Fig．4．Translation of Role Constraints［33］into Role Logic Formulas
$\mathcal{O} \llbracket$ fields $F$ ；slots $S$ ；identities $I$ ；acyclic $A \rrbracket=\mathcal{O} \llbracket$ fields $F \rrbracket \wedge \mathcal{O} \llbracket$ slots $S \rrbracket \wedge$
【identities $I \rrbracket \wedge \llbracket$ acyclic $A \rrbracket$
$\mathcal{O} \llbracket$ fields $f_{1}: S_{1}, \ldots, f_{n}: S_{n} \rrbracket=\mathcal{C} \llbracket$ fields $f_{1}: S_{1}, \ldots, f_{n}: S_{n} \rrbracket \circledast \operatorname{card}^{=0}\left(\bigvee_{i=1}^{n} f_{i}\right)$
$\mathcal{O} \llbracket g_{1}, \ldots, g_{m}$ slots $S_{1} . f_{1}, \ldots, S_{n} . f_{n} \rrbracket=\mathcal{C} \llbracket$ slots $S_{1} . f_{1}, \ldots, S_{n} . f_{n} \rrbracket \circledast \operatorname{card}^{=0}\left(\bigvee_{i=1}^{m} \sim g_{i}\right)$

Fig．5．Translation of Simultaneous Role Constraints［33，Section 7．2］into Role Logic Formulas．See also Figure 4.

Simultaneous Roles．In object－oriented programs，objects may participate in multiple data structures．The idea of simultaneous roles［33，Section 7．2］is to associate one role for the participation of an object in one data structure． When the object participates in multiple data structures，the object plays mul－ tiple roles．Role logic naturally models simultaneous roles：each role is a unary predicate，and if an object satisfies multiple roles，the the object satisfies the conjunction of predicates．Figure 5 presents the translation of field and slot con－ straints of simultaneous roles into role logic．Whereas the roles of［33，Section 3］translate to closed records and closed inverse records，the simultaneous roles of［33，Section 7．2］translate specifications that are closer to open records and open inverse records．

## 7 Eliminating Spatial Conjunction in $\mathrm{RL}^{2}$

Preserving the decidability．Previous sections have demonstrated the use－ fulness of adding record concatenation in the form of spatial conjunction to our notation for generalized records．However，a key question remains：is the result－ ing extended notation decidable？In this section we give an affirmative answer to this question by showing how to compute the spatial conjunction using the remaining logical operations for a large class of record specifications．

Approach. Consider two formulas $F_{1}$ and $F_{2}$ in first-order logic with counting, where both $F_{1}$ and $F_{2}$ have quantifier depth one. An equivalent way of stating the condition on $F_{1}$ and $F_{2}$ is that there are no nested occurrences of quantifiers. (Note that we count one application of $\exists^{\geq k} x$. $P$ as one quantifier, regardless of the value $k$.) We show that, under these conditions, the spatial conjunction $F_{1} \circledast F_{2}$ can be written as an equivalent formula $F_{3}$ where $F_{3}$ does not contain the spatial conjunction operation $\circledast$. The proof proceeds by writing formulas $F_{1}$, $F_{2}$ in a normal form, as a disjunction of counting stars [22], and showing that the spatial conjunction of counting stars is equivalent to a disjunction of counting stars.

As a consequence of the results in this section, adding the operation $\circledast$ to logic with counting does not change its expressive power provided that both $F_{1}$ and $F_{2}$ have quantifier depth at most one. Here we allow $F_{1}$ and $F_{2}$ themselves to contain spatial conjunction, because we may eliminate spatial conjunction in $F_{1}$ and $F_{2}$ recursively. Applying these results to two-variable logic with counting $C^{2}$, we conclude that introducing into $C^{2}$ the spatial conjunction of formulas of quantifier depth one preserves the decidability of $C^{2}$. Furthermore, thanks to the translations between $C^{2}$ and $\mathrm{RL}^{2}$ in [36], if we allow the spatial conjunction of $\mathrm{RL}^{2}$ formulas with no nested card occurrences, we preserve the decidability of the logic $\mathrm{RL}^{2}$. The formulas of the resulting logic are given by

$$
\begin{aligned}
F::= & A|f| \mathrm{EQ}\left|F_{1} \wedge F_{2}\right| \neg F\left|F^{\prime}\right| \sim F \mid \operatorname{card}^{\geq k} F \\
& \mid F_{1} \circledast F_{2}, \text { if } F_{1} \text { and } F_{2} \text { have no nested card occurrences }
\end{aligned}
$$

Note that record specifications in Figure 3 contain no nested card occurrences, so joining them using $\circledast$ yields formulas in the decidable fragment. Hence, in addition to quantifiers and boolean operations, the resulting logic supports a generalization of record concatenation, and is still decidable; this decidability property is what we show in the sequel. We present the sketch of the proof, see Appendix for proof details..

### 7.1 Atomic Type Formulas

In this section we introduce classes of formulas that correspond to the modeltheoretic notion of atomic type [44, Page 20] (see [25, Page 42] and [12, Page 78] for the notion of type in general). We then introduce formulas that describe the notion of counting stars $[22,45]$. We conclude this section with Proposition 12, which gives the normal form for formulas of quantifier depth one.

If $\mathcal{C}=C_{1}, \ldots, C_{m}$ is a finite set of formulas, then a cube over $\mathcal{C}$ is a conjunction of the form $C_{1}^{\alpha_{1}} \wedge \ldots C_{m}^{\alpha_{m}}$ where $\alpha_{i} \in\{0,1\}, C^{1}=C$ and $C^{0}=\neg C$. For simplicity, fix a finite language $L=\mathcal{A} \cup \mathcal{F}$ with $\mathcal{A}$ a finite set of unary predicate symbols and $\mathcal{F}$ a finite set of binary predicate symbols. We work in predicate calculus with equality, and assume that the equality " $=$ ", where $=\notin \mathcal{F}$, is present as a binary relation symbol, unless explicitly stated otherwise. We use $D$ to denote a finite domain of interpretation and $e$ to denote a model with variable assignment; $e$ maps $\mathcal{A}$ to $2^{D}$, maps $\mathcal{F}$ to $2^{D \times D}$ and maps variables to elements of $D$. Let $x_{1}, \ldots, x_{n}$ be a finite list of distinct variables. Let $\mathcal{C}$ be the set of all
atomic formulas $F$ such that $\mathrm{FV}(F) \subseteq\left\{x_{1}, \ldots, x_{n}\right\}$. The set $\mathcal{C}$ is finite (in our case it has $|\mathcal{A}| n+(|\mathcal{F}|+1) n^{2}$ elements). We call a cube over $\mathcal{C}$ a complete atomic type (CAT) formula.
Example 7. If $\mathcal{A}=\{A\}$ and $\mathcal{F}=\{f\}$, then

$$
\begin{aligned}
& A\left(x_{1}\right) \wedge \neg A\left(x_{2}\right) \wedge \\
& \neg f\left(x_{1}, x_{1}\right) \wedge \neg f\left(x_{2}, x_{2}\right) \wedge f\left(x_{1}, x_{2}\right) \wedge \neg f\left(x_{2}, x_{1}\right) \wedge \\
& x_{1}=x_{1} \wedge x_{2}=x_{2} \wedge x_{1} \neq x_{2} \wedge x_{2} \neq x_{1}
\end{aligned}
$$

is a CAT formula.
We may treat conjunction of literals as the set of literals, so we say that "a literal belongs to the conjunction" and apply set-theoretic operations on conjunctions of literals.

From the disjunctive normal form theorem for propositional logic, we obtain the following Proposition 8.

Proposition 8. Every quantifier-free formula $F$ such that $\mathrm{FV}(F) \subseteq$ $\left\{x_{1}, \ldots, x_{n}\right\}$ is equivalent to a disjunction of CAT formulas $C$ such that $\mathrm{FV}(C)=$ $\left\{x_{1}, \ldots, x_{n}\right\}$.

A CAT formula may be contradictory if, for example, it contains the literal $x_{i} \neq x_{i}$ as a conjunct. We next define classes of CAT formulas that are satisfiable in the presence of equality. Let $x_{1}, \ldots, x_{n}$ be distinct variables. A general-case $C A T$ (GCCAT) formula is a CAT formula $F$ such that the following two conditions hold: 1) $\mathrm{FV}(F)=\left\{x_{1}, \ldots, x_{n}\right\}$; 2) for all $1 \leq i, j \leq n$, the conjunct $x_{i}=x_{j}$ is in $F$ iff $i \equiv j$. Let $x_{1}, \ldots, x_{n}$ and $y_{1}, \ldots, y_{m}$ be distinct variables. An equality $C A T(E Q C A T)$ formula is a formula of the form $\bigwedge_{j=1}^{m} y_{j}=x_{i_{j}} \wedge F$, where $1 \leq i_{1}, \ldots, i_{m} \leq n$ and $F$ is a GCCAT formula such that $\mathrm{FV}(F)=\left\{x_{1}, \ldots, x_{n}\right\}$.

Lemma 9. Every CAT formula $F$ is either contradictory, or is equivalent to an $E Q C A T$ formula $F^{\prime}$ such that $\mathrm{FV}\left(F^{\prime}\right)=\mathrm{FV}(F)$.

From Proposition 8 and Lemma 9, we obtain the following Proposition 10.
Proposition 10. Every quantifier-free formula $F$ such that $\mathrm{FV}(F) \subseteq$ $\left\{x_{1}, \ldots, x_{n}\right\}$ can be written as a disjunction of EQCAT formulas $C$ such that $\mathrm{FV}(C)=\left\{x_{1}, \ldots, x_{n}\right\}$.

We next introduce the notion of an extension of a GCCAT formula. Let $x, x_{1}, \ldots, x_{n}$ be distinct variables and $F$ be a GCCAT formula such that $\mathrm{FV}(F)=\left\{x_{1}, \ldots, x_{n}\right\}$. We say that $F^{\prime}$ is an $x$-extension of $F$, and write $F^{\prime} \in \operatorname{exts}(F, x)$ iff all of the following conditions hold: 1) $F \wedge F^{\prime}$ is a GCCAT formula; 2) $\left.\mathrm{FV}\left(F \wedge F^{\prime}\right)=\left\{x, x_{1}, \ldots, x_{n}\right\} ; 3\right) F$ and $F^{\prime}$ have no common atomic formulas. Note that if $\mathrm{FV}\left(F_{1}\right)=\mathrm{FV}\left(F_{2}\right)$, then $\operatorname{exts}\left(F_{1}, x\right)=\operatorname{exts}\left(F_{2}, x\right)$ i.e. the set of extensions of a GCCAT formula depends only on the free variables of the formula; we introduce additional notation $\operatorname{exts}\left(x_{1}, \ldots, x_{n}, x\right)$ to denote exts $(F, x)$ for $\operatorname{FV}(F)=\left\{x_{1}, \ldots, x_{n}\right\}$.

To define a normal form for formulas of quantifier depth one, we introduce the notion of $k$-counting star. If $p \geq 2$ is a non-negative integer, let $p^{+}$be a new symbol which represents the co-finite set of integers $\{p, p+1, \ldots\}$. Let $C_{p}=\left\{0,1, \ldots, p-1, p^{+}\right\}$. If $c \in C_{p}$, by $\exists^{i} x$. $P$ we mean $\exists^{=i} x$. $P$ if $i$ is an integer, and $\exists^{\geq p} x$. P if $i=p^{+}$. We say that a formula $F$ has a counting degree of at most $p$ iff the only counting quantifiers in $F$ are of the form $\exists^{c} x . G$ for some $c \in C_{p+1}$.
Definition 11 (Counting Star Formula). Let $x, x_{1}, \ldots, x_{n}$, and $y_{1}, \ldots, y_{m}$ be distinct variables, $k \geq 1$ a positive integer, and $F$ a GCCAT formula such that $\mathrm{FV}(F)=\left\{x_{1}, \ldots, x_{n}\right\}$. A $k$-counting star function for $F$ is a function $\gamma$ : $\operatorname{exts}(F, x) \rightarrow C_{k+1}$. A $k$-counting-star formula for $\gamma$ is a formula of the form

$$
\bigwedge_{j=1}^{m} y_{j}=x_{i_{j}} \wedge F \wedge \bigwedge_{F^{\prime} \in \operatorname{exts}(F, x)} \exists^{\gamma\left(F^{\prime}\right)} x \cdot F^{\prime}
$$

where $1 \leq i_{1}, \ldots, i_{m} \leq n$.
Note that in Definition 11, formula $\bigwedge_{j=1}^{m} y_{j}=x_{i_{j}} \wedge F$ is an EQCAT formula, and formula $\bigwedge_{j=1}^{m} y_{j}=x_{i_{j}} \wedge F \wedge F^{\prime}$ is an EQCAT formula for each $F^{\prime} \in \operatorname{exts}(F, x)$.

The following Proposition 12 shows that formulas of quantifier depth at most one are equivalent to disjunctions of counting stars.

Proposition 12 (Depth-One Normal Form). Let $F$ be a formula of such that $F$ has quantifier depth at most one, $F$ has counting degree at most $k$, and $\mathrm{FV}(F) \subseteq\left\{x_{1}, \ldots, x_{n}\right\}$. Then $F$ is equivalent to a disjunction of $k$-counting-star formulas $F_{C}$ where $\mathrm{FV}\left(F_{C}\right)=\left\{x_{1}, \ldots, x_{n}\right\}$.

### 7.2 Spatial Conjunction of Stars

Sketch of the construction. Let $F_{1}$ and $F_{2}$ be two formulas of quantifier depth at most one, and not containing the logical operation $\circledast$. By Proposition 12, let $F_{1}$ be equivalent to the disjunction of counting star formulas $\bigvee_{i=1}^{n_{1}} C_{1, i}$ and let $F_{2}$ be equivalent to the disjunction of counting star formulas $\bigvee_{j=1}^{n_{2}} C_{2, j}$. By distributivity of law of $\circledast$ with respect to $\vee$, we have

$$
F_{1} \circledast F_{2} \sim\left(\bigvee_{i=1}^{n_{1}} C_{1, i}\right) \circledast\left(\bigvee_{j=1}^{n_{2}} C_{2, j}\right) \sim \bigvee_{i=1}^{n_{1}} \bigvee_{j=1}^{n_{2}} C_{1, i} \circledast C_{2, j}
$$

In the sequel we show that a spatial conjunction of counting-star formulas is either contradictory or is equivalent to a disjunction of counting star formulas. This suffices to eliminate spatial conjunction of formulas of quantifier depth at most one. Moreover, if $F$ is any formula of quantifier depth at most one, possibly containing $\circledast$, by repeated elimination of the innermost $\circledast$ we obtain a formula without $\circledast$.

To compute the spatial conjunction of counting stars we establish an alternative syntactic form for counting star formulas. The idea of this alternative form is roughly to replace a counting quantifier such as $\exists^{=k} x . F^{\prime}$ with a spatial conjunction of $k$ formulas each of which has the meaning similar to $\exists^{=1} x . F^{\prime}$, and
then combine a formula $\exists^{=1} x . F_{1}^{\prime}$ resulting from one counting star with a formula $\exists^{=1} x . F_{2}^{\prime}$ resulting from another counting star into the formula $\exists^{=1} x .\left(F_{1}^{\prime} \odot F_{2}^{\prime}\right)$ where $\odot$ denotes merging of GCCAT formulas by taking the union of their positive literals. We next develop this idea in greater detail.
Notation for spatial representation of stars. Let $G_{E}\left(x_{1}, \ldots, x_{n}\right)$ be the unique GCCAT formula $F$ with $\mathrm{FV}(F)=\left\{x_{1}, \ldots, x_{n}\right\}$ such that the only positive literals in $F$ are literals $x_{i}=x_{i}$ for $1 \leq i \leq n$. Similarly, there is a unique formula $F^{\prime} \in \operatorname{exts}\left(x_{1}, \ldots, x_{n}, x\right)$ such that every atomic formula in $F^{\prime}$ distinct from for $x=x$ occurs in a negated literal. We call $F^{\prime}$ an empty extension and denote it $\operatorname{empEx}\left(x_{1}, \ldots, x_{n}, x\right)$.

To compute a spatial conjunction of formulas $C_{1}$ and $C_{2}$ in the language $L$, we temporarily consider formulas in an extended language $L^{\prime}=L \cup\left\{B_{1}, B_{2}\right\}$ where $B_{1}$ and $B_{2}$ are two new unary predicates used to mark formulas. We use $B_{1}$ to mark formulas derived from $C_{1}$, and use $B_{2}$ to mark formulas derived from $C_{2}$. For $m \in\{\emptyset,\{1\},\{2\},\{1,2\}\}$, define

$$
\begin{array}{ll}
\operatorname{Mark}_{\emptyset}(x)=\neg B_{1}(x) \wedge \neg B_{2}(x) & \operatorname{Mark}_{1}(x)=B_{1}(x) \wedge \neg B_{2}(x) \\
\operatorname{Mark}_{2}(x)=\neg B_{1}(x) \wedge B_{2}(x) & \text { Mark }_{1,2}(x)=B_{1}(x) \wedge B_{2}(x)
\end{array}
$$

Note that, when we say that $F$ is a GCCAT formula, we mean that $F$ is GCCAT formula in language $L$ (and thus $F$ mentions symbols only from $L$ ), even when we use $F$ as a subformula of a larger formula in language $L^{\prime}$. Similarly, expressions exts $\left(x_{1}, \ldots, x_{n}, x\right)$, empEx $(F, x)$, and $G_{E}\left(x_{1}, \ldots, x_{n}\right)$ all denote formulas in language $L$.

On the other hand, $\operatorname{empEx}_{\emptyset}(F, x)$ and empe are formulas in language $L^{\prime}$. Formula empEx ${ }_{\emptyset}(F, x)$ is an empty extension of $F$ in language $L^{\prime}$. Formula empe asserts that $x_{1}, \ldots, x_{n}$ have an empty GCCAT formula and that the remaining elements have empty extension in $L^{\prime}$. Formula empe does not constrain the values $B_{1}\left(x_{i}\right)$ and $B_{2}\left(x_{i}\right)$, these values turn out to be irrelevant.
Let $F^{\prime} \in \operatorname{exts}\left(x_{1}, \ldots, x_{n}, x\right)$. Define

$$
\begin{aligned}
& \operatorname{empEx}_{\emptyset}\left(x_{1}, \ldots, x_{n}, x\right) \equiv \operatorname{empEx}\left(x_{1}, \ldots, x_{n}, x\right) \wedge \operatorname{Mark}_{\emptyset}(x) \\
& \operatorname{empe}\left(x_{1}, \ldots, x_{n}\right) \equiv G_{E}\left(x_{1}, \ldots, x_{n}\right) \wedge \forall x .\left(\bigwedge_{i=1}^{n} x \neq x_{i}\right) \Rightarrow \operatorname{empEx}_{\emptyset}\left(x_{1}, \ldots, x_{n}, x\right)
\end{aligned}
$$

We write $\operatorname{empEx}_{\emptyset}(F, x)$ for $\operatorname{empEx}_{\emptyset}\left(x_{1}, \ldots, x_{n}, x\right)$ if $\operatorname{FV}(F)=\left\{x_{1}, \ldots, x_{n}\right\}$, and similarly for empe $(F, x)$. We write simply empe if $F$ and $x$ are understood.

We next introduce formulas $\left(F^{\prime}\right)_{m}^{*}$ and $\left(F^{\prime}\right)_{m}$, which are the building blocks for representing counting star formulas. Formula $\left(F^{\prime}\right)_{m}^{*}$ means that $F^{\prime}$ marked with $m$ and empEx $\mathrm{en}_{\emptyset}(F, x)$ are the only extensions of $F$ that hold in the neighborhood of $x_{1}, \ldots, x_{n}$ ( $F^{\prime}$ may hold for any number of neighbors). Formula $\left(F^{\prime}\right)_{m}$ means that $F^{\prime}$ holds for exactly one element in the neighborhood of $x_{1}, \ldots, x_{n}$, and all other neighbors have empty extensions. More precisely, let $F^{\prime} \in \operatorname{exts}\left(x_{1}, \ldots, x_{n}, x\right)$. Define

$$
\begin{aligned}
& \left(F^{\prime}\right)_{m}^{*} \equiv G_{E}\left(x_{1}, \ldots, x_{n}\right) \wedge \forall x .\left(\bigwedge_{i=1}^{n} x \neq x_{i}\right) \Rightarrow\left(F^{\prime} \wedge \operatorname{Mark}_{m}(x)\right) \vee \operatorname{empEx}_{\emptyset}(F, x) \\
& \left(F^{\prime}\right)_{m} \equiv\left(F^{\prime} D_{m}^{*} \wedge \exists^{=1} x . \quad \bigwedge_{i=1}^{n} x \neq x_{i} \wedge F^{\prime} \wedge \operatorname{Mark}_{m}(x)\right.
\end{aligned}
$$

where $m \in\{\emptyset,\{1\},\{2\},\{1,2\}\}$. Observe that $G \circledast$ empe $\sim G$ if $G \equiv\left(F^{\prime}\right)_{m}^{*}$ or $G \equiv\left(F^{\prime}\right)_{m}$ for some $F^{\prime}$ and $m$. Also note that $\left(F^{\prime}\right)_{m}^{*} \circledast\left(F^{\prime}\right)_{m}^{*} \sim\left(F^{\prime}\right)_{m}^{*}$.

$$
\begin{aligned}
& E \wedge F-\text { EQCAT formula } \\
& F \quad-\mathrm{GCCAT} \text { formula } \\
& \mathcal{S}_{m} \llbracket E \wedge F \wedge \exists^{s_{1}} x . F_{1}^{\prime} \wedge \ldots \wedge \exists^{s_{k}} x . F_{k}^{\prime} \rrbracket= \\
& =E \wedge \mathcal{K} \llbracket F \rrbracket \circledast \mathcal{X}_{m} \llbracket \exists^{s_{1}} x . F_{1}^{\prime} \rrbracket \circledast \ldots \circledast \mathcal{X}_{m} \llbracket \exists^{s_{k}} x . F_{k}^{\prime} \rrbracket \\
& \mathcal{K} \llbracket F \rrbracket=F \wedge\left(\forall x .\left(\bigwedge_{i=1}^{n} x \neq x_{i}\right) \Rightarrow \operatorname{empEx}_{\emptyset}(F, x)\right) \\
& \mathcal{X}_{m} \llbracket \exists^{0} x . F^{\prime} \rrbracket=\text { empe } \\
& \mathcal{X}_{m} \llbracket \exists^{i+1} x . F^{\prime} \rrbracket=\left(F^{\prime} \rrbracket_{m} \circledast \mathcal{X}_{m} \llbracket \exists^{i} x . F^{\prime} \rrbracket\right. \\
& \mathcal{X}_{m} \llbracket \exists^{i^{+}} x . F^{\prime} \rrbracket=\mathcal{X}_{m} \llbracket \exists^{i} x . F^{\prime} \rrbracket \circledast\left(F^{\prime}\right)_{m}^{*}
\end{aligned}
$$

Fig. 6. Translation of Counting Stars to Spatial Notation

Translation of counting stars. Figure 6 presents the translation of counting stars to spatial notation. The idea of the translation is to replace $\exists^{=k} x$. $F^{\prime}$ with the spatial conjunction of $k$ formulas $\left(F^{\prime}\right)_{m} \circledast \ldots \circledast\left(F^{\prime}\right)_{m}$ where $m \in\{\{1\},\{2\}\}$. The purpose of the marker $m$ is to ensure that each of the $k$ witnesses for $x$ that are guaranteed to exist by $\left(F^{\prime}\right)_{m} \circledast \ldots \circledast\left(F^{\prime}\right)_{m}$ are distinct. The reason that the witnesses are distinct for $m \neq \emptyset$ is that no two of them can satisfy $B_{i}(x)$ at the same time for $i \in m$.

To show the correctness of the translation in Figure 6, define $e^{m}$ to be the $L^{\prime}$-environment obtained by extending $L$-environment $e$ according to marking $m$, and $\overline{e_{1}}$ to be the restriction of an $L^{\prime}$ environment $e_{1}$ to language $L$. More precisely, if $e$ is an environment in language $L$, for $m \in\{\emptyset,\{1\},\{2\},\{1,2\}\}$, define environment $e^{m}$ in language $L^{\prime}$ by 1) $e^{m} r=e r$ for $r \in L$ and 2) for $q \in\{1,2\}$, let $\left(e B_{q}\right) d=$ True $\Longleftrightarrow q \in m \wedge d \notin\left\{e x_{1}, \ldots, e x_{n}\right\}$. Conversely, if $e_{1}$ is an environment in language $L^{\prime}$, define environment $\overline{e_{1}}$ in language $L$ by $\overline{e_{1}} r=e_{1} r$ for all $r \in L$. Lemma 13 below gives the correctness criterion for translation in Figure 6.

Lemma 13. If $e$ is an environment for language $L, C$ a counting star formula in language $L$, and $m \in\{\{1\},\{2\},\{1,2\}\}$, then $\llbracket C \rrbracket e=\mathcal{S}_{m} \llbracket C \rrbracket e^{m}$.
(1) $\left(T_{1}\right)_{1} \circledast\left(T_{2}\right)_{2} \sim\left(T_{1} \odot T_{2}\right)_{1,2}$
(2) $\left(T_{1}\right)_{1} \circledast\left(T_{2}\right)_{2}^{*} \sim\left(T_{1} \odot T_{2}\right)_{1,2} \circledast\left(T_{2}\right)_{2}^{*}$
(3) $\left(T_{1}\right)_{1}^{*} \circledast\left(T_{2}\right)_{2} \leadsto\left(T_{1}\right)_{1}^{*} \circledast\left(T_{1} \odot T_{2}\right)_{1,2}$
(4) $\left(T_{1}\right)_{1}^{*} \circledast\left(T_{2}\right)_{2}^{*} \sim\left(T_{1}\right)_{1}^{*} \circledast\left(T_{2}\right)_{2}^{*} \circledast\left(T_{1} \odot T_{2}\right)_{1,2}^{*}$
(5) $\langle T\rangle_{1}^{*} \leadsto$ empe
(6) $(T T\rangle_{2}^{*} \sim$ empe

Fig. 7. Transformation Rules for Combining Spatial Conjuncts

Combining quantifier-free formulas. Let $C_{1} \circledast C_{2}$ be a spatial conjunction of two counting-star formulas

$$
\begin{aligned}
& C_{1} \equiv E \wedge F_{1} \wedge \exists^{s_{1,1}} x \cdot F_{1,1}^{\prime} \wedge \ldots \wedge \exists^{s_{1, k}} x \cdot F_{1, k}^{\prime} \\
& C_{2} \equiv E \wedge F_{2} \wedge \exists^{s_{2,1}} x \cdot F_{2,1}^{\prime} \wedge \ldots \wedge \exists^{s_{2, k}} x \cdot F_{2, l}^{\prime}
\end{aligned}
$$

where $F_{1}$ and $F_{2}$ are GCCAT formulas with $\mathrm{FV}\left(F_{1}\right)=\mathrm{FV}\left(F_{2}\right)=\left\{x_{1}, \ldots, x_{n}\right\}$, $E \wedge F_{1}$ and $E \wedge F_{2}$ are EQCAT formulas, and $E \equiv \bigwedge_{j=1}^{m} y_{j}=x_{i_{j}}$.

Note that we assume that the two GCCAT formulas $F_{1}$ and $F_{2}$ have same free variables and that the equalities $E$ in the two EQCAT formulas are the same. This assumption is justified because either 1) $C_{1} \circledast C_{2}$ make inconsistent assumptions about equalities among $x_{1}, \ldots, x_{n}$, and therefore $C_{1} \circledast C_{2}$ is equivalent to False, or 2) $C_{1} \circledast C_{2}$ make same assumptions about equalities among $x_{1}, \ldots, x_{n}$, so we can rewrite $C_{1}$ and $C_{2}$ to satisfy the our assumption by exchanging variables $x_{i}$ and $y_{j}$ in the definition of an EQCAT formula.

To show how to transform formula $\mathcal{S}_{1} \llbracket C_{1} \rrbracket \circledast \mathcal{S}_{2} \llbracket C_{2} \rrbracket$ into a disjunction of formulas of the form $\mathcal{S}_{1,2} \llbracket C_{3} \rrbracket$, we introduce the following notation. If $T$ is a formula, let $S(T)$ denote the set of positive literals in $T_{1}$ that do not contain equality. Let $T_{1} \in \operatorname{exts}\left(F_{1}, x\right)$ and $T_{2} \in \operatorname{exts}\left(F_{2}, x\right)$. (Note that exts $\left(F_{1}, x\right)=$ exts $\left(F_{2}, x\right)$.) We define the partial operation $T_{1} \odot T_{2}$ as follows. The result of $T_{1} \odot T_{2}$ is defined iff $S\left(T_{1}\right) \cap S\left(T_{2}\right)=\emptyset$. If $S\left(T_{1}\right) \cap S\left(T_{2}\right)=\emptyset$, then $T_{1} \odot T_{2}=T$ where $T$ is the unique element of exts $\left(F_{1}, x\right)$ such that $S(T)=S\left(T_{1}\right) \cup S\left(T_{2}\right)$. Similarly to $\odot$, we define the partial operation $F_{1} \oplus F_{2}$ for $F_{1}$ and $F_{2}$ GCCAT formulas with $\mathrm{FV}\left(F_{1}\right)=\mathrm{FV}\left(F_{2}\right)=\left\{x_{1}, \ldots, x_{n}\right\}$. The result of $F_{1} \oplus F_{2}$ is defined iff $S\left(F_{1}\right) \cap S\left(F_{2}\right)=\emptyset$. If $S\left(F_{1}\right) \cap S\left(F_{2}\right)=\emptyset$, then $F_{1} \oplus F_{2}$ is the unique GCCAT formula $F$ such that $\mathrm{FV}(F)=\left\{x_{1}, \ldots, x_{n}\right\}$ and $S(F)=S\left(F_{1}\right) \cup S\left(F_{2}\right)$. The following Lemma 14 notes that $\odot$ and $\oplus$ are sound rules for computing spatial conjunction of certain quantifier-free formulas.

Lemma 14. If $T_{1}, T_{2} \in \operatorname{exts}\left(x_{1}, \ldots, x_{n}, x\right)$ then $T_{1} \circledast T_{2} \sim T_{1} \odot T_{2}$. If $F_{1}$ and $F_{2}$ are $G C C A T$ formulas with $\mathrm{FV}\left(F_{1}\right)=\mathrm{FV}\left(F_{2}\right)=\left\{x_{1}, \ldots, x_{n}\right\}$, then $F_{1} \circledast F_{2} \sim$ $F_{1} \oplus F_{2}$.

Rules for transforming spatial conjuncts. We transform formula $\mathcal{S}_{1} \llbracket C_{1} \rrbracket \circledast \mathcal{S}_{2} \llbracket C_{2} \rrbracket$ into a disjunction of formulas of the form $\mathcal{S}_{1,2} \llbracket C_{3} \rrbracket$ as follows.

The first step in transforming $C_{1} \circledast C_{2}$ is to replace $\mathcal{K} \llbracket F_{1} \rrbracket \circledast \mathcal{K} \llbracket F_{2} \rrbracket$ with $\mathcal{K} \llbracket F_{1} \oplus F_{2} \rrbracket$ if $F_{1} \oplus F_{2}$ is defined, or False if $F_{1} \oplus F_{2}$ is not defined.

The second step is summarized in Figure 7, which presents rules for combining conjuncts resulting from $\mathcal{X}_{1} \llbracket \exists^{s_{1}} . F_{1} \rrbracket$ and $\mathcal{X}_{2} \llbracket \exists^{s_{2}} x . F_{2} \rrbracket$ into conjuncts of the form $\mathcal{X}_{1,2} \llbracket \exists^{s} x . F \rrbracket$. The intuition is that $\left(T D_{m}^{*}\right.$ and $\left\langle T D_{m}\right.$ represent a finite abstraction of all possible neighborhoods of $x_{1}, \ldots, x_{n}$, and the rules in Figure 7 represent the ways in which different portions of the neighborhoods combine using spatial conjunction. We apply the rules in Figure 7 modulo commutativity and associativity of $\circledast$, the fact that emp is a unit for $\circledast$, as well as the idempotence of $(T)_{m}^{*}$. Rules (1)-(4) are applicable only when the occurrence of $T_{1} \odot T_{2}$ on the right-hand side of the rule is defined. We apply rules $(1)-(4)$ as long as possible, and then apply rules (5), (6). Moreover, we only allow the sequences of
rule applications that eliminate all occurrences of $(T)_{1},(T\rangle_{1}^{*},\langle T)_{2},\langle T\rangle_{2}^{*}$, leaving only $\left(T D_{1,2}\right.$ and $\left(T D_{1,2}^{*}\right.$. Note also that the are only finitely many non-equivalent expressions that can be obtained by sequences of applications of rules in Figure 7. Namely, an application of rules (1)-(3) decreases the total number of spatial conjuncts of the form $(T)_{1}$ and $(T)_{2}$, multiple applications of rule (4) to the same pair of spatial conjuncts are unnecessary because of the idempotence of $\left(T_{1} \odot T_{2}\right)_{1,2}^{*}$ (so we never perform them), and rules (5), (6) reduce the total number of spatial conjuncts. The following Lemma 15 gives partial correctness of rules in Figure 7.

Lemma 15. If $G_{1} \sim G_{2}$, then $G_{2} \Rightarrow G_{1}$ is valid.
Define $G_{1} \stackrel{C}{\Longrightarrow} G_{2}$ to hold iff both of the following two conditions hold: 1) $G_{2}$ results from $G_{1}$ by replacing $\mathcal{K} \llbracket F_{1} \rrbracket \circledast \mathcal{K} \llbracket F_{2} \rrbracket$ with $\mathcal{K} \llbracket F_{1} \oplus F_{2} \rrbracket$ if $F_{1} \oplus F_{2}$ is defined, or False if $F_{1} \oplus F_{2}$ is not defined, and then applying some sequence of rules in Figure 7 such that rules (5), (6) are applied only when rules (1)-(4) are not applicable; 2) $G_{2}$ contains only spatial conjuncts of the form $\left(T D_{1,2}\right.$ and $\left\langle T D_{1,2}^{*}\right.$. From Lemma 15 and Lemma 14 we immediately obtain Lemma 16.

Lemma 16. If $G_{1} \xrightarrow{C} G_{2}$, then $G_{2} \Rightarrow G_{1}$ is valid.
The rule for computing the spatial conjunction of counting star formulas is the following. If $C_{1}, C_{2}$, and $C_{3}$ are counting star formulas, define $\mathcal{R}\left(C_{1}, C_{2}, C_{3}\right)$ to hold iff $\mathcal{S}_{1} \llbracket C_{1} \rrbracket \circledast \mathcal{S}_{2} \llbracket C_{2} \rrbracket \stackrel{C}{\Longrightarrow} \mathcal{S}_{1,2} \llbracket C_{3} \rrbracket$. We compute spatial conjunction by replacing $C_{1} \circledast C_{2}$ with $\bigvee_{\mathcal{R}\left(C_{1}, C_{2}, C_{3}\right)} C_{3}$. Our goal is therefore to show the equivalence

$$
\begin{equation*}
C_{1} \circledast C_{2} \sim \bigvee_{\mathcal{R}\left(C_{1}, C_{2}, C_{3}\right)} C_{3} \tag{3}
\end{equation*}
$$

The validity of $\bigvee_{\mathcal{R}\left(C_{1}, C_{2}, C_{3}\right)} C_{3} \Rightarrow\left(C_{1} \circledast C_{2}\right)$ follows from Lemma 16 and Lemma 13.

Lemma 17. $\left(\bigvee_{\mathcal{R}\left(C_{1}, C_{2}, C_{3}\right)} C_{3}\right) \Rightarrow\left(C_{1} \circledast C_{2}\right)$ is a valid formula for every pair of counting star formulas $C_{1}$ and $C_{2}$.
We next consider the converse claim. If $\llbracket C_{1} \circledast C_{2} \rrbracket e$, then there are $e_{1}$ and $e_{2}$ such that split $e e_{1} e_{2}, \llbracket C_{1} \rrbracket e_{1}$, and $\llbracket C_{2} \rrbracket e_{2}$. By considering the atomic types induced in $e, e_{1}$ and $e_{2}$ by elements in $D \backslash\left\{e x_{1}, \ldots, e x_{n}\right\}$, we construct a sequence of $\sim$ transformations in Figure 7 that convert $\mathcal{S}_{1} \llbracket C_{1} \rrbracket \circledast \mathcal{S}_{2} \llbracket C_{2} \rrbracket$ into a formula $\mathcal{S}_{1,2} \llbracket C_{3} \rrbracket$ such that $\llbracket C_{3} \rrbracket e=$ True.

Lemma 18. $C_{1} \circledast C_{2} \Rightarrow \bigvee_{\mathcal{R}\left(C_{1}, C_{2}, C_{3}\right)} C_{3}$ is a valid formula for every pair of counting star formulas $C_{1}$ and $C_{2}$.

From Lemma 17 and Lemma 18 we obtain the desired Theorem 19, which shows the correctness of our rules for computing spatial conjunction of formulas of quantifier depth at most one.

Theorem 19. The equivalence (3) holds for every pair of counting star formulas $C_{1}$ and $C_{2}$.

## 8 Further Remarks

In this section we present two additional remarks regarding spatial conjunction. The first remark notes that we must be careful when extracting a subformula from a formula and labelling it with a new predicate. The second remark shows how to encode spatial conjunction in second-order logic, thus providing some insight into the expressive power of spatial conjunction.

### 8.1 Extracting Subformulas in the Presence of $\circledast$

In two-variable logic with counting $C^{2}$ we may efficiently transform formula into an unnested form by introducing new predicate names and naming subformulas using these predicates. This transformations is a standard step in decidability proofs for two-variable logic with counting [22, 45].

The satisfiability of the resulting formula is equivalent to the satisfiability of the original formula. An extraction of a subformula $G$ and its replacement with a new predicate $P$ can be justified by a substitution lemma of the form:

$$
\llbracket F[P:=G \rrbracket \rrbracket e=\llbracket F \rrbracket(e[P:=\llbracket G \rrbracket e \rrbracket)
$$

where $e$ is the environment (model). This substitution lemma does not hold in the presence of spatial conjunction that splits the values of newly introduced predicates. Namely,

$$
\llbracket\left(F_{1} \circledast F_{2}\right)[P:=G] \rrbracket e \Rightarrow \llbracket F_{1} \circledast F_{2} \rrbracket(e[P:=\llbracket G \rrbracket e])
$$

holds, but the converse implication does not hold because the value $\llbracket G \rrbracket e$ of the relation $P$ might be split on the right-hand side.

It is therefore interesting to divide predicates into splittable and non-splittable predicates, and have spatial conjunction split only the interpretations of splittable predicates. The substitution lemma then holds when $P$ is a non-splittable predicate.

Note, however, that in the presence of non-splittable predicates we cannot translate counting stars into spatial notation and thus use unnested form to eliminate all spatial conjunctions from first-order formulas. As a result, adding spatial conjunction of formulas of large quantifier depth to two-variable logic with counting may increase the expressive power of the resulting logic.

We also remark that if the language contains only one splittable unary predicate $A_{S}$, then it is easy to simulate the splitting of objects of the universe, which is the semantics of spatial conjunction in [28]. Namely, we use some fixed unary predicate $A_{0}$ to denote all "live" objects, and make all quantifiers range only over the objects that satisfy $A_{0}$.

### 8.2 Representing $\circledast$ in Second-Order Logic

In this section we give a simple translation from the first-order logic with spatial conjunction and inductive definitions [27, Chapter 4] to second-order logic. This
gives an upper bound on the expressive power of first-order logic with spatial conjunction and inductive definitions.

Consider first-order logic extended with the spatial conjunction $\circledast$ and the least-fixpoint operator. The syntax of the least-fixpoint operator is

$$
\left(\operatorname{Ifp} P, x_{1}, \ldots, x_{n} . F\right)\left(y_{1}, \ldots, y_{n}\right)
$$

where $F$ is a formula that may contain new free variables $P, x_{1}, \ldots, x_{n}$. The meaning of the least-fixpoint operator is that the relation which is the least fixpoint of the monotonic transformation on predicates

$$
\left(\lambda x_{1}, \ldots, x_{n} \cdot P\left(x_{1}, \ldots, x_{n}\right)\right) \mapsto\left(\lambda x_{1}, \ldots, x_{n} . F\right)
$$

holds for $y_{1}, \ldots, y_{n}$. To ensure the monotonicity of the transformation on predicates, we require that $P$ occurs only positively in $F$.

$$
\begin{aligned}
& \mathcal{A}=\left\{A_{1}, \ldots, A_{n}\right\} \\
& \mathcal{F}=\left\{f_{1}, \ldots, f_{m}\right\} \\
& \llbracket F^{\prime} \circledast F^{\prime \prime} \rrbracket=\exists A_{1}^{\prime}, \ldots, A_{n}^{\prime}, f_{1}^{\prime}, \ldots, f_{m}^{\prime}, \\
& A_{1}^{\prime \prime}, \ldots, A_{n}^{\prime \prime}, f_{1}^{\prime \prime}, \ldots, f_{m}^{\prime \prime} . \mathcal{B} \llbracket F^{\prime} \circledast F^{\prime \prime} \rrbracket \\
& \mathcal{B} \llbracket F^{\prime} \circledast F^{\prime \prime} \rrbracket= \\
& \bigwedge_{i=1}^{n}\left(\text { split }_{1} A_{i} A_{i}^{\prime} A_{i}^{\prime \prime}\right) \wedge \bigwedge_{i=1}^{m}\left(\text { split }_{2} f_{i} f_{i}^{\prime} f_{i}^{\prime \prime}\right) \wedge \\
& \llbracket F^{\prime} \rrbracket\left[A_{i}:=A_{i}^{\prime}\right]_{i=1}^{n}\left[f_{i}:=f_{i}^{\prime}\right]_{i=1}^{m} \wedge \\
& \llbracket F^{\prime \prime} \rrbracket\left[A_{i}:=A_{i}^{\prime \prime}\right]_{i=1}^{n}\left[f_{i}:=f_{i}^{\prime \prime}\right]_{i=1}^{m} \\
& \text { split }_{1} A A^{\prime} A^{\prime \prime} \equiv \forall x .\left(A(x) \Leftrightarrow\left(A^{\prime}(x) \vee A^{\prime \prime}(x)\right)\right) \wedge \\
& \neg\left(A^{\prime}(x) \wedge A^{\prime \prime}(x)\right) \\
& \text { split }_{2} f f^{\prime} f^{\prime \prime} \equiv \forall x y .\left(f(x, y) \Leftrightarrow\left(f^{\prime}(x, y) \vee f^{\prime \prime}(x, y)\right)\right) \wedge \\
& \neg\left(f^{\prime}(x, y) \wedge f^{\prime \prime}(x, y)\right) \\
& \llbracket\left(\operatorname{lfp} P, x_{1}, \ldots, x_{n} . F\right)\left(y_{1}, \ldots, y_{n}\right) \rrbracket= \\
& \forall P .\left(\forall x_{1}, \ldots, x_{n} .\left(F \Leftrightarrow P\left(x_{1}, \ldots, x_{n}\right)\right)\right) \Rightarrow P\left(y_{1}, \ldots, y_{n}\right)
\end{aligned}
$$

Fig. 8. Translation of Spatial Conjunction and Inductive Definitions into Second-Order Logic

Figure 8 presents the translation from first-order logic extended with spatial conjunction and least-fixpoint operator to second-order logic. The translation directly mimics the semantics of $\circledast$ and Ifp.

In second-order logic, the relations in $L=\mathcal{A} \cup \mathcal{F}$ become free variables.

To translate $\circledast$, use second-order quantification to assert the existence of new unary and binary relations that partition the relations in $L$ into relations in $L^{\prime}$ and $L^{\prime \prime}$. Then perform a syntactic replacement of relations in $L$ with the corresponding relations in $L^{\prime}$ for the first formula, and with the corresponding relations in $L^{\prime \prime}$ for the second formula.

Translating Ifp is also straightforward. The property that $P$ is a fixpoint of $F$ is easily expressible. To encode that $y_{1}, \ldots, y_{n}$ hold for the least fixpoint of $F$, we state that $y_{1}, \ldots, y_{n}$ hold for all fixpoints of $F$, using universal second-order quantification over $P$.

We also note that the translation of $\circledast$ in Figure 8 uses only existential second-order quantification, which points to another class of formulas where spatial conjunction can be eliminated if we are only concerned with satisfiability. Namely, if $F^{\prime}$ and $F^{\prime \prime}$ are first-order formulas (without $\circledast$ or Ifp), then $F^{\prime} \circledast F^{\prime \prime}$ is satisfiable iff the first-order formula $\mathcal{B} \llbracket F^{\prime} \circledast F^{\prime \prime} \rrbracket$ in the extended language is satisfiable. As a slight generalization, define the following class of "interesting" formulas:

1. a first-order formula $F$ is an interesting formula;
2. if $F_{1}$ and $F_{2}$ are interesting formulas, so is $F_{1} \circledast F_{2}$;
3. if $F_{1}$ and $F_{2}$ are interesting formulas, so is $F_{1} \vee F_{2}$

The satisfiability of each interesting formula is equivalent to the satisfiability of the corresponding first-order formula in an extended vocabulary. In particular, the satisfiability of the class of formulas formed starting from formulas in twovariable logic with counting and applying only $\vee$ and $\circledast$ is decidable.

## 9 Further Related Work

Records have been studied in the context of functional and object-oriented programming languages $[11,14,23,29,42,46-48,57]$. The main difference between existing record notations and our system is that the interpretation of a record in our system is a predicate on an object, where an object is linked to other objects forming a graph, as opposed to being a type that denotes a value (with values typically representable as finite trees). Our view is appropriate for programming languages such as Java and ML that can manipulate structures using destructive updates. Our generalizations allow the developers to express both incoming and outgoing references of objects, and allow the developers to express typestate changes.

We have developed role logic to provide a foundation for role analysis [30-33]. We have subsequently studied a simplification of role analysis constraints and showed a characterization of such constraints using formulas [34,35]. Multifields and multislots are present already in [32, Section 8.1]. In this section we have shown that role logic provides a unifying framework for all these constraints and goes beyond them in 1) being closed under the fundamental boolean logical operations, and, 2) being closed under spatial conjunction for an interesting class
of formulas. The view of roles as predicates is equivalent to the view of roles as sets and works well in the presence of data abstraction [39, 40].

The parametric analysis based on there-valued logic was introduced in [53, 54]. Other approaches to verifying shape invariants include [13, 19-21, 26, 41]. A decidable logic for expressing connectivity properties of the heap was presented in [4]. We use spatial conjunction from separation logic that has been used for reasoning about the heap $[7,8,28,51,52]$. Description logics $[1,6]$ share many of the properties of role logic and have been traditionally applied to knowledge bases. $[9,10]$ present doubly-exponential deterministic algorithms for reasoning about the satisfiability of expressive description logics over all structures and over finite structures. The decidability of two-variable logic with counting $C^{2}$ was shown in [22], whereas [45] establishes the NEXPTIME-complexity of the satisfiability problem for the fragment $C_{1}^{2}$ with counting up to one.

## 10 Conclusions

We have shown how to add notation for records to two-variable role logic while preserving its decidability. The resulting notation supports a generalization of traditional records with record specifications that are closed under all boolean operations as well as record concatenation, allow the description of typestate properties, support inverse records, and capture the distinction between open and closed records. We believe that such an expressive and decidable notation is useful as an annotation language used with program analyses and type systems.

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## A Appendix: Correctness of Spatial Conjunction Elimination

Proposition 8. Every quantifier-free formula $F$ such that $\mathrm{FV}(F) \subseteq\left\{x_{1}, \ldots, x_{n}\right\}$ is equivalent to a disjunction of CAT formulas $C$ such that $\mathrm{FV}(C)=\left\{x_{1}, \ldots, x_{n}\right\}$.
Proof. Let $F$ be a quantifier-free formula and $\mathrm{FV}(F) \subseteq\left\{x_{1}, \ldots, x_{n}\right\}$. Transform $F$ to disjunctive normal form $F^{\prime}$. Let $C$ be a conjunction in $F^{\prime}$. If $C$ contains a literal and its negation, then $C$ is contradictory and we eliminate $C$ from $F^{\prime}$. Assume all conjunctions are non-contradictory, and let $C$ be one conjunction. If there exists an atomic formula $F_{A}$ in variables $\left\{x_{1}, \ldots, x_{n}\right\}$ such that $F_{A} \notin C$ and $\left(\neg F_{A}\right) \notin C$, then replace $C$ with the disjunction

$$
\left(C \wedge F_{A}\right) \vee\left(C \wedge \neg F_{A}\right)
$$

By repeating this process, we obtain a disjunction of CAT formulas.
Lemma 9. Every CAT formula $F$ is either contradictory, or is equivalent to an EQCAT formula $F^{\prime}$ such that $\mathrm{FV}\left(F^{\prime}\right)=\mathrm{FV}(F)$.
Proof. Let $F$ be a CAT formula. If $x_{i} \neq x_{i}$ occurs in $F$, then $F$ is contradictory. If $x_{i}=x_{j}$ occurs in $F$ for $i \not \equiv j$, then in all conjuncts other than $x_{i}=x_{j}$ replace all occurrences of $x_{i}$ with $x_{j}$. Repeat this process as long as it is possible. Suppose that the resulting formula was not established to be contradictory. Let $y_{1}, \ldots, y_{m}$ be variables that occur only on the left-hand side of some equality $y_{j}=x_{i_{j}}$. Removing all equalities of the form $y_{j}=y_{j}$ yields an EQCAT formula.

Proposition 10. Every quantifier-free formula $F$ such that $\mathrm{FV}(F) \subseteq$ $\left\{x_{1}, \ldots, x_{n}\right\}$ can be written as a disjunction of EQCAT formulas $C$ such that $\mathrm{FV}(C)=\left\{x_{1}, \ldots, x_{n}\right\}$.
Proof. Let $F$ be a quantifier-free formula such that $\mathrm{FV}(F) \subseteq\left\{x_{1}, \ldots, x_{n}\right\}$. Using Proposition 8, transform $F$ to disjunction of CAT formulas $F_{1}$. Then, for each conjunct $C$ of $F_{1}$ apply Lemma 9 to transform $C$ to an EQCAT formula.

Proposition 12. Let $F$ be a formula of such that $F$ has quantifier depth at most one, $F$ has counting degree at most $k$, and $\mathrm{FV}(F) \subseteq\left\{x_{1}, \ldots, x_{n}\right\}$. Then $F$ is equivalent to a disjunction of $k$-counting-star formulas $F_{C}$ where $\operatorname{FV}\left(F_{C}\right)=\left\{x_{1}, \ldots, x_{n}\right\}$.

Proof. Let $F$ be a formula of such that $F$ has quantifier depth at most one, $F$ has counting degree at most $k$, and $\mathrm{FV}(F) \subseteq\left\{x_{1}, \ldots, x_{n}\right\}$. Then $F$ is a boolean combination of 1) atomic formulas and 2) formulas of the form $\exists^{s} z . F^{\prime}$ where $F^{\prime}$ is quantifier-free and $\mathrm{FV}\left(F^{\prime}\right)=\left\{z, x_{1}, \ldots, x_{n}\right\}$. Because $z$ is a bound variable, rename it to $x$ in each formula $F^{\prime}$. Let $F_{1}$ be the result of transforming this boolean combination to disjunctive normal form. Consider a disjunct $C$ of $F_{1}$. As in the proof of Proposition 10, and treating quantified formulas as atomic syntactic entities, transform $C$ into disjunction of formulas of the form

$$
\bigwedge_{j=1}^{m} y_{j}=w_{i_{j}} \wedge F \wedge \bigwedge_{F^{\prime} \in S}\left(\exists^{\beta\left(F^{\prime}\right)} x . F^{\prime}\right)^{\alpha\left(F^{\prime}\right)}
$$

where $\beta\left(F^{\prime}\right) \in C_{k+1}, \alpha\left(F^{\prime}\right) \in\{0,1\}$ for $F^{\prime} \in S$, and where $\bigwedge_{j=1}^{m} y_{j}=w_{i_{j}} \wedge F$ is an EQCAT formula with $y_{1}, \ldots, y_{m}, w_{1}, \ldots, w_{p}$ distinct variables such that $\left\{y_{1}, \ldots, y_{m}, w_{1}, \ldots, w_{p}\right\}=\left\{x_{1}, \ldots, x_{n}\right\}$, and $\mathrm{FV}\left(F^{\prime}\right) \subseteq\left\{x, x_{1}, \ldots, x_{n}\right\}$ for $F^{\prime} \in$ $S$. Here $S$ is the set of formulas of the form $\exists^{\beta\left(F^{\prime}\right)} x . F^{\prime}$ that end up conjoined with the EQCAT formula as the result of transformation to normal form. By replacing each $y_{j}$ with $w_{i_{j}}$ in each $F^{\prime}$, enforce that $\mathrm{FV}\left(F^{\prime}\right) \subseteq\left\{x, w_{1}, \ldots, w_{p}\right\}$. Using Proposition 10, transform each $F^{\prime}$ to a disjunction of EQCAT formulas. By applying the equivalences

$$
\begin{aligned}
& \exists \geq k_{1} x . \bigvee_{i=1}^{q} B_{i} \sim \bigvee_{\sum_{j=1}^{q} l_{j}=k_{1}}^{\bigvee} \bigwedge_{i=1}^{q} \exists \geq l_{i} x . B_{i} \\
& \exists=k_{1} x . \bigvee_{i=1}^{q} B_{i} \sim \underset{\sum_{j=1}^{q} l_{j}=k_{1}}{\bigvee} \bigwedge_{i=1}^{q} \exists=l_{i} x . B_{i}
\end{aligned}
$$

for $B_{1}, \ldots, B_{q}$ mutually exclusive, and propagating the disjunction to the top level, ensure that every $F^{\prime}$ is an EQCAT formula. Then transform each term $\left(\exists^{\beta\left(F^{\prime}\right)} x . F^{\prime}\right)^{\alpha\left(F^{\prime}\right)}$ into positive boolean combination of formulas of one of the forms $\exists^{=i} x . F^{\prime}$ for $0 \leq i \leq k$ and $\exists^{\geq k+1} x . F^{\prime}$, using the properties

$$
\begin{aligned}
& \neg \exists \geq k_{1} x . F^{\prime} \sim \bigvee_{i=0}^{k_{1}-1} \exists=i x . F^{\prime} \\
& \neg \exists=k_{1} x . F^{\prime} \sim \bigvee_{i \in\{0, \ldots, k\} \backslash\left\{k_{1}\right\}} \exists^{i} x . F^{\prime} \vee \exists \geq k+1 x . F^{\prime}
\end{aligned}
$$

Next ensure that each $F^{\prime}$ is not merely an EQCAT, but in fact a GCCAT such that $F^{\prime} \in \operatorname{exts}(F, x)$, as follows.

Suppose that $F^{\prime}$ contains a literal $L_{1}$ complementary to some literal occurring in GCCAT formula $F$. If $L_{1}$ occurs in $\exists^{=i} x . F^{\prime}$ for $i>0$ or in $\exists^{\geq k+1} x . F^{\prime}$, then the entire conjunct is contradictory and we eliminate it. If $L_{1}$ occurs in $\exists^{=0} x . F^{\prime}$, then $\exists=0 x . F^{\prime}$ is implied by $F$, so eliminate it. Assume that $F^{\prime}$ has no literals complementary to literals in $F$. Then $F^{\prime}$ contains $w_{i} \neq w_{j}$ for all $i \not \equiv j$. Next ensure that $x \neq w_{i}$ is a conjunct for $1 \leq i \leq p$, as follows. Suppose that $F^{\prime}$ contains the conjunct $x=w_{i}$ for some $1 \leq i \leq p$.

There is clearly at most one interpretation of $x$ that is equal to interpretation of $w_{i}$, so if $\beta\left(F^{\prime}\right) \in\left\{2,3, \ldots, k,(k+1)^{+}\right\}$then $F$ and $F^{\prime}$ are contradictory and the entire conjunction is False, so assume $\beta\left(F^{\prime}\right) \in\{0,1\}$. For the same reason, $\exists^{=1} x . F^{\prime}$ is equivalent to $\exists x \cdot F^{\prime}$, so if $\beta\left(F^{\prime}\right)=1$, then replace $x$ with $w_{i}$ in $F^{\prime}$ giving a GCCAT formula $F^{\prime \prime}$ such that $\mathrm{FV}\left(F^{\prime \prime}\right)=\mathrm{FV}(F)$. By definition of GCCAT formulas, either $F$ and $F^{\prime \prime}$ are equivalent, so $F \wedge\left(\exists x . F^{\prime \prime}\right) \sim F$, or $F$ and $F^{\prime \prime}$ are contradictory, and the entire conjunction is False.

Assume therefore that $x \neq w_{i}$ occurs in $F^{\prime}$ for all $1 \leq i \leq p$. This means that $F^{\prime}$ is a GCCAT formula. Because $\mathrm{FV}\left(F^{\prime}\right)=\left\{x, w_{1}, \ldots, w_{p}\right\}$ and $F^{\prime}$ does not contain a literal complementary to a literal from $F$, eliminating from $F^{\prime}$ atomic formulas that occur in $F$ yields an element of exts $(F, x)$.

To ensure that there exists exactly one conjunct of the form $\exists^{s} x . F^{\prime}$ for each $F^{\prime} \in \operatorname{exts}(F, x)$, use the fact that the $k+1$ formulas $\exists^{=i} x . F^{\prime}$, for $0 \leq i \leq k$, and $\exists \geq k+1 x . F^{\prime}$ form a partition (they are mutually exclusive and their disjunction is True).

Lemma 13. If $e$ is an environment for language $L, C$ a counting star formula in language $L$, and $m \in\{\{1\},\{2\},\{1,2\}\}$, then $\llbracket C \rrbracket e=\mathcal{S}_{m} \llbracket C \rrbracket e^{m}$.
Proof. Formula $E$ contains only equalities, so $\llbracket E \rrbracket e$ iff $\llbracket E \rrbracket e^{m}$. It therefore suffices to show that

$$
\begin{equation*}
\llbracket \mathcal{K} \llbracket F \rrbracket \circledast \mathcal{X}_{m} \llbracket \exists^{s_{1}} x . F_{1}^{\prime} \rrbracket \circledast \ldots \circledast \mathcal{X}_{m} \llbracket \exists^{s_{k}} x . F_{k}^{\prime} \rrbracket \rrbracket e^{m}=\text { True } \tag{4}
\end{equation*}
$$

iff $\llbracket F \rrbracket e=$ True and for all $i, \llbracket \exists^{s_{i}} x . F_{i}^{\prime} \rrbracket e=$ True.
$\Rightarrow)$ : Let (4) hold. Then there exist $e_{0}, e_{1}, \ldots, e_{k}$ such that split $e^{m}\left[e_{0} e_{1} \ldots e_{k}\right]$, $\llbracket \mathcal{K} \llbracket F \rrbracket \rrbracket e_{0}=$ True, and $\llbracket \mathcal{X}_{m} \llbracket \exists^{s_{i}} x . F_{i}^{\prime} \rrbracket \rrbracket e_{i}=$ True for $1 \leq i \leq k$.

We first show $\llbracket F \rrbracket e=$ True. Note first that $\llbracket G_{E} \rrbracket e_{i}=$ True for $1 \leq i \leq k$. Namely, because both $\left(F^{\prime}\right)_{m}^{*}$ and $\left(F^{\prime}\right)_{m}$ entail $G_{E}$, so does $\mathcal{X}_{m} \llbracket \exists^{s_{i}} x . F_{i}^{\prime} \rrbracket$, by definition of $\mathcal{X}_{m} \llbracket \rrbracket$ and split. Therefore, $e_{0}$ is the only environment among $e_{0}, e_{1}, \ldots, e_{k}$ that may have non-empty relations between the elements interpreting $x_{1}, \ldots, x_{n}$. As a result, $\llbracket F \rrbracket e^{m}=\llbracket F \rrbracket e_{0}$. But $\llbracket F \rrbracket e_{0}=$ True because $\llbracket \mathcal{K} \llbracket F \rrbracket \rrbracket e_{0}=$ True. Therefore $\llbracket F \rrbracket e^{m}=$ True, and $F$ contains no symbols from $L^{\prime} \backslash L$, so $\llbracket F \rrbracket e=$ True.

We next show $\llbracket \exists^{s_{i}} x . F_{i}^{\prime} \rrbracket e=$ True for $1 \leq i \leq k$. For $s_{i}=p^{+}$, from $\llbracket \mathcal{X}_{m} \llbracket \exists^{s_{i}} x . F_{i}^{\prime} \rrbracket \rrbracket e_{i}=$ True we have that there exist $e_{i, 0}, e_{i, 1}, \ldots, e_{i, p}$ such that 1) split $e_{i}\left[e_{i, 0}, e_{i, 1}, \ldots, e_{i, p}\right]$, 2) $\llbracket\left(F^{\prime}\right)_{m}^{*} \rrbracket e_{i, 0}=$ True, and 3) $\llbracket\left(F^{\prime}\right)_{m} \rrbracket e_{i, j}=$ True for $1 \leq j \leq p$. Similarly, for $s_{i}<p$, we have that there exist $e_{i, 1}, \ldots, e_{i, s_{i}}$ such that 1) split $e_{i}\left[e_{i, 1}, \ldots, e_{i, s_{i}}\right]$, and 2) $\llbracket\left(F^{\prime} D_{m} \rrbracket e_{i, j}=\right.$ True for $1 \leq j \leq s_{i}$. Note that whenever $\llbracket\left(F^{\prime}\right)_{m}^{*} \rrbracket e_{i, j}$ or $\llbracket\left(F^{\prime}\right)_{m} \rrbracket e_{i, j}$ holds, we can split elements of the domain $D$ into two disjoint sets: elements $E_{i, j}$ for which empEx $x_{\emptyset}(F, x)$ holds, and elements $N_{i, j}$ for which $F^{\prime} \wedge \operatorname{Mark}_{m}(x)$ holds. If $\llbracket\left(F^{\prime}\right)_{m} \rrbracket e_{i, j}$, then $\left|N_{i, j}\right|=1$, by definition of $\llbracket\left(F^{\prime}\right)_{m} \rrbracket e_{i, j}$. Moreover, by definition of split and because $m \neq \emptyset$, we have $N_{i_{1}, j_{1}} \cap N_{i_{2}, j_{2}}=\emptyset$ for $\left\langle i_{1}, j_{1}\right\rangle \neq\left\langle i_{2}, j_{2}\right\rangle$. Observe that, for a given domain element $d \in D$, the atomic type extension corresponding to $e^{m}$ with $x \mapsto d$ is the union of atomic type extensions corresponding to each $e_{i, j}$. The atomic type extension for $d$ in $e_{i, j}$ is either $F^{\prime} \wedge \operatorname{Mark}_{m}(x)$, or empEx$(F, x)$. Therefore, the atomic type extension for $d$ in $e^{m}$ is either $F^{\prime} \wedge \operatorname{Mark}_{m}(x)$ if $d \in N_{i, j}$ for some $i, j$, or $\operatorname{empEx}_{\emptyset}(F, x)$ if for all $i, j, d \notin N_{i, j}$. If $N_{i}=\left\{d \mid \llbracket F_{i}^{\prime} \rrbracket e^{m}[x \mapsto d]=\right.$ True $\}$, then $N_{i}=\biguplus_{j} N_{i, j}$. If $s_{i}=k<p$ then $\left|N_{i}\right|=\sum_{j=1}^{s_{i}}\left|N_{i, j}\right|=\sum_{i=j}^{s_{i}} 1=s_{i}$, so $\llbracket \exists=k x . F_{i}^{\prime} \rrbracket e^{m}=$ True. Because $\exists^{=k} x$. $F_{i}^{\prime}$ is formula in language $L$, we have $\llbracket \exists^{=k} x . F_{i}^{\prime} \rrbracket e=$ True. Similarly, if $s_{i}=p^{+}$, then $\left|N_{i}\right|=\left|N_{i, 0}\right|+\sum_{j=1}^{p}\left|N_{i, j}\right|=\left|N_{i, 0}\right|+p \geq p$, so $\llbracket \exists \geq k x . F_{i}^{\prime} \rrbracket e^{m}=$ True and therefore $\llbracket \exists \geq p x . F_{i}^{\prime} \rrbracket e=$ True. In both cases, $\llbracket \exists^{s_{i}} x . F_{i}^{\prime} \rrbracket e=$ True.

This completes one direction of the implication, we next show the converse direction.
$\Leftarrow)$ : Let $\llbracket F \rrbracket e=$ True and for all $i$ where $1 \leq i \leq k, \llbracket \exists^{s_{i}} x . F_{i}^{\prime} \rrbracket e=$ True. We construct environments $e_{0}, e_{1}, \ldots, e_{k}$ such that 1) split $\left.e^{m}\left[e_{0}, e_{1}, \ldots, e_{k}\right] 2\right)$
$\llbracket \mathcal{K} \llbracket F \rrbracket \rrbracket e_{0}=$ True, and 3) $\llbracket \mathcal{X}_{m} \llbracket \exists^{s_{i}} x . F_{i}^{\prime} \rrbracket \rrbracket e_{i}=$ True for all $i$ where $1 \leq i \leq k$. We construct $e_{0}, e_{1}, \ldots, e_{k}$ by assigning the tuples of relations in $e$ to one of the environments $e_{0}, e_{1}, \ldots, e_{k}$, as follows. We only need to decide on splitting the tuples $\left\langle d_{1}, \ldots, d_{q}\right\rangle$ where all but one value $d_{1}, \ldots, d_{q}$ are from the set $D_{X}=$ $\left\{e x_{1}, \ldots, e x_{n}\right\}$, the values of relations on other tuples do not affect the truth value of formulas in question and can be split arbitrarily. If $\left\{d_{1}, \ldots, d_{q}\right\} \subseteq D_{X}$, then we assign the tuple to $e_{0}$, as a result, $\llbracket \mathcal{K} \llbracket F \rrbracket \rrbracket e_{0}=$ True. If $\left\{d_{1}, \ldots, d_{q}\right\} \backslash D_{X}=$ $\{d\}$, then let $i$ be such that $F_{i}^{\prime}$ is the unique extension of $F$ with the property $\llbracket F_{i}^{\prime} \rrbracket e[x \mapsto d]=$ True. Then assign the tuple $\left\langle d_{1}, \ldots, d_{q}\right\rangle$ to the environment $e_{i}$ and also assign the values $\left(e B_{l}\right) d$ for all $l \in m$ to $e_{i}$. Because we assign each relevant tuple to exactly one $e_{i}$, we ensure split $e^{m}\left[e_{0}, e_{1}, \ldots, e_{k}\right]$. Let $D_{E}=\{d \mid$ $\llbracket F_{i}^{\prime} \rrbracket e[x \mapsto d]=$ True $\}$, then also $D_{E}=\left\{d \mid \llbracket F_{i}^{\prime} \rrbracket e_{i}[x \mapsto d]=\right.$ True $\}$. Because $\llbracket \exists^{s_{i}} x . F_{i}^{\prime} \rrbracket e=$ True, $\left|D_{E}\right|=s_{i}$ for $s_{i}<p$ and $\left|D_{E}\right| \geq p$ for $s_{i}=p^{+}$. Let $s_{i}<p$. Then split $e_{i}$ into $e_{i, 1}, \ldots, e_{i, s_{i}}$ by assigning exactly one element $d \in D_{E}$ to one $e_{i, j}$. When assigning an element we assign the values of all relations from $L$, as well as the relations $B_{1}$ and $B_{2}$. This ensures that $\left.\llbracket\left(F_{i}^{\prime}\right)\right)_{m} \rrbracket e_{i, j}=$ True for all $1 \leq i \leq s_{i}$. For $s_{i}=p^{+}$, we split $e_{i}$ into $e_{i, 0}, e_{i, 1}, \ldots, e_{i, p}$ by assigning exactly one element to each of $e_{i, 1}, \ldots, e_{i, p}$ and assigning the remaining elements to $e_{i, 0}$. In both cases, we obtain $\llbracket \mathcal{X}_{m} \llbracket \exists^{s_{i}} x . F_{i}^{\prime} \rrbracket \rrbracket e_{i}=$ True.

Lemma 15. If $G_{1} \leadsto G_{2}$, then $G_{2} \Rightarrow G_{1}$ is valid.
Proof. We show the claim for each of the rules (1)-(6).
Rule (1): Let $T_{1} \odot T_{2}$ be defined and let $\llbracket\left(T_{1} \odot T_{2}\right)_{1,2} \rrbracket e=$ True for an $L^{\prime}$ environment $e$. Let $d \in D$ be the unique domain element such that $\llbracket T_{1} \odot T_{2} \rrbracket e[x \mapsto$ $d]=$ True. Let $e_{1}$ and $e_{2}$ be such that splite $e\left[e_{1}, e_{2}\right], \llbracket T_{1} \rrbracket e_{1}[x \mapsto d]=$ True and $\llbracket T_{2} \rrbracket e_{2}[x \mapsto d]=$ True, and $e_{p} B_{q} d=$ True iff $p=q$ for $p, q \in\{1,2\}$. In other words, $e_{1}$ and $e_{2}$ split $e$ by assigning tuples validating $T_{1}$ to $e_{1}$, tuples validating $T_{2}$ to $e_{2}$, and by assigning $B_{1}$ to $e_{1}$ and $B_{2}$ to $e_{2}$ on the element $d$. The values of relations er containing tuples with an element $d^{\prime} \notin\left\{e x_{1}, \ldots, e x_{n}, d\right\}$ are all False, because $\llbracket\left(T_{1} \odot T_{2}\right)_{1,2} \rrbracket e=$ True, so we let the values of $e_{1} r$ and $e_{2} r$ for those tuples also be empty. Then $d$ is the only element outside $\left\{e x_{1}, \ldots, e x_{n}\right\}$ such that $\llbracket T_{1} \rrbracket e_{1}[x \mapsto d]=$ True, and $d$ is also the only element outside $\left\{e x_{1}, \ldots, e x_{n}\right\}$ such that $\llbracket T_{2} \rrbracket e_{2}[x \mapsto d]=$ True. As a result, $\llbracket\left(T_{1}\right)_{1} \rrbracket e_{1}=$ True and $\llbracket\left(T_{2}\right)_{2} \rrbracket e_{2}=$ True, so $\llbracket\left(T_{1}\right)_{1} \circledast\left(T_{2}\right)_{2} \rrbracket e=$ True.

To show the claim for rules (2), (3), (4), we proceed similarly as for rule (1).
Rule (2): Let $T_{1} \odot T_{2}$ be defined and let $\llbracket\left(T_{1} \odot T_{2}\right)_{1,2} \circledast\left(T_{2}\right)_{2}^{*} \rrbracket e=$ True. Then there are $e^{\prime}$ and $e^{\prime \prime}$ such that split $e\left[e^{\prime}, e^{\prime \prime}\right], \llbracket\left(T_{1} \odot T_{2} \downarrow_{1,2} \rrbracket e^{\prime}=\right.$ True and $\llbracket\left(T_{2}\right)_{2}^{*} \rrbracket e^{\prime \prime}=$ True. Let $d$ be the unique element such that $\llbracket T_{1} \odot T_{2} \rrbracket e^{\prime}[x \mapsto$ $d]=$ True, and let $d_{1}, \ldots, d_{k}$ be the list of all (distinct) elements such that $\llbracket\left(T_{2}\right\rangle_{2}^{*} \rrbracket e^{\prime \prime}\left[x \mapsto d_{i}\right]=$ True. Note that $d \notin\left\{d_{1}, \ldots, d_{k}\right\}$, because $e^{\prime} B_{2} d=$ True, $e^{\prime \prime} B_{2} d_{i}=$ True for all $1 \leq i \leq k$, and split $e\left[e^{\prime}, e^{\prime \prime}\right]$. We construct $e_{1}$ and $e_{2}$ such that split $e\left[e_{1}, e_{2}\right]$ as follows. We assign $B_{1}$, as well as the values of relations that hold according to $T_{1}$ on element $d$ to $e_{1}$, and we assign $B_{2}$, as well as the values of relations that hold according to $T_{2}$ on element $d$ to $e_{2}$. We assign $B_{2}$ as well as the values of relations that hold according to $T_{2}$ on $d_{1}, \ldots, d_{k}$ to $e_{2}$. The values
of $B_{1}$ and the relations on $d_{1}, \ldots, d_{k}$ for $e_{1}$ are empty. For such $e_{1}$ and $e_{2}$ we have $\llbracket\left(T_{1}\right)_{1} \rrbracket e_{1}=$ True and $\llbracket\left(T_{2}\right)_{2}^{*} \rrbracket e_{2}=$ True, so $\llbracket\left(T_{1}\right)_{1} \circledast\left(T_{2}\right)_{2}^{*} \rrbracket e=$ True.

Rule (3) is analogous to rule (2).
Rule (4): Let $T_{1} \odot T_{2}$ be defined and let $\llbracket\left(T_{1}\right)_{1}^{*} \circledast\left(T_{2}\right)_{2}^{*} \circledast\left(T_{1} \odot T_{2}\right)_{1,2}^{*} \rrbracket=$ True. Then there are $e^{\prime}, e^{\prime \prime}, e^{\prime \prime \prime}$ such that split $e\left[e^{\prime}, e^{\prime \prime}, e^{\prime \prime \prime}\right], \llbracket\left(T_{1}\right)_{1}^{*} \rrbracket e^{\prime}=$ True, $\llbracket 0\left(T_{2}\right)_{2}^{*} \rrbracket e^{\prime \prime}=$ True, and $\llbracket\left(T_{1} \odot T_{2}\right)_{1,2}^{*} \rrbracket e^{\prime \prime \prime}=$ True. Then there are three sets of elements $N^{\prime}, N^{\prime \prime}$, $N^{\prime \prime \prime}$, where $N^{\prime}$ contains elements that validate $T_{1}$ in $e^{\prime}, N^{\prime \prime}$ contains elements that validate $T_{2}$ in $e^{\prime \prime}$, and $N^{\prime \prime \prime}$ contains elements that validate $T_{1} \odot T_{2}$ in $e^{\prime \prime \prime}$. We have $N^{\prime} \cap N^{\prime \prime \prime}=\emptyset$ and $N^{\prime \prime} \cap N^{\prime \prime \prime}=\emptyset$, whereas $N^{\prime} \cap N^{\prime \prime}$ need not be empty. Each element $d \notin\left\{e x_{1}, \ldots, e x_{n}\right\}$ validates in $e$ either 1) empEx $x_{\emptyset}(F, x)$, if $d \notin N^{\prime} \cup N^{\prime \prime} \cup N^{\prime \prime \prime}$, or 2) $T_{1}$, if $d \in N^{\prime} \backslash N^{\prime \prime}$, or 3) $T_{2}$, if $d \in N^{\prime \prime} \backslash N^{\prime}$, or 4) $T_{1} \odot T_{2}$, if $d \in\left(N^{\prime} \cap N^{\prime \prime}\right) \cup N^{\prime \prime \prime}$. We construct environments $e_{1}, e_{2}, e_{3}$ by assigning $B_{1}$ and relations from $T_{1}$ to elements in $N^{\prime} \backslash N^{\prime \prime}$ to $e_{1}$, assigning $B_{2}$ and elements in $N^{\prime} \backslash N^{\prime \prime}$ to $e_{2}$, and splitting relations on elements in $\left(N^{\prime} \cap N^{\prime \prime}\right) \cup N^{\prime \prime \prime}$ into those for $T_{1}$, which we assign to $e_{1}$, and those for $T_{2}$, which we assign to $e_{2}$. We then have $\llbracket\left(T_{1}\right)_{1}^{*} \rrbracket e_{1}=$ True and $\llbracket\left(T T_{2}\right\rangle_{2}^{*} \rrbracket e_{2}=$ True, so $\llbracket\left(T_{1}\right)_{1}^{*} *\left(T_{2}\right)_{2}^{*} \rrbracket=$ True.

Rules (5), (6): Directly from the definitions of empe and $\left(F^{\prime}\right)_{m}^{*}$ it follows that empe $\Rightarrow\left(F^{\prime}\right)_{m}^{*}$.

Lemma 17. $\left(\bigvee_{\mathcal{R}\left(C_{1}, C_{2}, C_{3}\right)} C_{3}\right) \Rightarrow\left(C_{1} \circledast C_{2}\right)$ is a valid formula for every pair of counting star formulas $C_{1}$ and $C_{2}$.

Proof. Let $\llbracket \bigvee_{\mathcal{R}\left(C_{1}, C_{2}, C_{3}\right)} C_{3} \rrbracket e$ hold for some $L$-environment $e$. Then $\llbracket C_{3} \rrbracket e=$ True for some $C_{3}$ such that $\mathcal{S}_{1} \llbracket C_{1} \rrbracket \circledast \mathcal{S}_{2} \llbracket C_{2} \rrbracket \stackrel{C}{\Longrightarrow} \mathcal{S}_{1,2} \llbracket C_{3} \rrbracket$. By Lemma 16, $\mathcal{S}_{1,2} \llbracket C_{3} \rrbracket \Rightarrow \mathcal{S}_{1} \llbracket C_{1} \rrbracket \circledast \mathcal{S}_{2} \llbracket C_{2} \rrbracket$ is valid. By Lemma 13 and $\llbracket C_{3} \rrbracket e=$ True, we have $\llbracket \mathcal{S}_{1,2} \llbracket C_{3} \rrbracket \rrbracket e^{1,2}=$ True. Therefore, $\llbracket \mathcal{S}_{1} \llbracket C_{1} \rrbracket \circledast \mathcal{S}_{2} \llbracket C_{2} \rrbracket \rrbracket e^{1,2}=$ True. This means that there are $e_{1}$ and $e_{2}$ such that split $e^{1,2}\left[e_{1}, e_{2}\right], \llbracket \mathcal{S}_{1} \llbracket C_{1} \rrbracket \rrbracket e_{1}=$ True, and $\llbracket \mathcal{S}_{2} \llbracket C_{2} \rrbracket \rrbracket e_{2}=$ True. From Lemma 13 we have $\llbracket C_{1} \rrbracket \overline{e_{1}}=$ True, and $\llbracket C_{2} \rrbracket \overline{e_{2}}=$ True. From split $e^{1,2}\left[e_{1}, e_{2}\right]$ it follows that split $e\left[\overline{e_{1}}, \overline{e_{2}}\right]$, so $\llbracket C_{1} \circledast C_{2} \rrbracket e=$ True.

Lemma 18. $\quad C_{1} \circledast C_{2} \Rightarrow \bigvee_{\mathcal{R}\left(C_{1}, C_{2}, C_{3}\right)} C_{3}$ is a valid formula for every pair of counting star formulas $C_{1}$ and $C_{2}$.

Proof. Let $\llbracket C_{1} \circledast C_{2} \rrbracket e=$ True for some $L$-environment $e$. Then there are $e_{1}$ and $e_{2}$ such that split $e\left[e_{1}, e_{2}\right], \llbracket C_{1} \rrbracket e_{1}=$ True and $\llbracket C_{2} \rrbracket e_{2}=$ True. By Lemma 13 , $\mathcal{S}_{1} \llbracket C_{1} \rrbracket e_{1}^{1}=$ True and $\mathcal{S}_{2} \llbracket C_{2} \rrbracket e_{2}^{2}=$ True. We construct $\mathcal{S}_{1,2} \llbracket C_{3} \rrbracket$ such that $\mathcal{S}_{1} \llbracket C_{1} \rrbracket \circledast \mathcal{S}_{2} \llbracket C_{2} \rrbracket \xlongequal{C} \mathcal{S}_{1,2} \llbracket C_{3} \rrbracket$ and $\llbracket C_{3} \rrbracket e=$ True, as follows.

Let $K_{1}$ be the GCCAT part of $C_{1}$ and let $K_{2}$ be the GCCAT part of $C_{2}$. Let $D_{X}=D \backslash\left\{e x_{1}, \ldots, e x_{n}\right\}$. For each $d \in D_{X}$, let $T_{1}^{d}$ be the type extension induced by $d$ in $e_{1}$, that is, let $T_{1}^{d} \in \operatorname{exts}\left(K_{1}, x\right)$ be the formula such that $\llbracket T_{1}^{d} \rrbracket e_{1}^{1}[x \mapsto d]=$ True. Similarly, let $T_{2}^{d} \in \operatorname{exts}\left(K_{2}, x\right)$ be the formula such that $\llbracket T_{2}^{d} \rrbracket e_{2}^{2}[x \mapsto d]=$ True. Because split $e\left[e_{1}, e_{2}\right]$, the operation $T_{1} \odot T_{2}$ is defined and $\llbracket T_{1} \odot T_{2} \rrbracket e^{1,2}[x \mapsto$ $d]=$ True. Because $\mathcal{S}_{1} \llbracket C_{1} \rrbracket e_{1}^{1}=$ True, with each $d$ we can associate an occurrence $\mu_{1}(d)$ in $\mathcal{S}_{1} \llbracket C_{1} \rrbracket$ of a formula $F_{\mu_{1}(d)}$ where $F_{\mu_{1}(d)}$ is of the form $\left(T_{1}^{d} D_{1}\right.$ or of the form $\left(T_{1}^{d}\right)_{1}^{*}$, and an environment $e_{1, \mu_{1}(d)}$ such that split $e_{1}^{1}\left[e_{1,0},\left(e_{1, \mu_{1}(d)}\right)_{\mu(d)}\right]$, such that $\mathcal{K} \llbracket K_{1} \rrbracket e_{1,0}=$ True, and such that for every $d, \llbracket F_{\mu_{1}(d)} \rrbracket e_{1, \mu_{1}(d)}=$ True.

Analogously, for each $d$ we can associate an occurrence $\mu_{2}(d)$ in $\mathcal{S}_{2} \llbracket C_{2} \rrbracket$ of a formula $F_{\mu_{2}(d)}$ of the form $\left(T_{2}^{d}\right)_{2}$ or of the form $\left(T_{2}^{d} \nu_{2}^{*}\right.$, and an environment $e_{2, \mu_{2}(d)}$ such that split $e_{2}^{2}\left[e_{2,0},\left(e_{2, \mu_{2}(d)}\right)_{\mu_{2}(d)}\right]$, such that $\mathcal{K} \llbracket K_{2} \rrbracket e_{2,0}=$ True, and such that for every $d, \llbracket F_{\mu_{2}(d)} \rrbracket e_{2, \mu_{2}(d)}=$ True.

We compute $C_{3}$ by first combining $\mathcal{K} \llbracket K_{1} \rrbracket$ and $\mathcal{K} \llbracket K_{2} \rrbracket$ into $\mathcal{K} \llbracket K_{1} \oplus K_{2} \rrbracket$. From split $e\left[e_{1}, e_{2}\right]$ we conclude that the operation $F_{1} \oplus F_{2}$ is well-defined and that $\llbracket \mathcal{K} \llbracket F_{1} \oplus F_{2} \rrbracket \rrbracket e_{0}^{1,2}=$ True where $e_{0}^{1,2}$ is given by split $e_{0}^{1,2}\left[e_{1,0}, e_{2,0}\right]$.

We next apply rules (1)-(4) in Figure 7, as follows:

1. apply rule (1) once to each pair of occurrences $\mu_{1}(d)$ and $\mu_{2}(d)$ if they are of the form $\left(T_{1}^{d} \nu_{1}\right.$ and $\left(T_{2}^{d}\right)_{2}$, respectively; let $\mu(d)$ be the occurrence of the resulting formula $F_{\mu(d)} \equiv\left(T_{1}^{d} \odot T_{2}^{d}\right)_{1,2} ;$
2. apply rule (2) once to each pair of occurrences $\mu_{1}(d)$ and $\mu_{2}(d)$ if $\mu_{1}(d)$ is an occurrence of the form $\left(T_{1}^{d} D_{1}\right.$ and $\mu_{2}(d)$ is an occurrence of the form $\left(T_{2}^{d} D_{2}^{*}\right.$; let $\mu(d)$ be the occurrence of the formula $F_{\mu(d)} \equiv\left\langle T_{1}^{d} \odot T_{2}^{d}\right\rangle_{1,2}$ obtained as one of the results;
3. apply rule (3) once to each pair of occurrences $\mu_{1}(d)$ and $\mu_{2}(d)$ if $\mu_{1}(d)$ is an occurrence of the form $\left(T_{1}^{d} D_{1}^{*}\right.$ and $\mu_{2}(d)$ is an occurrence of the form $\left(T_{2}^{d}\right)_{2}$; let $\mu(d)$ be the occurrence of the formula $F_{\mu(d)} \equiv\left\langle T_{1}^{d} \odot T_{2}^{d}\right\rangle_{1,2}$ obtained as one of the results;
4. apply rule (4) once for each pair of occurrences of formulas of the form $\left(T_{1}^{d}\right)_{1}^{*}$ and $\left(T_{2}^{d}\right)_{2}^{*}$; for each $d$ such that $\mu_{1}(d)$ is an occurrence of $\left(T_{1}^{d}\right)_{1}^{*}$ and $\mu_{2}(d)$ is an occurrence of $\left(T_{2}^{d} \nu_{2}^{*}\right.$, let $\mu(d)$ be the occurrence of the resulting formula $F_{\mu(d)} \equiv\left\langle T_{1}^{d} \odot T_{2}^{d}\right\rangle_{1,2}^{*}$.

Note that no rule is applied twice to a distinct pair of occurrences of formulas. This means that the number of applications of rules is uniformly bounded, despite the fact that there is no bound on the size of the model $e$. In particular, there is no bound on the number of elements $d$ covered by a single application of rule (4). Each formula of the form $(T)_{1}$ is $F_{\mu_{1}(d)}$ for some $d$ and each formula of the form $(T)_{2}$ is $F_{\mu_{2}(d)}$ for some $d$, and all such formulas are consumed by applications of rules (1)-(3), so the resulting formula has no subformulas of the form $(T)_{1}$ or $(T)_{2}$. After applying rules (1)-(4), apply rules (5) and (6) to all applicable formulas. The resulting formula $F_{R}$ has no occurrences of $(T)_{1}^{*}$ or $\langle T\rangle_{2}^{*}$ either, it contains only occurrences of formulas of forms $\langle T\rangle_{1,2}$ and $(T\rangle_{1,2}^{*}$.

For each of the finitely many occurrences $\mu(d)$ in $F_{R}$ we construct $e_{\mu(d)}^{1,2}$, splitting $e^{1,2}$ into the environment $e_{0}^{1,2}$ defined above, and the environments $e_{\mu(d)}^{1,2}$, by assigning the type extension of $d$ in $e^{1,2}$ to $e_{\mu(d)}^{1,2}$. By construction, split $e^{1,2}\left[e_{0}^{1,2},\left(e_{\mu(d)}^{1,2}\right)_{\mu(d)}\right]$. To show $\llbracket F_{R} \rrbracket e^{1,2}=$ True, it suffices to show

$$
\begin{equation*}
\llbracket F_{c} \rrbracket e_{c}^{1,2}=\text { True } \tag{5}
\end{equation*}
$$

for every occurrence $c=\mu\left(d_{0}\right)$. Fix an occurrence $c$, and let $\delta=\{d \mid \mu(d)=c\}$. By definition of $e_{c}^{1,2}$, the type extension induced by each $d \in \delta$ in $e_{c}^{1,2}$ is $T_{1}^{d} \odot T_{2}^{d}$, and the type extension of each $d \in D_{X} \backslash \delta$ is an empty extension. Therefore, $\llbracket \mid T_{1}^{d} \odot T_{2}^{d} \nu_{1,2}^{*} \rrbracket e_{c}^{1,2}=$ True. If $F_{c} \equiv\left(T_{1}^{d} \odot T_{2}^{d}\right\rangle_{1,2}^{*}$ then the equation (5) already
holds. If $F_{c} \equiv\left(T_{1}^{d} \odot T_{2}^{d}\right)_{1,2}$, then $F_{c}$ was generated by one of the rules (1)-(3), which means that $\delta$ is a singleton set. Namely, if $F_{c}$ was generated by rules (1) or (2), then there is exactly one $d$ such that $\mu_{1}(d)=c$, namely $d_{0}$, and similarly if $F_{c}$ was generated by rule (3), then there is exactly one $d$ such that $\mu_{2}(d)=c$, again $d_{0}$. In both cases, $\delta=\left\{d_{0}\right\}$, so $d_{0}$ is the unique $d$ with type extension $T_{1}^{d} \odot T_{2}^{d}$, which means that $\llbracket\left(T_{1}^{d} \odot T_{2}^{d}\right)_{1,2} \rrbracket e_{c}^{1,2}=$ True and the equation (5) holds.

We finally apply idempotence to ensure that no $\left(T D_{m}^{*}\right.$ occurs more than once. The resulting formula $F_{R}^{\prime}$ is equivalent to $F_{R}$, so $\llbracket F_{R}^{\prime} \rrbracket e^{1,2}=$ True, $F_{R}^{\prime}$ is of the form $\mathcal{S}_{1,2} \llbracket C_{3} \rrbracket$, and $\mathcal{S}_{1} \llbracket C_{1} \rrbracket \circledast \mathcal{S}_{2} \llbracket C_{2} \rrbracket \stackrel{C}{\Longrightarrow} \mathcal{S}_{1,2} \llbracket C_{3} \rrbracket$. From $\mathcal{S}_{1,2} \llbracket C_{3} \rrbracket$ we recover $C_{3}$ using the inverse of the translation in Figure 6. By Lemma 13 we have $\llbracket C_{3} \rrbracket e=$ True, completing the proof.


[^0]:    Version of September 1, 2018, 11:41pm.

[^1]:    ${ }^{1}$ Acyclicities go beyond first-order logic because they involve non-local transitive closure properties.

